USING UNCERTAINTY AND SENSITIVITY ANALYSIS TO INFORM THE DESIGN OF NET-ZERO ENERGY VACCINE WAREHOUSES

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USING UNCERTAINTY AND SENSITIVITY ANALYSIS TO INFORM THE DESIGN OF NET-ZERO ENERGY VACCINE WAREHOUSES

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LIST OF SYMBOLS

C_{th}	Thermal mass of product stored
c_p	Product specific heat
$COP_{Cooling}$	Cooling system Coefficient of Performance
$COP_{Heating}$	Heating system Coefficient of Performance
COP_{Nom}	Nominal COP
d	Doses per recipient
$E_{Protection}$	Effectiveness of the doorway protection mechanism
E_{Total}	Total electricity consumed by the building
$\acute{E}$	Non-HVAC electricity consumption of the building
$F_{DoorOpen}$	Fraction of time that the door is open
F_{Flow}	Doorway flow factor
$m_{Infiltration}$	Mass of infiltrating air
M_{Ice}	Mass of ice on the evaporator coils
$\dot{m}_{Infiltration}$	Mass flow rate of infiltrating air during a simulation timestep
n	Number of significant design variables
p	Target group percentage

$Q_{Cooling}$	Total building cooling load
$Q_{FullFlow}$	Heat exchanged assuming no door protection mechanism
$Q_{Heating}$	Total building heating load
Q_{latent}	Latent cooling loads in refrigerated zones
Q_{Mixing}	Heat exchanged through the doorway
s	Number of months of stock stored in the warehouse
$SR\acute{C}_{BC}$	Re-normalized building control parameter SRC
SRC_{BC}	Original building control SRC
T_{Cond}	Condensing temperature
T_{db}	Outdoor air dry bulb temperature
V	Product storage volume
v_d	Vaccine volume per dose
w	Wastage factor
$W_{ZoneAir}$	Humidity ratio of the infiltration air
$W_{ColdRoomAir}$	Humidity ratio of the cold room air
x_i	Value of each design variable
B_0	Y-intercept for regression

B_i	Regression coefficient for each design variable
β_i	Standardized Regression Coefficient
$\Delta h_{IceToVapor}$	Latent heat absorbed to change from ice to vapor
Δt	Length of the simulation timestep
ρ	Product density
σ_{Total}	Standard deviation of the output energy consumption
σ_i	Standard deviation of the input parameter i
σ_A	Output standard deviation of the architectural parameter MCA
σ_{BC}	Output standard deviation of the building control parameter MCA

LIST OF ABBREVIATIONS

ACH	Air Changes per Hour
AEDG	Advanced Energy Design Guide
ANOVA	Analysis of Variance
ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning Engineers
BPS	Building Performance Simulation
CDD	Cooling Degree Day
COP	Coefficient of Performance
CRT	Controlled Room Temperature
CTSP	Cooling Temperature Set-Point
CV	Coefficient of Variance
DOE	Design of Experiments
DOE	Department of Energy
DSSB	Department of Basic Health Care (French)
EUI	Energy Use Intensity
GUI	Graphical User Interface
HDD	Heating Degree Day
Hib	Haemophilus influenza type b

HPV	Human papilomavirus
HTSP	Heating Temperature Set Point
HVAC	Heating, Ventilating and Air-Conditioning
IDF	Input Data File
IUV	Insulation U-Value
LHS	Latin Hypercube Sampling
MCA	Monte Carlo Analysis
MDG	Millennium Development Goal
MDS	Managing Drug Supply
MoH	Ministry of Health
NBI	National Buildings Institute
NPV	Net Present Value
NREL	National Renewable Energy Lab
NZE	Net-Zero Energy
OPV	Oral Polio Vaccine
OSC	Occupancy Sensor Control
PATH	Program for Appropriate Technology in Health
PCT	Pharmacie Centrale de Tunisie

PDF	Probability Distribution Function
PNNL	Pacific Northwest National Laboratory
RMSE	Root Mean Square Error
RSF	Research Support Facility
SHGC	Solar Heat Gain Coefficient
SIP	Structurally insulated panel
SRC	Standardized Regression Coefficient
TMY	Typical Meteorological Year
TMHC	Thermal Mass Heat Capacity
USAID	United States Agency for International Development
VCC	Vaccine Cold Chain
VSST	Vaccine Storage Sizing Tool
WHO	World Health Organization
WWR	Window to Wall Ratio

SUMMARY

The Vaccine Cold Chain, an important part of the process of storing and distributing vaccines, is by nature an energy intensive procedure. Since vaccines must be kept at low temperatures throughout their life cycles prior to administration, dedicated refrigerated storage facilities are required to maintain the proper conditions while the vaccines are kept on the shelf. A key component of this cold chain for developing and transitional countries is the primary vaccine storage warehouse. As the starting point for the distribution of vaccines throughout the country, these buildings have a significant amount of refrigerated space and therefore consume large amounts of energy. In addition, due to the multiple separate temperature regimes required for various vaccines and related supplies such as diluents, these warehouses have unique combinations of thermal zones that makes them a fundamentally different type of facility in comparison to other buildings that also require refrigerated storage, such as grocery stores. However, despite the energy intensive nature of these buildings, there has been a lack of detailed examination of these buildings by the global health sector to improve their energy efficiency.

Therefore, this thesis focuses on analyzing the relative importance of parameters for the design of an energy efficient primary vaccine storage warehouse with the end goal of achieving Net-Zero Energy operation. A total of 31 architectural design parameters, such as roof insulation U-Value and external wall thermal mass, along with 13 building control parameters, including evaporator coil defrost termination and thermostat set-points, are examined. The analysis is conducted across five locations in the developing world with significant variations in climate conditions: Buenos Aires, Argentina; Tunis, Tunisia; Asuncion, Paraguay; Mombasa, Kenya; and Bangkok, Thailand. Variations in the parameters are examined through the implementation of a Monte Carlo-based global uncertainty and sensitivity analysis to a case study building layout. A regression-based sensitivity analysis is used to analyze both the main effects of each parameter as well as the interactions between parameter pairs. The building layout used is based on the plans drafted for a new primary vaccine warehouse for the Tunisian Ministry of Health.

The results of this research indicate that for all climates examined, the building control parameters have a larger relative importance than the architectural design parameters in determining the warehouse energy consumption. This is due to the dominance of the most influential building control parameter examined, the Chilled Storage evaporator fan control strategy, in comparison to all other parameters within the design space. This parameter has a standardized regression coefficient over three times that of the next most influential parameter for all but one location. Without the dominance of this parameter, the building control parameters as a group have a lower relative importance than the architectural design parameters. However, their influence is far from inconsequential. On average, the top five building control parameters account for 22% of the variance from the uncertainty analysis, while the top five architectural parameters account for 59%. The relative importance of the entire group of building control parameters across all climates emphasizes the need for an integrated design method to ensure the delivery of an energy efficient primary vaccine warehouse. Through the inclusion of the personnel responsible for the building life cycle stages post construction, the designers can increase the probability that the warehouse will in fact operate as designed. Based on the results, a set of recommendations to help direct the attention of designers to the most important energy saving parameters for each climate has been formulated.

CHAPTER 1: INTRODUCTION

1.1 Motivation and Essential Background

Vaccines are one of the most important innovations of modern society. With the exceptions of access to clean water and sanitation, no other measure so positively impacts reduction in mortality rates as the proper administration of vaccines (Plotkin, Orenstein, and Offit, 2008). The World Health Organization (WHO) estimates that vaccines prevent the death of over 2.5 million children every year (WHO, UNICEF, and World Bank, 2012). In addition, vaccines prevent millions of cases of debilitating disease and disability. Immunization is also a key component towards achieving the Millennium Development Goals (MDGs), which are a set of eight goals that world leaders committed to in the year 2000 for improving human development and reducing poverty on the global scale (United Nations, 2013). Increased efforts for vaccination are particularly relevant to the fourth MDG of reducing mortality rates for children under the age of five (WHO et al., 2012). For the first time in recorded history, the number of children dying each year has fallen below 10 million as the result of increased vaccinations, along with clean water, sanitation, and the delivery of essential health interventions (WHO et al., 2012).

As the fight to improve global health through immunization continues to expand, so too will the need to increase and improve the infrastructure required to support vaccination. Currently, the WHO recommends a vaccine regimen that protects against eight diseases: tuberculosis, diphtheria, tetanus, pertussis, polio, measles, hepatitis B, and haemophilus influenza type b (Hib). However, in the past decade scientists have developed several new lifesaving vaccines for diseases including rotavirus, human papillomavirus (HPV), and meningococcal meningitis (WHO et al., 2012). As countries look to add vaccines such as these into their regimens, even in nations where the populations are relatively stable there will be a need for larger and more efficient facilities for vaccine storage. For instance, Tunisia has a current population growth rate of only 0.98%, which is not anticipated to increase (Sims, 2011). However, the capacity of Tunisia's vaccine distribution system and the volume of vaccines handled are set to increase up to five-fold by 2020 as pneumococcal, rotavirus, and HPV vaccines are added (WHO and PATH, 2013).

In order to ensure the potency of vaccines, many of them must be maintained at low temperatures from the time that they are manufactured until the time that they are administered (Galazka, Milstien, Kartoglu, and Zaffran, 2006). Because of this requirement for low temperatures, the activities that surround this process of storage and distribution are referred to as the Vaccine Cold Chain (VCC). An integral component of this cold chain in developing countries is the primary vaccine storage warehouse, the principal level store that receives vaccine directly from suppliers for holding prior to distribution to smaller regional storage facilities (Garnett, 2002). Primary vaccine stores are by nature energy-intensive buildings due to the large amount of refrigerated space required to keep vaccines within the proper temperature windows. Despite the large energy consumption of these primary storage warehouses, they are often designed without a focus on energy efficiency. A common practice is to convert an existing warehouse into a vaccine storage facility through the addition of walk-in coolers and freezers in a piecemeal manner as storage needs increase. This results in highly inefficient buildings that consume far more energy than necessary.

From the lack of documentation in the global health sector addressing energy concerns for vaccine storage facilities, it is not surprising that energy efficiency is currently not a focal point of primary vaccine storage warehouse design. Only the most recent version of the industry leading Managing Drug Supply (MDS) guidebook mentions that energy consumption should be taken into consideration for the planning and construction of these warehouses (Garnett, 2012). The lack of guidelines from global health literature may stem from a lack of research in VCC energy efficiency. The only study known to this author that focused directly on improving the energy efficiency of the vaccine cold chain is the Tunisian portion of Project Optimize, a recently completed study led by PATH (Program for Appropriate Technology in Health) and WHO (WHO and PATH, 2013). Optimize focused on turning a regional portion of the Tunisian vaccine cold chain into a Net-Zero Energy (NZE) process through the implementation of electric vehicles, solar panels, and building efficiency improvements such as LED lighting. However, the study only focused on retrofits to a regional store, and did not address primary stores. In addition, the study did not present a method that could be used by a design team for incorporating energy efficiency into the design process for vaccine storage facilities.

However, Optimize does indicate that the global health sector is beginning to pay attention to the energy concerns of the vaccine cold chain. The study was conducted under a partnership between WHO and PATH, and was funded by the Bill and Melinda Gates Foundation. These are three of the most influential organizations in the global health sector, and the fact that all of them helped bring to fruition a study which in part advocates for energy issues in the vaccine cold chain opens the door for more research in this area. The increasing demand for new vaccine storage facilities as a result of the MGDs and the expansion of vaccine regimens provides further motivation for research into this specific field, as the conclusions from research could potentially help to save a significant amount of the energy required to operate the vaccine cold chain. Additionally, research that identifies a method through which a design team can incorporate energy efficiency concerns into the design process may help to support a shift in the global health sector towards energy efficiency.

As primary vaccine warehouses are key components of the vaccine cold chain in most all developing countries and are also the buildings with the largest potential for energy consumption in this cold chain due to their large storage volumes, the research in this thesis is focused on energy efficient design for this building genre. Primary vaccine warehouses present a unique type of building, mainly due to the combination of the several distinctive temperature zones required for vaccines, as well as vaccine-related supplies such as syringes and safety boxes. Therefore, even though a significant amount of research exists for similar buildings such as grocery stores, refrigerated warehouses, and non-refrigerated warehouses, the guidelines established by these studies are all of limited applicability towards designing a primary vaccine warehouse.

Further motivation for examining the energy efficient design of this portion of the vaccine cold chain is provided by an ongoing project to design a Net-Zero Energy primary vaccine warehouse for the Department of Basic Health Care (DSSB) in Tunis, Tunisia. As the DSSB and the Tunisian Ministry of Health (MoH) were partners in Project Optimize, both of these groups have vested interests in continuing to "green" the vaccine cold chain in Tunisia. While the scope of Project Optimize included retrofitting existing buildings with energy efficiency improvements and solar modules in order to produce a Net-Zero Energy facility, this thesis focuses on designing and constructing a completely new facility that will be NZE from the start of operation. If constructed, the project will be the first known health facility in North Africa and the Middle East that is designed to achieve Net-Zero Energy by design. A portion of this project is also funded by the Bill and Melinda Gates foundation, indicating that energy efficient vaccine storage is a larger priority within the global health sector.

In the design of a new building, the common impression exists that the most important parameters for determining the energy efficiency of the facility are the physical design variables such as the insulation thickness and window glazing properties (Heller, Heater, and Frankel, 2011). However, recent studies have shown that the building operational control parameters, such as temperature set-points, can also have a substantial impact on energy consumption (Heller et al., 2011; Ruiz, Bertangolio, and Lemort, 2012; Wang, Mathew, and Pang, 2012). Building operational control parameters are distinct from architectural design parameters because unlike architectural parameters, these parameters are not only under the control of the design team and can be adjusted post-construction. They are subject to active change during the commissioning and operation of the building without large capital or time investment, such as would be required for a retrofit to alter the architectural parameters. The significant impact that building control parameters can have on the energy consumption of a facility emphasizes the importance of an integrated design method as advocated for in building performance-based design methods (ASHRAE, 2008; Pope and Tardif, 2011). In order to help ensure that the building performs as close as possible to how it was designed, the personnel responsible for the life stages of the building post construction must be included in the design process and understand the impact of these parameters on the energy consumption of building.

1.2 Thesis Scope: Research Questions, Hypotheses and Method

The first goal of this thesis is to analyze the relative importance of architectural design parameters and building control parameters on the energy consumption of a primary vaccine warehouse. This thesis tests the following hypothesis:

Building control parameters are as significant as architectural design parameters in the creation of an energy efficient primary vaccine storage warehouse.

This hypothesis is tested through a case study examining the building design proposed for the new primary vaccine warehouse for the DSSB in Tunis. Using the basic layout created for the building, a building energy model is developed. The influence of these two types of parameters is explored through global uncertainty and sensitivity analysis. The architectural parameters varied include all building envelope thermal properties such as insulation U-value, thermal mass, and air infiltration, as well as mechanical system performance such as equipment Coefficients of Performance (COP). The second category of building control parameters includes factors such as the building temperature set-points, daylighting control strategy, and evaporator fan control strategy. In addition to comparing the effect of building control parameters and architectural design parameters, this thesis answers the following research question:

What are the most influential design and building control parameters in determining the energy consumption of a Net-Zero Energy primary vaccine warehouse?

The results of the global sensitivity analysis are also used to answer this question. This allows for the identification of the relative importance of the parameters, establishing where focus and resources should be directed towards improving energy efficiency during the design process. While the initial uncertainty and sensitivity analysis was conducted assuming that the building was located in Tunis, several other locations were tested in order to answer the question:

How does the relative importance of design and operational control parameters vary across the prominent climates of the developing world?

The four additional cities are Mombasa, Kenya; Bangkok, Thailand; Buenos Aires, Argentina; and Asuncion, Paraguay.

In the process of answering these research questions, a second goal of this thesis is to illustrate a method that can be applied during the design process of a primary vaccine warehouse to assist in the creation of an energy efficient building. While the conclusions of this research and guidelines presented can help to establish rules of thumb that in general will lead to improved energy efficiency, it is strongly recommended that the method implemented in this thesis is applied on a case-specific basis to the design process each time that a primary vaccine warehouse is created. In order to assist in the adaptation of the method implemented in this thesis, a simplified design tool is being considered. However, the creation of this tool is beyond the scope of this thesis and is discussed further in section *4.7.3 Improving Practicality for Design.*

1.3 Thesis Outline

This thesis is organized as follows:

Chapter 1 provides the motivating factors and essential background for the research conducted in this thesis. It then presents the hypothesis and research questions that are the focus of the work, along with the methods that will be used for investigation.

Chapter 2 gives a review of the relevant literature for the proposed research, and discusses the knowledge gained from this review. The major topics examined encompass several fields including building performance simulation, Net-Zero Energy design method, vaccine cold chain design, and energy efficiency guidelines from industry.

Chapter 3 provides a detailed description of the method used to investigate the proposed hypothesis and research questions. First the creation of the building layout for the proposed vaccine warehouse for the DSSB is discussed, followed by a section on the formulation of the building energy model from the layout. Then the global uncertainty and sensitivity analysis approach implemented for the architectural and building control parameter investigation is discussed.

Chapter 4 discusses the results of the research performed. First the main effects of the uncertainty and sensitivity analysis are discussed, followed by a discussion of the interactions between the influential parameters. Finally, an evaluation of the method implemented in this thesis is given.

Chapter 5 completes the thesis with a discussion of the meaningful conclusions and insights gained from the work. In addition, the chapter suggests paths for future work to build on the research conducted.

CHAPTER 2: LITERATURE REVIEW AND BACKGROUND

This chapter presents a review of topics pertinent to the research questions addressed by this thesis. The discussion begins with a background of the VCC as it is currently implemented in developing countries and details the functions and operations of the primary vaccine storage warehouse. As the scope of the research presented in this thesis is focused on a vaccine storage warehouse, the chapter provides a detailed discussion of the efforts of Project Optimize, which is the only study known to this author that has examined the implementation of a Net-Zero Energy vaccine storage facility. After this section, the scope of the literature review is widened to the realm of efficient warehouse design and Net-Zero Energy design in general. This includes current design guidelines for storage warehouses that have been produced by members of industry for improving the energy efficiency of these buildings beyond the baseline constructions required by legal codes such as ASHRAE 90.1 (ASHRAE, 2004). The review shows that there are currently no widely available guidelines for the design of energy efficient vaccine storage facilities, and that guidelines from organizations such as the WHO have thus far focused only on the logistical side of the supply chain. The latter portion of the section provides an overview of the general design method for the creation of Net-Zero Energy buildings, including an overview of the definitions for this important term. From this discussion it is clear that the implementation of building performance simulations, along with parametric analysis tools, play vital roles in the creation of energy efficient buildings by informing decision making to allow for a performance based design process. The chapter then reviews the application of uncertainty and sensitivity analysis during design, including previous studies that have examined building control and operational uncertainty. Lastly, an overview of the current barriers to the implementation of global uncertainty and sensitivity analysis in practice is given. As a result, this chapter summarizes the background knowledge necessary for understanding the research presented in this thesis on the application of uncertainty and sensitivity analysis to the design of Net-Zero Energy vaccine warehouses.

2.1 The Vaccine Cold Chain

The Vaccine Cold Chain, an important part of the process of storing and distributing vaccines, is by nature an energy intensive procedure. This cold chain encompasses the entire lifecycle of a vaccine from the time that it is produced until it is administered. Since vaccines must be kept at low temperatures throughout the duration of their life cycles, dedicated refrigerated storage facilities are required to maintain vaccines at the proper conditions. During transportation, passive or active means, or a combination of the two, can be used to maintain the vaccine within the required temperature regimes. To ensure the potency and safety of vaccines, careful attention must be paid to maintaining the temperature ranges recommended for storage by the WHO (Galazka et al., 2006). Many vaccines are susceptible to degradation as a result of both excessive heat and cold, and hence maintaining an acceptable thermal environment is of the upmost priority. For any given developing country, there are often several storage points in the VCC through which the product must pass, as the diagram for the VCC for Tunisia shown in Figure 1 illustrates. A key component of the Vaccine Cold Chain for developing and transitional countries is the primary vaccine storage warehouse (Garnett, 2002).

The primary warehouse is the starting point in the distribution of an in-country vaccine cold chain. These warehouses are responsible for the initial storage all of the vaccines that are imported into the country from international suppliers, as well as the vaccines produced in-country (Garnett, 2002; WHO and PATH, 2013). Due to the unique storage requirements of the different supplies that must be stored in a vaccine warehouse, the general layout of a primary vaccine warehouse encompasses four different temperature zones as recommended by WHO: a 20°C zone for frozen vaccine storage, a 5°C zone for refrigerated vaccine storage, a controlled room temperature zone kept between 15°C and 25°C for diluents, and an ambient zone for dry goods such as syringes and safety kits kept between 15°C and 32°C (Garnett, 2002; PATH, 2012). The combination of these unique multiple temperature zones makes the primary vaccine storage warehouse a fundamentally different facility than other buildings that also require refrigerated walk-in storage, such as a supermarket. While a typical supermarket is perhaps the most similar building type to a vaccine storage facility due to the multiple walk-in temperature zones required, the ratios between refrigerated and non-refrigerated storage volumes are significantly different, as are the heating and cooling set-points for the non-refrigerated zones in the store (Leach, Hale, Hirsch, and Torcellini, 2009).

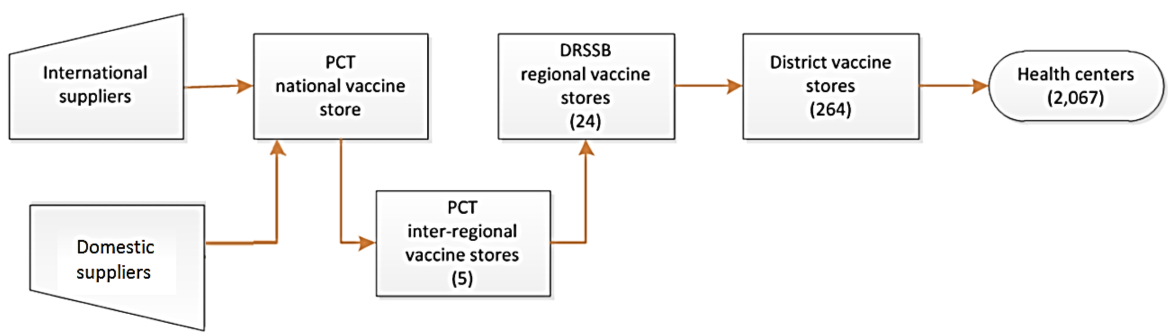


Figure 1. Prototypical Example of a VCC for developing and transitional countries; the VCC for Tunisia as adapted from (WHO and PATH, 2013)

On account of the substantial amount of vaccines that must be stored at primary vaccine warehouses, and the consequently large amount of refrigerated volume, these buildings have the potential to consume a considerable amount of energy. Therefore, improving the efficiency of these warehouses is a critical step towards reducing the energy consumption of the VCC in developing and transitional countries. However, to date there has been very little if any attention directed towards making primary level vaccine storage facilities more energy-efficient. This is evident when reviewing several recent publications from the large international players in global health such as the WHO and USAID (United States Agency for International Development). For instance, the most recent published guidelines from the WHO on vaccine storage facilities make no mention of energy efficient design throughout the entire publication (Garnett, 2002). It is only in some of the most recent documentation, published in MDS-3, that guidelines for energy efficiency are even discussed (Garnett, 2012). However, these are very general guidelines, and are not specific prescriptions for vaccine storage warehouses, which are based on target research. Instead, they are blanket recommendations and general rules of thumb for buildings based on climate zone, which fail to take into consideration the unique function and operation of the primary vaccine storage facility. Therefore, it is not surprising that in the currently implemented methods for constructing a primary vaccine warehouse there is little, if any, consideration of the building energy consumption throughout the design process. Instead, a common occurrence is that an aged building under the jurisdiction of a nation's Ministry of Health is selected for conversion into a vaccine storage facility. The building is retrofitted with a walk-in cold room and few if any other modifications are made. The current vaccine storage facility for the DSSB in Tunisia is an example of this process, as their vaccine warehouse comprises several small walk-in coolers within a large sheet metal building. The PCT facility in Tunis is a counter example, with purpose-built, energy efficient structures. So, the opportunity to construct such structures in developing and transitioning countries exists.

2.2 Project Optimize

The recently completed Project Optimize, a joint undertaking funded by the Bill and Melinda Gates Foundation partnering with WHO and PATH, was one of the most recent programs by international aid organizations to improve the management and storage of vaccines in developing and transitional countries. The scope of the program was extremely wide and examined vaccine supply chain related issues from on-line registry management to mobile vaccine warehouses in five countries around the world (PATH and WHO, 2013). The portion of the project that is relevant to this research is the Net-Zero Energy supply chain that was implemented in Tunisia, as it was the first organized initiative to radically improve the energy efficiency of the VCC in the developing and transitional worlds. The Tunisian portion of Project Optimize was carried out over three years, from 2009-2012, and the goal of the project was defined as follows (WHO and PATH, 2013):

To demonstrate at regional, district, and health center levels an environmentally friendly vaccine distribution system that met three objectives:

1. Net-Zero Energy – offsets the energy consumed with solar energy produced by photovoltaic panels;
2. Prevents Vaccine Freezing – prevents the accidental freezing of vaccines during transport; and
3. Temperature Monitoring – ensures that required temperatures for vaccine storage are maintained at all times.

For the purposes of reviewing this initiative, only the first objective is considered, as the other two are beyond the scope of this thesis. In order to establish the boundary for the energy consumption that will be taken into consideration, a unique definition of Net-Zero Energy was implemented: "Net-zero energy, in the context of the vaccine supply chain, describes a system that offsets the nonrenewable energy consumed by transporting and storing vaccines and medicines against the production of renewable solar electricity." (WHO and PATH, 2013) Unlike other definitions commonly offered in building performance literature, the system energy in this instance extends beyond the boundary of the building to include energy consumed to transport the vaccines. The transportation energy consumption is included due to the fact that the goal is to offset the energy of the entire supply chain, rather than solely the facility's energy demand. While the definition establishes a general idea of the scope for NZE, it leaves out the two key parameters as discussed later in section ***2.3 Defining Net-Zero Energy***: the specific metric of the energy balance and the balance period. However, from reviewing the final report, it was inferred that a site Net-Zero definition was implemented (WHO and PATH, 2013), an assumption that was confirmed through discussion with the lead NZE consultant of Project Optimize (Lloyd, 2013).

In order to obtain NZE operation, Project Optimize followed the established method of first assigning priority to energy demand reduction through efficiency measures, and then offsetting the remaining energy consumption with electricity generated from renewable electricity (Crawley, Pless, and Torcellini, 2009). However, the project did not involve the design or construction of new facilities, and so only efficiency improvements through retrofits were considered for the existing buildings. No specific details were included about the buildings in which the vaccines are stored; however the report does describe the facilities as "old, poorly insulated buildings with poorly fitting windows and doors" (WHO and PATH, 2013). Despite the noted poor thermal performance of the building, no significant retrofits of the facilities were undertaken. The measures to improve the energy efficiency of the building included upgrading to LED lighting, switching from desktop to laptop computers, and replacement of old refrigerators with new, more efficient equipment. Figure 2 shows the results of the upgrades in comparison to the baseline energy consumption in units of USD per year.

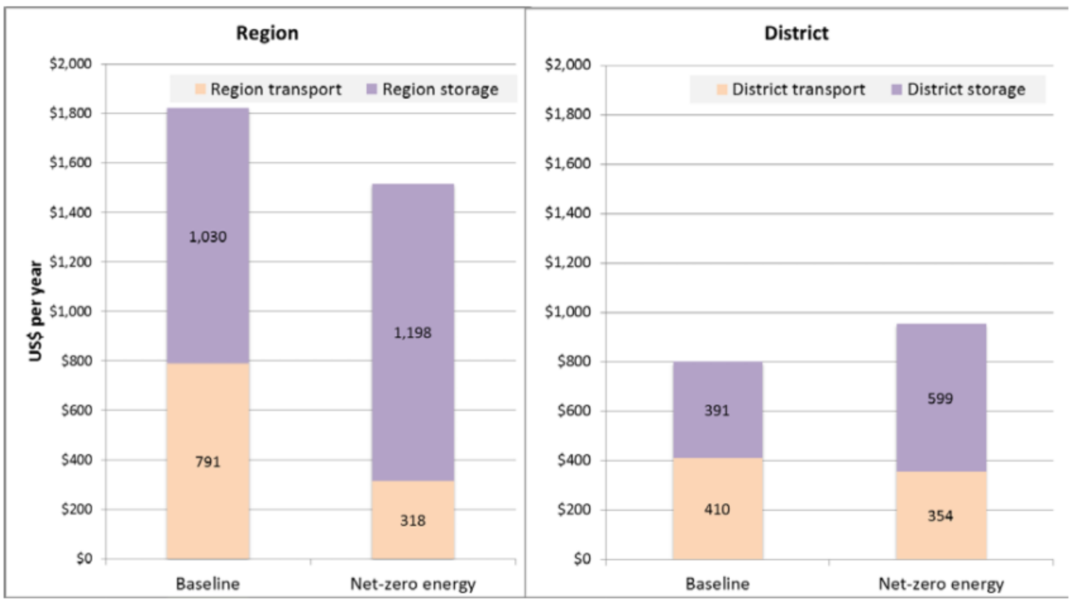


Figure 2. Annual cost of energy for the regional and district health stores; given for both the baseline cost prior to the NZE upgrades and with the NZE upgrades (WHO and PATH, 2013)

As Figure 2 illustrates, the energy consumption for the stores at both the district and regional levels increased from the baseline measurements during the monitoring period after the energy efficiency measures were implemented. The report acknowledges that the increased use of air-conditioning during the project monitoring phase is responsible for the increase in storage energy consumption observed. No data on the breakdown of the energy consumption are provided to support this claim; so it is difficult to assess the effectiveness of the energy efficiency upgrades. The increase in energy consumption despite the implemented efficiency upgrades suggests the importance of accessing building control uncertainties when selecting energy efficiency measures and was a significant motivation for the inclusion of this parameter type in this thesis.

While the report acknowledges that an energy audit was conducted to analyze the consumption of the system, it does not specify the calculated annual energy consumption of the facility and the corresponding target annual energy production for the solar system sizing. The facility consumption and solar production of the regional store that was monitored for nine months of the year after the Net-Zero initiative are shown in Figure 3. From the figure, it appears as though the solar array is significantly oversized. For the period monitored, the solar production exceeds consumption by 8548 kWh, so that the array is producing 167% of the monitored energy consumption. While the only monitored period shown is from January to September, it is safe to assume that this over-sizing factor would only increase if the months of October to December were included, as the trend in the data shows a much larger disparity between production and consumption for the winter months in comparison to the summer months. The significant over-sizing of the array may be purposeful or accidental, but without further information such as of the model projections for consumption and production it is difficult to draw any conclusions about the success of the design implemented method to efficiently achieve NZE operation.

Project Optimize is an extremely valuable resource. The project indicates that the world health arena is becoming aware of the energy costs of vaccine storage and the significant improvements that can be made to make the process more sustainable. Optimize established a foundation for Net-Zero Energy projects in the developing world cold chain, upon which the research of this thesis expands. The lack of method documentation and the absence of any new building design within the project scope leave a gap to be filled for establishing a process by which designers can create new Net-Zero Energy vaccine warehouses. The capacity of Tunisia's vaccine distribution system and the value of vaccines handled are set to increase up to five-fold by 2020 (WHO and PATH, 2013). This projection alone justifies planning for the construction of new, highly energy efficient storage warehouses to help ensure that the energy costs of storing vaccines does not become a burden to the Ministry of Health.

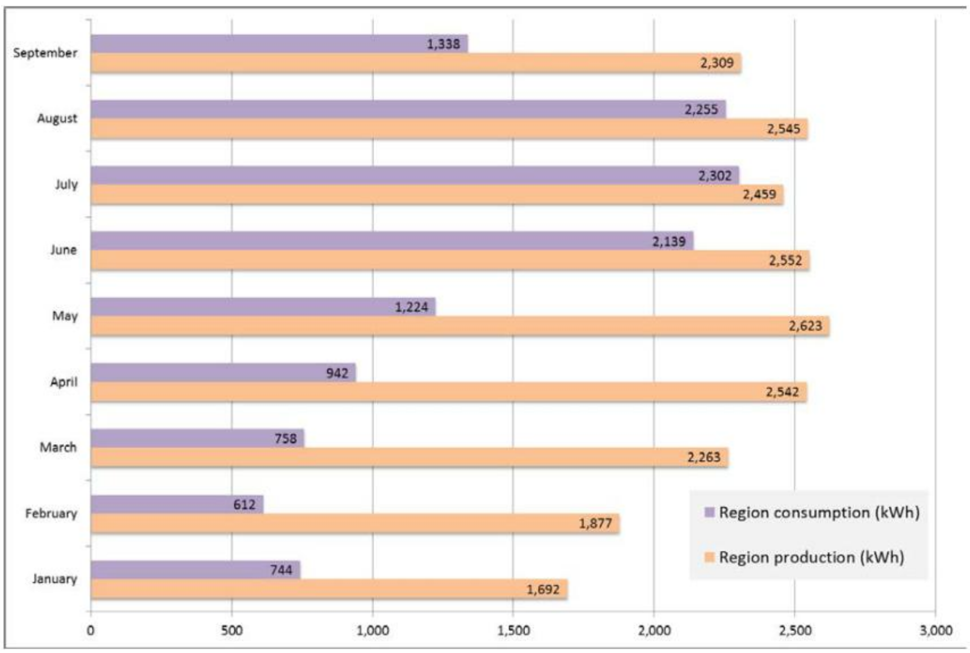


Figure 3. Monitored monthly energy consumption and solar array production at the regional level store, January – September 2012 (WHO and PATH, 2013)

2.3 Defining Net-Zero Energy

For the purposes of this thesis, it is important to examine the working definitions for the term *Net-Zero Energy Building*. Multiple definitions for Net-Zero Energy have been offered in the literature, although none has been recognized as the standard definition by the building energy performance community (Marszal et al., 2011). A significant factor for the lack of a common definition is that, based on the interests of the parties involved and the unique characteristics of a project, a particular definition may be more useful for the design team than the other alternatives. Torcellini summarizes these interests as (1) the project goals, (2) the motivations of the investors, (3) the concerns about the climate and greenhouse gas emissions, and (4) the energy costs (Torcellini, Pless, Deru, and Crawley, 2006). The definition of a goal such as NZE is critical to the design process because the way in which the goal of Net-Zero is defined will influence designers who strive to meet it (Deru and Torcellini, 2004). Therefore an overview of the existing definitions offered by literature is provided.

While NZE buildings have only recently started to gain international attention, the general concept of a zero energy building has been established in both theory and practice for over three decades. One of the first Net-Zero designs was the Zero Energy House in Denmark in 1975, which was a pioneer in formulating the Passive Haus method of design and construction that is now one of the standards for building energy efficiency (Esbensen and Korsgaard, 1977). Another well-documented early example is the Self Sufficient Solar House in Frieburg, built by the Fraunhofer Institute in 1992 (Stahl, Voss, and Goetzberger, 1994). This house was constructed as a demonstration project to show that, with the correct design, a German house could be powered solely by solar energy. While zero energy buildings have existed for over 30 years, it is only recently that there has been a critical examination of the definition for this genre of facilities. In general, there are two very different classifications of zero energy buildings. The first is the autonomous zero energy building, which is not grid-tied. These buildings operate completely independently of any external energy infrastructure and source all of their energy demand from renewable sources (Sartori, Napolitano, and Voss, 2012).

The second type is the Net-Zero Energy building, whose connection to the grid serves as a mechanism of energy balance. This allows for the excess electricity generated by the building during hours of low usage to be exported to the grid to be used by other facilities. In the same manner, when the renewable sources do not meet the energy demand of the building, electricity is imported from the grid to fill the gap between consumption and renewable energy production. This exchange of energy with the grid allows for the peak capacity of the renewable energy generation systems to be reduced in comparison to autonomous zero energy facilities, since the technology is not responsible for meeting the entire load of the building at any given time. Instead, the exported and imported energy must achieve a net zero balance, hence the name (Torcellini et al., 2006).

A literature review of Net-Zero Energy building definitions by Marszal argues that the most important parameter in an NZE definition is the metric for the energy balance (Marszal et al., 2011). In 2006, the National Renewable Energy Lab (NREL) published what has become one of the most widely referenced articles to offer concrete classifications for the different metrics that can be used in the definition of an NZE building (Torcellini et al., 2006). Four different definitions for a Net-Zero building are established, each with a different metric: Net-Zero Site Energy, Net-Zero Source Energy, Net-Zero Energy Costs, and Net-Zero Energy Emissions. Under the first definition of *Net-Zero Site Energy*, the facility produces at least as much energy as it uses in a year, when accounted for at the site (Torcellini et al., 2006). This is a very valuable definition as it is easily monitored on site. So, the relative proportions of generation and consumption can always be examined to assess whether the facility is on track to meet the NZE goal. Since this definition includes the fewest external fluctuations that influence the Net-Zero goal, it is the most consistent and repeatable definition. These characteristics are very favorable for comparing the relative performance between projects (Torcellini et al., 2006).

However, a shortcoming of this definition is that it does not account for the entropy difference between different supplies of energy. For instance, 1 kWh of natural gas is rated the same as 1 kWh of electricity, even though electricity is over three times more valuable than natural gas from an entropy standpoint. To correct for this accounting flaw, a second classification of Net-Zero is defined: *Net-Zero Source Energy* building. This is a building that produces as much energy as it uses as measured at the energy source (Torcellini et al., 2006). Power generation and transmission factors are used to correct for the losses and arrive at a comparable unit of primary energy. The method by which these factors are calculated is not universally established and results in a source of variability for the way in which the factor is calculated. For instance, one project may use standard regional utility averages based on monthly averages while another may use a more detailed factor to account for the hourly variation in the generation mix from the grid. As a result, even if the facilities are identical and therefore should use an equivalent amount of source energy, their respective energy balances will be different due to the discrepancy in source factors. In addition, as the generation mix from the grid changes over the lifetime of the building, the goal of achieving Net-Zero operation each year may become substantially easier or more difficult depending on the integration of renewable technologies.

The next two metrics by which an NZE building is defined are distinctly different from the first two because neither directly balances energy. The third classification is a *Net-Zero Energy Cost* building and is defined as a building that receives as much financial credit for exported energy as it is charged on its utility bills. This entails that the credit received for electricity exported offsets all of the charges for electricity and gas used including metering, distribution, peak demand, and taxes (Torcellini et al., 2006). In a similar manner to source NZE buildings, the ability of the facility to achieve Net-Zero for any given year can vary widely due to fluctuations in utility rates even if the energy performance is consistent. For a commercial building, the cost NZE goal is usually the hardest to reach. This is because several advantageous characteristics for the utility rate structure, such as low peak demand charges, no capacity limits on PV generation, and a renewable generation credit rate equal to the utility rate, are required for the goal to be feasible (Torcellini et al., 2006). The final classification is a *Net-Zero Energy Emissions* building and is defined as a building that produces at least as much emissions-free renewable energy as it uses from emissions-producing energy sources. For this type of building, the accounting does not penalize any utility grid sources that are non-carbon emitting. Therefore, a house that is completely fed by grid electricity that is generated with hydro or nuclear power is automatically a Net-Zero emissions building, without any efficiency improvements or on site renewable generation. Since this definition allows for substantial variation in the ability to achieve the NZE goal regardless of the merit of the building design, it has significant limitations for application to design practice.

2.4 Guidelines to Efficient Warehouse Design

As mentioned in section *2.1 The Vaccine Cold Chain*, the global health sector currently provides only very limited guidance on the design of energy efficient vaccine storage warehouses. Only one prominent guideline that directly addresses energy efficient vaccine warehousing was found, the third edition of Managing Drug Supply, the leading reference on managing vaccines and other essential medicines in developing countries (Garnett, 2012). In chapter 42 of this manual, Andrew Garnett, who was the lead architect of the warehouse implemented in this thesis, describes the steps for planning and building medical storage facilities. A brief section is included that provides a high level overview of the design strategies for different climates that may help to assist in conserving energy, as well as maintaining a comfortable indoor climate. The recommendations from this section are shown in Table 1. These recommendations are not directed specifically toward vaccine storage warehouses that include the large number of thermal zones required for a primary store, but are for all medical storage warehouses in general. Due to the fact that these are very high level recommendations and are not specifically directed towards vaccine storage warehouses, their use for designers in practice is limited. In addition, the vague language used in the chapter avoids adequate description of even some of the most basic rules of thumb, such as suggested orientations for daylighting.

Table 1. Recommendations for energy and environmental control for medical warehouses (Garnett, 2012)

Climate	• **Recommendation**
Cold Climate	• Storage buildings should be well insulated
Hot, Humid Climates	• Effective cross ventilation is required
Hot, Dry Climates	• Good construction and nighttime ventilation can maintain daytime temperatures several degrees below ambient temperatures
General application	• Passive design using trees for shade and shelter • Correctly orienting the building for natural lighting and ventilation • Selecting appropriate building materials and methods to control internal temperatures

Due to the lack of guidelines for the specific application to vaccine warehousing, two prominent guidelines for warehousing without refrigerated storage were examined. The first publication reviewed is the ASHRAE Advanced Energy Design Guide for Small Warehouses and Self-Storage Buildings (ASHRAE, 2008). This guide is aimed at helping warehouses achieve 30% energy savings in comparison to warehouses designed to the minimum requirements of ASHRAE 90.1-1999. It is intended to provide insight into cost effective efficiency measures for small warehouses and self-storage buildings in the range of 8,000 to

50,000 square feet (743 m^2 to 4,645 m^2), as a survey of currently existing warehouses in the United Stated found that this size range encompasses 80% of the most recent warehouse constructions (Liu, Jarnagin, Jiang, and Gowri, 2007). The guide provides prescriptive recommendations for energy efficient design and operation of these types of buildings across several different areas including: energy efficient electric lighting and daylighting, air infiltration reduction, improved building envelope insulation, improved glazing thermal properties, and energy efficient HVAC system selection and operation. The prescriptive recommendations of each type of warehouse are specific to eight different climate zones which ASHRAE uses to characterize the US climate (ASHRAE, 2008).

A technical study conducted by Pacific Northwest National Laboratory (PNNL) underpins the prescriptive recommendations presented in the guide, and allows for a more detailed examination of the method behind the study and the subsequent results (Liu et al., 2007). In order to analyze the differences in energy consumption between the baseline and improved warehouse buildings, the study employs an energy modeling and simulation approach using EnergyPlus. Two prototype building energy models were constructed for study: an 8,000 ft^2 Self-Storage Warehouse and a 50,000 ft^2 Small Warehouse. Three versions of these models were constructed for each climate zone: A 90.1-1999 base case, a 90.1-2004 base case, and an improved model that implements all of the prescribed recommendations.

The results indicate that reductions in lighting energy are by far the biggest source of energy efficiency improvements for warehouses in hot and mild climate zones as shown in Figure 4. For instance, lighting and daylighting alone provide a 44% reduction in total energy consumption for the 50,000 ft^2 warehouse in the hottest climate zone which includes locations such as Miami. In contrast, including all of the remaining efficiency improvements only reduces the energy consumption by an additional 6% (Liu et al., 2007). In cold climates, lighting and heating energy consumption dominate. Together they account for 97% of the energy savings in the cold, humid climate of Burlington, Vermont. However, neither the Advanced Energy Design Guide (AEDG) nor the more technical PNNL study behind it provides any insight into how significant each of the prescriptive recommendations is. For instance, no indication is given as to the portion of the reduced lighting consumption that comes from the inclusion of skylights versus the increased efficiency of the lighting fixtures. Therefore, the guide does not present the designer with a way to understand the effects of different design parameters, which is an essential for NZE design as discussed in the next section.

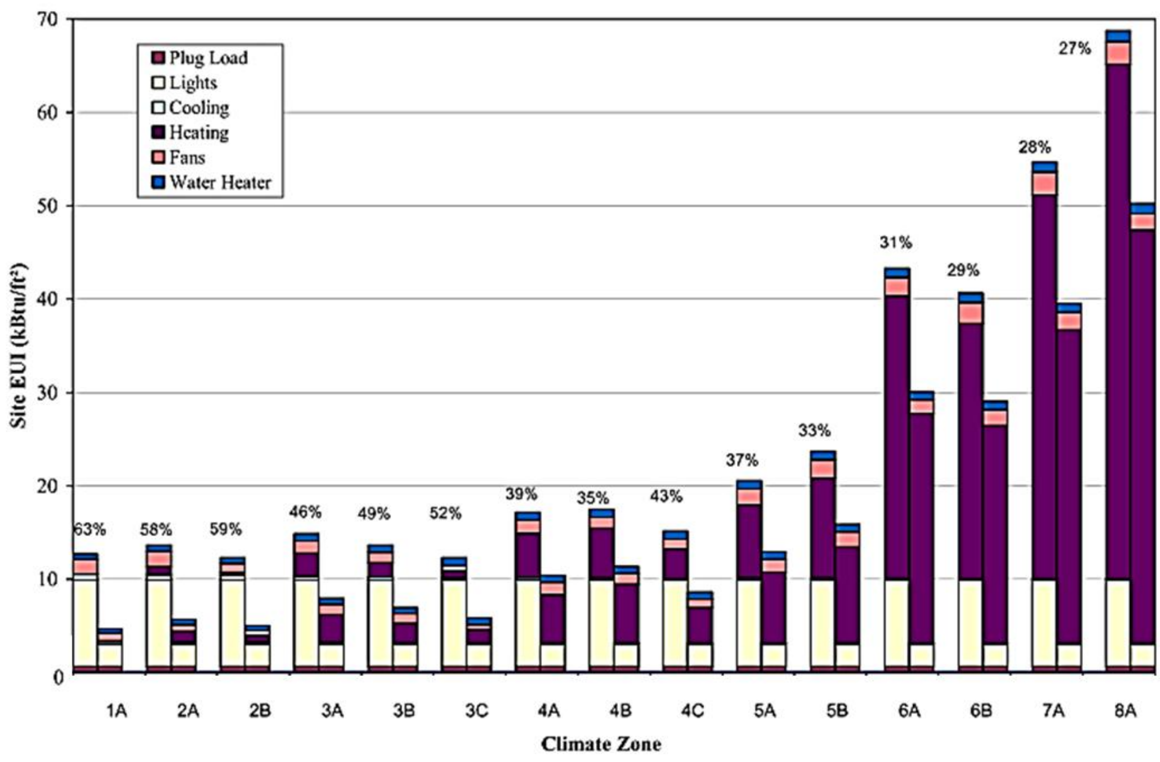


Figure 4. Baseline and improved end use energy for an 8,000 ft^2 Self Storage warehouse, ASHRAE 90.1-1999 as baseline (Liu et al., 2007)

While the ASHRAE Advanced Energy Design Guide focuses on energy efficiency towards Net-Zero Energy operation, the more recent Target Zero guideline funded by the UK steel construction sector focuses on both energy efficiency and renewable energy generation to achieve Net-Zero Energy in regards to a carbon emissions balance (Tata Steel, British Constructional Steelwork Association, AECOM, Cyril Sweett, and The Steel Construction Institute, 2011). Another significant difference is that the scope of the guide includes the concerns of embodied carbon for construction materials as well as the emitted carbon from operation. Lastly, this study is based on a significantly larger type of warehouse than the ASHRAE AEDG, with the prototype building that the research is based on being a 34,000 m^2 distribution warehouse.

The Target Zero study employs a similar method of prescriptive recommendation packages towards achieving NZE compared with a baseline standard building. However, instead of including only one prescriptive package, the Target Zero study presents three different levels of package recommendations, from moderate to intensive modifications to a baseline building configuration. Building energy simulation is used to compare the baseline building model with a building model for each the three different recommendation levels. A significant improvement over the ASHRAE study is that the Target Zero study directly addresses the individual effects of each of the recommended energy consumption measures, providing the percentage reduction in annual carbon dioxide emissions for each individual measure from each package. This allows a designer following the guidelines a much clearer understanding of the potential effect of each building efficiency improvement.

The results of the Target Zero study agree with the ASHRAE AEDG that lighting improvements offer the most substantial energy reduction potential for warehouse buildings. For the prototype warehouse, improvements in lighting fixture efficiency alone, from 4.2 W/m^2 per 100 lux to 1.79 W/m^2 per 100 lux, reduced the annual carbon dioxide emissions by more than

30% (Tata Steel et al., 2011). The sensitivity of the prototype warehouse to individual parameter variation is included in Figure 5. The study concluded that the most cost effective non-lighting efficiency improvements are skylight U-value improvement, air infiltration reduction, and reductions in envelope thermal bridging. However, none of the non-lighting efficiency measures studied produce near the improvements of lighting energy reduction, with each of the other very cost effective improvements producing less than a 5% reduction in carbon consumption.

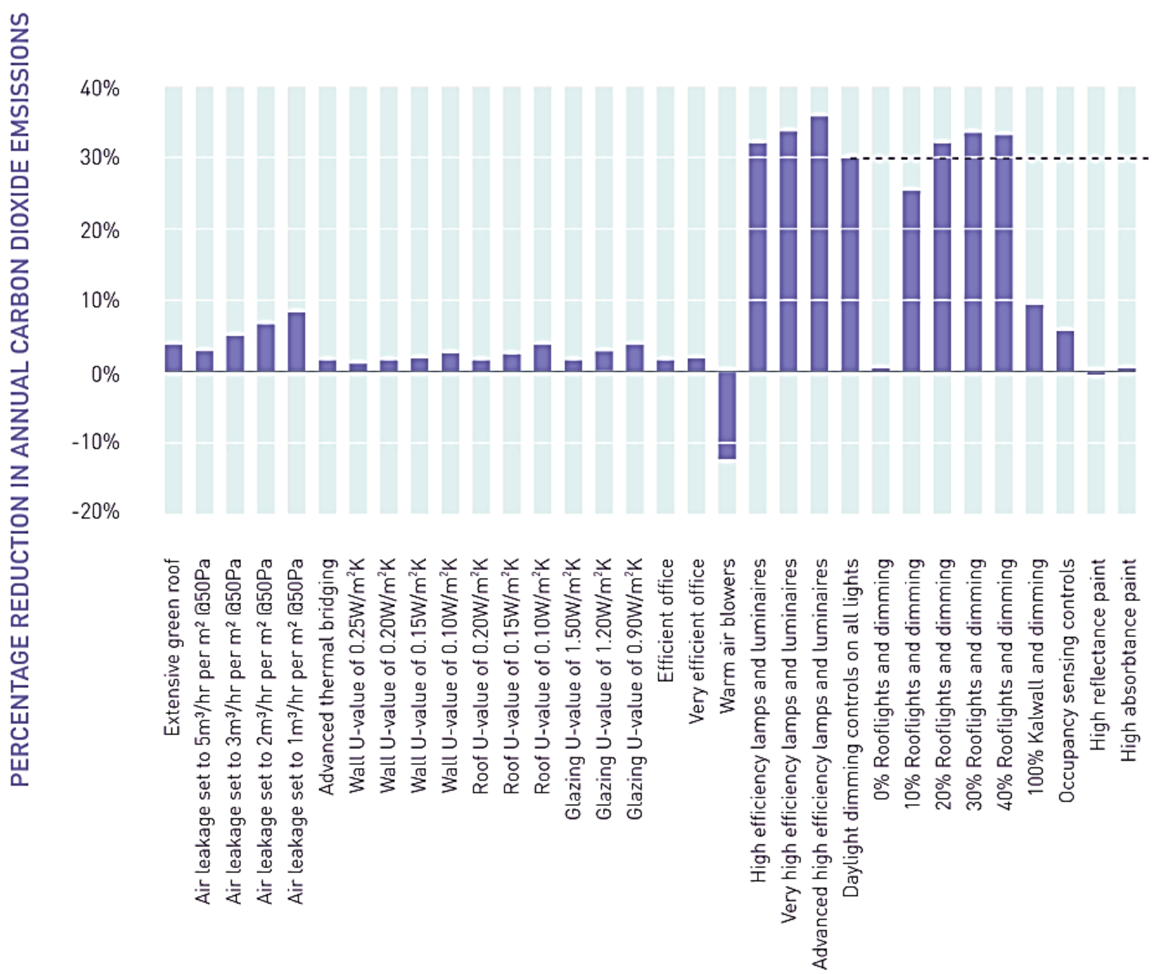


Figure 5. Energy Savings from individual parameters, Target Zero warehouse (Tata Steel et al., 2011)

2.5 Net- Zero Energy Design Method

Traditionally, building performance has not been at the center of focus for the building design process. In the established archetype, the building owner and architect produce a building program, which contains the specifications for the building in terms of functional, economic, and time requirements for the building (Deru and Torcellini, 2004). Performance goals often are not established in a program, and so the architect designs the building in the absence of any performance criteria other than those specified by building energy codes such as ASHRAE 90.1. Following the architectural design, the project engineers devise mechanical and electrical systems to meet the heating, cooling, and electrical demands of the building. Even if performance goals are set, the structure of the usual process hinders reaching these goals. The building design process has been a predominantly linear procedure, and often rules of thumb are used as the initial guidelines for the design (Attia, 2012; Mahdavi and Lam, 1993). The designers then model the building to verify that it meets the performance goals, and if the proposed design falls short then the design is reworked until the performance goals are met. This results in an often tedious trial and error approach to building design. Such a slow and cumbersome design approach is unacceptable for the creation of a Net-Zero Energy building; in order to accomplish such significant improvements in energy efficiency, a much more integrated design process is necessary (Anseeuw, Grove, and Marseille, 2008; ASHRAE, 2008; Pope and Tardif, 2011).

Recently, members of both academia and industry have advocated for, and in several cases implemented, a more informed and integrated design process for developing Net-Zero Energy buildings, and more energy efficient buildings in general. While the specifics of the methods may vary slightly from source to source, there are several common characteristics of this improved design method that most share and that establish a consistent framework. The first key characteristic is the establishment of clear and specific performance based design goals (ASHRAE, 2008; Deru and Torcellini, 2004; Hirsch, 2011; Marseille, 2011). To achieve the exceptional building performance that is necessary for a NZE building, the entire team needs to buy into the effort and have a focused performance goal in which to invest (Deru and Torcellini, 2004). This commitment comes first and foremost from the owner, who ensures that the rest of the project team including the architects, engineers, and building manager buy into the performance goals. It is integral that these goals are clear and specific. A study conducted by NREL of six high performance buildings showed that out of six buildings that had set clear performance goals, only one had energy performance that was significantly lower than expected during operation (Deru and Torcellini, 2004).

The second characteristic of an improved process for energy efficient design is to include a site climate and energy resource assessment prior to any building design (Amerongen and Richardson, 2011; Marseille, 2011). For a project in which the site for the building has not been determined as a result of prior constraints, this entails conducting assessments of multiple potential sites to analyze which have the most advantageous climates and renewable energy resource potential. Conducting a site assessment at the beginning of the design process allows for early feasibility studies of the potential to deploy various active and passive renewable strategies such as natural ventilation, daylighting, and solar PV panels. The higher that the renewable resource portfolio of a site is, the more options that the design team is able to explore and the greater the chances that the project will be able to achieve Net-Zero operation through on-site energy generation alone. During the site assessment phase, an important parameter to establish for each site is the project’s boundary. As the building site may be substantially larger than the anticipated footprint of the building itself, this additional area may provide space for renewable energy generation. However, it is always more favorable to keep the renewable energy generation within the building footprint, as this is the only area that a building is guaranteed to have as "its own" throughout its lifetime (Torcellini et al., 2006).

The third component of a Net-Zero Energy design process is what is commonly referred to as "Model Driven Design." Here, energy modeling is included in the design process from the very beginning of conceptual design, and is carried through the commissioning and into operation (Hirsch, 2011; Marseille, 2011). By modeling the building at the start of the conceptual design process, realistic assessments of the performance goals of the project can be made early on, and simplified models may help to reveal the most important energy efficiency measures. For instance, in the design process for the NREL Research Support Facility (RSF), early modeling indicated that daylighting and natural ventilation were integral to achieving the energy goals outlined for the project (Hirsch, 2011). Through the early implementation of modeling, the design team has a significantly larger body of knowledge to inform their decisions. This can lead to significant savings, as design decisions during the early stages have the largest potential impact on energy and cost (Krygiel and Nies, 2008). Properly informing early design decisions is crucial to a successful NZE building because 20% percent of the design decisions taken during early design phases subsequently influence 80% of all design decisions (Bogenstatter, 2000). Figure 6 summarizes the relationship between potential savings and the effort of an NZE design team over the course of the design process, showing that to achieve a successful Net-Zero Energy building, a substantially higher initial effort is required in comparison to a traditional building design process.

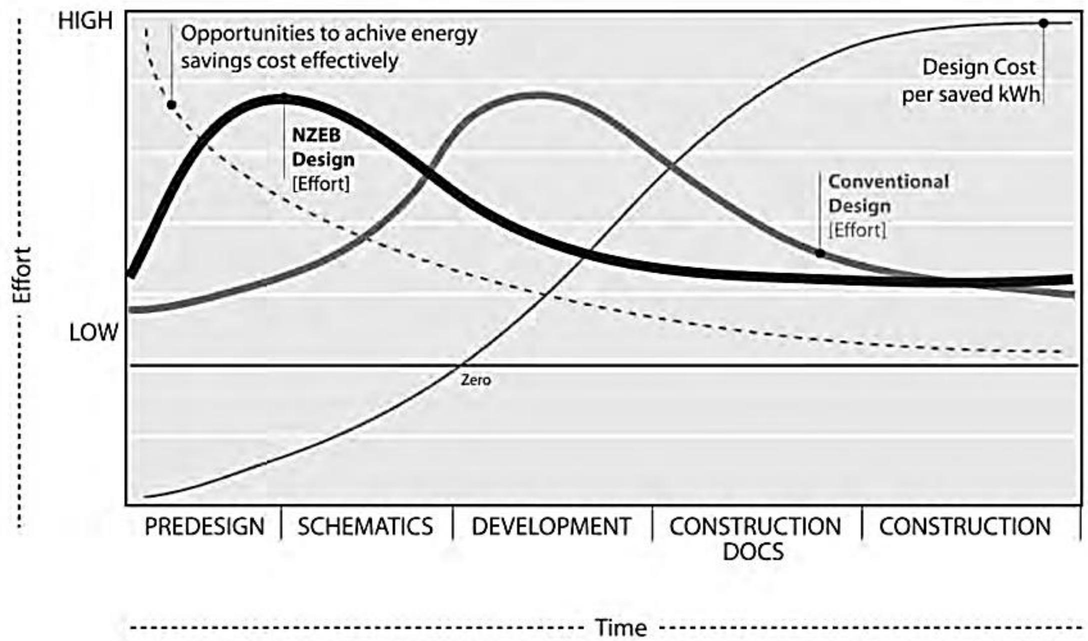


Figure 6. The design process in terms of effort, energy savings, and design cost for NZEB as suggested by IEA Task 40 (Attia, 2012)

The use of energy modeling and simulation is increasingly important as buildings become more complex and as the performance responses become less intuitive (Hobbs, Morbitzer, Spires, Strachan, and Waebster, 2003). For instance, the NREL RSF facility employed several novel technologies, such as an underground air labyrinth, for which separate models had to be constructed in order to properly design and understand the potential energy saving benefits (Hirsch, 2011). The energy model must therefore guide the team in decision making throughout the design and continue to evolve in sophistication as the design progresses. The RSF facility again provides a pertinent example, as the stringent Energy Use Intensity (EUI) goals required for the eQUEST energy model of the building to comprise 247 individual thermal zones (Hirsch, 2011). However, the use of the building energy model does not stop when the design is finished. In order to ensure that the building is operating at peak performance, the model should be used during operation to monitor and verify that the building performs as expected (Hirsch, 2011;

Marseille, 2011). For instance, using post-occupancy data such as lighting and small power loads as inputs for their building energy model, Menez and Crips were able to calibrate the electricity consumption of a large office building to within an accuracy of 3% (Menezes, Cripps, Bouchlaghem, and Buswell, 2012). The calibrated model revealed that the real building performed worse than designed as a result of unrealistic assumptions in the design energy model for occupancy behavior and facilities management.

This study by Minez and Crips illustrates the importance of reevaluating the merit of the design assumptions that the building energy model is based on throughout the design process (Menezes et al., 2012). A study by Wang and Matthew of a medium sized office building in San Francisco shows that, due to primarily to operational uncertainties, the discrepancy between anticipated and actual energy consumption may be as much as 18% at an 80% confidence level (Wang et al., 2012). Therefore, the assumptions behind an energy model must be documented thoroughly so that they can be referred to regularly and questioned if updated information becomes available (Marseille, 2011). The importance of assumptions is illustrated by the NREL RSF modeling process, in which the assumptions about the data center use and miscellaneous plug and process loads was as or more important than the thermal modeling of the building (Hirsch, 2011). Early modeling in the design process revealed that the data center housed in the RSF would consume approximately one third of the buildings anticipated electricity, and that plug loads would consume an additional 23%.

In order to achieve the performance goal of operating with Net-Zero Energy, the designers must first reduce the building demand through efficiency measures (Amerongen and Richardson, 2011; Torcellini et al., 2006). As discussed in previous paragraphs, this process should be driven by energy modeling from the onset, so that the most effective efficiency measures can be identified early. Demand reduction strategies encompass a wide scope of design options, including building envelope components, passive heating and cooling, daylighting, and natural ventilation. The elements of the design that are most difficult to change should receive the most attention early on, for example components such as insulation under floor slabs and insulation integrated with the foundation (Amerongen and Richardson, 2011). In addition to designing a building for significant lighting, heating, and cooling load reduction, the architects and engineers must include efficient active systems to support the remaining loads not met by passive measures. The active lighting, HVAC systems, and building controls must all be designed to efficiency meet the building loads. Therefore, the energy consumption of the building will be significantly reduced in comparison to minimally code compliant buildings of similar function. The remaining energy consumption of the building must be offset through the implementation of promising renewable energy strategies for the specific site, which were identified during the initial site assessment.

Under current prices, it is nearly always more cost effective to implement load reduction and active system efficiency improvements during the design process prior to renewable energy (Marseille, 2011). The optimal progression from a standard reference building to a Net-Zero Energy building is illustrated by the curve shown in Figure 7. The green line shows the lower bound of results from all possible building designs in terms of minimal annual cost, or equivalently, Net Present Value (NPV). Along the curve are five key points, the first of which is the reference baseline building. This is a building that fulfils all of the same functions as building being designed, but which has not been designed for energy efficiency and is minimally code compliant. The second point along the path is a building that has a minimal annual capital and energy cost, equivalent to a maximum Net Present Value (NPV), as a result of implementing cost effective energy efficiency improvements. Next, the third point illustrates when additional, non-cost effective energy efficiency improvements become comparable to renewable energy generation costs. At the fourth point, additional investment in renewable energy generation has reduced the NPV of the building so that it now once again is equal to the NPV of the baseline building. Finally, the fifth point shows where the building achieves Net-Zero with a combination of efficiency measures and renewable generation.

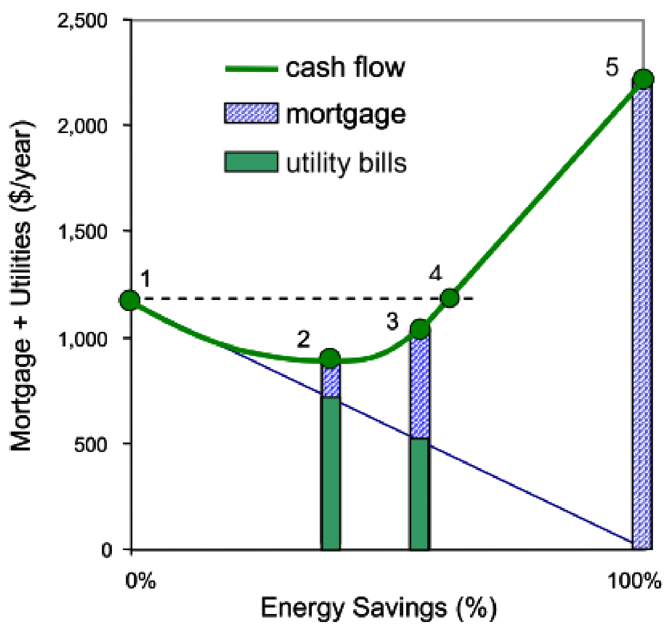


Figure 7. Conceptual plot of the optimal path to a Net-Zero Energy building (Horowitz, Christensen, and Anderson, 2008)

The last important pillar of an NZE design process is that it must properly integrate planning for the post design stages of commissioning, and operation (Deru and Torcellini, 2004; Marseille, 2011). While a building design may be highly efficient, if it is not properly executed, then it will likely fall short of its performance goals. A study by Hackel and Schuetter on the importance of proper daylighting commissioning showed that out of 20 daylit spaces in the

Midwest examined, every system did not achieve as much daylighting potential as possible due to less than ideal commissioning (Hackel and Schuetter, 2013). After a re-commissioning process, in which the daylighting sensors and light controllers were readjusted to achieve adequate light levels with minimal electricity consumption, the median energy savings from daylighting the spaces increased from 23% to 63%. This is equivalent to an additional 1061 kWh savings per kW of installed lighting capacity, including the effects of decreased HVAC energy usage. In an uncertainty analysis of operational parameters for office buildings in four different US climate zones, Wang and Mathew showed that operational uncertainties in building controls can result in large windows of uncertainty in energy consumption (Wang et al., 2012). For instance, in the San Francisco climate, bad practice in HVAC parameter settings such as night time setback temperature and supply air temperature control can result in a building consuming 70% more energy than if average practices are used. As a result of the substantial influence that commissioning and operation can have on energy consumption, the building manager, commissioning manager, and anyone else responsible for the proper operation of the building should be involved in the design process. Inclusion in the design process allows for these personnel to participate in forming the performance goals for the project, and therefore creates buy-in to the project.

The Net-Zero design process does not terminate after construction and commissioning, but rather continues on during the operational lifetime of a building through the activities of performance monitoring, verification, and continuous commissioning (Marseille, 2011; Reddy, 2006). During operation, the building energy model should be calibrated to the metered energy consumption of the building so that the model can be used to provide insight into detecting systems that perform below expectation (Reddy, 2006). The model can be used later in the lifetime of the building to analyze the energy and cost effectiveness of retrofits at building system and fabric technology improve and the original building components age. An important prerequisite for continuous commissioning is that, during the design stage, the team must develop a plan to monitor the performance of the building throughout its operational lifecycle to evaluate whether or not the performance goals are being met (Deru and Torcellini, 2004). This step is extremely important for the process, because, if a monitoring plan is not established, then there is no way to know if the goals outlined are being satisfied or even how the building is performing. For instance, in the study conducted by Hackel and Schuetter, due to a lack of monitoring the owner of one of the daylit spaces was under the impression that the system was providing significant energy savings, when in reality the system was contributing practically no savings at all (Hackel and Schuetter, 2013).

2.6 Classifying Uncertainty in Building Performance Simulation

When modeling a building during the design process, several different sources of uncertainty exist. These sources can be classified into several different groups: design uncertainties, specification uncertainties, scenario uncertainties (also referred to as operational uncertainties), modeling uncertainties, and numerical uncertainties. Design uncertainties are most prominent early in the design process when the building is ill-defined and are a result of the design team having not yet chosen a particular feature or characteristic for a building. These uncertainties can be analyzed for retrofit projects as well as new construction, as a study illustrates with the consideration of different retrofit measures to an existing university building in the UK (Tian and de Wilde, 2011). Specification uncertainties, also referred to as physical uncertainties, stem from the discrepancy between the design value of a component and the real value of the component as part of the actual building. These can be from sources such as thermal bridging and inconsistencies in material properties. For instance, Hopfe and Hensen considered uncertainties in the material properties, along with several other sources of uncertainty, for an office building and analyzed their impact on the building annual heating and cooling loads (Hopfe and Hensen, 2011). Scenario uncertainties, or operational uncertainties, are present due to the fact that the assumed situation under which a building is modeled does not fully reflect reality. These uncertainties include assumptions such as the number of occupants within a building and the weather under which a building is modeled. Domínguez-Muñoz et al. conducted a Monte Carlo based sensitivity and uncertainty analysis on peak cooling loads for an office building in Spain and included operational uncertainty from lighting gains, equipment gains, and occupant sensible gains (Domínguez-Muñoz, Cejudo-López, and Carrillo-Andrés, 2010). Model uncertainties are a result of the fact that the equations that make up the mathematical building model do not fully represent reality. Essentially they beg the question: are the equations used accurate? In a case study of a naturally ventilated office building in the Netherlands, De Wit and Augenbroe found that model uncertainties had a large impact on the calculated thermal comfort of the building occupants and the related decision of a building designer to implement a mechanical cooling system (de Wit and Augenbroe, 2002). Lastly, numerical uncertainties address the question: are the equations solved correctly? This source of uncertainty has not been widely addressed in the building performance simulation community and no literature advocating their importance was found.

The lines between these different types of uncertainties are not always clear. For instance, plug load, which is the load placed on a building by the electric equipment plugged into its outlets, is often considered an operational uncertainty. This is due to the fact that the behavior of the building occupants will influence the equipment that is plugged into outlets, and therefore the magnitude of this type of load on the building. However, this neglects the influence that recent innovations can have on mitigating the magnitude of the building plug load. In a study by Nakazawa and colleagues, a system to monitor and visualize the plug load energy consumption of each of the occupants in a 93 person office space was implemented, allowing the occupants to view and analyze their plug load energy consumption (Nakazawa et al., 2011). The study found that the implementation of this system resulted in a 15% decrease in the average daily power consumption. This study illustrates the impact that innovative systems can have on parameters that are often considered uncertain due to occupant behavior. Therefore, the uncertainty in occupant plug load has components of both a design uncertainty and scenario uncertainty.

2.7 Building Performance Uncertainty and Sensitivity Analysis for Design

While it is widely accepted that energy modeling is an integral component of a performance-based design process (Attia, De Herde, Gratia, and Hensen, 2013; Hirsch, 2011; Hygh, 2011; Marseille, 2011), there is less agreement about how it should best be incorporated in design practice. In a study of the methodological approaches to designing environmentally sustainable buildings, Dansen concludes that the most common way that energy modeling is implemented is by using the Case-Based Approach (Hansen and Knudstrup, 2008). In this type of approach, several design concepts are created and then energy modeling is used to help select the best solution with possibly few modifications. With this type of reactive approach, the ability of building simulation to inform design decisions is severely limited. The alternative is what Dansen calls the Parametric Approach, in which the robustness and sensitivity of the building energy consumption to variation in multiple parameters is examined. This type of parametric approach to building design has been advocated in numerous building performance studies as a way of providing adequate information to inform the building designers (Attia, Gratia, De Herde, and Hensen, 2012; Hopfe and Hensen, 2011; Hygh, DeCarolis, Hill, and Ranji Ranjithan, 2012; O'Brien, Athienitis, and Kesik, 2011; Ruiz et al., 2012). The two primary applications of this method are local and global sensitivity analyses, both of which have been implemented in the Building Performance Simulation community (Tian, 2013).

In local sensitivity analysis, each parameter of interest is varied one at a time, while the rest of the model parameters remain constant at a baseline level. The local method was used by O'Brien to analyze the most influential parameters for the design of a Net-Zero Energy solar house (O'Brien et al., 2011). The results indicate that the most influential parameters for the annual energy use of the building are the floor area and the cooling set-point, followed closely by the building Window to Wall Ratios (WWR) and the heating set-point. Local sensitivity analysis also was implemented by Lam, who employed the method to examine the effects of design parameter variation on the energy performance of office buildings in Hong Kong (Lam and Hui, 1996). Using simulations with DOE-2, he determined that the most influential parameters for these types of buildings are the occupancy density, lighting load, and equipment plug load. While local sensitivity analysis can be insightful, it is limited in application during the design stage as it focuses on the effects of parameter variation around a baseline point (Tian, 2013). In contrast, global uncertainty and sensitivity analysis allows for the investigation of the parameters influence over the entire input ranges, and therefore is a more appropriate method for investigation of the influence of multiple parameters throughout a design space. The distinction between global uncertainty analysis and global sensitivity analysis is that while global uncertainty analysis propagates the uncertainties of the inputs through the model to produce an uncertainty distribution for the output, the relative contributions of each of the input parameters are not identified. Global sensitivity analysis takes the uncertainty analysis a step further, and uses a method such as regression to link the uncertainties of the inputs to the uncertainty of the output.

Global sensitivity analysis has been widely employed in recent studies to examine the influence of design parameters. Hygh and DeCarolis used a Monte Carlo-based method to examine the most sensitive parameters for office buildings across four distinct United States climates: Miami, Winston-Salem, Albuquerque, and Minneapolis (Hygh et al., 2012). Their simulation-based study found that building area was the most important parameter for every climate; however, other influential parameters were heavily affected by the climate selection. For instance, the aspect ratio of the building was the second most important parameter for energy consumption in Minneapolis, while it had a much less substantial impact in Miami. The Morris method was used by De Wit and Augenbroe to investigate the most sensitive parameters for impacting the thermal comfort performance indicator for a naturally ventilated building (de Wit and Augenbroe, 2002). In the field of building performance simulation, the Morris method is the most widely implemented global sensitivity analysis method for screening a large number of parameters, however, this method is unsuitable for uncertainty analysis (Tian, 2013).

A parametric study by Hopfe and Hensen varied the glass surface area, room size, and thermal properties of the glazing for an office building in the Netherlands (Hopfe and Hensen, 2011). They examined the impact of these parameters on the under-heating and overheating hours of the building and found that the size of the room was also the most influential parameter, while the glazing thermal properties had minimal impact. Yildiz and Arsan also used a Monte Carlo based sensitivity analysis to examine the impact of 35 different design parameters on the heating and cooling loads of an apartment building in Turkey (Yildiz and Arsan, 2011). The analysis indicated that for the top floor, the heating and cooling set-points are both very influential; however, for their respective load type, neither is the most influential parameter. Instead, the width of the building is the most important parameter for the cooling load and the amount of infiltration is the most important for the heating load. While many global sensitivity analysis studies employ building simulation programs as the modeling method to calculate the desired output variable, Mechri and Capozzoli employed a quazi-steady simplified monthly modeling method presented in ISO 13790:2008 (Mechri, Capozzoli, and Corrado, 2010). Using an Analysis of Variance (ANOVA) based analysis, the sensitivity of heating and cooling demand for a typical office building to several conceptual design stage parameters such as compactness ratio, orientation, and external shading was studied. The sensitivity indices for each parameter were determined across five Italian climate zones. In every climate zone, the envelope transparent surface area ratio (equivalent to window to wall ratio) was by far the most important parameter for both heating and cooling demand with a sensitivity index ranging from 0.54 to 0.69 for heating and 0.79 to 0.82 for cooling.

During the design stage, the use of sensitivity analysis is not restricted to examining the building architectural parameters alone. As the previously discussed study by Yildiz and Arsan shows, parameters such as thermal set-points can have a significant influence on energy consumption, and therefore should be analyzed as a part of uncertainty and sensitivity analysis (Yildiz and Arsan, 2011). Several recent studies have shown the substantial effect that building controls and operational uncertainty can have on energy consumption. Wang and Mathew conducted an uncertainty analysis of operational parameters for a medium sized office building for four different climate zones across the United States (Wang et al., 2012). Through the use of a Monte Carlo technique, they showed that the HVAC control parameters such as heating set-point, cooling set-point, and supply air temperature control were by far the most significant parameters. For the San Francisco climate, uncertainty in all of the operational parameters examined indicated at best a 20% reduction in energy consumption from good operational practice and at worst a 42% increase in energy consumption from bad operational practice; both limits are within a 95% confidence interval. A recent study published by the National Buildings Institute (NBI) compares the sensitivity of a typical office building energy consumption to design and operational parameter variation, with operational parameters encompassing both control system settings and tenant behavior (Heller et al., 2011). The analysis covers variations in 28 parameters across 16 different climate zones. Due to this large number of input parameters and climates, the study uses the more limited method of local sensitivity analysis, however does attempt to account for some interactions through the local sensitivity analysis of different groups of parameters such as daylighting parameters, operations parameters, and commissioning and maintenance parameters. The study illustrates that both tenant related variables and commissioning and maintenance variables can have a substantial impact on the building energy consumption. For instance, in Atlanta, good commissioning and maintenance practice can result in nearly 20% energy savings over the baseline building. In comparison, good design practice for all variables controlled by the design team such as window U-Value and insulation thickness results in 50% energy savings over the baseline building.

Ruiz and colleagues also performed a sensitivity analysis comparing the relative impact of several different families of parameters for a prototype office building, including building envelope, building services and energy systems, building operation, occupant activities and human behavior, and indoor environmental quality provided (Ruiz et al., 2012). The study used a variance based global sensitivity analysis, and found that the most important parameters affecting annual fuel consumption for the building model when located in Lisbon are U-Value for the windows and U-Value for the external walls. Together these two parameters encompass 41.4% of the variation in the building model output. However, the results did show that the operational control parameters have a significant effect on energy consumption, as the heating temperature set-point was the third most influential parameter in the location of Lisbon, and provided 12% of the variance in energy consumption. The uncertainty in operational parameters was even more significant for the electricity consumption of the building, as appliance load density, synonymous with electric equipment density, accounted for 26.8% of the variance in cooling energy consumption in Lisbon and 28.9% in Brussels. Domínguez-Muñoz and colleagues also included operational parameters and scenario uncertainties in a study of the uncertainty of peak cooling loads for an office building in the south of Spain (Domínguez-Muñoz et al., 2010). Both electrical equipment gains and occupant sensible heat gains were included, along with modeling uncertainties from parameters such as convective heat transfer coefficients and design uncertainties such as window Solar Heat Gain Coefficients (SHGC). A Monte Carlo method was used to propagate the input uncertainties through the building model. The sensitivity of the parameters was analyzed using Standardized Regression Coefficients. Out of 20 uncertain parameters examined, the electric equipment load and the occupancy gains were the sixth and eighth most influential parameters, respectively.

While global sensitivity analysis has the potential to be a powerful tool to inform decision making during the initial design stages, there are several obstacles to its implementation in practice. One of the most significant barriers is that most available building simulation tools lack the capability of parametric analysis. In a review of ten building simulation tools by Attia, the only mainstream tool found to support parametric analysis was DesignBuilder (Attia and De Herde, 2011). However, this software only supports the analysis of up to two design parameters. So the use of this parametric analysis feature during the initial design phases when there are a large number of unknowns is limited (DesignBuilderUSA, 2014). Since the previously mentioned study, a second mainstream energy modeling tool, OpenStudio has also added the ability to conduct parametric analyses (NREL, 2014b). While the Parametric Analysis Tool that is now included as part of the software allows for an exploration of the design space using various alternatives, it does not allow for a full global sensitivity analysis of multiple design parameters. Only single parameter variations, or groups of parameter variations, can be explored in a local sensitivity analysis approach similar to that employed by Heller and Heater in their study of the important design and operational parameters for office buildings in the United States (Heller et al., 2011). A second substantial barrier to the adaptation of global sensitivity analysis in Net-Zero Energy design practice is that many of the currently available building simulation tools are not intended for use by architects, despite the fact that they are the individuals who guide the initial design (Attia, 2012; Weytjens, Attia, Verbeeck, and De Herde, 2011). In a study of six building simulation programs, Weytjens concluded that the software examined does not assist architects in decision making and that a major limitation of the current tools is their poor communication of the simulation results. Poor communication results in a substantial barrier to the implementation of sensitivity analysis due to the fact that architects must first be confident in working with energy modeling prior to energy modeling coupled with sensitivity analysis. A third obstacle to the implementation of sensitivity analysis in early building design is that, without a tool integrated into the energy modeling program, the time required to run a global sensitivity analysis can be extremely long (Hansen and Knudstrup, 2008; Zhang and Korolija, 2010). During the initial design phase, the energy model will be based on a large number of uncertain assumptions for details such as occupancy and equipment schedules, which should be updated as new information becomes available (Hirsch, 2011). This entails that a sensitivity analysis must be able to be redone quickly, since whenever the assumption parameters are changed, the results of the analysis may no longer be applicable (Hansen and Knudstrup, 2008).

Due to the useful information that sensitivity analysis can provide to building designers, several design tools and methods have been developed by members of the academy to assist in integrating sensitivity analysis into the design process (Attia et al., 2012; Hygh et al., 2012; O'Brien et al., 2011; Zhang and Korolija, 2010). Hygh and DeCarlos present a multivariate regression-based approach, in which the results of a regression model fitted to a Monte Carlo Analysis of an energy model are used to establish Standardized Regression Coefficients (SRC) for a sensitivity analysis as well as a meta-model (Hygh et al., 2012). The regression based meta-model serves as a quick and easy way to experiment with a practically infinite number of parameter combinations. However, this approach does not address the problem of the initial large time investment that is required to set up and run the global sensitivity analysis. Zhang developed the JEPlus tool to deal specifically with this issue, as the tool allows for the automation of the majority of the steps involved in global sensitivity analysis for any designer using the EnergyPlus building energy modeling program (Zhang and Korolija, 2010). Unlike DesignBuilder, JEPlus is an open source tool, which makes it extremely accessible since EnergyPlus is also available for free from the United States Department of Energy. However, the tool is primarily intended for use by researchers and not designers in industry, as it requires working directly with the EnergyPlus text input file. Another tool, which is currently under development by O'Brien, Athienitis and Kesik, is a solar house design tool to inform the conceptual design of low energy houses (O'brien, Athienitis, and Kesik, 2009). The tool is based on a simplified rectangular "shoebox" model of a house built in the energy simulation program ESPr and allows for the variation of 26 early design parameters such as window to wall ratio on each façade and building aspect ratio. The interface enables the user to examine the main effects of the parameters through a local sensitivity analysis, although it is not capable of a global sensitivity analysis. However, the tool does not ignore interaction effects completely, and uses interaction plots based on a two dimensional Design of Experiments (DOE) run for each combination of parameters to inform the user of interaction strength (O'brien et al., 2009).

The most significant attempt to create a flexible parametric tool for designing energy efficient buildings has been undertaken by Attia with the development of ZEBO, a tool built specifically for designing passive and active solar buildings in Egypt (Attia, 2012). This tool also uses a "shoebox" underlying model, although EnergyPlus is implemented as the simulation engine. The flexibility of the tool is increased by the fact that it allows for several different baseline shoebox constructions such as row apartment, high-rise, and open courtyard templates. However it does not allow for the user to create and model unique geometries. A significant limitation of the tool is that the assumptions of the building energy model behind the interface such as occupancy schedule and plug load density are not readily available to designers. This may result in the application of the design tool beyond its intended boundaries and result in inaccurate estimations of energy consumption. As several studies have discussed, the assumptions behind a building energy model can be very important (Hirsch, 2011; Marseille, 2011). During the development of ZEBO, Attia and De Herde conducted a study on the importance of sensitivity analysis in helping to develop Net-Zero Energy buildings (Attia et al., 2013). Three focus group experiments were carried out with the members in attendance including professional architect and engineers, as well as graduate students, professors, and undergrads. For the experiment, each group had to first design a Net-Zero Energy building without any Building Performance Simulation (BPS) tools. Then they were given an instructional lesson on NZE design and asked to perform the design again, and finally in the last round they were allowed to use BPS tools and asked to form a final design. In every group, the use of the parametric tool developed, as well as other Building Performance Simulation tools, resulted in a reduced energy demand of at least 40% in comparison to the baseline buildings designed. Furthermore, the lectures were only responsible for 13% of the energy savings on average. From this they conclude that BPS and sensitivity analysis play significant roles in promoting informed decision making in the design process.

2.8 Guidance Gained from Literature

From reviewing the literature, a solid foundation for examining the energy efficient design of primary vaccine warehouses was obtained. The global health literature allowed for thorough understanding of the primary vaccine warehouse as a building type. Project Optimize showed the first attempts to create an energy efficient vaccine cold chain. However, the lack of any method to assist in the design of an NZE primary vaccine warehouse motivated the progression towards the examination of NZE and performance based design literature in general. From a review of the building performance literature, global uncertainty and sensitivity analysis emerged as a valuable technique for determining the important design parameters for the creation of an energy efficient building. As this technique allows for establishing the relative importance of multiple building model parameters, it is very applicable to the research questions proposed. The literature on energy efficient design, in combination with the literature on uncertainty and sensitivity analysis, also provided significant guidance towards the shaping of the thesis scope. Within the literature discussing energy design methods, a common theme that continually emerged was the importance of an integrated design method and that the design process must carry through commissioning and operation of the building in order to ensure energy efficient operation. Similarly, several uncertainty and sensitivity studies indicated that uncertainty in the model parameters subject to variation during commissioning and operation could have a significant impact on energy consumption. From this, the research was guided in the direction of comparing the effect of uncertainty in design parameters to uncertainty in parameters which the design team can influence, but which are susceptible to active alteration during commissioning and operations. This is a research area of building performance simulation that is currently underexplored and can help to quantitatively investigate the importance of an integrated design process. The following chapter presents the method implemented to inspect the significance of these parameters for a primary vaccine warehouse. The specific building examined is based on a proposed layout for the new primary vaccine warehouse for the DSSB.

CHAPER 3: APPROACH AND METHOD

In this chapter, the methods used to test the hypothesis and answer the research questions are presented and discussed. The chapter begins with a discussion of a building retrofit analysis study conducted in parallel to this thesis which helped to inform the approach and method. It then progresses to the formulation of the building layout that is used in the case study for this thesis. First, the important building requirements such as the vaccine volumes and subsequent storage volumes are discussed along with the methods used to determine these parameters. Following this, additional influences on the layout such as the site constraints are discussed. Finally the conceptual floor plans and elevations that detail the proposed building are presented. The next section focuses on the development of the building energy model. This includes the modeling methods used, along with the important assumptions and equations behind the model. Next, the framework for the uncertainty and sensitivity analysis is presented along with details on the specific methods implemented. Lastly, an overview of the four additional locations selected for the analyses is provided.

3.1 Retrofit Analysis of an Existing Medical Warehouse

In parallel to this thesis, a retrofit analysis was conducted for an existing medical warehouse in Tunisia. This study helped to inform several portions of the thesis, including the construction of the thermal model as well as uncertainty and sensitivity analysis. While a full account of this retrofit is given in a separate report (Pudleiner et al., 2014), an overview of the study is provided here. The facility examined is a recently commissioned refrigerated warehouse under the management of the Pharmacie Central de Tunisie (PCT). It is located in Ben Arous, a southeast district of Tunis, Tunisia, and houses pharmaceutical drugs such as insulin. Figure 8 shows a picture of the building and Figure 9 shows the floor plan. As shown by the floor plan, there are three rooms in the facility, two storage rooms and an entrance vestibule, which is labeled as SAS in the floor plan. The key parameters for each room in the facility are included in Table 2. Both of the storage rooms in this facility are kept at 3-7°C, and the SAS zone is kept at 7-12°C. The Public Storage Room is the largest room with a floor area of 438 m^2. While the Private Storage Room is smaller with a floor area of 309 m^2, each of the storage rooms has three refrigeration systems present. All of the rooms are cooled by split refrigeration systems that utilize condenser-compressor racks.

Figure 8. External view of the PCT warehouse; southwest façade with entrance to cold rooms

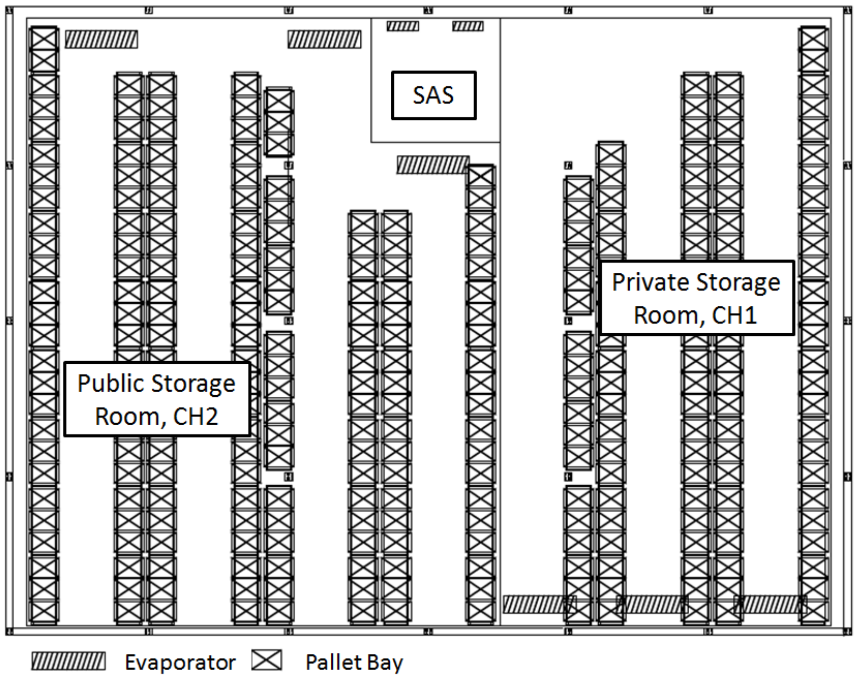


Figure 9. Floor plan of the PCT warehouse

Table 2. PCT warehouse parameters

	SAS (Vestibule Room)	**CH1 (Private Storage Room)**	**CH2 (Public Storage Room)**
Floor Area (m^2)	25	309	438
Height (m)	5.1	5.1	5.1
Volume (m^3)	129	1577	2235
Lighting Power (W)	232	2784	3248
Upper Temperature Limit (°C)	12	7	7
Lower Temperature Limit (°C)	7	3	3
Infiltration Protection	Strip Curtain	Strip Curtain	Strip Curtain
Number of Independent Refrigeration Systems	2	3	3
Evaporator Rated Cooling Capacity (W) *(For each refrigeration system)*	4940	30500	35600
Evaporator Fan Power (W) *(For each refrigeration system)*	290	1740	3800
Compressor Rated COP (W)	1.92	2.58	2.09
Sliding door openings (Height x Width) (m)	2.54 x 2.11	2.54 x 2.11	2.54 x 2.11

The study employed the analysis method shown in Figure 10. For this method, a detailed building energy model was constructed in EnergyPlus and a building performance monitoring setup was installed on site. The monitoring setup measured the operational parameters of the warehouse, such as the door opening and closing times, along with the weather conditions and the building energy consumption. For the building energy model, all standard EnergyPlus modeling methods were implemented, with the exception of the refrigeration equipment used to cool the rooms. Due to the presence of a bug in the EnergyPlus Refrigeration objects, a unique method for calculating the refrigeration electricity was used. In this method, the Ideal Air Loads object is used in combination with equations from building performance literature hand coded into Energy Management System objects, as described further in section 3.3.13 Building Model Assumptions: Refrigeration.

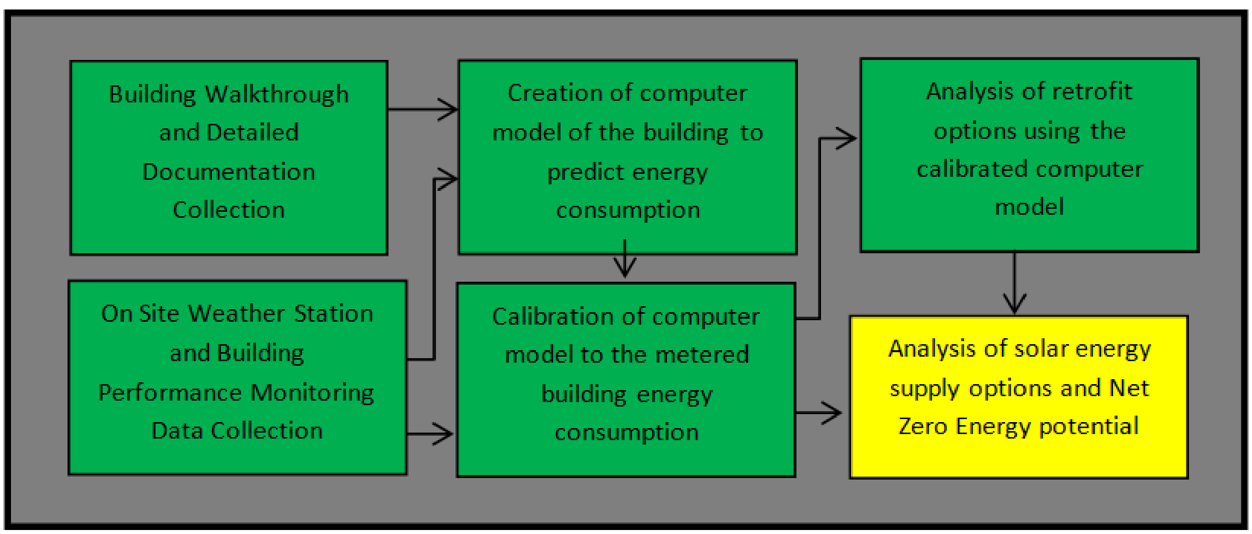


Figure 10. Method used to conduct the retrofit analysis for the PCT warehouse

Using a heuristic approach, the building energy model was calibrated to the metered energy consumption. Figure 11 shows the close agreement between the calibrated EnergyPlus model and the metered consumption. The calibrated model was able to achieve an average error of less than 1.5% in comparison to the daily metered energy consumption. This use of the unique modeling method was validated through the accuracy of the calibrated model. As a result, it was assumed that the unique modeling method implemented for the refrigeration electricity calculation could be used in the building energy model constructed for the proposed warehouse studied in this thesis.

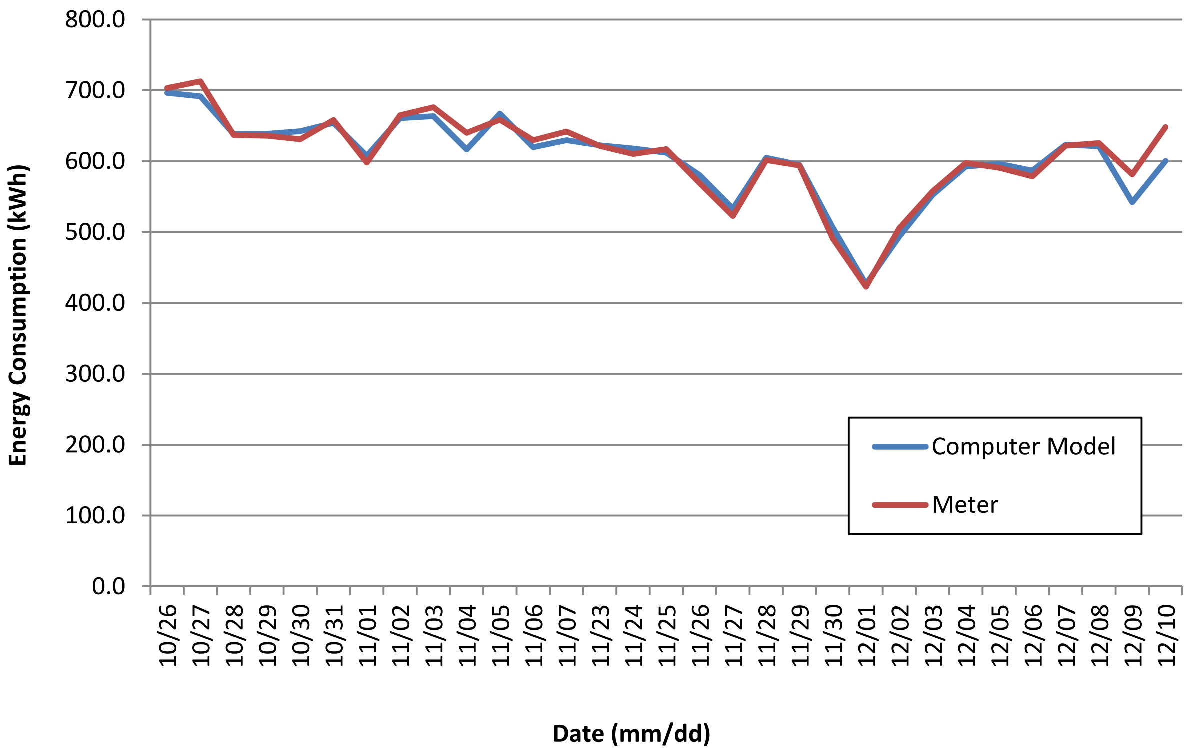


Figure 11. Calibration results for the PCT warehouse

From a breakdown of the calibrated building energy model consumption into the various end uses, the evaporator fans were shown to be the most dominant source of energy consumption. Therefore, the retrofit study focused on improvements to the evaporator fan control evaporator fan control scheme. In the Baseline control scheme, the evaporator fans in each of the storage rooms run constantly when the doors are closed. Consultation with the building manager revealed that this is done to ensure a uniform temperature throughout the zone. Consequentially, an improved control scenario (R1) was analyzed in which the evaporator fans run only for cooling, while purpose built thermal destratification fans are used to ensure a uniform temperature in each storage zone. Figure 12 shows the substantial savings in energy consumption predicted by implementing the improved control scheme for the PCT warehouse. In comparison to the Baseline scheme, the R1 scenario reduces the energy consumption by 69%, a savings of 178,000 kWh per year. These two control strategies presented here are used to inform the control levels investigated for the uncertainty and sensitivity analysis in this thesis. The R1 scheme is referred to as D1 in the analysis of the new building, and the Baseline scheme is referred to as D2.

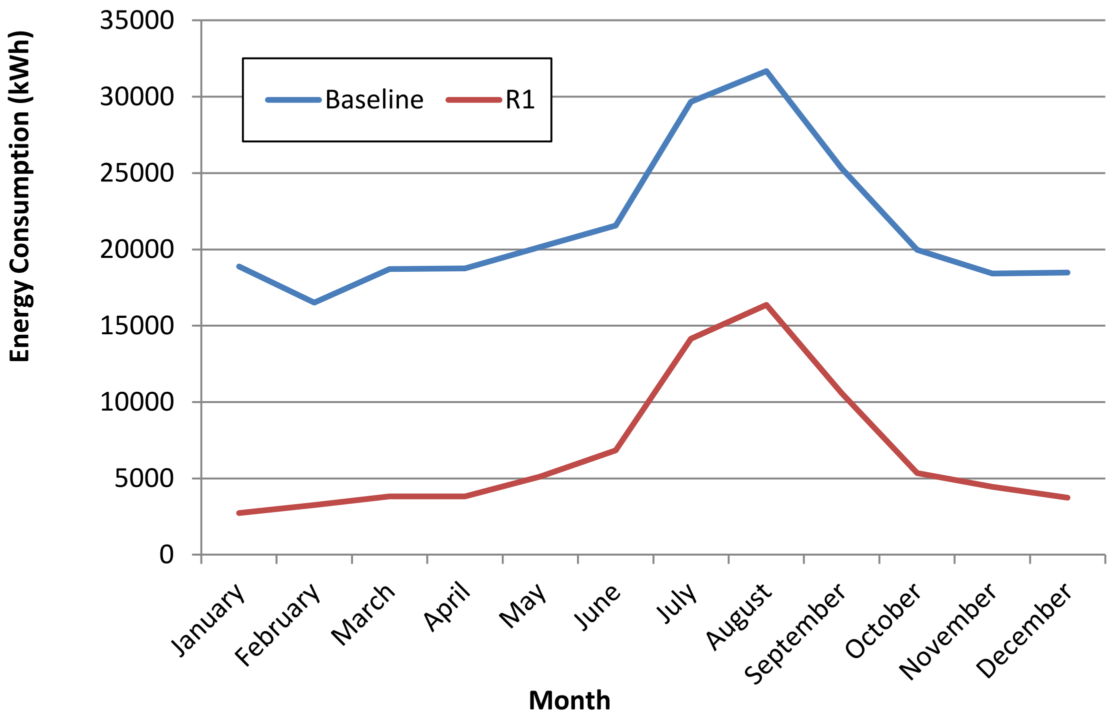


Figure 12. Retrofit analysis results for the PCT warehouse

3.2 Development of a Prototype Layout for a NZE Primary Vaccine Warehouse

The prototype warehouse layout used in this thesis is derived from the building geometry developed for a new primary vaccine warehouse in Tunis, Tunisia. While the building has not yet been constructed, the Government of Tunisia has included funding for a new primary vaccine warehouse in its 2014 government budget. The development process for the building layout is shown in Figure 13 and portions of the process are discussed throughout this section. The design process consists of three key phases that can be broken down by the important deliverables that marked the progression of the project: Calculation of the Warehouse Storage Requirements; Selection of the Appropriate Storage Methods and Drafting the Initial Layout; and Drafting the Improved Layout. The initial layout and revision process are not discussed, as only the final layout is relevant to the research conducted in this thesis.

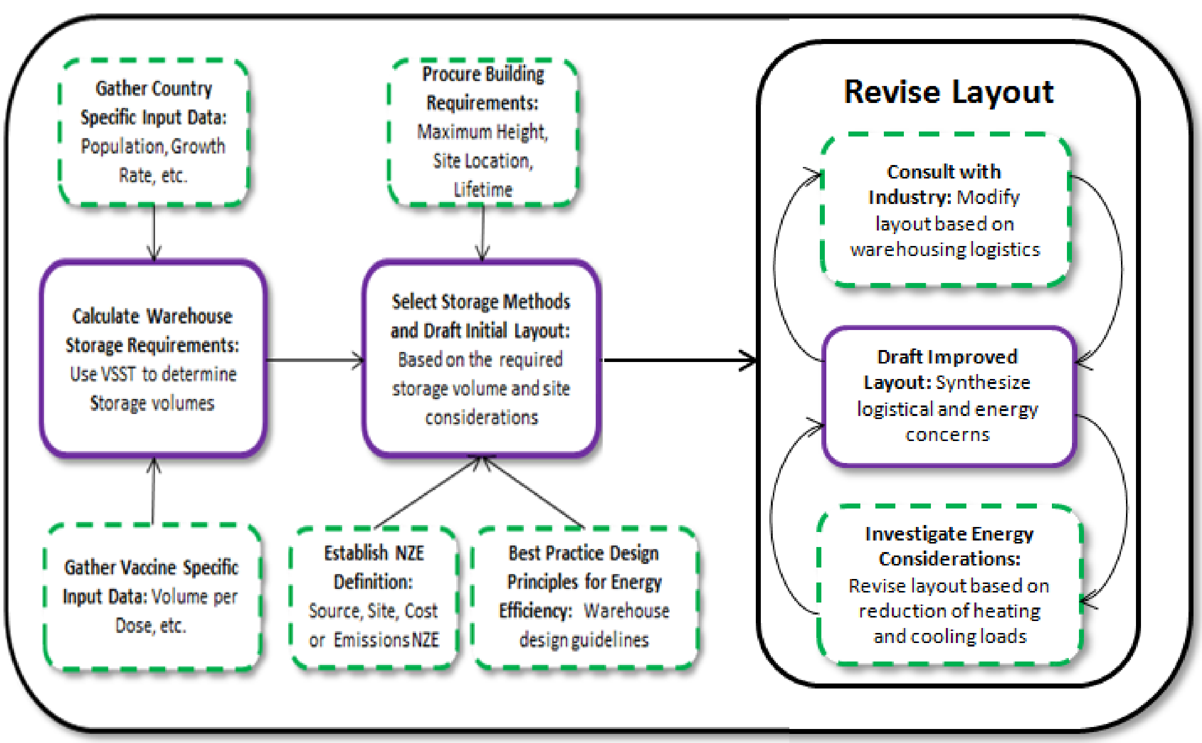


Figure 13. Process diagram for the development of the building layout used for this thesis

This layout is used in this thesis because the primary architect for the design is Mr. Andrew Garnett. Mr. Garnett has extensive experience in the design of vaccine storage facilities, was a key member of the Project Optimize team, and is a leader in the field of facility design for vaccine storage (Garnett, 2002, 2012). In addition, two more members from the Project Optimize team, Mr. John Lloyd and Mr. Steve McCarney, were involved in the design process for the layout. Finally, the layout was examined and validated by members of warehousing industry as well as the cold chain industry. Therefore, this layout has been assumed as a functionally validated layout that reflects the latest in vaccine storage warehouse design.

3.2.1 Using the VSST to Size Vaccine Demand

In order to calculate the required storage space for the warehouse, the Vaccine Storage Sizing Tool (VSST), which was developed under Project Optimize, was employed (Garnett, 2011). This is an Excel spreadsheet-based tool that calculates storage space requirements for each of the four temperature regimes in the warehouse based on country and vaccine supply and demand input information, such as population, target group percentage, supply intervals, and wastage rates. A significant advantage of this method is that it estimates the storage space requirements of each temperature zone for the three most commonly used manual warehouse storage methods: shelving storage, pallet standing storage, and pallet racking storage. The difference between pallet racking and pallet standing is that while pallet standing assumes that all pallets will be stored on the floor, pallet racking allows for pallets to be stacked vertically on tiers of scaffolding, so that two or more pallets can occupy the same floor area. The simultaneous presentation of three different storage methods allows for quick and easy comparisons during the creation of the building layout. The warehouse storage space requirements were calculated based on a population of 12.6 million people, which is the projected population figure for Tunisia in the year 2020 (United Nations, 2006). As a result of Tunisia's unusually low projected population growth rate for a transitional country of only 0.72% in 2020, the store was sized for the projected population without significant concerns of energy wastage due to excessive unused storage space (Sims, 2011). The current population is already 10.8 million people (CIA, 2014), and so, even if the building were operational today, the capacity of the store is only oversized by 15%. It should be noted that this 15% additional capacity for anticipated population expansion is on top of the 25% oversizing factor that is used in the vaccine warehousing industry to size storage facilities.

An overview of the vaccine information for Tunisia input into the VSST is shown in Table 3. As shown by the table, the regimen used to size the storage space includes the vaccines that WHO has recently added to its suggested schedule such as immunizations for rotavirus and HPV (WHO et al., 2012). While the VSST does provide default figures for vaccine volume per dose and wastage factor for each vaccine, these figures were taken from Tunisian national data obtained by Mr. John Lloyd in a consultation with the Tunisian Ministry of Public Health (Tunisian Ministry of Health, 2012). Mr. Lloyd also supplied the figures for the target population percentages. The number of months of shelf stock allotted for the vaccines was set at seven months at the request of the DSSB. The DSSB is a branch of the Tunisian MoH; it is responsible for the management of the vaccine supply chain within the country. The specific volume v_p for each vaccine, which is the volume of vaccine required as a function of the population, is calculated through the use of Equation 1, where v_d is the vaccine volume per dose, d is the doses per recipient, w is the wastage factor, p is the target group as a percentage of the population, and s is the number of months of stock stored in the warehouse.

$$v_p = v_d dwp \frac{s}{12} \quad (1)$$

Using this information, the VSST first calculates the raw storage volumes required for the vaccine and vaccine-related products according to the type of packaging in which the user assumes the product will be stored. The product can be stored in primary, secondary, or tertiary packaging; for this design, the product is assumed to be stored in tertiary packaging, as this is the current practice of the DSSB. These raw volumes are converted to the storage volumes for each of the three manual storage methods previously mentioned: pallet racking, pallet standing, and shelving. However, in order to properly estimate the required storage space from the cumulative vaccine volumes, the VSST requires additional information relevant to each specific storage method. For instance, if hand trucks are selected as the pallet handing equipment, the VSST assumes a narrower required aisle width than if a ride-on truck is selected. The assumptions that were input into the VSST for the calculation of each type of storage are shown in Table 4. The parameters in this table that are not design choices, shown in *italics*, are based on industry standard assumptions, or were informed by the expert knowledge of members on the design team, primarily Mr. Andrew Garnett and Mr. John Lloyd.

Table 3. Vaccine storage parameters used for the initial sizing of the building layout for the DSSB

Vaccine	Vaccine volume (cm^3/dose)	Shelf stock (months)	Doses per recipient (dose/Target Group Individual)	Wastage Factor	Target Group (percent of population)	Specific Vaccine Volume (cm^3/population)
BCG	4.9	7	1	5.00	1.16	0.165
DT	9.8	7	1	2.38	1.16	0.157
OPV	10.8	7	4	1.28	1.16	0.372
DTP-HepB-Hib	9.8	7	3	1.05	1.16	0.208
PCV-13	144.7	7	3	1.05	1.16	3.072
MR	9.8	7	2	1.82	1.16	0.240
Rubella	9.8	7	1	1.05	0.84	0.050

Table 3. Continued:

MR	9.8	7	1	1.18	1.16	0.078
HPV	15.4	7	3	1.05	0.84	0.237
DT	9.8	7	3	1.18	0.82	0.166
OPV	10.8	7	3	1.18	0.81	0.179
HepB	16.9	7	1	1.05	1.16	0.120
Rota_liq	49.5	7	2	1.05	1.16	0.703
Rabies	60.6	7	5	1.05	0.10	0.185
Rabies	126.0	7	1	1.05	0.49	0.378
IPV	51.0	7	1	1.05	1.16	0.362

Table 4. Assumptions input into the VSST for calculation of storage space

General Assumptions			
Total Catchment Population	12.7 million	Store Oversizing Factor	25%
Transfer Aisle Spacing (m)	20		
Shelving Storage Assumptions			
Shelf Volume Utilization Factor	*55%*	Shelf Depth (m)	0.5
Working Aisle Width (m)	0.9	Transfer Aisle Width (m)	0.9
Max Load Height (m)	*2.1*	Number of shelves	4
Pallet Standing Storage Assumptions			
Pallet Standing Utilization Factor	*55%*	Pallet Format	EUR pool
Pallet Arrangement	Single Deep	Pallet Width (m)	1.2
Pallet Orientation	Short	Pallet Depth (m)	0.8
Max Load Height (m)	*1.2*	Pallet Thickness (m)	0.15
Pallet Racking Storage Assumptions			
Pallet Racking Utilization Factor	*75%*	Pallet Format	EUR pool
Pallet Arrangement	Single Deep	Pallet Width (m)	1.2
Pallet Orientation	Short	Pallet Depth (m)	0.8
Max Load Height (m)	*1.2*	Pallet Thickness (m)	0.15
Number of pallet tiers	4		

The input parameters in Table 4 selected for the pallet racking and pallet standing storage methods assume that Jungheinrich EJC 212 Lift Trucks would be used to move pallets within the store (Jungheinrich, 2013). These trucks are currently in use at the recently completed PCT pharmaceutical warehouse in Tunis discussed in the previous section; due to their low energy consumption during operation, they were also selected for the DSSB layout. The number of pallet racking tiers was set to four, as this is the maximum number of tiers that can be reached by the selected lift trucks and also allows for the most compact layout to minimize the volume of cold storage space. The outputs of the VSST used to inform the design of the final building layout used in this thesis are shown in Table 5. The estimated lumped vaccine and auxiliary goods storage volumes for each temperature zone independent of any one specific storage method are 8,739 liters for the Frozen Storage zone (-20°C), 96,784 liters for the Chilled Storage zone (+5°C), and 158,742 liters for the Ambient zone (15-32°C). As expected, the Frozen Storage zone is the smallest, since only the Oral Polio Vaccine (OPV) is required to be kept at such low temperatures. Projections from the VSST indicate that with such a relatively small vaccine volume, a shelving storage method will help to minimize both required floor area and volume for storage. Both the Chilled Storage and Ambient zone require over ten times as much storage space as the Frozen Storage zone. For each of these zones, the VSST calculations show that reductions in floor area can be realized through the implementation of pallet racking storage.

Table 5. Results from the VSST: Storage space requirements

Frozen Storage zone (-20°C)					
Net Vaccine Volume (liters)			8,739		
Shelving Storage		*Pallet Standing Storage*		*Pallet Racking Storage*	
Shelving Store Floor Area (m^2)	17	Pallet Standing Floor Area (m^2)	53	Pallet Racking Floor Area (m^2)	23
Shelving Store Volume (m^3)	38	Pallet Standing Volume (m^3)	111	Pallet Racking Volume (m^3)	134
Chilled Storage zone (+5°C)					
Net Vaccine Volume (liters)			96,784		
Shelving Storage		*Pallet Standing Storage*		*Pallet Racking Storage*	
Shelving Store Area Floor (m^2)	183	Pallet Standing Floor Area (m^2)	483	Pallet Racking Floor Area (m^2)	95
Shelving Store Volume (m^3)	402	Pallet Standing Volume (m^3)	1,013	Pallet Racking Volume (m^3)	546
Ambient zone (15-32°C)					
Net Vaccine Volume (liters)			158,742		
Shelving Storage		*Pallet Standing Storage*		*Pallet Racking Storage*	
Shelving Store Area (m^2)	299	Pallet Standing Floor Area (m^2)	798	Pallet Racking Floor Area (m^2)	161
Shelving Store Volume (m^3)	658	Pallet Standing Volume (m^3)	1,675	Pallet Racking Volume (m^3)	930

The fourth temperature zone, Controlled Room Temperature (15-25°C) is not included in these estimates because the VSST does not differentiate between the supplies that are intended for this storage zone and the Ambient zone; instead it lumps these supplies into the Ambient zone. This reflects the current practice in the vaccine storage industry, as years of inconclusive discussion about the possibility of including these zones has not resulted in their being mandated by any storage regulations (PATH, 2012). However, many manufacturers advocate storage in this temperature regime (PATH, 2012). So, this project has chosen to include this temperature zone because the intention of the design is to reflect not only the latest energy efficient thinking but also best practices in vaccine storage.

3.2.2 Creation of the Building Layout

As the DSSB had already provided a site for the new warehouse, a site selection process was not required prior to designing the building layout. The site that was provided is an empty lot adjacent to an existing DSSB warehouse, as shown by the site plan in Figure 14. This site is bordered to the south and the west by a masonry wall, and vehicles can only access the site from the northwest corner of the lot between the existing administration building and the parking shelter. The storage requirements calculated by the VSST were increased at the request of the DSSB so that pharmaceutical drugs and related supplies could also be stored in the warehouse. However, no firm storage volumes for the drugs were provided; therefore the volumes were increased through the expert knowledge of Mr. Garnett. The addition of pharmaceutical drugs does not alter the function of the layout as a primary vaccine warehouse, as the temperature regimes required for drug storage are the same as those required for vaccine storage. Therefore, functionally there is no difference between the layout with or without the addition of the pharmaceutical products. As the calculations from the VSST showed that pallet racking was the most efficient storage option in terms of floor area for the Chilled Storage zone and Ambient zone, this method was selected for both of these zones. In the Frozen Storage zone, a shelving storage method was selected for the same reason of minimizing the required storage area. This is especially important for the Frozen Storage zone, due to the large cooling load produced by the temperature difference between this zone and the surrounding zones. In order to function as an independent facility, a primary vaccine warehouse must include several auxiliary zones to support the storage areas. The following additional areas were included in the design: individual offices, male and female restroom facilities, a workshop, a plant area for the building equipment, and a bay for shipping and receiving goods.

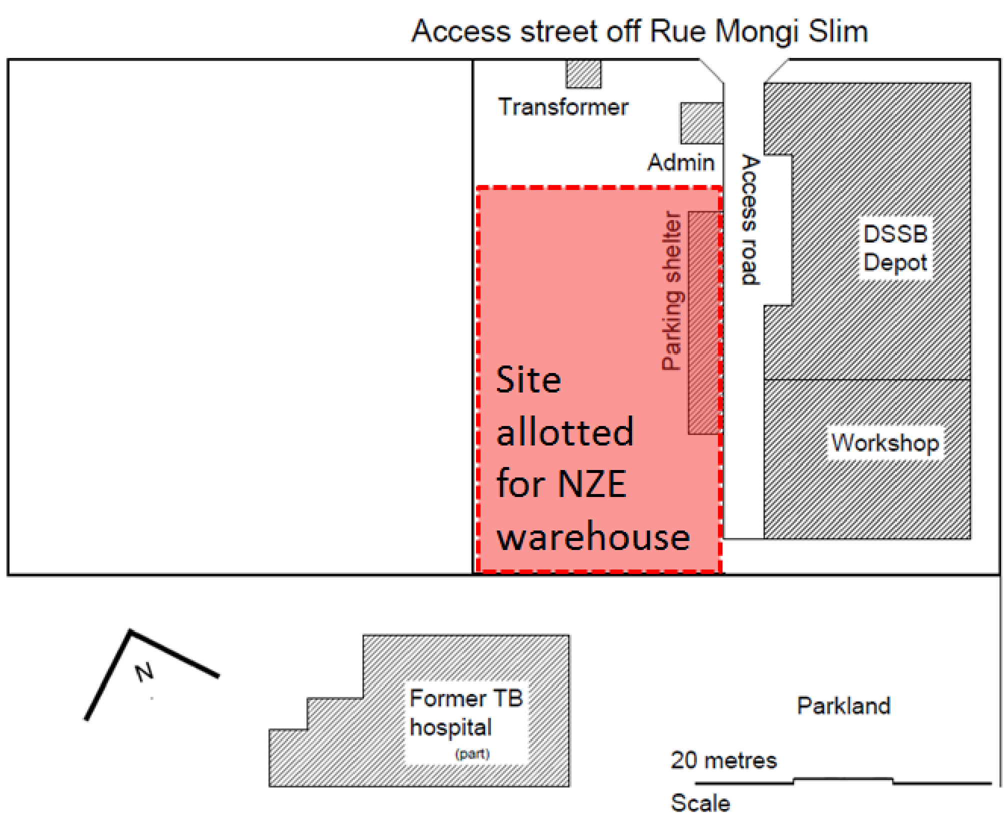


Figure 14. Site plan for the proposed building; Lot adjacent to the DSSB depot; adapted from (Garnett, 2013)

The final floor plans for the layout, from which the prototypical building energy model was created, are shown in Figure 15 and Figure 16. The detailed set of drawings for the building, including elevations, section drawings and the roof plan are included in Appendix A. The layout has a total internal floor area of 846 m^2, of which 124 m^2 are unconditioned plant area and 64 m^2 are internal mezzanine area. The building has a flat roof and an internal height of 6.85 m, with the mezzanine floor 3 m above the ground floor. The Ambient zone has the largest storage capacity, with 264 pallet bays, and expansion into the incoming and outgoing goods area allows for an additional 120 bays if needed. The Chilled Storage zone has a total of 152 pallet bays, and the Controlled Room Temperature (CRT) zone is the smallest zone to implement pallet racking with a total of 40 bays. The Frozen Storage zone allows for a total of 10,000 liters of vaccine storage space, slightly larger than the 8,739 liters suggested by the VSST. The walls and ceilings of the Chilled Storage zone, Frozen Storage zone, and CRT zone are independent of the external building envelope, and therefore are most accurately described as walk-in cold storage zones. Designing these zones as walk-ins allows for the Ambient zone to serve as a buffer and shield these zones from the extreme temperatures and solar radiation of the outdoor environment. In between the cold storage walls and the external walls, there is a gap of 100 mm to allow for moisture removal. The internal height of the CRT and Chilled Storage zones is 6 m, while the Frozen Storage zone requires an internal height of only 3 m due to its storage shelves. One of the key energy efficient features of the layout is the shared walls between the walk-in zones in order to reduce heat loss and subsequently reduce the cooling load for these zones. In addition, the walk-in zones have been arranged so that the CRT zone serves as a vestibule for the Chilled Storage and Frozen Storage zone to reduce the air infiltration heat load to these lower temperature zones.

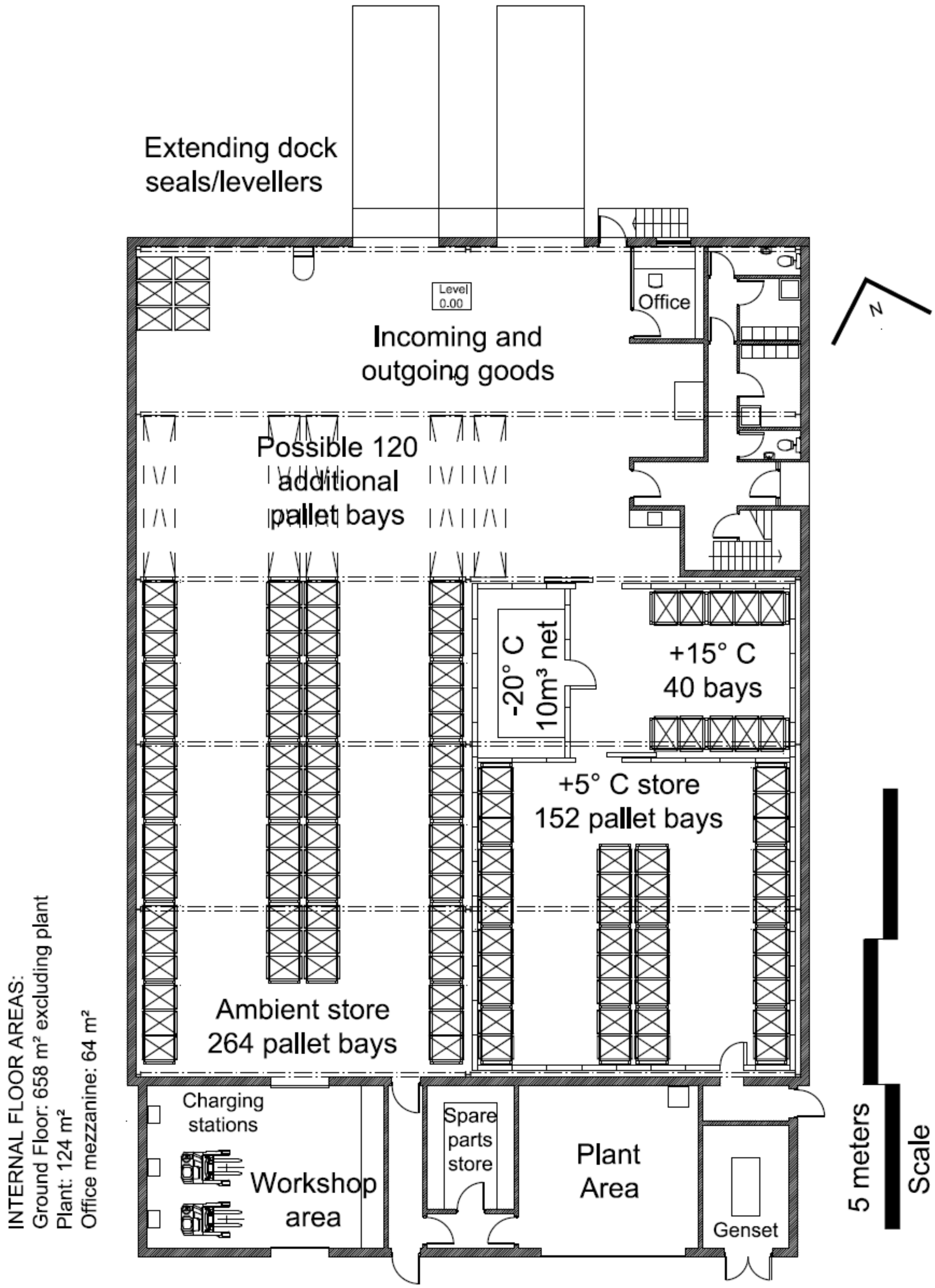


Figure 15. Final layout for the warehouse, ground floor; adapted from (Garnett, 2013)

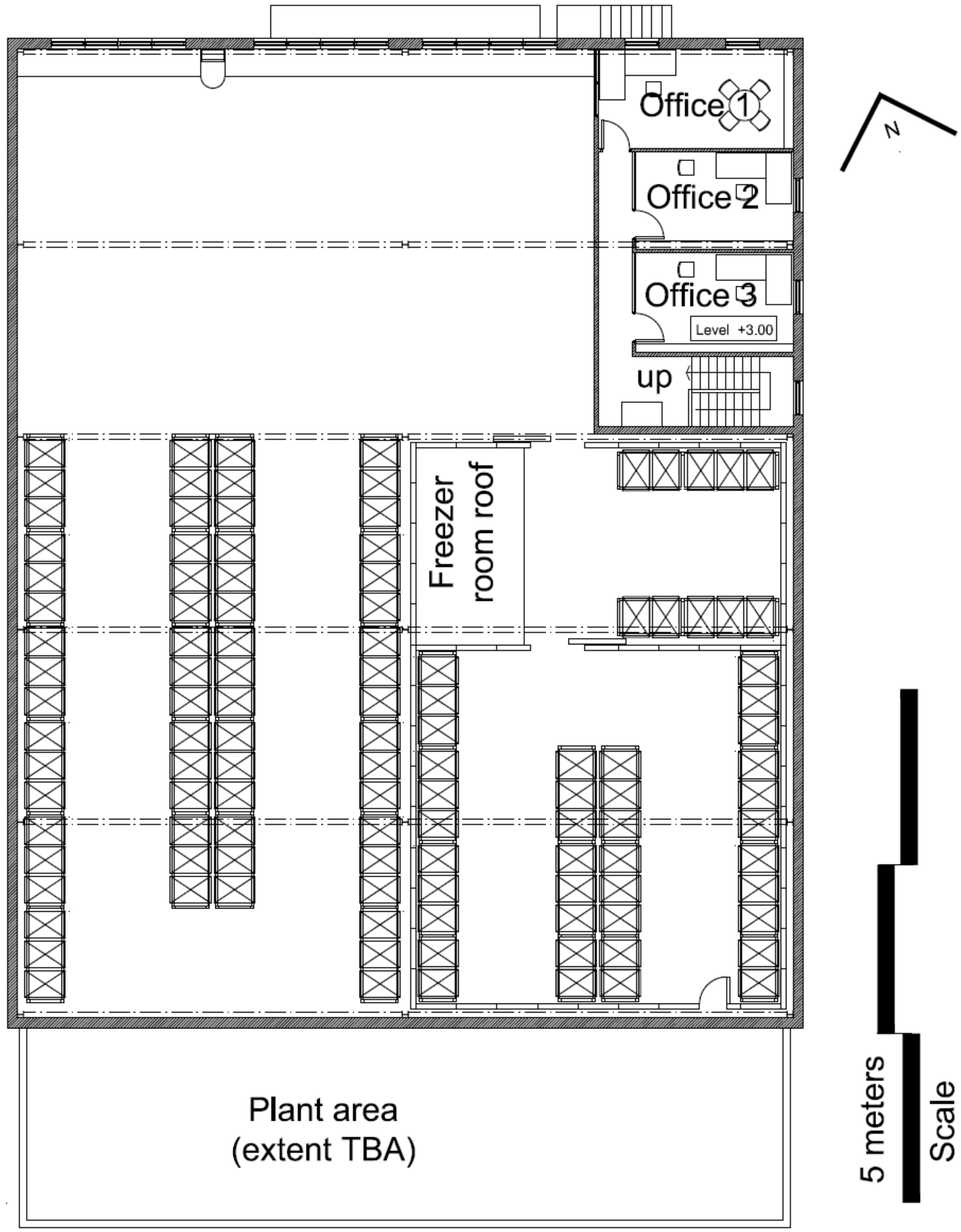


Figure 16. Final layout for the warehouse, first floor; adapted from (Garnett, 2013)

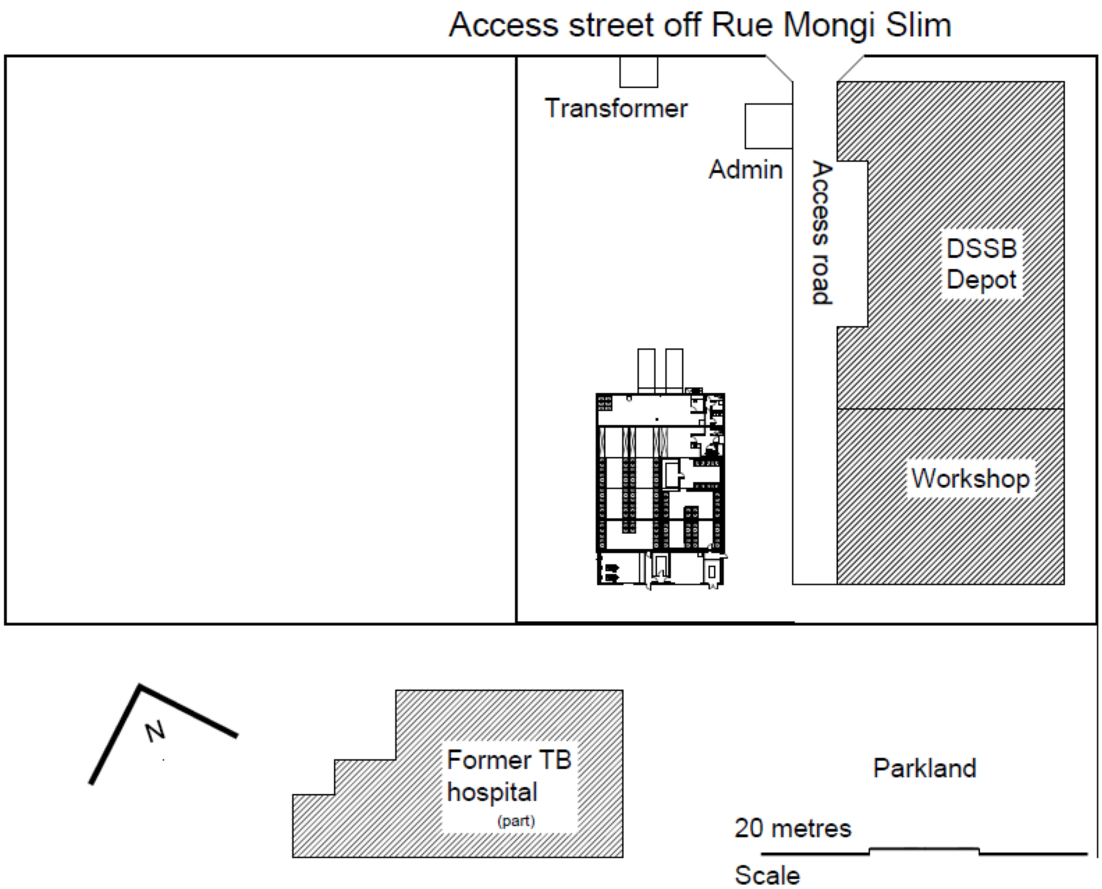


Figure 17. Site plan of the proposed location of the NZE warehouse; modified from (Garnett, 2013)

The building is located at the south end of the allotted site as shown in Figure 17, with the loading dock facing 19 degrees East of North, perpendicular to the street from which trucks will enter. This specific location on the site was selected based on the logistical concerns of allowing adequate space for the trucks to dock, as well as allowing for future expansion of the facility. The parking shelter included that is currently occupying a portion of the site has been removed to allow for easier access to the site. Stored goods enter and exit the warehouse through the two large overhead doors located on the north wall of the Ambient zone. Each overhead door was sized to be 2.5 m wide by 3 m tall, as this is one of the most common dock door sizes (Liu et al., 2007). The office mezzanine is located at the North West corner of the building, and is separated into three individual offices. The offices were placed in this location for easy observation of vehicles and people entering the compound. Below the mezzanine are separate restrooms, showers, and changing facilities for male and female warehouse workers. The plant area and workshop are located at the south end of the building, and both have an internal height of 3 m. The plant room is dedicated to housing refrigeration equipment such as the condensers for the cold rooms, along with a backup generator to ensure an uninterrupted power supply.

3.3 Development of the Building Energy Model

3.3.1 Model Creation Process

Once the final layout of the vaccine warehouse was completed, a building energy model of the facility was constructed. The model was constructed using EnergyPlus V8.0, a powerful energy analysis and thermal load simulation software developed by the US Department of Energy (DOE). This software was selected as an appropriate modeling program for a variety of reasons. Foremost, the algorithms behind EnergyPlus have been extensively tested and validated through experimental comparison (LBNL, 2014). In addition, the software has been widely implemented throughout the building performance simulation community for a variety of purposes. Heo, Choudhary and Augenbroe used EnergyPlus to validate a normative model used for examining retrofit analysis under uncertainty (Heo, Choudhary, and Augenbroe, 2012). Yildiz and Arsan used EnergyPlus to conduct a sensitivity analysis to identify influential parameters for apartment buildings in hot-humid climates (Yildiz and Arsan, 2011). Wang and colleagues used EnergyPlus to analyze uncertainties in building energy consumption due to weather and operational parameters for a medium-size office building (Wang et al., 2012). Another advantage of EnergyPlus is that it uses a text based input file, which allows to easy automation of the process for writing the large number of Input Data Files (IDFs) necessary for the Monte Carlo based sensitivity analysis as discussed later in this chapter. EnergyPlus is also capable of running parallel simulations and is easily run by a variety of external programs through command line controls. Therefore, an external program can be used to autonomously run the relatively large number of simulations required for a global sensitivity analysis in an efficient manner. Another benefit is that Typical Meteorological Year (TMY) weather files for running annual simulations of a building in average climate conditions are readily available from the DOE for a large number of developing world locations (US DOE, 2013).

In addition to utilizing EnergyPlus, DesignBuilder was leveraged to create the building 3D geometry and thermal zones from the 2D layout drawings (DesignBuilderUSA, 2014). As EnergyPlus is a text-based energy modeling program, it is difficult to create geometry directly from building drawings. Therefore, several Graphical User Interfaces (GUIs) have been created that serve as a front end for creating the building geometry (DesignBuilderUSA, 2014; NREL, 2014a) Often the entire energy modeling process can be conducted from these programs. However, for the purposes of this research, once the geometry is created, it is exported to an EnergyPlus IDF and the rest of the building model is constructed working directly with the text file. This is a more rigorous method as it allows for the modeler to examine the inputs and assumptions upon which the model is based, whereas often when using a GUI, assumptions that may not be valid are hidden deep within the modeling environment. DesignBuilder was selected due to its established reputation and subsequent widespread use in industry and academia.

3.3.2 Thermal Zoning

Using the two dimensional AutoCAD layout, the geometry of the building was created in the DesignBuilder 3-D modeling environment, similar to architectural design CAD software such as SketchUp or Revit (Autodesk, 2013; Trimble Navigation, 2013). The model of the building was separated into several thermal zones, guided by the zoning method implemented for the warehouse models constructed as part of the PNNL study for the ASHRAE Advanced Energy Design Guide for Small Warehouses (Liu et al., 2007). In this study, both of the warehouse models developed follow the zoning by space type method without concern for perimeter and core zones. With an internal height of 8.5 m and a floor area of 4645 m^2, the larger of the two models in the PNNL study is of greater height and larger floor area than the model used in this thesis. Yet, the PNNL study's model does not employ perimeter and core zoning. Therefore, it is assumed that, for the warehouse model constructed for this thesis, perimeter and core zones in addition to space type zones are not necessary.

Following the method of space type zoning, each storage area was assigned a unique thermal zone. The shipping and receiving area was included in the Ambient thermal zone as both of these spaces have the same suggested operational temperature range of 15-32 °C. The same reasoning was used to lump together all of the restroom and changing facilities into a single thermal zone, as all of these rooms have the same thermostat set-points. While all of the office zones share a common suggested temperature range, the offices were modeled separately so that the effect of day lighting on the required energy for electric lighting could be accurately modeled. The spare parts area, refrigeration equipment room, and generator room are lumped together as the plant room, as these are completely unconditioned spaces. Therefore, the building energy model is made up of a total of 11 thermal zones, which are identified on the building floor plan in Figure 18.

Figure 18. Final geometry exported from DesignBuilder; adapted from (Garnett, 2013)

The floor areas and volumes for each of these zones are included in Table 6. The thermostat set-points are included in Table 7. The volume of the Ambient zone shown in Table 6 is not the direct product of the floor area and the zone height due to the inclusion of the air between the gap of the ceiling of the walk-ins and the building roof. The floor area of 414.1 m^2 is the true floor area of the zone, which is used to calculate the lighting power and other floor area-dependent parameters. The thermal set-points shown in

Table 7 for the Chilled Storage, Frozen Storage, and CRT Storage zones are derived from the recommended temperatures windows documented in the global health literature (Garnett, 2002; PATH, 2012). The heating and cooling set-points for the office zones were taken from the average set-points listed by Wang and colleagues in a study examining operational parameters uncertainty in office buildings (Wang et al., 2012).

Table 6. Thermal Zone Floor Areas and Volumes

Zone	**Floor Area (m^2)**	**Volume (m^3)**	**Storage Volume (m^3)**	**Storage Volume (Pallet Bays)**
Ambient	414.1	3,011.6	304 [+138]	264 [+120]
Chilled Storage	113.1	678.8	175	152
CRT Storage	46.5	279.0	10	----
Frozen Storage	18.1	54.4	46	40
Office 1	16.4	62.0	----	----
Office 2	13.6	52.5	----	----
Office 3	14.3	55.1	----	----
Mezzanine Hallway	20.0	71.7	----	----
Restrooms	62.7	188.1	----	----
Workshop	49.2	172.1	----	----
Plant	82.9	290.1	----	----

Table 7. Building energy model thermal zone heating and cooling set-points

Thermal Zone	**Heating Set-Point (°C)**	**Cooling Set-Point (°C)**
Ambient	15	32
Chilled Storage	2	8
Frozen Storage	-25	-15
CRT Storage	15	25
Workshop	15	32
Restroom	15	32
Office 1	20 (15 night setback)	26 (32 night setback)
Office 2	20 (15 night setback)	26 (32 night setback)
Office 3	20 (15 night setback)	26 (32 night setback)
Mezzanine Hallway	20 (15 night setback)	26 (32 night setback)
Plant	*No heating	*No cooling

While there is no documentation on the suggested temperature range for the Ambient zone, the set-points for this zone were established based on the expert advice from members of the design team that these were the lowest and highest temperatures to which the dry goods should be subjected. The set-points for this zone were also used as the set-points for the

Workshop and Restroom zones because it is assumed that if the warehouse workers will tolerate such a wide temperature range for the main working zone, then it will also be tolerated in the auxiliary zones.

A three dimensional view of the geometry of the thermal model is shown in Figure 19, with the exterior windows shaded light gray and the external doors shaded red. As shown by this figure, the WWR for each window type was varied assuming horizontal ribbons instead of individual windows. This view of the building geometry also clearly shows the lower height of the workshop and plant room zones in the rear of the building (3 meters) in comparison to the main warehouse (6.85 meters). It should be noted that for the climates in the northern hemisphere, the front wall of the warehouse is assumed to face north, as indicated by the arrow in the figure. However, for the climates in the southern hemisphere the front wall faces south so that the clerestory glazing fulfills the same criteria of avoiding direct sunlight for the majority of the year. A simple rendering of the model geometry in DesignBuilder is shown in Figure 20 .

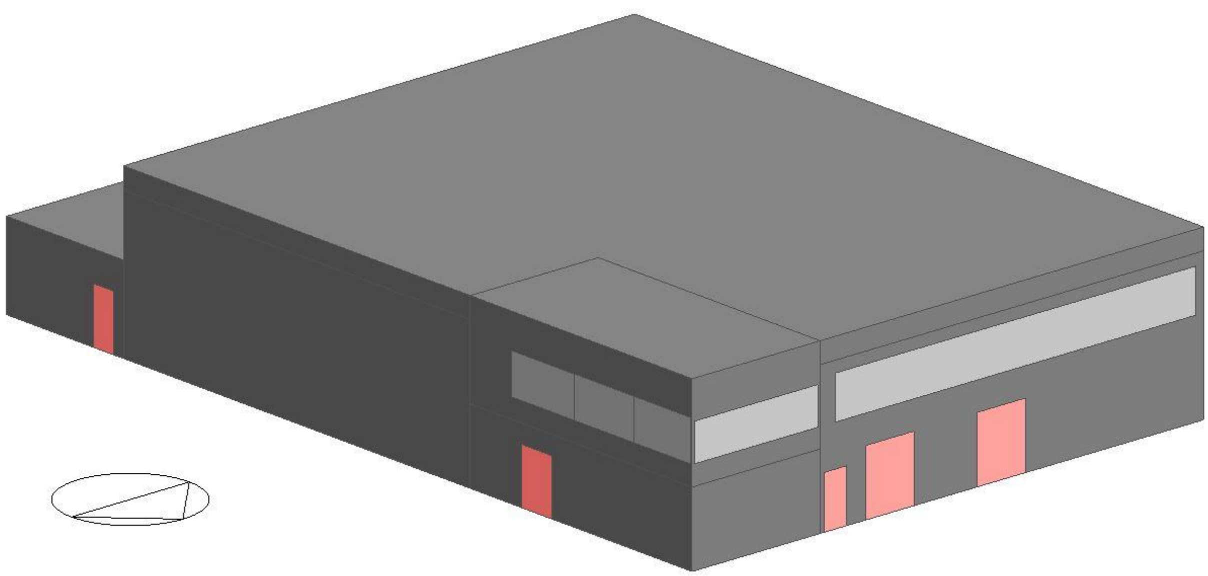


Figure 19. Building energy model geometry from DesignBuilder

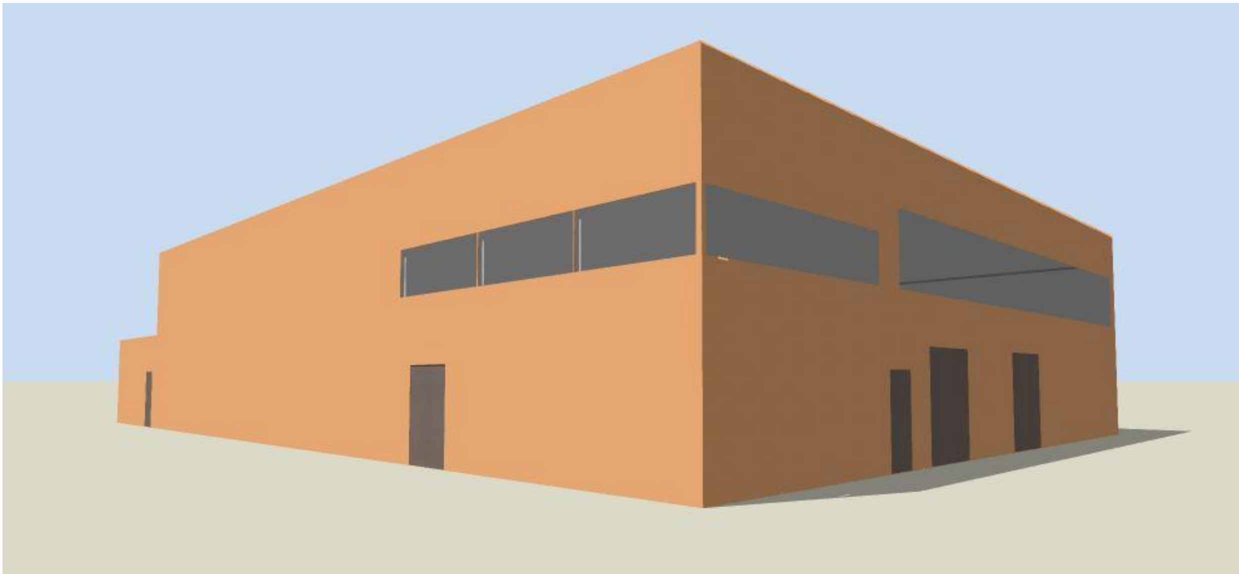


Figure 20. Rendering of the building energy model geometry in DesignBuilder

3.3.3 Building Energy Model Assumptions: Occupancy

The warehouse is assumed to be operational for six days a week, from 8 AM to 5 PM with a one hour lunch break in accordance with the assumptions made by Lui in the PNNL study on improving the energy efficiency of small to medium warehouses (Liu et al., 2007). For a typical weekday it is assumed that one person will be working in each of the office zones, as each of these spaces is intended to be a private office. In contrast, the plant area is assumed to be unoccupied during the entire work day in the model, as this zone would only rarely be occupied for maintenance and servicing of equipment in the actual building. For the rest of the thermal zones, a standard warehouse occupancy density of one person per 100 m^2 of floor area was used (ISO, 2008). Graphs of the occupancy schedules, as well as graphs of several other schedules, are included in Appendix B. To obtain meaningful load data from the occupancy information, an average activity level must be assumed for the zone occupants. Table 8 shows the activities and corresponding total heat gains assumed for each zone. For this research a constant heat gain for each type of activity was assumed, and EnergyPlus uses an internal function to estimate a latent and sensible fraction from each total heat gain.

Table 8. Heat gains for the activities within the building (ASHRAE, 2010; DesignBuilderUSA, 2014)

Activity	Zones Implemented	Heat Gain (W)
Office Work/ Standing/Walking	Offices	127
Light Manual Work	Ambient, Workshop, Restroom, CRT	180
Manual Work in -20ºC	Frozen Storage	395
Manual Work in 5ºC	Chilled Storage	246

3.3.4 Building Model Assumptions: Lighting

Since lighting power density has been selected as a variable design parameter for the sensitivity analysis, nominal lighting loads have not been assigned to each zone. The only assumption that has been made is that all of the warehouse zones (Ambient, Chilled Storage, Frozen Storage, CRT, Workshop, and Restroom zones) share a common lighting power density, as do the Mezzanine zones (Office 1, Office 2, Office 3, and Mezzanine Hallway). This distinction allows for different ranges of power densities in these two types of zones, as done in the PNNL small warehouse study (Liu et al., 2007). As several of the zones allow for daylighting, the desired luminance levels for each zone are shown in Table 9. The desired luminance level for the ambient zone is listed as variable, due to the inclusion of this parameter in the sensitivity analysis. Daylighting sensors were omitted in all of the model zones that have no windows due to their known negative impact on energy performance, the Frozen Storage and Chilled Storage zones. In addition, daylighting sensors were omitted for zones that have no design variables from sensitivity analyses that affect the lighting load levels: the Workshop, Restroom, and Plant zones. Figure 21 shows the zones that have daylighting sensors, highlighted in pink, and where they have been placed in the model. The Ambient zone light control has been separated into two distinct zones - the pallet racks and the open bay - to account of the fact that significant variations in the daylighting level will occur in this space, since a clearstory window over the dock doors is one of the designs considered by the sensitivity analysis. Two sensors are included in Office 1 based on similar logic, as the office has both north facing and east facing glazing designs considered. The daylighting system for each zone is assumed to allow for continuous dimming to the zone luminance set-point, and switching off of the electric lighting if the lighting needs are completely met by natural light. The lighting schedule for all of the zones is dependent on whether occupancy sensors are used, which is a building control variable investigated in the sensitivity analysis. See section

3.4.2 Defining the Building Control Parameter Variation for more detail.

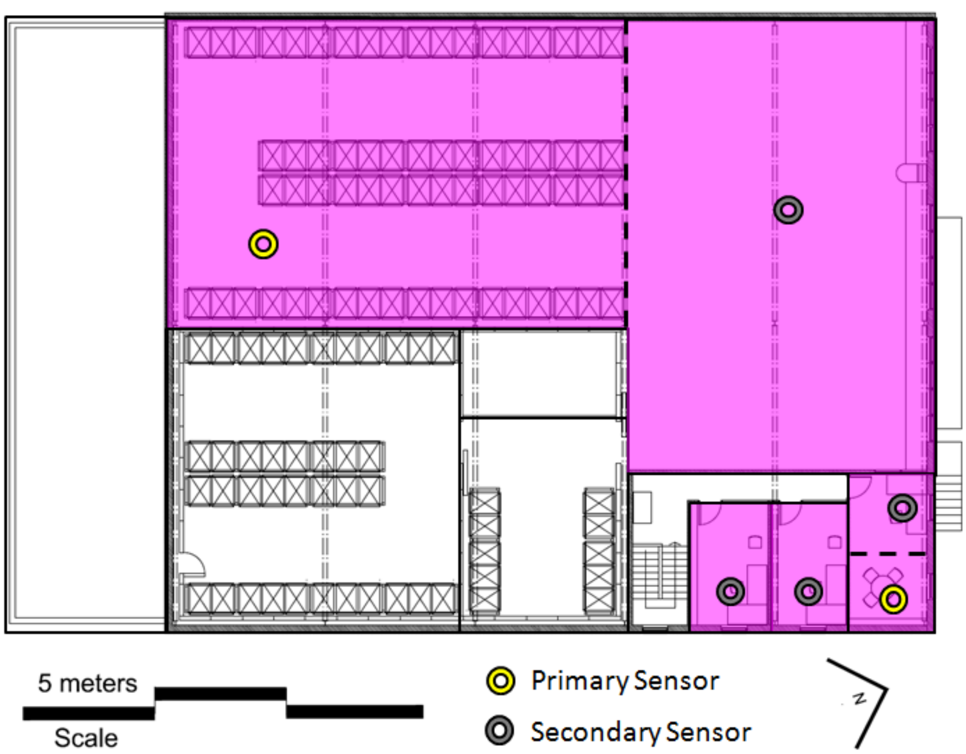


Figure 21. Daylighting primary and secondary sensor positions; adapted from (Garnett, 2013)

Table 9. Baseline desired luminance and daylighting information for each zone

Building Zone	Desired Luminance (lux)	Daylighting Sensor (Yes/No)
Ambient	Variable	Yes
Chilled Storage	150	No
Frozen Storage	150	No
CRT Storage	150	No
Workshop	150	No
Restroom	150	No
Office 1	300	Yes
Office 2	300	Yes
Office 3	300	Yes
Mezzanine Hallway	150	No
Plant	0	No

3.3.5 Building Model Assumptions: Plug Load

The plug load for a building is the load imposed on the building by equipment that is not permanently installed in the building, hence it must be plugged in; this term is synonymous with equipment load. The warehouse has two significant sources of electric plug load. In the office zones, the operation of standard office equipment such as computers and printers must be considered. Both the average power density and schedule for the plug loads of the office zones are varied as part of the sensitivity analysis, and are discussed further in section

3.4.2 Defining the Building Control Parameter Variation. The second major source of plug load is in the warehouse zones due to the operation of the fork lift trucks to move pallets. The fork lift load is calculated using the assumption that two Jungheinrich EJC 212 Lift Trucks (Jungheinrich, 2013). These are the lift trucks which the VSST sizing calculations assumed and are the same trucks that are currently used by the PCT (Pharmacie Centrale de Tunisie) for drug and vaccine warehousing. It is assumed that two forklifts will be used; however, each will only be utilized for 50% of the time during a regular work day, based on observations of warehouse operations from the building retrofit study conducted. The power consumption of these trucks is approximated using their rated VDI cycle power consumption of 1.25 kW. The VDI cycle is a performance testing cycle used to establish a rating for the expected power consumption of a fork lift under regular usage conditions (The Association of German Engineers, 2012). To convert the power that the trucks consume to the power that the building draws from the grid, a standard assumption of 75% charging efficiency is assumed as no specific charging efficiencies are listed for this specific truck (Argonne National Labs, 2008). Based on these assumptions, the total power consumed by the fork lift trucks daily is 13.3 kWh. The heat released by the trucks during operation is evenly distributed in the working zones according to area over the duration of the work day.

3.3.6 Building Model Assumptions: Internal Mass

For the zones in which the temperature fluctuates between the heating and cooling set-points, the thermal mass of the stored goods may have a significant influence on the temperature variation. To take this effect into account, the average thermal mass for the products stored in the CRT Storage and Ambient zones have been calculated. The thermal mass C_{th} is calculated by using Equation 2 where ρ is the product density, c_p is the product specific heat, and V is the product storage volume.

$$C_{th} = \rho c_p V \tag{2}$$

For the Ambient zone, the density and specific heat of the product are assumed to be 200 kg/m^3 and 836 J/kgK, respectively, as these numbers were used as the average parameters of room temperature storage warehouse goods in the PNNL small warehouse study (Liu et al., 2007). However, these numbers cannot be applied to the stored goods in the CRT zone, as products such as diluents, vaccines, and pharmaceuticals have higher specific heats due to a large percentage of their mass being water. The assumed density and specific heat of the product stored in the CRT Storage zone are 303.77 kg/m^3 and 2811 J/kg-K, which were calculated based on vaccine information available from the WHO (Park, Baek, No, and Gay, 2010). For both zones, it is assumed that half of the available racking storage is filled, resulting in 156 m^3 of product for the Ambient zone and 23 m^3 of product for the CRT Storage zone. From these assumptions, the resulting thermal masses for the Ambient and CRT zones are 26 million J/K and 19 million J/K, respectively.

3.3.7 Building Model Assumptions: Ventilation

To improve energy efficiency, the building is assumed to be ventilated only from the hour before the assumed work day starts until the hour after, encompassing the hours of 7 AM – 6 PM (Liu et al., 2007). The applied ventilation rate for the Ambient and Washroom zones is 0.03 L/s of outdoor air per m^2 of floor area, as suggested by ASHRAE ventilation standards (ASHRAE, 2007b). The Office zones (Office 1, Office 2, and Office 3) are also ventilated with the 0.03 L/s of outdoor air per m^2 and receive and an additional 10 L/s of outdoor air per person, as specified by ASHRAE ventilation standards.

3.3.8 Building Model Assumptions: Product Load

For all of the zones, it is assumed that there are no cooling or heating loads imposed by the incoming products. As vaccines and their associated supplies must be maintained within the same temperature window for both transportation and storage, the incoming products will be at the same temperature as their respective storage zones.

3.3.9 Building Model Assumptions: Infiltration

As the infiltration through the building envelope is a design parameter in the sensitivity analysis, it is modeled as a constant air change per hour rate in the building energy model. In reality, infiltration is a complex physical process, which depends primarily on the external wind speed, internal building pressure, and temperature difference between the interior air of a building and the outdoor environment (Gowri, Winiarski, and Jarnagin, 2009). However, it has been proven as an accurate method to simplify the infiltration down to a prescribed air change per hour rate. For instance, using a prescribed infiltration rate, Heo, Choudhary and Augenbroe were able to calibrate a model to the energy consumption of its actual building to an Index of Agreement rate of 0.97 (Heo et al., 2012). This technique has been widely applied throughout the building performance simulation community for design. It was applied by Hygh for a sensitivity analysis examining the most important design parameters for office buildings in several US climate zones (Hygh et al., 2012). Lastly, the use of a constant, prescribed infiltration rate provides an easily interpretable and meaningful parameter for designers. This lumped infiltration rate encompasses all of the infiltration sources through the building envelope, such as through the windows, walls, dock doors, and cracks between components.

3.3.10 Building Model Assumptions: Natural Ventilation

Instead of using a complex model to determine natural ventilation as a result of wind pressures or the stack effect, a simple design model is employed to explore the energy saving potential of natural ventilation using the EnergyPlus ZoneVentilation:DesignFlowRate object. A design flow rate in terms of Air Changes per Hour (ACH) is prescribed, such as 2 ACH. In addition, the assumption is made that natural ventilation is not allowed unless the outdoor air is at least two degrees Celsius cooler than the air inside of the warehouse. The value of the natural ventilation design flow rate is explored in the sensitivity analysis.

3.3.11 Building Model Assumptions: Cold Storage Door Operation

Due to the discrepancies between heating and cooling set-points for the building thermal zones, the internal door openings cannot be neglected, as is often the practice with building energy models. In order to account for the heat exchange that occurs between these zones as a result of the air infiltration through open doorways, the method formulated by Gosney and Olama is applied as this method is implemented by the RefrigeratedDoorMixing object in Energy Plus (Gosney and Olama., 1975). This method is widely applied in the refrigeration community and is included in the ASHRAE Refrigeration Handbook (ASHRAE, 2010). Equation 3 (taken from the method) indicates how that design parameter of doorway protection mechanism effectiveness considered by the sensitivity analysis influences the heat exchange through the door. Q_{Mixing} is the heat exchanged through the doorway, $Q_{FullFlow}$ is the heat exchanged assuming no door protection mechanism, $F_{DoorOpen}$ is the fraction of time that the door is open, F_{Flow} is the doorway flow factor, and $E_{Protection}$ is the effectiveness of the doorway protection mechanism.

$$Q_{Mixing} = Q_{FullFlow}\, F_{DoorOpen}\, F_{Flow}\, (1 - E_{Protection}) \tag{3}$$

The flow factor is calculated by EnergyPlus based on the temperature difference between the rooms exchanging air, and an effectiveness of 0.9 is assumed based on the implementation of a strip curtain for each doorway (LBNL, 2013a). The Frozen Storage door is assumed to be open for four minutes out of every operational hour, as is assumed by Stoeckle for a freezer room within a refrigerated warehouse (Stoeckle, 2000). The Chilled Storage and CRT Storage doors are both assumed to be open for eight and a half minutes out of every operational hour. This number was calculated from data provided by the PCT for their newly constructed refrigerated drugs warehouse in Tunis. Weekly averages for door open times were provided, and from these data the annual average door open time was calculated. The data provided by the PCT are the same that were used for a building energy audit of the facility (Pudleiner et al., 2014) and are included in Appendix C.

3.3.12 Building Model Assumptions: Warehouse/Office Heating and Cooling

In order to allow as much flexibility as possible, the efficiencies of the mechanical systems to heat and cool the various zones are considered to be design parameters in the sensitivity analysis. This facilitates an integrated design method, as it allows for improvements in the mechanical system design to be considered alongside modifications to the building fabric parameters. Therefore, the Ideal Loads Air heating and cooling system, one of the numerous HVAC (Heating, Ventilation and Air-Conditioning) objects that can be implemented in EnergyPlus, was selected as it allows for calculation of the building heating and cooling demand independent of any assumptions about building systems. This method calculates the latent and sensible cooling demand loads assuming 100% efficiency. The demand is converted into electricity consumed through the use of a COP value. Therefore, the total electricity consumed by the building, E_{Total}, is calculated as shown in Equation 4, where $\acute{E}$ is the non-HVAC electricity consumption of the building, $Q_{Cooling}$ is the total cooling load, $COP_{Cooling}$ is the cooling system Coefficient of Performance, $Q_{Heating}$ is the total heating load, and $COP_{Heating}$ is the heating system Coefficient of Performance. For all of the building zones except for the Frozen Storage and Chilled Storage zones, constant COPs were assumed.

$$E_{Total} = \acute{E} + \frac{Q_{Cooling}}{COP_{Cooling}} + \frac{Q_{Heating}}{COP_{Heating}} \tag{4}$$

3.3.13 Building Model Assumptions: Refrigeration

For the calculation of refrigeration electricity, the unique modeling method validated by the building energy retrofit discussed in section ***3.1 Retrofit Analysis of an Existing Medical Warehouse*** was used. In this method the Ideal Loads Air object in EnergyPlus was used as the basis for calculating the cooling loads of the Refrigeration Storage and Frozen Storage zones. However, several additional equations were used to ensure an accurate calculation of electricity consumption. While the Ideal Loads Air method properly accounts for the latent load in non-refrigerated zones, this method does not account for the freezing of moisture on the coils of the evaporators in cold storage zones. Therefore, Equation 5 was used to account for the latent loads Q_{latent} in these zones (LBNL, 2013a), where $m_{Infiltration}$ is the mass of infiltrating air, $\Delta h_{IceToVapor}$ is the latent heat absorbed to change from ice to vapor, $W_{ZoneAir}$ is the humidity ratio of the infiltration air, and $W_{ColdRoomAir}$ is the humidity ratio of the cold room air.

$$Q_{latent} = m_{Infiltration} \Delta h_{IceToVapor} \left(W_{InfilAir} - W_{ColdRoomAir} \right) \tag{5}$$

The total cooling load is converted to electricity consumption using Equation 5; however instead of assuming a constant COP, a variable COP_{refrig} is calculated based on Equation 6

(Leach et al., 2009) where COP_{Nom} is the nominal COP and T_{Cond} is the condensing temperature.

$$COP_{refrig} = COP_{Nom}(1.7603 - 0.0377 * T_{Cond} + 0.0004 * T_{Cond}^2) \quad (6)$$

The condensing temperature is calculated using an equation of similar form to that used by Stoekle to calculate the condensing temperature in a refrigerated warehouse study (Stoeckle, 2000); it is shown in Equation 7, where T_{db} is the outdoor air dry bulb temperature in degrees Celsius.

$$If\ T_{db} > 10, \quad T_{Cond} = T_{db} + 10 \quad ; \ Else \ldots \quad T_{Cond} = 20 \qquad (7)$$

In order to calculate the defrost loads for the Chilled Storage and Frozen Storage zones, the accumulation of ice on the evaporator coils M_{Ice} was calculated using Equation 8 (LBNL, 2013a), where $\dot{m}_{Infiltration}$ is the mass flow rate of infiltrating air during a simulation timestep and Δt is the length of the simulation timestep. For both zones, an electric coil defrost method was assumed with an effectiveness of 0.7 for the electric heating element as suggested by the EnergyPlus Engineering Reference (LBNL, 2013a).

$$M_{Ice} = \dot{m}_{Infiltration}(W_{InfilAir} - W_{ColdRoomAir})\Delta t \qquad (8)$$

For the Chilled Storage zone, the maximum cooling capacity and fan power for the evaporators were taken from the equipment recommended for the DSSB project through an industry consultation with Porkka. The technical data sheet for the equipment recommended is included in Appendix D, and gives an evaporator fan power of 1.88 kW and a maximum rated cooling capacity of 21.7 kW. As the size of the Frozen Storage zone was significantly reduced after the industry consultation, the maximum cooling capacity figures and fan capacity were derived by examining product literature. The datasheet for the evaporator selected is also included in Appendix D, and has a maximum cooling capacity of 10.1 kW and fan power of 390 W. For both the Chilled Storage and Frozen Storage zone, it is assumed that two redundant refrigeration systems are in place, as experience with the PCT warehouses in Tunisia showed that, at a minimum, two systems are installed in vaccine cold rooms due to the high value of the products stored. Therefore, two evaporators are assumed present in both the Chilled Storage and Frozen Storage zones.

3.3.14 Building Model Assumptions: EnergyPlus Methods Implemented

As EnergyPlus is a powerful and flexible software package, it allows for a variety of different methods to be used for various components of the building energy model. A summary of the EnergyPlus modeling methods selected for the building energy model and the reasons for their selection are shown in Table 10.

Table 10. EnergyPlus modeling methods selected for the warehouse building energy model

Building System/Component	**Modeling Method Selected**
Heating and Cooling System	Ideal Air Loads
Allows for calculation of the building heating and cooling demand loads independent of any assumptions about the mechanical systems implemented.	
Glazing System	Simple Glazing System
Simplified modeling of the glazing by numbers for SHGC, U-Value, and Transmittance allows for a much easier way to vary these design parameters instead of modifying a detailed window construction.	
Freezer Floor	Other Side Coefficients
Allows for prescription of the boundary condition temperature below the freezer floor, which through natural ventilation piping is assumed to maintain a temperature of 5°C to prevent frost heave.	
Chilled Storage Floor	Detailed Ground Heat Transfer
By assuming adiabatic boundary conditions at 15m below ground, allows for a detailed finite element analysis of the heat transfer through the ground floor.	

3.4 Sensitivity and Uncertainty Analysis

Figure 22 shows the progression of the method implemented in this thesis for its uncertainty and sensitivity analyses. First, the parameters for each classification are selected and their variations as building model inputs are defined. Next, an uncertainty analysis is conducted by propagating the variation for these parameters to variations in the building energy consumption through the use of a Monte-Carlo analysis. Finally, the input uncertainty is correlated to the output uncertainty through a regression based sensitivity analysis, allowing for the relative influence of the parameters to be determined.

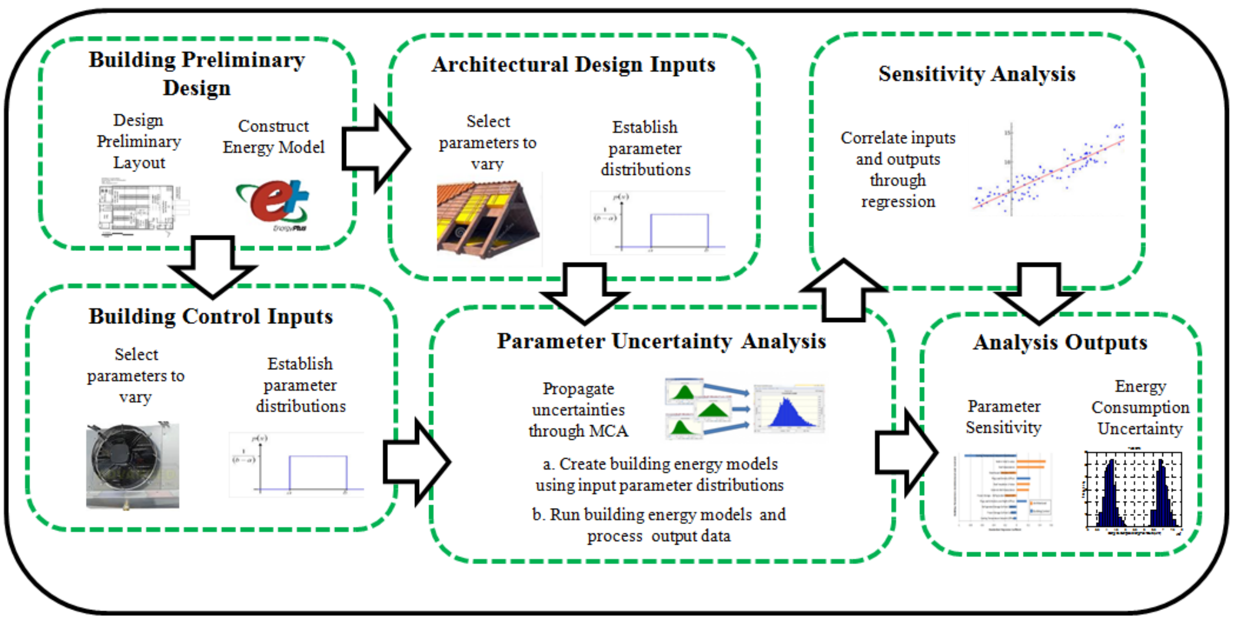


Figure 22. Method formulated for the uncertainty and sensitivity analyses conducted

3.4.1 Defining the Architectural Design Parameter Variations

The sensitivity and uncertainty literature discussed in the previous chapter provides a clear outline of the important architectural design parameters to vary and the common practices for simplifying parameter variation. A key step often underemphasized in the implementation of a global sensitivity analysis is to determine the distributions for the input parameters (Tian, 2013). For all of the architectural design parameters examined, uniform distributions were used, as suggested by Mechri and colleagues for investigating the effects of energy saving design measures (Mechri et al., 2010). This reflects the fact that during the design process, all of the values within the ranges that are being examined can be regarded as equally probable (Tian, 2013). The design variables that were varied for this sensitivity analysis encompass all of the influential building fabric and systems parameters, except for the parameters of building orientation and aspect ratio. Even though these two parameters are commonly referenced as important initial phase design parameters (Hygh et al., 2012; Mechri et al., 2010), their variation was not investigated due to the analysis being applied to the location specific layout designed for the DSSB site.

The remaining parameters examined fall into the following general categories: opaque component thermal properties, glazing properties, infiltration and natural ventilation, electric lighting, and heating and cooling system efficiencies. A comprehensive list of these parameters is included in Table 11. The first sub-category of parameters examined is the external wall and roof parameters, including U-Value, thermal mass, and absorptance. For all of the external wall parameters, the assumption was made that all of the walls employ the same construction, as is commonly assumed in sensitivity analysis studies (de Wilde and Tian, 2012; Jaffal, Inard, and Ghiaus, 2009). The second sub-category of window parameters encompasses variation in Window to Wall Ratio, SHGC and U-Value for three different groups of windows: clerestory glazing above the warehouse overhead doors, Office 1 front façade windows, and Mezzanine side façade windows (which includes the windows on the side façades of Office 1, Office 2, Office 3 and the Hallway zones). Shading overhangs are also implemented on the Mezzanine side façade windows, and their depth is varied. The window parameters are varied independently for each group, as each group impacts a different combination of daylit zones. In addition, previous research has shown that windows of different orientations can have significantly different impacts on energy consumption (O'Brien et al., 2011).

The insulation U-Value of the internal partitions is also varied, and the partitions are separated into two groups: office internal partitions and walk-in storage walls. The walk-in storage ceiling is assumed to have the same construction as the walls, since the warehouse model neglects thermal stratification. The floor insulation U-Values for the Chilled Storage and Frozen Storage zones are also varied independently for each zone to allow a complete examination of the walk-in envelope insulation. Variations in the building lighting power density are examined with the warehouse and mezzanine zones separated into two groups as described previously. The prescribed flow rate of infiltrating air is also varied, as well as the maximum potential flow rate for natural ventilation air, or natural ventilation design flow rate, as discussed previously in the *3.3.10 Building Model Assumptions: Natural Ventilation* section. Lastly, variations of the COPs assumed for the heating and cooling systems present within the building are examined.

The upper and lower bounds for the variables were selected based on a variety of sources. In general, the settings for the upper bounds for component performance were based on the best available products in industry. For instance, an external wall insulation U-Value of 0.18 represents the equivalent U-Value for a 150 mm structurally insulated panel (Kingspan). The lower bounds for performance were established either by assuming the component was, for all practical purposes, absent or was based on a minimal performance standard. Therefore, the ranges examined for this sensitivity analysis encompass the entire design space available for the warehouse at this point in time. Table 12 summarizes the sources referenced for the lower and upper bounds for each parameter. It should be noted that in the case of U-Values bounds that were derived from product literature, the insulation thickness and conductivity were used to calculate the equivalent U-Value based solely on the resistance provided by the insulation, and so these values may be different than the sources listed "equivalent" U-Value.

Table 11. Architectural design parameter lower and upper bounds for sensitivity analysis

Category	Design Parameter	Units	Lower Bound	Upper Bound
EXTERNAL WALLS	External Wall Insulation U-value	W/(m^2-K)	0.18	5
	External Wall Thermal Mass	J/(m^2-K)	10,000	404,000
	External Wall Absorptance	----	0	0.95
	Overhead Door Insulation U-Value	W/(m^2-K)	0.25	5
ROOF	Roof Insulation U-Value	W/(m^2-K)	0.18	5
	Roof Thermal Mass	J/K	10,000	404,000
	Roof Absorptance	----	0	0.95
WAREHOUSE CLERESTORY	Warehouse Clerestory WWR	----	0.5	40
	Warehouse Clerestory U-value	W/(m^2-K)	0.6	6.17
	Warehouse Clerestory SHGC	----	0.15	0.81
OFFICE 1 FRONT WINDOWS	Office Front Windows WWR	----	1	40
	Office Front Windows U-Value	W/(m^2-K)	0.6	6.17
	Office Front Windows SHGC	----	0.15	0.81
MEZZANINE SIDE WINDOWS	Office Side Windows WWR	-----	1	40
	Office Side Windows U-Value	W/(m^2-K)	0.6	6.17
	Office Side Windows SHGC	----	0.15	0.81
	Office Side Window SPF	----	5	100
INFILTRATION & NATURAL VENTILATION	Natural Ventilation	ACH	0	20
	Building Infiltration	(L/s)/m^2	0.175	0.7
OFFICE INTERNAL PARTITIONS	Partition Wall U-Value	W/(m^2-K)	0.33	5
	Mezzanine Floor U-Value	W/(m^2-K)	0.33	5
WALK-IN COLD STORAGE	Walk-In Storage Wall U-value	W/(m^2-K)	0.14	0.5
	Walk-In Storage Door U-value	W/(m^2-K)	0.18	0.5
	Frozen Storage Floor U-Value	W/(m^2-K)	0.16	0.66
	Chilled Storage Floor U-Value	W/(m^2-K)	0.22	5

Table 11. Continued:

LIGHTING	Office Lighting Power Density	W/m^2	9.7	10.8
	Warehouse Lighting Power Density	W/m^2	6.5	8.6
HVAC-R	Frozen Storage - COP at 30°C	----	1.48	2.14
	Chilled Storage – COP at 30°C	----	2.77	3.31
	A/C System - Average COP	----	2.9	3.86
	Heat Pump - Average COP	----	3.5	4.18

Table 12. Sources for upper and lower bounds

Design Parameters	**LB Source**	**UB Source**
External Wall Insulation U-value	150 mm SIP (Kingspan, 2013c)	No effective insulation
External Wall Thermal Mass	No effective thermal mass	300mm of brick (Daouas, Hassen, and Aissia, 2010)
External Wall Absorptance	Equivalent of being completely shaded	Black Asphalt Shingles (Sadineni, Madala, and Boehm, 2011)
Overhead Door Insulation U-Value	TKO Verticool Door (TKO, 2013)	No effective insulation
Roof Insulation U-Value	150mm SIP (Kingspan, 2013c)	No effective insulation
Roof Thermal Mass	No effective thermal mass	300mm of brick (Daouas et al., 2010)
Roof Absorptance	Equivalent of being completely shaded	Black Asphalt Shingles (Sadineni et al., 2011)
Warehouse Clerestory WWR	Practically no windows	Upper bound of suggested WWR based on effective aperture with 0.75 VT (O'Connor, 1997)
Warehouse Clerestory U-value	Pilkington Insulight Sun Triple Glazed Window (Pilkington, 2013)	Clear Single Glazed Window (Ihm and Krarti, 2012)
Warehouse Clerestory SHGC	Pilkington Insulight Sun Triple Glazed Window (Pilkington, 2013)	Clear Single Glazed Window (LBNL, 2013b)
Office Front Windows WWR	Practically no windows	Upper bound of suggested WWR based on effective aperture with 0.75 VT (O'Connor, 1997)
Office Front Windows U-Value	Pilkington Insulight Sun Triple Glazed Window (Pilkington, 2013)	Clear Single Glazed Window (Ihm and Krarti, 2012)
Office Front Windows SHGC	Pilkington Insulight Sun Triple Glazed Window (Pilkington, 2013)	Clear Single Glazed Window (LBNL, 2013b)
Office Side Windows WWR	Practically no windows	Upper bound of suggested WWR based on effective aperture with 0.75 VT (O'Connor, 1997)
Office Side Windows U-Value	Pilkington Insulight Sun Triple Glazed Window (Pilkington, 2013)	Clear Single Glazed Window (Ihm and Krarti, 2012)

Table 12. Continued:

Office Side Windows SHGC	Pilkington Insulight Sun Triple Glazed Window (Pilkington, 2013)	Clear Single Glazed Window (LBNL, 2013b)
Office Side Window SPF	Practically no overhang	Maximum tested overhang ratio (Hygh et al., 2012)
Natural Ventilation	No natural ventilation	Upper bound of practical natural ventilation rates (Tan, 2001)
Building Infiltration	Lower infiltration bound (Ihm and Krarti, 2012)	Upper infiltration bound (Ihm and Krarti, 2012; Liu et al., 2007)
Partition Wall U-Value	U-Value lower bound (Ihm and Krarti, 2012)	No Effective insulation
Mezzanine Floor U-Value	U-Value lower bound (Ihm and Krarti, 2012)	No Effective insulation
Walk-In Storage Wall U-value	200mm cold room panel (Ruukki, 2014)	50mm cold room panel (Kingspan, 2013a; TSSC, 2012)
Walk-In Storage Door U-value	150mm cold room door (Kingspan, 2013b)	50mm cold room door (Kingspan, 2013b)
Frozen Storage Floor U-Value	Styrofoam Floormate 300-A, 200cm (DOW, 2012)	Styrofoam Floormate 300-A, 50cm (DOW, 2012)
Refrig Storage Floor U-Value	Styrofoam Floormate 300-A, 150cm (DOW, 2012)	No Effective insulation
Office Lighting Power Density	ASHRAE Standard 90.1 – 2004 (ASHRAE, 2004)	ASHRAE AEDG Suggested Lighting Power Density (Liu et al., 2007)
Warehouse Lighting Power Density	ASHRAE Standard 90.1 – 2004 (ASHRAE, 2004)	ASHRAE AEDG Suggested Lighting Power Density (Liu et al., 2007)
Frozen Storage - Rated COP	Low Temperature Rack Equation (Leach et al., 2009)	Bitzer Econoline 4NES-20Y (Bitzer, 2013)
Chilled Storage - Rated COP	Medium Temperature Rack Equation (Leach et al., 2009)	Bitzer Econoline 4JE-15Y (Bitzer, 2013)
A/C System - Average COP	ASHRAE Standard 90.1 – 1999 (ASHRAE, 1999)	Ground Source Heat Pump (Coşkun, Pulat, Ünlü, and Yamankaradeniz, 2008)
Heat Pump - Average COP	ASHRAE Standard 90.1 – 1999 (ASHRAE, 1999)	Ground Source Heat Pump (Pulat, Coskun, Unlu, and Yamankaradeniz, 2009)

3.4.2 Defining the Building Control Parameter Variation

The variables examined for this portion of the analysis have been labeled as building control parameters. The most succinct definition for these parameters is that they are parameters that the design team can influence, but over which it does not have complete control to specify. These parameters blur the line between design variables and operational uncertainties, also commonly referred to as scenario uncertainties. For instance, while the building may be designed to operate at a set of specific temperature set-points, these may be substantially altered post-commissioning if the occupants have easy access to the thermostats. These parameters are considered to be distinct from the architectural design parameters of the previous section due to the ambiguous nature of their definition and the fact that they are susceptible to being actively changed during operation. In a similar study of uncertainty in energy consumption during operation, Wang and colleagues classify lighting control, temperature set-points, plug load control, and HVAC set-points as operational parameters (Wang et al., 2012). By contrast, in a sensitivity analysis of both operational and design parameters by NBI (New Buildings Institute), the temperature set-points are considered part of commissioning and maintenance and are not altered as part of operations (Heller et al., 2011). Despite semantic differences, another common framework that can be used to separate these parameters is that they can be altered after construction without substantial capital investment. For instance, as discussed in the previous chapter, a recent study by ASHRAE examined the re-commissioning of lighting control systems, in which the sensors and light controllers for daylit spaces were readjusted to achieve adequate light levels with minimal electricity consumption. Through the application of this process to several daylit spaces in the Midwest, the amount of energy that the systems saved increased from 23% to 63% on average without any additional capital investment (Hackel and Schuetter, 2013). The uncertainty in these parameters that arises during the life stages of the building post construction emphasizes the importance of an integrated design method if these translate into a large uncertainty in energy consumption. By involving the individuals who will be responsible for the commissioning and operations of the facility throughout the design process, the design team can help to ensure that a building's owner and manager, along with any other individuals responsible for the building under operation, also buy into the performance goals of the project and understand the impact of variation in the building control parameters.

The control parameters that were selected for examination in this analysis are the Chilled Storage zone evaporator fan control, Chilled Storage zone defrost control, Frozen Storage zone defrost control, daylighting control, occupancy sensing lighting control, thermostat set-points, and office plug load density and control. For all of these parameters, uniform distributions were also used for the MCA to examine parameter uncertainty. Uniform distributions were selected because, as Tian summarizes in his literature review of building sensitivity analysis, a uniform distribution should be implemented for a parameter whenever the goal of a study is to identify effective energy savings measures (Tian, 2013). As the design team, through an integrated design process, is assumed to be able to exert some influence on each of these parameters, all of the parameters can be assumed to be energy efficiency measures for the purpose of this research. The evaporator fan control, occupancy sensing lighting control, and defrost control were all examined as discrete two-level variables, with each having a baseline control strategy serving as the lower bound and an improved efficiency strategy serving as the upper bound. In the framework of uniform distributions, this translates into each of the discrete states having an equal probability.

For the Chilled Storage evaporator fan control, the two strategies discussed in section ***3.1 Retrofit Analysis of an Existing Medical Warehouse*** are used as the two control levels for the uncertainty and sensitivity analysis. The baseline strategy, labeled as D2, is that the evaporator fans inside the cold room are operated constantly except for when the doors are open. According to the building staff at the PCT warehouse, the fans were programmed this way to ensure adequate defrosting of the evaporators and thermal destratification in the storage rooms. As the cold rooms in the PCT warehouse have a ceiling height of 5.1 m, which is less than the internal height of the proposed Chilled Storage zone in this study of 6 m, it is assumed that the same argument could be made for constantly running the fans to ensure even temperatures within this zone. For the improved efficiency option, labeled as D1, the evaporator fans are assumed to operate only when a zone is actively cooled. Due to the large height and volume of the Chilled Storage zone, destratification fans are constantly operated to maintain a uniform temperature distribution. It is assumed that four Airius Model 25 fans are implemented, producing a constant load of 124 W. The datasheet for these fans is included in Appendix D.

For the evaporator coil defrost in both the Chilled Storage and Frozen Storage zones, the control mechanism is varied between temperature termination and scheduled time windows. In the baseline method of scheduled time windows, each of the zones is assumed to defrost for a full 20 minute period because this is the maximum defrost time assumed by Leach and colleagues for walk-in coolers and freezers (Leach et al., 2009). As the defrost is not demand-based in this scenario, the defrost continues for the full 20 minutes even if there is no ice left on the coils to melt. In the improved efficiency scenario, the defrost terminates prior to the scheduled time if there is no longer a need to melt ice on the evaporator coils, as is advocated for energy efficiency in supermarket refrigeration (Fricke and Sharma, 2011). Both of the zones are assumed to defrost once per day, during the middle of the night.

The effect of occupancy sensing lighting controls on the building energy consumption is also investigated in a discrete manner. However, the difference between the baseline control of no sensors and the advanced control of including the sensors is not actively simulated as are the daylighting controls. Rather, it is accounted for by altering the scheduled lighting load for the zones as was done by Liu and colleagues in the supporting technical study for the AEDG for small warehouses (Liu et al., 2007). The schedules assumed for the building lights with and without the use of occupancy sensors are included in Appendix B. A summary of the different discrete two level control systems investigated for this study is shown in Table 13.

Table 13. Summary of the baseline and improved discrete control system levels assumed

Category	Parameter	Baseline Control	Improved Control
BUILDING CONTROLS	Cold Room Evaporator Fan Control	Fans constantly operate, except when the entrance door is open	Fans cycle on and off with cooling, thermal de-stratification fans added
	Freezer Evaporator Fan Control	Fans cycle between off and on at full speed	Fans cycle with variable fan speed control
	Freezer Defrost Control	Defrost occurs for the duration of the scheduled time	Defrost terminates prior to scheduled time if all ice is melted
	Occupancy Sensing Light Control	No occupancy sensors for any zone	Occupancy sensors for all zones

Unlike the previous control strategies discussed, the thermostat set-points for several of the building zones are varied continuously. Only the non-walk-in storage set-points are varied, due to the fact that the walk-in set-points are mandated by WHO, and are pertinent in ensuring vaccine safety and potency. The set-points for the warehouse zones (Ambient, Workshop and Restroom zones) are varied as a group, as are the set-points for the mezzanine zones (Hallway, Office 1, Office 2, and Office 3 zones). Since the mezzanine zones are assumed to implement a nighttime setback, both the daytime and nighttime temperature set-points are examined. The upper and lower limits for the mezzanine temperatures examined are taken from the limits used in a study of office building operational uncertainty by Wang et al. (Wang et al., 2012). The upper limit for the warehouse cooling set-point of 32°C and lower limit for the heating set-point of 15°C are the temperatures assumed by the warehouse design team. The lower limit for the cooling set-point of 26°C and upper limit for the heating set-point of 18°C are taken from the temperatures assumed in a guide to NZE warehousing by Tata Steel (Tata Steel et al., 2011).

As a result of the significant savings that can be achieved through warehouse daylighting measures, the effect of alterations to the daylighting control strategy was examined. In the baseline strategy, the lights for the Ambient zone are assumed to have a luminance set-point of 300 lux, as is recommended by the IESNA (Illuminating Engineering Society of North America) for warehouse storage areas with small labels (IESNA, 2000). In the improved efficiency control strategy, the luminance set-point of the Ambient zone lights is assumed to be 100 lux, as suggested by the IESNA for warehouse storage with large labels.

The last type of continuous variables examined for this portion of the study is the uncertainties in the office plug loads. While plug load parameters are often considered pure scenario uncertainties (Heller et al., 2011), this ignores the influence that the building owner and manager can exert on these types of loads, as well as product innovations that help to mitigate the effect of office equipment on building energy consumption. For instance, the implementation of smart power strips by Nakazawa and colleagues, as discussed in the previous chapter, produced a 15% reduction in plug load electricity consumption (Nakazawa et al., 2011). As plug load is often a large fraction of building energy consumption, especially in office buildings, reframing this parameter as something which the design team can impact and potentially mitigate aids in the development of more robust energy efficient buildings. Uncertainties in both plug load density in the office and plug load level at night in the office are examined. A range of 2.3 to 21 W/m^2 is assumed for the plug load density as is assumed by Heller and colleagues in a study of office energy consumption uncertainty (Heller et al., 2011). For the plug load night level, the uncertainties from Heller's study are also employed, with a lower limit of 5% and an upper limit of 80%, in reference of the percentage of the installed plug load that is kept on at night. A summary of the bounds for the continuous parameters examined is included in Table 14.

Table 14. Upper and lower bounds for the continuous control parameters

Category	Parameter	Units	Lower Bound	Upper Bound
THERMOSTAT CONTROLS	Heating Temp Set-point (Warehouse)	°C	15	18
	Heating Temp Set-point (Office)	°C	20	22
	Cooling Temp Set-point (Warehouse)	°C	26	32
	Cooling Temp Set-point (Office)	°C	23	25
	Night Setback Heating (Office)	°C	12.7	18.3
	Night Setback Cooling (Office)	°C	26.7	30
PLUG LOADS	Plug Load Density (Office)	W/m^2	2.3	21
	Plug Load Level at Night (Office)	%	5	80

3.4.3 Monte Carlo Analysis

After the applicable parameters and ranges for variation were selected, a Monte Carlo Analysis (MCA) was used to examine the uncertainty of building energy consumption. This method was selected due to its widespread use throughout the building simulation community for uncertainty and sensitivity analysis (Hopfe and Hensen, 2011; Tian, 2013; Tian and de Wilde, 2011). A Latin Hypercube Sampling (LHS) method was implemented due to its efficient stratification properties, which allow for the use of more computationally demanding models such as EnergyPlus because a large amount of sensitivity and uncertainty information can be obtained with a relatively small sample size (Helton, Johnson, Sallaberry, and Storlie, 2006). However, even with LHS, the analysis still requires a sizeable number of samples for so many design parameters, on the order of hundreds or thousands. Therefore, to severely reduce the time necessary to conduct the analysis, the entire process of generating the input parameters, creating the building energy models for each input combination, running the building energy models, and collecting the output data was automated using Matlab. As mentioned in the previous chapter, the JEPlus tool was developed to help researchers conduct parametric analyses such as Monte Carlo Analysis; however this software was not selected due to the fact that it does not allow for the easy integration of a graphical user interface, as can be done with Matlab (Zhang and Korolija, 2010). The creation of a customized code allowed for maximum flexibility in expanding the capabilities of the sensitivity analysis for the design tool. For instance, the ability to create and delete files allowed for the elimination of the requirement of a large amount of storage space.

As EnergyPlus employs a text based input file, the baseline model was easily imported and manipulated in Matlab as a cell. The Matlab code was programmed to find EnergyPlus objects by name within the text and modify the appropriate parameters, allowing for significant modifications to the IDF without the worry of changes to line number. After modifications, the new block of text was exported as an IDF to be run later in the code. Once all of the simulations were created, they were run in parallel using the RunDirMulti batch file that comes standard with EnergyPlus. All of the simulations were run on an 8-core desktop computer, which allowed for eight simulations to be run in parallel. One batch of simulations took approximately five and a half minutes to complete. Once all of the simulation runs were complete, the data were input into a Matlab matrix by importing the CSV output files from EnergyPlus. The ease with which this post data processing was integrated into the automation of the sensitivity analysis was another advantage of conducting the entire analysis using Matlab.

The number of simulations run for the MCA was set at 1,000, as this is the near the upper limit of the number of simulations run for uncertainty and sensitivity analysis in the building performance field (Burhenne, Jacob, and Henze, 2010). This is far greater than the 100 simulations suggested by MacDondald (Macdonald, 2009); however, a similar design parameter study by Hygh and DeCarlos that explored 27 independent design parameters showed that significant improvements in the sensitivity analysis were possible by increasing the sample size of the MCA beyond 100 (Hygh et al., 2012). This same study also confirmed that increasing the number of simulations beyond 1000 had only a marginal impact on increasing the accuracy of the sensitivity analysis.

3.4.4 Multivariate Regression

Once the MCA was completed, a multivariate linear regression was used to examine the sensitivity of the building energy consumption to the variations in each of the design parameters. The analysis is based on the average annual energy consumption, obtained through simulation with Typical Meteorological Year (TMY) weather files. This metric was selected as the output parameter of interest since the objective of the sensitivity analysis is to identify influential design parameters to help obtain Net-Zero Energy on an annual basis. An inherent assumption in the selection of this sole output is that the grid connection is maintained constantly. While grid connectivity in the developing world is an issue, because primary vaccine warehouses are likely to be located in large cities with established grids, this is deemed a reasonable assumption.

A regression-based analysis was selected because it is the most widely used sensitivity analysis method employed in building energy analysis; therefore, it is a proven method for application to this field (Tian, 2013). In addition, this type of sensitivity analysis is relatively fast and easy to understand, which is a significant advantage towards its application in building design. First, a bi-directional, stepwise regression using Matlab was conducted to examine the significant main effects of the design variables. The stepwise regression produces an equation of the form shown in Equation 9, where E_{total} is the total building energy consumption, x_i is the value of each design variable, B_0 is the y-intercept, B_i is the regression coefficient for each design variable, and n is the number of significant design variables. The magnitude of each of the regression coefficients is proportional to the sensitivity of the building's total electricity consumption to variations in that parameter. Therefore, these coefficients are used to generate the sensitivity coefficients as described in the next section.

$$E_{total}(x_1, x_2, \dots, x_n) = B_0 + \sum_{i=0}^{n} B_i x_i \tag{9}$$

A second stepwise regression was conducted to examine the interaction of the significant parameters. This was also done using a bi-directional stepwise interaction, and only the first order interaction terms were considered because typical factorial analyses show that higher order interaction terms are less important (Macdonald, 2002). Two stepwise regressions were conducted to allow for the clear interpretation of both the main effects and the interaction terms, as the inclusion of the interaction term fundamentally alters the meaning of the regression coefficient for an individual parameter from unconditional to conditional. Equation 11 illustrates the form of the equation produced by the interaction stepwise model, where X_j is the interaction between two design parameters, for instance $x_j x_{j+1}$, B_j is the interaction term regression coefficient, and p is the total number of significant interactions.

$$E_{total}(x_1, x_2, \dots, x_n) = B_0 + \sum_{i=0}^{n} B_i x_i + \sum_{j=0}^{p} B_j X_j \tag{11}$$

This allows for a detailed examination of the moderating effects between parameter pairs. The larger the interaction regression coefficient, the greater effect that the value of x_j has on the main effect of x_{j+1}, and vice versa. The most commonly implemented global sensitivity analysis method for screening a large number of parameters in building performance simulation is the Morris method (Tian, 2013). Similar to the proposed bilinear method, the Morris method allows for the examination of the influence of interactions in the sensitivity analysis. However, this method does not allow for the formulation of an uncertainty distribution as does the Monte Carlo with LHS sampling. In addition, the Morris method examines interactions by comparing the standard deviation and mean of the elementary effect for each parameter, and so does not directly identify second order interactions between parameters. Both of these differences are key advantages of a global sensitivity analysis with a bilinear regression method in comparison to the Morris method. No previous building performance literature was found which implements this type of regression method for a global sensitivity analysis. Therefore, this thesis presents a new method for the field of building performance through which additional information about design parameters can be obtained.

3.3.5 Standardized Regression Coefficients

While the regression coefficients indicate the sensitivity of the model to each parameter, they do not provide an index that can be used to compare the relative importance of the parameters to help inform designers. This is a result of an inherent bias in the magnitude of the regression coefficient as a result of the scale used for each parameter. For instance, the WWR can be represented as either a percentage variation, from 1 to 40, or a ratio variation from 0.01 to 0.4. Depending on which input scale is used, the regression coefficient will vary by two orders of magnitude. In addition, the units for the regression coefficients depend on their corresponding variable, and so are not comparable. Several different methods exist for transforming the regression coefficients into meaningful indices post regression including SRCs (Standardized Regression Coefficients), Partial Correlation Coefficients, and the rank transformation versions of each of these methods (Tian, 2013). The method of SRCs was selected because it has been widely used in building performance sensitivity analysis (Breesch and Janssens, 2010; Domínguez-Muñoz et al., 2010; Yildiz and Arsan, 2011). In order to standardize each regression coefficient, it is transformed as shown in Equation 12 where β_i is the standardized regression coefficient, B_i is the regression coefficient, σ_{Total} is the standard deviation of the output energy consumption from the MCA, and σ_i is the standard deviation of the input parameter i.

$$\beta_i(x_i, E_{Total}) = \frac{B_i \sigma_i}{\sigma_{Total}} \tag{12}$$

Equation 12 was also used to standardize the interaction regression coefficients for the regression including bi-linear interaction terms. For these terms i is the interaction term and σ_i is the standard deviation of interaction.

3.4 Exploration across Multiple Climates

In order to examine how the average annual climate affects the results of the sensitivity analysis, four additional locations were selected for examination: Bangkok, Thailand; Mombasa, Kenya; Asuncion, Paraguay; and Buenos Aires, Argentina.

Table 15 summarizes key information about each of the selected cities, as well as Tunis. All are cities within a country listed by the USAID as a developing country or an advanced developing country (USAID, 2012a, 2012b). All of the cities, except for Mombasa, are capital cities, in which a primary national vaccine store may be located. However, as the second largest city in Kenya, Mombasa represents a possible location for a primary vaccine store, and was used instead of the capital city due to the availability of TMY weather data for EnergyPlus. A common standard for classifying climates on the international level is by using the ASHRAE climate zones, shown in Figure 23.

Table 15. Summary of key details about each of the selected sites

City	Country	Notes	Country Population	Country Classification by USAID	City ASHRAE Climate Zone Classification
Tunis	Tunisia	Capital City, Largest City	12 million	Advanced Developing Country (Transitional)	3A: Warm Humid
Bangkok	Thailand	Capital City, Largest City	70 million	Advanced Developing Country (Transitional)	1A: Hot Humid
Mombasa	Kenya	2nd Largest City	40 million	Lower Income Developing Country	1A:Very Hot Humid
Asuncion	Paraguay	Capital City, Largest City	6.5 million	Lower Middle Income Developing Country	2A: Hot Humid
Buenos Aires	Argentina	Capital City, Largest City	40 million	Advanced Developing Country (Transitional)	3A: Hot Humid

This method classifies locations into general climate zones based primarily on ranges of Heating Degree Days (HDD) and Cooling Degree Days (CDD). Tunis has 3,432 CDDs and is at the high end of the ASHRAE 3A/B Warm climate zone. Therefore, one additional location at the low end of the Warm climate zone and three additional locations in either the Hot or Very Hot zones were selected for the study, since the scope of this research is focused on warm and hot climates within the developing world. To ensure that cities with significantly different climates were selected the annual average HDDs and CDDs as reported by the EPW weather files were compared for the set of proposed locations (DOE, 2013). The HDDs and CDDs, as measured at their standard baseline points of 10°C and 18°C, respectively, are shown below for all five locations in Figure 24. In addition, Table 16 lists the HDDs and CDDs at both baseline temperatures. The graph shows an approximately linear increase in CDDs between climates, with an average difference of approximately 1000 CDDs between adjacent climates. This array of locations encompasses the full spectrum of variation for warm and hot climates in the developing/transitional world, as Bangkok is the hottest location for which annual weather data are obtainable and Buenos Aires is at the low boundary of the warm climate zone.

Zone Number	Zone Name	Thermal Criteria (I-P Units)	Thermal Criteria (SI Units)
1A and 1B	Very Hot –Humid (1A) Dry (1B)	9000 < CDD50°F	5000 < CDD10°C
2A and 2B	Hot-Humid (2A) Dry (2B)	6300 < CDD50°F ≤ 9000	3500 < CDD10°C ≤ 5000
3A and 3B	Warm – Humid (3A) Dry (3B)	4500 < CDD50°F ≤ 6300	2500 < CDD10°C < 3500
3C	Warm – Marine (3C)	CDD50°F ≤ 4500 AND HDD65°F ≤ 3600	CDD10°C ≤ 2500 AND HDD18°C ≤ 2000
4A and 4B	Mixed-Humid (4A) Dry (4B)	CDD50°F ≤ 4500 AND 3600 < HDD65°F ≤ 5400	CDD10°C ≤ 2500 AND HDD18°C ≤ 3000
4C	Mixed – Marine (4C)	3600 < HDD65°F ≤ 5400	2000 < HDD18°C ≤ 3000
5A, 5B, and 5C	Cool-Humid (5A) Dry (5B) Marine (5C)	5400 < HDD65°F ≤ 7200	3000 < HDD18°C ≤ 4000
6A and 6B	Cold – Humid (6A) Dry (6B)	7200 < HDD65°F ≤ 9000	4000 < HDD18°C ≤ 5000
7	Very Cold	9000 < HDD65°F ≤ 12600	5000 < HDD18°C ≤ 7000
8	Subarctic	12600 < HDD65°F	7000 < HDD18°C

Figure 23. ASHRAE international climate zone definitions (ASHRAE, 2007a)

Table 16. HDD and CDD for the five selected locations

	Buenos Aires	Tunis	Asuncion	Mombasa	Bangkok
CDD 10°C	2597	3432	4841	5959	6950
HDD 10°C	129	19	6	0	0
CDD 18°C	637	1186	2049	2917	3908
HDD 18°C	1211	814	254	0	0

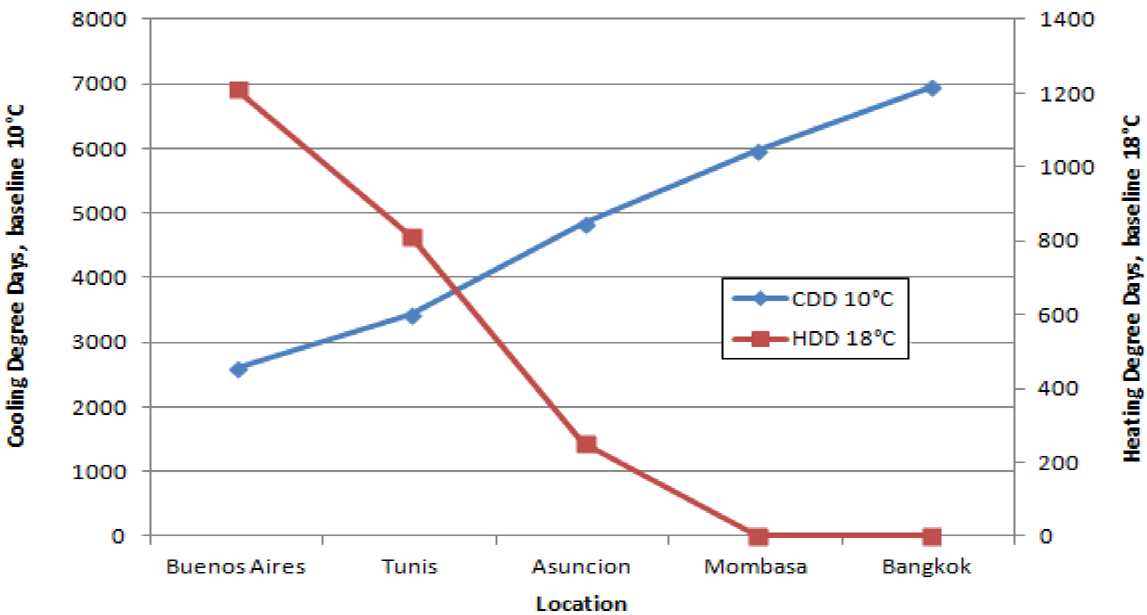


Figure 24. HDD 10°C and CDD 18°C for the four selected locations

3.5 Conclusions

This chapter proposes a method to answer the selected research questions and address the hypothesis. In addition, it illustrates an approach that can be applied to the design of future primary vaccine warehouses with energy efficiency performance goals. The building layout selected for the case study was designed as the new primary vaccine storage warehouse for Tunisia. Using this layout, an EnergyPlus building energy model was constructed to examine the energy consumption of the facility. Through the use of global uncertainty and sensitivity analysis on this model, the influence of architectural design parameters and building control parameters on the energy consumption of the warehouse can be compared directly. In addition, the inclusion of bilinear terms in the sensitivity analysis regression allows for an examination of the moderating effects between parameter pairs. The use of bilinear terms in sensitivity analysis is a method previously unapplied to the field of building performance simulation, and therefore presents a new way for interpreting the effects of interactions. Standardized Regression Coefficients are used to quantitatively measure the sensitivity of the building energy consumption to both main effects and interactions. The next section presents the results from the application of the approach described in this chapter and discusses the implications on both of the research questions and hypothesis.

CHAPTER 4: RESULTS AND DISCUSSION

This chapter presents the results obtained from the uncertainty and sensitivity analysis method described in the previous chapter. The results are organized by the steps in the method, rather than by the climates to which the method is applied, so that comparisons between the results for the climates can be made easily. First, the results of the uncertainty analyses are examined. The distributions for each climate are presented and their properties are analyzed. Next, the discussion focuses on the accuracy of the multivariate regression models used to formulate the main effects and interaction sensitivity analyses for each climate. Following this section the results of the main effects sensitivity analysis are presented, with an analysis of the variation in influential design parameters across the multiple climates. The discussion progresses to the results of the interaction term regression conducted; a similar organization of the results is used. The results presented allow for a thorough analysis of the hypothesis and research questions proposed, within the limiting assumptions of the case study building examined. In addition, they contribute towards an increased understanding of both the energy efficient design of the primary vaccine warehouses building type and the importance of the application of an integrated design method for this building type. An evaluation of the method implemented in this thesis is also included. Lastly, from the results obtained, generalized recommendations for designers are suggested.

4.1 Uncertainty Analysis Distributions

From the Monte-Carlo Analysis conducted, a total of 1,000 data points were obtained for the energy consumption of the warehouse in each location. As a result of the large number of data points for the MCA, the histogram shape is representative of the Probability Distribution

Function (PDF) for the warehouse energy consumption within the design space examined. The distributions for each of the climates examined have bimodal shapes, as shown in Figure 25. Detailed individual figures for each of the energy consumption distributions shown in Figure 25 are included in Appendix E.

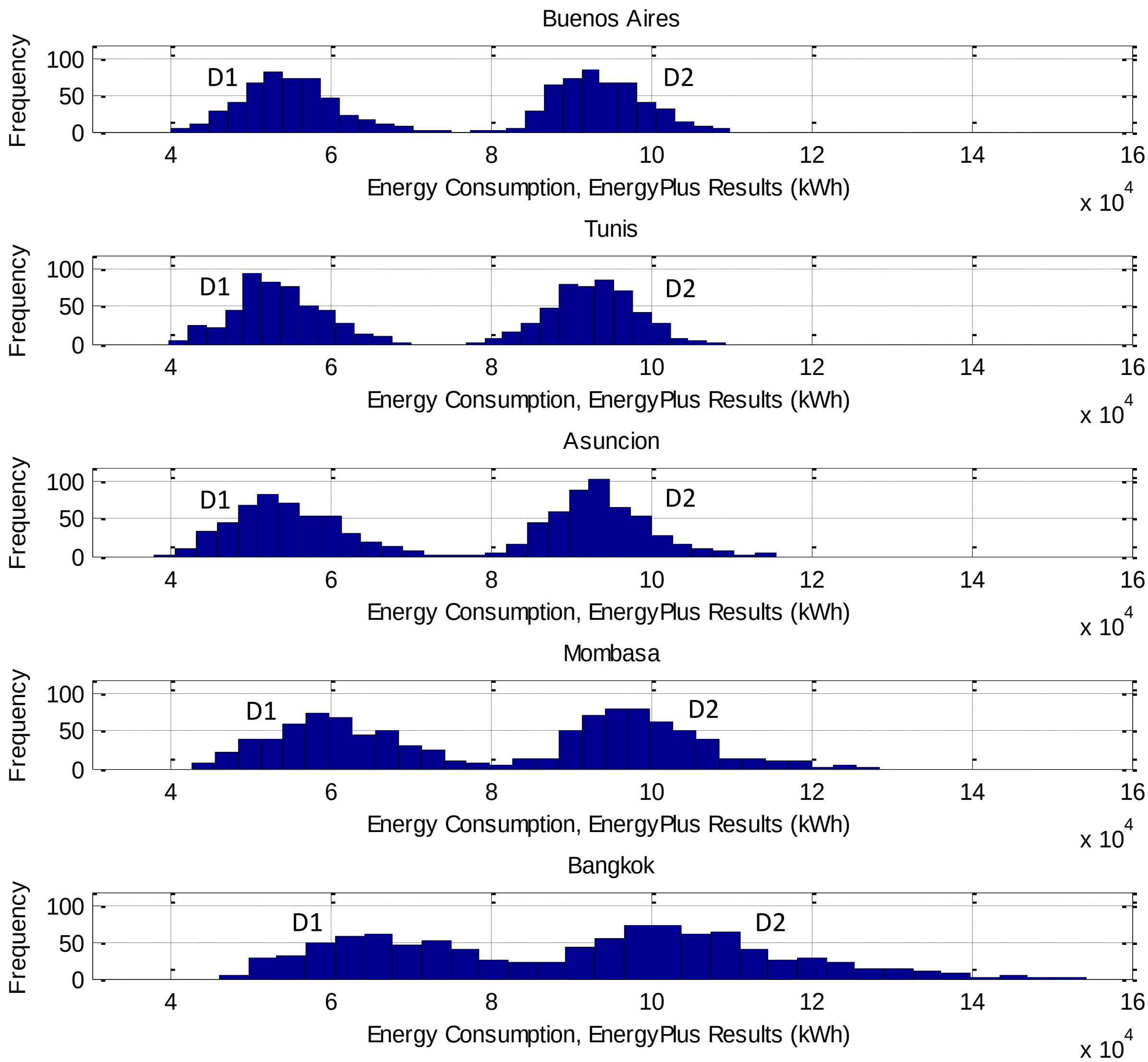


Figure 25. Comparison of uncertainty analysis distributions produced for the five locations examined

As discussed further in the following section on sensitivity analysis, the bimodal shapes of the distributions are a result of the overwhelming influence of the evaporator fan control strategy employed in the Chilled Storage zone. Since this control strategy is examined as a two level discrete variable, the variation in energy consumption produces the two peaks shown in Figure 25 for all of the climates examined. Therefore, for the purposes of this analysis, the energy consumption distribution for each location has been divided into two portions, based on the level of the Chilled storage evaporator fan control. The portion of the distribution in which the evaporator fans are used to maintain a uniform temperature (D1), corresponds to the left peak in the graphs in Figure 25. In contrast, the portion in which the thermal destratification fans are used to maintain a uniform temperature (D2) corresponds to the right peak. Comparison of the uncertainty analysis distributions reveals that in general, as the number of CDDs increases, the range of the energy consumption distribution widens. For instance, the energy consumption range for Buenos Aires is 69,926 kWh, whereas the energy consumption range for Bangkok is 108,325 kWh. A large fraction of this range for all locations, especially those with relatively cooler climates such as Buenos Aires and Tunis, is due to the impact of the Chilled Storage evaporator fan control level. For instance, the difference in the means of D1 and D2 for Tunis is 39,350 kWh while the total range is 69,506 kWh. In general, the difference between the means of D1 and D2 decreases as the climates warm. This agrees with expectations, due to the higher refrigeration cooling load and subsequent increased evaporator fan use in hot climates for the high efficiency control (D1) which cycles the evaporator fans. Therefore, the larger energy consumption ranges in the hotter climates, such as Mombasa and Bangkok indicate the increased relative importance of the other design parameters considered.

These key distribution parameters and several others for each location are summarized in Table 17. This table shows that the coefficients of variance for D1 and D2 follow a similar trend to the total range of the energy consumption, increasing substantially for the cooling dominated climates of Mombasa and Bangkok in comparison to the other climates. Across all climates, the coefficients of variance for D1 and D2 range from a minimum value of 0.056 for D2 in Tunis to a maximum of 0.19 in Bangkok. This range indicates that all of the distributions have a relatively low variance, as a coefficient of variation above one indicates a high level of variance. This relatively low value is initially surprising given the large number of parameters studied, as well the wide ranges over which they are examined. However, these values for the coefficient of variance agree with numbers obtained for the uncertainty distributions of similar building performance studies. For instance, Ruiz conducted a MCA on a large number of design and scenario uncertainties for an office building. The results of Ruiz's study display coefficients of variance for electricity consumption of approximately 0.15 on average across multiple climates, in the middle of the range of values obtained for this thesis (Ruiz et al., 2012).

Table 17. Distinguishing distribution parameters for the five locations analyzed

	Buenos Aires	**Tunis**	**Asuncion**	**Mombasa**	**Bangkok**
D1 Portion of the Distribution					
Mean (kWh)	54,793	53,309	54,308	61,016	70,490
Standard Deviation (kWh)	5,889	5,535	6,732	9,100	13,004
Coefficient of Variation	0.108	0.104	0.124	0.15	0.19
Range (kWh)	34,412	29,970	43,823	49,437	66,095
D2 Portion of the Distribution					
Mean (kWh)	93,626	92,659	93,464	99,318	108,532
Standard Deviation (kWh)	5,475	5,184	5,851	7,734	12,213
Coefficient of Variation	0.059	0.056	0.063	0.078	0.11
Range (kWh)	30,331	30,571	36,281	45,211	66,784
Total Distribution					
Minimum (kWh)	39,934	39,714	37,867	42,503	45,965
Maximum (kWh)	109,860	109,220	115,460	128,530	154,290
Range (kWh)	69,926	69,506	77,593	86,027	108,325
D1&D2 Mean Difference (kWh)	38,833	39,350	39,256	38,302	38,042

The general trend of the increase in the distribution ranges, as well as the increase in the standard deviations of D1 and D2, is in part explained by the increasing influence of interactions for the hot climates as discussed in section ***4.4 Parameter Interactions.*** Combinations of inefficient building control and architectural design parameters have a larger potential to negatively impact building energy consumption due to the substantially higher cooling demand of these climates. The distributions for the hotter climates, such as Mombasa and Bangkok, also reveal the waning returns of combinations of high performance parameters, in contrast to the detrimental effects of combinations of low performance parameters as the cooling demand increases. This trend is shown by Figure 26, which includes the 5%, 50%, and 95% quantiles for the D1 and D2 portions of the distribution for each climate. This graph emphasizes the increase in the size of the quantile range between the 50% and 95% quantiles for climates with a higher number of CDDs. Bangkok is the extreme example of this, with a range between the 50% and 95% quantile D1 of 26,813 kWh that is over 2.7 times the equivalent metric for Tunis (9,799 kWh). In addition, this range is approximately 1.6 times as large as the 5-50% range for Bangkok (16,470 kWh), emphasizing the imbalance between the effect of combinations of energy efficient parameters in comparison to combinations of inefficient parameters. This is an insight that cannot be gleaned from the results of the sensitivity indices of the parameters alone, and highlights the importance of using the uncertainty and sensitivity analysis in combination for informing the design. The whiskers on Figure 26 show the maximums and minimums in comparison to the quantile ranges for each climate. From this graph, it is evident that the cooling dominated climates also show significantly higher outliers than the more moderate climates. Once again Bangkok is the best example of this, with a span between the maximum and the 95%

quantile of 21,075 kWh for D2, nearly 70% of the total range of D2 for Buenos Aires. Table 18 lists the quantiles, minima, and maxima shown in Figure 26.

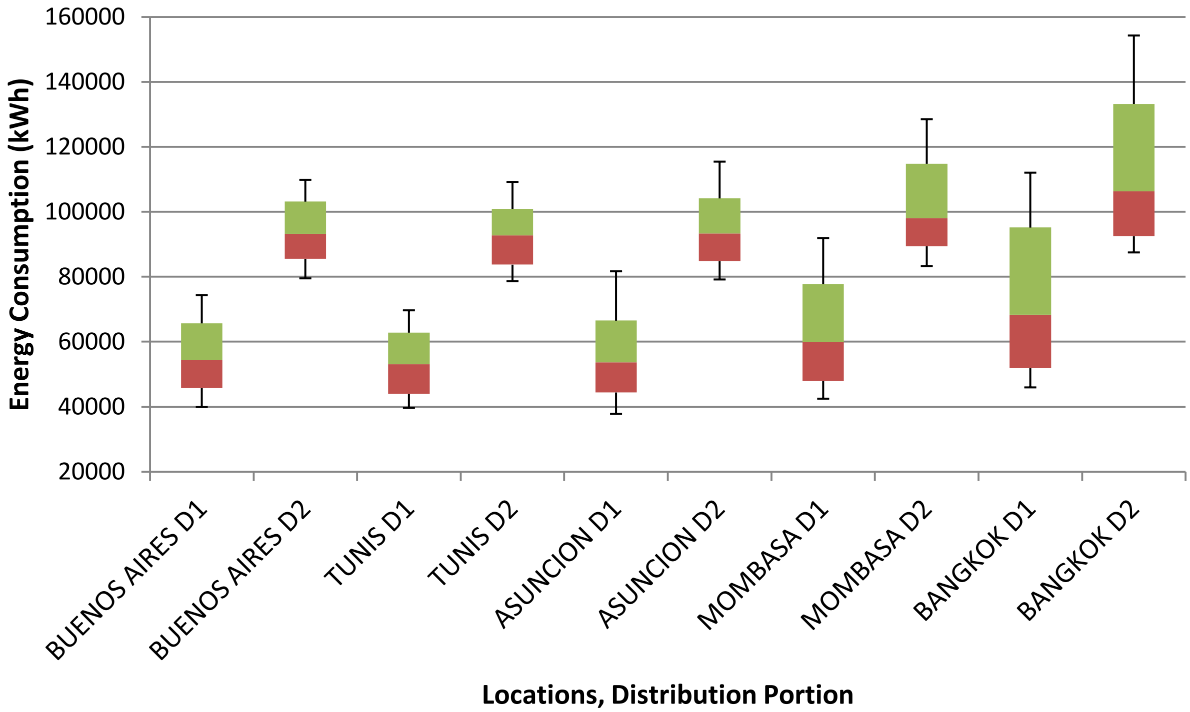


Figure 26. 5%, 50% and 95% quantile plot for the D1 and D2 portions of the energy consumption distribution for each location; whiskers show the minimums and maximums

Table 18. Minimum, maximum, 5%, 50% (Median) and 95% quantiles for the D1 and D2 portions of the energy consumption in kWh distribution for each location

	Minimum	5% Quantile	Median	95% Quantile	Maximum
Buenos Aires D1	39,934	45,723	54,313	65,666	74,346
Buenos Aires D2	79,529	85,547	93,222	103,130	109,860
Tunis D1	39,714	43,988	53,014	62,813	69,684
Tunis D2	78,649	83,736	92,733	100,910	109,220
Asuncion D1	37,867	44,398	53,642	66,502	81,690
Asuncion D2	79,179	84,846	93,272	104,140	115,460
Mombasa D1	42,503	47,928	59,981	77,744	91,940
Mombasa D2	83,319	89,383	98,068	114,795	128,530
Bangkok D1	45,965	51,860	68,330	95,143	112,060
Bangkok D2	87,506	92,508	106,300	133,215	154,290

4.2 Main Effect and Interaction Regression Models

In order to analyze the relative influence of the uncertain parameters on the warehouse energy consumption, a regression-based sensitivity analysis was used. First, a stepwise regression that considered the main effects, or first order effects, for all of the 44 parameters varied was conducted. The main effects regression was used to calculate the sensitivity indices for all of the individual parameters, as is suggested by Tian for research that prioritizes energy efficiency measures (Tian, 2013). As a result of the dominating effect of the Chilled Storage evaporator fan control level on the warehouse energy consumption in all climates, a second regression on the D1 portion of the distribution in which the fans are at a high efficiency control level was conducted. This second regression allowed for an improved interpretation of the relative importance of the remaining parameters examined, as discussed further in section ***4.3 Relative Influence of the Building Control and Architectural Design Parameters.*** The results for both the first regression encompassing all variables, referred to as Series 1, and the second regression with the evaporator fan control level fixed, referred to as Series 2, are shown for each of the five locations in Table 19.

Table 19. R^2, R^2_{adj} and RMSE values for the main effects stepwise regressions

Series 1: Main Effects Stepwise Regression (All variables)					
	Buenos Aires	**Tunis**	**Asuncion**	**Mombasa**	**Bangkok**
R^2	0.99	0.99	0.98	0.96	0.95
R^2_{adj}	0.99	0.99	0.98	0.96	0.95
RMSE	1,753	1,830	2,640	4,031	4,972
Series 2: Main Effects Stepwise Regression (Excluding Evaporator Fan Variation)					
	Buenos Aires	**Tunis**	**Asuncion**	**Mombasa**	**Bangkok**
R^2	0.92	0.92	0.86	0.84	0.86
R^2_{adj}	0.92	0.91	0.86	0.83	0.85
RMSE	1,705	1,645	2,556	3,752	4,969

For the Series 1 regressions, the high R^2_{adj} values indicate that most all of the variation observed in the model can be accounted for by the main effects of the parameters. This metric is highest in Buenos Aires and Tunis, where the R^2_{adj}value indicates that over 99% of the variation in the energy consumption is explained by the linear regression model. In general, as the climate becomes warmer, the R^2_{adj} values for the Series 1 regressions decrease. In contrast, the values of the Root Mean Squared Error (RMSE) increase as the climate warms. These two trends signify the increasing importance of interactions and non-linear effects in hotter climates. The R^2_{adj} values for the Series 2 regressions in each location are all lower than the corresponding adjusted R^2_{adj} values for the Series 1 regressions. Along with the moderate decreases in the RMSE values between these two regression series for each location, this indicates the highly linear effect of the evaporator fan control variation on the energy consumption of the warehouse.

The R^2_{adj} values for all of the Series 2 regressions except for Bangkok show a similar correlation to Series 1, with R^2_{adj} decreasing as the climates warm. The high R^2_{adj} value for Bangkok is due to the increase in the dominance of the warehouse cooling set-point temperature and roof absorptance for this location, as discussed further in section ***4.3 Relative Influence of the Building Control and Architectural Design Parameters.*** The moderately linear nature of the relationship between each of these two input variables and the building energy consumption has a similar effect to the evaporator fan control, resulting in a higher R^2_{adj} value in comparison to Mombasa, even though the value of the RMSE for Bangkok is also higher than for Mombasa. While the values of R^2 and R^2_{adj} are in general smaller than desired, the second series regression models are still deemed useful for the purposes of a main effects sensitivity analysis to identify the most important energy efficiency upgrades. For the majority of applications, a regression model is acceptable when R^2 is greater than 0.7 (Saltelli, Chan, and Scott, 2004). In addition, these values are within the ranges used by other building simulation studies for sensitivity analysis. For instance, Hygh conducted a main effects regression based sensitivity analysis of an office building across several US climates (Hygh, 2011). In this study, heating regressions for an office building in Albuquerque and Minneapolis have R^2 values of 0.743 and 0.816, respectively.

Lastly, a third series of regression models, referred to as Series 3, was formulated for investigating the relative importance of the interaction terms. Stepwise regression was once again used to investigate the relative importance of the parameters and the bi-linear interactions between parameters. Similar to Series 2, the Series 3 regression for each location was conducted on the D1 portion of the distribution. The results for the interaction regressions in each climate are included in Table 20. For all of the locations studied, the inclusion of the interaction terms decreases the RMSE and increases the R_{adj}^2 value in comparison to the Series 2 regression values, indicating the importance of the interaction terms in accounting for the variation in warehouse energy consumption. This is most noticeable in the warm climates, such as Asuncion where the R_{adj}^2 increases from 0.86 to 0.95. As observed for the Series 1 and Series 2 regressions, the RMSE consistently increases as the climates warm. The inclusion of interaction terms has the largest impact on the RMSE for Bangkok, as the value of this metric is reduced by 50% from 4,972 kWh to 2,470 kWh. In general, this reveals the increased importance of interactions in cooling dominated climates for primary vaccine warehouses.

Table 20. R^2, R^2_{adj} and RMSE values for the interaction stepwise regression

Series 3: Interaction Stepwise Regression					
	Buenos Aires	**Tunis**	**Asuncion**	**Mombasa**	**Bangkok**
R^2	0.95	0.95	0.95	0.93	0.97
R_{adj}^2	0.95	0.95	0.94	0.93	0.96
RMSE	1,367	1,267	1,650	2,453	2,471

4.3 Relative Influence of the Building Control and Architectural Design Parameters

As discussed previously in section ***4.1 Uncertainty Analysis Distributions***, the bimodal uncertainty distribution for every location studied indicates that one of the discrete two level parameters examined dominates the variation in energy consumption. The Standardized Regression Coefficients of the Series 1 regression for all locations reveal that the Chilled Storage evaporator fan control is the most influential parameter. The SRCs from the Series 1 regression for the evaporator fan control and the second most influential parameter in each location are shown in Figure 27. In the more moderate climates, such as Buenos Aires and Tunis, the SRC for this parameter is over six times greater than the SRC for the second most influential parameter. At a minimum, the evaporator fan SRC magnitude is two and a half times larger than the SRC for the second most influential parameter, as shown by the results for Bangkok.

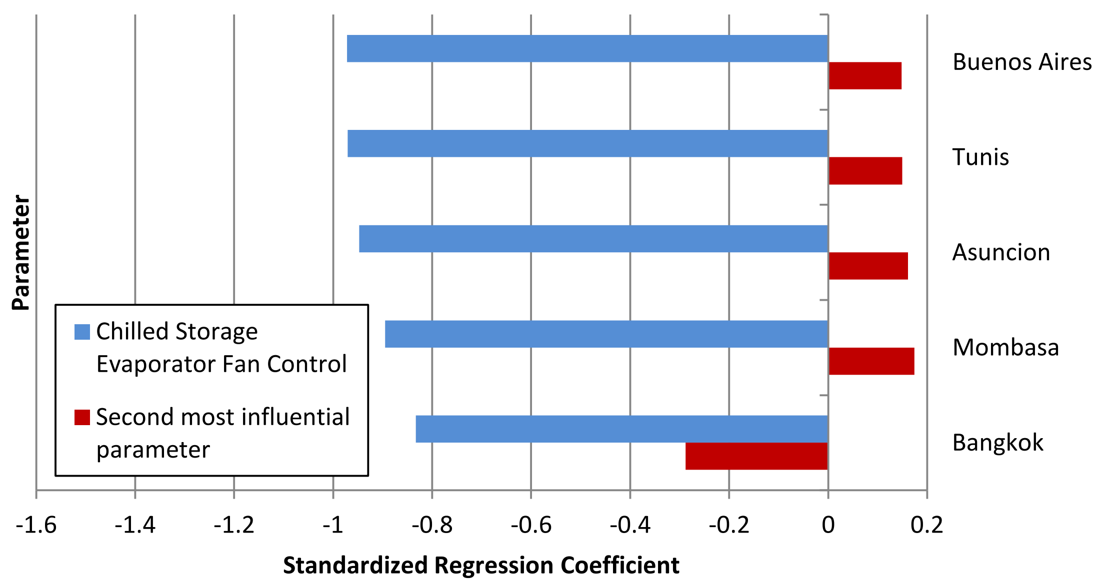


Figure 27. Series 1 main effect sensitivity analysis Standardized Regression Coefficients for the two most influential parameters; all locations

The extremely large influence that the variation in this control strategy has on the warehouse energy consumption is expected, due to the high power of the fans for each evaporator (1,880 W) in this zone and the presence of two evaporator units for reliability. While this parameter has an uncharacteristically large influence on energy consumption, the two control strategies examined both represent realistic assumptions for evaporator fan control, as discussed in section

3.4.2 Defining the Building Control Parameter Variation. It should be noted that if variable speed drives (VSDs) were assumed for the evaporator fans in the D1 control strategy, the average energy consumed by warehouses that use the D1 strategy, which is based on the fan running full speed or not at all, would be reduced. This is due to the relationship between fan power and speed, as fan power is proportional to the cube of fan speed (Saidur, Mekhilef, Ali, Safari, and Mohammed, 2012). As a result, the average difference in energy consumption between the D1 and D2 portions of the distribution, and therefore the relative importance of the evaporator fan control strategy, would be even greater because even less power would be used in the D1 strategy. However, as a result of limitations in the refrigeration modeling method this option was not explored. Even without considering VSDs, the large SRCs for the evaporator fan control show that the asserted hypothesis holds true for all locations. Due to the dominance of this parameter the building control parameters as a group are of equal or greater importance than the architectural design parameters in determining the building energy consumption in all locations. In fact, the building control parameters are substantially more important, solely as a result of the evaporator fan control. Because of the dominance of this parameter for all climates, it is also of interest to examine whether the hypothesis holds true without consideration of this parameter.

For this purpose, the relative importance of the building control and architectural parameters is more clearly established through the comparison of these two parameter groups on the basis of the amount of variance in the output data that is explained by the main effects of each parameter type. This is done using Equation 13 where R^2 is the coefficient of determination, β_i is the standardized regression coefficient for a parameter i, and n is the total number of parameters in the regression (Saltelli, 2008).

$$R^2 = \sum_{i=1}^{n} (\beta_i)^2 \tag{13}$$

From this equation, the relative amount of output variation correlated with each parameter input group can be calculated by determining the relative contribution of the parameters to the coefficient of determination as shown by Equation 14 where R_{BC}^2 is the portion of the coefficient of determination from the building control parameters, β_j is the standardized regression coefficient for the building control parameter j, and m is the total number of building control parameters.

$$R_{BC}^2 = \sum_{j=1}^{m} \left(\beta_j\right)^2 \tag{14}$$

For the comparison between these two groups the five most influential parameters for each category have been considered in summing their relative contribution to the coefficient of determination. Table 21 shows the relative contribution for the top five architectural design parameters (R^2_{AD}) and for the top five building control parameters (R^2_{BC}) to the Series 2 energy consumption variation. The results in this table show that without the uncharacteristically large influence of the evaporator fan control level, the relative importance of the building control parameters has significantly decreased. As the value of R^2_{BC} is less than R^2_{AD} for all climates examined, the hypothesis that the building control parameters are as significant as the architectural design parameters does not hold true when comparing these two groups without the evaporator fan control. However, Table 21 shows that while the building control parameters are not of equal or greater importance, they are far from inconsequential in comparison to the architectural design parameters. The ratio of R^2_{BC} / R^2_{AD} is highest in Bangkok, where the variation accounted for by the building control parameters is approximately half of that by the architectural design parameters. In addition, for all climates except Asuncion, the value of R^2_{BC} indicates that the most influential building control parameters account for at least 20% of the variation observed in the warehouse energy consumption. Therefore, even without the evaporator fan control, the results show that meaningful reductions in the building energy consumption are possible with efficient building control parameters.

Table 21. R^2_{AD} and R^2_{BC} for the Series 2 main effects regression

	Buenos Aires	**Tunis**	**Asuncion**	**Mombasa**	**Bangkok**
R^2_{AD}	0.60	0.64	0.67	0.56	0.50
R^2_{BC}	0.22	0.21	0.18	0.21	0.26
R^2_{BC} / R^2_{AD}	0.37	0.33	0.271	0.40	0.52

Due to the variable nature of the building control parameters post design, these results emphasize the importance of an integrated design method for the warehouse in which the personnel responsible for commissioning and maintaining the building buy-in to the energy performance goals. Table 22 shows the five most influential building control and architectural parameters for each climate which are used to calculate R^2_{AD} and R^2_{BC}.

Table 22. SRCs for the top five building control and architectural design parameters of each climate

Tunis			
Building Control		*Architectural Design*	
Parameter	**SRC**	**Parameter**	**SRC**
Warehouse Heating Temperature Set-point	0.26	Walk-In Storage Wall Insulation U-value	0.63
Chilled Storage Defrost Control	-0.24	Roof Insulation U-Value	0.31
Office Plug Load Density	0.22	Warehouse Clerestory WWR	-0.27
Warehouse Cooling Temperature Set-point	-0.15	Warehouse Lighting Average Power Density	0.17
Frozen Storage Defrost Control	-0.13	Frozen Storage - Refrig System Rated COP	-0.15
Buenos Aires			
Building Control		*Architectural Design*	
Parameter	**SRC**	**Parameter**	**SRC**
Warehouse Heating Temperature Set-point	0.32	Walk-In Storage Wall Insulation U-value	0.58
Office Plug Load Density	0.23	Roof Insulation U-Value	0.31
Chilled Storage Defrost Control	-0.20	Warehouse Clerestory WWR	-0.26
Frozen Storage Defrost Control	-0.12	Warehouse Lighting Average Power Density	0.21
Office Plug Load Schedule Level Night	0.11	External Wall Insulation U-value	0.20
Asuncion			
Building Control		*Architectural Design*	
Parameter	**SRC**	**Parameter**	**SRC**
Warehouse Cooling Temperature Set-point	-0.28	Walk-In Storage Wall Insulation U-value	0.62
Office Plug Load Density	0.21	Roof Absorptance	0.35
Chilled Storage Defrost Control	-0.19	Warehouse Clerestory WWR	-0.27
Frozen Storage Defrost Control	-0.11	Roof Insulation U-Value	0.23
Building Occupancy Sensor Control	-0.11	Warehouse Lighting Average Power Density	0.21
Mombasa			
Building Control		*Architectural Design*	
Parameter	**SRC**	**Parameter**	**SRC**
Warehouse Cooling Temperature Set-Point	-0.40	Walk-In Storage Wall Insulation U-Value	0.50
Office Plug Load Density	0.16	Roof Absorptance	0.45
Frozen Storage Defrost Control	-0.11	External Wall Absorptance	0.20
Building Occupancy Sensor Control	-0.11	Roof Insulation U-Value	0.19
Office Plug Load Schedule Level Night	0.10	Warehouse Lighting Average Power Density	0.18
Bangkok			
Building Control		*Architectural Design*	
Parameter	**SRC**	**Parameter**	**SRC**
Warehouse Cooling Temperature Set-Point	-0.49	Roof Absorptance	0.50
Office Plug Load Density	0.08	Walk-In Storage Wall Insulation U-value	0.36

Chilled Storage Defrost Control	-0.08	External Wall Absorptance	0.25
Building Occupancy Sensor Control	-0.05	Roof Insulation U-Value	0.22
Office Plug Load Schedule Level Night	0.05	External Wall Insulation U-Value	0.12

Table 22 shows that the general increase in the relative importance of the building control parameters as the climates warm is due to the large SRCs for the warehouse cooling temperature set-point in these locations. For Mombasa and Bangkok, the SRC of this parameter is several times greater than the SRCs for the other top four building control parameters. The roof absorptance shows a similar trend of significantly increased importance in these climates; however, the SRCs do not show that this parameter dominates the architectural design group to the same extent. For instance, while the warehouse cooling temperature set-point is over six times greater than the second most influential building control parameter in Bangkok, the roof absorptance SRC is less than twice that of the second most influential architectural design parameter. In general, Table 22 shows the importance of heating and cooling set-points for the warehouse, as for every climate examined one of these two is the most influential building control parameter. In addition, the results show that many of the parameters related directly to the walk-in storage areas, such as the walk-in wall insulation U-value and the Chilled Storage defrost control, have a large influence on building energy consumption. However, the results also indicate that the parameters of the surrounding warehouse have a comparable, and often greater, influence on the total building energy consumption (excluding the evaporator fan control level). Figure 28 shows a comparison of the relative contribution of the walk-in storage and non-walk-in storage (or surrounding warehouse) parameters, through the use of the same method employed for the comparison of building control and architectural design parameters. The relative importance of the surrounding warehouse parameters is highest in the cooling dominated climates of Mombasa and Bangkok. This shows the importance of considering the entire building for the design of an energy efficient warehouse, and the limitations of the current practice of placing new walk-in storage rooms in old warehouses.

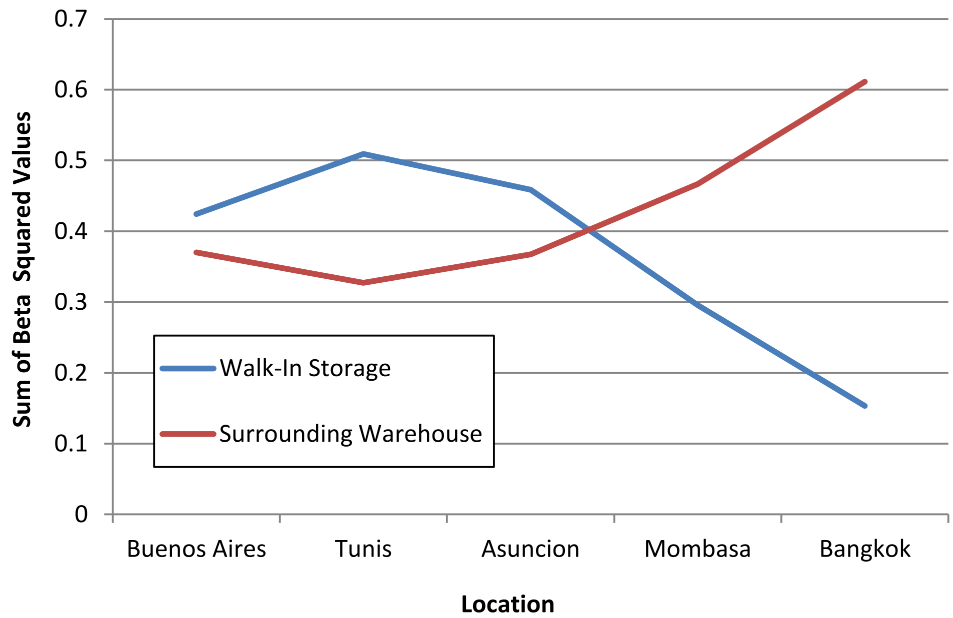


Figure 28. Relative importance of the walk-in storage and surrounding warehouse parameters

The SRCs for the twenty most influential parameters in the Series 2 regression for the five locations are shown in Figure 29. This plot provides a comparison of the relative importance of each of these parameters in the five climates examined, as well as the relative importance between parameters. For many of the influential parameters, the SRCs of an individual parameter exhibit a general trend of either increasing or decreasing as the climates warm. For instance, as expected the warehouse cooling temperature set-point has a strong correlation with the number of CDDs, as shown by the consistently increasing values of the SRC from Buenos Aires to Bangkok. Even with the presence of these general trends, several of the parameters in Figure 29 do not show a monotonic increase or decrease in their SRC as a function of CDDs or HDDs. However, this is not surprising given that the SRCs measure relative importance, and so a high SRC for one parameter, such as the roof absorptance in Bangkok, significantly reduces the SRCs for the remaining parameters.

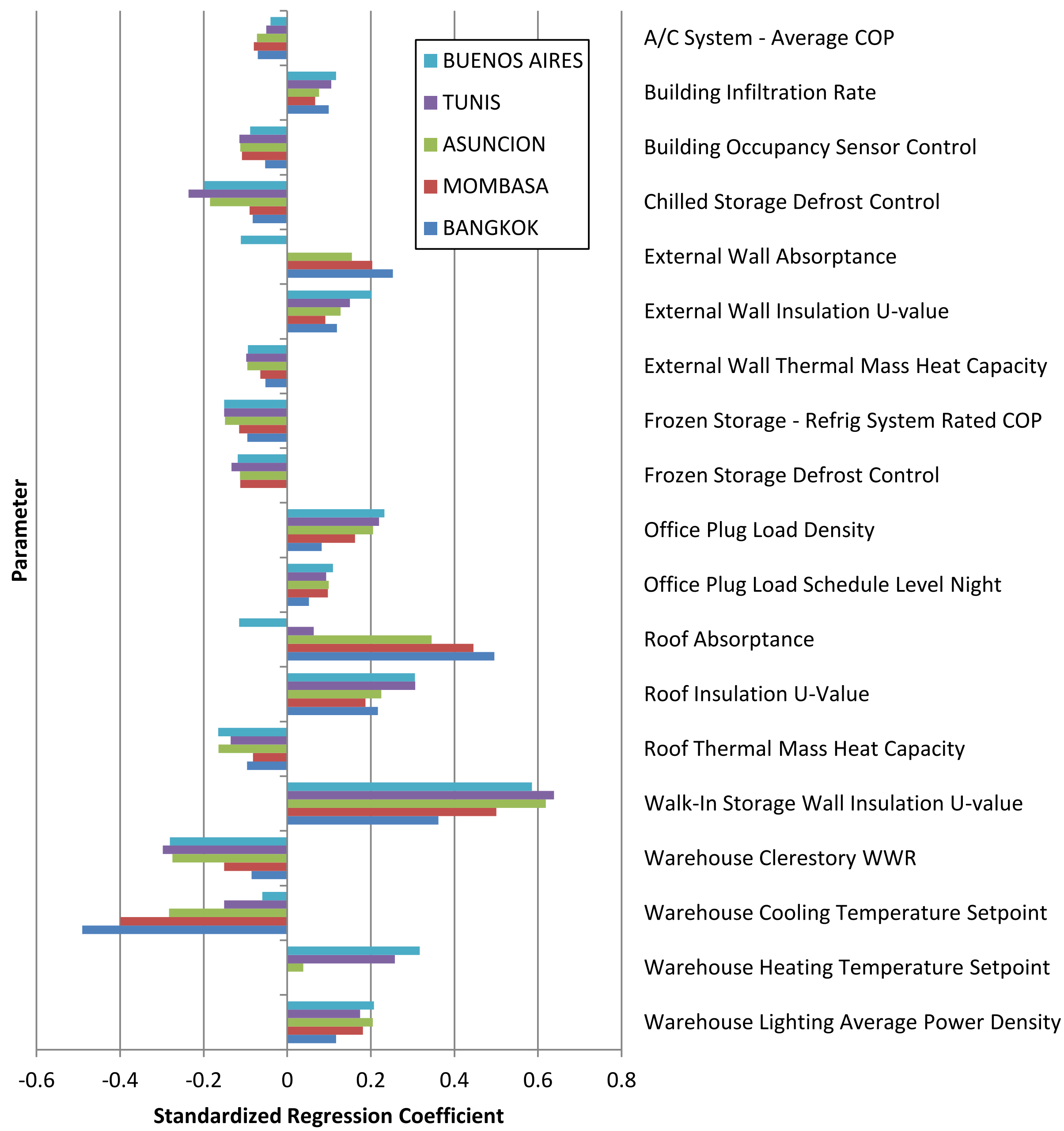


Figure 29. Standardized Regression Coefficients for the most influential parameters from the Series 2 regression across the five climates

The results shown in Figure 29 indicate several advantageous trends for the design and construction of primary vaccine storage warehouses in the developing world. These trends are summarized in Table 23. First, the substantial influence of the roof and external wall absorptance on reducing the building energy consumption in many of the climates examined is a trend that deserves significant attention. This indicates a cost savings opportunity for primary vaccine warehouses in the developing world, since shading and cool roofing are in general relatively inexpensive to implement in comparison to insulation and other architectural design elements (Dillon, 2014). In addition, the placement of solar panels on the roof of the warehouse for buildings designed to achieve NZE allows the solar panels to function as both a renewable energy source and an energy efficiency measure at the same time. The potential cost savings from a cool roof for the warehouse is further supported by the fact that it significantly reduces the impact of roof insulation in the cooling dominated climates as discussed in section ***4.4 Parameter Interactions.*** It should be noted though that the roof absorptance and external wall absorptance are the only parameters that are both positively and negatively correlated with energy consumption, depending on the climate. This shows that even in climates that are considered "Warm" by ASHRAE standards (ASHRAE, 2007a), such as Buenos Aires, cool roofs should not be applied without considering the effect on winter heating loads.

Table 23. Advantageous trends from the Series 2 sensitivity analysis for the design of energy efficient primary vaccine storage warehouses

1) High relative impact of the roof and external wall absorptance in most all climates
2) High relative impact of heating or cooling set-points in all climates
3) Low relative impact of clerestory SHGC and U-Value in comparison to WWR for all climates

Another trend observed in the results of Figure 29 is the high relative impact of the heating and/or cooling set-points for all of the climates examined. This trend is also a potential means of cost savings for vaccine warehouses in the developing world, due to the wider range of thermal comfort acceptable to individuals in developing countries (Givoni, 1992). For instance, Givoni suggests that while the comfort zone for individuals in developed countries may only extend to 25°C in the summer, those in the developing world will be comfortable with temperatures up to 27°C; with relative humidity below 70%. Therefore, there is an increased probability in the developing world that a set of low heating and high cooling set-points for the warehouse may be able to significantly reduce energy consumption, while still maintaining occupant thermal comfort. Finally, Figure 29 shows that for all climates the U-Value and SHGC of the warehouse clerestory window are not nearly as important as the clerestory WWR. In fact, for many of the locations these two parameters have a minor enough influence that they are evaluated as statistically insignificant in the stepwise regression. This shows that in general, the presence of windows for daylighting in the Ambient zone is much more important than the values of their thermal properties. Since the clerestory faces north in the northern hemisphere and south in the southern hemisphere, one would anticipate that the SHGC is not a driving parameter for the energy consumption. However, the fact that the variation in the clerestory U-Value has a negligible contribution to the warehouse energy consumption for many climates shows that even low quality windows can help the warehouse to achieve energy savings through daylighting. This is especially important for developing world construction, as it indicates an opportunity for cost savings with only a marginal reduction in energy performance.

Examining the parameters included in Figure 29, one can distinguish several additional parameters that are not highly influential for any of the climates. Most notably, natural ventilation does not significantly affect any of the climates examined. This is surprising given that locations such as Asuncion have large diurnal swings. However, a relatively high range for the cooling set-point temperatures (26 – 32°C) and a lack of large internal heat gains from equipment, as would be found in an office buildings, likely diminish the importance of natural ventilation on reducing cooling demand. The analysis also shows the absence of several parameters that were expected to have a much more minor influence on energy consumption. For instance, the U-Values of the internal walls and floors for the Mezzanine have little consequence, and the office window parameters have limited impact on the building energy consumption. However, one must keep in mind that the main effects analyses for all locations only account for a portion of the variation in energy consumption. For instance, the regression for Mombasa explains only 83% of the variation in energy consumption. Therefore, a global sensitivity analysis that examines the total effects of each parameter is recommended for making more conclusive statements on ruling out that a parameter has no substantial impact on the warehouse energy consumption (Tian, 2013).

In order to analyze the relative importance of the building control and architectural design parameters in more detail, the full results of the Series 2 regression for each location are presented and discussed. The Series 2 SRCs for Tunis are shown in Figure 30. As expected, the most influential parameter for the warehouse is the U-Value of the wall insulation for the walk-in storage areas, which has a SRC of 0.64. Due to the low temperatures of the Chilled Storage and Frozen Storage zones, a reduction in U-Value of the insulation for these zones has the combined effect of decreasing the refrigeration cooling load throughout the year as well as the Ambient zone heating load during the winter. The third most influential parameter is the warehouse clerestory WWR, with a SRC of -0.27. This shows the significant impact of reductions in lighting energy for improving the energy efficiency of the warehouse in Tunis, as the increase in WWR of the warehouse's clerestory directly benefits the daylighting of the Ambient zone. The importance of energy efficient lighting within the warehouse zones is further illustrated by the relatively high SRC of 0.17 for the warehouse lighting average power density, even though this parameter is only varied over a fairly small range from 6.5 to 8.6 W/m^2.

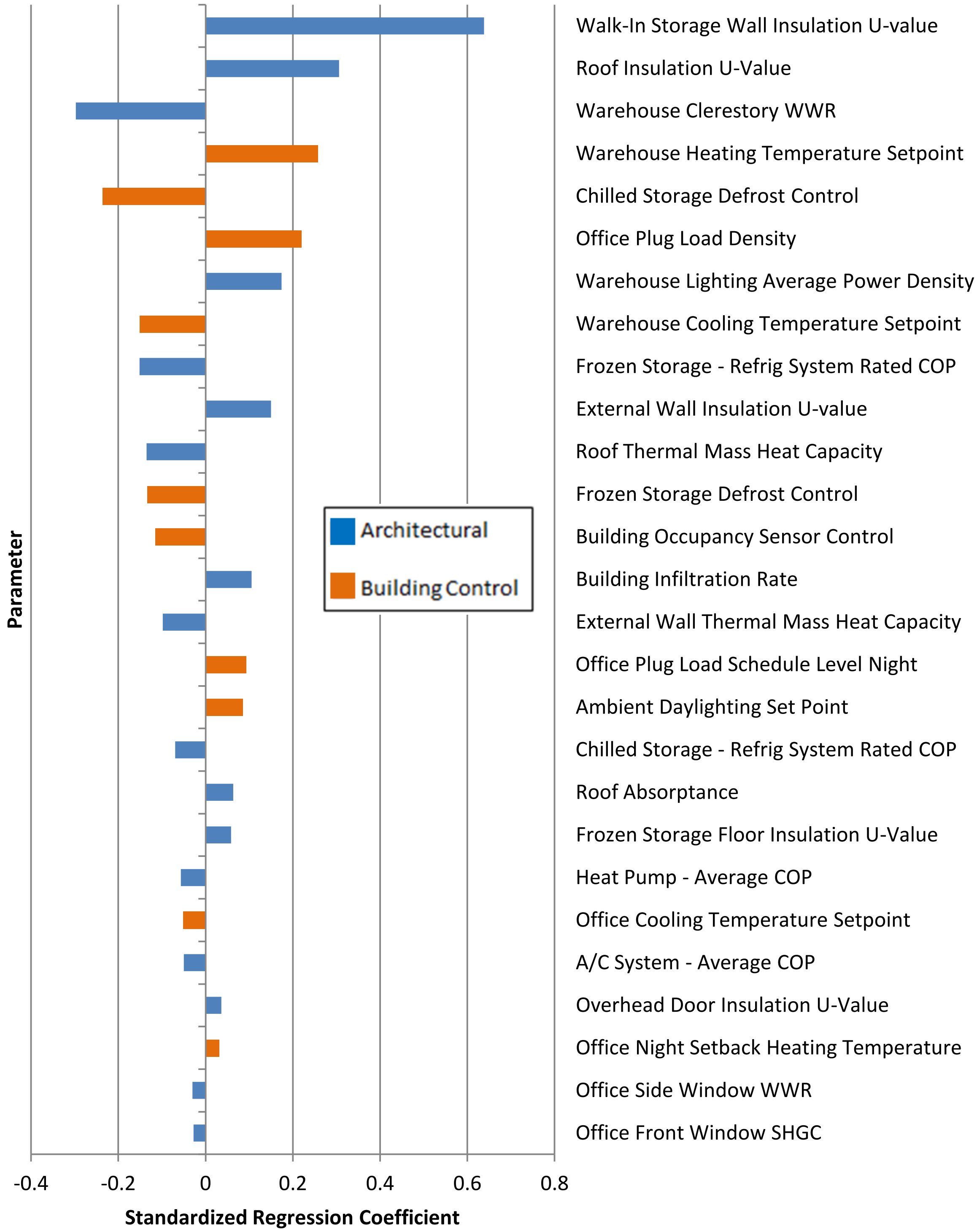


Figure 30. Series 2 main effects sensitivity analysis Standardized Regression Coefficients; Tunis

The warehouse heating energy use is also shown to be influential, as the second and fourth largest SRCs for Tunis are 0.31 for the roof insulation U-Value and 0.26 for the warehouse heating temperature set-point. While Figure 30 also shows that the warehouse cooling temperature set-point is significant, its SRC of -0.15 has a magnitude less than that of the warehouse heating set-point temperature (0.26). This shows that even though Tunis is at the upper end of ASHRAE's "Warm" climate zone, the reduction of warehouse heating loads is as, if not more, important than the reduction of warehouse cooling loads for the design space explored in this case study. In addition, although the heating set-point temperature was only varied over a 3°C range, the cooling set-point was varied over a 6°C range. From this it is concluded that on a per degrees basis, the heating set-point has a much more significant effect on the warehouse energy consumption in Tunis than the cooling set-point.

The second most influential building control parameter for Tunis is the Chilled Storage defrost control (SRC = -0.24). The greater relative importance of the Chilled Storage defrost control in comparison to the Frozen Storage defrost control (SRC = -0.13) is expected, due to the lower defrost demand as a result of the higher temperatures of the Chilled Storage zone. The relative importance of the Chilled Storage defrost control also exceeds that of the refrigeration equipment COPs for both the Chilled Storage (SRC = -0.07) and Frozen Storage (SRC = -0.15) zones. The relationship between the SRCs of these three parameters provides a clear example of the importance of building control parameters for designing an energy efficient vaccine warehouse. In addition, the relatively high value of the SRC for the Chilled Storage defrost control illustrates the detrimental effect that implementing standard operating procedures, such as defrosting for a set time window, can have on the energy performance of the building. Despite the small size of the Office zones, the next most influential uncertainty is the plug load density for these areas with a SRC of 0.22. This emphasizes the efficiency gains that can be achieved when a design team implements strategies to mitigate office equipment energy use. For instance, working with the building manager to ensure that energy efficient office equipment is procured for these areas, such as laptops instead of desktop computers.

The sensitivity analysis results for Buenos Aires have several similarities to the results for Tunis. Figure 31 shows the SRCs of the Series 2 regression for Buenos Aires. Comparing Figure 30 and Figure 31, one can see that Buenos Aires has the same top four most influential parameters as Tunis; however, the parameters are not in the same sequence. The walk-in storage wall insulation U-Value remains the most influential architectural design parameter, with a SRC of 0.59. However, the relative importance for the warehouse heating temperature set-point has increased and is now the second most influential parameter with a SRC of 0.32. This is a result of the increased heating loads for the average climate of this location in comparison to Tunis. The TMY weather file used for Buenos Aires has 397 more HDDs than the weather file used for Tunis. This difference in HDDs, along with a decrease of 835 CDDs, also produces a difference between the results of these two climates in the relative importance of the roof absorptance. While the roof absorptance is positively correlated with energy consumption in Tunis (SRC = 0.06), the direction of this correlation is reversed for Buenos Aires (SRC = -0.12). This negative correlation shows that for the design space considered, a cool roof can in fact negatively impact the warehouse energy consumption due to increased heating needs in the winter. The external wall absorptance is also negatively correlated with the warehouse energy consumption (SRC = -0.11). This shows that while the roof is the only surface that usually receives attention in the building performance literature for influencing energy consumption as a result of color or shading, the external wall absorptance can have a comparable significance to the roof absorptance in impacting building energy consumption.

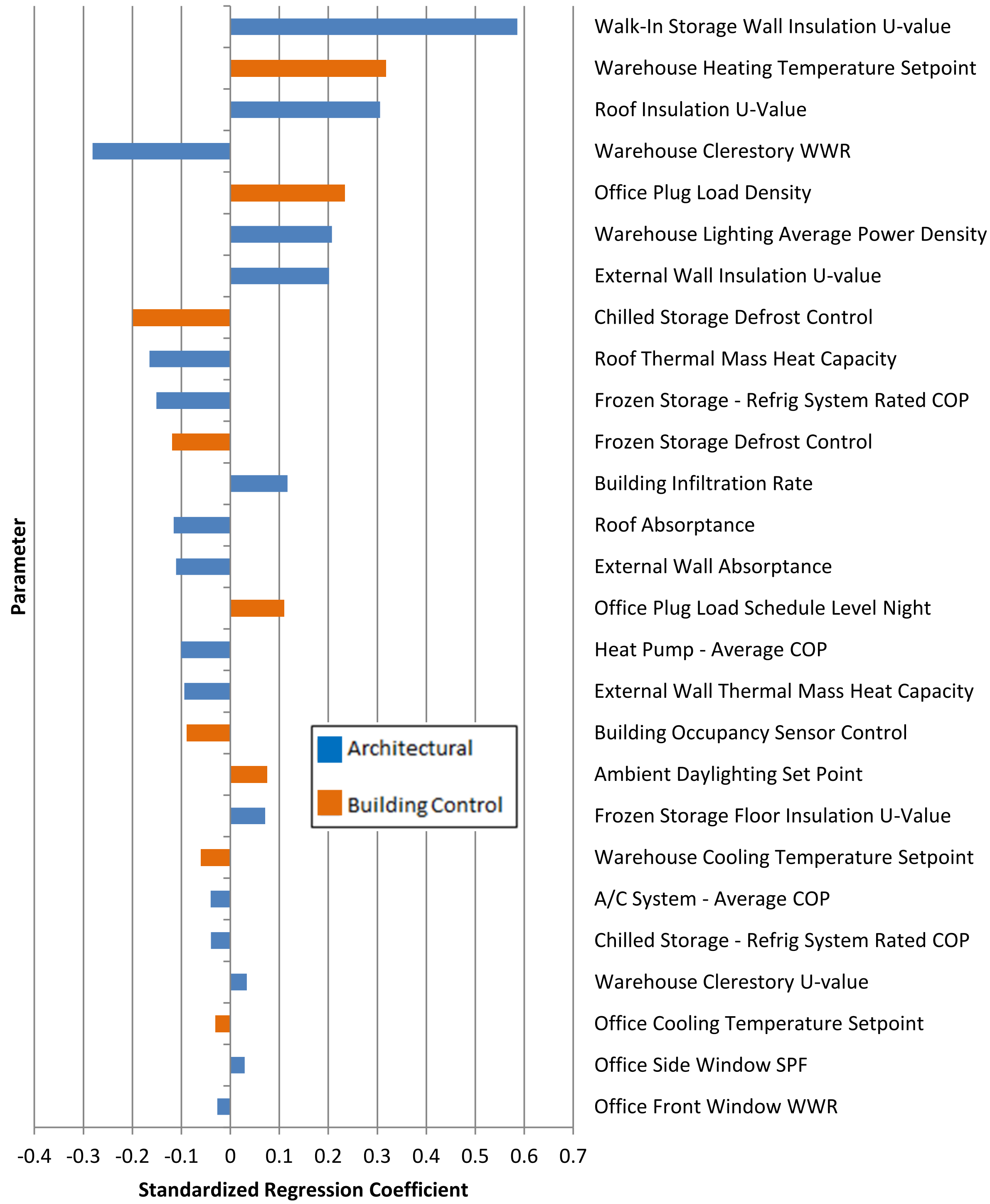


Figure 31. Series 2 main effects sensitivity analysis Standardized Regression Coefficients; Buenos Aires

As expected, the relative importance of the external wall insulation U-value has also increased for Buenos Aires (SRC = 0.20) in comparison to Tunis (SRC = 0.15) due to the increased heating load. Even with the increased demand for heating in Buenos Aires, sensitivity analysis once again indicates that the warehouse clerestory WWR is an influential parameter for energy consumption (SRC = -0.26), whereas the SHGC and U-value of the windows are significantly less important. The clerestory SHGC is not included in the Series 2 regression results, and the clerestory U-value has a SRC of only 0.03. This shows that even with a significant heating load, using low quality glazing for the warehouse clerestory can still offer positive reductions in energy consumption. Another interesting observation despite the higher heating loads of this climate is the high relative importance of the second most influential building control parameter for Buenos Aires, the office plug load density. With a SRC of 0.23, the influence of the variation in this parameter exceeds many of the heating related architectural components, such as the building infiltration rate (SRC = 0.12) and heat pump average COP (SRC = -0.10). This emphasizes the importance of using sensitivity analysis to focus resources on the most influential design parameters, rather than using intuition alone. As a result of the high relative importance of this parameter, the design team must work on strategies towards reducing the amount of energy consumed for plug loads, so that during operation, the contribution of this load type towards the total building energy consumption is minimized.

In comparison to the large influence of the warehouse heating temperature set-point, the main effects of the other temperature set-points examined have a much smaller relative effect on the warehouse energy consumption uncertainty. The significant decrease of the warehouse cooling set-point temperature SRC for Buenos Aires (-0.06) in comparison to Tunis (-0.15) is expected based on the reduction in CDDs. The Series 2 regression results of both Buenos Aires and Tunis show that even with the significant number of HDDs and CDDs for both of these climates, the office set-point temperatures are much less influential than the warehouse set-point temperatures. As the cooling and heating loads are a function of the zone envelope area exposed to the outdoor environment, it is not surprising that the thermostat set-points of the office zones, which have a collective envelope area nearly ten times smaller than the warehouse zones, have significantly smaller SRCs. Figure 31 shows that all of the other building control parameters examined have a higher relative importance than the office and heating cooling set-point temperatures, and many of these temperatures are not included in the regression results. The low relative importance of these temperatures holds true for all climates examined.

While the results of the Series 2 regressions for Tunis and Buenos Aires have a large number of similarities, the Series 2 sensitivity analysis for Asuncion includes several key differences. As shown in Figure 32, the roof absorptance and the external wall absorptance parameters for Asuncion are strongly positivity correlated with energy consumption. With a SRC of 0.35, the influence of the roof absorptance is second only to the walk-in storage wall insulation U-value (SRC = 0.62). The positive SRCs for the roof absorptance and external wall absorptance (0.16) are not surprising, given that Asuncion only has 254 HDDs. Therefore, the color and shading of the roof and walls help to reduce the summer cooling load, with a minimal negative impact on the heating load during the winter. In addition, a low absorptance helps to moderate the increase in the Ambient zone temperatures during the day and subsequently reduce the refrigeration load for the Chilled Storage and Frozen Storage zones. With over 1,400 more CDDs than Tunis, the warehouse cooling set-point temperature has a significantly higher relative importance for Asuncion, and is the third most influential parameter for the Series 2 regression in this location. The SRC of the warehouse cooling set-point (-0.28) shows the large importance of this parameter for determining the building cooling load, as many of the architectural design variables commonly associated with building cooling loads such as the roof insulation U-value (SRC = 0.23) and the A/C system COP (-0.07) have lower main effects.

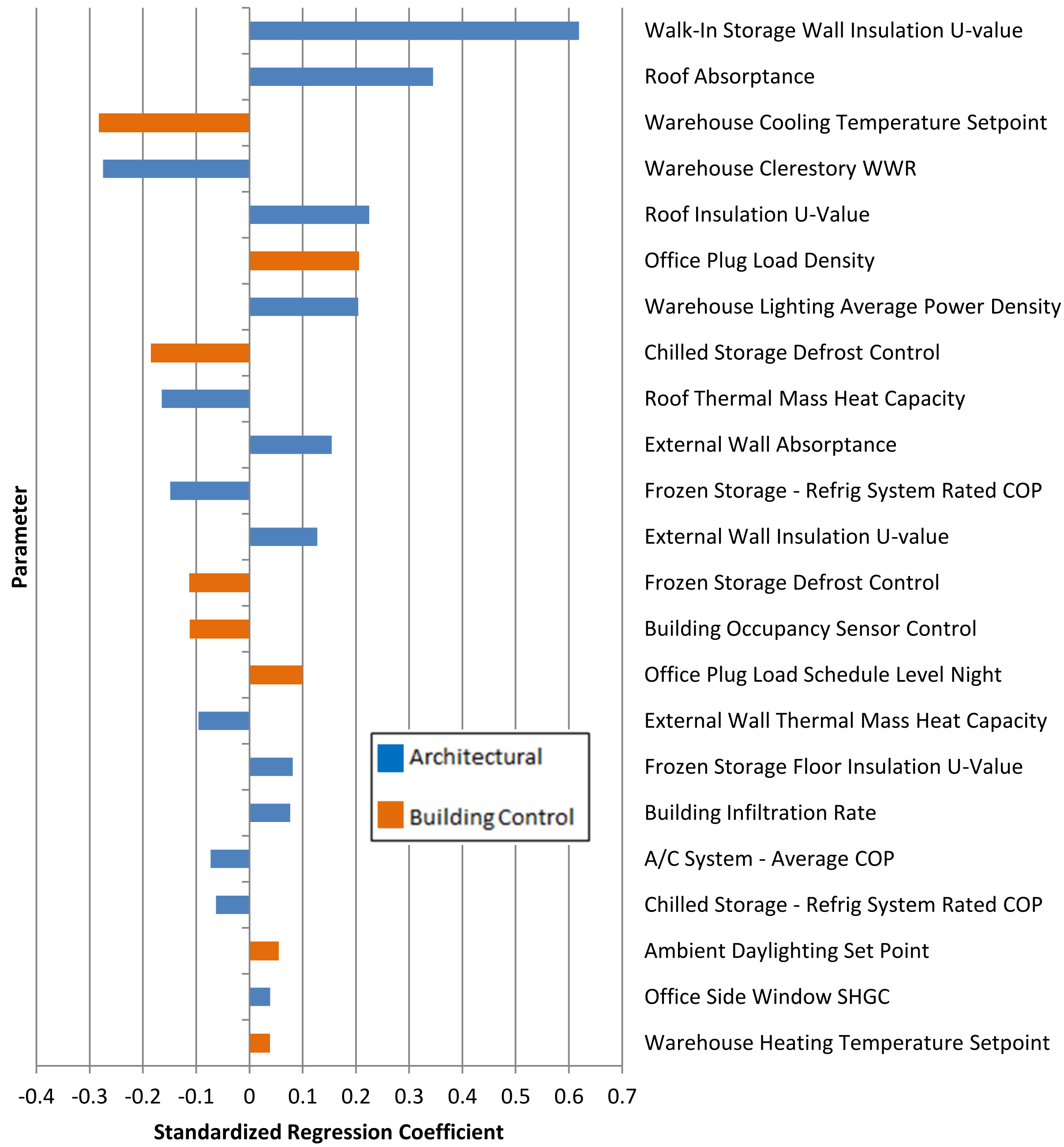


Figure 32. Series 2 main effects sensitivity analysis Standardized Regression Coefficients; Asuncion

While increases in the warehouse cooling set-point temperature may result in a decrease in thermal comfort for the occupants, as previously discussed, the location of the warehouse in the developing world should help to reduce this effect. The relatively small magnitude of the SRC for the A/C system COP, despite the large influence of cooling loads on the building energy consumption, shows that over the design space considered for this case study many of the building envelope parameters which determine the system loads are more important than the efficiencies of the systems that meet the loads. This also holds true for the walk-in storage zones, in particular the Chilled Storage zone. While the walk-in storage wall U-value is the most important architectural design variable considered with an SRC of 0.62, the Chilled Storage system rated COP is much less influential and has an SRC one tenth as large (0.06). This relatively minor impact of the Chilled Storage COP in comparison to the walk-in storage U-value holds true for all of the climates examined. In addition to the differences observed in the results for Asuncion, there are several similarities to the previous sensitivity analyses. For instance, the architectural parameters that directly influence the Ambient zone daylighting continue to exhibit high SRCs. The warehouse clerestory WWR is the fourth most important parameter for this location, with a SRC of -0.27, and the warehouse average lighting power density is the seventh most influential parameter with a SRC of 0.21. Also, the office plug load density maintains a high relative importance for this location with an SRC of 0.22.

The results of the Series 2 regression for Mombasa are shown in Figure 33. This plot indicates that while the walk-in storage wall insulation U-value continues to have the highest SRC (0.50), the margin between this parameter and the next most influential parameter has decreased in comparison to the less extreme climates. This is a result of the increased relative importance of the roof absorptance, which has a SRC of 0.45 for this location. The increased relative importance of both of the roof absorptance and the warehouse cooling temperature set-point (-0.40) is a result of the substantial increase in CDDs for Mombasa in comparison to Asuncion, totaling 1,118 CDDs. This emphasizes the increasing relative importance of the surrounding warehouse parameters as the climate warms in comparison to the walk-in storage parameters. The effects of this increase in cooling demand are also evident by the fact that for Mombasa, the external wall absorptance has become the fourth most important parameter for the Series 2 regression, surpassing all daylighting and plug load related parameters. However, there is a significant gap between the importance of the three most influential parameters and the external wall absorptance, as the SRC for this parameter of 0.20 is half that of the warehouse cooling temperature set-point.

In comparison to all of the climates examined with fewer CDDs, the results for Mombasa indicate a significantly lower relative importance of the warehouse clerestory WWR. This parameter has a SRC of -0.17 for Mombasa, in comparison to -0.27 in Tunis. Intuition suggests that this is due to the effects of the window SHGC or U-Value; however, neither of these parameters is significant for the main effects regression. In addition, as shown by the interaction analysis for this climate in section ***4.4 Parameter Interactions***, there are no significant interactions between the warehouse clerestory WWR and either of these parameters. While increases in the relative importance of parameters such as the roof absorptance and warehouse cooling set-point temperature contribute to the decrease in SRC, analysis of the unstandardized regression coefficients reveals that the predicted absolute impact of this parameter has in fact increased marginally.

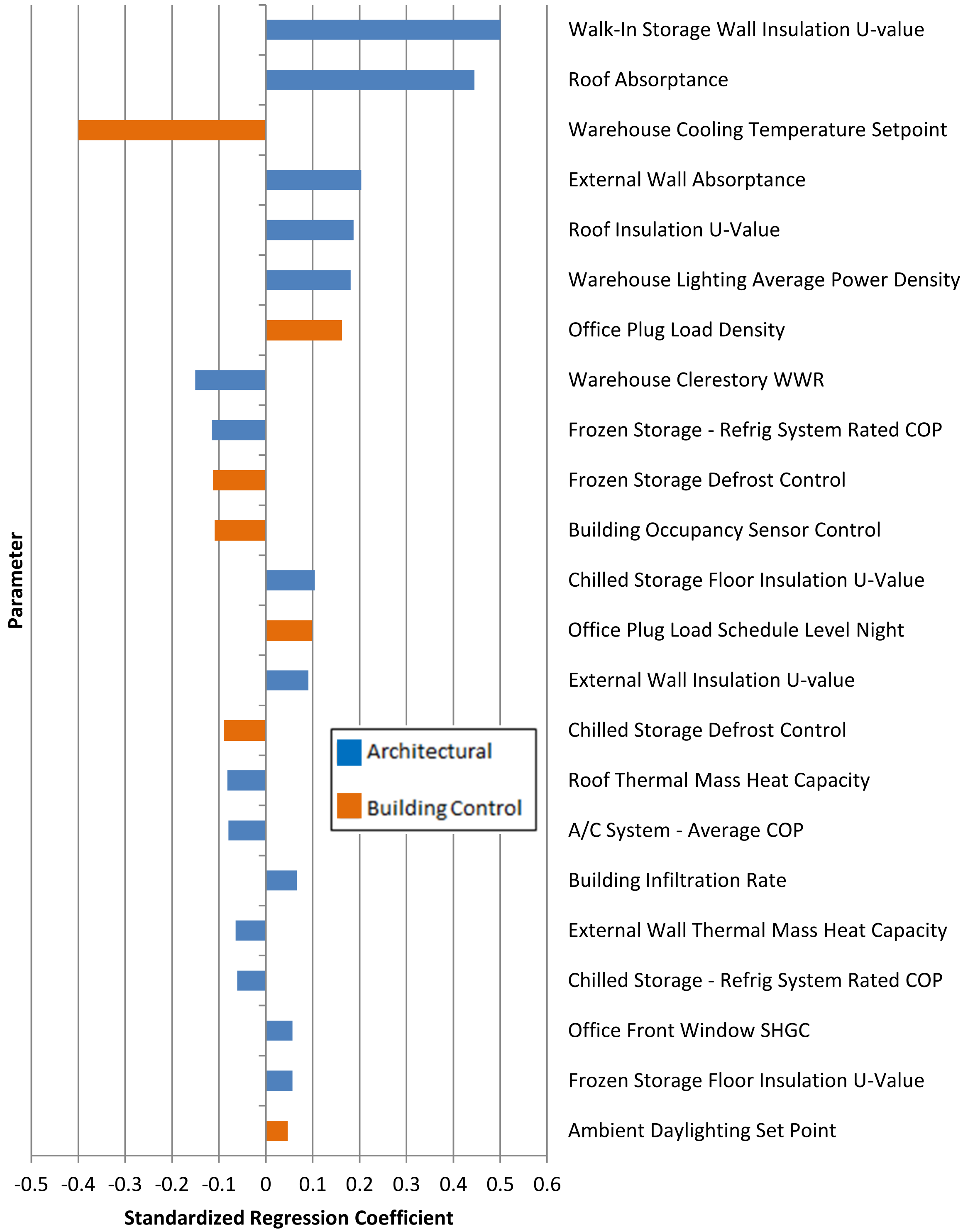


Figure 33. Series 2 main effect sensitivity analysis Standardized Regression Coefficients; Mombasa

The unstandardized regression coefficients indicate that while an increase in the warehouse clerestory WWR of one standard deviation has a predicted absolute impact of decreasing the warehouse energy consumption by 1,495 kWh in Tunis, this impact is increased to 1,547 kWh in Mombasa. This agrees with expectations, as Mombasa has a greater solar resource than Tunis with an average daily solar radiation of 6.4 kWh/m^2 in comparison to 6.0 kWh/m^2, as calculated using the TMY weather files used for simulation. This emphasizes that while the SRCs are useful for comparing the relative importance of a parameter across climates, the unstandardized coefficients must be used for comparing the absolute impact on energy consumption.

The last location examined is Bangkok, Thailand, which has over 2000 more CDDs than Mombasa. The Series 2 regression results are shown in Figure 34 and indicate that unlike the results for all other climates, the walk-in storage insulation U-Value (SRC = 0.36) is not the most influential parameter for determining the warehouse energy consumption. Instead, both the roof absorptance and the warehouse cooling set-point temperature have surpassed this parameter with SRCs of 0.50 and -0.49, respectively. Due to the extremely high influence of the cooling set-point, a viable strategy for energy efficiency would be for the designers to implement measures to limit uninformed occupant control of the warehouse cooling thermostat set-point. For instance, the design team could work with the building manager and owner to ensure that the individuals responsible to oversee the building during operation understand the negative energy implications of alterations to the thermostat set-points. However, as discussed further in section ***4.4 Parameter Interactions***, a low roof and external wall absorptance can be used to help to lower the impact of variation in the cooling set-point. This provides a solution to increase the robustness of the warehouse design against uncertainty in the cooling set-point during operation.

Figure 34. Series 2 main effect sensitivity analysis Standardized Regression Coefficients; Bangkok

Similar to Mombasa, the results for Bangkok show the decreased relative importance of the warehouse daylighting parameters in comparison to the warehouse cooling related parameters. Figure 34 shows that the relative importance of the warehouse average lighting power density is lower (SRC = 0.12) in comparison to climates with fewer CDDs such as Buenos Aires (SRC = 0.21). However, evaluation of the unstandardized regression coefficients reveals that, similar to the previously examined warehouse clerestory WWR, the absolute importance of this parameter in fact increases. In Buenos Aires decreasing the lighting power density by one standard deviation reduces the energy consumption by an average of 1237 kWh, while in Bangkok this same decrease produces an average decrease of 1560 kWh. This is a result of the impact of lighting on HVAC loads; as while higher lighting power densities help to reduce building heating demand in cooler climates, they increase cooling demand in hotter climates.

4.4 Parameter Interactions

While several studies in the building performance literature mention the importance of parameter interactions in influencing the energy consumption of buildings, a limited number employ a method to examine the strength of the interactions between pairs of building parameters. Through the use of bi-linear interaction terms in the regression, the presence of a basic interaction between parameter pairs is investigated. Table 24 shows the three most influential interaction terms for each location. It is important to note that while the SRCs of the interaction terms are presented without the first order effects for each term in the interaction in this table, for the purposes of design the SRC for an interaction effect should always be interpreted in the context of the SRCs for the first order effects. The most prominent interactions observed are between roof parameters, such as the roof absorptance and roof insulation U-value. In addition, there is a significant presence of interactions between the roof parameters and the warehouse cooling set-point temperature. In general, the results indicate that as the number of CDDs increase, the importance of interactions also increase, as shown by the larger SRCs for interactions in Mombasa and Bangkok. The increasing importance of interaction terms in hotter climates is also supported by the larger discrepancies between the R^2 values for the main effects and interaction regressions as shown by comparing the results in Table 19 and Table 20 and discussed in section ***4.2 Main Effect and Interaction Regression Models.***

Table 24. Standardized Regression Coefficients of the top three interaction terms for each location

Interaction Term	SRC
Buenos Aires	
Roof Insulation U-Value * Roof Thermal Mass Heat Capacity	-0.08
Walk-In Storage Wall IUV * Frozen Storage - Refrig System Rated COP	-0.06
Warehouse Clerestory WWR * Building Occupancy Sensor Control	0.05
Tunis	
Roof Absorptance * Warehouse Cooling Temperature Set-point	-0.08
Roof Insulation U-Value * Roof Thermal Mass Heat Capacity	-0.07
Roof Thermal Mass Heat Capacity * Roof Absorptance	-0.06
Asuncion	
Roof Insulation U-Value * Roof Absorptance	0.16
Roof Absorptance * Warehouse Cooling Temperature	-0.14
Roof Insulation U-Value * Roof Thermal Mass Heat Capacity	-0.08
Mombasa	
Roof Absorptance * Warehouse Cooling Temperature Set-point	-0.18
Roof Insulation U-Value * Roof Absorptance	0.16
External Wall Absorptance * Warehouse Cooling Temperature Set-point	-0.09
Bangkok	
Roof Insulation U-Value * Roof Absorptance	0.19
Roof Absorptance * Warehouse Cooling Temperature Set-point	-0.15
External Wall Insulation U-value * External Wall Absorptance	0.10

The results for the Series 3 regression of Tunis are shown in Figure 35, which includes the interaction terms added to the stepwise regression up to the tenth largest SRC. The most important interaction for this location is the (roof absorptance * warehouse cooling temperature set-point) term, with a SRC of -0.08.

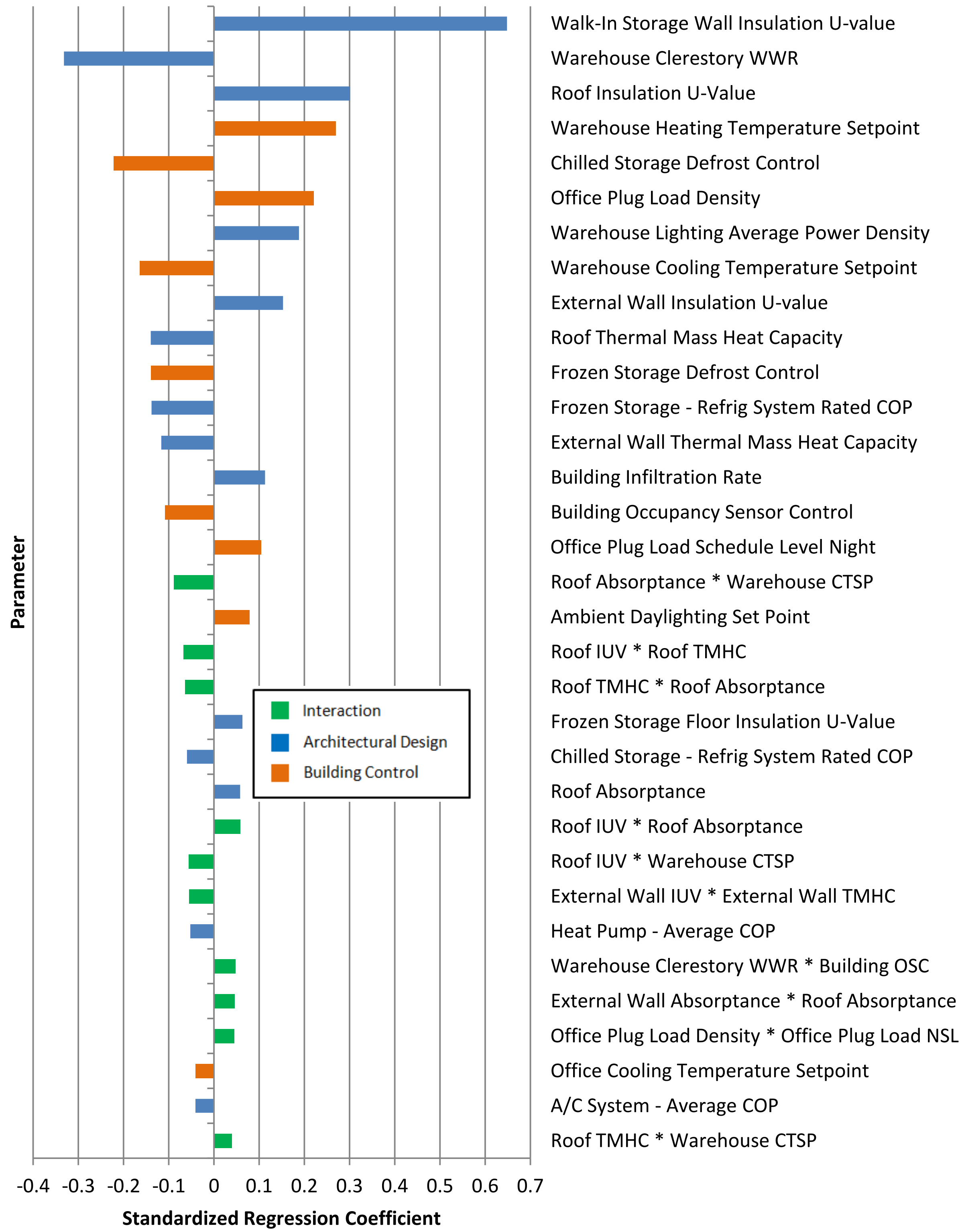


Figure 35. Series 3 interaction sensitivity analysis Standardized Regression Coefficients up to the tenth most important interaction; Tunis

In comparison, the warehouse cooling set-point temperature SRC is -0.16. The relationship between these two shows that when the roof absorptance is low (which corresponds to a negative value since the data are mean-centered), the significance of the warehouse cooling temperature set-point decreases so that it has a weaker negative correlation with the building energy consumption. In a similar manner, the interaction effect can be interpreted in reference to the roof absorptance, which has a SRC of 0.06. The interaction effect shows that a high warehouse cooling set-point decreases the already low relative importance of the roof absorptance. The multiple roof parameters considered also show several interactions between each other. For instance, the second most influential interaction is between the roof insulation U-value and the roof thermal mass heat capacity. With a value of -0.07 for the SRC of this interaction and 0.31 for the roof insulation U-Value, increasing the thermal mass of the roof moderately decreases the impact that insulation has on the warehouse energy consumption. Additionally, the roof thermal mass heat capacity and roof absorptance exhibit an interaction of comparable magnitude to that between the roof thermal mass and insulation, with a SRC of -0.06 for this location. In general, the results for Tunis show a relatively low impact of interaction effects in comparison to the first order effects. Therefore, while the interaction sensitivity analysis does provide the designer with additional insight, its impact is limited for this location in comparison to the main effects analysis.

The Series 3 regression results for Buenos Aires show several differences in the order of the most influential interactions as compared to Tunis. Figure 36 shows that the most influential interaction for this climate is between the roof insulation U-value and the roof thermal mass heat capacity (SRC = -0.08). The relationship between the SRC for this interaction and that of the roof thermal mass (-0.16) demonstrates that the effectiveness of the roof thermal mass is reduced by low insulation U-values for the roof, decreasing the relative importance of this parameter.

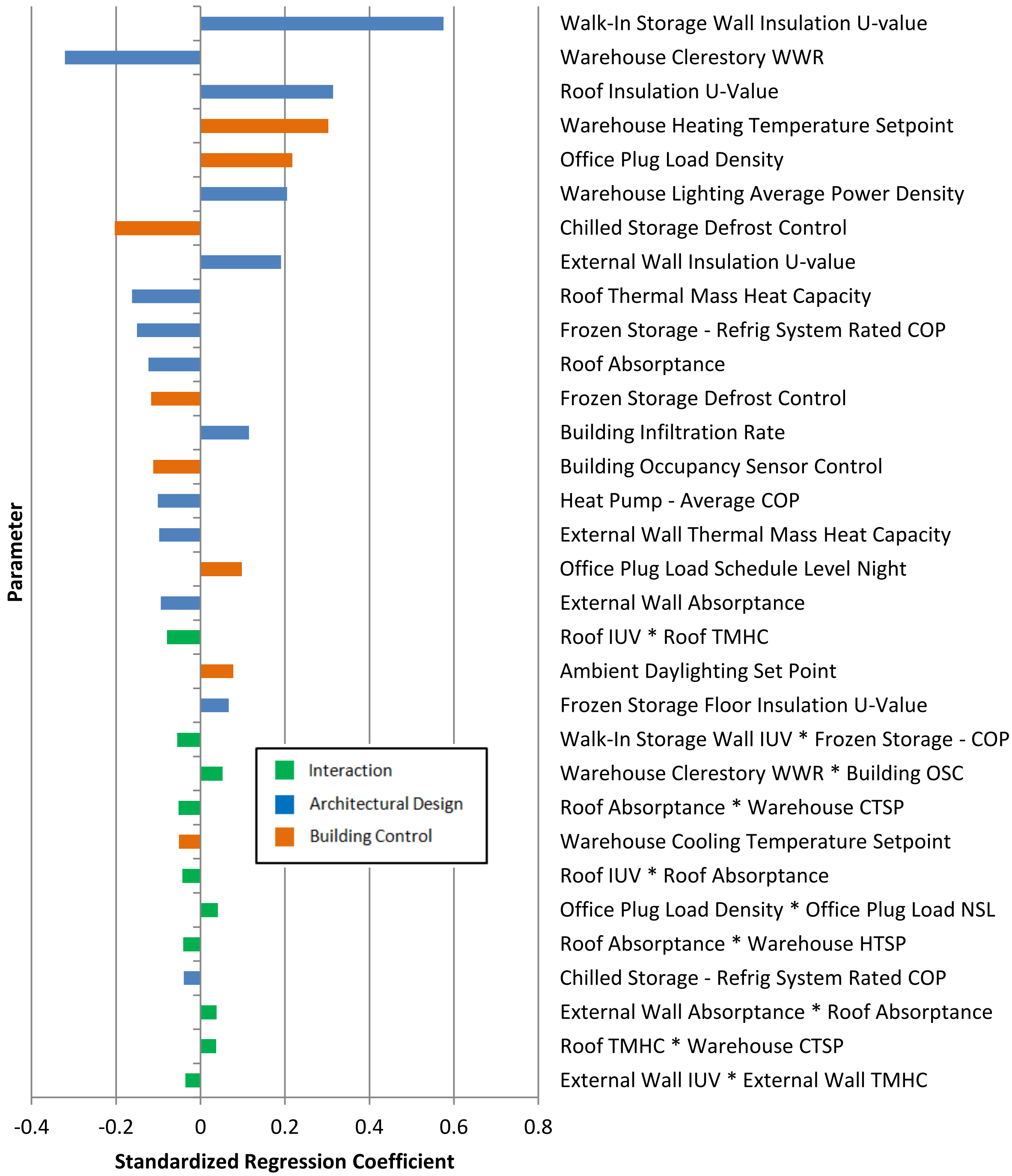


Figure 36. Series 3 interaction sensitivity analysis Standardized Regression Coefficients up to the tenth most important interaction; Buenos Aires

The same conclusion of the decreased importance of the roof thermal mass could be obtained by re-running the global sensitivity analysis after selecting a lower insulation U-value for the roof due to the significantly higher importance of the roof insulation U-value (SRC = 0.37). However, this requires extra time for a new set of simulations. Therefore, the interaction results help to keep the sensitivity analysis results relevant with fewer iterations, saving time, and potentially allowing for a faster progression of the building design. The second most influential interaction for this location is between the walk-in storage wall insulation U-value and the Frozen Storage zone refrigeration system rated COP (SRC = 0.06). However, this interaction has a low relative impact on the importance of the walk-in storage wall insulation U-value (SRC = 0.58). Therefore, even with the implementation of highly efficient cooling equipment, designers should focus on decreasing the U-value of the walk-in storage insulation to achieve an energy efficient warehouse. Lastly, the interaction results for Buenos Aires show the presence of an interaction between the warehouse clerestory WWR and the building occupancy sensor control (SRC = 0.05). Though similar to the previously examined interaction, this term has a limited impact as the SRC of the warehouse clerestory WWR is over five times larger (-0.26). Both of these examples show that in general, the results for Buenos Aires exhibit a similar low relative influence of interaction effects in comparison to first order effects.

In contrast, the results of Asuncion show several relatively influential interaction terms. This is shown by the more substantial difference between the R^2 values for the Series 2 and Series 3 regressions for this location. For instance, the difference between the R^2 values of these two series for Buenos Aires is 0.031, whereas for Asuncion this difference is 0.083, over two and a half times as large. Figure 37 shows that the most influential interaction for Asuncion is between the roof insulation U-value and the roof absorptance, which has a SRC of 0.16.

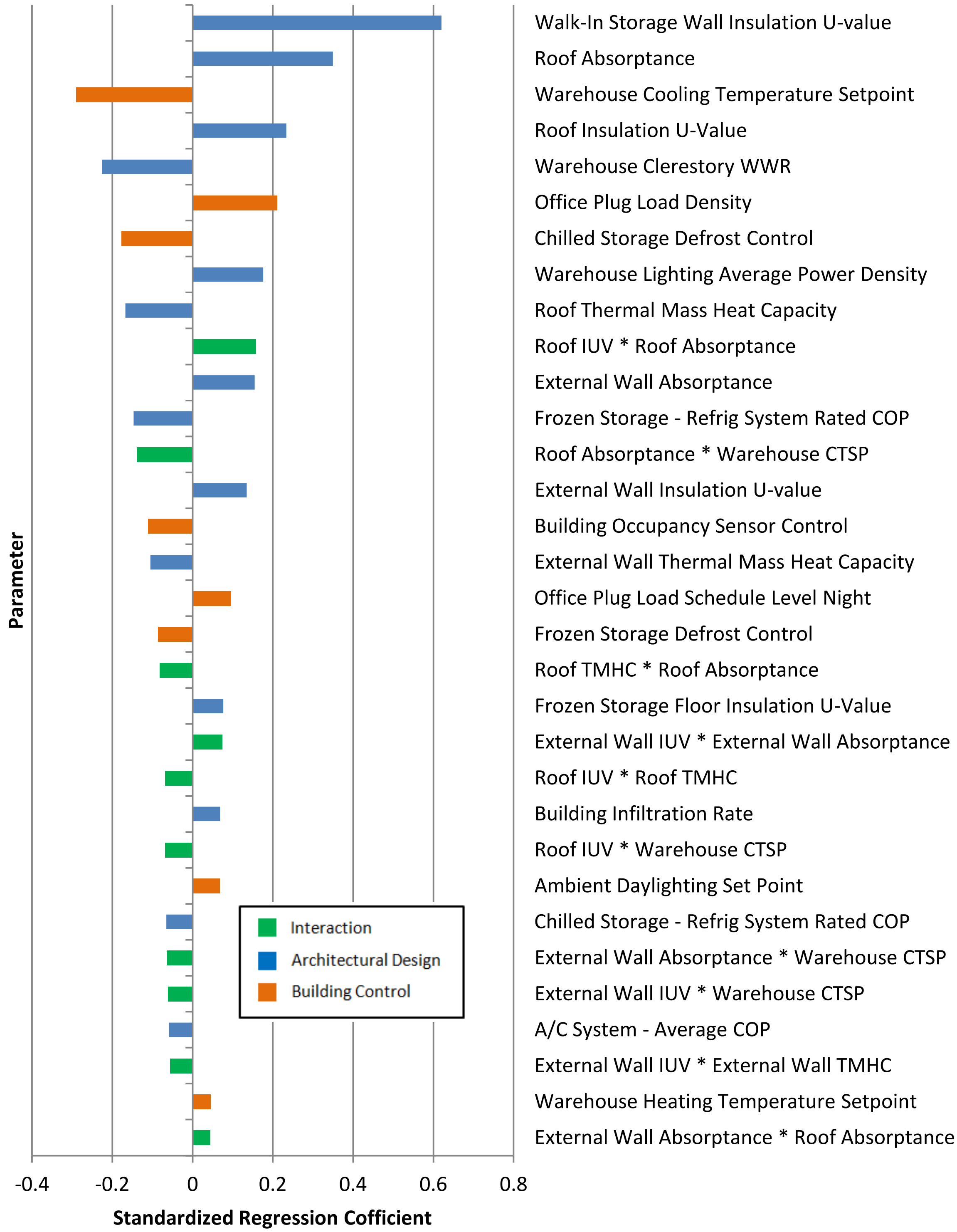


Figure 37. Series 3 interaction sensitivity analysis Standardized Regression Coefficients up to the tenth most important interaction; Asuncion

While the first order effects indicate that both the roof insulation U-value (SRC = 0.23) and the roof absorptance (SRC = 0.35) are influential in reducing the warehouse energy consumption, the interaction reveals that investment in one of these energy efficiency measures reduces the importance of the second parameter. Therefore, it is not necessary to use a large amount of insulation on the roof if a low absorptance can be maintained. The large SRC for this interaction agrees with a study conducted by ORNL, which shows that as roof absorptance decreases, roof insulation levels can be significantly reduced while maintaining a constant building cooling load (Bianchi, Miller, Desjarlais, and Petrie, 2007). This interaction once again emphasizes the advantage of mounting the solar panels on the roof for a NZE warehouse in cooling dominated climates, as they can serve the dual purpose of energy generation and roof shading. The second most significant interaction for this location is between the roof absorptance and the warehouse cooling set-point temperature (SRC = -0.14). This shows that decreasing the roof absorptance can help to significantly reduce the first order effect of the warehouse cooling set-point temperature (SRC = -0.29). Therefore, this interaction illustrates a design choice which can help to reduce the uncertainty of the warehouse energy consumption during operation and increase the robustness of the design, without imposing any oppressive restrictions on the building occupants. In addition, it allows for a possible increase in thermal comfort of the occupants, with a reduced impact on energy consumption.

The external wall parameters show similar interactions to those observed for the roof parameters. An interaction between the external wall absorptance and the warehouse cooling set-point temperature also exists, and has a SRC of -0.06. This shows that the impact of uncertainty in the warehouse cooling set-point temperature can be further reduced through the use of a low absorptive material for the outermost layer of the external wall. A similar effect could also be achieved through the use of vegetation surrounding the building, thereby reducing the amount of incident sunlight on the walls. Knowledge of influential interaction effects such as those discussed for Asuncion have the potential to provide designers with a more sophisticated understanding of the influence of the parameters on the building energy consumption than the main effects global sensitivity analysis alone, and can help to illustrate the different options available within the design space for creating an energy efficient warehouse.

The Series 3 results for Mombasa (Figure 38) show an increased relative importance of the (roof absorptance * warehouse cooling set-point temperature) term in comparison to the results of Asuncion. For Mombasa, this term is the most influential interaction with a SRC of 0.18. This interaction term therefore supersedes many for the first order terms in relative importance, such as the roof insulation U-value (SRC = 0.17) and office plug load density (SRC = 0.17). Since Mombasa is also a cooling dominated climate, this interaction shows that a low roof absorptance will once again significantly reduce the uncertainty in energy consumption introduced by the cooling temperature set-point (SRC = -0.38) during operation. Similar to Asuncion, all of the ten most influential interactions included in Figure 38 directly affect the warehouse cooling load. This emphasizes the relative importance of interactions related to cooling demand for the design space examined, as all of these surpass intuitive interactions such as between the office plug load density and the plug load night level schedule. The results for this location also show the presence of an interaction between the walk-in storage wall insulation U-value, and the warehouse cooling temperature set-point (SRC = 0.06). However, increasing the warehouse cooling set-point temperature does not significantly decrease the relative importance of the walk in storage wall insulation U-value, due to the high SRC for this parameter (0.53).

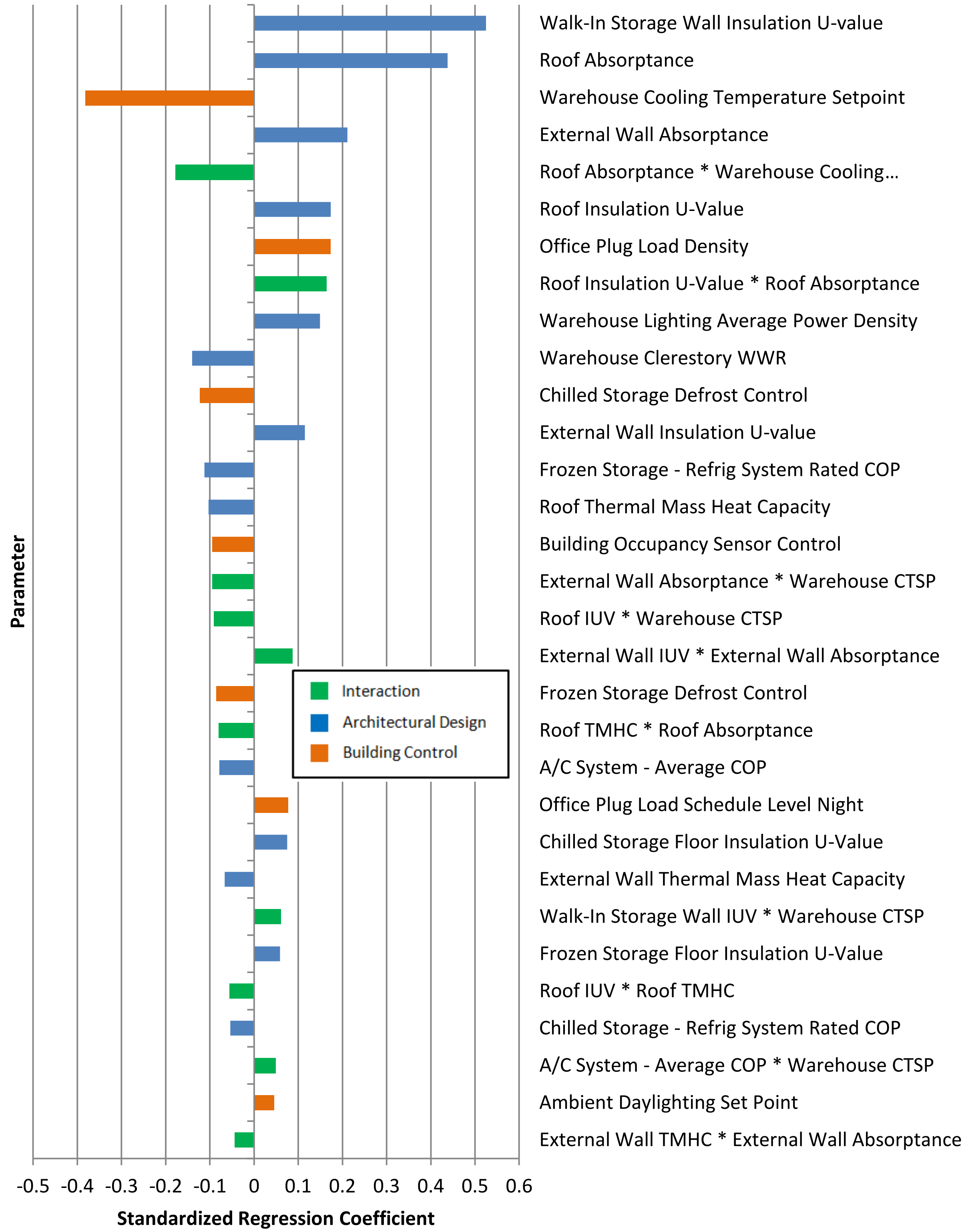


Figure 38. Series 3 interaction sensitivity analysis Standardized Regression Coefficients up to the tenth most important interaction; Mombasa

This agrees with expectations, as while a higher cooling temperature set-point allows for increased temperature differences between the walk-in storage zones and the Ambient zone, a substantial temperature difference already exists. For instance, since the average temperature of the Frozen Storage zone is -20°C, increasing the Ambient zone temperature from 26 to 30 only increases the temperature differential by nine percent.

For Bangkok, the Series 3 results show that similar to the results for Asuncion, the most influential interaction is between the roof insulation U-value and the roof absorptance. With a SRC of 0.19, a low roof absorptance effectively mitigates the impact that the roof insulation has on the warehouse energy consumption (SRC = 0.23). Reduction in the roof absorptance also has a significant impact on the SRC of the warehouse cooling temperature set-point for the results of Bangkok, as the SRC for the roof absorptance * warehouse cooling set-point temperature term is -0.15. However, the results show that in comparison to Mombasa, decreasing the roof absorptance is not as effective for mitigating the uncertainty produced by the warehouse cooling temperature set-point. This is not surprising due to the substantial increase in CDDs for Bangkok in comparison to Mombasa and the resulting dominance of the warehouse cooling temperature set-point. With a SRC of 0.50, the warehouse cooling set-point is more than four times greater than the SRC for the (roof absorptance * warehouse cooling temperature set-point) interaction term. In comparison, this interaction term is only 2.1 times less than the first order term for the warehouse cooling set-point in Mombasa. In general, Bangkok continues to show the trends for interactions established by the results for Mombasa and Asuncion. For instance, all of the ten most influential interactions once again directly impact the cooling of the warehouse zones.

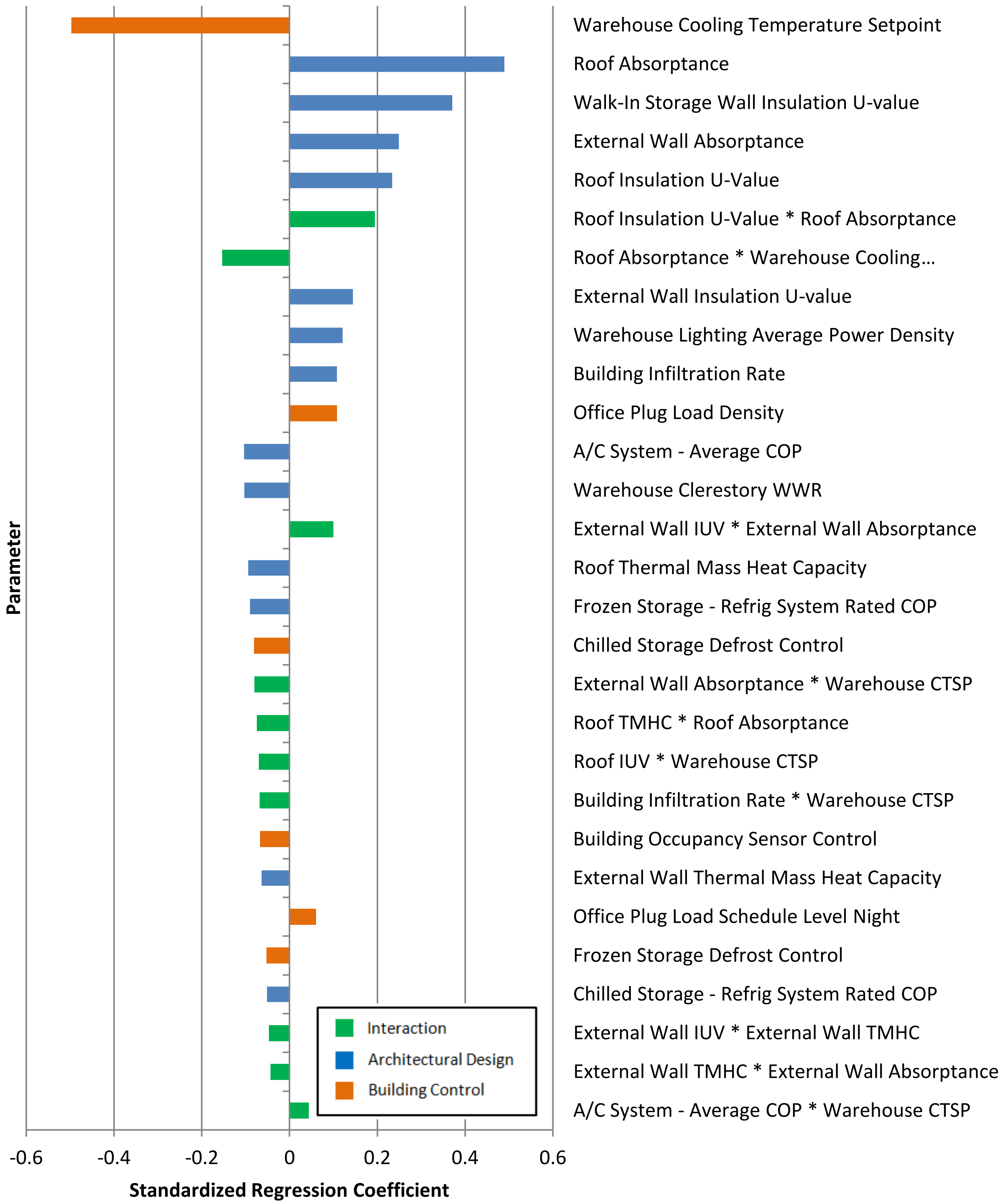


Figure 39. Series 3 interaction sensitivity analysis Standardized Regression Coefficients up to the tenth most influential interaction; Bangkok

4.5 Preliminary NZE Designs from Sensitivity Analysis

Using the sensitivity analysis results, a preliminary design for a Net-Zero Energy vaccine warehouse in each location was formulated. The ten most influential energy efficiency measures in each location, while accounting for the effects of interactions, were used for the preliminary designs. For the continuous parameters, the levels were increased or decreased one standard deviation as suggested by the SRCs in comparison to the average values, and for the discrete control parameters the higher efficiency option was implemented. The defrost controls were lumped into one parameter, as were the office plug load parameters. The energy efficiency measures implemented for each location are listed in Table 30 in section ***4.8 Generalized Recommendations for Designers***. The remaining continuous parameters were assumed to be at the average levels, while the remaining discrete parameters were assumed to be at the low efficiency levels.

The predicted energy consumption from these models is listed in Table 25. All of these values are below the respective 5% quantiles from the uncertainty analysis for D1, as listed in Table 18. The energy consumption for several of the locations is even below the minimum values from the uncertainty analysis. For instance, the minimum energy consumption from the uncertainty analysis for Buenos Aires is 39,934 kWh, while the predicted consumption from the preliminary NZE design is 39,192 kWh. These low energy consumption figures confirm the results of the sensitivity analysis, and show that in general resources should be directed towards the parameters with the highest SRCs to achieve an energy efficient warehouse. The predicted energy consumption figures were used to calculate the size of a photovoltaic solar array for each location that allows the preliminary building design to operate as NZE facility. NREL's PV Watts software was used to calculate the annual energy production of 1kW of solar array for each location (NREL, 2014c). The value of the predicted production per kW of solar array for each location assumes that the array will be tilted at the latitude of the respected location, and that the azimuth of the system is 0° in the Southern Hemisphere and 180° in the Northern Hemisphere. Both of these are the default assumptions suggested by PV Watts. The predicted production per kW and resulting total solar panel system size for each location are shown in Table 25. The results from PV Watts show a similarity between the solar resources at the five locations examined, as the solar energy production per kW of array varies less than 10% between sites. This table also includes a preliminary cost estimation for each solar panel system, based on the assumption of $4.50 per installed Watt of solar power (Goodrich, James, and Woodhouse, 2012). Due to the low amount of variation in the solar panel energy production, the trends for solar panel size and cost closely match the trend for the building energy consumption. Therefore, Tunis shows the lowest anticipated solar cost with a total of $132,941 needed to install a 29.5 kW array. In comparison, Bangkok requires the largest solar panel system, with a 36.8 kW array and an installed system cost of $165,482.

Table 25. Predicted annual energy consumption and solar panel system characteristics for preliminary Net-Zero Energy vaccine warehouse designs

Location	Building Energy Consumption (kWh)	Solar Panel Energy Production (kWh/kW)	Solar Panel System Size (kW)	Solar Panel System Cost ($)
Buenos Aires	39,192	1,305	30.0	135,144
Tunis	39,144	1,325	29.5	132,941
Asuncion	40,266	1,305	30.9	138,847
Mombasa	43,968	1,374	32.0	143,999
Bangkok	45,857	1,247	36.8	165,482

Figure 40 shows a breakdown of the total building energy consumption by end use for the preliminary NZE design warehouses in each location.

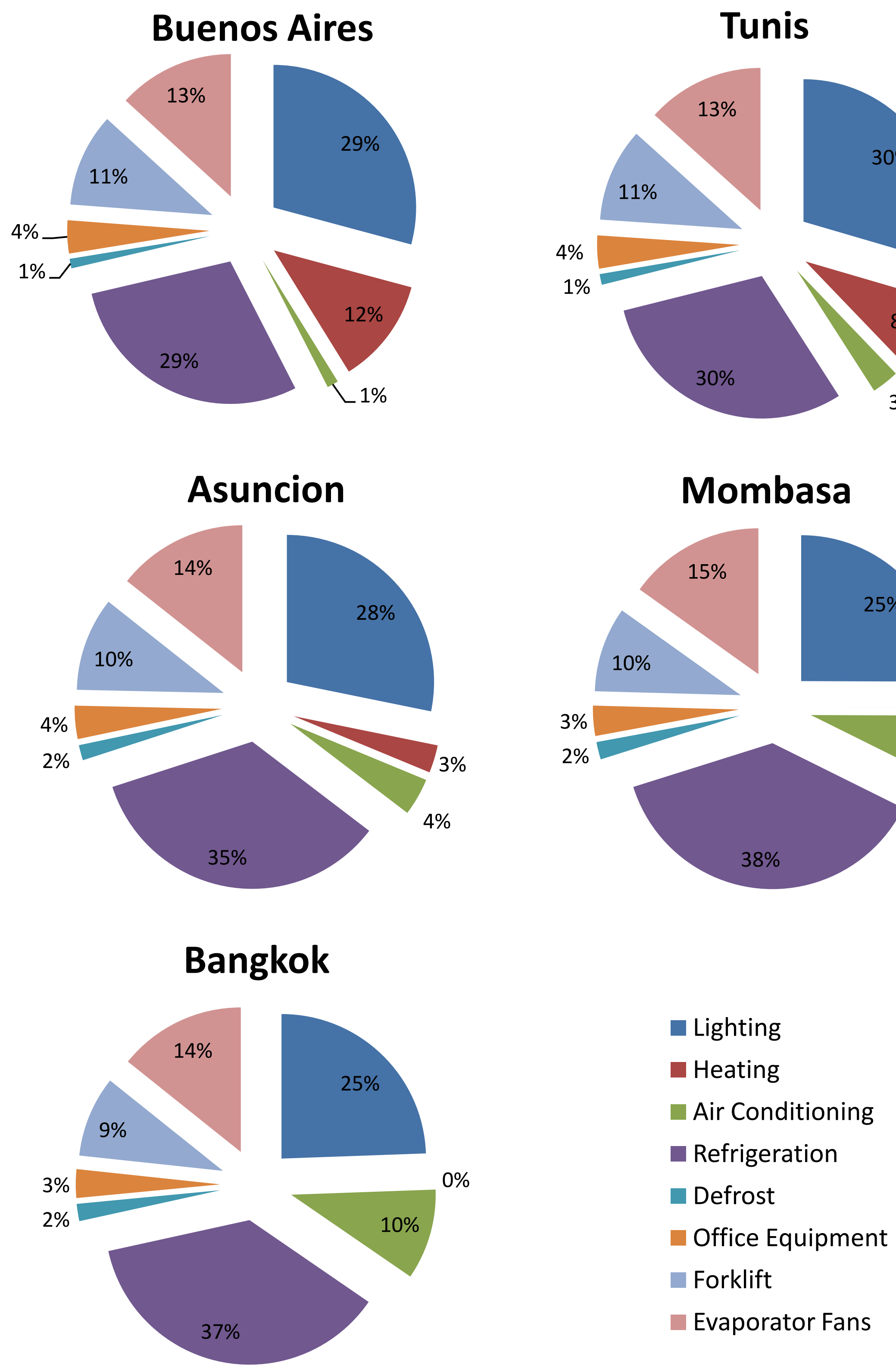


Figure 40. Breakdown of the warehouse energy consumption by end use for the preliminary NZE design warehouses; all locations

These pie charts show that for all locations, the portion of the load directly related to cooling the walk-in storage zones (evaporator fan and refrigeration electricity) encompass at least 40% of the total energy consumption. Additional improvements in the evaporator fan control strategy beyond the bounds investigated in this thesis may help to further reduce both the evaporator fan and refrigeration load. For instance, the use of a variable frequency drive controller for the evaporator fans is an option that has been advocated for reducing both fan and associated compressor energy consumption (Bhattacharje, 2009). This strategy was not investigated due to errors in the EnergyPlus object that models this control type.

The next most influential end use for all climates is the lighting energy consumption. The high contribution of this end use agrees with the relatively large SRCs for the lighting power density across all climates, despite the small range examined for this parameter. The relatively large contribution of the lighting load, even with the energy efficiency measures implemented, is supported by the results of similar studies in the literature. For instance, even with sky lighting, occupancy sensors and a lighting power density of 6.5 W/m^2, the lighting load for a non-refrigerated warehouse in Miami (ASHRAE Climate Zone 1A) of comparable size was found to be over twice as large as the next most significant load in a modeling study by PNNL (Liu et al., 2007). Another insightful observation from Figure 40 is the relatively small contribution of the air conditioning energy with the assumed parameter levels, even for the hotter climate zones. For instance, the consumption of the air conditioning for the warehouse in Asuncion is only slightly larger (1660 kWh) than the heating energy consumption (1230 kWh). This is non-intuitive for a climate that is considered hot, however, is a result of the building design; with the presence of the walk-in storage zones, the high warehouse cooling set-point and the low roof absorptance. The similar relative importance of heating in comparison to cooling for warehouses in hot climates also agrees with the results of the modeling study by PNNL, as a non-refrigerated warehouse of similar size in Houston (Climate Zone 2A) was shown to have a higher heating load than cooling load (Liu et al., 2007).

4.6 Regression Model Accuracy versus Number of Simulations

For a Monte-Carlo based global sensitivity analysis, the most time consuming step of the process in terms of computer run time is the simulation of the hundreds or thousands of models required. In order to help integrate global sensitivity analysis into the design process, a balance between the number of simulations required, and subsequently the simulation runtime, and the accuracy of the regression model results should be reached. To investigate this balance, several regression models were formed for the MCA data of Tunis, each with a different number of simulations used for the creation of the stepwise regression model. The number of simulations included was tested over a wide range of eight different nominal levels: 50, 60, 75, 100, 200, 500, 1,000, and 2,000. The accuracy of the regression model was investigated by comparing the energy consumption predicted by the regression model to the actual energy consumption of the EnergyPlus model for a validation set of 1,000 simulations. A similar method is used by Hygh and colleagues for a sensitivity analysis of an office building across several American climates (Hygh et al., 2012). From this comparison, the average percent error between the two energy consumptions over the validation set, as well as the standard deviation, was used to measure how the accuracy of the regression model varied as the number of simulations increased.

First, the accuracy of the main effects regression was investigated. Figure 41 shows that both the mean value and standard deviation of the energy consumption percent error decrease substantially between 50 and 100 simulations. The average percent error reduces from 7.17% at only 50 simulations to 3.47% at 100 simulations. However, while Macdonald advocates for approximately 100 simulations for a typical Monte Carlo based uncertainty analysis (Macdonald, 2009) the results for this analysis continue to show noticeable improvements in accuracy up to approximately 500 simulation runs. Table 26 compares the top ten Standardized Regression Coefficients for the stepwise regression including 100 simulations to that for the regression including 2,000 simulations. While many of the parameters have comparable SRCs the regression with only 100 simulations leaves out the office plug load density, which is in fact omitted completely from the regression results. This could potentially lead to the neglect of this parameter and a subsequent decrease in energy efficiency for the building during operation. Figure 41 shows that above 500 simulations, the improvements in accuracy of the regression model are negligible. From this, it is estimated that the time required to conduct the sensitivity analysis could be reduced to approximately one fourth of the time used for the regression models in this thesis to six hours on a modern computer with eight processor cores.

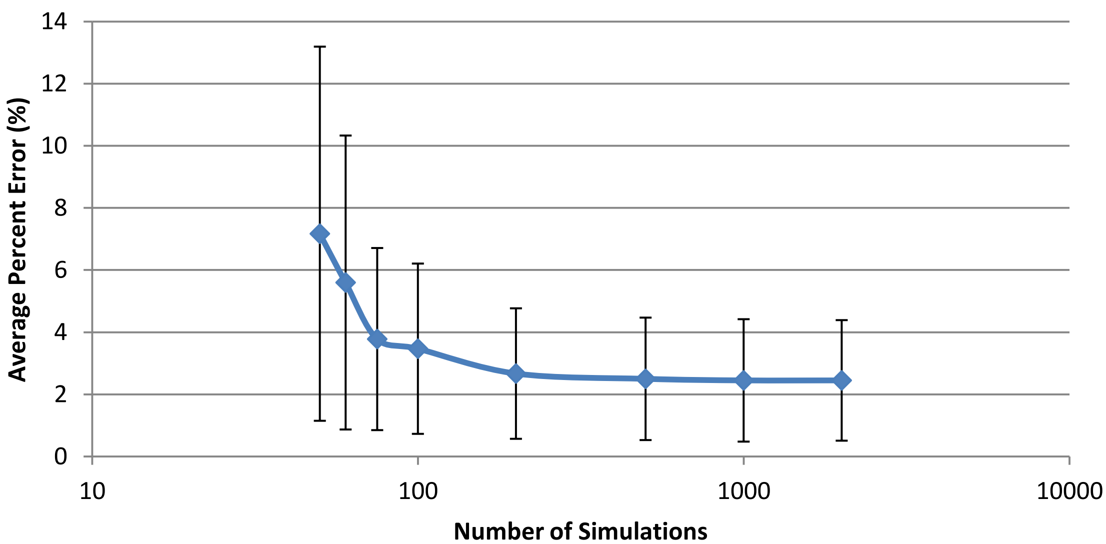


Figure 41. Variation in main effects regression model accuracy based on the MCA data of Tunis as a function of the number of simulations used for the regression; validated against a set of 1,000 simulations

Table 26. Comparison between the top ten SRCs from the main effects stepwise regression including 100 simulations and 2,000 simulations

100 Simulations		*2,000 Simulations*	
Parameter	**SRC**	**Parameter**	**SRC**
Chilled Storage Evaporator Fan Control	-0.960	Chilled Storage Evaporator Fan Control	-0.946
Walk-In Storage Wall Insulation U-value	0.149	Walk-In Storage Wall Insulation U-value	0.142
Warehouse Heating Temperature Set-point	0.118	Warehouse Clerestory WWR	-0.133
Warehouse Clerestory WWR	-0.115	Roof Insulation U-Value	0.114
Roof Insulation U-Value	0.097	Warehouse Heating Temperature Set-point	0.091
External Wall Insulation U-value	0.090	Office Plug Load Density	0.081
Warehouse Cooling Temperature Set-point	-0.080	Warehouse Lighting Average Power Density	0.072
Roof Thermal Mass Heat Capacity	-0.073	Warehouse Cooling Temperature Set-point	-0.072
Warehouse Lighting Average Power Density	0.067	Frozen Storage - Refrig System Rated COP	-0.064
Frozen Storage - Refrig System Rated COP	-0.067	External Wall Insulation U-value	0.064

Next, the accuracy of the regression including interaction effects was investigated using the same process. Figure 42 shows that the interaction regression results exhibit a similar curve to the main effects regression investigation. In comparison to main effects regression, the plot indicates that the curve begins to level off closer to between 500 and 1,000 simulations, rather than between 200 and 500 simulations as observed for the main effects regression. This indicates that 500 simulations remains a good target value for conducting the sensitivity analysis, however, is reducing the number of simulations below this value will likely decrease the accuracy of the interaction regression results. This graph also shows that the standard deviation of the energy consumption percent error decreases significantly as the number of simulations is increased. In comparison to the regression in which 2,000 simulations are included, the standard deviation for the regression with only 100 simulations is over twice as large. A summary of the average accuracy and standard deviation values for both the main effects and interaction regression model investigations is shown in Table 27.

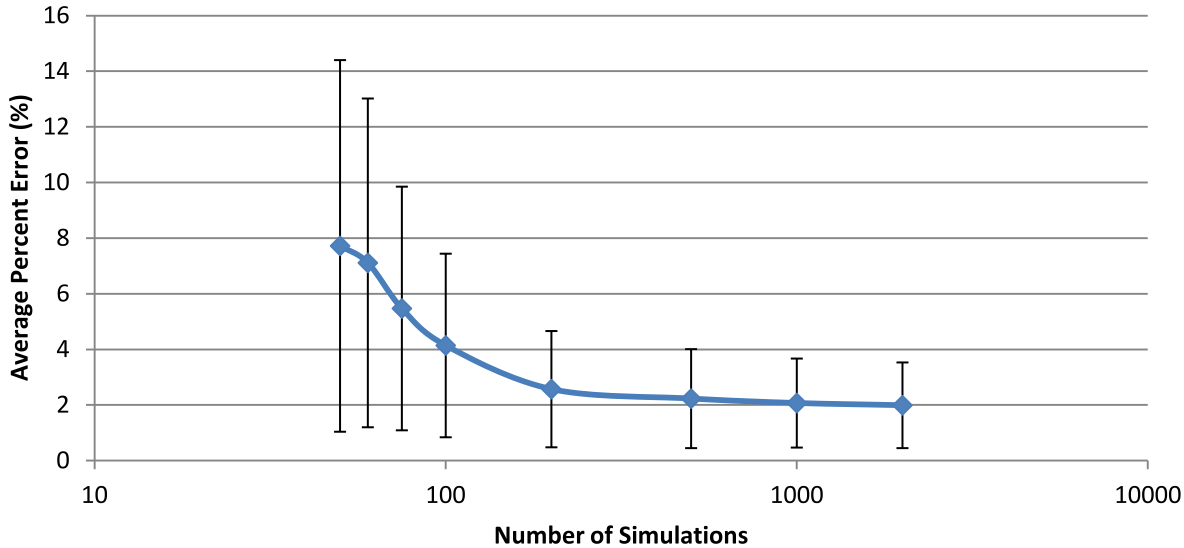


Figure 42. Variation in the interaction regression model accuracy based on the MCA data of Tunis as a function of the number of simulations used for the regression; validated against a set of 1,000 simulations

Table 27. Mean value and standard deviation for the main effects and interaction stepwise regressions as a function of the number of simulations included

Interaction Regression								
Number of Simulations	**50**	**60**	**75**	**100**	**200**	**500**	**1,000**	**2,000**
Average Error	7.72	7.11	5.47	4.14	2.57	2.23	2.07	1.99
Error Standard Deviation	6.68	5.91	4.38	3.3	2.09	1.78	1.6	1.54
Main Effects Regression								
Number of Simulations	**50**	**60**	**75**	**100**	**200**	**500**	**1,000**	**2,000**
Average Error	7.17	5.6	3.78	3.47	2.67	2.5	2.45	2.45
Error Standard Deviation	6.02	4.73	2.93	2.74	2.1	1.97	1.97	1.94

4.7 Evaluation of the Method Implemented

4.7.1 Theoretical methods

The method outlined in the previous chapter provided a successful way to examine the proposed research questions and hypotheses, and an improved understanding of the method's strengths and weaknesses was gained through the course of its implementation,. A shortcoming of the method for its implementation in design practice is that, while it helps to focus the attention of designers on the most important design variables, it doesn’t allow the designer to confidently state that a variable has no significant impact on energy consumption. This is due to the fact that a main effects sensitivity analysis is used, as is recommended by Tian for establishing the most important energy saving measures (Tian, 2013). As a main effects sensitivity analysis does not account for all of the variation in the building energy consumption, it cannot be used to declare that variation in a parameter is inconsequential. To make the method capable of informing such claims, a total effects sensitivity analysis should be implemented (Tian, 2013). This accounts for all interactions and higher order effects for every parameter, so that if a parameter has any significant contribution to the energy consumption it will be identified. Another proposed improvement to the general method of this thesis is the use of a second global sensitivity analysis method to compare and validate the relative sensitivities established by Standardized Regression Coefficients. Several variance-based methods, such as Sobol and Fourier Amplitude Sensitivity Test, have been implemented previously in building performance simulation (Mechri et al., 2010; Spitz, Mora, Wurtz, and Jay, 2012), and a Matlab toolbox exists for implementing both of these methods (Cannavo, 2012), which would allow for an easier integration into the already existing analysis framework. An added benefit of these methods is that they allow for the easy establishment of both main and total effects indices.

4.7.2 Software

The use of Matlab and EnergyPlus to carry out the proposed method resulted in a set of software specific strengths and weaknesses. While overall EnergyPlus proved an effective tool for this thesis, a significant limitation of this software for modeling primary vaccine warehouses is the lack of accurate refrigeration components. This is due to the discovery that the AirChiller object included in EnergyPlus for modeling refrigeration systems does not provide a correct breakdown of latent and sensible cooling loads for an evaporator. As a result, a significant portion of the refrigeration system described in the previous chapter is programmed into the Energy Management System objects, which is a much more cumbersome method of modeling the system. In addition, it decreases the flexibility of the model as it can no longer be passed on to other experienced EnergyPlus users without a thorough explanation of this unique solution strategy. Despite this drawback, a significant strength of EnergyPlus is that it allowed for the integration of other complex modeling needs, such as daylighting into the building energy model, without the need for multiple models. The use of other popular thermal modeling software packages, such as TRNSYS, would have necessitated calculating the contributions to the energy model from daylighting in an external program, such as Radiance. In addition, EnergyPlus allows for users to write their own modules to expand the capabilities of the program. Therefore, a module for the simplified refrigeration modeling method implemented in this thesis can be constructed so that the model is more easily shared.

In contrast to the obstacles faced in the construction of the building energy model in EnergyPlus, wrapping the entire uncertainty and sensitivity analysis in Matlab allowed for a straightforward integration of the entire process. The large number of tasks required for the MCAs including the process of input file generation, building energy model modification, model simulation and output data processing were efficiently automated so that a minimal amount of time was expended on actively setting up and executing each analysis. As Matlab also contains a sophisticated statistical analysis toolbox, the entire sensitivity analysis was automated and conducted in Matlab, without having to implement an external statistical analysis program.

4.7.3 Improving Practicality for Design

Wrapping the entire analysis in Matlab also helps to decrease the potential effort required to commercialize a simple and targeted design tool to allow vaccine warehouse design teams to more easily implement the method outlined in this thesis. As Matlab has built-in features for designing a graphical user interface, it is likely that a design team could implement the method without having to work directly with any code. The only limitation imposed by the use of Matlab in the potential development of a design tool is that it is not an open source software; therefore access to it may be limited depending on the resources of the design team. However, a very close derivative of the software, GNU Octave, is available to the public for free (Eaton, 2014). Therefore, this platform could be used to make the tool widely available.

In order to be turned into a useful tool for designers, several significant expansions to the method are necessary. Foremost, the geometry of the building energy model must be adaptable to the requirements of the design team. In the current form of the method, the building energy model geometry is fixed, and only the orientation of the building is easily modified. At the very least, the floor areas and volumes of each thermal zone, such as the Ambient zone and Chilled Storage zone, need to be adaptable to the required storage volumes as prescribed by the user. As only the sizes of the zones would be altered, and not the basic layout, this proposed approach is similar to the simplified approach employed by other design tools (O'brien et al., 2009). A more advanced option would be to include several shoebox templates, to allow for different building shapes and cold room arrangements. This type of approach is implemented by Attia in ZEBO tool, which includes templates for several different residential style buildings (Attia, 2012). In addition, as part of the conversion to a design tool, further research is necessary to investigate potential ways to reduce the computational cost of each individual simulation while maintaining an accurate energy consumption estimation. Decreasing the number of simulation time-steps and the frequency of daylighting and shading calculations provide two areas in which reductions in detail may result in a significant reduction in simulation time without a decline in accuracy.

Lastly, to reduce the chances of the inappropriate application of the tool, the scenario assumptions behind the model must be readily apparent and alterable. For instance, the workday and weekend schedules that are assumed in this thesis likely do not provide an accurate representation of the operation of all vaccine warehouses. In addition, assumptions about the building model architecture such as the use of strip curtains in the walk-in storage doorways should also be clearly visible and flexible. Due to the lack of information on primary vaccine warehouses, it is unlikely that a meaningful database of suggested levels for assumptions could be included; however, the absence of default levels may help to encourage design teams to rigorously question their input assumptions.

4.8 Generalized Recommendations for Designers

This section provides designers with recommendations for the creation of an energy efficient primary vaccine storage warehouse. First, a discussion of the important points for the application of the design method presented in this thesis is given. Second, general recommendations to direct attention towards the most influential building control and architectural parameters are presented for designers unable to conduct their own uncertainty and sensitivity analysis.

4.8.1 Application of the global uncertainty and sensitivity analysis method in practice

When implementing the method of global uncertainty and sensitivity analysis outlined in this thesis (Figure 43) in design practice, several guidelines should be followed, which are summarized in Table 28.

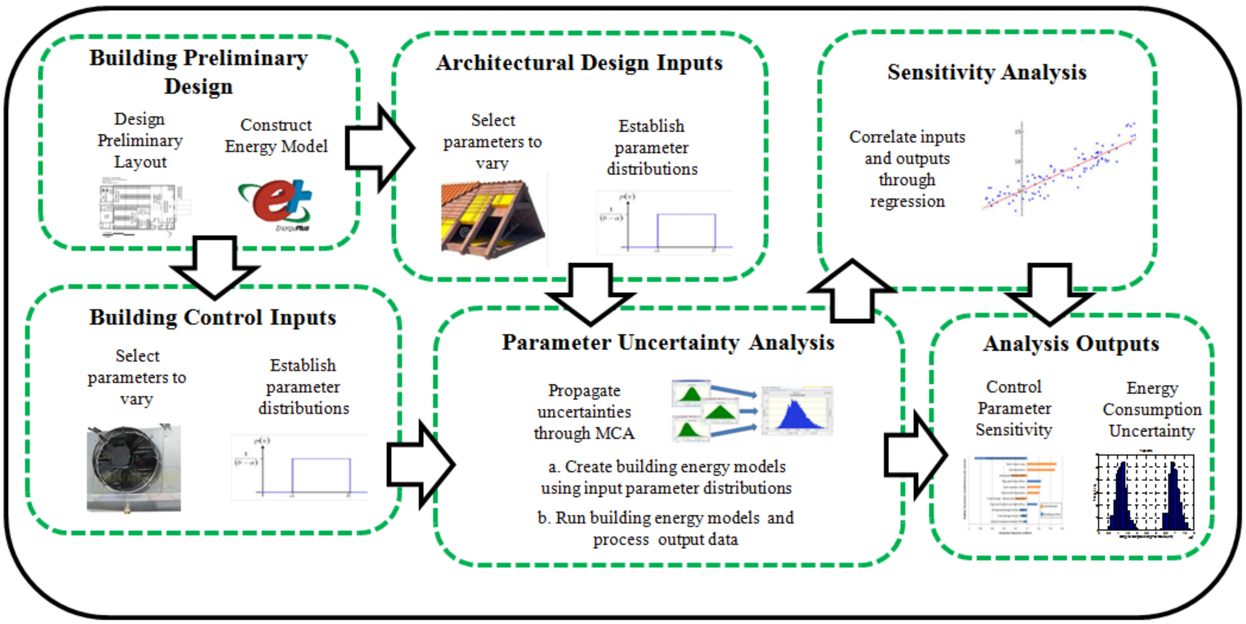


Figure 43. Global uncertainty and sensitivity analysis method applied in this thesis

First, the analysis should be constructed as early in the design process as practically feasible. Since the highest potential for building energy savings is during the early design stages (Krygiel and Nies, 2008), the use of this method early in the design process will help to identify energy efficiency measures prior to a large number of the design parameters being arbitrarily established without proper investigation. In addition, the initial analysis should be used to investigate a large design space, so that opportunities for energy savings are not overlooked. This entails considering a large number of parameters, as well as a wide range for each of the parameters. As part of considering a wide design space, the analysis should consider both building control and architectural design parameters. As the results of this thesis show, both of these parameter types are influential in determining the energy consumption of a primary vaccine warehouse. This is particularly important for considering the effects of the cooling set-point in climates with a high number of CDDs, as this thesis has shown the significant impact this building control parameter has on numerous building envelope components. It is also recommended that underlying scenario assumptions of the building energy model be tested through this method. While pure scenario assumptions are beyond the scope of this thesis, the importance of the building control parameters, which are similar in nature, suggests that these assumptions may have a significant effect on the building energy consumption.

Table 28. Recommendations for the application of the global uncertainty and sensitivity analysis method formulated for this thesis to design practice

1	Conduct the first iteration of the analysis early in the design process
2	Start with a wide design space, both in terms of parameter ranges and the number of parameters considered
3	Include building control and architectural design parameters
4	Test sensitivity to underlying assumptions, especially scenario assumptions
5	Carry out multiple iterations of the analysis as the design progresses
6	Conduct an interaction and main effects sensitivity analysis
7	Test the correlation between sensitivity analysis accuracy and number of simulations

The global uncertainty and sensitivity analysis should also be redone as the design progresses. Ideally, an iteration of the analysis should be conducted each time that the design space under consideration changes, so that the results accurately inform the designers. However, using both a main effects and interaction sensitivity analysis can help to reduce the need for the number of iterations, as the interaction analysis assists in the prediction of how changes in a design parameter will affect the influence of the remaining parameters within the design space. Lastly, in order to increase the efficiency of the method, it is recommended that an analysis similar to that conducted in section ***4.6 Regression Model Accuracy versus Number of***

Simulations be used to determine how the number of simulations affects the accuracy of the sensitivity analysis. This will allow for a significant reduction in the computational time required, and subsequently an increase in the potential number of iterations of the analysis that can be conducted.

4.8.2 Guidelines

Based on the analysis conducted, the following set of general recommendations is put forth for designers that are unable to conduct their own uncertainty and sensitivity analyses. These recommendations are limited by the underlying assumptions on which the research is based, the most important of which are listed in Table 29. The recommendations are listed in Table 30, and are given in order starting with the highest potential energy savings. They have been derived by using the interaction sensitivity analysis results for the five locations examined. The suggestions should be followed in the order they are presented to achieve the design and operation of an energy-efficient, primary vaccine warehouse. Table 31 provides a description of each of the energy efficiency measures recommended.

Table 29. Assumptions for and limitations of the application of the generalized recommendations

1	Foremost, the guidelines listed are only relevant towards informing the design of primary vaccine warehouses, and not any other building type.
2	The Chilled Storage and Cold Storage Spaces must be walk-in cold storage; primary stores that employ chest freezers or refrigerators are not within this scope.
3	The relevance of the generalized recommendations is limited by the design and geometry of the case study building employed; most significantly the relative sizes between the thermal zones, the use of a naturally ventilated floor for the Frozen Storage zone, the arrangement of the walk-in zones for shared walls, and the use of the CRT zone as a vestibule.

Table 29. Continued:

4	The recommendations are limited by the specific building model assumptions employed, such as the assumed schedules and the deterministic levels assumed for all of parameters not investigated such as the use of strip curtains for all walk-in doorways.
5	The list of parameters included in this investigation is not exhaustive. Energy conservation measures not included, such as skylights, may also result in significant energy savings.
6	The uncertainty bounds used and corresponding design space investigated further limit the applicability of the recommendations; designers considering parameter values outside this design space should apply the guidelines tentatively.
7	These guidelines are only pertinent to addressing the relative importance of parameters on the warehouse energy consumption and neglect the impact that they may have on other aspects of building performance such as glare and thermal comfort.
8	Cost-effectiveness of the energy efficiency measures is not taken into account. Therefore, the guidelines should not be used as a justification for neglecting the energy efficiency measures not recommended, as they may be highly cost effective.

Table 30. Summary of the most influential parameters for each climate in terms of energy consumption; listed in order of importance starting with lower numbers indicating a higher importance

Moderate Climate Zones: (2500 < CDD < 3500; Baseline Temperature 10°C) (HDD>1000; Baseline Temperature 18°C)	
1) Evaporator Fans	*6) Demand Defrosting*
2) Walk-In Walls & Ceiling	*7) Heating Set-point*
3) Clerestory Glazing	*8) Efficient Active Lighting*
4) Roof Insulation	*9) External Wall Insulation*
5) Plug Loads	*10) Frozen Storage Compressor*
Warm Climate Zones: (2500 < CDD < 3500; Baseline Temperature 10°C) (HDD<1000; Baseline Temperature 18°C)	
1) Evaporator Fans	*6) Roof Insulation*
2) Walk-In Walls & Ceiling	*7) Heating Set-point*
3) Clerestory Glazing	*8) Efficient Active Lighting*
4) Demand Defrosting	*9) External Wall Insulation*
5) Plug Loads	*10) Frozen Storage Compressor*

Table 30. Continued:

Hot Climate Zones: (3500 < CDD < 5000; Baseline Temperature 10°C)	
1) Evaporator Fans *2) Walk-In Walls & Ceiling* *3) Low Absorptive Roof* *4) Plug Loads* *5) Demand Defrosting*	*6) Clerestory Glazing* *7) Efficient Active Lighting* *8) Low Absorptive External Wall* *9) Frozen Storage Compressor* *10) Cooling Set-Point*
Very Hot Climate Zones: (CDD > 5000; Baseline Temperature 10°C)	
1) Evaporator Fans *2) Walk-In Walls & Ceiling* *3) Low Absorptive Roof* *4) Plug Loads* *5) Low Absorptive External Walls*	*6) Demand Defrosting* *7) Efficient Active Lighting* *8) Clerestory Glazing* *9) Frozen Storage Compressor* *10) Cooling Set-Point*
Extremely Hot Climate Zones: (CDD > 6500; Baseline Temperature 10°C)	
1) Evaporator Fans *2) Low Absorptive Roof* *3) Walk In Walls & Ceiling* *4) Cooling Set-Point* *5) Low Absorptive External Wall*	*6) Plug Load* *7) Efficient Active Lighting* *8) Demand Defrosting* *9) Clerestory Glazing* *10) Frozen Storage Compressor*

Table 31. Descriptions of the energy efficiency measures recommended for each climate in Table 30

Clerestory Glazing	• Reduce the need for artificial lighting by using a large WWR for the clerestory glazing and lighting level sensors in the Ambient zone. • The glazing should be north facing in the northern hemisphere and south facing in the southern hemisphere. • The storage aisles should be perpendicular to the wall that contains the glazing.
Cooling Set-point	• Maintain a high cooling thermostat set-point for the Ambient zone. • Work with the building manager and owner to ensure that this set-point is used during the operation of the building.
Demand Defrosting	• Implement demand defrosting to minimize defrost heat load in both the Chilled Storage and Frozen Storage zones.

Table 31. Continued:

Efficient Active Lighting	• Reduce the power demand for the Ambient zone lighting through the use of efficient luminaries such as T8 Fluorescents or LEDs.
Evaporator Fans	• In the Chilled Storage zone, use evaporators with electronically commutated fans and minimize their operation time to decrease their energy consumption and heat load. • To keep the air well mixed while significantly reducing energy consumption, use thermal destratification fans. The evaporator fans should operate only when needed to distribute cold air from the cooling coils.
External Wall Insulation	• Use insulation on the external walls to lessen the building heating load.
Frozen Storage Compressor	• Use an energy efficient refrigeration compressor with a high COP to cool the Frozen Storage zone.
Heating Set-Point	• Maintain a low heating thermostat set-point in the Ambient storage zone • Work with the building manager and owner to ensure that these set-points are used during the operation of the building.
Low Absorptive Roof	• Use a low absorptive (highly reflective) external layer to reduce the amount of sunlight absorbed by the roof, or use passive shading methods such as solar panels to reduce the amount of sunlight that strikes the roof.
Low Absorptive External Wall	• Reduce the amount of sunlight absorbed by the external walls through the use of a low absorptive (highly reflective) external layer, or use passive shading such as vegetation to reduce the amount of sunlight that strikes the external walls.
Plug Loads	• Minimize the office plug load through an integrated design method. • Work with the building manager and owner to ensure that the office area is fitted with energy efficient equipment. • Plan a monitoring and verification strategy that measures energy consumption by end use so that occupants are aware of the impact of their plug loads. • Use methods, such as smart power strips, to automatically turn off equipment and reduce the night time power consumption of plug loads.

Table 31. Continued:

Roof Insulation	• Reduce the amount of heat loss through the roof by using roof insulation.
Walk-In Walls & Ceiling	• Reduce heat transmission through the walk-in room's walls and the ceilings of the Chilled Storage and Frozen Storage zones by the use of low U-Value SIPs.

4.9 Conclusion

This chapter presents the results of the global uncertainty and sensitivity analyses conducted. Overall, the results show that the relative importance of the parameters investigated can vary significantly as a result of climate. However, for all climates, the most influential parameter by a large margin is the Chilled Storage evaporator control strategy. Several of the other most important parameters for the warehouse are also related to the walk-in storage rooms, such as the walk in rooms' wall and ceiling U-Value, the Frozen Storage compressor COP, and the defrost control strategies implemented for the Chilled Storage and Frozen Storage zones. Yet, many of the building control and architectural parameters that are not directly related to the walk-in rooms are also significant, such as the Ambient zone temperature set-points and the warehouse clerestory window to wall ratio. This shows that the entire building, and not just the walk-in storage zones, must be taken into consideration during design. In addition, across all climates, the building control parameters are more significant than the architectural design, due to the dominance of the evaporator fan control. However, even excluding this parameter, the results show that both of these groups are important to consider during the design of an energy efficient vaccine warehouse. Lastly, the presence of significant interactions between the building control and architectural design parameters in the hotter climates examined shows the importance of including interactions to improve the understanding of sensitivity analysis results.

CHAPTER 5: CONCLUSIONS

This chapter provides the conclusions obtained from the research conducted in this thesis. First the hypothesis and research questions presented in the first chapter are addressed, and the limitations of this thesis and subsequent suggestions for future work are presented and discussed. The research in this thesis focuses on analyzing the relative importance of building control and architectural design parameters on the energy consumption of a primary vaccine warehouse. A Monte Carlo-based uncertainty analyses is conducted in order to compare the variation in the building energy consumption as a result of each of these parameter classifications. In addition, a regression-based sensitivity analysis is used to examine the main effects of the individual parameters on the warehouse energy consumption, as well as the interactions between parameter pairs. This method is applied in the form of a case study to the building layout proposed for the design of the new primary vaccine warehouse for the DSSB in Tunis, Tunisia.

5.1 Hypothesis and Research Questions

Hypothesis: <u>Building control parameters are as significant as architectural design parameters in the creation of an energy efficient primary vaccine storage warehouse.</u>

The results of the analysis for all five locations studied (Buenos Aires, Argentina; Tunis, Tunisia; Asuncion, Paraguay; Mombasa, Kenya; and Bangkok, Thailand) show that the variation in the warehouse energy consumption due to the building control parameters is larger than that from the architectural parameters. This is a result of the prevailing influence of the Chilled Storage evaporator fan control level, which for all climates was the most influential parameter examined. In all climates except for Bangkok, the Standardized Regression Coefficient for this parameter is at least three times larger than the next most influential parameter. Without the inclusion of this uncharacteristically dominant parameter, the remaining building control parameters show a lower importance in comparison to the architectural design parameters; as evaluated on the basis of the percentage of variation in the total building energy consumption accounted for by the main effects of each parameter group. However, the building control parameters are by no means insignificant. On average, the main effects of the top five building control parameters account for 22% of the variance from the uncertainty analysis, while the top five architectural parameters account for 59%. The similar magnitude of these two parameter types emphasizes the importance of an integrated design method for the creation of an energy efficient primary vaccine storage warehouse. Through the inclusion of the personnel responsible for the building post construction in the design process, the effects of variation in building control parameters during operation on warehouse energy consumption uncertainty can be reduced.

<u>What are the most influential design and building control parameters in determining the energy consumption of a Net-Zero Energy primary vaccine warehouse?</u>

Using the stepwise regression based sensitivity analysis, the relative importance of all the influential parameters investigated was established. As mentioned in addressing the hypothesis, the sensitivity analysis results show that the most influential parameter across all climate zones, within the design space investigated, is the Chilled Storage evaporator fan control. Several more of the most influential parameters also directly affect the energy consumption of the walk in storage areas, such as the walk-in wall insulation U-value and the defrosting control strategy. However, the building energy consumption in all locations also shows a high sensitivity to the architectural and building control parameters of the surrounding warehouse; two prominent examples are the roof absorptance and the warehouse clerestory WWR. The high relative importance of these type of parameters indicate that it is not sufficient to only consider the walk-in storage areas when designing a primary vaccine warehouse for energy efficiency, and that rather the entire building must be considered. In addition, the sensitivity analyses that include interaction terms were shown to be highly valuable to properly interpret the results of the main effects sensitivity analyses and guide the progression of design in the hotter climates. For instance, the main effect sensitivity analysis of Bangkok showed the high importance of both the roof insulation U-value and absorptance, potentially leading to investment in both of these energy efficiency measures. However, the interactions revealed that investment in reducing the roof absorptance rendered further investment in the roof insulation U-value null.

<u>How does the relative importance of design and operational control parameters vary across the prominent climates of the developing world?</u>

The sensitivity analyses conducted show that the relative importance of many of the parameters investigated varies significantly as the climate changes. This is largely a result of the dominance of the warehouse cooling temperature set-point and the external wall and roof parameters as the climate warms. The high influence of these parameters, particularly the roof absorptance and the warehouse cooling set-point temperature, decreases the relative importance of many of the remaining parameters examined. In general, as the climate warms, the amount of the variance that is accounted for by the main effects of the five most influential building control parameters (disregarding the evaporator fan control level) increases. This is solely a result of the dominance of the warehouse cooling temperature set-point, as the relative importance for all other building control parameters decreases as the climate warms.

In the process of answering the research questions and hypothesis, this thesis presents a method that can be implemented during the design process to assist in the creation of an energy efficient primary vaccine warehouse. The method can be used by a design team to explore the design space of energy conservation measures for the warehouse, and prioritize the measures with the highest potential for reducing energy consumption. This allows resources to be focused on the most influential parameters early in the design process, as the conceptual design phase is the most important for reducing building energy consumption. For design teams that are unable to implement this method, the results of the analysis for the case study building have been generalized and converted into easy to follow guidelines.

5.2 Limitations and Future Work

The results and conclusions from this research are limited to the specific building type of a primary vaccine warehouse, as well as large regional warehouses that store product in walk-in cold rooms and freezer rooms. Due to the combination of multiple temperature zones and their relative sizes, the results are not applicable to similar building genres such as grocery stores or refrigerated warehouses without modification. District vaccine stores and health clinics are also not within the relevant scope, as the refrigeration employed to keep vaccines at temperature in these smaller facilities is not comparable to the equipment used in primary warehouses. This research is also limited to moderate and cooling dominated climates, as no heating dominated climates are investigated. Therefore it is recommended that a similar study for heating dominated climates be conducted, as currently there is no research to aid the energy efficient design of primary vaccine warehouses in these types of locations. An additional limitation of this research in this thesis is that it does not account for other important building design criteria such as occupant thermal comfort. While interpreting the results of this research, it must be kept in mind that all of the design suggestions are only within the scope of reducing the building energy consumption. Therefore, while parameters such as natural ventilation have shown little effect on building energy consumption, they may substantially affect other building performance criteria. Thus, future work on primary vaccine warehouse design should investigate criteria other than energy consumption for this building type.

While global uncertainty and sensitivity analysis is a very appropriate method to examine the relative influence of a large number of design parameters in a research context, its application in design practice is currently limited. As several of the papers from this thesis' literature review discuss, a relatively large amount of time is required to setup and run the analysis due to the lack of design tools incorporating this type of analysis. This large time investment and lack of software that easily integrate with the design process currently hinder the implementation of this method. Therefore, future work that builds onto the method of this thesis should investigate reducing the time that is required to setup and execute a global design parameter sensitivity analysis. In addition, more research on the integration of uncertainty and sensitivity analysis into design practice is needed.

This study is also limited by a lack of information for establishing relevant uncertainty bounds for the parameters examined, in particular the building control parameters. For many of these, only a handful of sources could be found, and so best judgment was used to determine which should be used for upper and lower bounds. Due to the lack of this type of information, more research examining the uncertainty of building control parameters is needed, so that unrealistic bounds for uncertainty do not lead to meaningless results.

Lastly, while this thesis shows the large amount of energy that can be saved through the implementation of thermal destratification fans, the impact of the research is limited by the assumption that the use of thermal stratification fans does not result in a loss of product quality. Currently, there are no experimental studies in the literature that validate that thermal destratification fans ensure well mixed air in vaccine storage facilities. Due to the extremely high value of the vaccines stored in comparison to building energy costs, it is not likely that any efficiency measure which sacrifices product quality will be implemented. Therefore, future experimental research is needed to determine whether the use of thermal destratification fans results in any noticeable decrease in product quality. This could help to significantly improve the energy efficiency of new vaccine warehouses conducted, as well as encourage retrofits for already existing buildings.

APPENDIX A: WAREHOUSE DRAWINGS

This Appendix includes all of the drawings completed my Mr. Andrew Garnett for the NZE primary vaccine warehouse design proposed to the DSSB (Garnett, 2013).

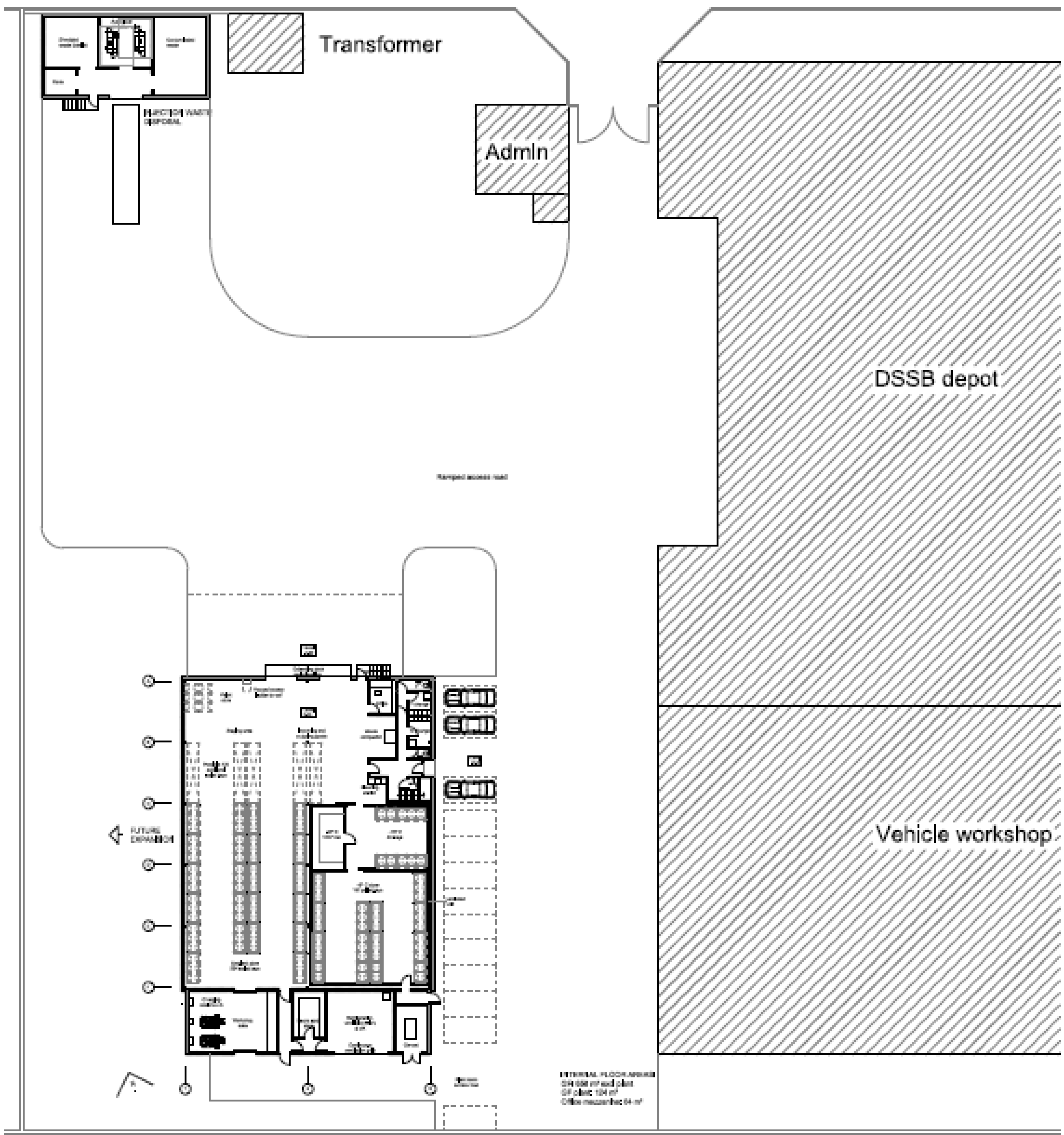


Figure 44. Building Site plan

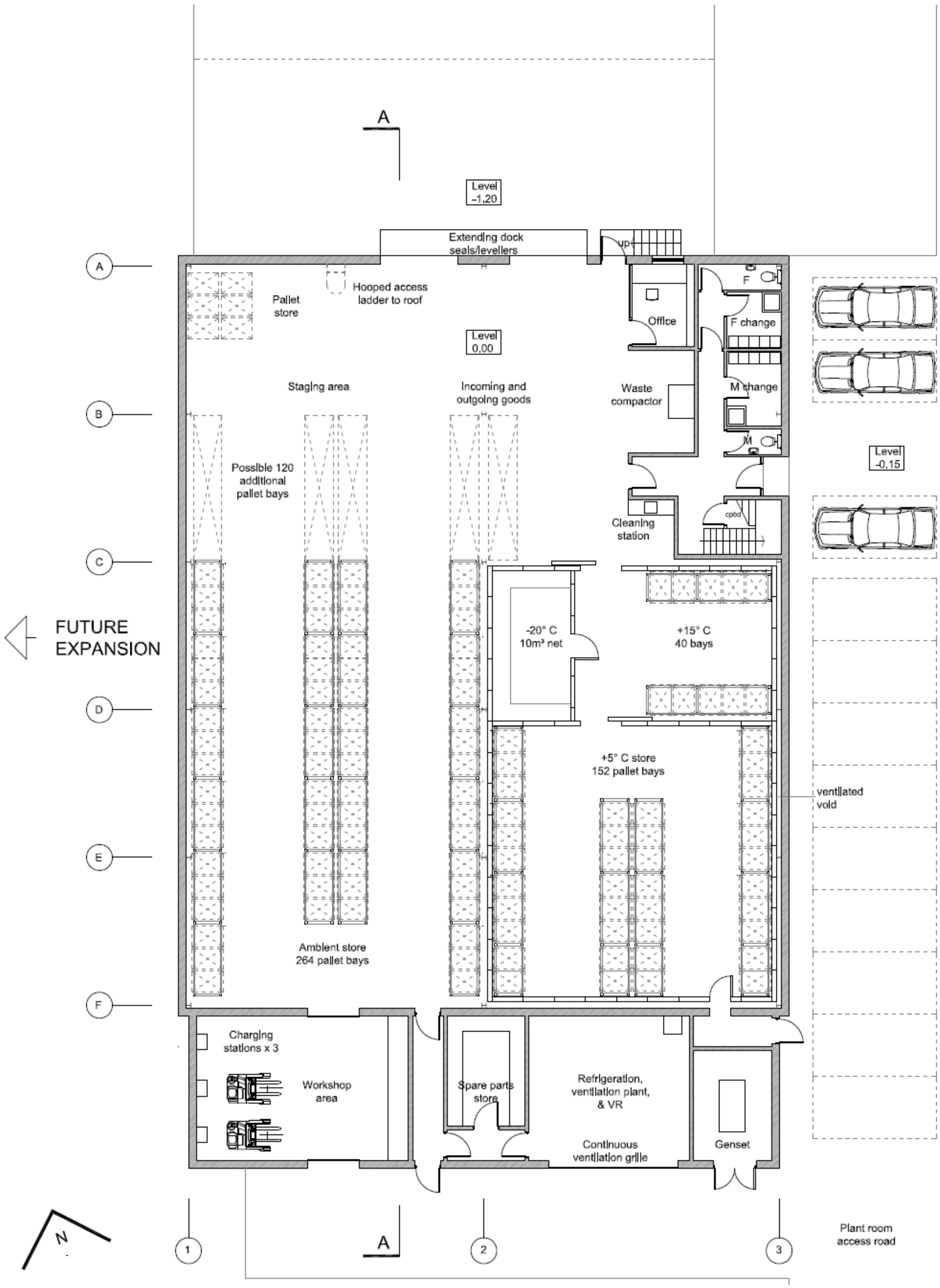


Figure 45. Ground Floor Plan

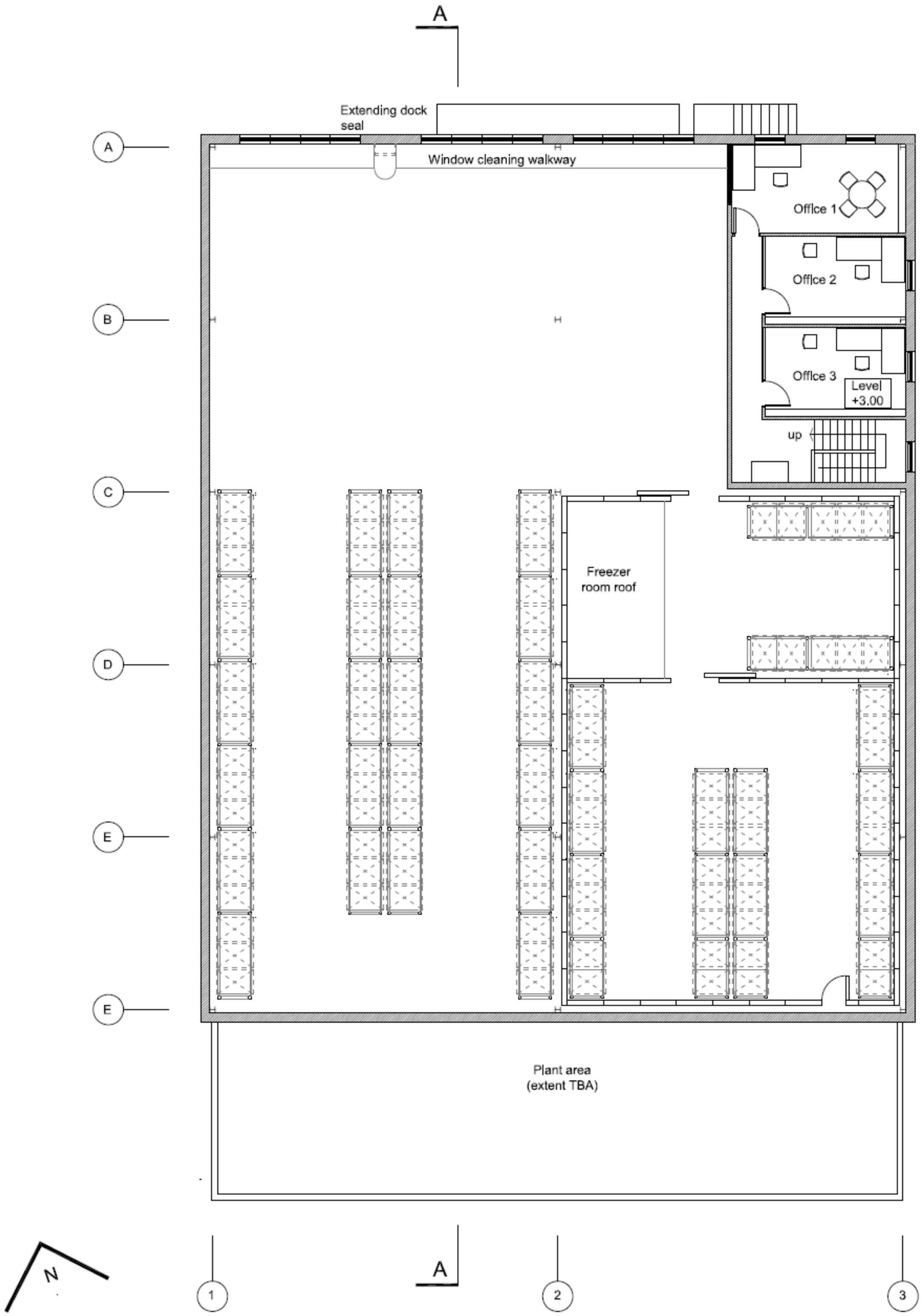


Figure 46. First floor plan

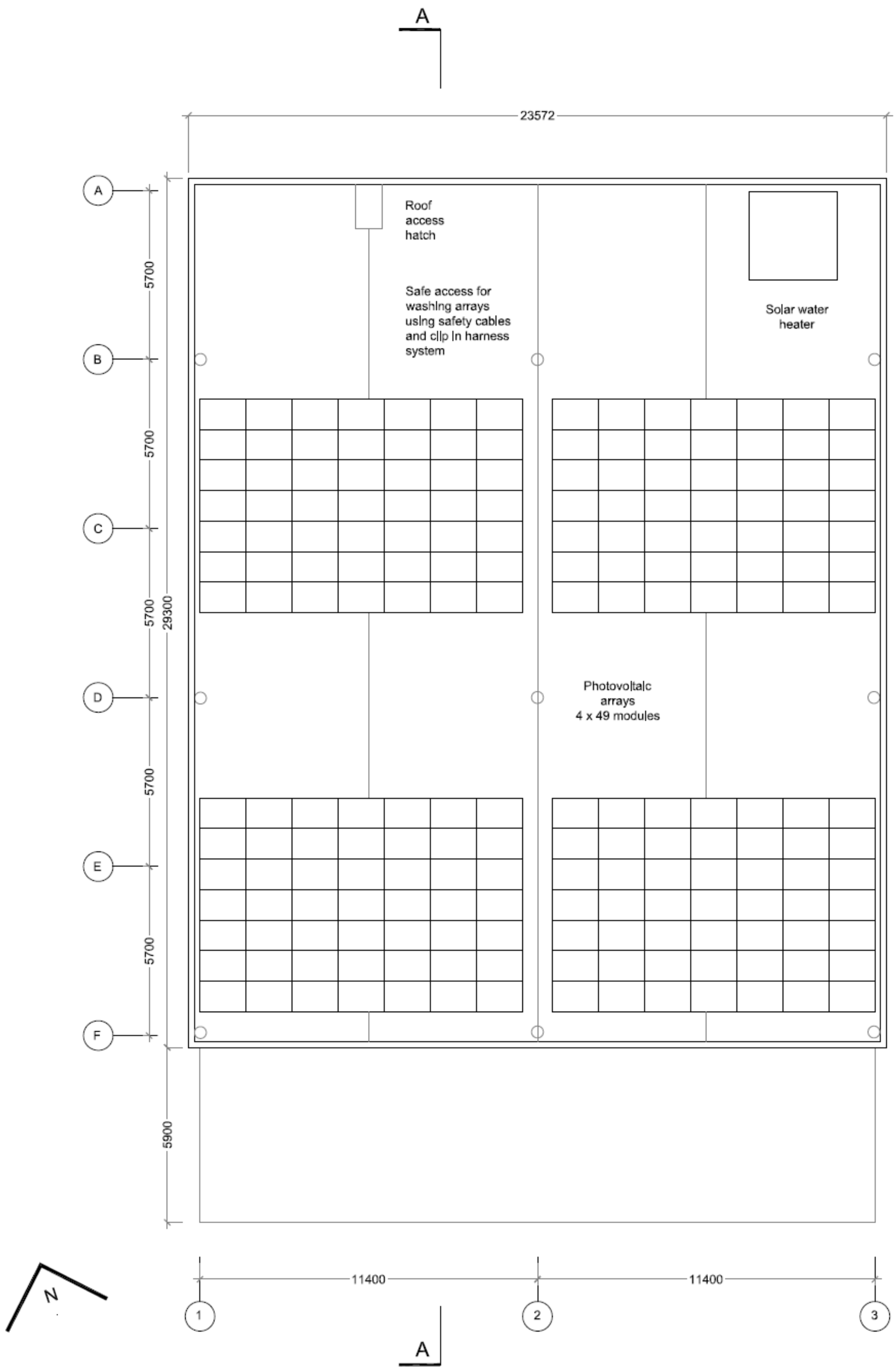


Figure 47. Roof Plan

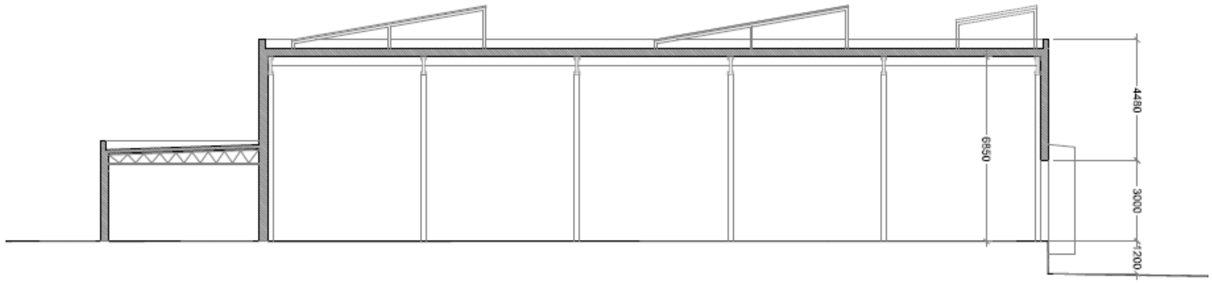


Figure 48. Section View, A-A

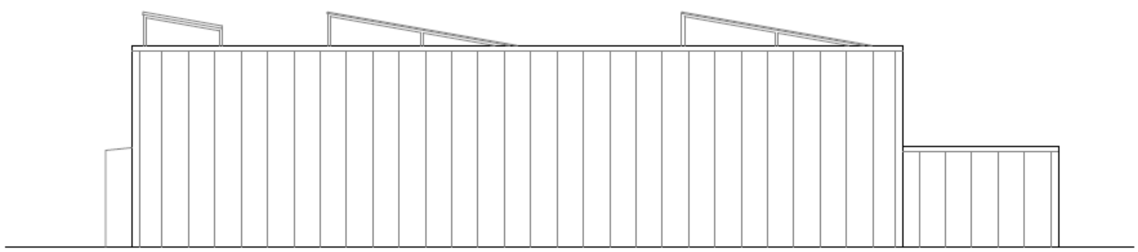


Figure 49. West Elevation

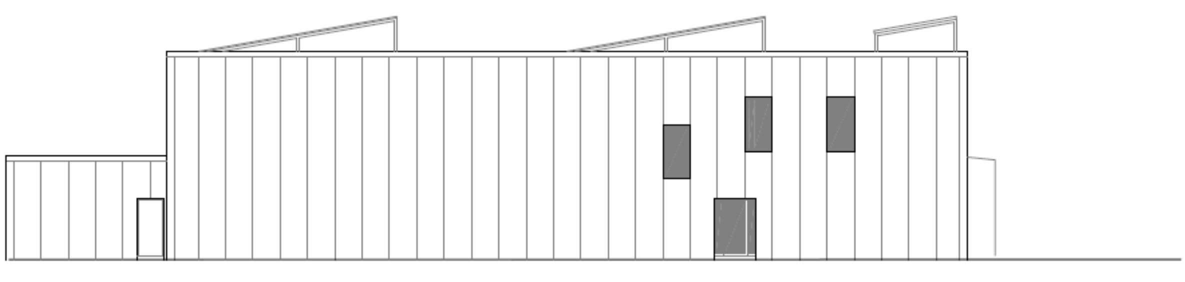


Figure 50. East Elevation

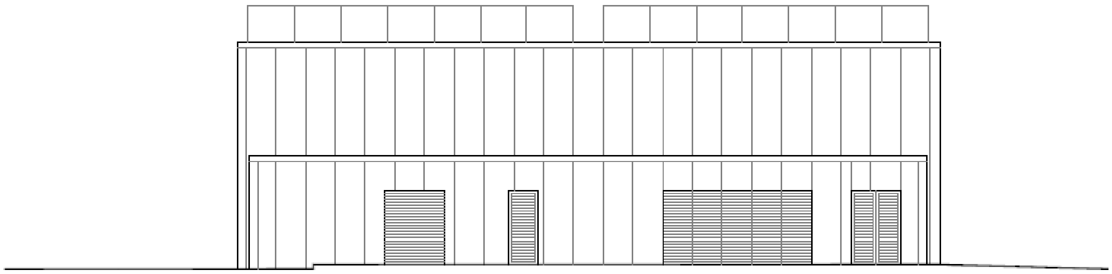


Figure 51. South Elevation

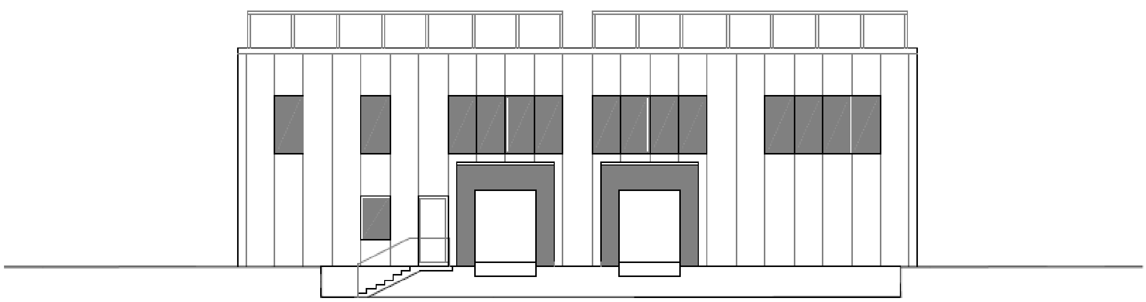


Figure 52. North Elevation

APPENDIX B: BUILDING ENERGY MODEL SCHEDULES

This appendix contains all of the baseline schedules implemented for the warehouse building energy model. Unless otherwise noted, these are the schedules used for simulation.

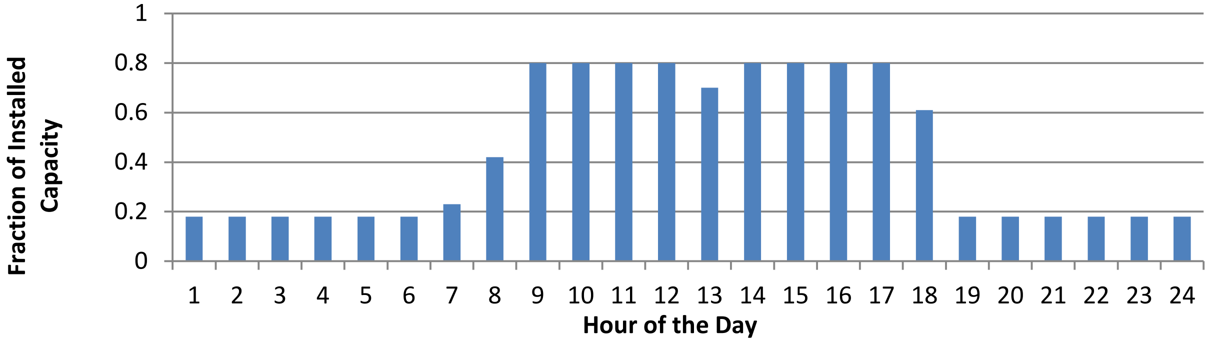


Figure 53. Weekday lighting schedule

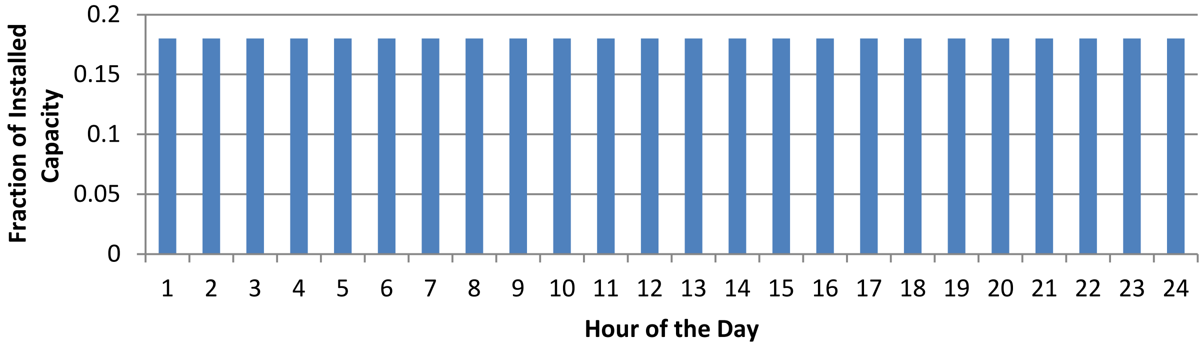


Figure 54. Weekend lighting schedule

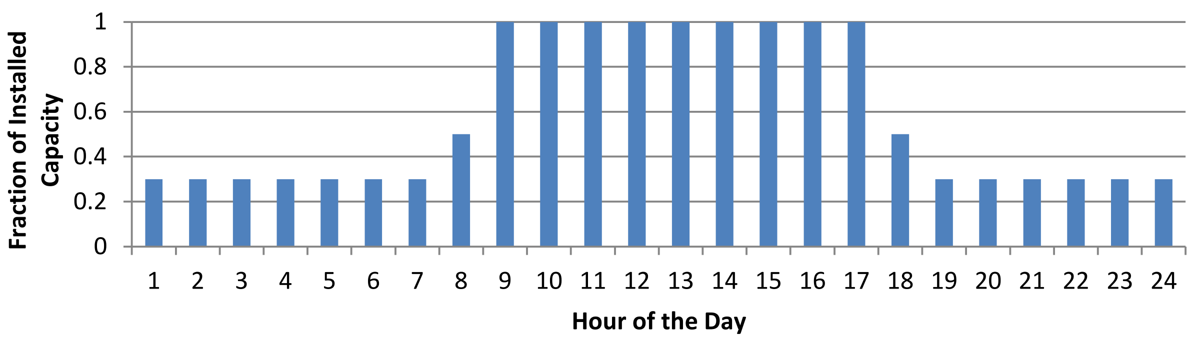


Figure 55. Weekday office equipment schedule

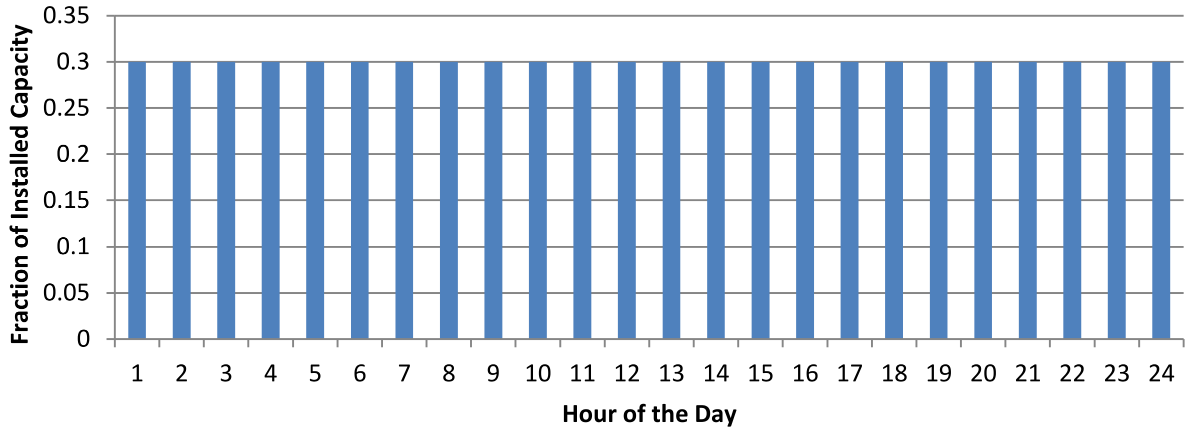


Figure 56. Weekend office equipment schedule

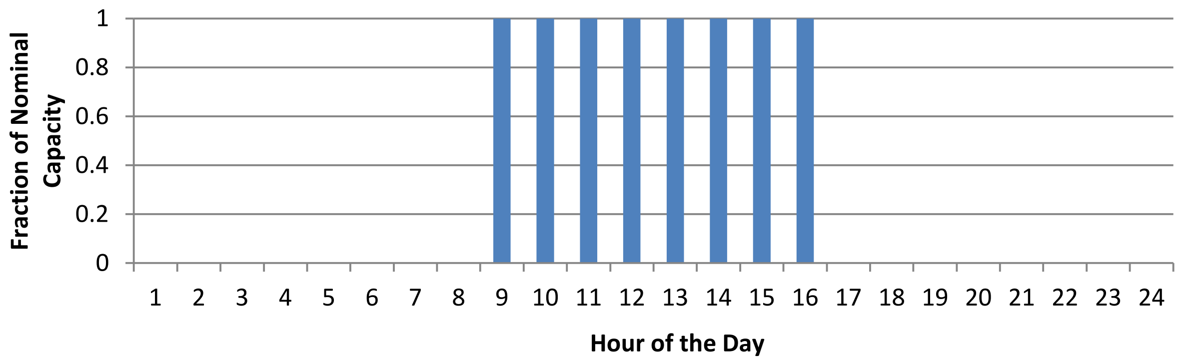


Figure 57. Weekday fork lift operation schedule

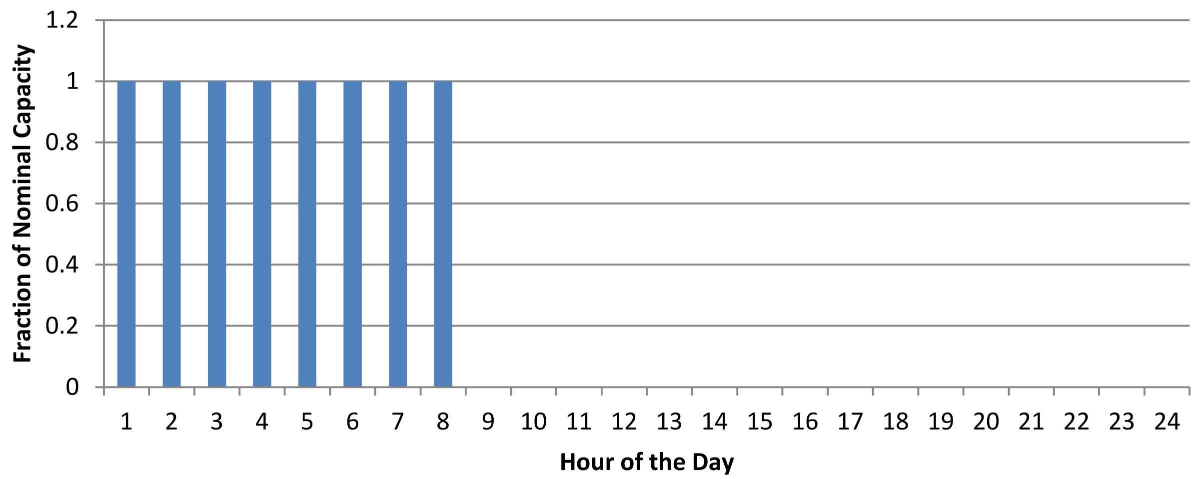


Figure 58. Weekday fork lift charging schedule

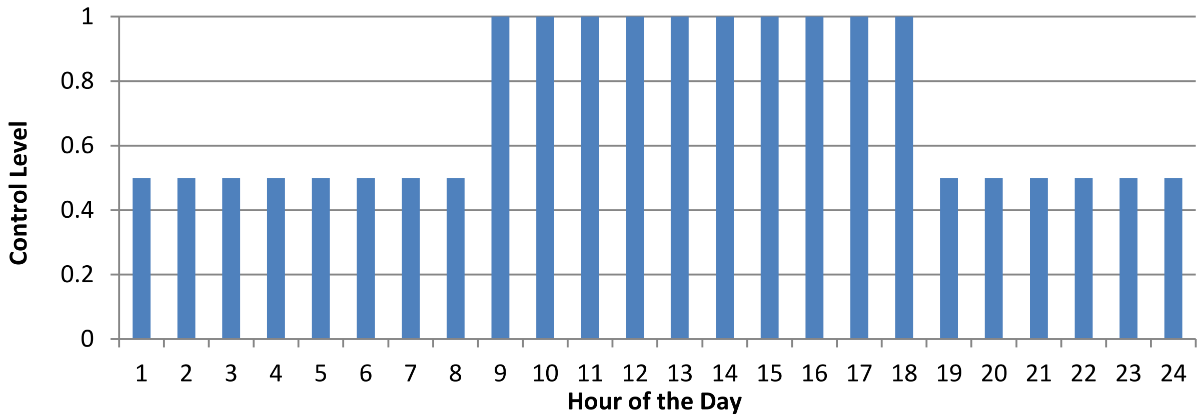


Figure 59. Control level for mezzanine heating and cooling set-points; 0.5 indicates setback

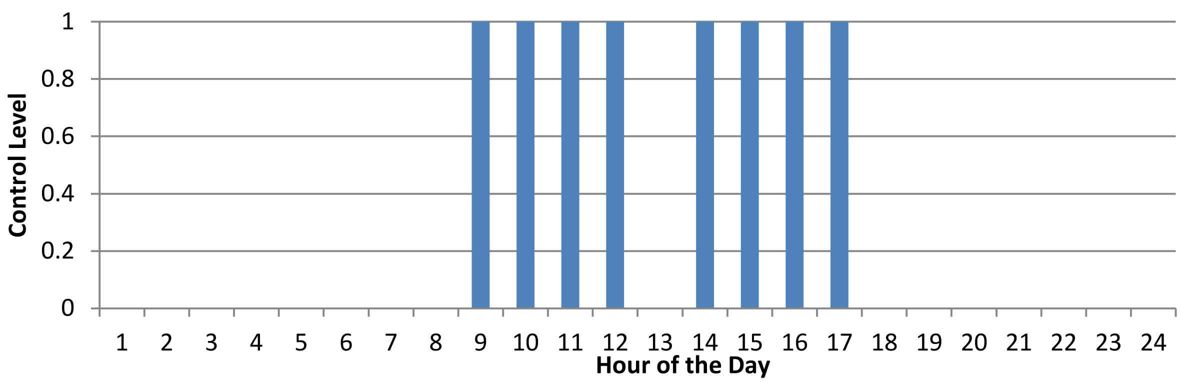


Figure 60. Walk-in door infiltration level; A control level of 1 indicates the hours mixing between zones is assumed to occur due to the walk-in doors opening

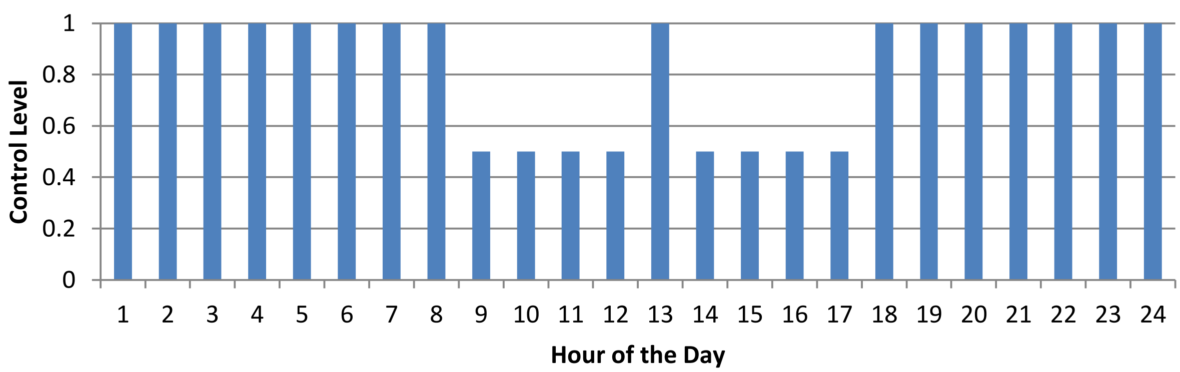


Figure 61. Chilled Storage and Frozen Storage evaporator fan control level; Control level of 0.5 indicates reduced fan load due to opening of walk-in doors, while control level of 1 indicates fans operate at full capacity

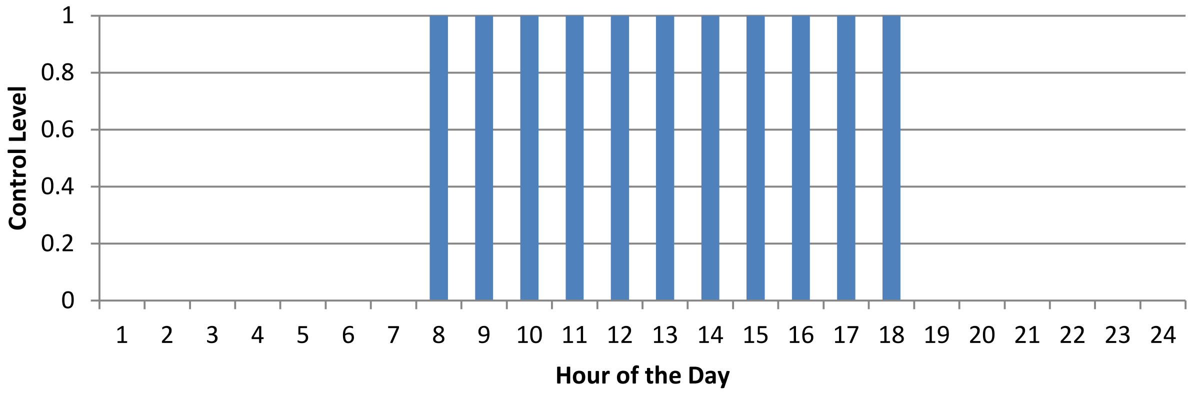


Figure 62. Workday Warehouse Ventilation Schedule; Control level 1 signifies active ventilation

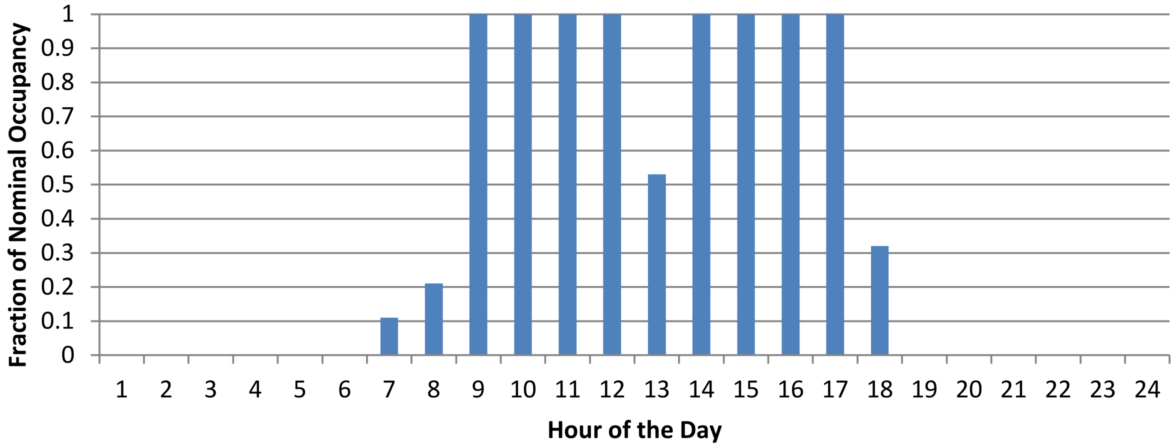


Figure 63. Workday warehouse occupancy

APPENDIX C: PCT DOOR OPENING DATA

Table 32. The weekly average door opening percentages recorded during 2013, used in the annual energy projections to compare the baseline and improved scenarios (Pudleiner et al., 2014)

Week	Public Storage Door Open Time (% Open)	Private Storage Door Open Time (% Open)	SAS Door Open Time (% Open)
07.01.2013	2.40%	3.42%	4.92%
14.01.2013	0.43%	0.02%	0.75%
21.01.2013	0.04%	0.03%	0.22%
28.01.2013	0.23%	0.23%	0.27%
04.02.2013	2.55%	9.07%	3.53%
11.02.2013	5.98%	23%	14.26%
18.02.2013	7.21%	8.47%	14.23%
25.02.2013	8.91%	7.48%	12.45%
04.03.2013	5.45%	9.90%	10.67%
11.03.2013	4.10%	7.88%	9.14%
18.03.2013	5.73%	7.49%	10.51%
25.03.2013	5.74%	4.35%	8.56%
01.04.2013	9.10%	11.71%	15.81%
08.04.2013	3.93%	4.16%	7.63%
15.04.2013	4.78%	7.33%	19.13%
22.04.2013	2.41%	6.47%	28.49%
29.04.2013	4.52%	6.33%	8.10%
06.05.2013	5.78%	9.55%	13.72%
13.05.2013	4.36%	11.10%	13.72%
20.05.2013	4.02%	8.40%	11.48%
27.05.2013	3.80%	7.15%	9.13%
03.06.2013	6.73%	8.04%	12.38%
10.06.2013	3.07%	7.17%	10.30%
17.06.2013	4.16%	5.90%	9.75%
24.06.2013	3.54%	7.56%	10.43%
01.07.2013	4.49%	10.47%	15.63%
08.07.2013	3.27%	6.44%	8.84%
15.07.2013	1.77%	7.67%	8.98%
22.07.2013	2.70%	7.04%	8.79%
29.07.2013	2.55%	5.59%	7.58%
05.08.2013	1.60%	3.84%	5.49%
12.08.2013	1.60%	3.84%	5.49%
19.08.2013	2.42%	5.77%	8.16%
26.08.2013	6.87%	9%	12.17%

Table 32. Continued:

02.09.2013	3.36%	7%	9.99%
09.09.2013	4.44%	8.73%	10.85%
16.09.2013	5.46%	9.21%	13.49%
23.09.2013	3.25%	7.86%	10.80%
30.09.2013	3.09%	6.95%	9.49%
07.10.2013	13.25%	10.29%	18.17%
14.10.2013	12.55%	7.17%	15.05%
21.10.2013	2.70%	4.37%	6.91%
28.10.2013	6.22%	9.40%	12.28%
04.11.2013	7.46%	5.92%	11.15%
11.11.2013	10.02%	7.21%	12.20%
18.11.2013	11.23%	7.68%	12.65%
25.11.2013	8.01%	8.55%	10.97%
02.12.2013	7.21%	13.36%	9.89%
09.12.2013	8.39%	33.04%	16.80%
16.12.2013	8.12%	10%	13.63%
23.12.2013	5.70%	7.51%	10.60%
30.12.2013	7.18%	7.51%	10.60%

APPENDIX D: BUILDING EQUIPMENT DATA SHEETS

This appendix contains the data sheets that support the assumptions for the equipment implemented in the building energy model.

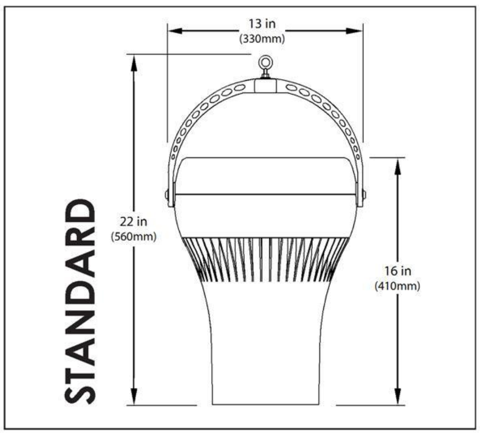
Air Pear®
BY AIRIUS MAR 2011
MasterFormat: HVAC Fans - 23 34 00

Air Pear® THE THERMAL EQUALIZER BY AIRIUS

Page 1 of 4

Model 25

25-120V
25-230/277V



MODEL 25 FEATURES

DESCRIPTION

- *De-stratification Fan/Air turbine*
- *Designed to deliver columnar laminar flow of air from ceiling to floor*

USES

- *Used to de-stratify/thermally equalize buildings*
- *Used to equalize humidity*
- *Used to increases thermal comfort during summer and winter*
- *Used in suspended ceilings with optional kit*
- *Used to reduce ceiling temperature to extend life of lighting ballasts*
- *Optional accessories to adapt unit to varying requirements and conditions*

ATTRIBUTES AND CHARACTERISTICS

- *Columnar laminar flow*
- *Easy installation*
- *Fractional amp draw*
- *Quiet & energy efficient operation*
- *Free hanging, unit can be angled up to 90˚ off vertical*
- *Long throw*

SELECTION

- *Reduce energy consumption up to 30%*
- *Air curtain alternative in many retail applications*
- *Can be used in low/suspended ceilings*
- *30 to 35 watt Energy efficient operation*
- *Capable of Temperature balance within 0˚ to 3˚ F*
- *Mounting height up to 25 feet*
- *Contact manufacturer for a selection consultation*

SUSTAINABILITY

- *Meets LEED EA Credit - Optimize Energy Performance*
- *Made from recyclable materials*
- *Recyclable corrugated packaging*

CODE APPROVAL

- *Conforms to Underwriters Laboratories Standard 507 for Safety Electric Fans*
- *Edison Testing Laboratories certified fan and components*
- *5VA flame resistance rating*
- *RoHS compliant*

PERFORMANCE

- *Standard model capable of covering up to 1200 ft² or a 40 ft coverage diameter*
- *Capable of temperature control within 0˚ to 3˚ F with proper array/density of units*
- *Performance and results of the Air Pear are subject to many variables such as, but not limited to, the interior environment, exterior environment, conditions of building structure, HVAC system performance and/or electrical service and thus actual results may vary*

SHIPPING & HANDLING

- *Product will ship based on availability, contact manufactuer or reseller*
- *All products are shipped FOB factory*

WARRANTY

- *Warranty offered - 3-year from shipping date*
- *Money back guarantee - 30 days*
- *Refurbish program after 3-year warranty period*

Figure 64. Airius Air Pear Model 25 thermal destratification fan technical datasheet

Customer
Date 10/05/2013
Project
Reference
Quotation No

Stefani S.p.A.
Via del Lavoro, 9
Castegnero (VI) - ITALY
Tel. +39 0444 639 999
Fax. +39 0444 638 240

EVAPORATOR
Model 1 x SHCN 050/2 E 6 E 4D EC

Capacity	21,7	kW	Refrigerant	R404A	
Air Inlet Temperature	2,0	°C	Evaporating Temperature	-5,0	°C
Air Outlet Temperature	-0,9	°C	Superheating	5	K
Relative Humidity In	87	%	Condensing Temp	55,0	°C
Relative Humidity Out	100	%	Subcooling	0	K
Altitude	0	m			

Air Flow	16650	m³/h	RPM rate	100	%
Air throw	42,5	m	Fan Speed	1600	1/min
Number fans	2		Noise Power Level	84	dB(A)
Fan Diameter	500	mm	Noise Pressure Level ISO 3744	58	dB(A) at 5 m
Voltage	400	V	Power comsumption	1880	W
Frequency	50	Hz	Nominal Power	1880	W
Power Supply	EC Fan Three Phases		Nominal Current (*)	3,2	A

Surface	73,7	m²	Tubes	Copper	
Internal Volume	19,0	dm³	Fins	Aluminium	
Fin Spacing	6,0	mm	Casing	Aluminium / Galvanized steel painted	
Weight	128	kg	Length	1922	mm
Connections IN	28 mm		Height	861	mm
Connections OUT	42 mm		Width	591	mm
			PS	30	bar

Defrosting	Electric	8,4 kW

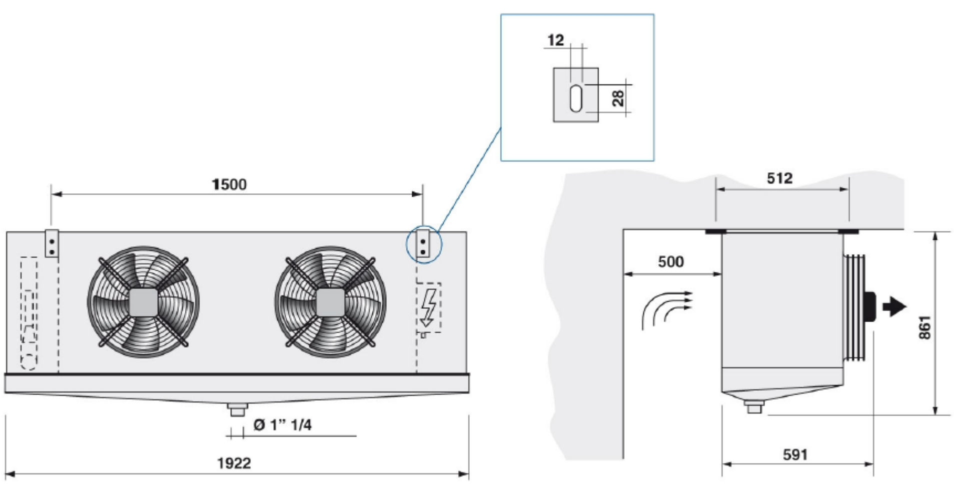


Figure 65. Stefani SCHN-0502 data sheet used for Chilled Storage evaporator assumptions

forget your habits

Modello Model Type Modèle	Potenza - Capacity Leistung - Capacité		Portata aria Air flow Luftvolumenstrom Débit d'air	Superficie - Surface Fläche - Surface	Freccia aria - Air Throw Wurfweite - Jet air	Livello di pressione sonora (5m) Noise pressure level (5m) Pression acoustique (5m) Schalldruckpegel (5m)	Ventilatori - Fans Ventilatoren - Ventilateurs		Sbrinamento elettrico Electric defrosting Elektrisch Abtauung Électrique dégivrage	Connessioni Connection Anschluß Raccord		Volume tubi - Tubes volume Rohrvolumen - Volume tubes	Peso -Weight - Gewicht - Poids
	SC2, R404A, Tair = 0°C DT1 = 8K	SC3, R404A, Tair = -18°C DT1 = 7K					N X Ø	Caratteristiche Features Kennzeichnen Caractéristiques		Ingresso - Inlet Eintritt - Entrée	Uscita - Outlet Austritt - Sortie		
	kW	kW	m³/h	m²	m	dB(A)	mm	1ph/230V - 50Hz	W	mm	mm	dm³	kg
4 mm - PASSO ALETTE - FIN SPACING - ÉCARTEMENT AILETTES - RIPPENABSTAND													
SHCP 035/1 C4	3,9	2,9	2400	16	19	52	1x350	130W - 0,58A - 1400 1/min	1480	12	22	1,8	28
SHCP 035/1 E4	4,6	3,2	2150	23	18	52	1x350		1850	12	22	2,7	31
SHCP 035/2 C4	7,7	5,5	4800	31	22	55	2x350		3000	12	28	3,6	47
SHCP 035/2 E4	9,5	6,6	4350	47	21	55	2x350		3750	16	28	5,3	54
SHCP 035/3 C4	11,5	7,9	7250	47	25	56	3x350		4480	16	28	5,3	67
SHCP 035/3 E4	14,4	10,1	6500	70	24	56	3x350		5600	22	35	8,0	77
SHCP 035/4 C4	15,7	11,2	9650	62	28	57	4x350		5960	22	35	7,1	86
SHCP 035/4 E4	19,6	14,1	8650	93	27	57	4x350		7450	22	42	10,7	100

Figure 66. Stefani SHCP-0353 data sheet used for Frozen Storage evaporator assumptions

APPENDIX E: UNCERTAINTY ANALYSIS DISTRIBUTIONS

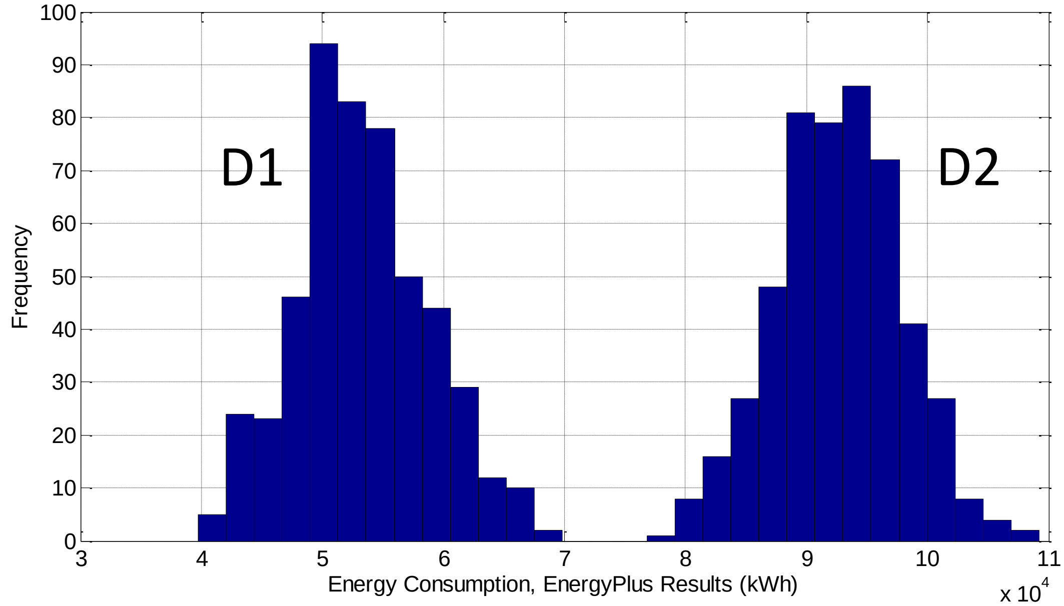


Figure 67. Uncertainty analysis distribution; Tunis

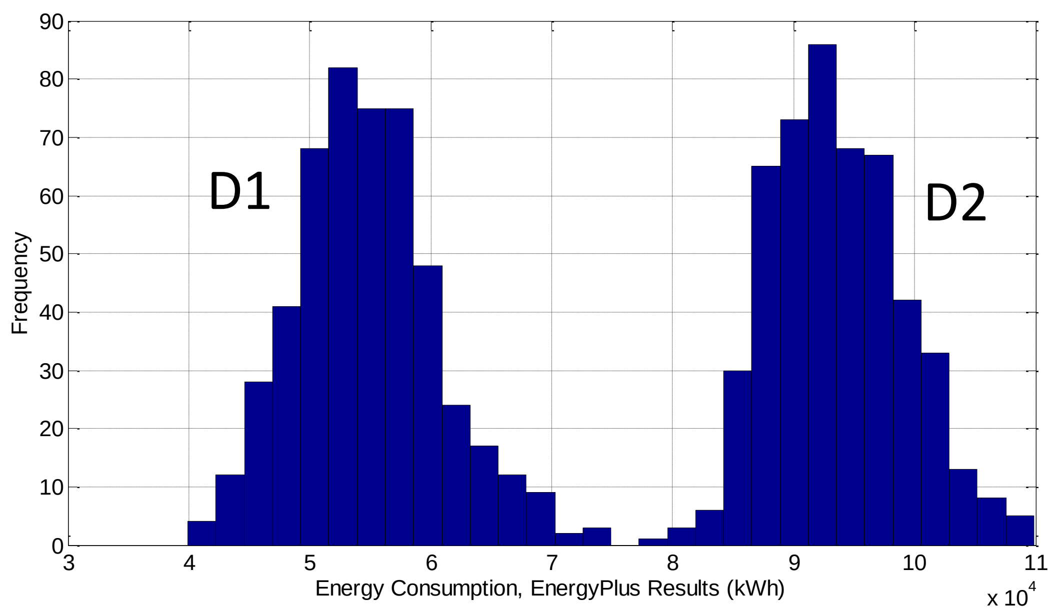


Figure 68. Uncertainty analysis distribution; Buenos Aires

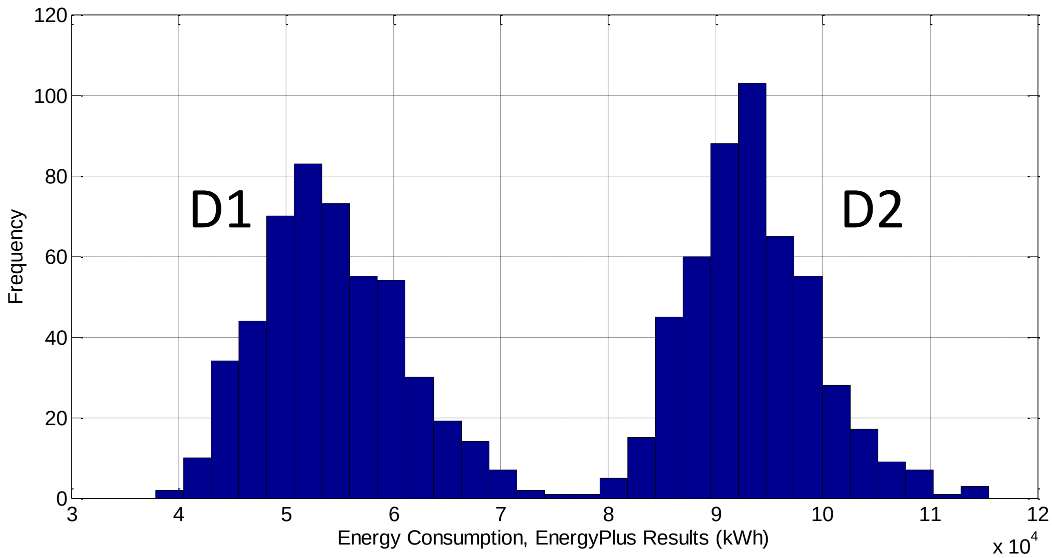


Figure 69. Uncertainty analysis distribution; Asuncion

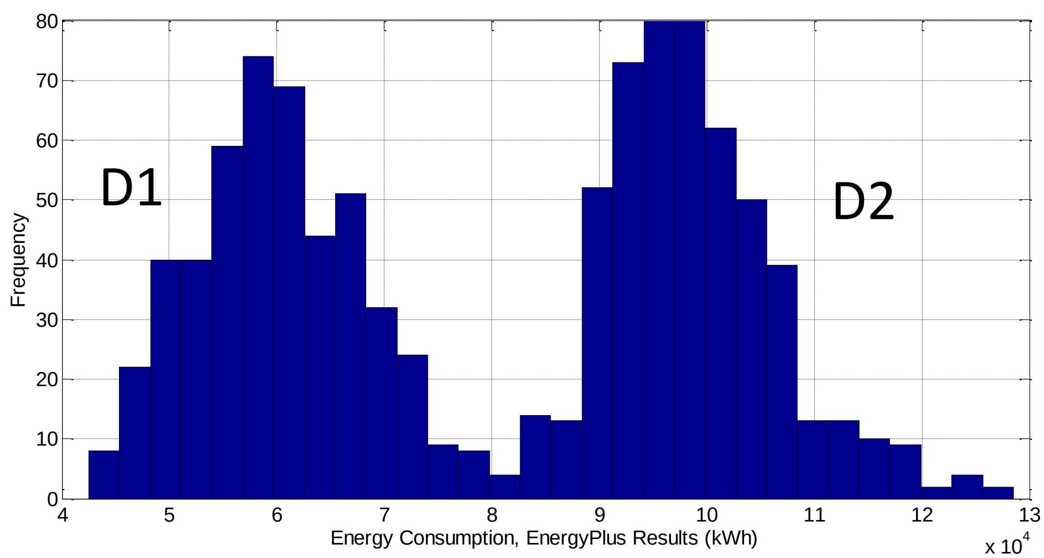


Figure 70. Uncertainty analysis distribution; Mombasa

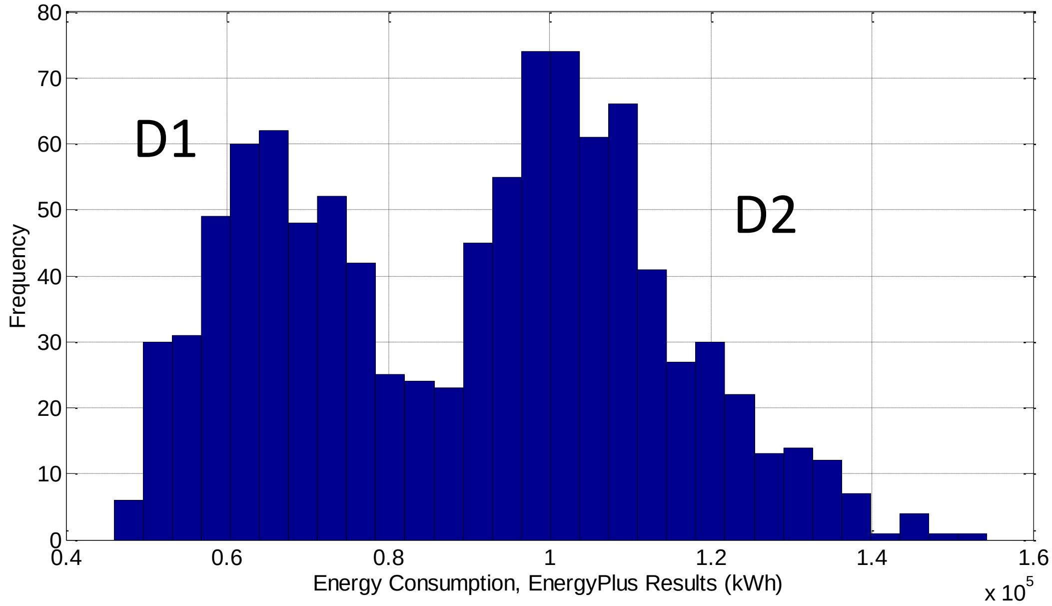


Figure 71. Uncertainty analysis distribution; Bangkok

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