A SIMULATION-OPTIMIZATION METHOD FOR ECONOMIC EFFICIENT DESIGN OF NET ZERO ENERGY BUILDINGS

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A SIMULATION-OPTIMIZATION METHOD FOR ECONOMIC EFFICIENT DESIGN OF NET ZERO ENERGY BUILDINGS

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NOMENCLATURE

ANME	Agence Nationale pour la Maîtrise de l'Energie (Translation: National Agency for Energy Conservation)
BIMS	Building Information Management System
CCA	Cloud Cover Average
CDD	Cooling Degree Day
COP	Coefficient of Performance
CSV	Comma-separated values
DoE	Department of Energy
DOE	Design of Experiment
EEM	Energy Efficiency Measures
EPS	Expanded Polystyrene
GA	Genetic Algorithm
HDD	Heating Degree Day
HVAC	Heating, Ventilation and Air Conditioning
LCA	Life Cycle Analysis
LCC	Life Cycle Cost
MOGA	Multi-Objective Genetic Algorithm
NREL	National Renewable Energy Laboratory
NZE	Net Zero Energy
NZEB	Net Zero Energy Buildings
OSB	Orientated Strand Board
PV	Photovoltaic
ROI	Return on Investment
SDK	Software Development Kit
SHGC	Solar Heat Gain Coefficient

SIP	Structurally Insulated Panel
SSC	SAM Simulation Core
STEG	Société Tunisienne de l'Electricité et du Gaz (Translation: Tunisian Electricity and Gas Company)
WHO	World Health Organization

SUMMARY

Buildings have a significant impact on energy usage and the environment. Much of the research in architectural sustainability has been centered on economically advanced countries because they consume the most energy and have the most resources. However, sustainable architecture is important in developing countries, where many buildings are poorly built and, as a result, are wasteful of energy. One large problem in developing countries is vaccine storage. Vaccines and drugs in many low and middle income countries are typically warehoused in old buildings that are poorly designed and wasteful of energy. Studies using building energy optimization for warehouses are scarce and the lack of research makes it difficult to find recommendations for the design of an energy efficient vaccine warehouse.

The goal of this thesis is to create and study a decision support tool that can be used to aid in the design of an economically feasible Net Zero Energy vaccine warehouse for the developing world. Net Zero Energy (NZE) is when the amount of energy that a building consumes on-site over the course of a year is equal to or less than the amount of renewable energy generated on-site. The decision support tool will investigate two different optimization techniques combined with a building performance simulation program to determine the optimal building parameter values. To test the effectiveness of this tool, a hypothetical building located in Tunis, Tunisia is used. The building is designed to be the new national vaccine storage facility for Tunisia. Nine building parameters are investigated to see which have the most significant effect on the annual energy usage and initial construction cost of the building.

First, the optimal design of the warehouse was investigated using two construction techniques, common construction practices for the developed world and for the developing world. The optimal results had a similar annual energy usage for the two constructions techniques and produced a 58.41% energy savings for the developed country construction and 55.67% energy savings for the developing country construction when compared to a reference case. Then, the effect of climate on the optimum building parameters was investigated. The

results from these tests were used to correlate the optimum building parameters to climatic conditions including, cloud cover range, heating degree days (HDDs), and cooling degree days (CDDs). It was found that the suggested exterior wall insulation thickness and freezer room floor insulation thickness correlated to the number of CDDs; whereas the suggested freezer room floor insulation thickness and air infiltration rate correlated to the number of HDDs. The suggested roof insulation thickness correlated to HDDs and the cloud cover range. A design of experiments (DOE) was used to investigate the interactive effects of the parameters that did not correlate to climatic conditions. The coefficient of performance of the HVAC system, cold storage insulation thickness, roof reflectivity, and efficiency of the windows were found to correlate to a combination of climatic conditions and other building parameters. The final test showed the benefits of combining two optimization techniques, a Design of Experiments (DOE) and a Genetic Algorithm (GA), to aid in the building design in the early stages and final stages of the design process.

Currently, there are few resources to help design an energy efficient, cold storage warehouse and even less resources to help design energy efficient buildings in developing countries. The decision support tool proposed in this thesis uses proven optimization methods and free simulation programs in order to make a useful and practical tool to aid developing countries in the design of NZE buildings. The GA options chosen proved to make the tool computationally faster than previous methods while still finding the global optimal solution. The case study's results were used to provide generalized climatic recommendations, and these recommendations will be beneficial for designers who wish to create an economical energy efficient vaccine warehouse. In conclusion, this thesis provides a decision support tool and generalized construction recommendations to aid in the design of an economically feasible NZE vaccine warehouse for the developing world.

CHAPTER 1

INTRODUCTION

This chapter introduces the thesis. First, the research motivation will be described. This includes the importance of Net Zero Energy buildings and the reason for focusing this thesis on developing countries. Then, the problem under investigation will be defined. Finally, the scope of work for this thesis will be outlined.

1.1 Research Motivation

Buildings have a significant impact on energy usage and the environment. Commercial and residential buildings use almost 40% of the primary energy and approximately 70% of the electricity in the United States (Pless and Torcellini 2010). A new approach to mitigate the energy demands from the building sector is the concept of a Net Zero Energy Building (NZEB). Net Zero Energy (NZE) can be defined as when the amount of energy that a building consumes on-site over the course of a year is equal to or less than the amount of renewable energy generated on-site. A NZEB is designed to greatly reduce operational energy needs so that the renewable technology needed to accomplish NZE is economically feasible.

Much of the research in architectural sustainability has been centered on economically advanced countries because these consume the most energy and have the most resources. However, sustainable architecture is important in developing countries, where many buildings are poorly built and as a result are wasteful of energy. Also, the energy consumption of the building sector in many developing countries is increasing significantly. For example, in the country of Tunisia, the residential and commercial building sector is expected to be the highest energy consumer in the country by 2020 (Daouas 2011).

One large problem for developing countries is vaccine storage. Vaccines and drugs in many low and middle-income countries are warehoused in old buildings within crowded

Ministry of Health compounds. The logistics systems and supply chains in most low and middle income countries were developed some thirty years ago, before the availability of new technologies and systems solutions for improved vaccine management and at a time when the cost for all vaccines that were administered to children combined was less than one dollar. To face the needs of tomorrow, supply chain systems must accommodate the increasing volumes of goods and be adapted to the needs for new vaccines (PATH 2013).

Studies on energy efficient warehouses are scarce because the focus when designing low-energy buildings is typically on residential buildings. Domestic buildings usually present a more straight-forward design problem than more complicated commercial building types. In the commercial building sector, refrigerated warehouses have one of the highest electric energy usage intensities (Faramarzi, Colburn et al. 2002). Due to the high energy usage of refrigerated warehouses, they provide a large potential for energy savings. If NZE warehouses can be provided to low and middle income countries, which typically have challenging climates, then this will help ensure that vaccines will be stored safely and effectively.

1.2 Problem Definition

At a time of increasing demand for vaccines and drugs and of rapidly rising energy costs, a NZE warehouse can eliminate the energy costs for the storage and distribution of vaccines and drugs. This is true for all countries, but can provide the most help to low and middle income countries. There are examples of NZEBs that have been constructed, which show that the concept is feasible (Kapsalaki, Leal et al. 2012). However, it has not been proven that the design choices, besides being technically effective, efficiently utilize economic resources. Finding cost-optimal minimum energy performance requirements and NZEB solutions is an arduous task. It requires exploring a large number of design solutions, which are combinations of energy saving measures and energy supply systems, under a comparative framework.

The first step in designing a NZEB is to minimize its energy usage. Several design features can affect the energy usage of the building, including the shape of the building, wall and roof construction, foundation type, insulation levels, window type and area, thermal mass, and shading. It is important to develop decision support tools that allow building designers to identify the combination of design variables, from the millions of possible combinations, which will make the building energy efficient while having the near-optimal lowest cost. The design solution either can be selected arbitrarily or by using a scientific method of evaluation. Previous research has shown that combining optimization techniques with energy simulations programs is an effective way to explore the set of possible solutions (Wright, Loosemore et al. 2002). However, the practice of evaluating solutions using an energy simulation program takes a large amount of computation time if one does not use the proper optimization technique. This problem will be examined more in depth in Chapter 2.

1.2.1 Research Hypothesis

The overall research hypothesis of this thesis is as follows:

Create and study a decision support tool to aid in the design of an economically feasible Net Zero Energy vaccine warehouse for the developing world.

1.2.2 Research Foundation

Many previous studies have investigated using an optimization technique with an energy simulation program to find the optimal building design. However, these studies focused on making the buildings energy efficient but did not strive to accomplish net zero energy. The studies that have strived to accomplish net zero energy buildings did not used an energy simulation program in order to accurately estimate the building energy usage. Building simulation software model the heating, cooling, lighting, ventilation, water use, and other energy flows in buildings to make accurate yearly building energy usage estimates. A key shortcoming of the previous studies is they were more concerned with finding the optimum result and less concerned with developing a tool that can easily be adapted for real world use. These studies will be examined further in Chapter 2.

This thesis will expand on the scope of previous work in order to create a decision support tool to aid in the economic efficient design of a NZE warehouse for the developing world. One case study, a vaccine warehouse, is studied with this tool. To investigate the effect of building this warehouse in a developing country versus a developed country, the costs of using new state of the art technology will be compared to the cost of using construction that is typical for the developing world. This thesis will show that, even when using local, common construction practices, a building in the developing world can be as energy efficient as a building built in the developed world, where there are no construction limitations, and still be economically viable.

1.3 Project Scope

To investigate the optimal building parameters and annual energy use of a vaccine warehouse, a case study building and design problem were created. This section outlines the overall scope of the research including details of the case study building, the optimization techniques used, overall parameters, and the research goals.

A hypothetical test building located in Tunis, Tunisia is used as the basis of this study. Four other cities that represent low and middle income countries are studied to determine the effect of climate on the optimum result: Buenos Aires, Argentina; Mombasa, Kenya; Asunción, Paraguay; and Bangkok, Thailand. The building is designed to be the new national vaccine storage facility and to supply the predicted population of Tunisia for the year 2020 (12.6 million people). It has a gross floor area of 528 m^2 and a volume of 4916 m^3. The warehouse will contain a cold storage room at 5°C with a gross floor area of 113 m^2 and a volume of 679 m^3, and a freezer storage room at -20°C with a gross floor area of 18 m^2 and a volume of 54 m^3. Details of the building are presented in Chapter 3.

The goal of this thesis is to optimize nine building parameters to have the lowest initial investment building cost and still have the building accomplish net zero energy. The initial investment includes the cost of the construction materials and the photovoltaic (PV) system.

Building parameters that have a large effect on the energy usage of the vaccine storage facility are studied. A list of the parameters that are varied can be seen in Table 1.

Table 1: Building parameters of vaccine warehouse that are optimized

Design Variables
Roof Insulation Thickness
Exterior Wall Insulation Thickness
Cold Storage Insulation Thickness
Cold Room Floor Insulation Thickness
Freezer Room Floor Insulation Thickness
Air Infiltration Rate Reduction
Roof Reflectivity
Efficiency of the Windows
Coefficient of Performance of HVAC System

In order to determine the optimum value of each parameter, the decision support tool will utilize a simulation-optimization approach. This method involves integrating an optimization technique in Matlab with simulation programs to find the cost-optimal NZE design solution. Two simulation programs, EnergyPlus and PVWatts, are used to determine the building energy usage and the size of PV system needed to accomplish NZE. EnergyPlus is a building simulation program that estimates the yearly energy usage of the building based on the building construction and climatic conditions. PVWatts is a calculator that determines the energy production of a grid-connected photovoltaic (PV) energy systems based on the PV system parameters and climatic conditions. A genetic algorithm (GA) and a design of experiments (DOE) are used as the optimization techniques. The GA is used to determine discrete optimal parameters values and the DOE is used to study the interactive effects between the parameters to better understand the design space. A detailed description of the simulation-optimization method and its components is presented in Chapter 3. The decision support tool will be used to conduct five trials that study the case study building. A description of the each of the trials is in Table 2. The first four trials investigate the effect of different construction practices, changing renewable energy prices, and climatic conditions on the optimum parameter values. The final trial suggests how to use a GA and a DOE together to aid in the design of a NZE building. The suggested process uses a DOE that only considers energy usage in the early stages of design and a GA that considers energy usage and the construction cost of the building in the final stages of design.

Table 2: Description of Trial Runs

Trial Run	Description
Trial 1	Construction sensitivity analysis using a Genetic Algorithm
Trial 2	Climate sensitivity analysis using a Genetic Algorithm
Trial 3	PV sensitivity analysis using a Genetic Algorithm
Trial 4	Parameter sensitivity analysis using a Design of Experiments
Trial 5	Two-step process combining a Genetic Algorithm and a Design of Experiments

These trials use the proposed decision support tool to suggest building parameters values for a cost-optimal vaccine warehouse that achieves net zero energy. In the first trial, the results from the comparison of construction methods show that it is feasible to design the warehouse in the developing world as compared to the developed world. The results from the next three trials are used to create generalized recommendations based on a correlation between climatic factors, other building parameters, and the suggested parameter value. The results of the last trial, the two-step process, show the parameter rankings are consistent between the two optimization techniques and that the proposed process is beneficial. This thesis provides a decision support tool to aid developing countries in the design of a NZE vaccine warehouse and provides generalized recommendations for all the parameters studied. Chapter 2 presents the background information and reviews the relevant literature on building optimization.

CHAPTER 2

BACKGROUND

This chapter presents background information and reviews relevant literature on the topics needed to develop a decision support tool to aid in the design of an economically efficient, net zero energy building for the developing world. First, the relevant literature on energy efficiencies in developing countries and the definition of a Net Zero Energy Building (NZEB) is presented. The next section provides background on building energy optimization including summaries of previous studies and descriptions of the simulation software used in this thesis, EnergyPlus and PVWatts, to perform the building optimization. The final sections discuss the chosen optimization techniques, a Genetic Algorithm (GA) and Design of Experiments (DOE). The sections provide background on the optimization techniques and summaries of studies that use the optimization techniques for building design. The information presented in this chapter is used as a foundation for the proposed decision support tool outlined in Chapter 3.

2.1 Net Zero Energy in Developing Countries

This research aims to create and study a decision support tool to aid in the design of a net zero energy building for the developing world. First, this section summarizes previous studies that investigate energy efficient buildings in developing countries. One developing country, Tunisia, is chosen as the case study for this thesis. This section summarizes previous studies on building energy optimization in the Tunisia climate. Finally, this section defines Net Zero Energy (NZE) and explains its importance in the building sector.

2.1.1 Energy Efficiency in Buildings in Developing Countries

There has not been a significant amount of research on developing energy efficient buildings in the developing world. The lack of research is most likely due to the fact that many developing countries have not created building energy standards. The following is a brief summary of a study that examines this issue.

A study in 2010 investigates the implementation status of building energy standards in developing countries and its implications for sustainable energy efficient design of buildings (Iwaro and Mwasha 2010). This study chose to investigate developing countries due to the fact that energy consumption is experiencing an unprecedented growth of 70 percent in developing countries as compared to a smaller increase, about 25 percent, that is expected for developed countries in Europe. This study investigates the present implementation status of building energy standards in 60 developing countries around the world. To exploit this important area of research, this paper used mail surveys to gather detailed information about building energy standards. The survey was sent to approximately 145 contacts in government, research organizations, and professionals in 95 countries and had a response rate of 46%. The building energy standards development and adoption are investigated in this research and the results showed that 42% of developing countries surveyed have no energy standards in place, 20% have mandatory, 22% have mixed, and 16% proposed. The results from the survey can be seen in Figure 1. The results of this study showed that, in general, the performance of building implementation in developing countries is still at the infant stage, especially in the emerging developing countries. The researchers recommend ways to address the challenges of the sustainability gap and recommend sustainable energy efficient building initiatives that can be implemented. This study states that one of the main problems is lack of knowledge on energy-saving construction techniques among architects in developing countries. The study states "Sustainable construction, design and know-how need to be introduced into the base curriculum of architects, engineers and other construction-related professions all over the world. This is very important for developing countries because of the often much more dynamic new construction designs. As the training of countries' own nationals will take some time, technical assistance through international consultants and organizations can be engaged in order to bridge this sustainability gap." (Iwaro and Mwasha 2010) The developing world needs tools designed for them to aid in the design of energy efficient buildings.

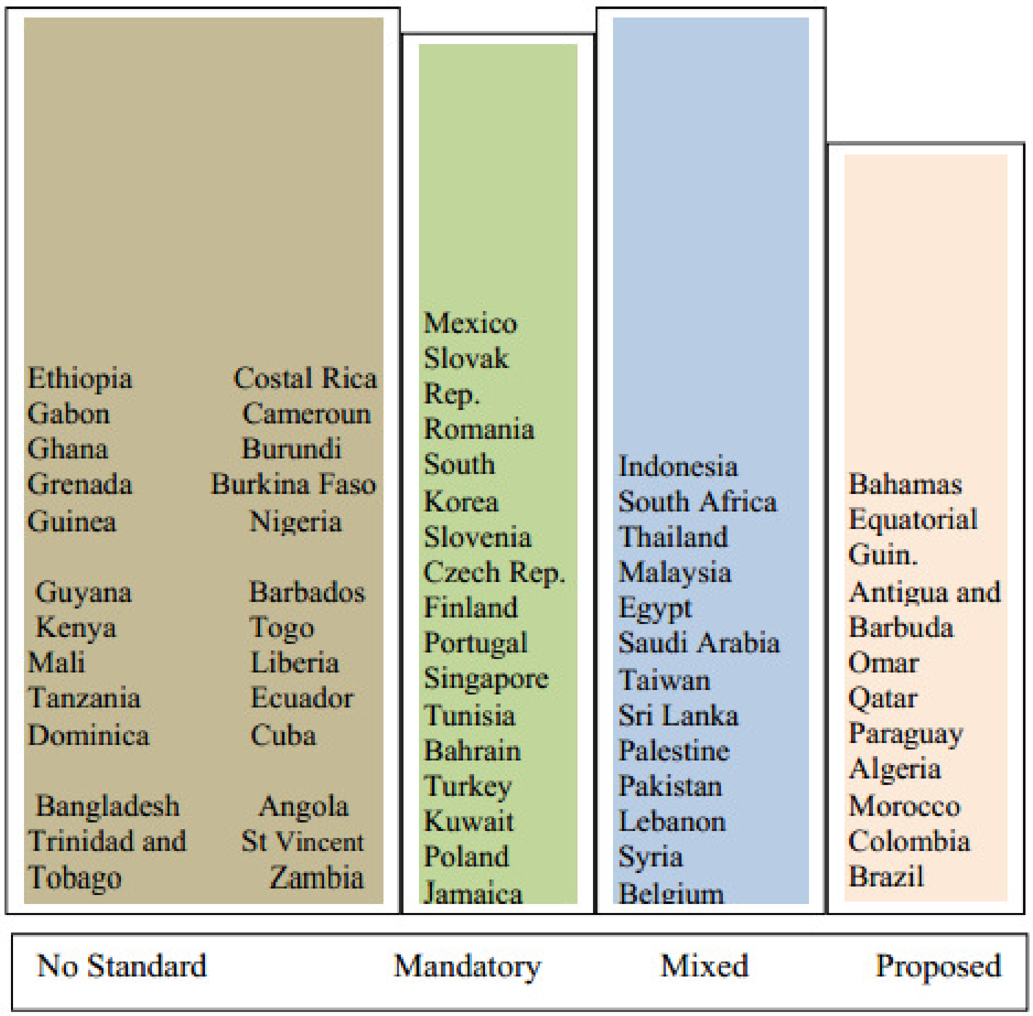


Figure 1: Status of Building Energy Standards implementation status in 60 developing countries extracted from (Iwaro and Mwasha 2010).

There are a few studies that have investigated energy efficient buildings in developing countries. A study in 2005 looked at implementing passive cooling systems in buildings in developing countries (La Roche 2005). Its focus was on a prototype microcomputer-controlled thermostat that improved the efficiency of passive cooling. The thermostat was combined with smart window blinds in order to implement passive cooling. This study demonstrated that when conditions are suitable, it is possible to use ventilated cooling with a smart thermostat to reduce the maximum temperature inside buildings in warm climates. A study in 2010 reviewed financing energy efficiency in developing countries (Sarkar and Singh 2010). This study examined experiences with financing energy efficiency in developing countries to explore the key factors of various programmatic approaches and financing instruments that have been applied successfully for delivering energy efficiency solutions. It was determined that it is often institutional issues that become a key challenge to address in order to finance and implement robust programs. One issue is a lack of availability of modern energy saving technologies and the study stated "as further operational experience is gained, increased knowledge sharing can lead to scaling-up of such energy efficiency investments." (Sarkar and Singh 2010) Most of the studies for energy efficiency buildings in developing countries are similar to one of the two studied presented. The studies either discuss one new technology that can be implemented in developing countries or discuss the policies and finances behind implementing energy efficiency standards. These studies show that it is important to create energy efficient buildings for developing countries, but the studies do not actually provide tools or recommendations for the design of energy efficient buildings.

The developing country, Tunisia, was chosen to be the case study of this thesis. The literature review on energy efficient buildings in developing countries was shifted, for the purposes of this thesis, to reviewing studies that focused on energy efficient buildings in Tunisia. After the research focus was narrowed to Tunisia, studies were found that investigated the optimal parameters for energy efficient buildings. The following are brief summaries of previous studies on designing energy efficient buildings in the Tunisian context.

A study in 2007 investigated glass curtain walls in the Tunisia climate (Bouden 2007). This study stated that glass curtain walls had been recently introduced in Tunisia and investigated whether the glass curtain walls were appropriate for the Tunisian local climate. An energy simulation was performed on an administration building using TRNSYS. TRNSYS is a transient system simulation program that is primarily used to for building simulation for active and passive solar design. The study investigated the effect of the glass curtain wall on the building heating and cooling loads. The building was modeled in five thermal zones with the glass wall implemented only on the main building façade. The glass wall parameters that were varied were the glazing sizes and glass types. The results of this study showed that, in relation to space heating, the glass curtain wall can be very effective in the Tunisian context if the orientation and the type of glazing are carefully selected. For the case of an administrative building, it showed that glass curtain walls can perform better than normal masonry walls that have small windows covering 20% of the total wall area. It was determined that, in summer, double glazing with one clear layer and one reflecting layer has the lowest energy consumption. For winter conditions, double glazing with one clear layer and one low emissivity layer with argon in between had the lowest energy consumption. On an annual basis, double glazing with one clear layer and one reflecting layer had the lowest energy consumption. The limitation of this study was that it only proved that these glass curtain walls were effective in terms of energy consumption and did not consider the cost of the windows. These results did show the importance of using better windows in the Tunisia climate and the results found in this study will be compared to the optimum result found in Chapter 4 of this thesis.

A study in 2009 investigated the optimum thickness of insulation in an external wall construction in Tunisia (Daouas 2011). Typical construction in Tunisia applies an insulation layer thickness ranging between 4 cm and 5 cm, regardless of the climatic conditions, type and cost of insulation material, and other economic parameters. An analytical method, based on Complex Finite Fourier Transform, was used to estimate yearly transmission cooling loads from two types of insulation materials and two types of wall structures. In order to find the optimum solution, a life cycle analysis was used. The results showed that the most profitable case used expanded polystyrene insulation with a thickness of 5.7 cm. In this case, energy savings up to 58% were achieved with a payback period of 3.11 years. Figure 2 shows the variation of insulation cost, electricity cost, and total cost with increasing insulation thickness. The results showed that the savings in electricity cost had a steep slope in the beginning and the slope flattened out near the optimum point. The figure also has a legend with two different wall types. Wall one was 2 cm plaster, 15 cm brick, thermal insulation, 6.5 cm for brick, and then 2 cm of plaster. Wall two was 2 cm plaster, 30 cm stone, thermal insulation, 6.5 cm for brick, and then 2 cm of plaster. The two wall constructions had similar results, which illustrated that an extra 15 cm of material in the wall construction did not have a significant impact on the building energy usage. The optimum insulation thickness found in this study will be compared to the optimum result found in Chapter 4 of this thesis.

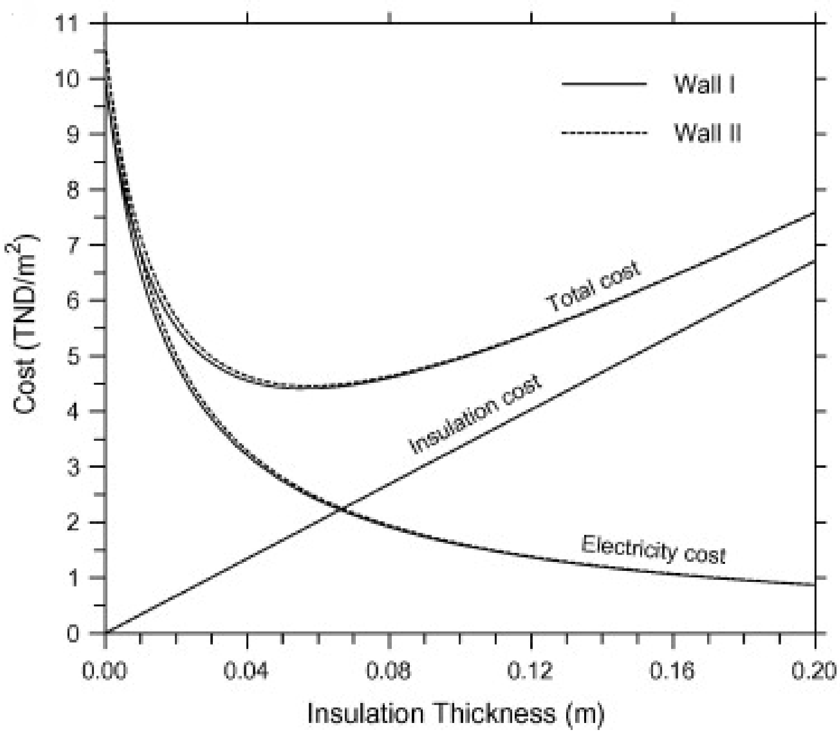


Figure 2: Variations of insulation, electricity, and total cost extracted from (Daouas 2011).

A study in 2012 investigated the optimum value of eleven parameters for the design of an energy efficient residential building in Tunisia (Ihm and Krarti 2012). A sequential search technique was used to minimize life cycle costs. The goal of the study was to increase the energy efficiency of the building so that the building could accomplish Net Zero Energy (NZE). The optimization method found the suboptimal path to design a NZE building. First, all of the energy efficiency measures (EEMs) were individually considered for an initial building design with a specific life cycle cost. Then, the most cost-effective EEM option was chosen based on the steepest slope consisting of the LCC to energy savings ratio. The selected EEM optimal option was then removed from the parameter search space for future evaluation, and the remaining EEMs were simulated to find the next optimal option. This process was repeated until the optimal solution was reached. A brute force method was used as a comparison in order to prove the accuracy of the results from this method. The simulation environment utilized DOE-2 as the whole-building energy simulation engine to identify the detailed building energy performance. The study investigated the impact of the climatic conditions, by studying four cities in Tunisia, on the optimum building parameter values. The study found that source energy use savings up to 59% can be achieved cost-effectively by using an optimal design compared to the current construction practices in homes in Tunisia. It found that the specific selection of optimal design features vary depending on the climatic and economic conditions. Typically, "adding roof insulation, reducing air infiltration, installation energy efficient appliances, lighting fixtures, and heating and cooling equipment are common energy efficiency measures recommended for optimal homes designs for all climatic zones in Tunisia." (Ihm and Krarti 2012) The limitation of this study is that it claimed to be designing a NZE building; however renewable energy prices were never mentioned in the study. The study claimed "the sequential search technique allows the identification of not only the optimal design but also the most cost-effective set of energy efficiency measures that can achieve a desired energy use savings level include the net-zero energy design configuration." (Ihm and Krarti 2012) However, the study never stated the desired energy use savings level. Table 3 shows the optimum result for minimizing the LCC for the four climates studied. The optimum result for Tunis, Tunisia recommended no insulation for the exterior wall or the roof. The results from this study will be compared to the optimum result found in Chapter 4 of this thesis.

Table 3: Summary of the residential building design options and costs for minimizing LCC for four Tunisia sites extracted from (Ihm and Krarti 2012).

	Tunis (ZT1)	Medenine (ZT1)	Gafsa (ZT2)	Nefta (ZT3)
Azimuth [degree]	270	180	90	90
Exterior wall insulation	No insulation	No insulation	No insulation	No insulation
Roof insulation	No insulation	No insulation	polystyrene 2 cm	polystyrene 2 cm
WWR [%]	40	40	10	10
Glazing type	Single clear	Single clear	Single clear	Single Bronze
Lighting level [%]	70	70	70	70
Infiltration level [%]	0	0	75	75
Refrigerator energy level [%]	65	65	65	65
Air-Conditioner COP	3.3	3.5	3	3
Boiler efficiency [%]	80	80	80	80
Cooling Set point [°C]	26	26	26	26
Initial cost [TND]	19,072	19,222	21,128	21,265
Utility cost [TND]	8952	8988	7612	7909
Life cycle cost [TND]	28,024	28,210	28,740	29,174
Energy saving [%]	30	33	48	48

A study performed in 2013 investigated the optimal parameters for an energy efficient office building in Tunisia (Ihm and Krarti 2013). The study was completed by the same researchers as the previous study and used the sequential search technique for optimization. Several design and operation features were considered including orientation, window location and size, glazing type, wall and roof insulation levels, lighting systems, day-lighting controls, temperature settings, and efficiencies of heating and cooling systems. The optimization aimed to find the solution with the lowest life cycle cost, and simulations were conducted in four cities across Tunisia. The study showed that the optimal design configurations for office buildings reduce the life cycle costs by about 23% to 27% compared to the current design and operating practices in Tunisia. The cost-effectiveness of designing net zero energy office buildings was evaluated using the simulation environment developed for this thesis. "It was found that when the PV costs are below 4500 TND per kW, designing zero net office buildings can be cost-effective." (Ihm and Krarti 2013) The optimization results indicated that utilizing day-lighting controls, energy efficient lighting fixtures, low-e double glazing, and roof insulation are required energy measures to design energy efficient offices throughout climatic zones in Tunisia. Table 4 shows the optimum result for minimizing the LCC for the four climates studied. The results from this study will be compared to the optimum result found in Chapter 4 of this thesis.

Table 4: Summary of the office building design options and costs for minimizing LCC for four Tunisia sites extracted from (Ihm and Krarti 2013).

	Tunis (ZT1)	Medenine (ZT1)	Gafsa (ZT2)	Nefta (ZT3)
Azimuth	180	180	180	180
Exterior Wall insulation	polystyrene 2cm	polystyrene 4cm	polystyrene 4cm	polystyrene 2cm
Roof insulation	polystyrene 2cm	polystyrene 4cm	polystyrene 4cm	polystyrene 2cm
WWR [%]	10	10	10	10
Glazing type	Double Low-e	Double Low-e	Double Low-e	Double Low-e
Lighting reduction [%]	30	30	30	30
Infiltration reduction [%]	25	25	50	25
Cooling Set point [C]	26	26	26	26
Chiller COP	4.5	4.5	4.5	4.5
Boiler efficiency [%]	85	85	85	85
Daylighting control	YES	YES	YES	YES
Initial cost [TND]	110,077	113,441	113,010	110,077
Utility cost (TND)	94,309	92,377	95,213	99,387
Life cycle cost (TND)	204,385	205,818	208,223	209,463
Energy saving [%]	47	51	51	51

These studies included cost data and material properties that are later used in this thesis to characterize typical Tunisian construction. The details used are listed in Chapter 3. Also, the optimum results from these studies are compared to the optimum result found by using the decision support tool in Chapter 4. The last two studies summarized in this section aimed to design a net zero energy building instead of just an energy efficient building. The next section presents the definition of net zero energy buildings.

2.1.2 Net Zero Energy Buildings

A net zero energy building (NZEB) is a residential or commercial building with greatly reduced energy needs created through efficiency gains such that the balance of energy needs can be supplied with renewable technologies (Torcellini 2006). A NZEB typically uses traditional energy sources, such as the electricity and natural gas when on-site generation does not meet the loads. When the on-site generation is greater than the building's loads, excess electricity is exported to the utility grid. By using the grid to account for the energy balance, excess production from the on-site generation can offset later building energy use. Achieving a NZEB without the grid is very difficult, as the current generation of storage technologies is limited (Torcellini 2006).

There are four well-documented net zero energy definitions: net zero site energy, net zero source energy, net zero energy cost, and net zero energy emissions. The definition of a net zero site energy is a building that produces at least as much energy as it uses in a year, when accounted for at the site. A net zero source energy building produces at least as much energy as it uses in a year, when accounted for at the source. Source energy refers to primary energy used to generate and deliver the energy to the site. In a cost net zero energy building, the amount of money the utility pays the building owner for the energy that the building exports to the grid is at least equal to the amount the owner pays the utility for the energy services and energy used over the year. A net-zero emissions building produces at least as much emissions-free renewable energy as it uses from emissions-producing energy sources (Torcellini 2006). In this thesis, the net zero site energy definition is used.

Various renewable energy technologies are available for use to create a NZEB. Typical examples of technologies available today include photovoltaic (PV), solar hot water, wind, hydroelectric, and biofuels. These renewable sources are favorable but a chart created by National Renewable Energy Laboratory (NREL) ranks renewable energy sources in the NZEB context. Table 5 shows the NREL ranking for NZEB renewable energy supply options. This hierarchy is weighted toward renewable technologies that are available within the building footprint and at the site. Rooftop PV and solar water heating are the most applicable supply-side technologies for widespread application of NZEBs. Other supply-side technologies such as parking lot-based wind or PV systems may be available for limited applications. Renewable energy resources from outside the boundary of the building site arguably could be used to achieve a NZEB.

Table 5: ZEB Renewable Energy Supply Option Hierarchy (Torcellini 2006)

Option Number	NZEB Supply-Side Options	Examples
0	Reduce site energy use through energy efficiency and demand-side renewable building technologies.	Daylighting; insulation; passive solar heating; high-efficiency heating, ventilation, and air-conditioning equipment; natural ventilation, evaporative cooling; ground-source heat pumps; ocean water cooling
On-Site Supply Options		
1	Use RE sources available within the building footprint and connected to its electricity or hot/chilled water distribution system.	PV, solar hot water, and wind located on the building
2	Use RE sources available at the building site and connected to its electricity or hot/chilled water distribution system.	PV, solar hot water, low-impact hydro, and wind located on parking lots or adjacent open space, but not physically mounted on the building
Off-Site Supply Options		
3	Use RE sources available off site to generate energy on site and connected to the building's electricity or hot/chilled water distribution system.	Biomass, wood pellets, ethanol, or biodiesel that can be imported from off site, or collected from waste streams from on-site processes that can be used on site to generate electricity and heat
4	Purchase recently added off-site RE sources, as certified from Green-E (2009) or other equivalent REC programs. Continue to purchase the generation from this new resource to maintain NZEB status.	Utility-based wind, PV, emissions credits, or other "green" purchasing options. All off-site purchases must be certified as recently added RE. A building could also negotiate with its power provider to install dedicated wind turbines or PV panels at a site with good solar or wind resources off site. In this approach, the building might own the hardware and receive credits for the power. The power company or a contractor would maintain the hardware.

There are two main principles used when designing a NZEB: building annual energy consumption reductions and on-site energy production. A good NZEB first encourages energy efficiency to reduce a building's annual energy consumption, and then uses renewable energy sources to offset its energy usage. Energy efficiency is generally the most cost-effective strategy, and maximizing efficiency opportunities before developing renewable energy plans will minimize the cost of the renewable energy system. Energy efficiency measures include design strategies and features that reduce the demand-side loads, such as high-performance envelopes, air barrier systems, day-lighting, shading devices, careful selection of windows and glazing, passive solar heating, and natural ventilation. Once building loads are reduced, they should be met with efficient equipment and systems. This may include energy efficient lighting, electric lighting controls, high-performance HVAC, and geothermal heat pumps. Typically, to find the most cost effective NZEB solution an optimization technique is used to investigate the optimum value of building parameters. The next section describes how optimization techniques are used to design an energy efficient building.

2.2 Building Optimization

The proposed decision support tool uses a simulation-optimization approach in order to aid in the design of an economically feasible NZE vaccine warehouse for the developing world. This section provides the background needed to create an efficient simulation-optimization approach. This section first summarizes previous studies that use optimization techniques to aid in the design of energy efficient buildings. Many studies were reviewed, but only the studies that use a simulation-optimization approach will be presented. The summaries will include the simulation programs, optimization technique, and economic equation used in the study. Two simulation programs, EnergyPlus and PVWatts, were chosen to be used in this thesis. This section provides descriptions of these programs and discusses why they were chosen.

2.2.1 Studies using Optimization for Building Design

The proposed decision support tool in this thesis builds upon the work of previous building optimization studies. Previous studies have used different approaches but this thesis focused its literature review on studies that used a simulation-optimization approach. This section will present brief summaries of the previous studies that have used this approach.

A study from 2008 investigated minimizing the life cycle cost (LCC) of a single family detached home by using a combined simulation and optimization method (Hasan, Vuolle et al. 2008). The combined simulation and optimization method is performed using GenOpt and IDA ICE 3.0. GenOpt is an optimization program for the minimization of a cost function that is evaluated by an external simulation program. It is developed for optimization problems where the cost function is computationally expensive and its derivatives are not available. IDA ICE 3.0 is a whole-building dynamic simulation program. The interface between the two programs can be seen in Figure 3. The house studied used typical Finnish construction with initial U-values in accordance with Finnish National Building Code C3 of 2003. Three continuous variables (insulation thicknesses of the external wall, roof, and floor) and two discrete variables (U-value of the windows and type of heat recovery) were investigated. In order to find the optimum solution the LCC is calculated over two life spans, 20 and 50 years, and the escalation in electricity prices are all varied in order to see how this affects the optimal result. A brute-force method is implemented in the end to check the results obtained by GenOpt. The algorithm used in GenOpt is the hybrid global optimization algorithm, which combines a generalized pattern search particle swarm optimization with a constriction coefficient Hooke–Jeeves algorithm. This hybrid algorithm initially performs a particle swarm optimization for the continuous and discrete variables and then switches to the Hooke–Jeeves generalized pattern search algorithm to refine the continuous variables.

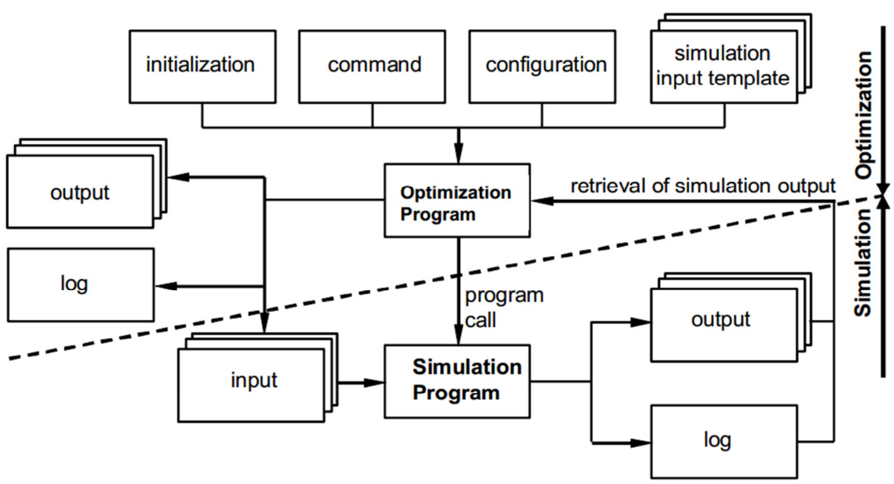


Figure 3: GenOpt and simulation model interface extracted from (Hasan, Vuolle et al. 2008).

The solutions from the optimization suggest lowering the U-values for the external wall, roof, floor, and window from their initial values (Hasan, Vuolle et al. 2008). The exact values of the optimized design variables depend on the set up of the LCC data. The results show reductions of 23-49% in the space heating energy for the optimized house when compared to the reference case. This study shows the advantages of using a combined simulation and optimization method. The GenOpt results were verified by comparing them with results obtained by a brute-force search method, which showed that minimum global values of the objective function are reached. The limitation with this study, in respect to this thesis, is that the focus is on residential construction and only aims to make the building energy efficient and not accomplish net zero energy. Also, this study used IDA ICA 3.0 for the building simulation, which is not a free program; since this study is focusing on developing countries, this thesis will only use software that is free. Also, GenOpt only has seven optimization algorithms built in. These include Generalized Pattern Search, Particle Swarm Optimization, Discrete Armijo Gradient, Nelder and Mead's Simplex algorithm, Golden Section, and a hybrid global optimization algorithm that uses Particle Swarm Optimization for the global optimization and Hooke-Jeeves for the local optimization. However, none of these algorithms are used in this thesis, so this program cannot be used. The main benefit of this study is that it is one of the first studies to show a successful combined simulation and optimization method.

A study from 2011 investigated applying a multi-objective optimization for the design of a low-emission cost-effective dwelling (Hamdy, Hasan et al. 2011). A three-phase multi-objective optimization approach was used. The approach aimed to reduce the random behavior of the genetic algorithm (GA) by selecting an initial population from a preparation phase. After a low number of generations the third phase, the refine phase, of the optimization approach started and used fast and realistic stopping criteria to find the optimal solution. The approach was combined with IDA ICE 3.0 (Building performance simulation program) to minimize the CO2-equivalent emissions related to building energy consumption and the investment cost of the design variables. The interface between the two programs is seen in Figure 4. A two-story house in the cold climate of Finland was selected as a case study. Eight different design variables were considered, with three being continuous and five being discrete. The study concluded that when compared to the reference design, 32% less CO2-equivalent emissions and 26% lower investment cost solution could be achieved, and the type of heating energy source has a significant influence on the optimal solution. This study showed that simulation-based optimization approach show great potential for multi-objective building design problems, and if the approach is used in the design phase, it will help to better understand the performance of the building and its HVAC systems. The simulation-based optimization method used in this study was the foundation for the decision support tool proposed in this thesis. The components are modified and added to in order to fit the needs of this thesis but the basic flow and relationships remains the same. The details of the simulation-optimization approach used for the decision support tool are presented in Chapter 3.

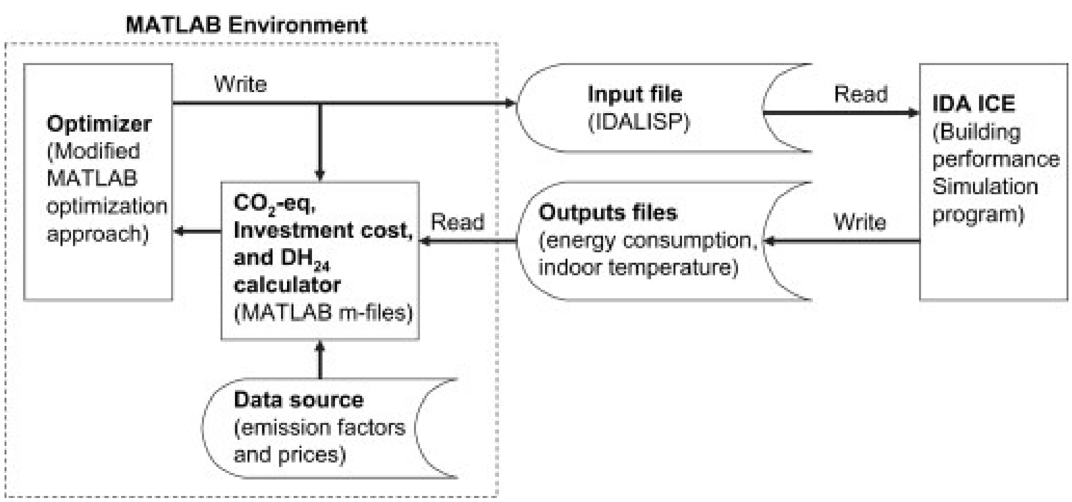


Figure 4: Simulation-based optimization extracted from (Hamdy, Hasan et al. 2011)

A study in 2012 investigated using a three-stage optimization framework to find a high-performing, cost effective design (Evins, Pointer et al. 2012). The study investigated 103 variables for a two bedroom, mid-level apartment. Figure 5 shows a graphical representation of the steps. The first step in the optimization was a comprehensive full-factorial Design of

Experiments analysis. The full-factorial DOE was decoupled into sub-systems and this reduced the required number of experiments from 10^{31} to 76,924. This analysis determined the significance of each variable to the objective function. Next, a multi-objective optimization algorithm was applied the top 26 highly significant variables based on the results from the full-factorial DOE. The final step was a more detailed multi-objective optimization using greater precision. The optimization algorithm used in this work was the Non-dominated Sorting Genetic Algorithm (NSGA-II), which is a genetic algorithm with a modified selection function. The modified selection function drove the population towards the optimum Pareto front while maintaining diversity along the front by creating some members of the next generation from the previously rejected population. The genetic algorithm had 200 generations with a population size of 100. The initial optimization was intended to remove those variables which, while highly significant, only act in one direction on both objectives. Eliminating these variables allowed the completion of these detailed studies. The detailed optimization produced a wealth of information regarding optimal solutions. The method presented in the study cannot be done for this thesis, since it would take 103 days to do just the first step of the process. However, this thesis does investigate the benefit of combining a design of experiments and the genetic algorithm together.

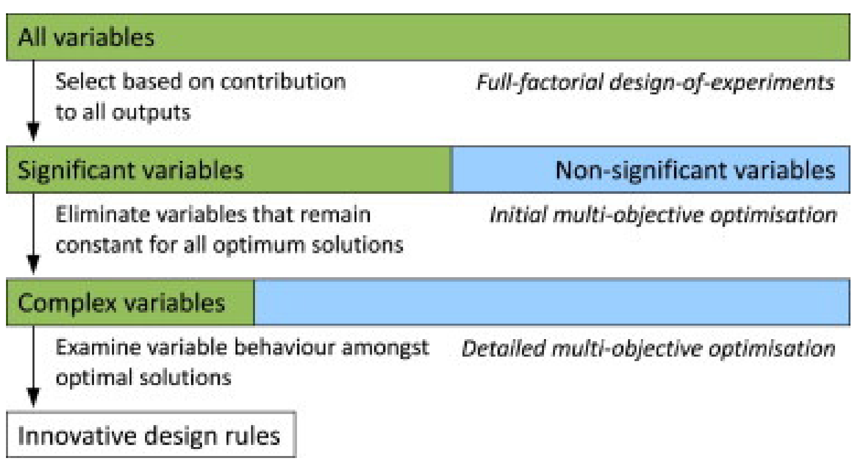


Figure 5: Optimization framework extracted from (Evins, Pointer et al. 2012)

Another study from 2012 investigated a methodology for the economic efficient design of net zero energy buildings (Kapsalaki, Leal et al. 2012). The study designs a residential building considering the influence of the local climate, the endogenous energy resources, and the local economic conditions. The aim of this study was to help designers in the early design stage. In order to do this, equations were used to estimate the building energy usage of a conceptual building design. This differs from previous studies with used building energy simulation software to determine the optimum parameters for the final building design. The equations were combined into a GUI so that the tool could be easily used. The study investigated the optimal thermal insulation, air leakage reduction, window types and shades, heating and cooling equipment, DHW equipment, ventilation, lighting, appliances, and renewable energy systems by minimizing LCC. The renewable energy systems studied included photovoltaic panels and wind turbines. The results showed "as a general trend, the most expensive NZEB design solution in terms of initial cost was at least three times more expensive than the cheapest design solution. The same at least about 3:1 ratio, was generally observed in terms of life cycle cost." (Kapsalaki, Leal et al. 2012) This result illustrated the importance of an economic analysis for NZEBs in order to reach the energy goals with economic efficiency. This study also investigated the optimal solutions sensitivity to climate. The results showed the optimal design solution for mild winter climates was significantly cheaper than for cold winter climates. This is due to the fact that cold winter climates require more energy efficient solutions and because these climates had lower solar radiation so greater PV area was required. The goal of this study was to create a tool to provide guidance in the early stage, and this goal caused the study to not to use building simulation software. This thesis will use the idea considering local climate, endogenous resources, and local economic conditions and couple this idea with building simulation software in order to find an economic efficient NZEB for the final stages of design.

A study from 2013 presented a comprehensive review of all significant research applying computational optimization to sustainable building design problems (Evins 2013). Seventy-four studies that focused on the application of optimization to different fields of sustainable building design were reviewed. The study reviewed the dates that they were published, the optimization technique used, and the objective function of the design problem. Figure 6 shows a summary of the optimization techniques used in the reviewed studies. The most common optimization method was a Genetic Algorithm, which was used in more than half the cases. Genetic algorithms are discussed in greater detail in Section 2.3. Direct search methods were also popular, used in a quarter of cases. Direct search optimization is an unconstrained optimization technique that does not explicitly used derivatives. To search for an optimal point, the direct search algorithm searches a set of points around the current point, looking for where the value of the objective function is lower than the value at the current point.

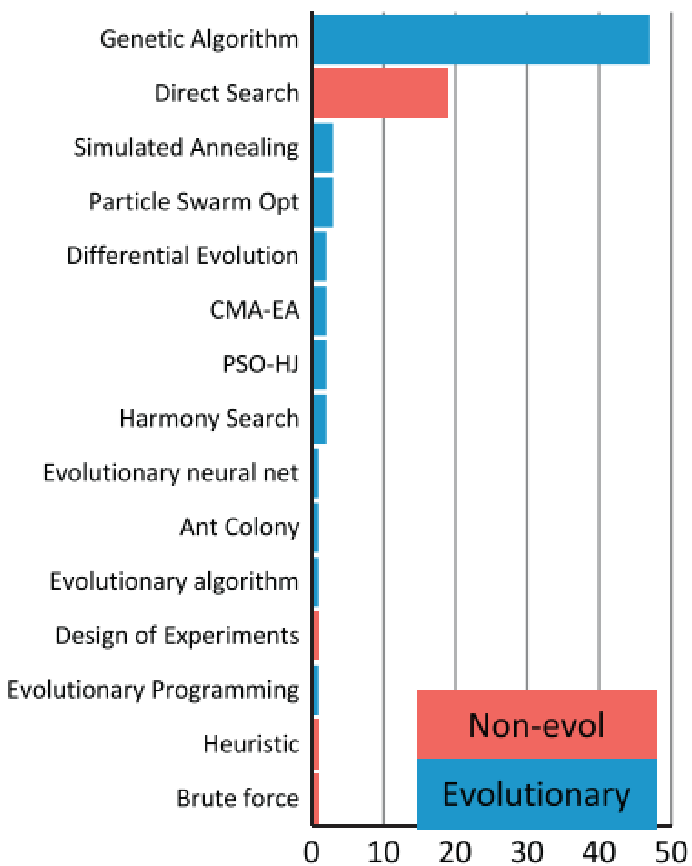


Figure 6: Optimization methods used in building design extracted from (Evins 2013)

Figure 7 shows a summary of the objective functions used in the reviewed studies. The most common objective was energy use, which was used in 60% of cases. The next three most common objective functions involved cost. There are several variations for cost objectives including: construction cost, life cycle cost, operational cost, and total cost. A cost objective was present in about 60% of the studies reviewed.

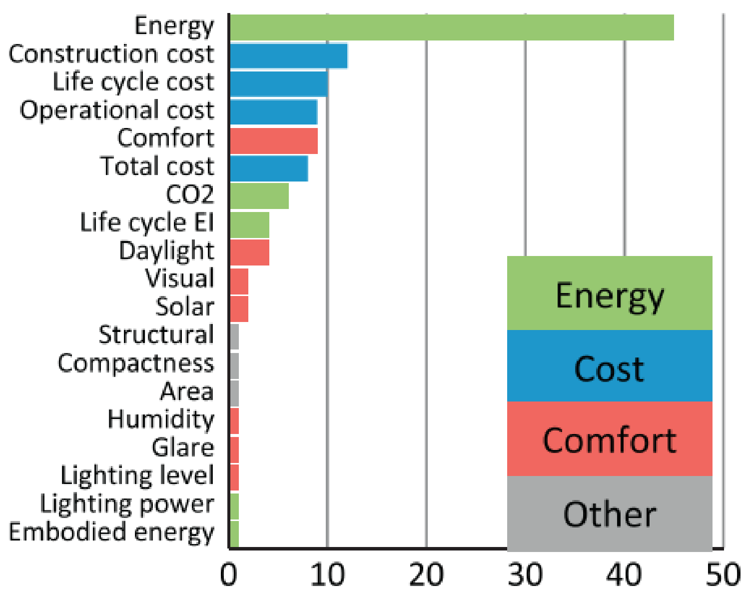


Figure 7: Objective functions used in sustainable building design extracted from (Evins 2013)

Based on the reviewed studies, it was decided to use a genetic algorithm and a design of experiments for the optimization techniques in the decision support tool. The next two sections of this chapter discuss these concepts in greater detail. The rest of this section discusses the two simulation programs, EnergyPlus and PVWatts, used in the proposed decision support tool.

2.2.2 EnergyPlus

EnergyPlus is a free, whole-building dynamic simulation program that makes simultaneous performance assessments of all issues fundamental building design. It is an energy analysis and thermal load simulation program developed by the U.S. Department of Energy

(DoE). EnergyPlus models heating, cooling, lighting, ventilation, water use, and other energy flows in buildings (DoE 2013).

In order to create a building model in EnergyPlus, the building must first be modeled using a 3-D drawing interface. Then the 3-D building file is imported into EnergyPlus, and building features are input into the model. The EnergyPlus model inputs include building materials and constructions, building occupancy, building lighting and electric loads, HVAC system compositions, thermostat set points, and building schedules. Once the building model is complete, a weather file must be selected so the model can be simulated. EnergyPlus includes many options for viewing the results of the simulation, and displays the selected output data in a common-separated (CSV) file. Output options for EnergyPlus models include time-based building energy consumption, building energy metering, and time-based building component and zone energy consumption.

EnergyPlus completes a rigorous thermodynamic analysis of each building simulated, and the level of detail necessary for the model inputs and the analysis performed results in highly reliable and accurate building load data. The accuracy of the data produced by this software makes EnergyPlus an excellent tool for simulating building load data and was chosen to simulate the energy usage of the building in this thesis. The main reason for using EnergyPlus to be used in this thesis is due to the fact that it is free software. The proposed decision support tool is designed for developing countries, so it is crucial that the simulation components are easily accessible and free so that the decision support tool can be used.

2.2.3 PVWatts

NREL has developed PVWatts; a calculator that determines the energy production of grid-connected photovoltaic (PV) energy systems throughout the world (NREL 2013). The PVWatts calculator works by creating hour-by-hour performance simulations that provide estimated monthly and annual energy production in kilowatts. Users can select a location and choose to use default values for the PV system or their own system parameters for size, array type, tilt angle, and azimuth angle of the PV system. In addition, the PVWatts calculator can provide hourly performance data for the selected location.

Using typical meteorological year weather data for the selected location, the PVWatts calculator determines the solar radiation incident of the PV array and the PV cell temperature for each hour of the year. The DC energy for each hour is calculated from the PV system DC rating and the incident solar radiation and then corrected for the PV cell temperature. The AC energy for each hour is calculated by multiplying the DC energy by the overall DC-to-AC de-rate factor and adjusting for inverter efficiency as a function of load. Hourly values of AC energy are then summed to calculate monthly and annual AC energy production (NREL 2013).

In order to use the PVWatts calculation in the optimization, the SAM Simulation Core (SSC) software development kit (SDK) is used (NREL 2010). It is a collection of developer tools for creating renewable energy system models using the SSC library. SAM is a desktop application that provides a front end for the SSC library. The SDK allows one to create one's own applications using the SSC library. The software allows the user to input the same parameters that are used in the online version of PVWatts to get the annual AC energy production. NREL's PVWatts calculator is used in the simulation-optimization process of this thesis in order to get an accurate sizing for the PV system needed to accomplish NZE for each annual energy usage. PVWatts is free software, which is one reason that it was chosen for this thesis. Also, it is important to know that all of the studies reviewed that investigated solar systems used simplified equations to estimate the necessary solar system size. PVWatts is used to ensure the proposed decision support tool provides accurate results.

2.3 Introduction to Genetic Algorithms for Building Design

One of the two optimization methods used in this thesis for the proposed decision support tool is a Genetic Algorithm (GA). This section provides background information on Gas including how they work and the important features and summaries of previous studies that have implemented a GA in building energy optimization.

2.3.1 Genetic Algorithms (GAs) Background

One method that has been used in construction optimization, as well as building energy optimization, is called an evolutionary algorithm or a Genetic Algorithm (GA). A GA is loosely based on models of genetic changes in a population of individuals. Initially, the algorithm defines a randomly selected population within the search space. This population is called the "solution set." The variables for each solution are defined as strings of characteristics that make up its identity. To complete the analogy, this characteristic set of "genes" is called a chromosome. The fitness of each solution is determined based on the optimization parameters, and the samples are subsequently ranked (De Jong 1988).

As indicated by the metaphor, the solution set will "evolve" based on the fittest individuals and the process is repeated over many generations of simulations. There are a large number of variations that have been used to modify the specific details of the GA, but three main operators are generally associated with the organized populations. These main operators are the selection, crossover, and mutation function. The selection operator chooses the fittest instances of the population for reproduction based on the goals of the optimization. The crossover function then takes the fittest solutions and mimics biological recombination by splicing and switching their chromosomes at strategic points. This is analogous to two parents distributing a portion of their genes to their offspring; the children do not always receive the same number of characteristics from each parent. The last operator is the mutation operator, which randomly switches genes within a chromosome string. This optimization method guard from converging at a local optimum is by allowing some non-optimal solutions to continue in the process. Such a strategy allows the solution set to temporarily become less optimal, with the goal of discovering global optimal solutions not necessarily near the current search set. The mutation strategy is the main way that GA allows sub-optimal solutions to enter the solution set, and prevent the results from remaining at a local optimal (Mitchell 1998).

The great appeal of mimicking natural selection is the idea of searching for optimal solutions in a huge number of possibilities (Mitchell 1998). Convergence is the term used to describe the way that a large search space becomes an optimal solution set. A significant amount of research has focused on determining the best combination of selection, crossover, and mutation factors that lead to the most beneficial convergence. Typical factors are the number of individuals in the solution set, the number of individuals to become parents, the method of crossover, the rate of mutation, and the number of generations. This balancing act of methods recognizes that an optimal solution set that converges too quickly may become trapped in a local optimal search space, but the convergence that occurs too slowly may take a long time and a large amount of computing power to reach an optimal solution set, if at all.

The two types of genetic algorithms are multi-objective genetic algorithms (MOGAs) and single-objective genetic algorithms. They differ in the fact that MOGAs measure more than one fitness objective simultaneously. This provides a major divergence for how the GA works because simple GAs can closely relate the fitness of the solution to its selection for reproductions and MOGAs cannot. In other words, the fittest solutions will become parents of future generations with a simple GA. With MOGAs, the selection of parents related to the Pareto-front, which may include less fit solutions for any particular objective functions.

A Pareto-front is used when no solution exists that simultaneously minimizes all of the objective functions for a problem. A feasible solution, *X,* is called Pareto optimal if there exists no other feasible solution, *Y,* such that $f_i(Y) \leq f_i(X)$ for *i*=1, 2, … *k* with $f_j(Y) < f_i(X)$ for at least one *j*. In other words, a feasible vector *X* is called Pareto Optimal if there is no feasible solution *Y* that would reduce some objective function without causing a simultaneous increase in at least one other objective function (Rao 2009). Figure 8 shows a graphical representation of the Pareto optimal definition being used to find the Pareto front.

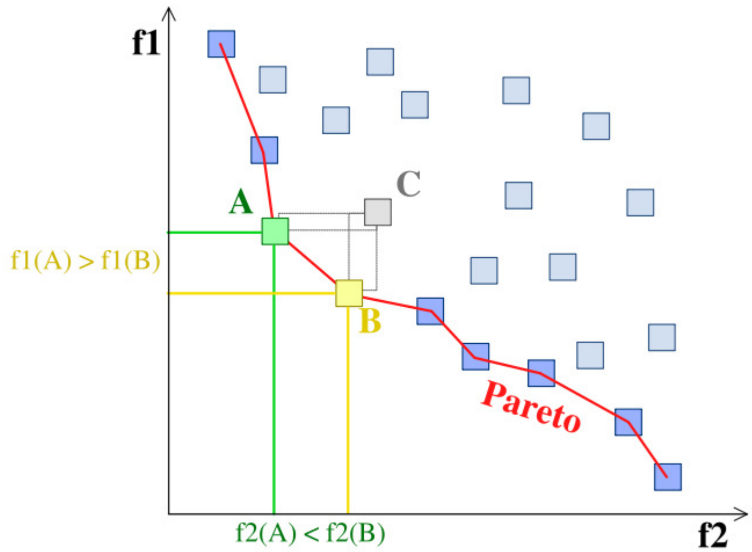


Figure 8: Description of the Pareto-Front and its components extracted from (Stacey 2011)

The benefits of using Pareto optimization are that all objectives are considered simultaneously, every element of the Pareto front is a good solution, and a diversity of solutions is maintained. A simple way to model a multi-objective program is to construct an overall objective function as a linear combination of the multiple objective functions (Rao 2009). Thus if $f_1(X)$ and $f_2(X)$ denote two objective functions, the new, overall objective can be seen in Equation 1.

$$f(x) = \propto_1 f_1(X) + \propto_2 f_2(X) \tag{1}$$

In the objective function, $\propto_1$ and $\propto_2$ are constants whose values indicate the relative importance of one objective relative to the other. The next section summarizes studies that have implemented a GA for building energy optimization.

2.3.2 Genetic Algorithm Use in Building Energy Analysis

The decision support tool proposed in this thesis expands upon the work of previous studies. Previous studies have explored the role that genetic algorithms can play in the optimization of building parameters using energy analysis and simulations techniques. This section will present brief summaries of relevant previous studies.

A study performed in 2002 looked at the optimization of building thermal design and control by multi-criterion genetic algorithm (Wright, Loosemore et al. 2002). The study looked at three objectives for buildings: capital expenditure, operation cost, and occupant thermal comfort. Its focus was on the application of the multi-criterion decision making methods. The multi-criterion decision making process has two elements, "1) the designer must make a decision as to which pay-off between the criteria results is the most desirable design solution; 2) a procedure to search for one or more solutions that reflect the desired pay-off between the criteria." (Wright, Loosemore et al. 2002) It looked at various design days for the analysis of HVAC systems: a summer design day, a winter design day, and a spring design day. The trials were evaluated progressively from a one design day optimization to a three design day optimization. To find the optimum, the design day energy costs versus the thermal comfort were investigated. The metric for operating costs looked at hot water from a gas fired boiler and at chilled water from an electric powered chiller while the metric for thermal comfort was the maximum predicted percentage of dissatisfied. The problem's variables were redistricted to the HVAC system. "The size of the HVAC system is represented by the width, height, number of rows, and number of water circuits of each coil, and the supply fan diameter. The maximum water flow rate to each coil is also a problem variable. The size of the heat recovery device has been fixed as has the return fan diameter. This adds a further 11 problem variables, which together with the control variables, give a total of 200 problem variables." (Wright, Loosemore et al. 2002) The researchers concluded that the multi-criterion genetic algorithm exhibited fast progress toward the Pareto-optimal solutions. Even before a truly Pareto-optimal solution was discovered, the trials yielded feasible solutions within very few generations. This allows designers relatively fast feedback on the potential implications of their design decisions. The study predicted that multi-criterion genetic algorithms based optimizers have great potential and may "be used in the design process to enhance the understanding of the characteristic behavior of the building and design solutions." (Wright, Loosemore et al. 2002) From this study, Figure 9 illustrates the Pareto-front obtained by looking at the two objectives of energy cost and cost pay-off. This study presents a way to compare two different objective functions by using a Pareto-front optimal objective function. The Pareto-front proved to be useful way to examine the pay-off between two objectives. This thesis will plot a Pareto-front of the results in order to graphically see the trade-off in the two objectives considered. Also, this study obtained results close to the truly Pareto-optimal solution after only a few generations. These results show the importance of having carefully selected GA operators, so that the problem will not converge too quickly and get stuck at a local minimum.

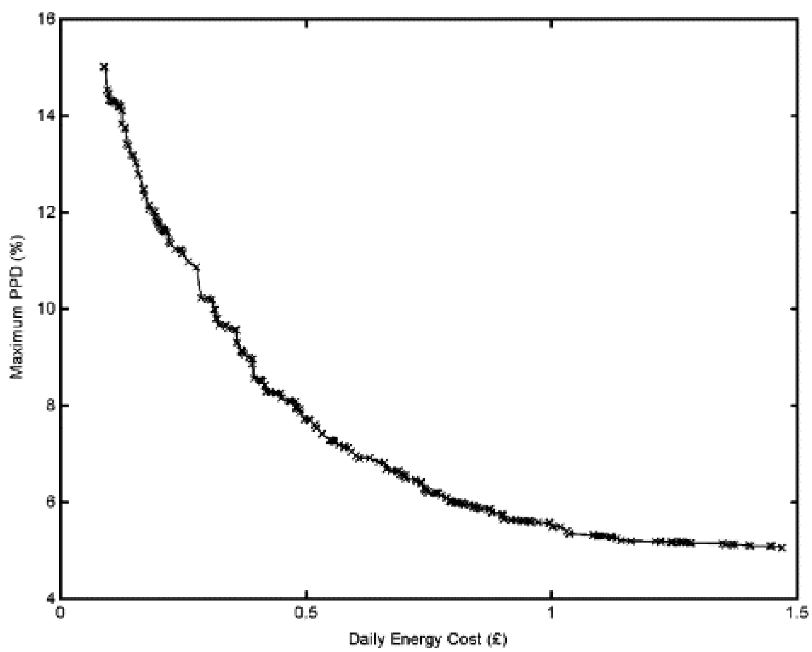


Figure 9: Energy Cost vs. Pay-Off Difference extracted from (Wright, Loosemore et al. 2002)

A study from 2005 applied a multi-objective genetic algorithm to green building design optimization (Wang, Zmeureanu et al. 2005). This study continued the research of multi-objective genetic algorithms with energy analysis, but looked at green building design much more holistically than simply studying the HVAC system. In addition to looking at the design of the HVAC system, the researchers explored the use of using GA's to optimize the building envelope. This included the orientation of building, building shape, window type, window-to-wall ratio, wall construction type, and roof construction. Instead of measuring energy costs, the study looked at the entire energy use, of the building through Life Cycle Analysis (LCA). The researchers concluded the study by identifying the Pareto-optimal front of their trials. The graphical nature of mapping the Pareto-front allowed the identification of explicit trade-offs, as well as easy analysis of the data output. For example, groupings of Pareto-optimal solutions showed discrete regions with different optimal solutions, as can be seen in Figure 10. This study combined the two objective functions into one objective and later plotted the two objective function values to find a Pareto-front. This technique of combining the two objectives into one objective function will be used in this thesis.

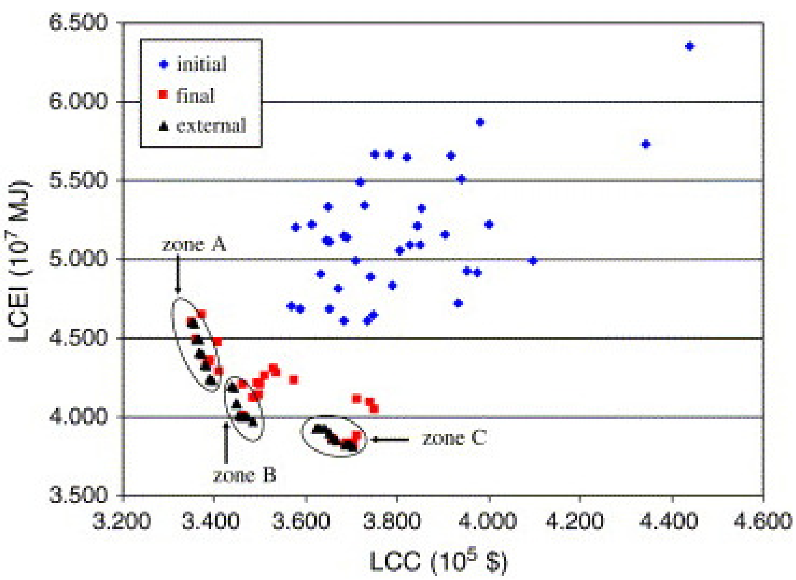


Figure 10: Distributed External Populations in Performance Space extracted from

A study from 2009 investigated using a genetic algorithm for the optimization of a building envelope and the HVAC system parameters of a residential building (Palonen, Hasan et al. 2009). This study concentrated on the features of the GA needed to solve the simulation-based optimization problem. The optimal values of the following five variables were investigated: external wall insulation, roof insulation, floor insulation, window U-value, and type of heat recovery. The objective function took a different approach than the previous studies. Instead of using LCC, they minimized the difference in the LCC versus a reference case. The researchers stated the reason for doing this is that “this way, there is no need to include cost data from all components of the building and system but only the differences produced by the variation of specified parameters between the reference case and any other case.” (Palonen, Hasan et al. 2009) The main focus of this study was to investigate the GA features. The parameters that were varied include crossover, mutation, populations, generations, runs, bits, length of each bit string, and coding of the GA. Figure 11 shows how the total number of simulations affected the results and how much the optimum varied between runs.

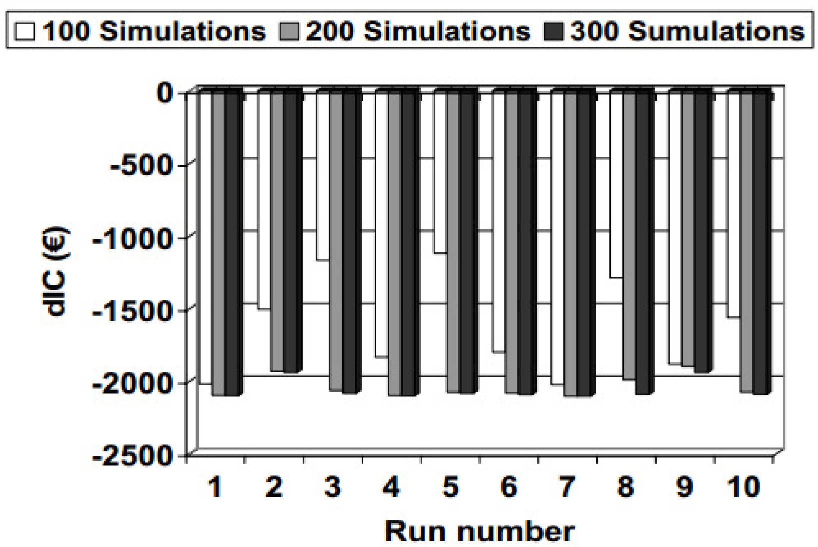


Figure 11: Results from varying simulations extracted from (Palonen, Hasan et al. 2009).

The researchers studied 26 evolutionary strategies in total. The researchers concluded that, to reduce computation time of the GA, the stopping criterion has to be optimized. The researches stated the “actual number of simulations needed to reach optimal or near optimal solutions is in general much less than simulations done with the naïve stopping criterion used in this study." (Palonen, Hasan et al. 2009) They also observed the randomness of using a genetic algorithm stating that "because of the stochastic behavior of the GA it is also concluded that there are no guarantees that GA will reach the optimal solution in every run. However, it is shown that all results obtained with GA are close to optimal." (Palonen, Hasan et al. 2009) This study helped to determine the options of the GA on which this research will focus. The study suggests the GA options, crossover, populations, and generations, had a significant impact on the effectiveness of the GA. The optimal value for these options, in the context of the thesis, will be investigated will be investigated in Chapter 3. Also, this study provided a different approach for an objective function compared to previous studies. The objective function used the difference in LCC instead of just LCC, and this provides an easy way to compare the building costs during optimization without having to collect cost from all of the building components. The idea of using the difference in costs for the objective function is used in this thesis.

A final example of using genetic-algorithms in building energy optimization is a study published in 2010 (Tuhus-Dubrow and Krarti 2010). This study developed a simulation-optimization tool and applied it to optimize building shape and building envelope features. The parameters in this study differed from the previous studies due to the fact they were all discrete and use prices from industry. In addition to looking at the optimum, they provided a sensitivity analysis on the results. The impact of climate, utility rates, and operation strategies were investigated to see how they affect the optimum result. The results of the optimization indicated rectangular and trapezoidal shaped buildings consistently had the best performance (lowest life-cycle cost) across five different climates. However, when all of the building envelope features were allowed to vary, the square shape provided the lowest life-cycle costs in all climates (Tuhus-Dubrow and Krarti 2010). This study showed the sensitivity of the optimal result to utility rates and climates. This thesis will perform a similar investigation for the case study building to explore the sensitivity of the optimal values with varying climatic conditions and energy prices.

In conclusion, a prime reason for using a GA in building energy optimization is the discrete nature of building variables. Differential equations that rely on continuous variables are not effective in finding optimal solutions in building applications. As one NREL research paper explains "for buildings, search methods need to handle discrete variables and should attempt to identify a broad portion of the Pareto-optimal front. Genetic algorithms are applicable to discrete variables and have been studied in the building context by multiple research teams." (Ellis 2006)

However, the studies reviewed showed two main challenges with GAs: computing power and convergence. Most of the studies reviewed used far more computational resources than is accessible to the personal computer user or even a commercial firm. For example, the web-based "best-fit" baseline study of 300,000 simulations took over fourteen days and used two computer clusters in parallel, one 96-core private cluster and one 320-core cloud based cluster (Burton and Shaxted 2012). Also, as previously described, convergence is the term used to describe how long it takes for the GA to find the optimal solution. There may be many local optimums that are inferior to the global optimum within the design space and if the GA converges too quickly, then it may have found a local optimum rather than the global optimum. However, if the GA converges too slowly, then it may never find the optimal solution. Both of these problems will be addressed in Chapter 3 of this research.

2.4 Introduction to Design of Experiments for Building Design

The other optimization method used in this thesis is a Design of Experiments (DOE). This section provides background on DOE and summaries of previous studies that used a DOE for building energy optimization.

2.4.1 Design of Experiments (DOE) Background

Design of Experiments (DOE) is a branch of applied statics that deals with planning, conducting, analyzing, and interpreting controlled tests to evaluate the factors that control the value of a parameter or a group of parameters. Many experiments involve holding certain factors constant and altering the levels of another variable to study the effects of the factors. A strategically planned and executed experiment may provide a great deal of information about the effect on a response variable due to one or more factors (Bower 2013).

The DOE method has a long history of theoretical development as well as applications. Many studies using the DOE method for industry have already been published (Chlela, Riederer et al. 2009). There are many different types of DOE designs available and the choice depends on the objectives of the experimental study and the current state of knowledge of the system. The types are classified into two design families: first order design and the second order design.

A first order design is usually full factorial or fractional factor. Each factor has two levels. These levels are called "high" and "low." The use of two levels is only recommended if the process output is linear between the two levels. A design with all possible high/low combinations of the input factor is called a full factorial design in two levels. When the number of factors is equal to six or greater, a full factorial design will require a large number of runs and is not very efficient. In this case, the use of a fractional factorial design is recommended (Chlela, Riederer et al. 2009). Fractional factorial design is defined as a factorial experiment in which only an adequately chosen fraction of the combinations required for the complete factorial experiment is selected to be run. One example of a fractional factorial design is the Taguchi method.

The Taguchi method involves reducing the variation in a process through robust design of experiments. The overall objective of the method is to produce high quality product at a low cost (Fraley, Oom et al. 2007). The Taguchi method offers ready to use design tables for fractional factorial Design of Experiments. The experimental design proposed by Taguchi involves using orthogonal arrays to organize the parameters affecting the process. Instead of testing all of the possible combinations like the factorial design, the Taguchi method tests pairs of combinations. This allows for the collection of the data necessary to determine the factors that most affect product quality with a minimum amount of experimentation, thus saving time and resources.

Second order design, also known as surface response design, is a three-level design that allows estimating linear, two-factor interactions and nonlinear effects of all factors studied. They are used when there is an indication of nonlinear behavior or when a factorial experiment reveals the presence of nonlinear behavior. Frequently used second order designs are the face-centered composite design, the Box-Behnken design, and the D-optimal design (Chlela, Riederer et al. 2009). The face-centered composite design adds experiments onto a factorial design. These additional experiments are added to faces of the domain formed by the factorial design. This method is used when the parameters are shown to have nonlinear behavior. The Box-Behnken design is used when there is prior information about the existence of nonlinear effects. The experiments are located on the edges of the experimental domain. The D-optimal design is provided by a computer algorithm based on a chosen optimal criterion and the model that will be fitted. These types of computer-aided designs are particularly useful when classical designs do not apply (Chlela, Riederer et al. 2009).

Design of experiments requires a good knowledge of the phenomenon studied in order to consider the most significant factors (Plessis, Filfli et al. 2011). The domain and levels must be selected carefully. If the number of levels is limited over a large domain, the correlation can be very complicated to find or will not be very accurate. DOE have recently been used in studies that focus on the optimization of energy efficient buildings. The next section summarizes these studies.

2.4.2 Design of Experiments Use in Building Energy Analysis

There has not been a significant amount of studies which use a DOE to optimization parameters for an energy efficient building. The following are brief summaries of the studies that can be found on this topic.

A study in 2009 used design of experiments as part of their new methodology for the design of low energy buildings (Chlela, Riederer et al. 2009). The methodology is based on the DOE method; it is intended to perform parametric studies that reduce the required number of experiments. First- and second-order studies are conducted to create a meta-model of the building. The steps used in this study are as follows:

- Factors screening: For any experiment, there are many possible related factors that can be studied. The designer has to screen out the inactive factors, so that the focus can be on the few active factors.
- Construction of a design for the experiments: It is important to determine a DOE approach with an appropriate number of runs and levels for each variable. This is an important early step in the experimental design to ensure that the design space is sufficiently covered. The number of runs and levels depends on the complexity of the considered meta-model.
- Meta-model search: This step includes the selection of appropriate modelling techniques as well as estimation of the model parameters. Several alternative modelling techniques for a given data set can be considered.
- Test of the meta-models: Several alternative modelling methods have to be considered to find the most suitable model.
- Further study: If a satisfactory meta-model based on the data set cannot be developed, it may be because of a poor design selection or the meta-model choice. If the latter is the problem, other techniques (Neural network, Bayesian approach, etc.) may be more efficient.

The meta-models that were developed showed good results for the annual heating demand and final energy consumption of the building, and less accurate results were obtained for the annual cooling demand. Figure 12 shows the different methods of the DOE that were used in this study. The seven DOE methods used in this study are the starting point for the DOE design selection of this thesis.

Design table		Required simulations number
1st order	Taguchi L32	32
	Taguchi L64	64
2nd order	Taguchi L81	81
	CCD L32	51–55
	CCD L64	83–87
	Box–Behnken	177
	D-optimal	81–110

Figure 12: Design of Experiments design table, extracted from (Chlela, Riederer et al. 2009)

A study in 2011 used design of experiments to develop a low energy building model (Plessis, Filfli et al. 2011). This paper combined methods of model order reduction and DOE to investigate low energy building models. This paper had two main steps: first it reduced the order of the model, and then it found a multi-polynomial expression of the reduced model coefficients. Four parameters were investigated with five different levels for the DOE. A full factorial design for this problem consisted of 625 experiments. A D-optimal design composed of 15 experiments (three main levels were considered) was used for comparison. The results from the paper compared a D-optimal design to a full factorial design. The results showed that the D-optimal design results were slightly less precise than the full factorial design. The results from the design of experiments were not discussed, just the fact that a D-optimal design can be used in place of a full factorial design when investigating model order reduction.

These studies were the only studies that used a DOE for building energy optimization that could be found. The studies show that using a DOE with a building energy model can help to see the effect that parameters have on the design space using a small number of simulations. In order to use a DOE design for this thesis the program, JMP Pro 11, is used. The next section provides a description of this software.

2.4.3 JMP Pro 11

In order to perform the DOE analysis, JMP Pro 11 is used to create and analyze the DOE design. For nearly 25 years, JMP statistical discovery software from SAS has been used by scientists, engineers, and other data explorers in almost every industry and government sector. JMP is a powerful statistical analysis linked with interactive graphics, in memory and on the desktop (JMP 2013).

JMP offers a proven and practical approach using a DOE for exploring and exploiting the multifactor opportunities that exist. JMP offers both a custom designer, which constructs a design to fit one's problem, and preloaded designs. The preloaded designs include classical screening (fractional factorial), response surface, full factorial, nonlinear, and mixture designs, as well as advanced designs, including accelerated life tests and designs for computer simulation, such as cluster-based, space-filling designs that allow for inequality constraints on factors. Also, JMP is the only software that implements definitive screening designs. Definitive screening designs are used to efficiently and reliably separate the vital few factors that have substantial effects from the trivial many that have negligible impacts. A traditional screening design may erroneously screen out a factor that actually has a strong curved effect. If there are two-factor interactions, then traditional screening designs will require follow-up experimentation to resolve the ambiguity. Neither of these limitations exist when using definitive screening designs (JMP 2013).

2.5 Conclusion

This chapter presented summaries of previous studies that had similar goals to those outlined in Chapter 1. The studies highlighted proven optimization methods and effective ways to implement a simulation-optimization approach to aid in the design of buildings. A genetic algorithm and design of experiments were chosen as the optimization methods for this thesis and this chapter presented summaries of studies implementing these optimization techniques for building energy optimization. The studies reviewed showed the benefits of using these techniques and presented some of the challenges that need to be overcome in order for the optimization techniques to be efficient and accurate.

The objective of this research is to create and study a decision support tool that can be used to aid in the design of an economically feasible Net Zero Energy vaccine warehouse for the developing world. The proposed decision support tool uses proven optimization methods to study the optimal parameters of a vaccine warehouse. A similar application has not been seen in previous building energy optimization studies. Most of the previous studies focused on residential buildings in developed countries, and this thesis focuses on designing a NZEB for developing countries. Also, this thesis performs sensitivity analysis larger than those seen in the studies reviewed. Two construction practices, three photovoltaic system prices, and five different climates around the world are investigated in order to show the sensitivity of the optimal design solution. Chapter 3 presents the details of the decision support tool including details of the simulation-optimization approach, the design problem, and case study building to be studied with the tool.

CHAPTER 3

METHODOLOGY

The goal of this thesis is to create and study a decision support tool that can be used to aid in the design of an economically feasible Net Zero Energy vaccine warehouse for the developing world. The proposed tool will use a simulation-optimization approach that combines simulation software with optimization techniques in order to determine the optimal building parameters. This tool is used to study a vaccine warehouse by conducting five different sets of tests. A description of the five trials can be seen in Table 6. The first four trials are used to validate the decision support tool and obtain results that can be used to create generalized construction recommendations. The final trial suggests a combination of two optimization techniques, a genetic algorithm and design of experiments, to aid in the design of the building through the design process.

Table 6: Trials performed in this research

Trial Run	Description
Trial 1	Construction sensitivity analysis using a Genetic Algorithm
Trial 2	Climate sensitivity analysis using a Genetic Algorithm
Trial 3	PV sensitivity analysis using a Genetic Algorithm
Trial 4	Parameter sensitivity analysis using Design of Experiments
Trial 5	Two-Step Process with Genetic Algorithm and Design of Experiments

This chapter outlines the methodology utilized in this research and is divided into four sections. The first section describes the vaccine storage facility that was designed for this thesis. The second section provides descriptions of the steps of the simulation-optimization approach and details of the proposed two-step process investigated in Trial 5. The third section summarizes the parameters and framework set up of the proposed decision support tool. The final section describes the research's goals, as well as its limitations.

3.1 Case Study Building

This section describes the general scope and conceptual design of a new national vaccine storage facility in Tunis, Tunisia. The warehouse will be the sole national vaccine store from which all of the regional stores are re-supplied. The new national vaccine storage facility is designed to support the predicted population size of Tunisia for the year 2020 of 12.6 million people. The warehouse will store vaccines three different vaccine groups: routine immunization 0-18 months, school vaccination in first trimester, and rabies vaccines. Details of the vaccines that are included in these vaccine groups can be seen in Table 7.

Table 7: Vaccines that will be stored in the warehouse

Service	Vaccine	Doses per vial	Target fraction of pop.	Vaccine utilization rate
Routine	BCG	20.00	0.0116	50.00
Routine	DT	10.00	0.0116	75.00
Routine	MR	10.00	0.0100	60.00
Routine	OPV	10.00	0.0116	75.00
Routine	IPV	1.00	0.0116	95.00
Routine	Rota_liq	1.00	0.0100	95.00
Routine	DTP-HepB-Hib	10.00	0.0116	75.00
Routine	PCV-13	1.00	0.0116	95.00
School	MR	10.00	0.0116	60.00
School	Rubella	10.00	0.0084	60.00
School	HPV	10.00	0.0042	75.00
School	Td	10.00	0.0082	75.00
School	OPV	10.00	0.0084	75.00
School	OPV	10.00	0.0081	75.00
School	OPV	10.00	0.0077	75.00
Rabies	Rabies AV	1.00	0.0010	95.00
Rabies	Rabies V	1.00	0.0049	95.00

The anticipated population number for Tunisia in year 2020 was translated into required storage volumes of vaccines and supplies for the warehouse using the Vaccine Store Sizing Tool

(VSST) developed by Andrew Garnett in conjunction with Project Optimize (WHO 2010). The VSST is formatted as a Microsoft Excel® spreadsheet, and calculates volumes based on vaccine specific national data for parameters such as Volume per Dosage, Wastage Rate, and Target Group Percentages for each vaccine. From this information, the tool generates an estimated net raw volume of supplies to be stored at each temperature. The information is used to estimate store size for three different storage methods - shelf storage, pallet standing, and pallet racking - based on aisle widths, bay depths, and other method-specific parameters. This tool was used in order to help determine the size of each room. It was assumed that vaccines will be shipped in the insulated shipping containers in which they are stored, the warehouse will be re-stocked every 4-6 months, outgoing shipments to the regional stores will occur either quarterly or monthly, and the warehouse will store only vaccines and vaccine-related supplies, with the only exception being for pharmaceutical products. In order to store all of these vaccines and vaccine-related supplies, the warehouse will have a cold room, freezer room, controlled ambient storage area, and ambient storage area. All of the storage areas will use four-tier pallet racking systems and have store over-sizing factors of 25%. The quarantine area for each storage section will be a fenced pallet rack bay; it is assumed that only 1% of the total volume of each storage area is required for quarantine.

Next, the building requirements were determined. It was assumed that the staff will consist of both men and women and include four office workers and five warehouse workers. It was assumed that the warehouse will have operational hours between 8 am and 5 pm for six days a week and will need to accommodate simultaneous receiving and shipping. Table 8 shows the room breakdown determined in order to meet the building and storage requirements.

Table 8: National Vaccine Storage Room Breakdown

Room	Area (m^2)	Volume (m^3)	Number of Pallets	Temperature Range of Room
Cold Room Storage Area	74	444	88	+2˚C to +8˚C
Freezer Room Storage Area	13	78	12	-15˚C to -25˚C
Controlled Ambient Storage Area	32	192	16	+15˚C to +25˚C
Ambient Storage Area	132	858	160	+15˚C to +32˚C
Office and Kitchen Mezzanine	66	429		+20˚C to +24˚C
Plant Room and Workshop	146	949		+15˚C to +25˚C
Incoming/Outgoing Goods Area	235	1,528		+15˚C to +25˚C

The table shows the details of each of the room in the warehouse. The warehouse will have four storage areas including a cold room, a freezer room, a controlled ambient room and the ambient storage area. The table includes the details of the storage areas including the volume of the room, the number of pallets that can be stored in the area, and the temperature range of the room. The temperature range for each room specifies the temperature the room must maintain to ensure the vaccines remain viable. The ambient storage area will provide gross capacity for a minimum of 5 m^3 of diluents in addition to storage space for pharmaceutical products. These space requirements were used to create the building layout.

The building layout was designed to provide enough room to store all of the vaccines and vaccine-related supplies based on the results from the VSST, to be functional, and to be energy efficient. The first floor layout can be seen in Figure 13. The building is oriented so that the shipping and receiving docks and areas are located on the north side of the building, which is closest to the street from where the trucks will come. An office is located in the northeast corner of the building and provides an efficient way to view the warehouse operations; in addition, it allows the warehouse manager to view all incoming and outgoing trucks. The refrigerated storage is located in the middle section of the warehouse, with only one wall adjacent to an external wall, minimizing the transmission of heat from the outside. The plant area is located along the entire south wall of the building.

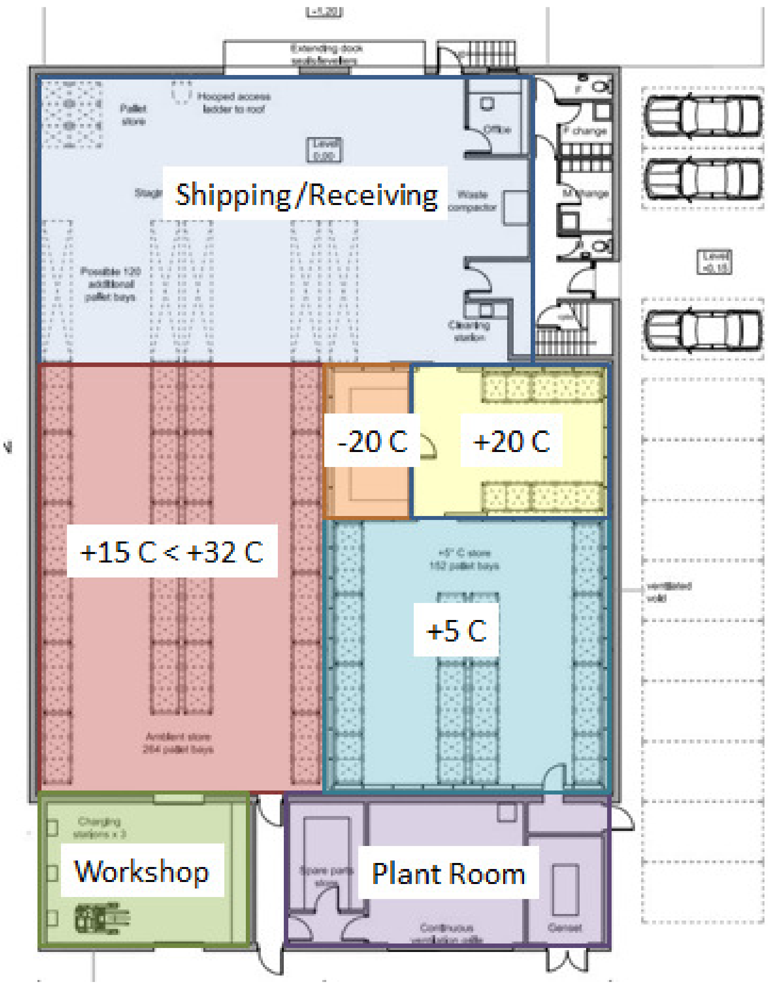


Figure 13: Building Layout, First Floor

The shipping and receiving area will have two docking bay doors warehouse so the warehouse can accommodate simultaneous receiving and shipping. The bay doors will be fitted with dock shelters and insulated roller shutter systems to minimize energy loss and for weather protection of facilities and products. Also, the bays will be fitted with dock leveling equipment to accommodate a range of vehicles. A pallet store will be located adjacent to loading and unloading area for easy and quick access. This adaptable space will be used for receiving, order assembly, and shipping. This area also will be equipped with work tables that are 900 mm high, space for assembling orders onto pallets, space for storing packaging materials and packaging tools, filing trays for storing order vouchers and packing lists, and space for the storage of assembled pallets that are awaiting shipping. The basic flow of goods through the warehouse is shown in the Figure 14.

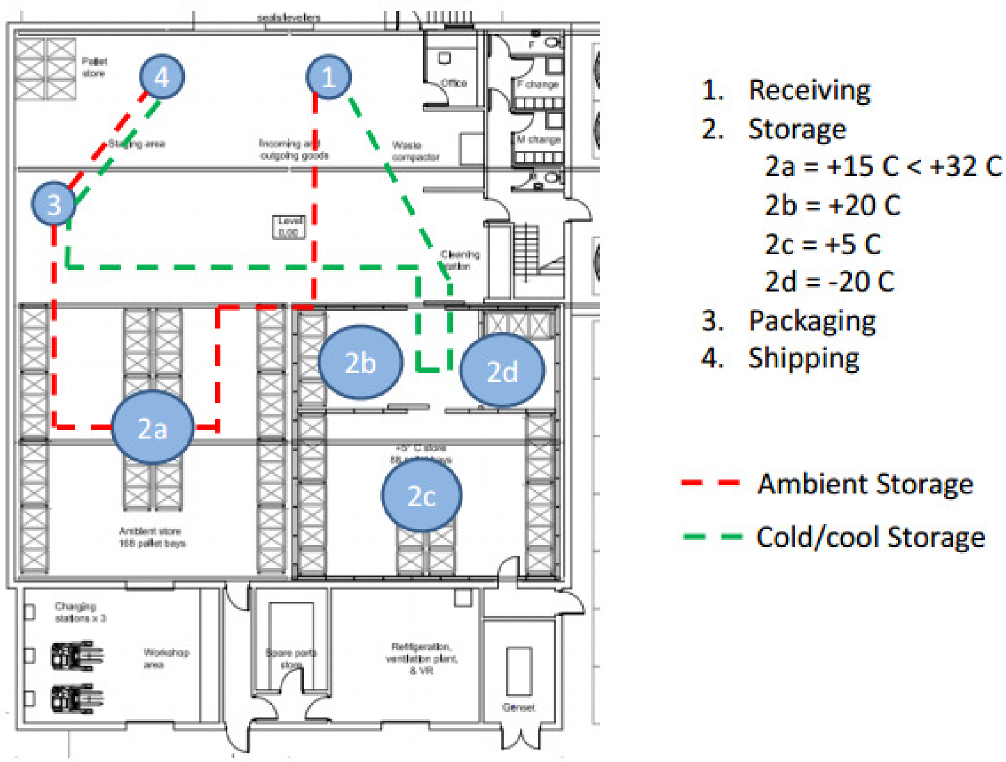


Figure 14: Material flow through warehouse

The vaccine storage facility will be located on an access street off Rue Mongi Slim in Tunis, Tunisia. The proposed project is located on the empty plot of land adjacent to the existing DSSB warehouse and vehicle repair shop. The proposed building is located in the southeast corner of the plot, to allow for vehicle access. Figure 15 shows the truck turning diagram for the site.

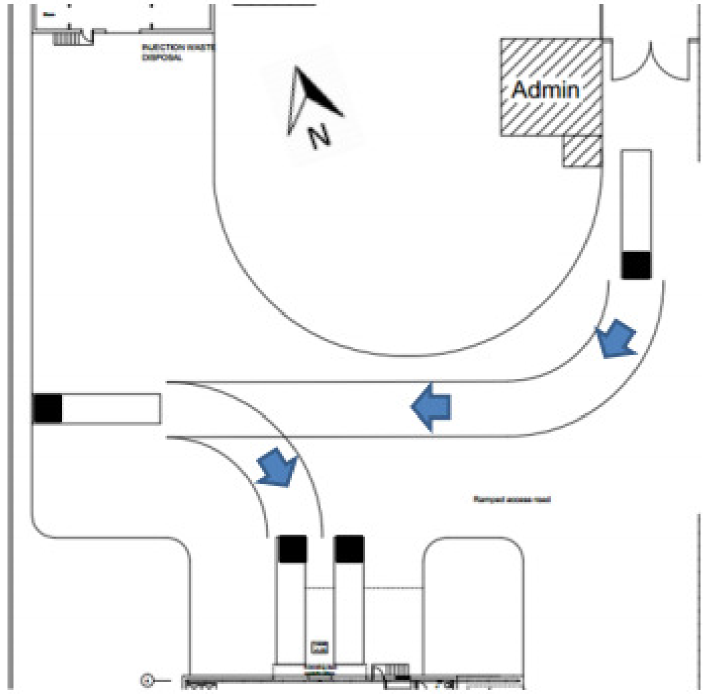


Figure 15: Truck turning diagram

Energy consumption of the warehouse was determined by using a computer energy model in EnergyPlus version 8.0.0. The EnergyPlus model was created by another student at the Georgia Institute of Technology, David Pudleiner (Pudleiner 2014). The energy model incorporated many green aspects including highly insulating materials, reduced air infiltration, innovation fans that maintain uniform temperature and reduce stratification, energy efficient equipment, energy efficient lighting, high efficiency natural gas heating, and a building information management system (BIMS). The highly insulating material included 150 mm of floor insulation under the cold room and freezer room, 150 mm structurally insulated panels for the exterior walls, 150 mm of polyisocyanurate insulation for the roof, and 150 mm structurally insulated panels for the walls and roof of the cold storage areas. The warehouse lighting and window orientation was optimized to make the best use of day lighting for shipping, receiving, and the offices. Double-pane argon filled windows were chosen since they are highly energy efficient. Fluorescent T8 lights are used with occupancy sensors and daylight sensors. The sensors will reduce the energy consumption used by lighting. For the HVAC, a parallel sensible cooling and heating unit, consisting of a mini-split heat pump, will be used for the ambient storage areas and offices. A BIMS will be added to the building to make best use of ambient energy resources, including automatic ventilation control openings, and control lighting systems.

Assumptions about the average operations of the warehouse were incorporated in the computer model. These assumptions include one forklift being operated for eight hours each work day and charged every night, the controlled ambient room, freezer room and cold room are open for nine minutes of every hour of building operation, the occupancy load of the five works is split evenly by floor area between the warehouse zones, the warehouse employees will take a shower at the start of their shift, with the average shower lasting seven minutes, and, on average, there will be one truck per day that will be loaded or unloaded for 2 hours.

Once the energy model was created, the simulation was completed and the annual energy usage of the building was determined. Then, a renewable energy system size had to be determined so that the building would accomplish net zero energy. Solar photovoltaic (PV) panels were chosen to be the only source of renewable energy. One main reason for this choice is the Tunisia laws for gird interconnections. Tunisia's policies for renewable energy and energy efficiency make this project feasible. The law on energy conservation, dated August 2003 was amended on February 9, 2009 to allow independent production of electricity based on renewable energy. This means that large consumers of electricity will be able to produce electricity for their own consumption from renewable sources, and sell their electricity surplus back to the grid. This law gives to any institution engaged in industry or in the service sector, equipped for its own use with an energy efficient cogeneration facility the right to transport the electricity produced on the national grid to its consumption points and the right to sell surpluses exclusively to Société Tunisienne de l'Electricité et du Gaz (STEG), up to a given upper limit in the frame of a standard contract approved by the National Agency for Energy Conservation (ANME). The ability to sell surplus electricity to the grid is necessary for the successful implementation of this project. Due to these laws and the high solar potential for the area, a grid-tied PV system is used.

It was decided that the warehouse will be grid-tied, so that when the warehouse requires more energy than the PV panels can supply, the difference is made up with grid electricity. Inversely, when the panels are producing more energy than the warehouse demands, the excess electricity will be sent back to and sold to the grid. The final model predicted a total annual energy consumption of 73,695 kWh and 196 photovoltaic modules were required to accomplish NZE. The photovoltaic system will have a tilt altitude of 10 degrees and be orientated south. All of the final building drawings can be seen in Appendix A. These drawings include the ground floor layout, first floor layout, roof layout, site layout, and the elevations. A design of experiments was used to investigate which parameters had a significant effect on the building energy usage, and the results from the DOE were used to design the building presented in this section. However, this DOE analysis did not consider construction costs. In order to determine the cost-optimal NZE solution, the building components need to be investigated by considering construction cost and energy usage. The next section discusses the framework of the proposed decision support tool that will determine the optimal parameters by considering construction costs and energy usage.

3.2 Decision Support Tool Framework

The decision support tool uses a simulation-optimization approach in order to aid in the design of an economically feasible NZE vaccine warehouse. This section describes the framework of the simulation-optimization method. The method uses two optimization techniques, a Genetic Algorithm (GA) and a Design of Experiments (DOE), in order to find the optimum building parameters. The following sections describe the initial set up for the research and the steps of the simulation optimization approach. The final section suggests a two-step process of using the GA and DOE together to aid in the design of a building from the conceptual phase to the final design.

3.2.1 Energy Model Set Up

This section outlines the basic set up performed to initialize the case study building to be studied with the proposed decision support tool. In order for the decision support tool to be used in real world applications, it was desired for the tool to be accessible on all computers. Therefore, all simulations were performed on a standard personal computer with four-core processing capabilities and a 2.3 GHz processor running Windows 7, 64 bit. All screenshots provided in this section are taken from the researcher's personal computer to illustrate the steps performed.

The experiment was initialized with the creation of the energy model of the building designed in Section 3.1. The energy model was created in part using the EnergyPlus simulation add-on programs EP-Launch and IDF Editor. The energy model used in this thesis was created by another student at the Georgia Institute of Technology, David Pudleiner (Pudleiner 2014), and was modified to fit the design problem of this thesis.

Figure 16 shows a screenshot of the EP-Launch program. The EP-Launch program is the add-on program that is used to run the simulation. The two input files shown in the screenshot are the energy model data file, IDF file, and the weather file for Tunis, Tunisia. The series of the buttons on the lower portion of the dialogue box indicate the many output forms that are potentially created through the energy simulation.

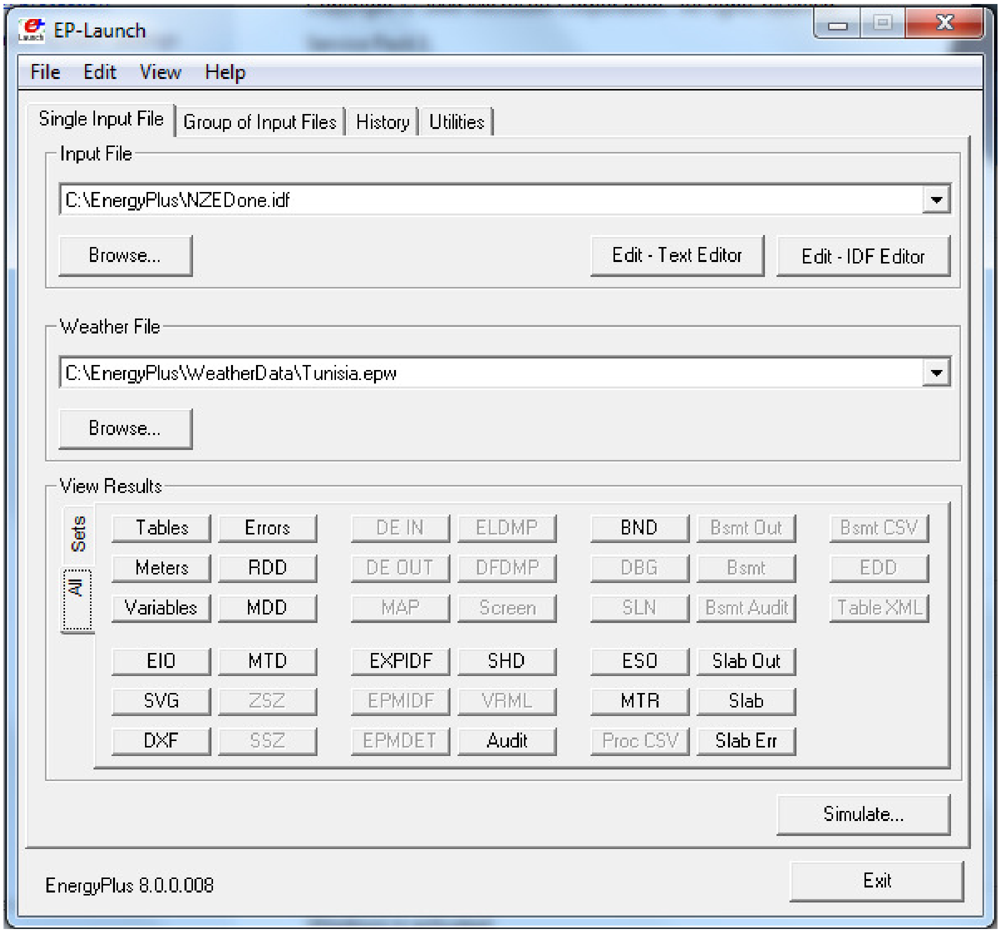


Figure 16: Screenshot of EP-Launch Used for the Energy Model

Figure 17 shows part of the actual energy model used for simulations using the IDF Editor program. All data pertaining to the energy model can be created or edited using this dialogue. For example, the screenshot provided highlights the materials and material properties found in the energy model. The materials are compiled into construction assemblies, which are subsequently assigned to building geometries.

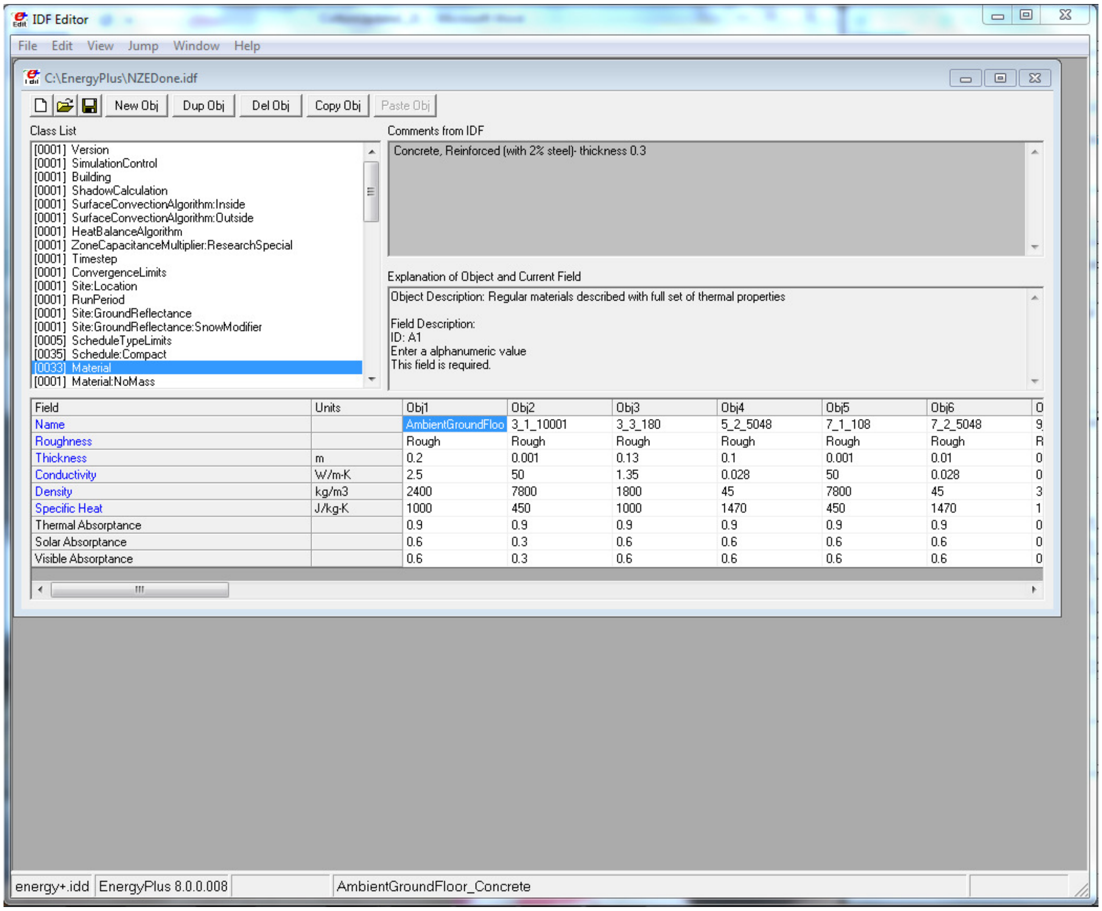


Figure 17: Screenshot of IDF Editor used for the Energy Model

Once the IDF was complete, the simulation-optimization method was created. The next section describes the steps and components of the simulation-optimization approach.

3.2.2 Simulation Optimization Approach

Two different optimization techniques, a genetic algorithm and a design of experiments, are used to investigate the optimal solutions of the case study building. First the optimum solution in terms of discrete variables is investigated with a genetic algorithm. After this is complete, a design of experiments is performed to further investigate the design space by showing the effects of each parameter on the objective function. The section outlines the steps of the simulation-optimization approach of each of the optimization techniques.

3.2.2.1 Genetic Algorithm Process

The first three trials conducted in this thesis use a Genetic Algorithm (GA) for the optimization technique in the simulation-optimization approach. The GA is combined with two simulation programs, EnergyPlus and PVWatts, under the MATLAB environment as shown in Figure 18.

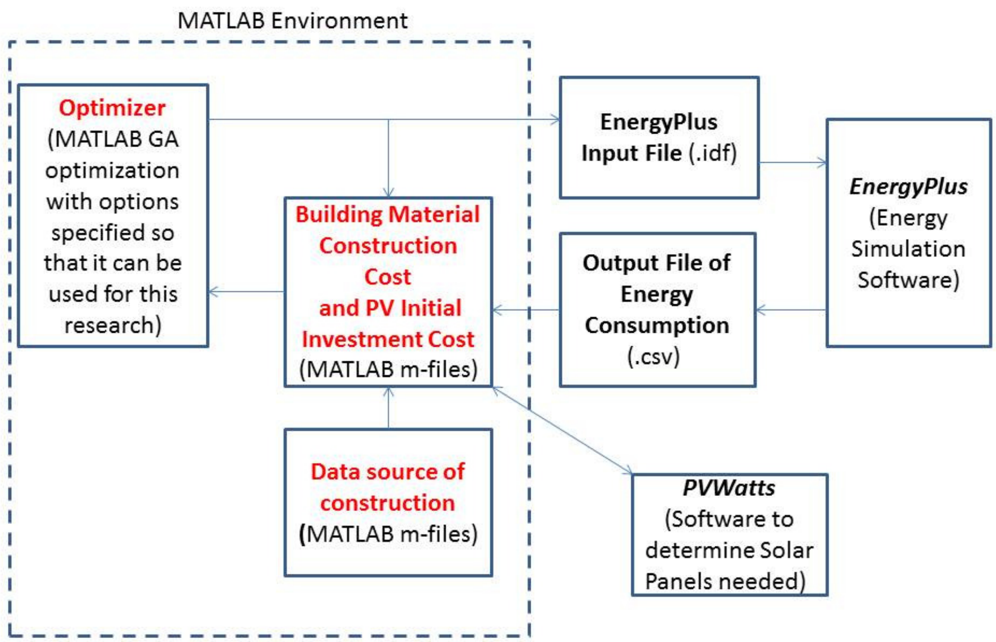


Figure 18: Components and their relationships for simulation-based optimization

The names that are in *italics* are of the programs that are used. The names in red are orginial contributions of this thesis. The construction data prices were collected from RSMeans and previous studies, and the data prices are put into an m-file to be used in the optimization. RSMeans is a construction estimation database that is used by professional estimators for up to date labor, materials, and overhead costs for specific project types and locations. RSMeans data is typically used by professionals to help to calculate the costs of construction prior to beginning construction. The building material construction cost and PV initial investment m-file uses the data from all of the compoents in order to find the value of the objective function. The details of the simulation-optimization approach are outlined below:

Step 1: An initial population of 25 solutions is created by the optimizer, the built-in Matlab GA function with modified options. For each solution, the values of each variable are chosen at random. Therefore, each solution in the initial population is a random selection within the design space.

Step 2: Matlab uses one chosen solution to modify an IDF file. The chosen solution is the next solution in the generation, and Matlab will know what solution need to be investigated next. After the IDF file is written in Matlab, a DOS command is used to simulate the modified IDF file in EnergyPlus. After EnergyPlus finishes its simulation, it outputs a common-separated values (CSV) file containing the electricity use for the facility and ideal loads zone for each zone.

Step 3: Matlab calculates the total building material construction cost and the PV initial investment costs. The material construction costs are calculated for the specified parameters by using the construction data m-file. To calculate the PV initial investment cost, Matlab first reads data from the EnergyPlus output CSV file. The ideal loads are multiplied by the selected COP and then added together with the electricity usage of the facility to determine the annual energy usage of the building. The annual energy usage is then sent to PVWatts under the SAM Simulation Core (SSC) software development kit (SDK) (NREL 2010) in order to calculate the number of solar panels needed to accomplish NZE. The PV system size is sent back to Matlab, and the value is converted into a cost by using an estimated PV price of $4.50/Installed Watt (Goodrich, James et al. 2012). The material construction costs and PV cost are combined in order to find the value of the objective function. The process will restart at Step 2 until the objective function value is calculated for all of the 25 solution in the generation. Once the 25 objective values are complied, they are then sorted by rank.

Step 4: The next generation of 25 solutions is created from the current solution set. These solutions are often called children during this stage. The algorithm selects a group of individuals in the current population, called parents, who contribute their genes, the entries of their vectors, to their children. The algorithm usually selects individuals that have better objective values as parents. There are three elite children in this study. Elite children are the individuals in the current generation with the best fitness values, and they automatically survive to the next generation. There is also a crossover fraction of 0.8. This is the fraction of individuals in the next generation, other than elite children, that are created by crossover. With these parameters, there are three elite children, eighteen crossover children and four mutation children. Crossover children are created by selecting vector entries, or genes, from a pair of individuals in the current generation and combines them to form a child. Mutation children are created by applying random changes to a single individual in the current generation to create a child.

Step 5: The children become the solution population for the next geneation, and the process restarts at Step 2. If it is the final generation, the children become the last solution population. A set number of 30 geneations is used for this study.

In Step 2, Matlab modifies an incomplete IDF file. To do this, first an incomplete IDF file was created that does not include any of the parameter that are being investigated. This IDF cannot be simulated in EnergyPlus until the missing data is written into the file. Matlab copies this incomplete file into a new file called "NZEDone". This copied file is created so that the orginial IDF file remains unmodified and is consistent for every run in the optimization. The Matlab code opens “NZEDone” and inserts the missing parameter descriptions so that the IDF file is completed and can be simulated. Figure 19 shows a screenshot of part of the code written in Matlab to write the new window description in the IDF file. First the Matlab code opens the IDF file and then starts to write the new window properties. Two components of the window properties are changed in the optimization. These two properties are written as the variables, “windowu” and “windowshgc”, so that they can be changed for each solution from the optimizer. Once the new material property is written, Matlab closes the IDF file. All of the parameter descriptions are written in this manner.

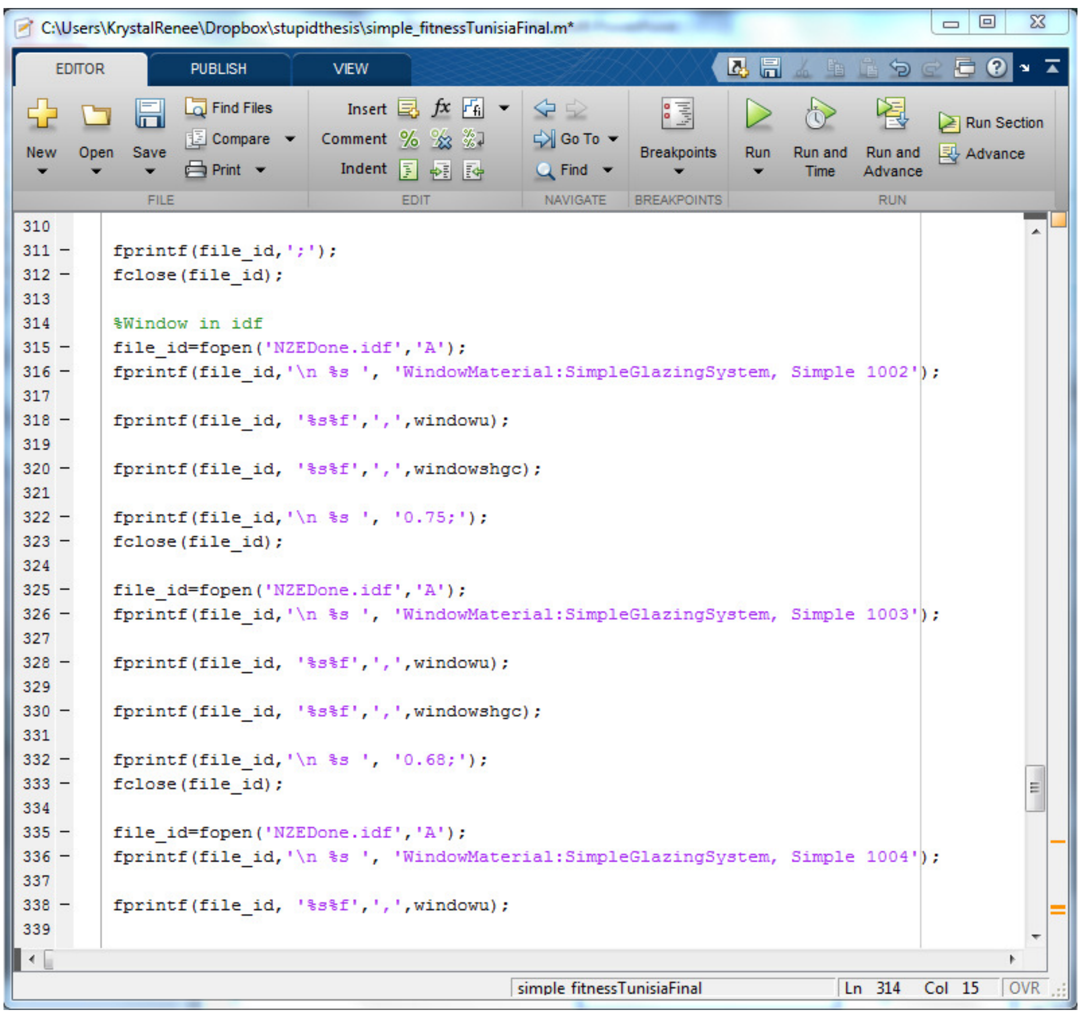
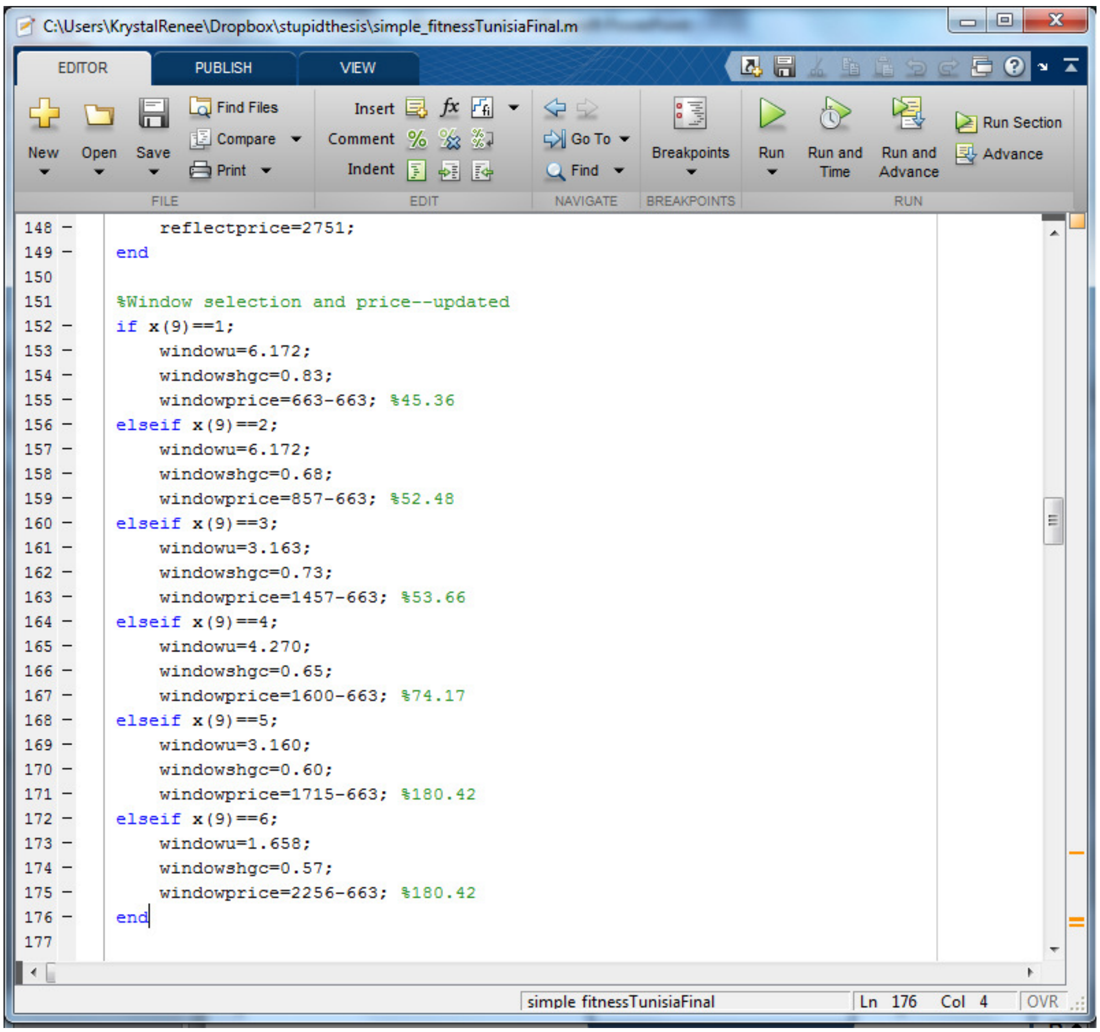


Figure 19: Screenshot of Matlab modifying IDF

After the IDF is completed, a dos command performs the simulation. The code used in the Matlab file is “`dos('runeplus NZEDone Tunisia')`”. This code runs the file “NZEDone” with the weather file “Tunisia” using the EnergyPlus program. The next step of the process finds the initial investment costs. To do this, Matlab finds the cost associated with the variable selected. Figure 20 shows a screenshot from the code on the window variable. Variable 9 in the optimizer is the window and it is given a range of 1 to 6. Based on the solution from the optimizer, the assosiated cost is chosen and stored to be later used by the cost function.



```
    reflectprice=2751;
end

%Window selection and price--updated
if x(9)==1;
    windowu=6.172;
    windowshgc=0.83;
    windowprice=663-663; %45.36
elseif x(9)==2;
    windowu=6.172;
    windowshgc=0.68;
    windowprice=857-663; %52.48
elseif x(9)==3;
    windowu=3.163;
    windowshgc=0.73;
    windowprice=1457-663; %53.66
elseif x(9)==4;
    windowu=4.270;
    windowshgc=0.65;
    windowprice=1600-663; %74.17
elseif x(9)==5;
    windowu=3.160;
    windowshgc=0.60;
    windowprice=1715-663; %180.42
elseif x(9)==6;
    windowu=1.658;
    windowshgc=0.57;
    windowprice=2256-663; %180.42
end
```

Figure 20: Screenshot of Matlab cost data

In order to calculate the PV system needed to accomplish NZE, the PVWatts software is used. EnergyPlus outputs the annual building energy usage. PVWatts works by inputting a PV system size and the program outputs the energy production in kilowatts over a year for the given climate. Therefore, in order to use this program, the code iteratively searches for the needed PV size. The size of the PV system is increased in 0.1 kW increments until the necessary yearly watt production is greater than or equal to the yearly energy consumption of the building. Figure 21 shows the code written in Matlab to do this.

```
watts=0;
systemsize=150;
t=0;

while systemsize<170
systemsize=systemsize+0.1;

cd C:\Users\KrystalRenee\Dropbox\Learning\PVWatts\languages\matlab

SSC.ssccall('load');

% create a data container to store all the variables
data = SSC.ssccall('data_create');

% setup the system parameters
SSC.ssccall('data_set_string', data, 'file_name', '../../examples/Tunisia.epw');
SSC.ssccall('data_set_number', data, 'system_size', systemsize);
SSC.ssccall('data_set_number', data, 'derate', 0.77);
SSC.ssccall('data_set_number', data, 'track_mode', 0);
SSC.ssccall('data_set_number', data, 'tilt', 10);
SSC.ssccall('data_set_number', data, 'azimuth', 180);

% create the PVWatts module
module = SSC.ssccall('module_create', 'pvwattsv1');

% run the module
ok = SSC.ssccall('module_exec', module, data);
if ok
```

Figure 21: Screenshot of PVWatts code.

The results from the optimization are output into two files. The first output file will contain the parameter selection and objective value for the 25 tests in each genenation, and this file is output after every generation. This file is used to see the optimium result from each generation and observe the number of geneations it takes for the GA to converge to the optimum solution. The other output file contains the value of the two cost fuctions at every point simulated. The values from the two cost functions are later plotted in order to identify the Pareto Front. As previously mentioned, two optimization techniques are used for the decision support tool. The details of the design of experiments simulation-optimization approach are described in the next section.

3.2.2.2 Design of Experiments Process

After completing the GA, the optimal values did not correlate to climatic conditions for all of the parameters. A Design of Experiments (DOE) method was used to further investigate the design space so that generalized recommendations could be created. The DOE results will be used to study the main effects and the interactive effects between the parameters. To use the DOE, first a matrix for the chosen DOE design is created in JMP Pro. The setup of the simulation optimization approach using a DOE matrix can be seen in Figure 22.

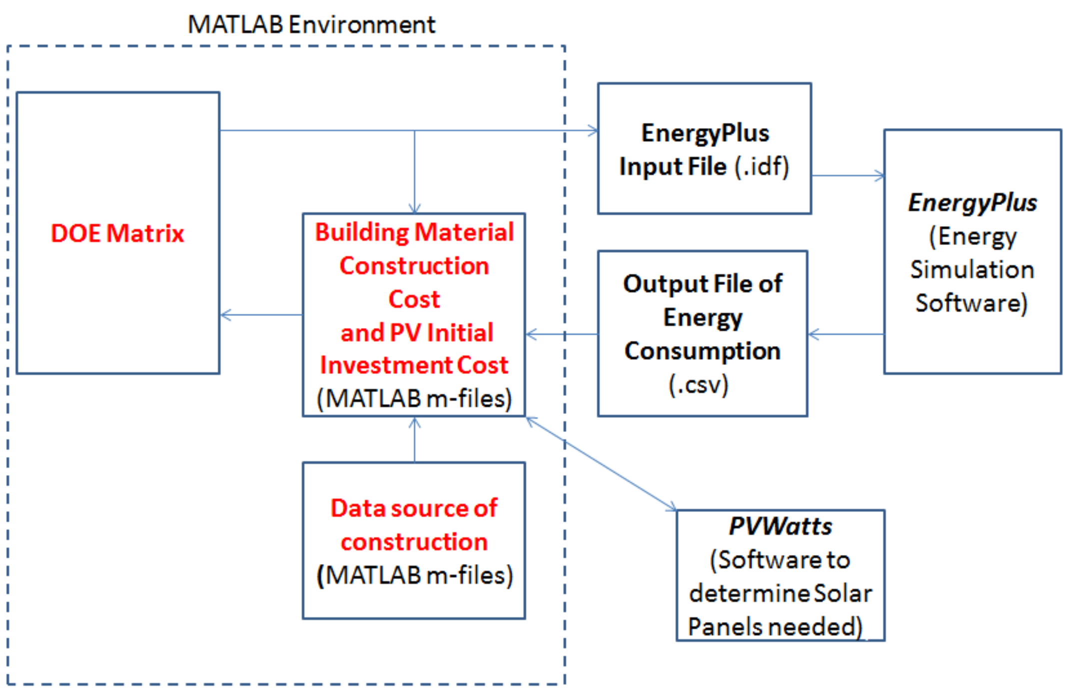


Figure 22: Components and their relationships for simulation-based optimization

A DOE is non-evolutionary optimization and will have different steps from the evolutionary GA process previously described. The GA process needs data from previous generations in order to decide the next test, but the simuations needed for the DOE are known before the optimization is started. Since all of the needed simulations are known, the process is more straight forward than the GA process. The details of the steps are outlined below:

Step 1: Factors and their ranges are input into the DOE design table in JMP. JMP produces a matrix that provides all of the necessary simulations needed to investigate the effects of the parameters.

Step 2: The DOE matrix is input into Matlab. Matlab reads one complete solution set, a row in the DOE matrix, to find the parameter values used to modify the IDF file. Then a DOS command will be used in Matlab in order to simulate the new IDF file in EnergyPlus. After EnergyPlus finishes its simulation, it outputs a CSV file containing the electricity use for the facility and ideal loads for each zone.

Step 3: Matlab calculates the total building material construction cost and the PV initial investment costs. The material construction costs are calculated for the specified parameters by using the construction data m-file. In order to calculate the PV initial investment cost, the Matlab file reads data from the EnergyPlus output CSV file. The ideal loads are multiplied by a COP and then added together with the electricity usage of the facility. The annual energy usage is then sent to PVWatts under the SAM Simulation Core (SSC) software development kit (SDK) (NREL 2010) in order to calculate the number of solar panels needed to accomplish NZE. The PV system size is sent back to Matlab, and the value is converted into a cost by using an estimated PV price of $4.50/Installed Watt

(Goodrich, James et al. 2012). The material construction costs and PV cost are combined in order to find the value of the objective function.

Step 4: The objective function is added into a new column in the matrix that corresponds to the row that was just simulated. Then a loop inside the Matlab code moves to the next row of the DOE matrix and the process restarts at Step 2. Once the matrix is completed, the completed matix is entered into JMP Pro 11 for analysis.

In Step 1, factors and their ranges are input to the DOE Design Creater in JMP Pro 11. Figure 23 shows a screenshot of the input factors for the full factorial design. The DOE aims to find the set of parameters that have the greatest effect on maximizing the value y, which is the objective function for the problem. The factors are entered as catergorial parameter, because this thesis uses discrete variables. Each parameter has two levels, meaning the DOE investigates the effect of each parameter at two different values. For example, the first item in the DOE is the roof insulation with catergorial parameter values of 0 and 0.06. This means that roof insulation thicknesses of 0 mm and 60 mm are investigated by the DOE. Each parameter has two levels because this requires 512 simulations, whereas increasing to three levels would require 19,683 simulations. 19,683 simulations would be too computationally expensive for the work of this thesis. Once the categorical parameters levels were created for all nine parameter, JMP Pro 11 created a matrix that contains all the solution sets that need to simulated.

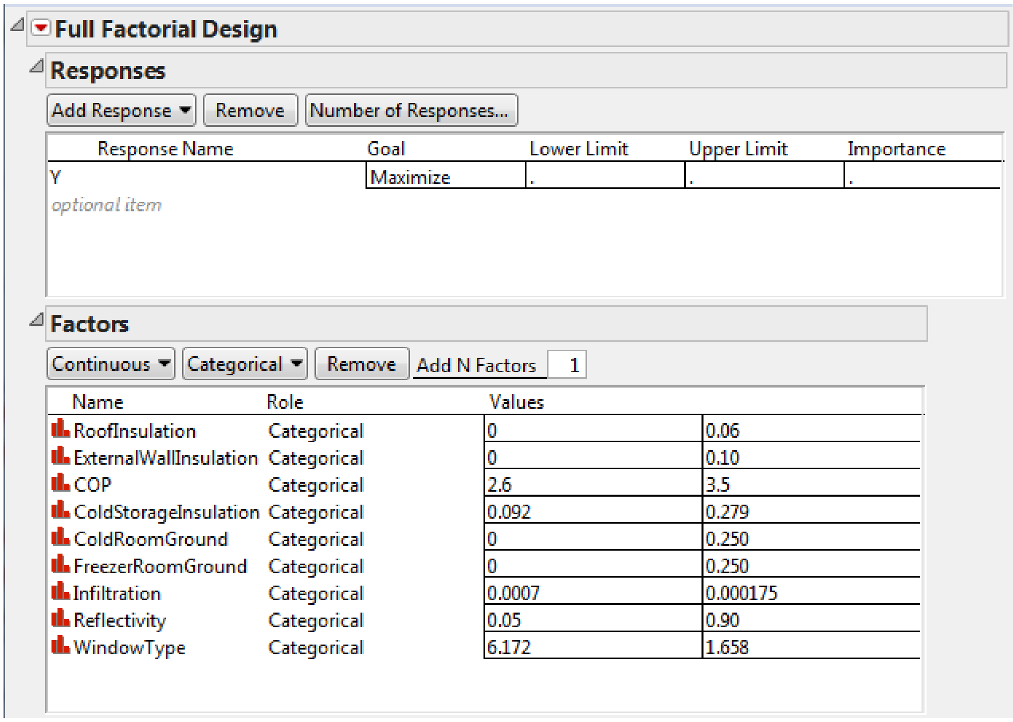


Figure 23: Screenshot of input factors into JMP

The design of experiments and genetic algorithm processes will be used to understand the design space and find the optimal parameters values. However, there are benefits for using these optimization techniques together. The process of combining the GA and DOE together for a design process will be examined in the next section.

3.2.3 Building Design Process

The goal of this thesis is to create and study a decision support tool to aid in the design of an economically feasible NZE vaccine warehouse for the developing world. The section describes the suggested process to complete the entire design of a vaccine warehouse for developing countries. This design process will start be detailing the information that needs to be collected in order to design the vaccine warehouse and then the decision support tool will be used in order to aid in the design of cost-optimal NZE solution. Figure 24 show the flow of the steps.

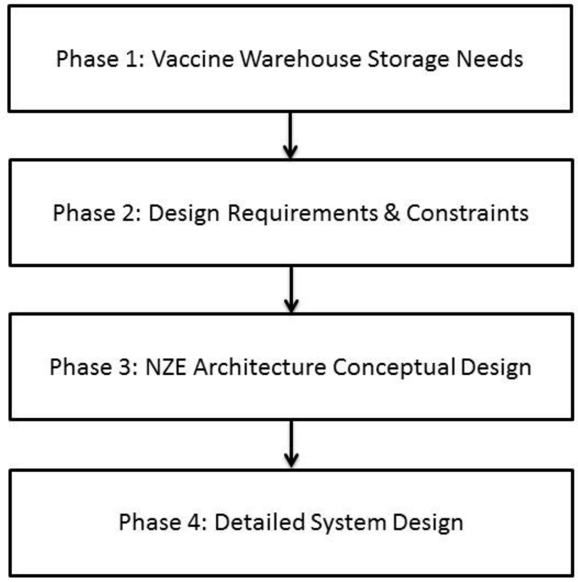


Figure 24: Design process to create economically feasible NZE warehouse

Phase 1 of the process determines the vaccine warehouse's storage needs. To do this, the basic needs of the warehouse are determined. This includes the target groups for the vaccines, the projected population, the supply interval of the vaccines, and the size of the required safety stock. After the information is gathered, the Vaccine Store Sizing Tool (VSST) calculates the required size of the freezer rooms, cold rooms, cool rooms, and dry stores. This tool allows the user to systematically investigate and compare alternative product storage arrangements based on shelving, pallet standing, or pallet racking. Determining the storage requirements for the proposed warehouse is a crucial in order for the warehouse to accommodate the vaccine storage needs of the future.

Phase 2 determines the design requirements and constraints. This phase assesses the design space for the building with regard to climate, construction capabilities, material availability, and other constraints that will limit the ranges of the design parameters. In this phase, performance targets are established for a broad range of parameters and develop preliminary strategies to achieve these targets. This phase helps the designer to know what is feasible for the area before creating a conceptual building design.

Phase 3 creates an NZE conceptual building design. This phase requires many alternative designs be created and studied to find the architecture of a building that best achieves NZE. The best design is chosen via the use of energy models and a sensitivity analysis performed by a DOE. The goal of this phase is to minimize heating and cooling loads and to maximize day lighting potential through orientation, building configuration, an efficient building envelope, and careful consideration of the amount, type, and location of fenestration. Also, the minimization of plug loads, such as fork lifts, and other design concerns, such as thermal comfort of occupants, is considered. The DOE in this phase is completed by only investigating the parameter sensitivity on the annual energy usage of the building.

Phase 4 is the detailed system design. This is where the final materials and renewable technologies are selected and construction drawings are completed. A GA will investigate the cost of the materials and the energy usage of the building in order to determine the final building recommendations. The parameters in the GA will only use discrete levels so that the recommendations can be used for construction. This phase determines the most cost effective way to make the building accomplish NZE and completes the building design process.

The main focus of the thesis is on Phase 4 of the design process. Phases 1 and 2 of this design process were completed by with a team of experts and were used to create the case study warehouse presented in Section 3.1. Phase 3 was completed by another Georgia Tech student, David Pudleiner (Pudleiner 2014), and was used to create the highly energy efficient version of the building design in Section 3.1 This thesis completes Phase 4 of the process by using discrete parameters for the final construction recommendations for a cost effective building.

It was previously mentioned that in Trial 4, a DOE analysis that considers construction cost and energy usage is performed to better understand the design space. This analysis was selected after the GA results from Trials 2-3 had unexpected results and trends that could not be explained with climatic conditions. The DOE analysis was completed to investigate the interactive effects between the parameters to better understand the results obtained previously. This was necessary since the optimum results from the trials were used to create generalized recommendations for the studied building parameters. However, it is not recommended for future designers to use a DOE that considers the construction costs and energy usage in the final stages of design since it will provide no benefit to the final design; it should only be done if the researcher is trying to create generalized recommendations and wants to examine the interactive effects between the parameters. However, this thesis does suggest using a DOE that only considers energy usage and a GA that considers energy usage and construction costs together in a two-step process to aid in the design for the complete building design process.

The proposed two-step process is similar to Phases 3 and 4 shown in Figure 24. In this proposed process, the first step is to complete a DOE analysis in the early stages of the building design process. The DOE will investigate the sensitivity of each parameter on the building's energy usage. The parameters that have a significant effect on the building's energy usage will then be further investigated with a GA. The second step is to use the GA in the final stages of the building design process. The GA will consider the cost of discrete building parameters and the building energy usage in order to make final construction recommendations.

There are many benefits to this two-step process. The main reason for using the two-step process is that the DOE is computationally faster than the GA. The GA is an evolutionary optimization technique which means that the results of the previous simulation are used to determine the next simulation. The DOE is non-evolutionary technique which means all of the needed simulations are determined before running the optimization. Since the simulations are predetermined for the DOE, it can run multiple, simultaneous simulations to reduce computational time. Also, by ignoring the construction costs when running the DOE allows one to easily investigate any of the building parameters without having to invest the time in finding accurate cost data. The DOE will show the effect of each parameter on the building energy usage and the sensitivity will be used to select meaningful parameters for the GA analysis. Using the DOE results will prevent the GA from wasting time studying trivial variables in the final stages of the building design. However, the DOE will only show the parameter sensitivity and not provide a construction recommendation, which is why the GA is needed as the second step. The results from Trial 5 will show the benefits of using this proposed two-step method and the implications of not considering the construction costs in the DOE. The next section describes the objective function, energy model, and parameters used in design problem investigated with the decision support tool.

3.3 Decision Support Tool Parameters

In order to investigate the optimal parameters of the NZE vaccine warehouse, a design problem was created. The most important decision for the design problem was choosing the economic equation to be used to determine if the building is economically efficient. The design problem was created under the assumption that the funds for the warehouse and renewable energy system will not be financed, rather are available at the start of the project, so financing of the building will not be considered. Since this thesis is investigating net zero energy, there will be no future cash flows because the building is designed to offset as much energy as it uses on an annual basis, meaning that no money will be spent or gained on energy. Due to this fact, the net present value of the building will not be investigated. Also, this thesis does not include the maintenance and upkeep costs associated with the building material. Based on these financial assumptions, it was decided to optimize the initial cost of the building, and a summary of the design problem is presented in Table 9.

Table 9: Design problem for NZE vaccine warehouse

Objective Function	Minimize cost of building construction materials and renewable energy system ($Minimize\ \Delta CC_i + \Delta RE_i$)
Constraint	Annual energy consumption of warehouse ≤ Annual energy generation of on-site renewable energy system
Design Variables	Roof Insulation Thickness
	Exterior Wall Insulation Thickness
	Cold Storage Insulation Thickness
	Cold Room Floor Insulation Thickness
	Freezer Room Floor Insulation Thickness
	Air Infiltration Rate Reduction
	Roof Reflectivity Value
	Efficiency of the Windows
	Coefficient of Performance of the HVAC System

The values and associated costs used for the design variables will be presented in Section 3.3.3. The details presented in the table and the reason for choosing them will be described in this section. First the objective function of the thesis is explained. The next two subsections describe the energy model used and the design variables. The last two subsections describe the GA options and DOE design methods used in order to perform the optimization.

3.3.1 Objective Function

If the target is to reduce the energy consumption alone, then the obvious solution is to add more insulation or use highly efficiency systems to reduce energy consumption. However, there is a limit for the insulation thickness and efficiency of systems beyond which any increase will not be economically beneficial. The three most common objectives for building optimization are energy, construction cost, and life cycle cost (Evins 2013). Since this thesis is concerned with making a decision support tool using proven methods, these objectives will be investigated. For these objectives, energy refers to the annual energy usage of the building and construction cost refers to the initial investment in materials. Life Cycle Cost (LCC) assesses the total cost of facility ownership and takes into account the initial investment options and identifies extra costs, including maintence and replacement costs, over a selected time period. Using the life cycle cost for the objective function was investigated and the results of the tests can be seen in Appendix B. The results show that including life cycle costs makes less than a 1% difference in the function value due to the parameters that are being investigated in this thesis. As a result, it was decided to not include the maintenance and upkeep costs associated with the building materials.

The design problem was created under the assumption that funds to build the warehouse and renewable energy system are available, so financing of the building will not be considered in this study. Also, it is common for building optimization to study the net present value of the building. This thesis is investigating a net zero energy building, this means there will be no future cash flows because the building is designed to offset as much energy as it uses on an annual basis, meaning that no money will be spent or gained on energy. Since there is no future cash flow on energy, a net present value analysis cannot be used for the proposed warehouse. Based on these assumptions and the results from the LCC tests that showed that maintenance and other recurring costs were negligible, it was decided to use the initial construction cost of the building and the energy usage of the warehouse to find the optimal solution.

Two costs will be investigated, the construction cost of the building materials and the cost of the renewable energy system. The annual energy consumption for the building will be calculated and then monetized (US dollars) by converting the yearly energy consumption of the building into the cost of a solar system needed to accomplish net zero energy. The building studied in this thesis will be net zero energy according to following site neutral definition from the National Renewable Energy Laboratory: "The amount of energy that the building consumes on-site over the course of a year will, on average, be equal to or less than the amount of renewable energy generated on-site." (Pless and Torcellini 2010) The construction costs of the building materials will use cost data for two different construction types, US construction and

Tunisian construction. US construction values were found from RSMeans (RSMeans 2012) and Tunisian construction cost data will used from the studies that were reviewed in Chapter 2. These costs are detailed later in this section.

The objective function in this thesis compares different designs in the specified solution space to a reference case, rather than the absolute value of the construction cost. This is done to compare the building materials costs without having to collect the cost data for all the building components. The reference case of the building will be the most economical building. This building will have no insulation and will have standard systems. For any specified design, the investments in building materials will be found by calculating the difference (ΔCC_i) between the construction cost for any design *i* (CC_i) and the construction for the reference case (CC_r). This objective function is shown in Equation 2.

$$\Delta CC_i = CC_i - CC_r \quad (2)$$

The difference in construction costs ΔCC_i looks only at the prices for construction materials and not the cost of the renewable energy system. In order to ensure the building accomplished NZE, a constraint was added to the design problem. The added constraint is, the amount of electricity consumed by the building over a year must be equal to or less than the renewable energy generated onsite. This constraint will govern the size of the renewable energy system. For this thesis, only a solar PV system will be investigated for the renewable energy. The difference in the initial cost of the renewable energy system (ΔRE_i) of the design solution (IC_i) and the reference case (IC_r) will be calculated with Equation 3.

$$\Delta RE_i = IC_i - IC_r \quad (3)$$

With the NZE constraint in place and the two investment equations presented, the objective function of the design problem is formed. The final objective function for this thesis is Equation 4. This objective function will be used to find the cost optimal set of building parameters for a NZEB.

$$Minimize \ \ (\Delta CC_i + \Delta RE_i) \tag{4}$$

The cost-optimal NZEB solution is found by suggesting investments in material to make the building more energy efficient and this causes the annual energy usage of the building to be reduced so less money is spent on the renewable energy system. The difference in the renewable energy system when compared to the reference case will be a negative number and the material investment will be a positive number. The objective function will be minimized since it represents the amount of money saved. It is expected that the optimal objective function value will be negative since the cost of the PV system is very high. However, if the optimum objective function is zero, then this shows that the reference case is the most economical case.

It is also important to investigate whether a PV system is economically feasible. A payback time model is usually used to determine such feasibility. However, the payback model conveys a return pay into the future that may be hard to integrate into an annual budget. In this study, the payback period and the annual return on investment for the PV system are calculated. In order to calculate these values, the total initial renewable energy system investment (RESI) is calculated, as is the annual electricity consumption of the building (AEC). These values come from the optimum result found by the genetic algorithm. The annual electricity consumption and the areas electricity cost are used to determine the yearly benefit of the system (YB) as shown in Equation 5.

$$YB = AEC * Electricity\ Cost \tag{5}$$

Once the yearly benefit of the system is determined, then the payback period (PP) of the system is determined. Equation 6 is used to calculate the payback period of the renewable energy system.

$$PP = \frac{RESI}{YB} \tag{6}$$

The yearly benefit is used to determine the return on investment (ROI). Equation 7 is used to calculate the annual return of investment.

$$ROI = \frac{YB}{RESI} \tag{7}$$

The benefits of using the PV system and if it is economically feasible are investigated in Chapter 4. The next section describes the building energy model's output file.

3.3.2 Energy Model Output

Section 3.1 describes the case study building. An energy model of the building was created in EnergyPlus, and the output from the simulation has 23 outputs values. The first output is the electricity usage of the facility. The other twenty two outputs include the ideal load zone total heating energy and ideal load zone total cooling energy for eleven different zones. The eleven different zones can be seen in Table 10.

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Table 10: Eleven different zones in the IDF

Load Zones
Controlled Ambient Storage Room
Ambient Storage Area
Freezer Storage Room
Cold Room Storage Room
Support Area: Plant Room
Support Area: Workshop
Washrooms
Mezzanine: Office 1
Mezzanine: Office 2
Mezzanine: Office 3
Mezzanine: Hallway

The ideal load for each zone does not take into account a coefficient of performance (COP) for the system. In order to calculate an accurate energy consumption of the building, each of the ideal loads must be multiplied by a COP to calculate the actual load. The final annual energy consumption of the building is found by adding all of the actual loads together with the electricity usage of the facility.

The building has four different refrigeration and HVAC systems. The cold room, freezer room, and controlled ambient storage have separate refrigeration systems and each has an associated COP value. The rest of the warehouse uses parallel sensible cooling and heating units, consisting of mini-split heat pumps, for its HVAC needs. The sensitivity of changing the COP for each zone is investigated in Appendix C. When the COP of the HVAC system is changed to investigate different efficiencies, the suggested roof insulation thickness, cold storage insulation thickness, cold room floor insulation thickness, freezer room floor insulation thickness, and window efficiency change. However, no cost values were found for refrigeration systems needed for the cold rooms; cost values were only found for the split heap pump. It was decided to use the average efficiencies for the refrigeration systems since the high efficiency systems decreased the suggested thickness of the cold room floor insulation and the low efficiency system increased the suggested thickness of the freezer room floor insulation. The average COP efficiencies for the cold storage rooms' refrigeration system are 1.45 for the cold room, 1.35 for the freezer room, and 2.4 for the controlled ambient storage. This annual energy usage is used to find the total PV system needed in order to accomplish NZE. The next section describes the levels of the COP of the split heat pump investigated and the details of the other parameters that are varied.

3.3.3 Energy Simulation Variables

The parameters varied in this thesis are a combination of parameters common to energy efficiency studies, in addition to the parameters that have a significant impact on the energy usage of a refrigerated warehouse. There are two different set of parameters used in this thesis. These include parameters used to demonstrate common construction for the developed world, US construction, and parameters used to demonstrate common construction for the developing world, Tunisian construction. The following sections describe the parameters used in this study.

3.3.3.1 US Construction

This section describes the parameters used to demonstrate US construction. In all of the following variables, "Level 1" designates the reference building. The reference building is the most economical version of the building. The reference case is created by using the standard options for the building systems and not investing in increased insulation. The highest level studied matches the building initially designed for Tunisia that was presented in the Section 3.1. This building is highly energy efficient and was designed without consideration to cost, making it the best building possible using current US construction practices. The number of levels between the reference building and the highest level is determined by the cost values found. The cost values used in this study are for products that are available commercially, and this is why the parameters have discrete levels. This results in every parameter having a different number of levels. The levels for each parameter can be seen in Table 11.

Table 11: Details of levels for US construction

	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6	Level 7	Level 8
Roof Insulation Thickness (m)	0	0.025	0.050	0.064	0.075	0.089	0.100	0.150
External Wall Insulation Thickness (m)	0.092	0.143	0.187	0.245				
COP value of HVAC system	2.6	3.0	3.3	3.5				
Cold Storage Insulation Thickness (m)	0.092	0.143	0.187	0.238	0.279			
Cold Room Floor Insulation Thickness (m)	0	0.025	0.050	0.075	0.100	0.150	0.200	0.250
Freezer Room Floor Insulation Thickness (m)	0	0.025	0.050	0.075	0.100	0.150	0.200	0.250
Infiltration (1/h)	4	3	2	1	0.5			
Roof Reflectivity	0.05	0.9						
Windows: U-Value SHGC	5.10 0.70	2.80 0.63	2.70 0.63	1.60 0.63	1.60 0.50			

The rest of this section will discuss the details of the building parameters and the associated costs.

3.3.3.1.1 Roof Construction

The roof construction of the warehouse will use Metsec type trusses on main gridlines to provide support. On top of the trusses will be a 130 mm concrete deck. Above the concrete deck will be a layer of insulation and then a roof coating. The warehouse originally designed for Tunisia had 150 mm of polyisocyanurate insulation on the roof. An image of the Metsec trusses and a detailed drawing of the roof construction can be seen in Figure 25.

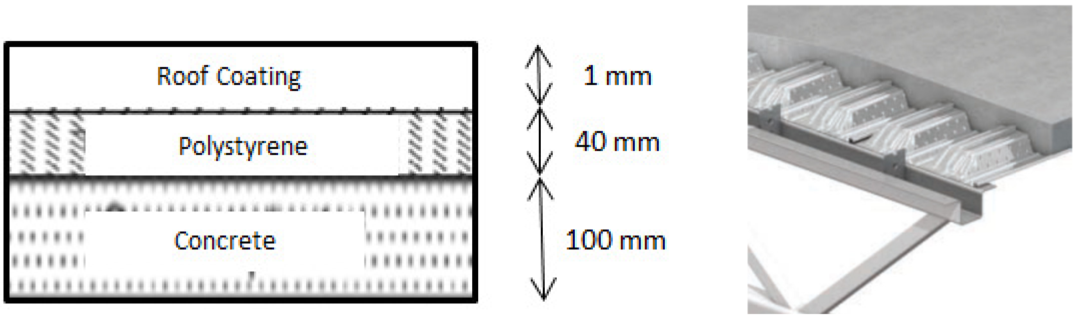

Figure 25: Left: Roof Construction; Right: Picture of Metsec trusses with concrete deck

It was chosen to optimize the thickness of the insulation in the roof construction, and RSMeans offers many different roof insulations. Since polyisocyanurate was chosen for the warehouse originally designed for Tunisia, it is also used in this thesis. The total cost including labor, and material needed to install the insulation is included in the price. The full description of the insulation in RSMeans is "Polyisocyanurate Insulation, for roof decks, (19, 25, 38, 50, 64, 75, and 89) mm thick, 32 kg/m^3 density" (RSMeans 2012). In order to get the same U-Value as designed in the Tunisian warehouse, the thickness of the insulation needs to 150 mm thick. The price for the 100 mm and the 150 mm thick insulation is found by interpolating the insulation prices from RSMeans. The suggested roof construction does not require insulation in order to support the building, so the reference case will have no insulation. Table 12 lists the values used.

Table 12: Details of Roof Insulation Thicknesses values used for US Construction

Roof, Polystyrene Insulation								
Level	1	2	3	4	5	6	7	8
Thickness (m)	0	0.025	0.050	0.064	0.075	0.089	0.100	0.150
Cost(USD/m²)	0	8.60	12.50	15.25	18.00	20.04	22.03	31.09
Area (m²) =788.28								
Investment Cost (USD)	0	6,779	9,853	12,021	14,189	15,787	17,365	24,508

It was also chosen to optimize the roof coating properties. RSMeans has a white, elastomeric, reflective roof coating for $16.20 a gallon with a gallon covering approximately 50 square feet. The reference case for this parameter will be using standard roof coating. The reflectivity values used for the standard roof and the white roof are the average values based on a previous study (Wong). Table 13 lists the values used.

Table 13: Details of Roof Reflectivity values used for US Construction

Roof Reflectivity		
Level	1	2
Reflectivity	0.05	0.90
Cost (USD/m²)	0	3.49
Area (m²) =788.28		
Investment Cost (USD)	0	2,751

3.3.3.1.2 External Wall Construction

The external wall construction will implement a new insulation type - structurally insulated panels (SIPs). SIPs are panels that consist of an insulating foam core sandwiched between two structural facings, typically oriented strand board (OSB). The external wall construction will have SIPs fixed to horizontal metal rails. An image of SIPs attached to metal rails can be seen in Figure 26. The warehouse originally designed for Tunisia had 150 mm of polyisocyanurate insulation for the SIPs.

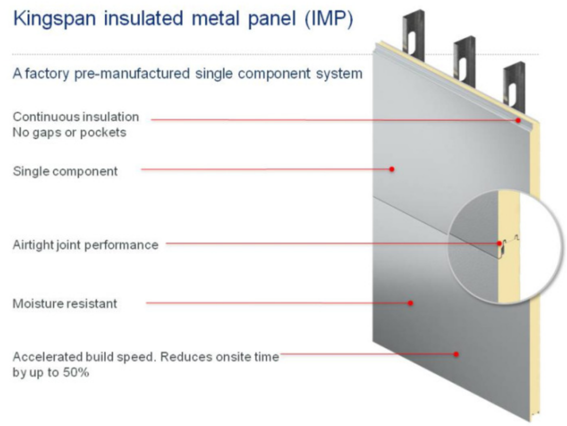

Figure 26: Picture of SIP fixed to horizontal metal rails

It was chosen to optimize the thickness of the SIP, and RSMeans only offers one type of SIP, expanded polystyrene (EPS) insulation. The total cost including labor, material, and equipment needed to install the SIP is included in the price. The full description of the SIPs in RSMeans is, "Structural Insulated Panels, 11 mm orientated strand board(OSB) both faces, expanded polystyrene (EPS) insulation (92, 143, 187 and 238) mm thick" (RSMeans 2012). In order to get the same U-Value as designed for the Tunisian warehouse, the thickness of the EPS insulation needs to be 245 mm thick. Due to this fact, 92, 143, 187 and 245 mm insulation thicknesses are used in the study. The price for the 245 mm thick insulation is found by interpolating the four insulation prices. The suggested construction requires a SIP, so the reference case is the SIP in RSMeans with the smallest thickness. Table 14 lists the values used.

Table 14: Details of External Wall Insulation Thicknesses values used for US Construction

External Wall, Expanded Polystyrene Insulation SIP				
Level	1	2	3	4
Thickness (m)	0.092	0.143	0.187	0.245
Cost (USD/m²)	47	54	61	70.24
Area (m²) =744.29				
Investment Cost (USD)	34,982	40,192	45,402	52,279

3.3.3.1.3 Floor Construction

The floor construction of the freezer room (-20°C) and cold room (+5°C) will two layers of concrete with insulation in between. The originally designed warehouse for Tunisia had 150 mm of polyurethane insulation for the floor insulations in both of the rooms. An image of the floor insulation to be used and details of the floor construction can be seen in Figure 27.

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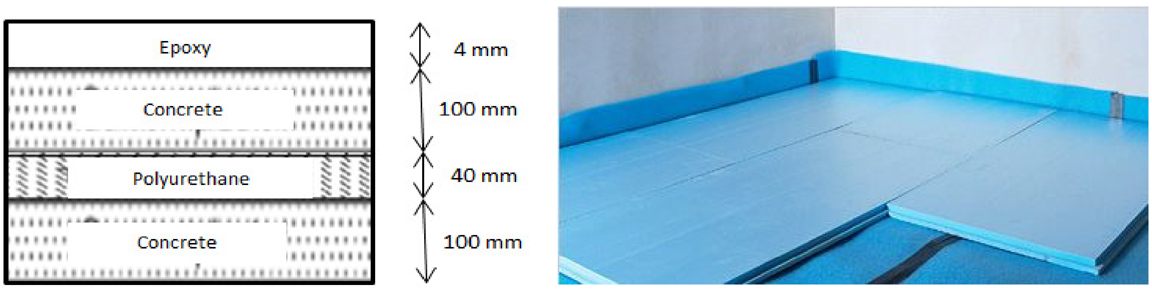

Figure 27: Left: Floor construction; Right: Picture of floor insulation

It was chosen to optimize the thickness of the floor insulation for these two rooms. Since polyurethane insulation was chosen for the Tunisian warehouse, it is used here. Instead of considering the cold storage floor as a single parameter, the cold room floor and the freezer room floor are analyzed separately. The total cost, including labor and material needed to install the insulation, is included in the price. The full description of the insulation in RSMeans is as follows: "Insulation, polyurethane foam, (25, 50, 75, 88, 100, 125, 138 and 150) mm thick" (RSMeans 2012). In order to have the same U-Value as the Tunisian warehouse described in the previous section, the thickness of the insulation will need to be 150 mm. Initial tests always had results of 150 mm, so two higher increments are added. The suggested floor construction does not require insulation in order to support the building, so the reference case will have no insulation. Table 15 and Table 16 list the values used.

Table 15: Details of Cold Room Floor Insulation Thicknesses used for US Construction

Cold Room Floor, Polyurethane Insulation								
Type	1	2	3	4	5	6	7	8
Thickness (m)	0	0.025	0.050	0.075	0.100	0.150	0.200	0.250
Cost (USD/m²)	0	10.20	17.60	27.00	32.50	48.53	63.79	79.05
Area(m²)=113.13								
Investment Cost (USD)	0	1,154	1,991	3,055	3,677	5,490	7,217	8,943

Table 16: Details of Freezer Room Floor Insulation Thicknesses used for US Construction

Cold Room Floor, Polyurethane Insulation								
Type	1	2	3	4	5	6	7	8
Thickness (m)	0	0.025	0.050	0.075	0.100	0.150	0.200	0.250
Cost (USD/m²)	0	10.20	17.60	27.00	32.50	48.53	63.79	79.05
Area(m²)=113.13								
Investment Cost (USD)	0	185	319	490	589	880	1,157	1,434

3.3.3.1.4 Cold Storage Construction

The cold storage wall and roof will be construction out of SIPs. The cold storage refers to the cold room (+5°C), the freezer room (-20°C), and the ambient storage room (+20°C). The originally designed warehouse for Tunisia had 150 mm of polyurethane insulation for both the walls and roof. An image of SIPs being used to construct a cold room can be seen in Figure 28.

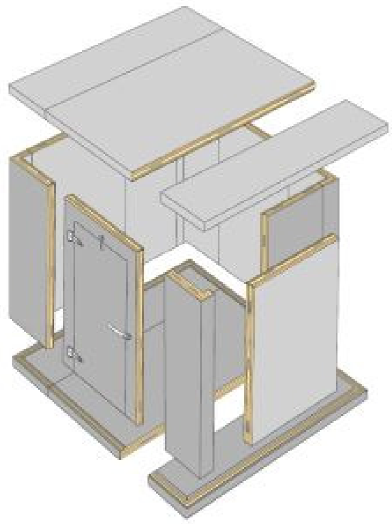

Figure 28: Picture of SIP's being used to construction cold storage room.

It was decided to optimize the thickness of the SIPs for the cold storage areas. RSMeans only offers one type of structural insulated panel, EPS insulation, for the cold storage walls and room. The total cost including labor, material, and equipment needed to install the SIP is included in the price. The full description of the SIPs in RSMeans is as follows: "Structural Insulated Panels, 11 mm OSB both faces, EPS insulation (92, 143, 187 and 238) mm thick" (RSMeans 2012). In order to get the same U-Value as designed in the Tunisian warehouse, the thickness of the EPS insulation needs to be around 235 mm thick, so the 238 included in RSMeans is used. The suggested construction requires a SIP, so the reference case is the SIP in RSMeans with the smallest thickness, and Table 17 lists the values used.

Table 17: Details of Cold Storage Wall and Roof Insulation values for US Construction

Cold Storage Walls and Roof, Expanded Polystyrene Insulation SIP					
Level	1	2	3	4	5
Thickness (m)	0.092	0.143	0.187	0.238	0.279
Cost (USD/m²)	47	54	61	69.5	75.5
Area (m²) =834.44					
Investment Cost (USD)	39,219	45,060	50,901	57,994	63,000

3.3.3.1.5 Window Type

It was also chosen to investigate the window efficiency. The window variations include the glazing, thermal break, and frame. The window parameters needed for the energy model are the U-Value and the solar heat gain coefficient (SHGC). The SHGC is the ability to control solar heat gain through the glazing. Therefore, with a lower SHGC there is less heat gain by the building. The costs and characteristics of the windows were extracted from a previous study (Asadi 2012). The Level 1 window is the reference case since it is the cheapest of the options and the least energy efficient of all the window types considered. Level 1 is a single glazed window. Level 2 has double glazing, no thermal break, an uncoated air-filled metallic frame, 4-12-4 (4 mm of glass, a 12 mm air gap, and a 4 mm of glass). Level 3 has double glazing, no thermal break, an uncoated air-filled metallic frame, and 4-16-4 (4 mm of glass, a 16 mm air gap, and a 4 mm of glass). Level 4 is a double glazed, Low-E window with thermal break, coated air-filled metallic frame, and 4-12-4 (4 mm of glass, a 12 mm air gap, and a 4 mm of glass) NEUTRALUX. Level 5 is a double glazed, Low-E window with thermal break, coated air-filled metallic frame, and 6-12-4 (6 mm of glass, a 12 mm air gap, and a 4 mm of glass) SOLARLUX Supernatural 70/40, Temprado. The Level 5 window is comparable to window selected for the designed Tunisian warehouse. Table 18 lists the values used.

Table 18: Details of Window Types values used for US Construction

Window Type					
Level	1	2	3	4	5
U-Value (W/m2K)	5.10	2.80	2.70	1.60	1.60
Solar Heat Gain Coefficient	0.70	0.63	0.63	0.63	0.50
Cost (USD/m²)	46.63	53.91	55.13	76.21	185.36
Area (m²) =31.312					
Investment Cost (USD)	2,046	2,366	2,419	3,344	8,134

3.3.3.1.6 Air Infiltration Rate

An important parameter that will be optimized is the building's air tightness, or infiltration rate. Improving the building tightness requires careful work and strict control on the construction site; this results in no increase in materials cost, only in labor costs. Three of the studies reviewed considered the infiltration rate for one of their parameters (Hamdy, Hasan et al. 2011), (Hamdy, Hasan et al. 2013), and (Kapsalaki, Leal et al. 2012). After reviewing these studies and ASHRAE construction guidelines (ASHRAE 2009), the infiltration levels chosen to characterize the airtightness of the building, expressed in air changes per hour (ach) on average, are 0.5, 1, 2, 3 and 4 ach. Table 19 lists the values used.

Table 19: Details of building tightness values used for US Construction

Building Tightness					
Level	1	2	3	4	5
Air Changes (1/h)	4	3	2	1	0.5
Cost (USD/m²)	0	6.63	15.91	29.16	39.77
Area (m²) =788.28					
Investment Cost (USD)	0	5,226	12,542	22,986	31,350

3.3.3.1.7 COP of HVAC System

The final parameter to be optimized is the coefficient of performance (COP) of the HVAC used to heat and cool the ambient storage and offices. The HVAC system used will be a split system. A split system comprises indoor and outdoor units, which allow for a peaceful inside environment by enabling the contractor to install louder components, such as compressors and motors, outdoors. A split system is chosen due the fact that it is more energy efficient than traditional forced air systems because it does not require the use of ducts. None of the studies reviewed for US construction techniques considered a split system's COP as one of their parameters or if they did, then they did not include cost data in the study. Therefore, Tunisia cost data from a previous study were selected for this parameter (Ihm and Krarti 2012). Table 20 lists the values used.

Table 20: Details of Split System COP values used for US Construction

COP of HVAC System				
Level	1	2	3	4
COP	2.6	3.0	3.3	3.5
Investment Cost (USD)	3,566	4,635	5,705	7,131

This concludes the discussion of all of the parameters and costs that will be used to represent US construction. The next section gives the parameters used to represent Tunisian construction.

3.3.3.2 Tunisia Construction

This section describes the parameters used to demonstrate Tunisia construction. In all of the following variables, Level 1 designates the reference building. The reference building is the most economical version of the building being considered, and uses construction methods common for Tunisia. The number of levels between the reference building and the highest level is determined by the cost values found in previous studies. It was decided to use the highest level found in previous studies and not interpolate to higher values since these materials are common for the area. The cost values used in this study are for products that are available, and this is why the parameters have discrete levels. This results in every parameter having a different number of levels. The levels for each parameter can be seen in Table 21.

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Table 21: Details of levels for Tunisian construction

	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6	Level 7	Level 8
Roof Insulation Thickness (m)	0	0.02	0.04	0.06				
External Wall Insulation Thickness (m)	0	0.02	0.04	0.06	0.08	0.10		
COP value of HVAC system	2.6	3.0	3.3	3.5				
Cold Storage Insulation Thickness (m)	0.092	0.143	0.187	0.238	0.279			
Cold Room Floor Insulation Thickness (m)	0	0.025	0.050	0.075	0.100	0.150	0.200	0.250
Freezer Room Floor Insulation Thickness (m)	0	0.025	0.050	0.075	0.100	0.150	0.200	0.250
Infiltration (L/s*m2)	0.7	0. 525	0. 35	0.175				
Roof Reflectivity	0.05	0.9						
Windows: U-Value SHGC	6.172 0.83	6.172 0.68	3.163 0.73	4.270 0.65	3.160 0.61	1.658 0.57		

The rest of this section will discuss the details of the building parameters in the table and present the costs that are used for each level.

3.3.3.2.1 Roof Construction

In Tunisia, roofs are usually construction with reinforced concrete (Johansson and Kalantari 1989) and the typical insulation used in roof construction is polystyrene (Ihm and Krarti 2012). The roof construction is the same as previously described for the US construction. In the energy model, the construction of the roof has three layers. The outer layer is a roof coating. The next layer is the polystyrene insulation. The innermost layer is a 130 mm thick layer of concrete. The roof coating is changed in this study to determine the benefits of investing in a white roof. Also, the effect of varying thicknesses of the insulation is studied. The concrete is assigned a conductivity of 0.72 W/m-K based on a previous study (Daouas 2011). A heat capacity of 837 J/kg-K and a density of 1922 kg/m³ are chosen as a match for concrete with similar conductivity (IES 2013).

The costs for the roof insulation in Tunisia used are shown in Table 22. The cost values used are from a previous study and contain the price of the overall roof construction (Ihm and Krarti 2012). The polystyrene insulation is assumed to have a conductivity of 0.030 W/m-K, density of 25 kg/ m³ and a specific heat of 1380 J/kg-K (IES 2013). The price is converted into USD in order to easily compare it to the other prices used.

Table 22: Roof insulation costs for Tunisia construction (Conversion 1 TND= 0.60 USD)

Roof, Polystyrene Insulation				
Level	1	2	3	4
Thickness (cm)	0	2	4	6
Cost (TND/m²)	85.0	90.0	94.0	116.3
Area (m²) =788.28				
Investment Cost (TND)	67,004	70,945	74,098	91,977
Investment Cost (USD)	40,515	42,906	44,813	55,615

The addition of a reflective roof coating to the building was not considered in previous Tunisian studies. Therefore, no cost data can be found and the RSMeans cost data shown in Table 23 is used (RSMeans 2012). In order to account for this in the energy model, Solar Absorptance and the Visible Absorptance are modified for the roof coating material properties.

Table 23: Roof Reflectivity cost for Tunisia construction

Roof Reflectivity		
Level	1	2
Reflectivity	0.05	0.90
Cost (USD/m²)	0	3.49
Area (m²) =788.28		
Investment Cost (USD)	0	2,751

3.3.3.2.2 External Wall Construction

In Tunisia, external walls are typically constructed with either brick or stone (Daouas 2011). A visit to Tunisia by David Pudleiner observed the wall construction shown in Figure 29. This figure also images of the bricks that are typical used in for exterior wall construction in Tunisia.

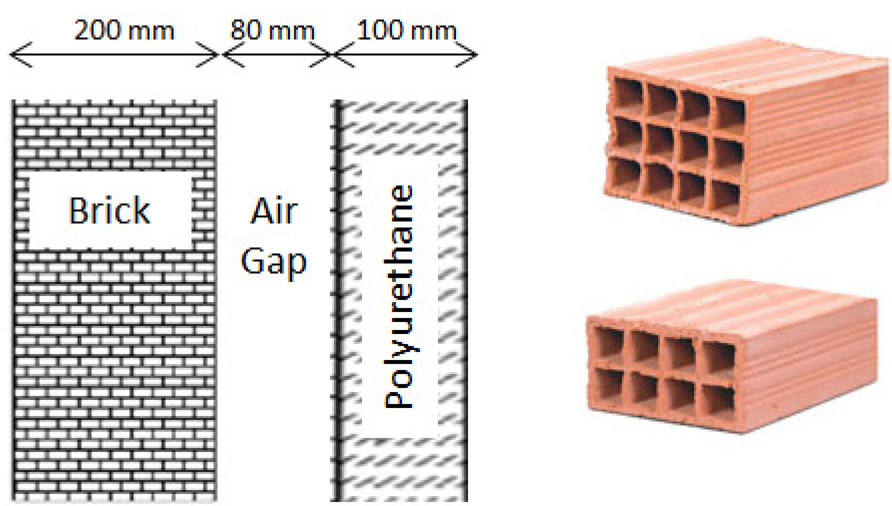


Figure 29: Left: Wall construction observed by David Pudleiner; Right: Examples of brick

This wall construction is used in the Tunisian energy model. The construction is modified slightly to use expanded polystyrene instead of polyurethane because polystyrene prices for Tunisia were found in previous studies. In the energy model, the construction of the wall has three layers. The outer layer is 200 mm thick brick. The next layer is an 80 mm air gap. The innermost layer is the polyurethane insulation. The effect of varying thicknesses of the insulation is studied. The brick is assigned a conductivity of 0.69 W/m-K based on a previous study (Daouas 2011). A heat capacity of 800 J/kg-K and a density of 1700 kg/m³ are chosen to match brick with similar conductivity (IES 2013). The air gap is assigned a conductivity of 0.167 W/m-K based on a previous study (Daouas 2011). The cost values are obtained for the polystyrene insulation from a previous study; they are the prices for typical wall construction with this insulation (Ihm and Krarti 2012). The values used are listed in Table 24. In the energy model the polystyrene insulation, it is assumed to have a conductivity of 0.030 W/m-K, density of 25 kg/m³, and specific heat of 1380 J/kg-K (IES 2013).

Table 24: External Wall Insulation for Tunisia Construction (Conversion 1 TND= 0.60 USD)

External Wall, Polystyrene Insulation with wall construction						
Type	1	2	3	4	5	6
Thickness (m)	0	0.02	0.04	0.06	0.08	0.10
Cost (TND/m²)	54.9	59.2	62	64.6	68.2	71.3
Area (m²)=744.29						
Investment Cost (TND)	40,862	44,062	46,146	48,081	50,761	53,068
Investment Cost (USD)	24,712	26,648	27,908	29,078	30,694	32,089

3.3.3.2.3 Floor Construction

The construction and costs used for the cold room floor and freezer room floor are the same for the US and Tunisian construction case since no previous studies investigated cold storage parameters in Tunisia. The floor construction of the freezer room and cold room will two layers of concrete with insulation in between. An image of the floor insulation to be used and details of the floor construction can be seen in Figure 30.

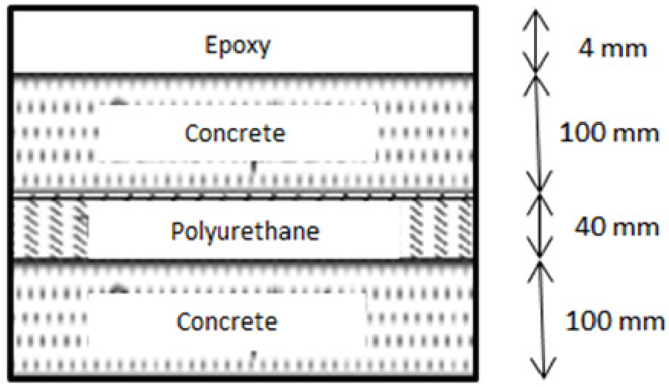


Figure 30: Floor Construction Details

The effect of varying thicknesses of the insulation will be studied. The concrete is assigned a conductivity of 0.72 W/m-K based on a previous study (Daouas 2011). A heat capacity of 837 J/kg-K and a density of 1922 kg/m³ are chosen to match concrete with similar conductivity (IES 2013). The RSMeans cost data used are shown in Table 25 (RSMeans 2012). In the energy model, the polyurethane insulation it is assumed to have a conductivity of 0.023 W/m-K, density of 24 kg/m³ and a specific heat of 1590 J/kg-K (IES 2013).

Table 25: Details of Cold Room floor for Tunisia Construction

Cold Room Floor, Polyurethane Insulation								
Type	1	2	3	4	5	6	7	8
Thickness (m)	0	0.025	0.050	0.075	0.100	0.150	0.200	0.250
Cost (USD/m²)	0	10.20	17.60	27.00	32.50	48.53	63.79	79.05
Area(m²)=113.13								
Investment Cost (USD)	0	1,154	1,991	3,055	3,677	5,490	7,217	8,943

The same thicknesses and cost/m² will be used for the Freezer Room Floor, which has an area of 18.13 m².

3.3.3.2.4 Cold Storage Construction

No studies that optimized the parameters of a cold storage facility in Tunisia were found. Therefore, the modeling of the cold storage for the Tunisia construction uses the same construction and costs as in the US construction, structurally insulated panels, because they are specifically designed to be interlocked and are typically used in industry for cold storage rooms. The RSMeans values used are seen in Table 26 (RSMeans 2012). In the energy model the construction of the cold storage room's walls and roof has three layers. The two outer layers are thin layers of oriented strand board. In between them is a foam core made of expanded polystyrene. The effects of varying the thickness of the insulation are studied. In the energy model, the expanded polystyrene insulation is assumed to have a conductivity of 0.035 W/m-K, density of 29 kg/m³, and a specific heat of 1213 J/kg-K (IES 2013).

Table 26: Details of Cold Storage Walls and Roof insulation for Tunisia Construction

Cold Storage Walls and Roof, Expanded Polystyrene Insulation SIP					
Type	1	2	3	4	5
Thickness (m)	0.092	0.143	0.187	0.238	0.279
Cost (USD/m²)	47	54	61	69.5	75.5
Area (m²)=834.44					
Investment Cost (USD)	39,219	45,060	50,901	57,994	63,000

3.3.3.2.5 Window Type

Glazing prices and characteristics used to represent Tunisian construction are from a previous study (Ihm and Krarti 2012) and the values are summarized in Table 27. Level 1 is a single clear window, with single glazing; this is the typical construction. Level 2 is a single stained glass (green), with single glazing. Level 3 is double clear glass panes with an air gap: 6 mm +air gap of 6 mm + 6mm. Level 4 is double glazing with stained glass (green) panes, an air gap: 6 mm + 6 mm + 6mm. Level 6 is double glazing with Low-E glass panes, and an air gap: 6 mm + 12 mm air gap + 6 mm. This study only gave the U-Values for these windows. The solar heat gain coefficients were found from Solar Heat Gain Coefficient (SHGC) Worksheet (California Energy Commission 2009).

Table 27: Details of Window Types for Tunisia Construction (Conversion 1 TND= 0.60 USD)

Window Type						
Level	1	2	3	4	5	6
U-Value (W/m^{2}K)	6.172	6.172	3.163	4.270	3.160	1.658
Solar Heat Gain Coefficient	0.83	0.68	0.73	0.65	0.60	0.57
Cost (TND/m²)	25.0	32.3	54.9	60.3	64.6	85.0
Area (m²)=43.88						
Investment Cost (TND)	1,097	1,417	2,409	2,646	2,835	3,730
Investment Cost (USD)	663	857	1,457	1,600	1,715	2,256

3.3.3.2.6 Air Infiltration Rate

The typical air infiltration level in Tunisia is 0.7 L/s/m². Improving the building tightness requires careful work and strict control on the construction site; this results in no increase in materials costs, only in labor costs. EnergyPlus can model only infiltration by using design flow rate (m³/2), flow per zone floor area (m³/s*m²), flow per exterior surface area (m³/s*m²), or air changes per hour (1/hour). The values from Tunisia are converted into a flow per exterior surface area that can be used in EnergyPlus. The values found from a previous study are used to determine the average infiltration rates for the country (Ihm and Krarti 2012) and the levels this thesis will use. However, the costs in that paper are for a residential building and are much lower than the costs one would actually invest to reduce air infiltration for a commercial building. The cost from this study were multiplied by a factor of 4 due to the relationship seen between two previous studies (Hamdy, Hasan et al. 2013) (Kapsalaki, Leal et al. 2012), which include the commercial and residential costs of reducing air infiltration in Europe. The values used can be seen in Table 28.

Table 28: Building tightness for Tunisia Construction (Conversion 1 TND= 0.60 USD)

Building Tightness				
Level	1	2	3	4
Air Infiltration Level (L/s/m²)	0.7	0.525	0.35	0.175
Cost (TND/m²)	0	2.4	4.8	6.8
Area (m²) =1532.57				
Investment Cost (TND)	0	3,678	7,356	10,420
Investment Cost (USD)	0	2,207	4,414	6,253

3.3.3.2.7 COP of HVAC system

A split system for the heating, ventilation and air conditioning (HVAC) system is used in the ambient storage and office areas of the warehouse. In a previous study, a split system was used for a one story building with a floor area of 221 m² (Ihm and Krarti 2012). The costs of the split system from this study are scaled up by a factor of seven to account for the difference in floor area, 221 m² as compared to 1576 m² of the case study warehouse. The costs used can be seen in Table 29.

Table 29: Details of HVAC COP for Tunisia Construction (Conversion 1 TND= 0.60 USD)

COP of Split System				
Level	1	2	3	4
COP	2.6	3.0	3.3	3.5
Investment Cost (TND)	5,943	7,725	9,508	11,885
Investment Cost (USD)	3,566	4,635	5,705	7,131

This concludes the description of the parameters and their associated costs that will be used to represent Tunisian construction. In order to perform the optimization, the two selected optimization techniques had to be investigated to make sure they would work for this design problem. The next section discusses the options selected for the genetic algorithm,

3.3.4 Genetic Algorithm Parameters

The built-in Genetic Algorithm (GA) in Matlab is used in this study. In order to make this algorithm work for this thesis, many of the GA options are changed. The GA in Matlab is designed for the use of continuous variables. However, this thesis implemented prices of available materials by using discrete variables. In order to get the GA to effectively handle discrete variables, the 'IntCon' option is used. Each level of insulation is assigned an integer value with "1" being the most economical and least energy efficient option as seen in the previous section. The value of the level increases with price and energy efficiency through all of the desired options. Restrictions exist on the types of problems that the genetic algorithm can solve with integer variables. The restrictions are as follows:

- No linear equality constraints.
- No nonlinear equality constraints.
- Only double vector population type.
- No custom creation function, crossover function, mutation function, or initial scores. If any of these are supplied, then the GA overrides their settings.
- GA uses only the binary tournament selection function and overrides any other setting.
- No hybrid functions.
- GA ignores the ParetoFraction, DistanceMeasureFcn, InitialPenalty, and PenaltyFactor options.

As stated in Chapter 2, the main two challenges with genetic algorithms are the computing power and convergence. In most studies, the crossover, mutation, and selection functions are modified in order to address these two challenges. However, since the IntCon option overrides any changes made in these settings, changing the crossover, mutation, and selection cannot be done. The most important decision to reduce the computing power is to determine the population size and number of generations needed to reach the optimum. Matlab has simple equations in order to determine the population size and maximum number of generations. However, these equations are written for continuous problems and will not be effective for this problem. The use of population versus generations was investigated in a study in 2000 (Vrajitoru 2000). The study states it is better to have a large population and fewer generations in order to reach the optimal solution. In order to optimize the convergence of the genetic algorithm, the elite count and crossover fraction are investigated. The values determine how the next generation is determined and will help to prevent the GA from converging too slowly or too quickly. Appendix D shows the tests performed to select the optimum configuration of population size, generations, elite count, and crossover fraction. The results of these tests are presented in Table 30.

Table 30: Genetic Algorithm Parameters

Option	Value
Generations	30
Population Size	25
Elite Count	3
Crossover Fraction	0.8

The values in Table 30 were used for all of the trials in this thesis. After the GA parameters were determined, the design of experiments design method was chosen. The next section describes the selected design method.

3.3.5 Design of Experiment Methods

A Design of Experiments (DOE) is used to investigate the sensitivity of the parameters. In order for the DOE to work, the correct design method needs to be studied. JMP Pro 11 is used to investigated the design methods, and create the associated matrixes. The thesis uses the DOE to investigate the main effects caused by each parameter and then investigate the interactions effects. Tests were conducted for multiple DOE designs. The tests were conducted for the design methods used in the studies reviewed in Chapter 2. The results from all of the test are shown in Appendix E. After the tests were completed, two methods proved to be efficient and accurate. The Taguchi 64 method is used to investigate the main effects, while the full factorial design will be used to determine the interactions.

3.4 Research Limitations and Goals

This chapter describes the framework and parameters of this research. It is important to recognize the limitations of this thesis. The weakness of this research mainly resides in the reduction of scope and the reliance on cost data found from other sources. Therefore, the results and analysis in the following chapters are valid only for general comparisons in terms of costs. Also, this thesis did not use a "brute force" method or other methods to determine the actual global optimal solutions for each trial. A brute force method was used only to prove that a three variable test reached the optimum.

The goal of this thesis is to create and study a decision support tool that can be used to aid in the design of an economically feasible Net Zero Energy vaccine warehouse for the developing world. The decision support tool is created by using proven optimization techniques and is used to study a building type that has not been previously researched. The next chapter presents the results obtained by using the decision support tool and parameters presented in this chapter.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter presents and discusses the results produced by studying the case study vaccine storage facility with the proposed decision support tool. The decision support tool uses the simulation-optimization method described in Chapter 3 to aid in the design of a cost-optimal NZE vaccine warehouse. The design problem being investigated with this tool is summarized in Table 31.

Table 31: Design problem for NZE vaccine warehouse

Objective Function	Minimize cost of building construction materials and renewable energy system ($Minimize\ \Delta CC_i + \Delta RE_i$)
Constraint	Annual energy consumption of warehouse ≤ Annual energy generation of on-site renewable energy system
Design Variables	Roof Insulation Thickness
	Exterior Wall Insulation Thickness
	Cold Storage Insulation Thickness
	Cold Room Floor Insulation Thickness
	Freezer Room Floor Insulation Thickness
	Air Infiltration Rate Reduction
	Roof Reflectivity Value
	Efficiency of the Windows
	Coefficient of Performance of the HVAC System

The details of the design variables, and assumptions made to select the economic equation were presented in Chapter 3. This design problem is used to investigate the optimal parameters for a NZE vaccine warehouse. First a genetic algorithm (GA) is used for the optimization technique. The GA has thirty generations and a population size of twenty five and takes approximately one day to set up, run, and compile data for each test. The GA is used to determine the optimum results for the first three sections of this chapter; these include the results from the construction sensitivity, the climate sensitivity, and the PV price sensitivity. Then, a design of experiments (DOE) is used for the optimization technique. The DOE has 512 simulations and takes approximately fifteen hours to set up, run, and compile data for each test. The fourth section of this chapter displays the results from the DOE, which show the effect of each variable on the objective function. The fifth section in this chapter presents the results from using the proposed combined method of a DOE and GA. The last section of this chapter provides an analysis of all of the results and provides generalized recommendations for each parameter based on climatic conditions, and discusses the adaptability and effectiveness of the decision support tool.

4.1 Results from Construction Sensitivity

The first trial conducted focused on the sensitivity of the optimal result to construction conditions. Two construction practices, US and Tunisian, are optimized for the vaccine warehouse in the Tunisian climate. This section first presents the results for the US construction case and then the Tunisian construction case. This section concludes with a comparison of the two construction methods.

4.1.1 Results from US Construction Case

By combining the US construction parameters listed in Chapter 3 with the genetic algorithm simulation-optimization approach, the optimum point described in Table 32 was found. The table also includes the reference case construction and the high end construction values.

Table 32: Results from US Construction in Tunisia Climate

Parameter / Level	Roof (mm)	External Wall (mm)	COP	Cold Wall (mm)	Cold Floor (mm)	Freezer Floor (mm)	Air Infiltration (ach)	Roof Reflectivity	Window Type
High	150	245	3.5	279	250	250	0.5	0.9	1.6 W/m²K SHGC: 0.50
Reference	0	92	2.6	92	0	0	4	0.05	5.10 W/m²K SHGC: 0.70
Optimum Point	25	92	3.3	187	150	250	1	0.9	5.10 W/m²K SHGC: 0.70

The optimum point, Pareto front, and all other points tested in the simulation are graphed in Figure 31.

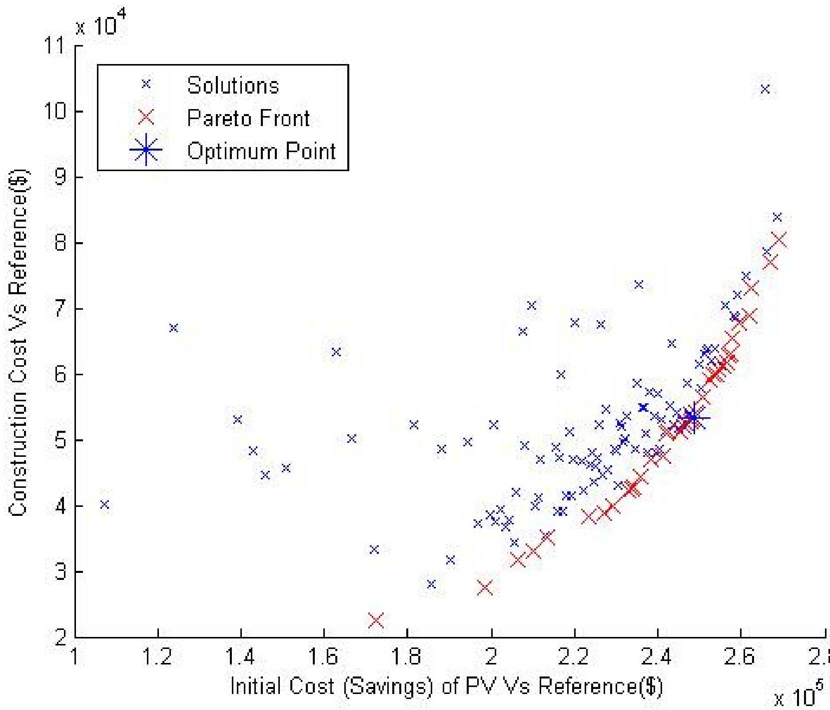


Figure 31: Plot of two objective functions for Pareto front; US Construction, Tunisian Climate

The optimal result shows 58.41% energy savings versus the reference case with an extra $53,261 being invested in construction costs. The result suggests significant insulation investment for the cold storage parameters; the suggested freezer room floor insulation thickness, cold room floor insulation thickness, and cold storage walls insulation thickness are 250mm, 150 mm and 187 mm respectively. The results also suggest investing in a higher COP value of the HVAC system, reducing the air infiltration rate, and increasing the roof reflectivity. The result suggests the selection of the reference case construction for the window type and the external wall insulation thickness. After this test was completed, the energy model is changed to reflect the Tunisian construction; the results are shown in the next section.

4.1.2 Results from Tunisian Construction

By combining the Tunisian construction parameters listed in Chapter 3 with the Genetic Algorithm, the optimum point described in Table 33 are found. The table also includes the reference case construction and the high end construction values.

Table 33: Results from Tunisian Construction in Tunisian Climate

Parameter / Level	Roof (mm)	External Wall (mm)	COP	Cold Wall (mm)	Cold floor (mm)	Freezer Floor (mm)	Air Infiltration (L/s*m²)	Roof Reflectivity	Window Type
High	60	100	3.5	279	250	250	0.175	0.9	1.658 W/m²K SHGC:0.57
Reference	0	0	2.6	92	0	0	0.7	0.05	6.172 W/m²K SHGC: 0.83
Optimum Point	40	20	3.0	187	150	25	0.175	0.9	6.172 W/m²K SHGC: 0.83

The optimum point, Pareto front, and all other points tested in the simulation are graphed in Figure 32.

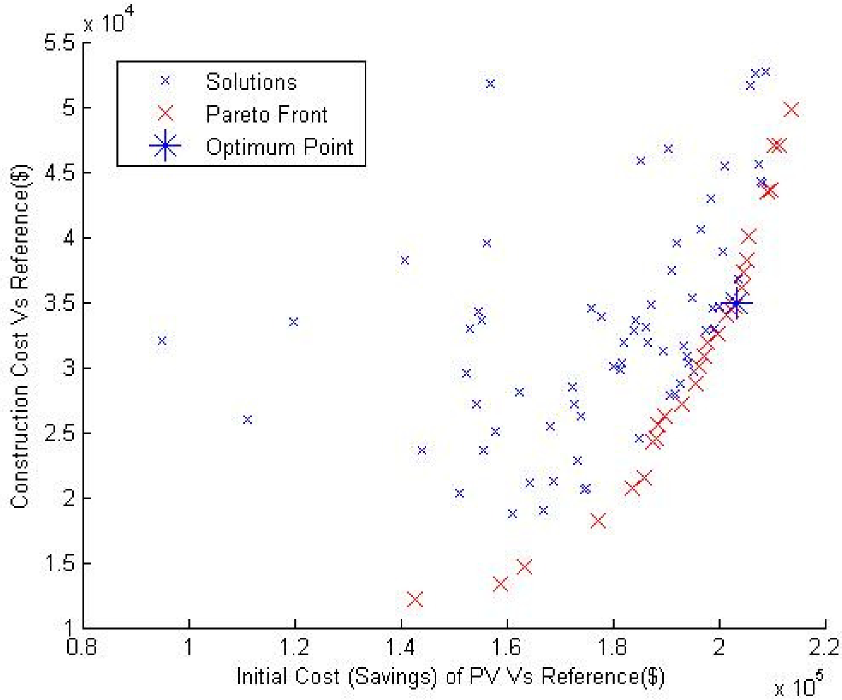


Figure 32: Plot of objective functions for Pareto front; Tunisian Construction, Tunisian Climate

The optimal result has a 55.67% energy savings versus the reference case with an extra $34,912 being invested in construction costs. The result suggests significant insulation investment for the cold storage parameters; the suggested freezer room floor insulation thickness, cold room floor insulation thickness, and cold storage walls insulation thickness are 250mm, 150 mm and 187 mm respectively. The results also suggest investing in a higher COP value of the HVAC system, increasing the roof insulation thickness, increasing the exterior wall insulation thickness, reducing the air infiltration rate, and increasing the roof reflectivity. The results suggest the selection of the reference case construction for the window type, this means to use the least efficient window. The optimum result found in this test are compared to the results of previous studies conducted for typical Tunisian construction. Table 34 presents the optimum building parameters that are found in the previous studies reviewed in Chapter 2 for the climate of Tunis, Tunisia and the results found in this thesis.

Table 34: Results from previous Tunisian studies compared to Thesis results for Tunisian construction

Building Component \ Study	(Bouden 2007)	(Daouas 2011)	(Ihm and Krarti 2012)	(Ihm and Krarti 2013)	Thesis
Objective Function	Min Energy Consumption	Min Life Cycle Cost (LCC)	Min LCC	Min LCC	Min $\Delta CC_i + \Delta RE_i$
Exterior Wall Insulation		57 mm of polystyrene	0 mm of polystyrene	20 mm of polystyrene	20 mm of polystyrene
Roof Insulation			0 mm of polystyrene	20 mm of polystyrene	40 mm of polystyrene
Window Type	Double glazing (U-Value: 2.3)		Single Clear (U-Value: 6.172)	Double Low-e (U-Value: 1.658)	Single Glazed: 6.172 W/m²K SHGC: 0.83
Air-Conditioner COP			3.3		3.0
Air Infiltration Level			0.175 L/s/m2	0.263 L/s/m2	0.175 L/s/m2
Energy Savings %	12	58	30	47	55.7

As seen in Table 34, the results from this thesis are mostly consistent with previous studies. The energy savings percentage is higher than the previous studies due to the energy savings from the cold storage areas. The main difference is that the suggested roof insulation thickness is greater for this thesis than what was seen in previous studies. However, the roof area is larger for the case study warehouse of this thesis when compared to the roof area of the buildings in the other studies. The previous studies recommended no insulation for the roof of the residential building, which had a roof area of 221 m² (Ihm and Krarti 2012) and 20 mm of insulation for the roof of the building office, which had a roof area of 335 m² (Ihm and Krarti 2013). These studies show the significance of increasing roof insulation for greater roof areas.

The suggested result of 40 mm of roof insulation is consistent with the previous studies, since the roof area of the case study warehouse is 788 m².

The optimal external wall insulation thickness is also significantly less than one of the previous studies (Daouas 2011) that investigated only wall insulation thickness and had a suggested exterior wall insulation thickness of 57 mm. The cost values for insulation used in Daouas's study were much lower than the cost values used in this thesis. The difference in suggested insulation thickness shows the impact of cost values on the optimum result, as well as the importance of using the most accurate cost values possible. The cost values in Daouas's study were obtained from a quote with one local construction company; this thesis uses cost values that came from previous studies which used government reports as their source for their cost values. The government reports are believed to be the source with the highest accuracy since they collected actual construction costs from the entire country and provide an average as compared to using a quote from one company. Overall, the results of this thesis are consistent with previous studies, and this shows that the building energy model is accurate.

4.1.3 Comparison of Results

This section compares the results found from the two construction cases. The two differences between the construction cases are the cost of materials and the energy model. The differences between the energy models are the way that air infiltration and the exterior wall construction are modeled. The air infiltration rate is modeled as air changes per hour for the US construction and flow per exterior area for the Tunisian construction. The exterior wall construction is modelled as a SIP for the US construction and a brick wall with insulation for the Tunisian construction. The brick wall in the Tunisian construction acts as a thermal mass, and the US construction has no thermal mass for the exterior wall. Table 35 presents the optimal solution of the two different construction techniques.

Table 35: Results from Tunisian Construction in Tunisian Climate

Parameter / Level	Roof (mm)	External Wall (mm)	COP	Cold Wall (mm)	Cold Floor (mm)	Freezer Floor (mm)	Air Infiltration	Roof Reflectivity	Window Type
US Construction	25	92	3.3	187	150	250	1 ach	0.9	5.10 W/m²K SHGC: 0.70
Tunisian Construction	40	20	3.0	187	150	250	0.175 L/s*m²	0.9	6.172 W/m²K SHGC: 0.83

The US and Tunisian construction suggest the same cold storage insulation thickness, cold room floor insulation thickness, freezer room floor insulation thickness, and roof reflectivity value. Also, the suggested window type for both results is the reference case, or not investing in higher efficiency windows. The suggested roof insulation thickness is slightly higher for the Tunisian construction as compared to the US construction. This is most likely due to the cost difference between the two construction types. The cost for 20 mm of roof insulation for the Tunisian construction is a $2,391 investment, while 25 mm of roof insulation for the US Construction is $6,779. However, it is hard to compare the other parameters due to the differences in construction/modeling. Table 36 compares the final results for the two construction techniques.

Table 36: Comparison of Tunisian Construction and US Construction for Tunisian Climate

	Tunisian Construction	US Construction
Energy Savings	55.67%	58.41%
PV System Size to achieve NZE (kW)	36	39.3
Material Investment (USD)	34,912	53,261
Cost difference between optimal and highly energy efficient solution (USD)	21,484	47,471

The optimal result for the US construction costs has a larger material investment and uses more energy than the optimum result for the Tunisian construction. The reason behind this is believed to be the cost data used to represent the construction. The cost data used show the cost of materials for the Tunisian construction is less than the cost of material for the US construction. For example, 20 mm of roof insulation for the Tunisian construction is a $2,391 investment and 25 mm of roof insulation for the US construction is $6,779. The US construction cost data was collected mostly from one source, RSMeans; the Tunisia cost data came from previous studies which referenced government reports written for the Tunisia National Agency for Energy Conservation. In order to get more accurate cost data for the Tunisian construction, research would need to be done in Tunisia to find the referenced government reports to check the accuracy of the cost data. However, a trip to Tunisia to perform this research was beyond the scope of this thesis. For the rest of these results in this chapter, the two constructions are not compared to each other with exact numbers, but instead general trends due to the different sources used to find the cost values.

The last row in the Table 36 compares the cost difference between the optimal solution and a highly energy efficient solution. The highly energy efficient NZE design solution represents the building that was designed in Section 3.1 and uses all of the high parameter levels considered in the optimization. The cost of the solutions includes the cost of the PV system and the initial investment of the construction materials. The Tunisian and US construction optimal construction are significantly less than the highly energy efficient building, $21,484 and $47,471 respectively. These results illustrate the importance of an economic analysis of NZEBs in order to reach NZE with economic efficiency.

It is also important to investigate whether or not installing a PV system is economically feasible. A payback time model and the return on investment (ROI) are used to determine such feasibility. Three different costs of electricity and the annual electricity consumption of the optimum result for the Tunisian construction will be used to determine the ROI and Payback Period for Tunisia. By regional standards, electricity prices in Tunisia are at a medium level. In

November 2008, they ranged between a minimum of 0.081 $/kWh and a maximum of 0.155 $/kWh (ENEC 2008). The Payback Time and ROI are only calculated for the Tunisia construction due to the similarities in the PV system size of the US and Tunisian construction. The results can be seen in Table 37.

Table 37: Return of Investment and Payback Period for PV Panels at $4.50/installed watt

USD per kWh	ROI	Payback Period
0.081	2.29%	43.49 years
0.118	3.34%	29.85 years
0.155	4.39%	22.73 years

The payback period for the PV panels is approximately 30 years for the average electricity price. If the price of electricity increases, then the payback time is reduced to approximately 23 years. PV systems on the market currently have a lifespan of 25 years. This shows that the PV systems are feasible, but would be a better investment if the PV systems could be purchased for less than the assumed PV cost used in this thesis, $4.50 per installed watt. After these tests were completed, the simulation is modified to change the climate; the results are shown in the next section.

4.2 Results from Climate Sensitivity Analysis

The second trial conducted focused on the sensitivity of the optimal result to climatic conditions. The decision support tool is used to study the optimal results of two construction practices, US and Tunisian, for five different climates. This section first characterizes the five climates being investigated. Then this section provides the results for the US construction case and then the Tunisian construction case. Finally, this sections presents a general comparison of the climatic trends found.

4.2.1 Characterization of Climates

The climate of Tunis, Tunisia is chosen as the case study for this thesis. Four other cities that represent low and middle income countries were studied to determine the effect of climate on the optimal result: Buenos Aires, Argentina; Mombasa, Kenya; Asunción, Paraguay; and Bangkok, Thailand. Table 38 provides a description of the climate, Heating Degree Days (HDD), and Cooling Degree Days (CDD) for each city.

Table 38: Characterization of five climates data from (WeatherUnderground, 2013)

Country	City	Climate Description	HDD	CDD
Argentina	Buenos Aires	Warm humid temperate climate with hot summers and no dry season	1705	1595
Kenya	Mombasa	Tropical savannah climate with dry winters	0	5319
Paraguay	Asunción	Warm humid temperate climate with hot summers and no dry season	687	3829
Thailand	Bangkok	Tropical savannah climate with dry winters	4	6626
Tunisia	Tunis	Mediterranean climate with dry hot summers and mild winters	1501	2350

Heating degree day (HDD) is a measurement designed to reflect the demand for energy needed to heat a building. The heating requirements for a given building at a specific location are considered to be directly proportional to the number of HDDs at that location. HDDs are defined relative to a base temperature, the outside temperature above which a building needs no heating. A similar measurement, cooling degree day (CDD), reflects the amount of energy used to cool a building. The base temperature is usually an indoor temperature that is adequate for human comfort. A base temperature of 65°F was used to calculate the HDDs and CDDs in Table 38. To calculate the heating degree days for a particular day, first one must calculate the day's average temperature by adding the day's high and low temperatures and dividing by two. If the number is above 65, there are no heating degrees days that day. If the number is less than 65, subtract it from 65 to find the number of heating degree days. For example, if the day's high temperature is 60 and the low is 40, the average temperature is 50 degrees. HDDs would be calculated as follows: 65 minus 50 meaning there are 15 heating degree days. Inversely, the number of CDDs is calculated from when the average temperature is above 65. The number of HDDs and CDDs will be used to correlate the optimal results to climatic conditions. HDDs and CDDs were chosen since they are commonly used for tracking energy use (NOAA, 2010). Table 39 provides insights on the climates that cannot be known by simply looking at the number of HDDs and CDDs.

Table 39: Characterization of five climates data from (WeatherSpark 2013)

Country	City	Relative humidity Range	Cloud Cover Range	Temperature Range	Precipitation Range
Argentina	Buenos Aires	48% (comfortable) to 91% (very humid)	36% (mostly clear) to 65% (partly cloudy)	47°F to 82°F	36% of days to 28% of days
Kenya	Mombasa	52% (mildly humid) to 96% (very humid)	45% (partly cloudy) to 57% (partly cloudy)	70F to 91°F	49% of days to 10% of days
Paraguay	Asunción	36% (comfortable) to 96% (very humid)	74% (partly cloudy) to 87% (mostly cloudy)	53°F to 93°F	44% of days to 21% of days
Thailand	Bangkok	41% (comfortable) to 90% (very humid)	44% (partly cloudy) to 90% (mostly cloudy)	73°F to 95°F	86% of days to 5% of days
Tunisia	Tunis	36% (comfortable) to 94% (very humid)	17% (mostly clear) to 58% (partly cloudy)	46°F to 93°F	46% of days to 8% of days

The temperature range reflects the averages over the course of a year and includes the average high during the warm season and average low during the cold season. The cloud cover range is the median cloud cover range from the cloudiest and clearest times of the year. The precipitation range is the probability that precipitation will be observed at this location during the peak of the warm season and the cold seasons. The relative humidity is the average of the humidity during the driest and the most humid times of the year. The climatic characteristics, HDDs and CDDs, will be used in the following sections to better understand the optimal results.

4.2.2 Results from US Construction

In order to investigate climate, the weather input file for the building simulation and the PVWatts program were changed for every city before starting the optimization. By combining the US construction parameter listed in Chapter 3 with the genetic algorithm simulation-optimization approach, the optimal results described in Table 40 were found for the five climates. The table also includes the values for the reference case construction and the high end construction.

Table 40: Results from GA for US Construction

Parameter / Level	Roof (mm)	External Wall (mm)	COP	Cold Wall (mm)	Cold Floor (mm)	Freezer Floor (mm)	Air Infiltration (ach)	Roof Reflectivity	Window Type
High	150	245	3.5	279	250	250	0.5	0.9	1.6 W/m²K SHGC: 0.50
Reference	0	92	2.6	92	0	0	4	0.05	5.10 W/m²K SHGC: 0.70
Argentina	25	92	3.0	187	150	200	1	0.9	2.80 W/m²K SHGC: 0.63
Kenya	0	92	3.0	187	150	250	4	0.9	2.70 W/m²K SHGC: 0.63
Paraguay	0	92	3.3	187	150	250	3	0.9	2.70 W/m²K SHGC: 0.63
Thailand	0	92	3.3	238	150	250	4	0.9	2.80 W/m²K SHGC: 0.63
Tunisia	25	92	3.3	187	150	250	1	0.9	5.10 W/m²K SHGC: 0.70

The results suggested the same roof reflectivity value and external wall insulation thickness be selected for all five countries. The results suggest a roof reflectivity value at its highest value - a white roof. The cost for the white roof is $2,751, while the costs to increase the roof insulation are $6,779 for 25 mm and $9,853 for 50 mm. These costs make it cheaper to pay for the white roof than to invest in roof insulation. As a result, it is suggested that all of the countries invest in white roofs. The results suggest that the external walls insulation thickness should be at the reference value, a 92 mm structurally insulated panel (SIP), for all five climates. SIPs are a new technology and have a high associated cost. It costs $5,210 to increase the SIP insulation thickness to the next level; as a result of this high cost, none of the climates selected a higher level of external wall insulation.

The suggested value for the other parameters can be explained by climatic conditions, HDDs and CDDs. The results suggest investing in roof insulation thickness for Tunisia and Argentina. Tunisia and Argentina have the highest number of HDDs of all of the countries studied, 1501 and 1705 HDDs respectively. However, it should be noted that the results for Paraguay, which has 687 HDDs, do not suggest added investment in roof insulation. This shows the number of HDDs needs to reach a certain level before roof insulation is a good investment. Thailand has a higher suggested thickness for the cold storage walls than other countries; Thailand also has the highest number of CDDs of all of the climates studied. Argentina has a lower suggested thickness for the freezer room floor insulation than other countries; Argentina also has the lowest number of CDDs of all of the climates studied. Another example of using HDDs and CDDs to explain the optimum parameter is the air infiltration rate. Figure 33 shows the suggested air infiltration rate and the number of HDDs for the five countries. In the figure, a lower infiltration rate is better.

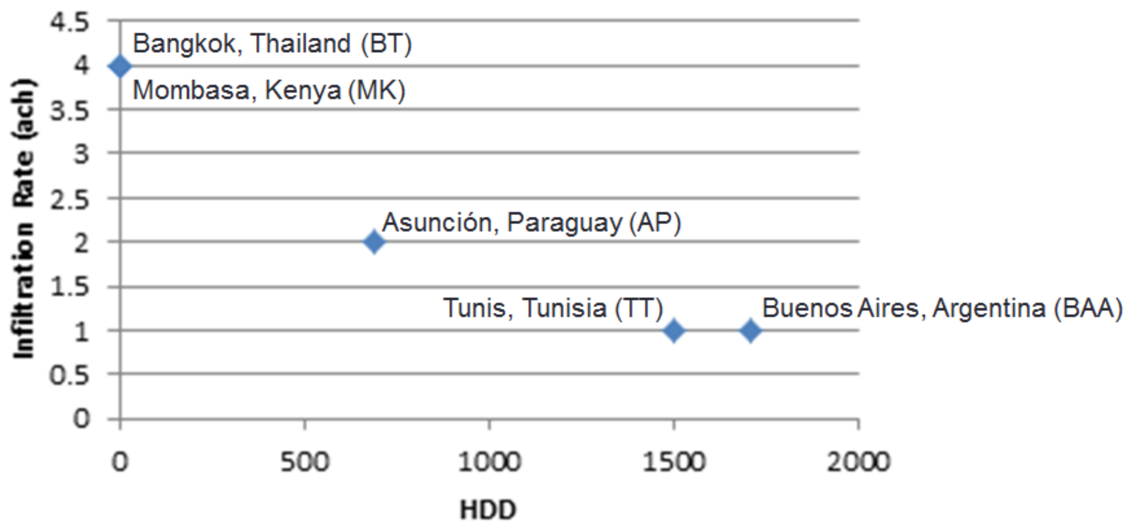


Figure 33: Correlation between infiltration rate and HDD for US Construction

The correlation shows that if the number of HDDs is high, then investments should be made to reduce the air infiltration rate. A lower air infiltration rate is better, and had a higher investment. As the number of HDDs decreases, the suggested investment is air infiltration reduction decreases. In conclusion, these climate sensitivity results show that HDD correlates with the overall building parameters, including the air infiltration reduction, freezer room floor insulation, and roof insulation thickness. The correlation shows that as the number of HDDs increases, the investment in these parameters should also increase. The number of CDDs correlates with the optimum cold storage insulation thickness. However, two of the parameters that had variation, window type and HVAC COP, showed no direct correlation with either HDDs or CDDs. The design of experiments in Section 4.4 will study the interactive effects of these parameters to better under the results found. The costs associated with the optimal solution for the five climates are presented in Table 41.

Table 41: Comparison of NZE costs for US Construction

Optimal Solution Values	Argentina	Kenya	Paraguay	Thailand	Tunisia
Material Investment (USD)	55,478	27,784	34,357	33,876	53,261
Energy Usage (kWh)	44,948	54,974	51,774	57,385	50,221
PV System Size (kW)	42.5	40.7	45.4	46.1	39.3
Cost for materials and PV (USD)	246,728	210,934	238,657	241,326	230,111
Cost difference between optimal and highly energy efficient solution (USD)	47,064	68,908	57,385	59,216	47,481

The results show that climates with a high number of HDDs, Tunisian and Argentina, require more energy efficient solutions which increase the material investment. Also, the climates with a significant amount of cloud coverage, Paraguay, have a lower amount of solar radiation, and a large PV system is required to offset the energy usage. The results show that Kenya has the lowest total investment costs of all this climates. Kenya has a high numbers of CDDs and no HDDs and this result was unexpected. The vaccine warehouse has large cooling loads due to the vaccine storage, so it was expected for climates with a low number of CDDs to be the most economical. The reasoning for this will be explored later in this chapter. The table also shows the cost difference between the optimal solution and a highly energy efficient solution. The highly energy efficient NZE design solution represents the building that was designed in Section 3.1 and uses all of the high parameter levels considered in the optimization. The cost of the solutions includes the cost of the PV system and the initial investment of the construction materials. The difference in cost between the optimal solution and highly energy efficient solution ranged from $47,000 to $69,000. These results illustrate the importance of an economic analysis of NZEBs in order to reach the energy goals with economic efficiency. The optimum point, Pareto front, and all other points tested in the simulation for all five climates are graphed in Figure 34.

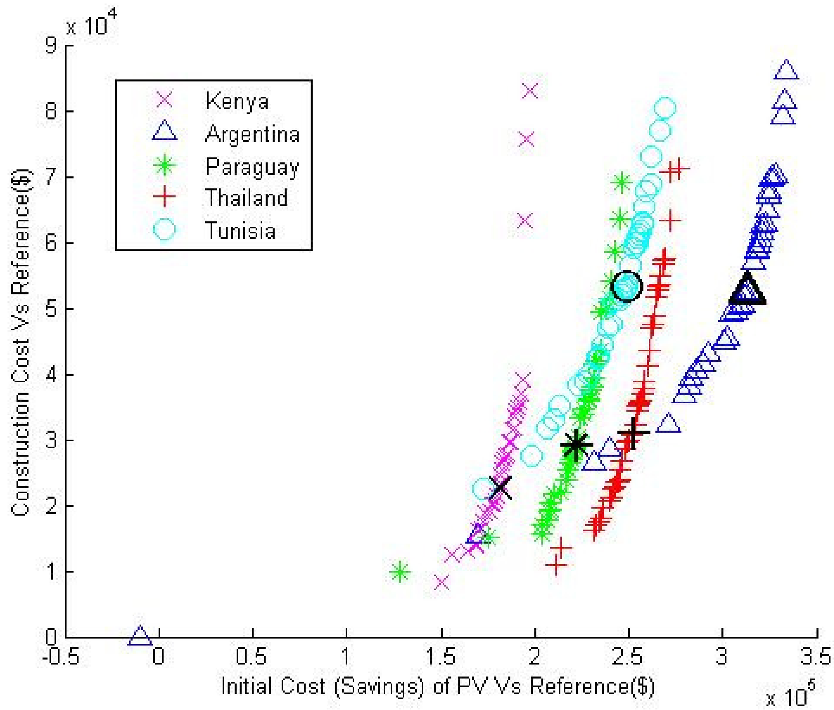


Figure 34: Five Pareto plots for US Construction

As can be seen in Figure 34, the Pareto fronts have two distinct slopes. The countries with a high number of HDDs, Argentina and Tunisia, have similar slopes while the countries with a high number of CDDs, Kenya, Paraguay, and Thailand, have similar slopes. The plots are collapsed on top of each other in order to determine if a scaling factor could be found. If one can be found, then this value may relate the Pareto plots to the climatic parameters. In order to collapse the Pareto plots, the x and y parameters of all of the points are multiplied by a coefficient. First, Kenya, Paraguay, and Thailand are shifted to match Thailand. Thailand is chosen because it has the highest number of HDDs. The curves are shifted by using a guess and check method with one value used to shift both the x and y axis. Then Argentina and Tunisia are shifted to match Thailand. Since the slopes are different for these countries, the x and y values are assigned different multiplicative factors. Tunisia cannot be successfully shifted, but the other four countries successfully collapse onto the Thailand Pareto plot. The final results can be seen in Figure 35.

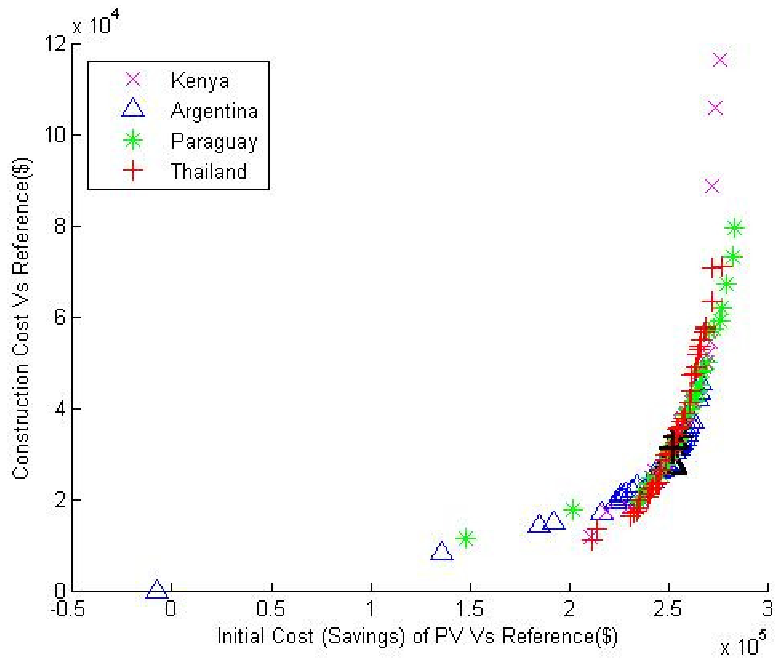


Figure 35: Four of five Pareto plots collapsed on top of each other for US Construction.

In order to get their Pareto plots to line up with Thailand, Kenya's is multiplied by 1.4 and Paraguay's is multiplied by 1.15. Argentina's Pareto plot has a different slope than Thailand's Pareto plot, and more than one coefficient is needed in order to make the plots collapse on top of each other. To makes the slopes match, Argentina has a different value for the X and Y axis; hence it is multiplied by 0.8 for X and 0.53 for Y. These values do not correlate to any known relationships between HDDs and CDDs, but these values are compared to the Tunisian construction later in this section to see if similar constants are found. After these tests were completed, the optimization code is switched to simulate the Tunisian construction model for the five climates; the results are shown in the next section.

4.2.3 Results from Tunisian Construction

In order to investigate climate, the weather input file for the building simulation and the PVWatts program is changed for every city before starting the optimization. By combining the Tunisian construction parameters listed in Chapter 3 with the genetic algorithm simulation-optimization approach, the optimal results described in Table 42 are found for the five climates. The table also includes values for the reference case construction and the high end construction.

Table 42: Results from GA for Tunisian Construction

Parameter / Level	Roof (mm)	External Wall (mm)	COP	Cold Wall (mm)	Cold Floor (mm)	Freezer Floor (mm)	Air Infiltration (L/s*m²)	Roof Reflectivity	Window Type
High	60	100	3.5	279	250	250	0.175	0.9	1.658 W/m²K SHGC:0.57
Reference	0	0	2.6	92	0	0	0.7	0.05	6.172 W/m²K SHGC: 0.83
Argentina	20	20	2.6	187	150	250	0.175	0.9	6.172 W/m²K SHGC: 0.83
Kenya	0	20	2.6	187	100	250	0.175	0.9	3.160 W/m²K SHGC:0.60
Paraguay	0	20	2.6	187	150	250	0.175	0.9	3.160 W/m²K SHGC:0.60
Thailand	0	40	3.0	187	150	250	0.175	0.9	3.160 W/m²K SHGC:0.60
Tunisia	40	20	3.0	187	150	250	0.17	0.9	6.172 W/m²K SHGC: 0.83

The results for all five climates suggested that the same roof reflectivity value, cold storage insulation thickness, freezer room floor insulation thickness, and air infiltration rate reduction. The results suggest a roof reflectivity value at its highest value - a white roof. The cost for the white roof is $2,751, while the cost to increase the roof insulation thickness is $2,391 for 20 mm and $4,298 for 40 mm. The cost of the roof insulation and roof coating are very similar. This suggests that increasing the roof reflectivity is a better investment than increasing the roof insulation thickness, which is the reason that a white roof is suggested for all countries. The suggested cold storage insulation thickness and freezer room floor insulation thickness are consistent for the five climates. However, the suggested cold room floor insulation thickness is less for Kenya than the other countries; Kenya also has the lowest number of HDDs of all of the climates studied. The suggested air infiltration reduction is always at the highest level, meaning to select the lowest air infiltration rate possible for this construction. This is most likely due to the cost values used in the optimization. In Section 3.3.3.2.6, it was discussed that since these prices seemed very low (they were for a residential building), and original prices are scaled up based the ratio of costs between residential and commercial buildings seen in previous studies. However, even with this scale up factor, the prices still seemed to be low. The price to reduce air infiltration for the building using Tunisian construction is about 20% of the cost to reduce air infiltration for the US construction. The cost difference explains why there is variation in the suggested air infiltration rate for the US construction but no variation for the Tunisian construction.

The suggested value of the other parameters can be explained by the number of HDDs and CDDs for the climate. The investment in more efficient windows correlates with the number of CDDs. Argentina and Tunisia, which have the lowest number of CDDs of all the countries studied, have results that suggest the selection of the reference case window. The other three countries' results suggest investing in more energy efficient windows. This shows that for a climate with a large number of CDDs, investments should be made to obtain higher efficiency windows. The suggested exterior wall insulation thickness is also linked to CDDs. Thailand's results suggest a thicker insulation for the exterior wall than the other countries; Thailand also has the highest number of CDDs of all of the climates studied. The suggested roof insulation thickness shows a trend that correlates closely to HDDs. The optimal results suggest investing in roof insulation for Tunisia and Argentina, the countries with the highest HDD of the climates studied, 1501 and 1705 HDD, respectively. However, even though Argentina has a higher number of HDDs, Tunisia's optimum suggests a larger thickness of roof insulation. If the cloud cover range of the two cities is investigated, then one sees that Tunis, Tunisia has a coverage range of 17% (mostly clear) to 58% (partly cloudy) while Argentina has a coverage range of 36% (mostly clear) to 65% (partly cloudy). The cloud coverage provides possible explanation for the reason that results for Tunisia suggest more insulation than for Argentina. Tunisia has less cloud coverage and this leads to more solar gains through the roof. The increased solar gains makes Tunisia suggest more roof insulation. This result shows the problem with using only HDDs and CDDs to make construction recommendations, since the cloud coverage has an effect on the suggested insulation thickness. Only one parameter, the HVAC COP, showed no direct correlation with either HDDs or CDDs. The optimum point, Pareto front, and all other points tested in the simulation are graphed for all five climates in Figure 36.

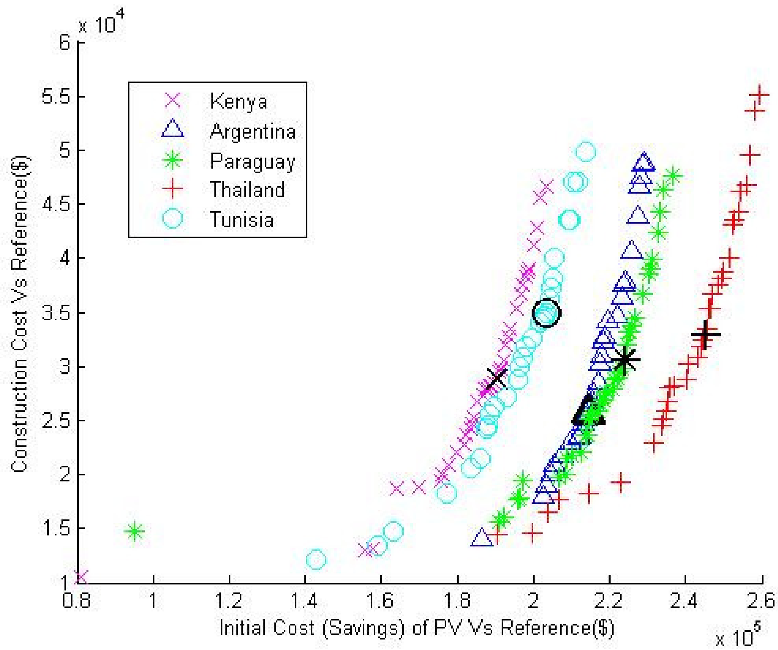


Figure 36: Five Pareto plots for Tunisian Construction

As can be seen in Figure 36, all of the Pareto plots have similar slopes. The same method used in Section 4.2.2 is used to collapse the plots on top of each other in order to determine a scaling factor. There is one slight difference from the method presented previously. In Section 4.2.2, Tunisia and Argentina have different slopes and had to have their x and y coefficients multiplied by different factors. For the Tunisian construction, all of the countries have the same slope, so only one coefficient is needed to shift all of the Pareto plots. The final results can be seen in Figure 37.

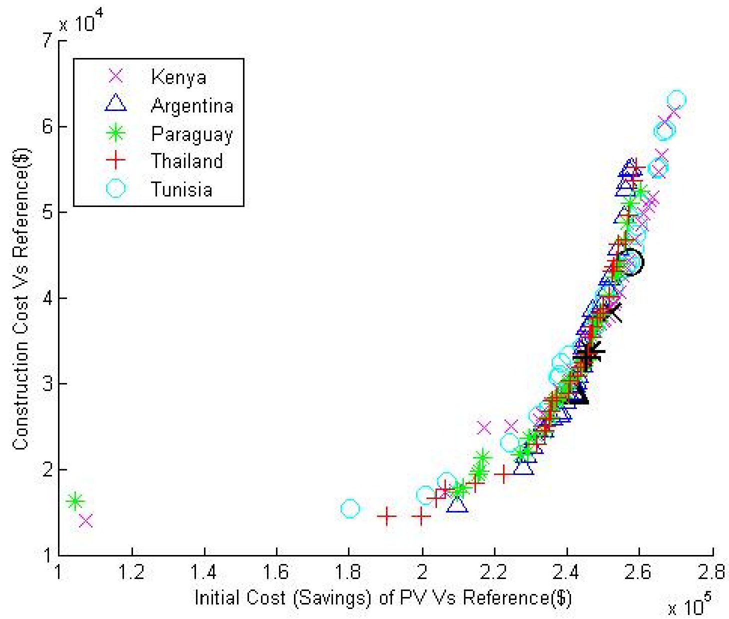


Figure 37: Five Pareto plots collapsed on top of each other for Tunisian Construction.

In order to get its Pareto plot to align with Thailand, Kenya's is multiplied by 1.325, Paraguay's is multiplied by 1.1, Tunisia's is multiplied by 1.265, and Argentina's is multiplied by 1.125. These values do not correlate to any known relationships between HDDs and CDDs. These values are compared with the US construction scaling factors in the next section to see if similar constants are found. The next section presents a full comparison of the results from the two construction techniques.

4.2.4 Comparison of Climate Sensitivity Results

After completing the optimization for both construction techniques, the general trends are compared. Even though the construction techniques are different, the general trends between the climates should be similar due the effect of the climatic conditions. The general trends from the two climate sensitivity tests are summarized in Table 43.

Table 43: Comparison of results from Climate Sensitivity

Building Parameter	US Construction	Tunisian Construction
Roof Insulation	Higher HDD, invest in more insulation	Higher HDD, invest in more insulation also taking into account cloud coverage
External Wall Insulation	Consistent, no investment suggested	Higher CDD, invest in more insulation
HVAC COP	No correlation	No correlation
Cold Wall Insulation	Higher CDD, invest in more insulation	Consistent, medium investment in more insulation
Cold Room Floor Insulation	Consistent, medium investment	Higher CDD, invest in more insulation
Freezer Room Floor Insulation	Higher HDD, invest in more insulation	Consistent, invest to upper bound of insulation
Air Infiltration Level	Higher CDD, invest more in air infiltration reduction	Consistent, invest in the maximum reduction in air infiltration possible
Roof Reflectivity	Consistent, invest in the maximum roof reflectivity	Consistent, invest in the maximum roof reflectivity
Window Type	No correlation	Higher CDD, invest in better windows

The two construction techniques both showed similar trends. However, both tests had building parameters that had a constant construction suggestion throughout the five climates but many of the other variables did vary throughout the climates so that climatic trends can be found. The following conclusions can be made based on the trends observed from the climate sensitivity analysis:

- If the number of HDDs is high, then investments should be made to increase the roof insulation thickness and the freezer room floor insulation thickness. However, cloud coverage will also affect the suggested roof insulation thickness. If the cloud coverage for the area is low, then additional investments should be made for increasing the roof insulation thickness.
- If the number of CDDs is high, then investments should be made to increase the exterior wall insulation thickness, increase the cold storage wall insulation thickness, increase the cold room floor insulation thickness, reduce the air infiltration rate, and increase the window efficiency.
- In general, a large investment should be made to increase the insulation thickness for all the cold storage parameters regardless of the climatic conditions. The cold storage parameters include the cold storage wall insulation, cold room floor insulation, and the freezer room floor insulation.

The results show that HDDs and CDDs can be useful tools when recommending building parameters. However, they cannot always make accurate construction recommendations and sometimes other climatic conditions need to be considered. The suggested roof insulation thickness for the Tunisian construction did not correlate with HDDs, but the results could be explained when cloud coverage of the climate was considered. Also, the suggested HVAC COP value did not correlate with the number of HDDs or CDDs. However, the suggested COP values are similar between the two constructions techniques, suggesting that a correlation exists; it could just not be found be only looking at the climatic conditions. A possible explanation for this correlation will be explored in Section 4.4 by investigating the interactive effects between the parameters with a DOE analysis. This section also looks at finding a scaling factor for the Pareto plots. The Pareto plots are collapsed on top of each other using the coefficients shown in Table 44.

Table 44: Pareto Plot Constants

Country	US Construction Shift	Tunisian Construction Shift	Thailand CDD / Country CDD	Thailand HDD / Country HDD
Thailand	(x,y)*1	(x,y)*1	1	1
Argentina	(x,y)*(0.8,0.53)	(x,y)*1.125	4.1542	4/1705=0.00234
Kenya	(x,y)*1.4	(x,y)*1.325	1.2457	4/0
Paraguay	(x,y)*1.15	(x,y)*1.1	1.7305	4/687=0.00582
Tunisia	N/A	(x,y)*1.265	2.8196	4/1501=0.00266

Table 44 presents the CDD and HDD ratios and the scaling factors previously found. These values are used in order to investigate a possible relationship with the building parameters. First, a relationship between Thailand, Kenya, and Paraguay is investigated since they have similar slopes for both construction techniques. The two construction techniques have consistent scaling factors for Kenya and Paraguay, and the results show that Kenya has a larger scaling factor than Paraguay. The scaling factors do not correlate to the CDD ratio; Paraguay has a larger CDD ratio than Kenya and a smaller scaling factor. If the climatic conditions in Table 39 are compared to the scaling factors, then the cloud coverage range seems to explain the shift. Kenya has a lower cloud cover range than Paraguay while the cloud cover range for Paraguay is similar to Thailand. This explains why Kenya would have a larger shift than Paraguay. Also, it can be seen that Tunisia has a large scaling factors and a lower cloud cover range than Thailand. The cloud cover range can explain all of the scaling factors, except for Argentina. Argentina has a low scaling factor, meaning that to follow the trend seen for the other climates; it would need to have a high cloud cover range. However, Argentina has a low cloud cover range. The only climatic condition that is similar between Argentina and Thailand is the relative humidity range. However, Kenya also has a relative humidity range similar to Argentina and Thailand, but Kenya has a significantly higher scaling factor than Argentina. In the end, no simple relationship between can be found between the climates that explains the scaling factors. The results are a factor of many climatic effects and interactive effects between parameters, which makes it impossible to explain the shifts by only using a few climatic parameters. The next section of this chapter looks at the sensitivity on the selection of the optimum parameter for each climate based on varying the renewable energy system cost.

4.3 Results for PV Sensitivity Analysis

The third set of tests conducted focused on the sensitivity of the optimum parameter values when changing the cost of the photovoltaic (PV) system. This objective function of the design problem is to minimize the initial cost of the building. This is accomplished by investing in construction materials to make the building more energy efficient which reduces the cost of the renewable energy system need to accomplish NZE. Three different PV cost are investigated. A high PV cost is $5.50/installed watt, the regular PV cost is $4.50/installed watt, and the low PV cost is $3.50/installed watt (Goodrich, James et al. 2012). This section provides the results for the five climates at the three specified PV costs and then compares the results to see if the trends previously found still hold true.

4.3.1 Climates Results

The PV sensitivity tests are conducted for all five climates at three different PV costs. These tests are used to see which parameters vary when the cost of the energy system changes. It is expected that when the PV cost is higher, then the suggested construction cost will be higher. Inversely, it is expected that when the PV cost is lower, the suggested construction cost will be lower. By combining the Tunisian construction parameters listed in Chapter 3 with the Genetic Algorithm, the optimum points described in Table 45 were found for the three PV cost levels for all five of the climates. The table also includes the values for the reference case construction and the high end construction.

Table 45: Results from PV Sensitivity for all five countries

Parameter / Level	Roof (mm)	External Wall (mm)	COP	Cold Wall (mm)	Cold Floor (mm)	Freezer Floor (mm)	Air Infiltration (L/s*m²)	Roof Reflectivity	Window Type
High	60	100	3.5	279	250	250	0.175	0.9	1.658 W/m²K SHGC:0.57
Reference	0	0	2.6	92	0	0	0.7	0.05	6.172 W/m²K SHGC: 0.83
Argentina High	40	20	2.6	238	150	200	0.175	0.05	6.172 W/m²K SHGC: 0.68
Argentina	20	20	2.6	187	150	250	0.175	0.9	6.172 W/m²K SHGC: 0.83
Argentina Low	20	20	2.6	187	100	250	0.175	0.9	6.172 W/m²K SHGC: 0.83
Kenya High	0	20	3.0	187	150	250	0.175	0.9	3.160 W/m²K SHGC:0.60
Kenya	0	20	2.6	187	150	250	0.175	0.9	3.160 W/m²K SHGC:0.60
Kenya Low	0	20	2.6	187	100	250	0.175	0.9	3.160 W/m²K SHGC:0.60
Paraguay High	0	20	3.0	238	150	250	0.175	0.9	6.172 W/m²K SHGC:0.68
Paraguay	0	20	2.6	187	150	250	0.175	0.9	3.160 W/m²K SHGC:0.60
Paraguay Low	0	20	2.6	187	100	250	0.175	0.9	6.172 W/m²K SHGC:0.68
Thailand High	0	40	3.0	238	150	250	0.175	0.9	1.658 W/m²K SHGC:0.57
Thailand	0	40	3.0	187	150	250	0.175	0.9	3.160 W/m²K SHGC:0.60
Thailand Low	0	20	3.0	187	100	200	0.175	0.9	3.160 W/m²K SHGC:0.60
Tunisia High	40	20	3.3	187	150	200	0.175	0.9	6.172 W/m²K SHGC: 0.68
Tunisia	40	20	3.0	187	150	250	0.175	0.9	6.172 W/m²K SHGC: 0.83
Tunisia Low	40	20	3.0	187	100	250	0.175	0.9	6.172 W/m²K SHGC: 0.68

Buenos Aires, Argentina had the suggested value of six parameters change during the PV sensitivity analysis. Four of these parameters, roof insulation thickness, window efficiency, cold storage insulation thickness, and cold room floor insulation thickness, varied as expected. However, the suggested roof reflectivity value, and freezer room floor insulation thickness did not vary as expected. The suggested roof insulation thickness increased at the high PV cost. This means that when the cost of the PV system increases, more money should be invested in roof insulation. Buenos Aires has a high number of HDDs, so increasing the roof insulation will make the building have a lower heating demand and therefore consume less energy. However, when the roof insulation thickness increased, the result suggested not to invest in increasing the roof reflectivity. This result was unexpected since the investment of a parameter was not expected to decrease at the higher PV cost. This relationship will be further explored with the DOE in the Section 4.4. The suggested cold storage wall insulation thickness increased at the high PV cost, the suggested cold room floor insulation thickness decreased at the low PV cost, and the suggested freezer room floor insulation thickness decreased at the high PV cost. The freezer room floor insulation result was unexpected since the suggested thickness of the freezer room floor insulation decreased at the high PV cost. It was assumed that since the cold storage rooms consume a significant amount of energy that none of the suggested insulation thicknesses would decreased at the higher PV cost. Finally, the results suggested a higher efficiency window for the high PV cost level. The higher efficiency window type reduced the suggested SHGC of the window while the U-Value suggested remained the same. The SHGC is the ability to control solar heat gain through the glazing. Therefore, with a lower SHGC there is less heat gain by the building. Buenos Aires has a high number of HDDs and these results show which parameters will lower the heating demand of the building.

Mombasa, Kenya had the suggested value of two parameters change during the PV sensitivity analysis; both of them varied as expected. The suggested COP value of the HVAC system increased at the high PV cost level. Kenya has a large number of CDDs and the vaccine warehouse is cooling intensive, therefore a climate with a high number of CDDs would benefit from a more efficient HVAC system. The suggested cold room floor insulation thickness decreased at the low PV cost level; this shows that this parameter is not as important when PV costs are lower. These results show that for Kenya, a climate that had no HDDs, that the COP of the HVAC system and cold room floor insulation have a noticeable effects on the building energy use.

Asunción, Paraguay had the suggested value of four parameters change during the PV sensitivity analysis. Three of the parameters, the COP of the HVAC, cold storage wall insulation, and cold room floor insulation, varied as expected. The suggested COP value of the HVAC and the cold storage wall insulation thickness increased at the high level PV cost. This was expected due to the large number of CDDs for this climate and both of these parameters would help to lower the cooling needs of the building. The suggested cold room floor insulation thickness decreased for the low PV cost level; this shows that this parameter is not as important when PV costs are lower. The parameter that did not vary as expected was the window type. A highly energy efficient window was selected for the normal PV cost level, while a less energy efficient window was chosen for the high and low PV cost levels. The only other variable that is changing that could have an effect on the window type is the COP of the HVAC system. The effect between the HVAC COP and the window type could be the reason for the unexpected variation in the window type. The interactive effects with the window type will be investigated with the DOE in Section 4.4.

Bangkok, Thailand had the suggested value of five variables change during the PV sensitivity analysis; all of the variables varied as expected. The results suggest increasing the external wall insulation thickness and selecting a more energy efficient window for the high PV cost. Thailand has a high number of CDDs, meaning that the increasing the insulation of the external wall and choosing a more energy efficient window reduces the building's cooling demand and therefore it requires less energy. Reductions in the thickness of all three of the cold storage parameters, cold storage wall insulation, cold room floor insulation, and the freezer room floor insulation, were suggested when the PV cost decreased. Thailand has a high number of

CDDs, and these results show that when the cost of energy is high, extra investments in the cold store insulation should be made to reduce the cooling demands of the building. The results from this PV sensitivity analysis show that for a climate with a high number of CDDs, external wall insulation, energy efficient windows, and cold storage insulation should be invested in to lower the cooling needs of the building.

Tunis, Tunisia had the suggested value of four variables change during the PV sensitivity analysis. Two of the variables, the HVAC COP and the cold room floor insulation thickness, varied as expected, while the freezer room floor insulation thickness and window efficiency did not vary as expected. The suggested COP value of the HVAC system increased for high PV cost. Tunisia has a high number of HDDs and a lower number of CDDs. The increased COP value suggests that the HVAC system is consistently over the year and a significant benefit comes from increasing the COP value. The suggested cold room floor insulation thickness decreased at the low PV cost level; this shows that this parameter is not as important when PV costs are lower. The two variables that did not vary as expected were the freezer room floor insulation and the window type. The suggested freezer room floor insulation thickness decreased at the high PV cost, and none of the other parameters varied in a way that would explain this decreased. Also, the suggested window type did not vary as expected. A highly energy efficient window was selected for both the high and low PV costs, while a less energy efficient window was chosen for normal PV cost. The only other variable that is changing that could have an effect on the window type is the COP of the HVAC system. The effect between the HVAC COP and the window type could be the reason for the unexpected variation in the window type. The two parameters with unexpected variations will be investigated by the DOE in Section 4.4.

Each country had suggested values vary when the cost of PV changed. Many of them vary as expected, but others did not. The next section compares the results from the five climates to each other in order to identify correlations between the suggested parameter value and climatic conditions.

4.3.2 Comparison of Results

After completing the PV sensitivity analysis for all of the climates, the general climatic trends are investigated. The suggested air infiltration reduction did not change during the PV price sensitivity analysis; this is due to the low cost of reducing air infiltration for the Tunisian construction that was discussed previously. The suggested COP value of the HVAC system found in the PV price sensitivity analysis shows no correlation to climatic conditions and this parameter will be investigated the with the DOE. However, the suggested roof insulation thickness, roof reflectivity value, and external wall insulation thickness correlated to climatic conditions. Argentina, which has the climate with the highest number of HDDs, is the only city for which changing the roof insulation thickness and the roof reflectivity are suggested. The results suggest when the roof insulation thickness is increased; investments should not be made to increase the roof reflectivity. Bangkok, Thailand, which has the climate with the highest number of CDDs, is the only climate to have changes suggested in the exterior wall insulation thickness. The results suggest decreasing the exterior wall insulation thickness at the low PV cost level, and this suggested that when the cost of PV is low, the energy reduction from the thicker exterior wall insulation is no longer economically beneficial.

The suggested window type varies for four of the countries. Argentina and Thailand both show results that are as expected, meaning as the PV costs increase, the efficiency of the window also increases. However, for Paraguay and Tunisia, the suggested window type varied unexpectedly. For Paraguay, the most energy efficient window type is selected for the average PV cost, while a less energy efficient window is chosen for the high and low PV cost levels. Tunisia's result show an opposite variation, the most energy efficient window type is selected for the high and low PV costs while a less energy efficient window is chosen for average PV cost level. This variation cannot be explained by the results found in this section, and the variation is most likely caused by an interactive effect between parameters. The interactive effects with the suggested window efficiency will be investigated with the DOE in Section 4.4.

All of the suggested cold storage parameter values had variation. The suggested cold room floor insulation thickness is similar for most of the countries, with the exception of the suggested cold room floor insulation thickness being lower for Kenya. The suggested thickness of the freezer room floor insulation decreased for Argentina and Tunisia at the high PV cost level, and decreased for Thailand and the low PV cost level. The Thailand result is expected, but the suggestion for Argentina and Tunisia is unexpected. There are two possible explanations for why the results suggest decreasing the insulation thickness at the high PV price; there is either an interactive effect between parameters or since the counties have a high number of HDDs, other investments are more beneficial for the building at the high PV price. The last cold storage parameter is the cold storage insulation. The suggested thickness of the cold storage insulation is increased for Argentina, Paraguay and Thailand at the high PV cost. These results do not support the correlation between the number of CDDs and cold storage parameters seen in Section 4.2; Kenya has a higher number of CDDs than Argentina, but has a lower suggested insulation thickness. This result cannot be explained by climatic conditions, and the variation is most likely caused by an interactive effect. The cold storage insulation will be investigated with the DOE in Section 4.4.

The conclusions from Section 4.2 are modified in order to reflect the trends observed from the PV price sensitivity analysis. The new recommendations are as follows:

- If the number of HDD is high, then investments should be made to increase the roof insulation thickness and increase the freezer room insulation thickness. However, if the roof insulation thickness is too large, then increasing roof reflectivity is no longer a good investment.
- If the number of CDDs is high, then investments should be made to increase the exterior wall insulation thickness. However, if the price of PV is low, then increasing the exterior wall insulation thickness is no longer a good investment.

- In general, increasing the thickness of insulation for the cold storage parameters - the cold storage wall insulation, the cold room floor insulation and the freezer room floor insulation - should always be invested in, regardless of climate.

The next section discusses the results from the DOE. These results are used to explain all the trends found from the climate sensitivity analysis and PV price sensitivity analysis that did not correlate to climatic conditions.

4.4 Results from Design of Experiments

The fourth set of tests conducted focus on the effect that each parameter had on the objective function. Two construction practices, US and Tunisian, are investigated using a Design of Experiments (DOE). The results will display the main effects to better understand which parameters are significant for each climate and then displayed the interactive effects in order to better understand the optimal solution design space. This section first gives the results for the US construction case and then the Tunisian construction case.

4.4.1 US Construction

This section details the results from the DOE for the US Construction. The results for the Tunisian climate can be seen in Figure 38 and Figure 39.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Infiltration[0.5]	13652.344	796.6394	17.14	<.0001*
Roof Insulation[0]	-9057.469	796.6394	-11.37	<.0001*
COP[2.6]	-6366.719	796.6394	-7.99	<.0001*
Cold Wall Insulation[0.092]	-4752.469	796.6394	-5.97	<.0001*
External Wall Insulation[0]	4187.7188	796.6394	5.26	<.0001*
Window U-Value[1.6]	-2811.969	796.6394	-3.53	0.0009*
Reflectivity[0.05]	-2667.469	796.6394	-3.35	0.0015*
Freezer Storage Ground[0.075]	-913.1562	796.6394	-1.15	0.2567
Cold Storage Ground[0.075]	307.28125	796.6394	0.39	0.7012

Figure 38: Main Effects from US Construction in Tunisian Climate

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Infiltration[4]	-13554.79	36.11217	-375.4	<.0001*
Roof Insulation[0]	-9056.59	36.11217	-250.8	<.0001*
COP[2.6]	-6320.137	36.11217	-175.0	<.0001*
Cold Storage Insulation[0.092]	-4739.285	36.11217	-131.2	<.0001*
COP[2.6]*Infiltration[4]	-4186.23	36.11217	-115.9	<.0001*
External Wall Insulation[0]	4128.832	36.11217	114.33	<.0001*
Window U-Value[5.1]	2818.1211	36.11217	78.04	<.0001*
Reflectivity[0.05]	-2670.105	36.11217	-73.94	<.0001*
Roof Insulation[0]*COP[2.6]	-2106.738	36.11217	-58.34	<.0001*
Roof Insulation[0]*Reflectivity[0.05]	-2039.941	36.11217	-56.49	<.0001*
Roof Insulation[0]*External Wall Insulation[0]	1022.168	36.11217	28.31	<.0001*
Freezer Room Ground Insulation[0.075]	-947.4336	36.11217	-26.24	<.0001*
External Wall Insulation[0]*Reflectivity[0.05]	607.32422	36.11217	16.82	<.0001*
Cold Storage Insulation[0.092]*Reflectivity[0.05]	-505.3711	36.11217	-13.99	<.0001*
Cold Room Ground Insulation[0.075]	308.16016	36.11217	8.53	<.0001*
Roof Insulation[0]*Infiltration[4]	-297.9492	36.11217	-8.25	<.0001*
External Wall Insulation[0]*Infiltration[4]	229.39453	36.11217	6.35	<.0001*
Cold Storage Insulation[0.092]*Infiltration[4]	-208.3008	36.11217	-5.77	<.0001*
Infiltration[4]*Reflectivity[0.05]	194.23828	36.11217	5.38	<.0001*
Roof Insulation[0]*Cold Storage Insulation[0.092]	-181.9336	36.11217	-5.04	<.0001*
Cold Storage Insulation[0.092]*Cold Room Ground Insulation[0.075]	159.08203	36.11217	4.41	<.0001*
COP[2.6]*Cold Storage Insulation[0.092]	-101.0742	36.11217	-2.80	0.0053*
External Wall Insulation[0]*COP[2.6]	94.042969	36.11217	2.60	0.0095*
COP[2.6]*Reflectivity[0.05]	79.980469	36.11217	2.21	0.0273*
Cold Storage Insulation[0.092]*Freezer Room Ground Insulation[0.075]	71.191406	36.11217	1.97	0.0493*
External Wall Insulation[0]*Cold Storage Insulation[0.092]	-69.43359	36.11217	-1.92	0.0551

Figure 39: Top Interactive Effects from US Construction in Tunisian Climate

Figure 38 shows the all the main effects and Figure 39 show the significant interactive effects. The rest of the DOE results for the other climates can be seen in Appendix F. The top five interactive effects for each climate are shown in Table 46. If the term is in *italics*, then the DOE has a positive "t-Ratio" for that parameter, which means not to invest in increased quality.

Table 46: Top five interactive effects for US Construction

Country	First Interactive Effect	Second Interactive Effect	Third Interactive Effect	Fourth Interactive Effect	Fifth Interactive Effect
Argentina	Infiltration	Roof Insulation	COP of HVAC	COP* Infiltration	Cold Storage Insulation
Kenya	*Infiltration*	Roof Reflectivity	Cold Storage Insulation	Roof Insulation* Roof Reflectivity	*External Wall Insulation*
Paraguay	Roof Reflectivity	Roof Insulation* Roof Reflectivity	Cold Storage Insulation	Roof Insulation	*Infiltration*
Thailand	Roof Reflectivity	Roof Insulation* Roof Reflectivity	Roof Insulation	Cold Storage Insulation	*External Wall Insulation*
Tunisia	Infiltration	Roof Insulation	COP of HVAC	Cold Storage Insulation	COP* Infiltration

The DOE results are gathered in order to investigate two parameters, HVAC COP and window type, that could not be correlated to HDDs or CDDs in Section 4.2. The GA results suggest for Argentina and Kenya to have HVAC COP values of 3.0, and for Paraguay, Thailand, and Tunisia to have HVAC COP values of 3.3. When looking at the climatic conditions, Argentina has a high number of HDDs and Kenya has no HDDs and it is unexpected for the results to suggest that these two countries should have the same COP value since their climatic conditions are significantly different. The top four interactive effects that involve COP are listed in Table 47. If the term is in *italics*, then the DOE has a positive “t-Ratio” for that parameter, which means not to invest in increased quality.

Table 47: Top Four COP interactive terms for US Construction

Country	First COP term	Second COP term	Third COP Term	Fourth COP Term
Argentina	COP	COP* Infiltration	Roof Insulation* COP	*COP* Roof Reflectivity*
Kenya	COP* Roof Reflectivity	Roof Insulation* COP	COP* Infiltration	COP
Paraguay	COP	Roof Insulation* COP	COP* Infiltration	COP* Reflectivity
Thailand	COP	COP* Reflectivity	Roof Insulation* COP	COP* Infiltration
Tunisia	COP	COP* Infiltration	Roof Insulation* COP	COP* Cold Storage Insulation

First, the DOE interactive terms are used to provide an explanation for why the suggested COP value for Tunisia is higher than the suggested COP value for Argentina. Tunisia and Argentina typically have similar suggested values due to their similar number of HDDs; the only difference between the DOE interactive terms for these two countries is the fourth interactive term. For Argentina, the fourth interactive term is negative effect from (COP*roof reflectivity). A negative effect means that if both of the parameters are invested in, the objective function will be lowered. A higher roof reflectivity reduces the amount of solar energy that is absorbed by the roof, and results in a cooler roof temperature. Tunisia has low cloud coverage and this causes a large amount of solar heat gain through the roof. Since Argentina has more cloud coverage than Tunisia, Argentina will not benefit as much as Tunisia from increasing the roof reflectivity. This means that the high cloud coverage of Argentina causes the negative interactive effect between COP and roof reflectivity. These results show if the number of HDDs is high, then investments should be made for a higher COP value. However, if the area has a significant amount of cloud coverage and investments are made for roof reflectivity, then increasing the COP value of the HVAC system is no longer a good investment.

Next, the DOE interactive terms are used to provide an explanation for why the suggested COP value for Kenya is lower than expected. The DOE results show that Kenya is the only country to have an interactive effect as its first COP term, as opposed to a main effect from the COP. Kenya is the only country studied that has no HDDs. When there are no HDDs, the HVAC system will not be used during the cold season for the ambient storage zones, causing the COP of the HVAC system to be insignificant. Since the HVAC system is not used during the cold season, Kenya does not a main effect from the COP, and this resulted in the suggested COP value for Kenya being lower than expected when looking only at CDDs. The results show if the number of CDDs is high, then investments should be made to obtain a higher COP value. However, if the number of HDDs is very low, then the HVAC system will not be used enough throughout the year and therefore increasing the COP of the HVAC system is no longer a good investment. From these results, it can be concluded that investments to increase the COP of the HVAC system should be made for countries that do not have an extremely high CDDs or HDDs, i.e., are "mid-range" climates.

The other variable for which no correlation with HDDs or CDDs was identified in Section 4.2 is the window type. The Tunisian construction showed a correlation between windows type and CDDs, with the results suggesting investment in more energy efficient windows for countries with a high number of CDDs. However, this relationship is not seen for the suggested window efficiency for the US construction. Thailand's optimum result should have suggested the most energy efficient window since it has the highest number of CDDs of all the countries studied. However, Thailand's suggested window is less energy efficient than the selected window type for Kenya and Paraguay. The interactive effects from the DOE for Thailand and Paraguay are the same; the US construction DOE has no interaction terms with the window type and the Tunisian construction DOE has an interaction term between the external wall insulation and window type. The reason for this interaction term appearing for the Tunisian construction and not the US construction is due differences in the energy model. The US construction reference exterior wall construction has a higher U-value than the Tunisian construction reference exterior wall construction and this difference causes the interactive effect between window type and external wall to not have a large effect on the US Construction. The Tunisian construction results suggest for Paraguay to have 20 mm of exterior wall insulation and Thailand to have 40 mm of exterior wall insulation, and the results suggest for both countries to have the same efficiency window. For the US construction, the results suggest for both countries to have 92 mm of exterior wall insulation. This means that for the US construction, Thailand suggests a less efficient window because the suggested exterior wall insulation was not thick enough to affect the suggested window efficiency.

Also, Argentina’s optimum result should have suggested the least energy efficient window since it has the lowest number of CDDs of all the countries studied. However, Argentina’s suggested window is more energy efficient than the window type selected for Tunisia. The interactive effects from the DOE for Tunisia and Argentina are the same; the US construction DOE has no interaction terms with the window type and for the Tunisian construction DOE have an interaction term between the roof insulation and window type. The Tunisia construction results suggest for Argentina to have 20 mm of roof insulation and Tunisia to have 40 mm of roof insulation, and the results suggest for the two countries to have the same efficiency window. For the US construction, the results suggest for both countries to have 25 mm of roof insulation. This means for the US Construction, Tunisia suggests a less efficient window because the suggested roof insulation is not thick enough to affect the suggested window efficiency. These results show how the suggested window efficiency is largely impacted by the other building parameters.

The DOE results also explain Figure 34 in Section 4.2 where two distinct Pareto Fronts slopes are seen. The countries with high numbers of CDDs, Kenya, Paraguay, and Thailand, have similar slopes, and the countries with high numbers of HDDs, Tunisia and Argentina, have similar slopes. The DOE results show that Tunisia and Argentina have the same top five parameters. These are air infiltration rate, roof insulation thickness, COP of HVAC system, (COP of HVAC system*air infiltration rate), and the cold storage walls insulation thickness. For the countries with a high number of CDDs, Kenya, Paraguay, and, Thailand, three parameters are consistent throughout the top five results. These parameters are roof reflectivity, cold storage wall insulation, and (roof insulation thickness* roof reflectivity). Based on the top five parameters from the DOE, the air infiltration rate explains the different Pareto-front shapes. Argentina and Tunisia have significant investments in reducing air infiltration and this causes the slopes to be different. After these tests were completed, the DOE was switched to simulate the Tunisian construction model for the five climates; the results are shown in the next section.

4.4.2 Tunisian Construction

This section details the results from the DOE for the Tunisian construction. The results for the Tunisian climate can be seen in Figure 40 and Figure 41.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Roof Insulation[0]	-6997.656	499.8639	-14.00	<.0001*
Cold Wall Insulation[0.092]	-4457.156	499.8639	-8.92	<.0001*
Reflectivity[0.05]	-3665.906	499.8639	-7.33	<.0001*
COP[2.6]	-2035.469	499.8639	-4.07	0.0002*
External Wall Insulation[0]	1839.2813	499.8639	3.68	0.0005*
Infiltration[0.000175]	1085.7188	499.8639	2.17	0.0343*
Freezer Storage Ground[0.075]	-927.2187	499.8639	-1.85	0.0691
Window U-Value[1.658]	-423.8438	499.8639	-0.85	0.4002
Cold Storage Ground[0.075]	349.46875	499.8639	0.70	0.4875

Figure 40: Main Effects from Tunisian Construction in Tunisian Climate

Term	Estimate	Std Error	t Ratio	Prob>|t|
Roof Insulation[0]	-6994.141	26.44465	-264.5	<.0001*
Cold Storage Insulation[0.092]	-4464.187	26.44465	-168.8	<.0001*
Reflectivity[0.05]	-3690.516	26.44465	-139.6	<.0001*
Roof Insulation[0]*Reflectivity[0.05]	-2612.109	26.44465	-98.78	<.0001*
COP[2.6]	-2058.32	26.44465	-77.84	<.0001*
Roof Insulation[0]*COP[2.6]	-2005.664	26.44465	-75.84	<.0001*
External Wall Insulation[0]	1823.4609	26.44465	68.95	<.0001*
Roof Insulation[0]*External Wall Insulation[0]	1137.3047	26.44465	43.01	<.0001*
Infiltration[0.0007]	-1038.258	26.44465	-39.26	<.0001*
Freezer Room Ground[0.075]	-936.0078	26.44465	-35.39	<.0001*
Cold Storage Insulation[0.092]*Reflectivity[0.05]	-555.4687	26.44465	-21.00	<.0001*
COP[2.6]*Infiltration[0.0007]	-446.4844	26.44465	-16.88	<.0001*
Window U Value[6.172]	437.90625	26.44465	16.56	<.0001*
External Wall Insulation[0]*Reflectivity[0.05]	377.92969	26.44465	14.29	<.0001*
Cold Room Ground[0.075]	333.64844	26.44465	12.62	<.0001*
Roof Insulation[0]*Cold Storage Insulation[0.092]	-256.6406	26.44465	-9.70	<.0001*
Infiltration[0.0007]*Reflectivity[0.05]	219.72656	26.44465	8.31	<.0001*
External Wall Insulation[0]*Cold Storage Insulation[0.092]	-205.6641	26.44465	-7.78	<.0001*
Cold Storage Insulation[0.092]*Cold Room Ground[0.075]	149.41406	26.44465	5.65	<.0001*
External Wall Insulation[0]*Infiltration[0.0007]	140.625	26.44465	5.32	<.0001*
External Wall Insulation[0]*COP[2.6]	-137.1094	26.44465	-5.18	<.0001*
Cold Storage Insulation[0.092]*Infiltration[0.0007]	-131.8359	26.44465	-4.99	<.0001*
Roof Insulation[0]*Window U Value[6.172]	98.4375	26.44465	3.72	0.0002*
COP[2.6]*Window U Value[6.172]	-75.58594	26.44465	-2.86	0.0045*
COP[2.6]*Cold Storage Insulation[0.092]	-72.07031	26.44465	-2.73	0.0067*
Cold Storage Insulation[0.092]*Freezer Room Ground[0.075]	65.039063	26.44465	2.46	0.0143*
Roof Insulation[0]*Infiltration[0.0007]	-54.49219	26.44465	-2.06	0.0399*
External Wall Insulation[0]*Window U Value[6.172]	43.945312	26.44465	1.66	0.0972

Figure 41: Top Interactive Effects from Tunisian Construction in Tunisian Climate

Figure 40 shows all the main effects. Figure 41 shows the significant interactive effects. The rest of the DOE results can be seen in Appendix G. The top five interactive effects for each climate are shown in Table 48. If the term is in *italics*, then the DOE has a positive "t-Ratio" for that parameter, which means not to invest in increased quality.

Table 48: Top five interactive effects for Tunisian Construction

Country	First Interactive Effect	Second Interactive Effect	Third Interactive Effect	Fourth Interactive Effect	Fifth Interactive Effect
Argentina	Cold Storage Wall Insulation	Roof Insulation	*External Wall Insulation*	Roof Insulation* COP of HVAC	Freezer Room Floor Insulation
Kenya	Roof Reflectivity	Roof Insulation* Roof Reflectivity	Cold Storage Wall Insulation	*Roof Insulation* External Wall Insulation*	Roof Insulation* Cold Storage Wall Insulation
Paraguay	Roof Reflectivity	Roof Insulation* Roof Reflectivity	Cold Storage Wall Insulation	Roof Insulation	*External Wall Insulation*
Thailand	Roof Reflectivity	Roof Insulation* Roof Reflectivity	Cold Storage Wall Insulation	Roof Insulation	Infiltration Rate
Tunisia	Roof Insulation	Cold Storage Wall Insulation	Roof Reflectivity	Roof Insulation* Roof Reflectivity	COP of HVAC

The DOE results are gathered in order to investigate the parameters that cannot be correlated to HDDs or CDDs in the climate sensitivity results from Section 4.2 and the PV sensitivity results from Section 4.3. In Section 4.2, no direct correlation between the HVAC COP and HDD or CDD is found. For the HVAC COP, Argentina, Kenya, and Paraguay have values of 2.6, while Thailand and Tunisia have values of 3.0. The top four interactive effects that involve COP are listed in Table 49. If the term is in *italics*, then the DOE has a positive "t Ratio" for that parameter, which means not to invest in increased quality.

Table 49: Top four COP interactive terms for Tunisian Construction

Country	1st COP term	2nd COP term	3rd COP Term	4th COP Term
Argentina	Roof Insulation* COP	COP	*COP* Reflectivity*	COP* Infiltration
Kenya	COP* Reflectivity	Roof Insulation* COP	COP* Infiltration	COP* Window Type
Paraguay	Roof Insulation* COP	COP* Reflectivity	COP	COP* Infiltration
Thailand	COP	COP* Reflectivity	Roof Insulation* COP	COP* Infiltration
Tunisia	COP	Roof Insulation* COP	COP* Infiltration	External Wall Insulation* COP

The interactive terms in shown in Table 49 are almost identical to the interactive terms seen in Table 47 from Section 4.4.1, where the COP interactive terms are investigated for the US construction. Since the two construction methods suggest similar results, the conclusions found in Section 4.4.1 are not changed.

The results from the PV sensitivity analysis in Section 4.3 had four variables that did not vary as expected. These variables include the roof reflectivity, freezer room floor insulation, cold storage insulation, and window type. For Argentina at the high PV price, the suggested roof insulation increases and the result suggested to not invest in increasing the roof reflectivity. The DOE interactive effects for Argentina show that the change in the roof reflectivity is actually not linked to the roof insulation thickness, but instead to the cold storage insulation thickness. This means that when the cold storage insulation thickness increases, then investments should not be made to increase the roof reflectivity. However, at the high PV price the results also suggested for Paraguay and Thailand to increase the cold room wall insulation but the results suggested investing in roof reflectivity. The climatic conditions, number of CDDs, provides a reason for why there is an interaction between roof reflectivity and cold storage insulation for Argentina and not for the other two countries. Argentina has the lowest number of CDDs and therefore would benefit the least from increasing the cold storage insulation thickness. A higher roof reflectivity reduces the cooling energy use of the building by preventing solar heat gain. Since Argentina has a small number of CDDs, these results show it is more beneficial to reduce the cooling needs of the cold storage rather than to use higher roof reflectivity to reduce the cooling requirements of the entire building.

The freezer room floor insulation thickness for Argentina and Tunisia did not vary as expected; the suggested insulation thickness decreased at the high PV cost level. For Tunisia, the suggested COP value increased and a more energy efficient window was suggested for the same solution set. For Argentina, the roof insulation thickness increased, the cold storage wall insulation thickness increased, and a more energy efficient was suggested for the same solution set. The DOE does not show significant interactive effects between any of these parameters and the freezer room floor insulation. This means that the reason for decreasing the freezer room floor insulation thickness is correlated to number of CDDs. The number of CDDs is low for both of these countries, meaning that when the cost of PV is increased, the investments in the other building parameters are more beneficial than the investment in the freezer room floor insulation. For example, the Argentina results suggest increasing the roof insulation thickness, and the cold storage wall insulation thickness in the same result that suggests decreasing the freezer room floor insulation thickness. Even though there are no interactive effects found between the parameters, the roof insulation thickness and cold storage wall insulation thickness have a more significant effect than the freezer room floor insulation on the objective function. These results show that the freezer floor insulation thickness is not significant for countries with a low number of CDDs.

The suggested window efficiency for Paraguay and Tunisia varied unexpectedly. For Paraguay, the best window type was selected for the average PV cost level, while a less energy efficient window was chosen for the high and low PV cost levels. For Tunisia, the result are the opposite, with the most energy efficient window type selected for the high and low PV prices while a less energy efficient window is chosen for average PV price. The top four interactive effects that involve the window type are listed in Table 50. If the term is in *italics*, that means the DOE had a positive "t Ratio" for that parameter, which means not to invest in increased quality.

Table 50: Top four window type interactive terms for Tunisian Construction

Country	First Window term	Second Window term	Third Window Term	Fourth Window Term
Argentina	*Window Type*	*Roof Insulation* Window Type*	Roof Reflectivity* Window Type	
Kenya	Window Type	*Roof Insulation* Window Type*	*External Wall Insulation* Window Type*	*Roof Reflectivity* Window Type*
Paraguay	Window Type	*External Wall Insulation* Window Type*	*Roof Insulation* Window Type*	COP* Window Type
Thailand	Window Type	COP* Window Type	*External Wall Insulation* Window Type*	
Tunisia	*Window Type*	*Roof Insulation* Window Type*	COP* Window Type	*External Wall Insulation* Window Type*

For Paraguay and Tunisia, the only parameter that varies in the PV sensitivity analysis and is an interactive effect in the DOE is the COP of the HVAC system. For Paraguay, the suggested COP value is 3.0 for the high PV cost level and 2.6 for the other two cost levels. For Tunisia, the suggested COP value is 3.3 for the high PV cost level and 3.0 for the other two cost levels. The change is COP explains why the suggested window efficiency changes, but does not explain why Paraguay and Tunisia varies differently. The DOE also shows that both of these countries have a main effect from the window type as the top effect in the DOE. However, for

Tunisia the window type has a negative effect and for Paraguay the window type has a positive effect. This difference is what causes the results to have opposite effects. For Tunisia, when the suggested COP value stays constant and the PV price decreases, it is suggested to invest in a more efficient window. This shows that when the price of the PV decreases, the negative effect from the window efficiency has less of an impact on the overall cost. The opposite relationship is seen for Paraguay. For Paraguay, when the suggested COP value stays constant and the PV price decreases, it is suggested to not invest in a more efficient window. This shows that when the price of the PV decreases, the positive effect from the window efficiency will have not have a significant impact on the cost, and therefore the investment is not as important. The DOE also shows that Thailand has an interactive effect with the COP and the window type. However, Thailand does not have the COP change during the PV sensitivity analysis, which is why the suggested window efficiency varies as expected. These results show that the suggested window efficiency is related to the HVAC COP for the “mid-range” climates.

The last parameter investigated is the cold storage insulation thickness. At the high PV cost, the results suggest an insulation thickness of 238 mm for Argentina, Paraguay, and Thailand and an insulation thickness of 187 mm for Tunisia and Kenya. These results do not support the correlation between CDDs and cold storage parameters seen in Section 4.2, because Kenya has a higher number of CDDs than Paraguay and Tunisia has a higher number of CDDs than Argentina. The DOE results interactive terms with the cold storage wall are investigated and it is noticed that all five of the countries have the three similar interactive terms. There is a negative effect with the cold room floor insulation and a positive effect with the roof insulation and roof reflectivity. For the PV sensitivity, Kenya is the only country that recommends increasing the cold room floor insulation thickness for the high PV cost level case. Since Kenya has a negative relationship between the cold room floor insulation thickness and the cold room floor insulation thickness, the cold storage insulation thickness remains the same when the floor insulation thickness increases. Tunisia also does not suggest increasing the cold storage insulation thickness. Tunisia has the highest suggested roof insulation thickness of all the countries. The high roof insulation thickness suggested for Tunisia causes the cold storage insulation to not be a significant factor. The other countries results suggest either a small amount of roof insulation or no roof insulation which is why the cold storage insulation increases. These results show how the suggested cold storage insulation thickness is related to other building parameters.

This section shows that the interactive results found from the DOE can help to understand all of the interactions between variables that could not be previously explained by using only considering climatic conditions. These interactive effects will be used to complete the generalized recommendations in Section 4.6. The next section shows the benefit of using a DOE and the GA together in a two-step process.

4.5 Results from Two-Step Process

The final trial conducted investigated combining a DOE with a GA for a two-step process. A detailed DOE is performed by David Pudleiner (Pudleiner, 2014) and the results are compared to the GA results to show the effectiveness of the two-step process. The energy model used in the DOE is slightly different then the model used in this thesis, but has the same building layout as the energy model discussed in Chapter 3. It was decided to use his energy model in order to maintain consistency between the results. This section first explains how the results were obtained and presents the results for the Tunisian climate. Then the results from the other four climates are presented and the effectiveness of this method will be discussed.

4.5.1 Combined Results Tunisia

First a Design of Experiments was performed by David Pudleiner using the method of his thesis (Pudleiner, 2014). He used a Latin hypercube analysis to perform the DOE. The DOE analysis was conducted without considering the cost of any of the building components; instead it investigates the effects the parameters have on the building energy usage. The DOE showed the effects of each parameter on the energy usage of the building; the results can be seen in Figure 42.

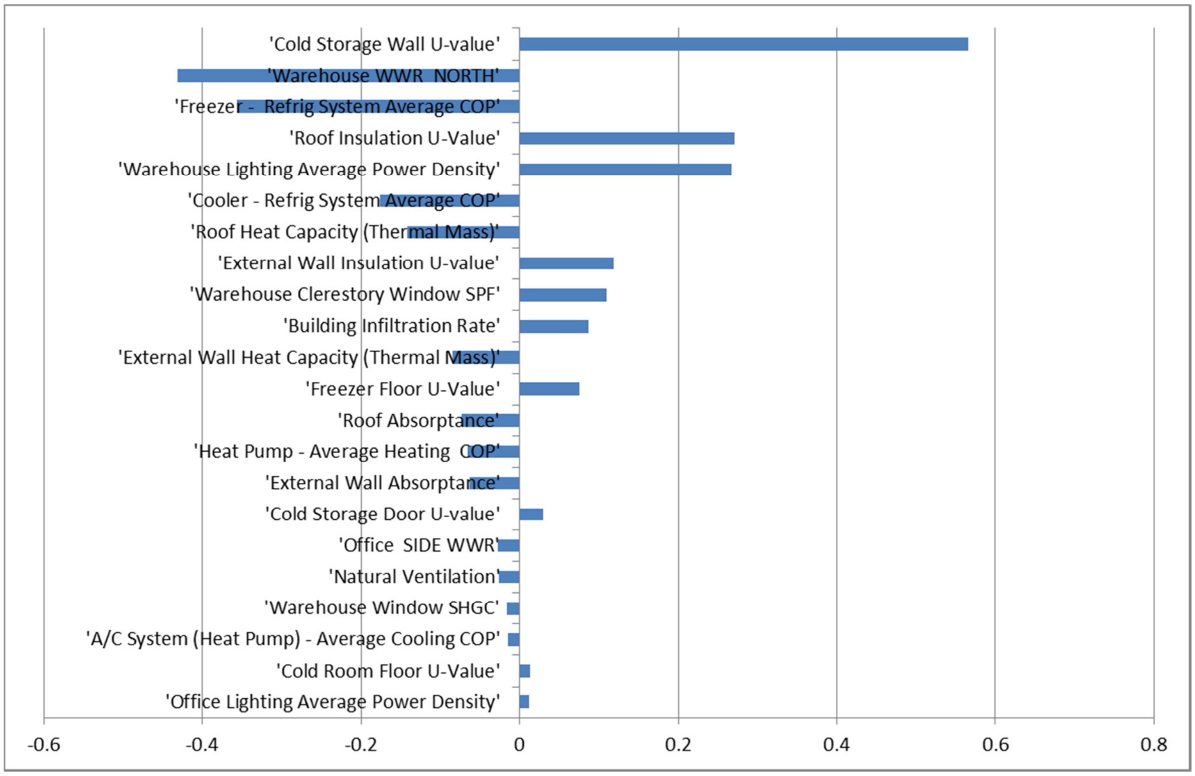


Figure 42: Main Affects from Latin Hypercube DOE for Tunisia

The DOE results show that the cold storage wall U-value has a large effect on the building energy usage and should have a significant investment. The office lighting average power density has a low effect on the building energy usage. After the DOE was performed, a GA was completed using nine parameters that were investigated with the DOE. The GA will find the optimal parameter values based on construction cost and energy usage. The GA uses the Tunisian construction cost data presented in Chapter 3 and the energy model used for the DOE. The results can be seen in Table 51.

Table 51: Results from GA for DOE Energy Model for Tunisia

Parameter / Level	Roof (mm)	External Wall (mm)	COP	Cold Wall (mm)	Cold Floor (mm)	Freezer Floor (mm)	Air Infiltration (L/s*m²)	Roof Reflectivity	Window Type
High	*6*	*100*	*3.5*	*279*	*250*	*250*	*0.175*	*0.9*	*1.658 W/m²K SHGC:0.57*
Reference	*0*	*0*	*2.6*	*92*	*0*	*0*	*0.7*	*0.05*	*6.172 W/m²K SHGC: 0.83*
Optimum Point	40	20	3.3	143	50	150	0.7	0.05	3.160 W/m²K SHGC: 0.61
Construction Cost (USD)	4,298	1,936	2,139	5,841	1,154	880	0	0	1,052

It is difficult to compare the results between the two techniques since the DOE focuses solely on energy usage and the GA accounts for construction costs and the building energy usage. However, in order to compare the two results, the construction costs for the GA optimal results are calculated. The investment in construction costs is used to rank the parameters, and by ranking the parameters, a comparison can be made. Table 52 presents the parameter ranking for the GA and DOE. If the term is in *italics*, it means the DOE has a positive "t-Ratio" for that parameter, which means not to invest in increased quality.

Table 52: Rank ordering of the top parameters from the DOE and the GA for Tunisia

DOE	GA Ranking by Construction Costs
Cold Storage Wall U-Value	Cold Storage Wall U-Value
Roof Insulation U-Value	Roof Insulation U-Value
External Wall Insulation U-Value	Heat Pump-Average Heating COP
Building Infiltration Rate	External Wall Insulation U-Value
Freezer Floor U-Value	Cold Room Floor U-Value
Roof Reflectivity	Warehouse Window SHGC
\Heat Pump-Average Heating COP	Freezer Floor U-Value
Warehouse Window SHGC	Roof Reflectivity
Cold Room Floor U-Value	Building Infiltration Rate

The top three parameters from the DOE, the cold storage insulation, roof insulation, and roof insulation, were in the top four ranked investments for the GA. This shows that the significant parameters are the same for both methods even though the DOE does not consider construction cost. Two of the parameters, the building infiltration and the HVAC COP, differ significantly in ranking between the two tests. The GA suggests selecting the reference case for the building air infiltration rate, meaning a $0 investment, but the building infiltration rate came out mid-range of importance in the DOE. The HVAC COP was one of the top three investments suggested by the GA but was fairly low in the DOE ranking. However, there are other similarities between the two tests. The DOE suggests not investing in increased roof reflectivity and the GA suggested the reference case for roof reflectivity, meaning a $0 investment. Also, increased freezer room floor insulation thickness is suggested for both tests. Overall, the results show that the DOE can be used to determine the most significant parameters.

The DOE is the first step of a two-step process. For the DOE, the building parameters are investigated without considering the cost of construction; rather, the DOE investigates the effect that each parameter has on the building energy usage. The reason for using the DOE first is to quickly investigate a large number of parameters and to see the effect of the parameters on the energy usage. Once the DOE found the significant building parameters, then the detailed GA was completed for these parameters. The GA uses discrete variables and their associated costs to find the cost-optimal solution.

It is not necessary for the DOE to be performed first; it is just a helpful step to determine which building parameters have a large effect on the building energy usage. If the parameters with a significant effect on the energy usage are not known, then time can be wasted studying trivial parameters with the GA. Initially, the thesis considered the thickness of the ambient storage floor insulation to be optimized. However, all of the initial tests showed not to invest in the insulation. Since this parameter proved to be trivial, it was replaced with a significant parameter. If the DOE had been performed initially, then it would have been known that the ambient floor insulation had a small effect on the building energy usage and should not be investigated.

It is necessary to use the GA after completing a DOE in order to determine the parameter values that are economically feasible. For example, the DOE has the Cold Storage Wall U-Value as the most important parameter and shows that the recommended U-Value is around 0.19 W/m²K, while the GA suggests an insulation thickness with a U-Value around 0.25 W/m²K. In order to get cold storage insulation with a U-Value similar to the DOE recommendation, an extra $5,000 would need to be invested in construction costs as compared to the GA results. Another example is the GA suggests a window with a U-Value of 3.160 W/m²K and SHGC of 0.61, while the DOE suggests a U-Value of 2.02 W/m²K and SHGC of 0.50. In order to obtain a window with parameters similar to the DOE's recommendation, an extra $900 would need to be invested in construction costs when compared to the GA results. This shows that while the DOE can help to determine the significant parameters, the values suggested by the DOE create an extremely energy efficient building that is not cost effective. If the aim of a project is to design an energy efficient building, then the DOE will be sufficient. However, if an cost-optimal building is to be designed, then the GA must be performed. Since this method proved to be successful in determining the significant parameters for the Tunisian climate, it is investigated for the other four climates.

4.5.2 Combined Results Other Climates

The same process as explained above is repeated for the other four studied climates. The details of the results from the DOE and GA can be found in Appendix H; only the final results are presented in this section. Table 53 presents the results from Argentina. If the term is in *italics*, then the DOE had a positive "t-Ratio" for that parameter, which means not to invest in increased quality.

Table 53: Rank ordering the top parameters from the DOE and the GA for Argentina

DOE	GA Ranking by Construction Costs
Cold Storage Wall U-Value	Cold Storage Wall U-Value
Roof Insulation U-Value	Roof Insulation U-Value
Roof Reflectivity	External Wall Insulation U-Value
External Wall Insulation U-Value	Heat Pump COP
Building Infiltration Rate	Freezer Floor U-Value
Heat Pump-Average Heating COP	Cold Room Floor U-Value
Freezer Floor U-Value	Warehouse Window
Warehouse Window SHGC	Roof Reflectivity
Cold Room Floor U-Value	Building Infiltration Rate

For Argentina, the top two ranked parameters from the DOE, cold storage wall insulation and roof insulation, are consistent with the top two investments suggested by the GA. The third parameter in the DOE results suggests not investing in roof reflectivity; this agrees with the GA results that suggest selecting the reference case for roof reflectivity, meaning a $0 investment. The fourth parameter in the DOE is external wall insulation; the GA also suggests investing in increasing the external wall insulation thickness. The top four parameters are similar between the two methods showing that the DOE is an effective way to determine the parameters that should have a significant investment. However, aside from the top parameters, the rankings are not consistent. The DOE ranks the air infiltration rate as the fifth most important effect, and the GA suggested not investing in air infiltration reduction. Also, the DOE results suggest not investing in increasing the heat pump COP while the GA shows increasing the heat pump COP as one of its top investments. Overall, these results show that the DOE ranking and the GA ranking agree on which parameters are the most significant. The comparison of results for Kenya can be seen in Table 54. If the term is in *italics*, then the DOE has a positive "t-Ratio" for that parameter, which means not to invest in increased quality.

Table 54: Rank ordering the top parameters from the DOE and the GA for Kenya

DOE	GA Ranking by Construction Costs
Cold Storage Wall U-Value	Cold Storage Wall U-Value
Roof Reflectivity	Roof Reflectivity
Roof Insulation U-Value	Freezer Floor U-Value
Cold Room Floor U-Value	Cold Room Floor U-Value
Freezer Floor U-Value	Heat Pump COP
External Wall Insulation U-Value	Warehouse Window
Building Infiltration Rate	Roof Insulation U-Value
Warehouse Window SHGC	External Wall Insulation U-Value
Heat Pump-Average Heating COP	Building Infiltration Rate

For Kenya, the top two ranked parameters from the DOE, cold storage insulation and roof reflectivity, are consistent with the top two investments suggested by the GA. The third parameter for the DOE is roof insulation; yet the GA results suggest not investing in roof insulation. Also, the DOE has external wall insulation as an important parameter and the GA suggests not investing in external wall insulation. The other parameters are mostly consistent between the tests; the cold room floor insulation and freezer room floor insulation are highly ranked for both tests, and the air infiltration rate is at the bottom of the ranking for both tests. Overall, the results from the DOE and the GA have significantly different suggestions on the insulation for the building envelope, but are fairly consistent for the other parameters. The comparison of results for Paraguay can be seen in Table 55. If the term is in *italics*, then the DOE has a positive "t-Ratio" for that parameter, which means not to invest in increased quality.

Table 55: Rank ordering the top parameters from the DOE and the GA for Paraguay

DOE	GA Ranking by Construction Costs
Cold Storage Wall U-Value	Cold Storage Wall U-Value
Roof Reflectivity	Roof Reflectivity
Roof Insulation U-Value	Roof Insulation U-Value
External Wall Insulation U-Value	External Wall Insulation U-Value
Freezer Floor U-Value	Freezer Floor U-Value
Building Infiltration Rate	Cold Room Floor U-Value
Cold Room Floor U-Value	Heat Pump COP
Heat Pump-Average Heating COP	Warehouse Window
Warehouse Window SHGC	Building Infiltration Rate

For Paraguay, the top five ranked parameters from the DOE are consistent with the top five investments suggested by the GA. Only one parameter, building infiltration rate, is different between the two rankings. If building infiltration rate is removed from the list, the two tests have a consistent ranking of parameters. Since the results are consistent between the two tests, two of the recommends parameters are investigated. For the cold storage insulation, the DOE recommends a U-Value around 0.19 W/m²K, while the GA suggests a U-Value around 0.187 W/m²K. For the roof insulation, the DOE recommends a thickness of 0.0277 m, while the GA suggests a roof insulation thickness of 0.03 m. The suggested parameter value from the GA and DOE are similar for both of the parameters. Paraguay has been considered a "mid-range" climate throughout this chapter due to its number of HDDs and CDDs. These results show that the DOE and GA rankings are consistent when a "mid-range" climate is investigated. The comparison of results for Thailand can be seen in Table 56. If the term is in *italics*, then the DOE has a positive "t-Ratio" for that parameter, which means not to invest in increased quality.

Table 56: Rank ordering the top parameters from the DOE and the GA for Thailand

DOE	GA Ranking by Construction Costs
Cold Storage Wall U-Value	Cold Storage Wall U-Value
Roof Reflectivity	Roof Reflectivity
Roof Insulation U-Value	Heat Pump COP
External Wall Insulation U-Value	External Wall Insulation U-Value
Building Infiltration Rate	Freezer Floor U-Value
Freezer Floor U-Value	Cold Room Floor U-Value
Cold Room Floor U-Value	Warehouse Window
Warehouse Window SHGC	Roof Insulation U-Value
Heat Pump-Average Heating COP	Building Infiltration Rate

For Thailand, the top two parameters from the DOE, cold storage insulation and roof reflectivity, are consistent with the top two investments suggested by the GA. After the first two ranking, the results have two significant differences. The third parameter for the DOE is roof insulation; yet the GA results suggest not investing in roof insulation. The third parameter for the GA is the Heat Pump COP; this is the lowest ranked parameter for the DOE test. However, both tests suggest investing in increasing the thicknesses of the external wall insulation, freezer room floor insulation, and cold room floor insulation.

This method proved to be more effective for some climates than others. The consistency of the results correlates with HDDs and CDDs. Thailand has a high number of CDDs and has the least amount of consistency between the two tests. Paraguay has a mid-range number of CDDs and the two tests show almost an exact match. Argentina has a low number of CDDs and is consistent for the first half of the parameters and do not match for the second half. These inconsistencies are due to the fact that the DOE does not consider cost. Since cost is not considered, the DOE has similar top parameters for all the climates. The DOE ranked roof insulation in the top three parameters for all the climates while the GA suggests not investing in roof insulation for two of the countries, Thailand and Kenya. However, it is important to notice that both methods do agree on the top two variables for all of the countries. Overall, these results show that it is effective to use the DOE without considering costs to help identify the significant parameters in the early stages of design. By using the DOE in the early stages of design you can determine what parameters should be studied by the GA in the final stages of design. The next section of this chapter provides an analysis of all the results presented in this chapter.

4.6 Analysis of Results

This section presents an analysis of the results found in this chapter. First, this section provides a summary of the results and a generalized final recommendation for each parameter. Then this section discusses the effectiveness of the proposed decision support tool.

4.6.1 Final Parameter Recommendations

The five trials conducted in this thesis extend the understanding of how each of the building parameters correlates to climatic conditions and other building parameters. This section presents the significant results found in the five trials and then presents a generalized recommendation for each parameter.

The suggested roof insulation thickness is found to correlate to the number of HDDs and cloud coverage of the climate. The suggested roof insulation thickness was consistent through all the trials. The suggested roof insulation thicknesses from Section 4.2, Tunisian construction for the five countries, are plotted as a function of two climatic conditions and can be seen in the Figure 43.

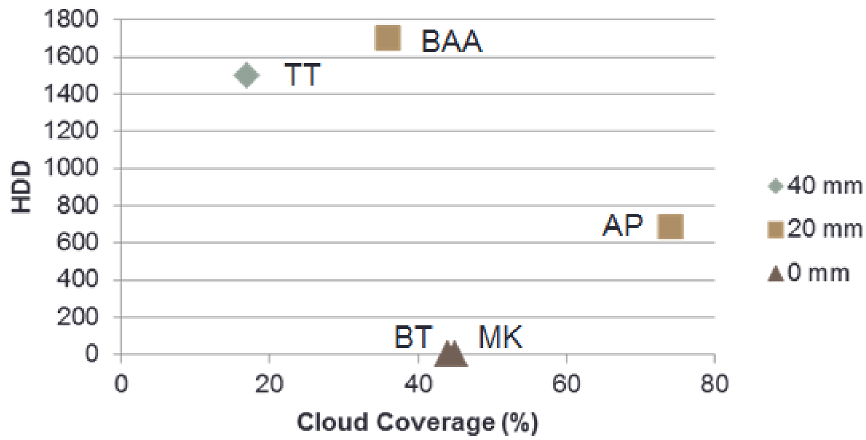


Figure 43: Tunisian construction results for suggested roof insulation thickness

The results show that Tunisia (TT) has a lower number of HDDs when compared to Argentina (BAA), but also has the lowest cloud coverage range. Cloud coverage prevents the amount of direct sunlight on the roof. The low cloud cover range in Tunisia causes the roof to have a significant amount of direct sunlight, and increased solar gain through the roof. The increased solar gains lead to Tunisia having a higher suggested investment in roof insulation and explain the deviation from the direct correlation with the number of HDDs. The final recommendation for roof insulation thickness can be seen in Equation 8. These recommendations are for the Tunisian construction building described in Section 3.3.3.2 and the gaps in the graphical representations of results were used to determine where to shift the recommendation.

$$\begin{gathered} If\ HDD \geq 1501;\ 40\ mm\ of\ insulation \\ If\ 1501 > HDD \geq 687;\ 20\ mm\ of\ insulation \\ If\ 687 > HDD\ \geq\ 0; 0\ mm\ of\ \ insulation \\ If\ Minimum\ Cloud\ Coverage\ \leq 20\%; Add\ an\ additional\ 20\ mm\ of\ insulation \end{gathered} \tag{8}$$

The climates that were investigated showed a trend between HDDs and cloud coverage. The climates with a high number of HDDs had low cloud coverage; inversely the climates with a low number of HDDs had high cloud coverage. Cloud coverage prevents the amount of direct sunlight on the roof, and if there is low cloud coverage then there will be a large amount of solar gain through the roof. Increasing the roof insulation thickness is suggested for countries with a high number of HDDs and low cloud coverage. Roof insulation is recommended for these climates in order to prevent solar heat gains through the roof and to reduce the heating demands of the building.

A more generalized version of the roof insulation thickness recommendations is presented in Equation 9. The insulation thickness recommendations are created based on the results for the Tunisia construction model presented in this thesis. The insulation thickness recommendations are not tested for any other construction, so the cost effectiveness of these recommendations for different construction techniques is not guaranteed. The suggested roof construction in the Tunisia model has three layers: the outer layer is a roof coating; the next layer is the polystyrene insulation; and the innermost layer is a 130 mm thick layer of concrete. The suggested construction placed the insulation on the outside of the building; it is not suggested to use these recommendations if the insulation is to be placed on the inside of the building since this will change the effectiveness of the insulation. The recommendations are based on polystyrene insulation with a conductivity of 0.030 W/m-K. In the equation, CCA represents the cloud coverage average.

$$
\begin{array}{l}
If\ HDD > 0.5 * CDD\ \ and\ (CCA - 20\%) < 0;\ significant\ investment\ in\ roof insulation \\
Else\ \ If\ HDD > 0.5 * CDD\ \ and\ (CCA - 20\%) \geq 0; moderate\ investment\ in\ roof\ insulation \\
Else\ If\ HDD > 0.15 * CDD;\ small\ investment\ in\ roof\ insulation\ investment \\
Else\ If\ HDD \leq 0.15 * CDD;\ no\ invesment\ in\ roof\ insulation
\end{array} \tag{9}
$$

The suggested exterior wall insulation thickness correlates with the number of CDDs. The suggested exterior wall insulation was consistent through all the trials. The suggested exterior wall insulations from Section 4.2, Tunisian construction for five countries, are plotted as a function of CDDs and can be seen in the Figure 44.

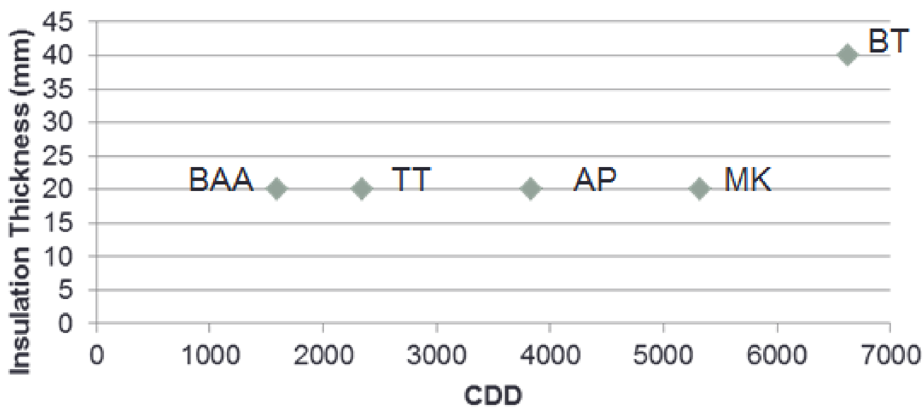


Figure 44: Tunisian construction results for suggested exterior wall insulation thickness

In Section 4.3, the PV sensitivity analysis results suggest for Thailand (TT) to have 20 mm insulation at the low PV cost, and 40 mm of insulation at the medium and high PV cost. These results show that when the PV price is reduced, investing in increased exterior wall insulation is no longer a good investment for Thailand. The final recommendation for exterior wall insulation thickness the can be seen in Equation 10. These recommendations are for the Tunisian construction building described in Section 3.3.3.2 and the gaps in the results were used to determine where to shift the recommendation.

$$\begin{aligned} &If\ CDD \geq 6626;\ 40\ mm\ of\ insulation \\ &If\ 6626\ \geq\ CDD \geq 2350;\ 20\ mm\ of\ insulation \end{aligned} \tag{10}$$

Increasing the exterior wall insulation is suggested for countries with a high number of CDDs. The exterior wall construction consists of a brick wall with a layer of insulation on the inside. If no insulation is used with the brick wall, then the brick will extract heat from the building. Due to this effect, investing in exterior wall insulation is recommended for every climate. However, climates with a high number of CDDs will benefit the most from exterior wall insulation since the vaccine warehouse is cooling intensive; the exterior wall insulation will prevent heat transfer through the walls, and this will keep the air cool inside.

A more generalized version of the exterior wall insulation thickness recommendations is presented in Equation 11. The insulation thickness recommendations are based on the results for the Tunisia construction model presented in this thesis. The insulation thickness recommendations are not tested for any other construction, so the cost effectiveness of these recommendations for different construction techniques is not guaranteed. The suggested exterior wall construction in this mode has three layers: the outer layer is a 200 mm of thick; the next layer is an 80 mm air gap; and the innermost layer is polyurethane insulation. The insulation thickness recommendations are not to be used if a brick is not used for the exterior wall construction. In the previous tests, when a SIP is used for the exterior wall construction, the smallest thickness SIP is suggested, regardless of climate. The suggested construction places the insulation on the inside of the building; it is not suggested to use these recommendations if the insulation is to be placed on the outside of the exterior walls since this will change the effectiveness of the insulation. The recommendations are based on polystyrene insulation with a conductivity of 0.030 W/m-K. If the cost of PV is low, then a moderate external wall insulation investment is no longer recommended for climates with a high number of CDDs and instead just a small external wall insulation investment should be made.

$$If\ CDD > 6 * HDD;\ moderate\ investment\ in\ exteral\ wall\ insulation$$
$$If\ CDD \leq 6 * HDD;\ small\ investment\ in\ exteral\ wall\ insulation \tag{11}$$

The COP value of the HVAC system correlates with the number of HDDs, CDDs, the cloud coverage range, and the suggested roof reflectivity. The suggested COP values of the HVAC system were consistent through all of the trials. The suggested COP values for five countries using the US construction model can be seen in Figure 45.

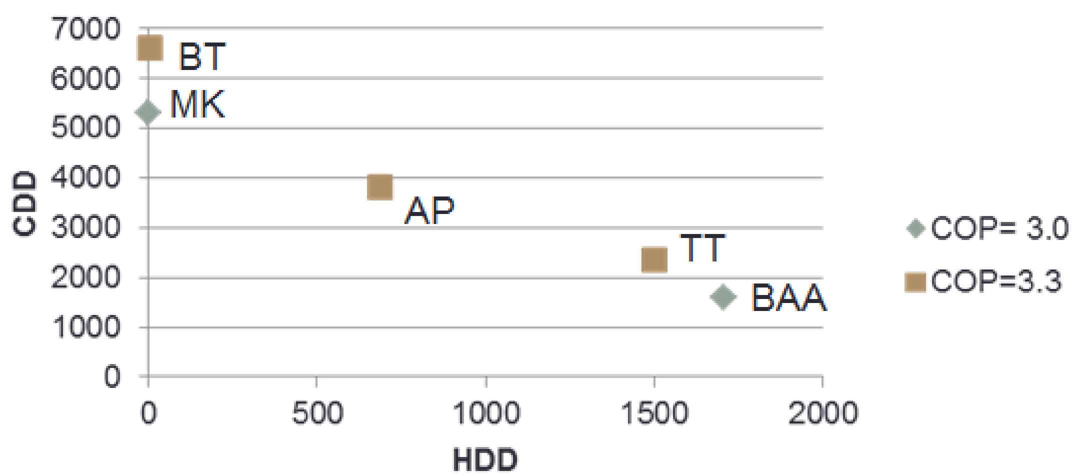


Figure 45: US construction results for suggested COP value of the HVAC system

The figure shows that the results do not correlate to climatic conditions, so the DOE in Section 4.4 is used to investigate the interactive effects. It is found that if the climate has a large number of HDDs, a significant amount of cloud coverage, and it is suggested for the building to have a significant investment in roof reflectivity, then there should be less of an investment in increasing the COP value of the HVAC system. Also, if the climate has a large number of CDDs and no HDDs, then a small investment should be made to increase the COP value of the HVAC system. From these results, it is concluded that moderate investments to increase the COP of the HVAC system should be made for countries that do not have an extremely high CDDs or HDDs, i.e., are "mid-range" climates.

The suggested COP value for the HVAC system correlates with climatic conditions and building parameters. Due to the complexity of these relationships, generalized recommendations are provided instead of equations. The final recommendations for the COP value of the HVAC are listed below. The recommendations are for a HVAC system used for the ambient storage and offices, and not for the refrigeration systems used in the cold storage rooms. The COP value recommendations are created based on results for the Tunisian construction and US construction models presented in this thesis. The COP value recommendations are not tested for any other construction, so the cost effectiveness of these recommendations for different construction techniques is not guaranteed. The gaps in the results of this thesis were used to determine where to shift the recommendation.

- If the number of HDDs is high ($HDD > 0.75 * CDD$), then a moderate investment should be made to increase the COP value of the HVAC system. However, if the cloud coverage range is low ($Minimum\ Cloud\ Covrage\ \leq 50\%$) and roof reflectivity has a significant investment, then a small investment should be made to increase the COP value of the HVAC system.
- If the number of CDDs is high ($CDD > 6 * HDD$), then a moderate investment should be made to increase the COP value. However, if the climate has no HDDs, then small investments should be made to increase the COP value of the HVAC system.
- If the climate is considered to be "mid-range" ($HDD < 0.75 * CDD\ and\ CDD < 6 * HDD$), then a moderate investment should be made to increase the COP value of the HVAC system.

The suggested cold storage insulation thickness correlates to the number of CDDs, HDDs, suggested cold room floor insulation thickness, and the suggested roof insulation thickness. The suggested cold storage insulation thickness varied between the climatic sensitivity and PV sensitivity. The climatic sensitivity showed a direct correlation between cold storage insulation thickness and CDD. The PV sensitivity results did not show this correlation, and the suggested cold storage insulations for five countries at the high PV price are plotted as a function of two climatic conditions in Figure 46.

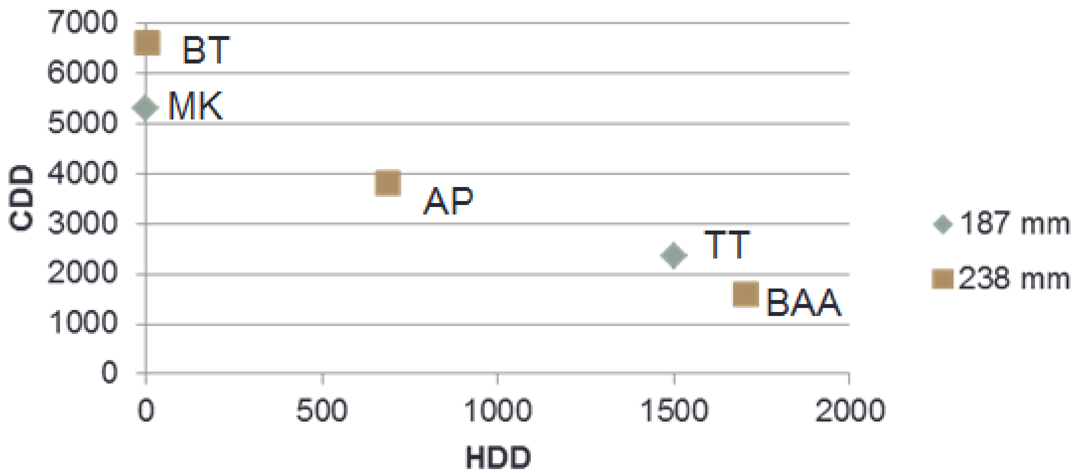


Figure 46: Tunisian construction results at high PV price for cold storage insulation

These results do not support a correlation between CDDs and the suggested cold storage insulation thickness as seen in Section 4.2, so the DOE is used to investigate the interactive effects between the parameters. All five countries have the same interactive terms for the cold storage insulation; a negative effect with the cold room floor insulation and a positive effect with the roof insulation and roof reflectivity. For the PV sensitivity results, Kenya is the only country that recommends increasing the cold room floor insulation thickness at the high PV level. Due to the negative effect with the cold room floor insulation, the cold storage insulation thickness remains the same when the floor insulation thickness is increased. Tunisia has the highest suggested roof insulation thickness of all of the countries; so, with a significant investment in roof insulation, the cold storage insulation is no longer a significant factor. The significant roof insulation for Tunisia causes the suggested cold storage insulation thickness to not increase.

The suggested thickness of the cold storage insulation correlates with climatic conditions and building parameters. Due to the complexity of these relationships, generalized recommendations will be provided instead of equations. The final recommendations for the cold storage insulation thickness are listed below. These insulation thickness recommendations are created based on the results for the Tunisia construction and US construction models presented in this thesis. The insulation thickness recommendations are not tested for any other construction, so it the cost effectiveness of these recommendations for different construction techniques is not guaranteed. However, since the suggested cold storage insulation is related to two building parameters, it is not recommended to use these recommendations for significantly different construction techniques. The recommendations are based on SIPs that have a conductivity of 0.035 W/m-K. The gaps in the graphical representations of the results of this thesis are used to determine where to shift the recommendation.

- If the number of CDDs is high ($CDD > 6 * HDD$), then a significant investment should be made to increase the cold storage insulation thickness. However, if a significant investment is made in the cold room floor insulation thickness, then only a moderate investment should be made to increase the cold storage insulation thickness.
- If the number of HDDs is high ($HDD > 0.25 * CDD$), then a significant investment should be made to increase the cold storage insulation thickness. However, if a climate has a low amount of cloud coverage (M$inimum\ Cloud\ Coverage\ \leq 20\%$) and there is a significant investment in roof insulation, then only a moderate investment should be made to increase the cold storage insulation thickness.

The suggested cold room floor insulation thickness correlates with the number of HDDs. The suggested cold room floor insulation thickness was consistent though all the trials. The suggested cold room floor insulation thicknesses from the Tunisian construction in Section 4.2 are plotted as a function of HDDs and can be seen in Figure 47.

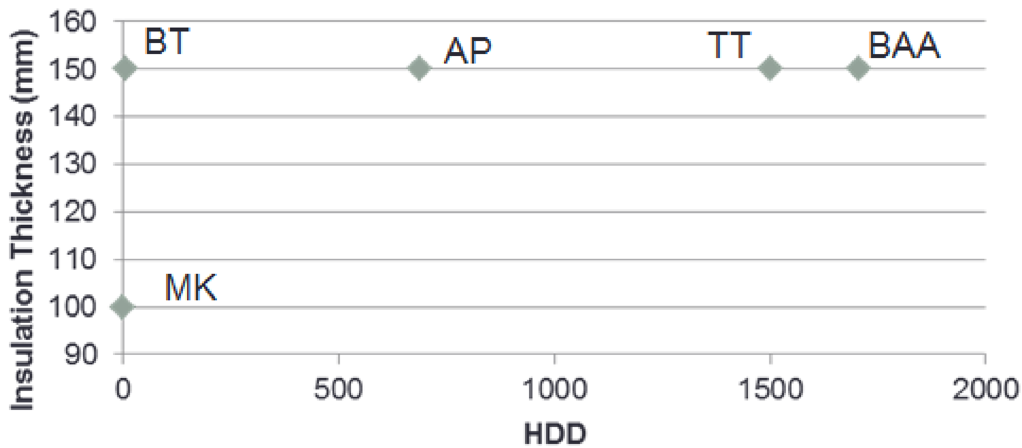


Figure 47: Tunisian construction results for suggested cold room floor insulation thickness

Also, it should be noted that the DOE main effects for the Tunisian construction showed that the cold storage floor insulation was one of the lowest ranked parameters for all the climates except for Kenya. The DOE showed that for Kenya, significant investments in cold storage floor insulation will have a negative effect on the objective function. The DOE results are consistent with the GA results and the generalized recommendation for the cold room floor insulation can be seen in Equation 12. The insulation thickness recommendations are created based on the results for the Tunisia construction model presented in this thesis. The insulation thickness recommendations are not tested for any other construction, so the cost effectiveness of these recommendations for different construction techniques is not guaranteed. The recommendations are based on using polyurethane insulation that has a conductivity of 0.023 W/m-K. The gaps in the graphical representations of the results of this thesis were used to determine where to shift the recommendation.

$$\begin{aligned} &If\ HDD < 0.15 * CDD;\ \ small\ investment\ in\ cold\ room\ ground\ insulation \\ &If\ HDD \geq 0.15 * CDD; moderate\ investment\ in\ cold\ room\ ground\ insulation \end{aligned} \quad (12)$$

The suggested freezer room floor insulation thickness correlates with the number of CDDs. The suggested freezer room floor insulation thickness varied between the climatic sensitivity and PV sensitivity. The climatic sensitivity showed a direct correlation between the freezer room floor insulation and CDD. However, the PV sensitivity results did not show this correlation, and the suggested freezer room floor insulations at the high PV price are plotted as a function of two climatic conditions in Figure 48.

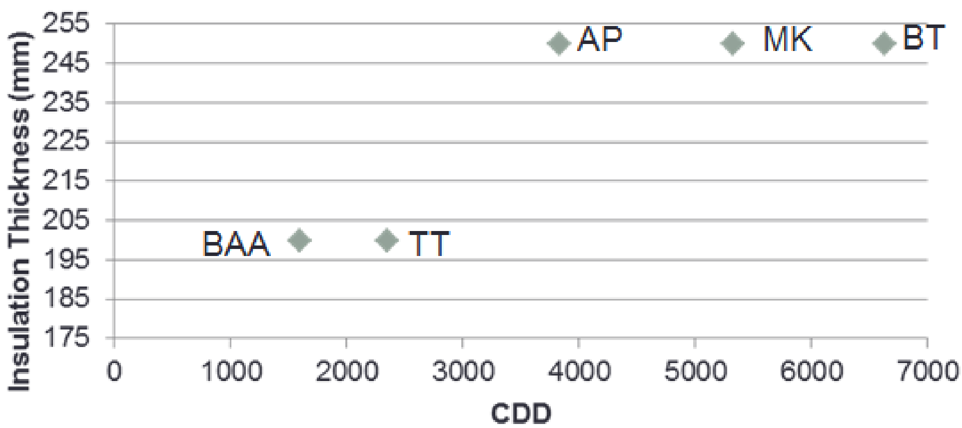


Figure 48: Tunisian construction results at high PV price for freezer room insulation

Tunisia (TT) and Argentina (BAA) have the lowest number of CDDs of all the climates studied and the results suggested investing less in the freezer floor insulation at the high PV cost level for these climates. The DOE in Section 4.4 is used to try and explain why the suggested insulation decreased at the higher PV cost. However, the DOE does not show any significant interactive effects to explain why the insulation thickness would decrease at the higher PV price. Since no significant interactive effects exist. The results show that for countries with a low number of CDDs, the freezer room insulation thickness is not significant. The generalized recommendation for the freezer room floor insulation can be seen in Equation 13. The insulation thickness recommendations were created based on the results for the Tunisia construction model presented in this thesis. The insulation thickness recommendations are not tested for any other construction, so the cost effectiveness of these recommendations for different construction techniques is not guaranteed. The recommendations are based on using polyurethane insulation that has a conductivity of 0.023 W/m-K. The gaps in the graphical representations of the results of this thesis were used to determine where to shift the recommendation.

$$\begin{gathered} If\ CDD < 2 * HDD;\ moderate\ investment\ in\ freezer\ room\ ground\ insulation \\ If\ CDD \geq 2 * HDD;\ significant\ investment\ in\ freezer\ room\ ground\ insulation \end{gathered} \quad (13)$$

The suggested reduction in the air infiltration rate correlates with the number of HDDs. The suggested air infiltration rate only varied for the US construction tests, due to low cost data for air infiltration reduction used for the Tunisian construction. The suggested air infiltration rates from the US construction in Section 4.2 are plotted as a function of HDDs and can be seen in Figure 49.

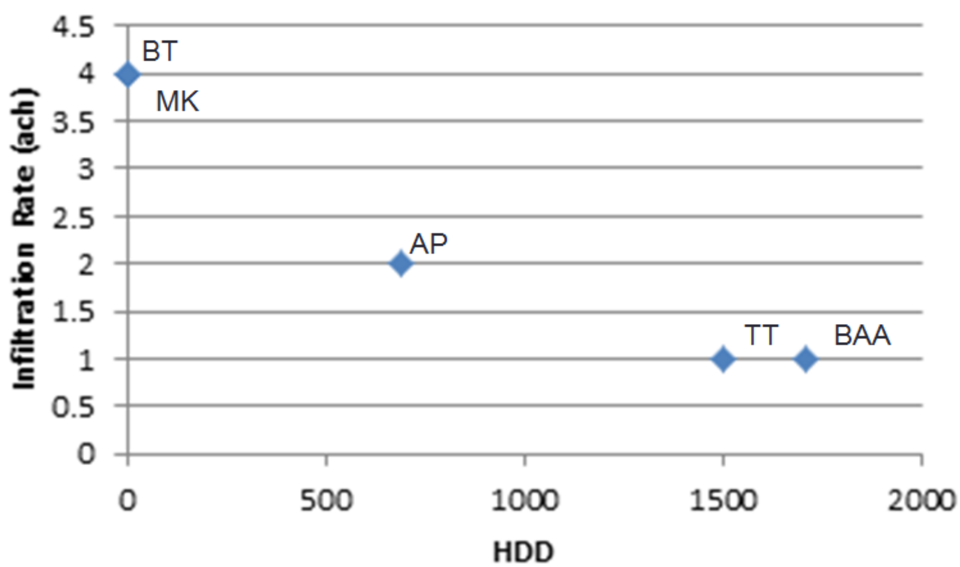


Figure 49: US construction results for suggested air infiltration rate

The final recommendations for the reduction of air infiltration are seen in Equation 14. These recommendations are for the US construction building described in Section 3.3.3.1 and the gaps in the results of this thesis were used to determine where to shift the recommendations.

$$\begin{aligned} &If\ 687 > HDD \geq 0;\ no\ investment\ in\ air\ infiltration\ reduction, goal: 4\ ach \\ &If\ 1501 > HDD \geq\ 687; small\ investment\ in\ air\ infiltration\ reduction, goal: 3\ ach \\ &If\ HDD\ \geq 1501;\ significant\ invesmentt\ in\ air\ infiltration\ reduction, goal: 1\ ach \end{aligned} \tag{14}$$

Reducing the air infiltration rate is suggested for climates with a high number of HDDs. Air infiltration is the unintentional introduction of air into a building, typically through cracks in the building envelope. It is important to reduce air infiltration in cool climates because of the "stack effect," which is when warm air moves upward in a building. This happens in summer and winter, but is most pronounced in the winter because indoor-outdoor temperature differences are the greatest. Warm air rises because it's lighter than cold air, and when the indoor air is warmer than the outdoor air, it escapes out of the upper levels of the building. Due to this effect, it is recommended that climates with a high number of HDDs to reduce air infiltration.

A more generalized version of the air infiltration reduction recommendations is presented in Equation 15. The air infiltration reduction recommendations are based on the US construction model. The suggested air infiltration rate is not investigated for any other construction, so the cost effectiveness of these recommendations for different construction techniques is not guaranteed. However, it is important to note that the suggested air infiltration reduction is not affected by any other building parameters and that these recommendations should be valid for any construction technique.

$$If\ HDD > 0.5 * CDD;\ significant\ investment\ in\ air\ infiltration\ reduction$$
$$If\ 0.5 > HDD > 0.15 * CDD; small\ investment\ in\ air\ infiltration\ reduction \quad (15)$$
$$If\ HDD \leq 0.15 * CDD;\ no\ investment\ in\ air\ infiltration\ reduction$$

The suggested roof reflectivity value correlates with the number of CDDs and the suggested roof insulation thickness. The suggested roof reflectivity varied between the climatic sensitivity and PV sensitivity. The climatic sensitivity showed for all climates to invest in increased roof reflectivity. The PV sensitivity results suggest decreasing the roof reflectivity for Argentina at the high PV cost level. The DOE results in Section 4.4 show that the suggested decrease roof reflectivity correlates with the increase in cold storage insulation thickness. The PV sensitivity also suggests for Paraguay and Thailand to increase the cold room wall insulation thickness at the high PV cost level, but does not suggest decreasing the roof reflectivity. Argentina has a low number of CDDs (1595) and therefore benefits less than Paraguay (CDDs = 3829) or Thailand (CDD s= 6626) from increasing the cold storage insulation thickness. These results show it is more beneficial for Argentina to reduce the cooling needs of the building by increasing the insulation thickness of the cold storage as opposed to investing in higher roof reflectivity to reduce the cooling needs of the entire building.

The suggested roof reflectivity correlates to climatic conditions and building parameters. Due to the complexity of these relationships, generalized recommendations are provided instead of equations. The final recommendations for the roof reflectivity value are listed below. These recommendations are created based on the results for the Tunisian construction and US construction models presented in this thesis. The recommended roof reflectivity is not tested for any other construction, so the cost effectiveness of these recommendations for different construction techniques is not guaranteed. The gaps in the graphical representations of the results of this thesis are used to determine where to shift the recommendations.

- If the number of CDDs is high ($CDD > 2 * HDD$), then a significant investment should be made to increase the roof reflectivity.
- If the number of CDDs is low ($CDD < 2 * HDD$), then a significant investment should be made to increase the roof reflectivity. However, if a significant investment is made in the cold storage insulation thickness, then no investment should be made to increase the roof reflectivity.

The suggested efficiency of the windows correlates with the number of CDDs, the external wall insulation thickness, the roof insulation thickness, and the COP value of the HVAC system. The suggested efficiency of the windows varied through the tests. Overall, the tests showed a correlation with the number of CDDs. The suggested efficiencies from the high PV price are plotted as a function of CDDs and can be seen in Figure 50.

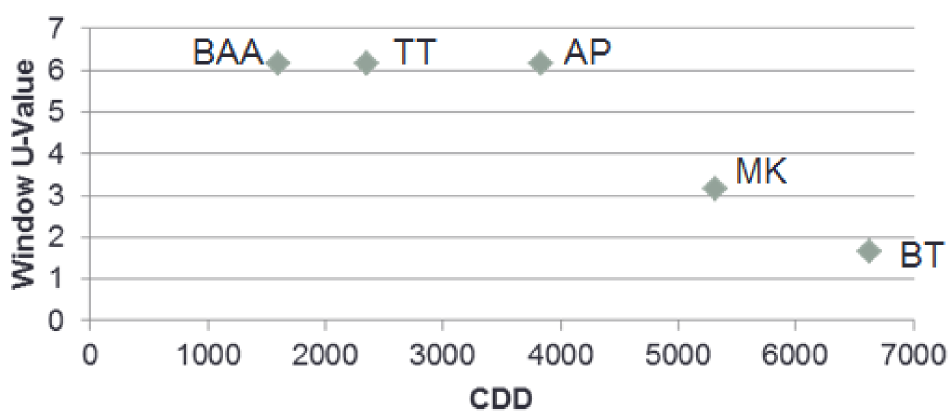


Figure 50: Tunisian construction results at high PV price for suggested window efficiency

The Tunisian construction results show a correlation between windows type and CDD, but this correlation is not seen in the US construction results. The DOE in Section 4.4 is used to investigate why the constructions had different recommendations. It is found that Paraguay and Thailand have an interactive effect between the exterior wall insulation thickness and the window efficiency, while Tunisia and Argentina have an interactive effect between the roof insulation thickness and the window efficiency. These interactive effects cause the results of the US construction to not correlate to the number of CDDs.

In Section 4.3, the PV sensitivity analysis results shows unexpected variation in the suggest window efficiency for Paraguay and Tunisia. For Paraguay, the best window type is selected for the average PV price, while a less energy efficient window is chosen for the high and low PV prices. The result for Tunisia is the opposite, the most energy efficient window type selected for the high and low PV price while a less energy efficient window is chosen for average PV prices. The DOE in Section 4.4 shows that an interactive effect between the HVAC COP and the window efficiency causes the results to vary. However, the window type has a negative effect for Tunisia, yet the window type has a positive effect for Paraguay; and difference is what caused the results to have opposite effects. Overall, these results show how the suggested window efficiency is impacted by the other building parameters. However, the climate can be used to determine which building parameter will impact the suggested window efficiency.

The suggested window efficiency correlates to climatic conditions and building parameters. Due to the complexity of these relationships, generalized recommendations are provided instead of equations. The final recommendations for the window efficiency value are listed below. These recommendations are created based on the results for the Tunisian construction and US construction models presented in this thesis. The recommended window efficiency is not tested for any other construction, so the cost effectiveness of these recommendations for different construction techniques is not guaranteed. In the recommendations, a higher efficiency window means that the window has a lower U-Value and a lower SHGC. The recommendations are based on using windows that range from the reference window, U-Value of 6.172 W/m²K and SHGC of 0.83, to a highly energy efficient window, U-Value of 1.658 W/m²K and SHGC of 0.57. The gaps in the graphical representations of the results of this thesis are used to determine where to shift the recommendations.

- If the number of HDDs is high ($HDD > 0.5 * CDD$), then a small investment should be made to increase the efficiency of the windows. However, if there is a significant roof insulation investment, then no investment should be made to increase the efficiency of the windows. Unless, if the number of CDDs is low ($CDD < 6 * HDD$) and there is a large investment in the COP of the HVAC system, then a small investment should be made to increase the efficiency of the windows. The effect from the HVAC system is more significant than the effect from the roof insulation, and this recommendation should be used if the condition is met.
- If the number of CDDs is high ($CDD > 2 * HDD$), then a significant investment should be made to increase the efficiency of the windows. However, if there is not a significant exterior wall insulation investment, then a moderate investment should be made to increase the efficiency of the windows. Also, if the number of HDDs is high ($HDD > 0.25 * CDD$) and there is a large investment in the COP of the HVAC system, then a moderate investment should be made to increase the efficiency of the windows.

This section provides the recommendations for each parameter based the climatic conditions and suggested investment in other parameters. For future designers, these recommendations can be used to decide the most important parameters for a climate. The climate's number of HDDs and CDDs needs to be calculated in order to determine the appropriate range and recommendation. There are numerous online resources that discuss how to determine HDDs and CDDs. The next section evaluates the proposed decision support tool.

4.6.2 Decision Support Tool Evaluation

The goal of this thesis is to create and study a decision support tool that can be used to aid in the design an economically feasible Net Zero Energy vaccine warehouse for the developing world. So far this chapter has presented the results found from studying the case study building with the decision support tool. This section discusses the effectiveness and generalizability of the tool.

The decision support tool utilizes a simulation-optimization approach in order to find the optimal result. The simulation-optimization approached described in Section 3.2 has five main components: an energy model, PVWatts, construction costs, the objective function, and an optimization technique. The five components are combined together in one Matlab code, which forms the method's framework. The method has five steps, which occur after the parameter levers have been selected by the optimization technique:

1. Determine the material costs and associated properties for the chosen parameter levels
2. Modify the building energy model with the new parameter properties
3. Run EnergyPlus to determine the annual energy consumption
4. Run PVWatts to size the PV system needed to accomplish NZE
5. Calculate the value of the objective function.

The most important component of the process is the optimization technique used to find the optimum results. Two different optimization techniques are used, a design of experiments and a genetic algorithm. For the design of experiments, the required combination of parameters is determined in JMP Pro. JMP Pro outputs the required simulation into a design matrix, and this matrix is placed at the beginning of the main Matlab code. The Matlab code uses a loop to iterate through the design matrix and find an objective value for each simulation. For the genetic algorithm, the main Matlab code is a function. The function has the objective function value as its output and the different parameter levels as its input. A file is written that executes the genetic algorithm and supplies the parameter levels under investigation to the function code. The main framework code is consistent for both techniques; only the way the selected parameters are supplied to the main code is varied. A basic version of the GA code in Matlab can be seen in Figure 51. This code allows for the number of generations, the population size, and any of features of interest in the GA to be easily changed.

```
ObjectiveFunction=@simple_fitness;
nvars=9;                        %Number of variables
LB=[1 1 1 1 1 1 1 1 1];         %Lower Bound
UB=[4 6 4 5 8 8 4 2 6];         %Upper Bound

IntCon=[1 2 3 4 5 6 7 8 9];     %Make each parameter only used intergers
options = gaoptimset('Generations',30, 'PopulationSize', 25, 'EliteCount', 3);  %GA paremters

OptimumResult=ga(ObjectiveFunction,nvars,[],[],[],[],LB,UB,[],IntCon,options);
```

Figure 51: GA Code in Matlab

"Simple_fitness" is the name of the main code. The parameters chosen by the GA is supplied to the main code in a vector, x, and then the code returns the objective function's value. The vector provides an integer for every parameter from the range specified in the GA code. Once the parameter levels are selected, the construction costs are determined for each parameter. For each parameter, multiple levels are assigned and each level has an associated cost. For example, the first parameter in the vector correlates with the roof insulation thickness. The code written in Matlab to find the corresponding roof thickness and price can be seen in Figure 52.

```
%Roof Insulation selection and price
if x(1)==1;
    roof=0.00001;
    roofprice=40515-40515;
elseif x(1)==2;
    roof=0.02;
    roofprice=42906-40515;
elseif x(1)==3;
    roof=0.04;
    roofprice=44813-40515;
elseif x(1)==4;
    roof=0.06;
    roofprice=55615-40515;
end
```

Figure 52: Code to determine cost and thickness of roof insulation

The value of x (1) is determined by the GA, and the ‘if’ and ‘else if’ statements are used to find the corresponding level. Once the correct level is found, the roof insulation thickness and its associated cost become active variables. This same process is repeated for every variable. This code is written to be adaptable to changing prices, material properties, and number of levels. If the cost values need to be changed for any material, then only one variable, “roofprice” in this case, needs to be updated. Also, more ranges can be added by simply adding more levels inside the “if, else if” statement loop. However, if the number of levels is changed, then it must also be changed in the “UB” line of the initial GA code. The difficult part of this step is finding accurate cost values. The process of finding cost data is difficult and time consuming and if the cost data is not accurate then the result found by the GA will not be beneficial.

The next step is requires the building energy model input file to be modified with the new parameter properties. The Matlab code uses the parameters selected in step 1 to write a new energy model. For the continuing example of roof insulation, “Roof_Insulation” is the name of the material property in the energy model file that had to be changed. The code can be seen in Figure 53.

```
%Roof Insulation in idf
file_id=fopen('NZEDone.idf','A');
fprintf(file_id,'\n %s ', 'Material, Roof_Insulation, Rough');

fprintf(file_id, '%s%f',',',roof);

fprintf(file_id,'\n %s ', '0.030, 25, 1380, 0.9, 0.6,0.6;');
fclose(file_id);
```

Figure 53: Code to change material properties of roof insulation in energy model

In this step, the material properties must be written in the correct format so they can be read by EnergyPlus, and then the material names must consistent between the Matlab code and the energy model. The code used to write components in the correct format is created in this thesis only for building materials, window types, and air infiltration. If an investigated parameter does not fall into one of these three categories, then a new code will have to be written. In this step, it is important to make sure the material name being changed in the Matlab code is consistent with the material name in the energy model. To do this, first the energy model must be investigated. The building surface details in the energy model need to match the construction that is being changed, and the construction details must include the material that is being changed. If the building surface detail portion of the code incorporates the correct construction, and the construction portion of the code incorporates the correct material, then the material name can be implemented into the Matlab code. This step is not difficult if the energy model is created by the user. However, for this thesis, the energy model was created by another student and then modified to fit the needs of this thesis. As a result, it was time consuming to modify the energy model to have consistent material properties with the Matlab file. Overall, this step is highly adaptable due to the fact that three templates were competed to write the construction properties in the correct format for the energy model.

The next step in the process is to run EnergyPlus. EnergyPlus will simulate the building and then output the annual energy consumption into a CSV file that is read by Matlab. In order to run the simulation, a DOS command was implemented in the Matlab code. The code is simply is DOS (‘runeplus file_name weather_file’). It was decided to run the simulation in EnergyPlus using the DOS command due to its simplicity. In the code, “file_name” refers to the name of the EnergyPlus IDF and the “weather_file” is the climate in which the building is simulated. If a new building energy model or climate is to be studied; then the DOS command is the only line in the code that has to be changed. Due to the simple nature of this code, the code could quickly be modified for the changing construction methods in Section 4.2 and changing the weather file to study climate sensitivity in Section 4.3. Since the code can be changed quickly, this allows for this thesis to perform the large sensitivity analysis.

The next step is to run the simulation of PVWatts to determine the necessary PV size needed to accomplish NZE for each annual energy usage. Originally, it was planned to have the code call the PVWatts program and iteratively search for the result. However, this process proved to be very computationally expensive. The optimization process took more time to determine the size of the PV system need then to determine the building annual energy use. To fix this problem, the PVWatts was run for a large range and the output data were stored in a matrix. This process was done for all of the climates studied, and the final data was input into the main code. Figure 54 shows the matrix in the main file. "TunPVdata" is the matrix of data found from PVWatts. A loop was used to iteratively search the matrix, in the same manner as was originally done in the separate PVWatts program, in order to find the necessary PV size. If a new climate is to be studied, the PV data matrix needs to be changed to contain the data for that climate.

```
energy=Tunisia*2.77778*10^-7;

TunPVData=[15.1000000000000,19275.8962091637;15.2000000000000,19403.5504158847;15.30
low=energy-75;
high=energy+75;
xx=1;
tt=0;
Watts=TunPVData(xx,2);
while tt<1

if Watts>low && Watts<high
PVNeeded=TunPVData(xx,1); %System Size
tt=22525;

else
xx=xx+1;
Watts=TunPVData(xx,2); %Watts

end
end
```

Figure 54: PV iterative search in code

After all of these steps, the code calculates the costs of the PV system and materials. These costs are used to determine the value of the objective function. Overall, the two different techniques used for optimization proved to be efficient. The DOE was investigated earlier in this thesis in order to find the most efficient DOE design to show accurate main effects and interactive effects. The DOE designs used in this chapter were not computationally expensive and the results helped to create the generalized recommendations. The GA proved to be both efficient and accurate for all of the trials. The GA options selected make the optimization converge quickly, without getting stuck at a local minimum. In the beginning stages of the research, the GA code was ran multiple times for the same problem to check for accuracy. When multiple tests were done, the results converge to the same optimal point showing that the GA provides the global minimum. The code is set to end after 30 generations, and when looking at the final results from the Tunisian construction case, the optima are found for the Tunisia, Argentina, Thailand, Paraguay, and Kenya after 21 generations, 22 generations, 19 generations, 25 generations, and 16 generations, respectively. Examples from the two of the GA results can be seen in Figure 55. Due to the random behavior of the GA, the number of generations needed for the problem to converge changes for every test. However, the results show that using 30 generations allowed the code sufficient time to find the optimum solution while not wasting a significant amount of computational time.

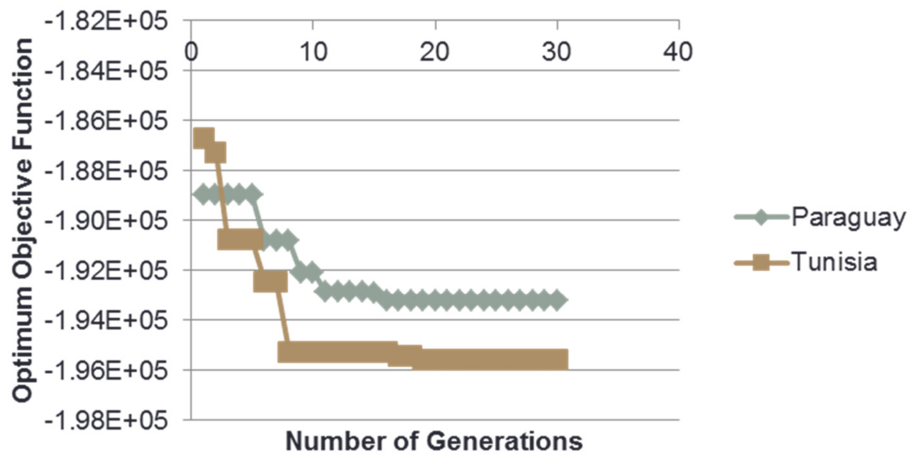


Figure 55: Optimum Objective Function from two of the tests to show GA convergence

There is one main limitation to the decision support tool. The GA options are selected for a problem with nine building parameters. If the number of building parameters varied is changed, then the GA option, including the number of generations, population size, elite count and crossover fraction, are no longer guaranteed to be effective. If these numbers of parameters varied are to be changed, then it is recommended that the GA options be investigated in a manner similar to what is shown in Appendix D.

In order to this tool to be helpful for future designer, it was written to be adaptable. This section showed how the simulation parameters, which include the cost of construction material, types of material, energy model, and climate file, can be modified by only changing a few lines of the code. Other simulation parameters, including the PV price and objective function, also can be modified by only changing a few lines in the code. This adaptability allows for a sensitivity analysis to be easily executed without having to change the overall framework of the code. The framework code for this decision support tool is given in Appendix I. This framework provides a shell of the process described in this section and includes comments on what to include in each section. This code can be used to implement decision support tool to aid in the design for any building. The details of the code are presented in Section 3.3 and this section provides more information how the code was implemented; both of these sections provide examples of the code used for this thesis. It is believed that, with the provided examples and detailed description of the code presented in this thesis, the tool can be used by anyone who has basic coding knowledge to quickly design an economically feasible NZE vaccine warehouse.

The main purpose of this thesis is to create a decision support tool that can be used to aid in the design of an economically feasible Net Zero Energy vaccine warehouse for the developing world. To do this, the tool uses only free software, cannot be computationally expensive, and must be easy to use. The simulation programs, EnergyPlus and PVWatts, were chosen due to the fact that they are free and are proven programs that provide accurate results. In order to reduce computational time of the complete building design process, this thesis suggests using a two-step process. The results showed that the proposed two-step process was an efficient way to save time during the building design process. The process suggests using a DOE, only considering energy usage, in the early stages of design to determine the significant parameters that should be investigated by the GA. By using this two-step process, time is saved by not wasting time studying insignificant parameters with the GA. The selected GA options proved to be efficient and reliable way to find discrete recommendations for the final stages of design. The GA options were chosen to make the program converge faster than the tools and methods presented in previous studies. Overall, the decision support tool proposed in this thesis uses proven optimization methods and free software in order to make a useful and practical tool to aid developing countries in the design of NZE buildings.

4.6.3 Results Summary

This section summarizes the important results of this thesis. In this thesis, a decision support tool is created in order to help design an economically feasible NZE vaccine warehouse for the developing world. The decision support tool is used to investigate the effect of climate and PV price on nine different building parameters. The results from these tests are used to generate generalized design recommendations. The generalized climatic recommendations for these parameters can be seen in Table 57. If the parameter is in *italics* then it is also correlated to other building parameters; however, only the overall climatic trends are presented in the table.

Table 57: Generalized climatic trend summary

Parameter	Significant Investment	Moderate Investment	Small Investment	No Investment
Roof Insulation	If HDD>0.5*CDD and (CCA-20%)<0	Else if HDD>0.5*CDD and (CCA-20%)≥0	Else if HDD≥0.15*CDD	Else if HDD<0.15*CDD
External Wall Insulation		If CDD>6*HDD	If CDD≤6*HDD	
COP value of HVAC System		If HDD≤0.75*CDD and CDD≤6*HDD	Else if HDD>0.75*CDD or CDD>6*HDD	
Cold Storage Insulation	If CDD>2*HDD	If CDD≤2*HDD		
Cold Room Floor Insulation		If HDD≥0.15*CDD	If HDD<0.15*CDD	
Freezer Room Floor Insulation		If CDD<2*HDD	If CDD≥2*HDD	
Air Infiltration Reduction		If HDD>0.5*CDD	Else if HDD>0.15*CDD	Else if HDD≤0.15*CDD
Roof Reflectivity	If CDD>2*HDD			If CDD≤2*HDD
Window Efficiency		If CDD>6*HDD	Else if CDD≤6*HDD	Else if CDD≤2*HDD

For colder climates, the roof insulation, cold room floor insulation, and air infiltration reduction are the most important parameters. For warmer climates, the external wall insulation, the cold storage insulation, the freezer room floor insulation, the roof reflectivity and the window efficiency are the most important. These general climatic trends can be used by future designers to create an economic efficient design.

Through the tests conducted with the decision support tool, the code is shown to be highly adaptable to changing simulation parameters, including the cost of building material, type of material, energy model, and climate. Even with the changing simulation parameters, the GA quickly converges to the global optimum. The general framework of the code is provided so that the tool can be used by anyone who has basic coding knowledge to quickly get a reliable optimum solution for a building design. This decision support tool was created to aid developing countries in the design of a NZE vaccine warehouse. With the tools use of free simulation programs and its fast computational time, the proposed decision support tool is a useful and practical tool to aid in the design of NZE buildings for developing countries.

CHAPTER 5

CONCLUSION

This chapter presents this thesis's conclusions. First, a summary of the research outcomes and the final recommendations are presented. Then, suggestions for future work are discussed.

5.1 Research Summary

This thesis created and studied a decision support tool. This tool was used to aid in the design of an economically feasible NZE vaccine warehouse for the developing world. The decision support tool utilizes a simulation-optimization method that combines an optimization technique with a building energy simulation program in order to investigate building parameters. In order determine an economic efficient NZE solution, the initial cost of the case study warehouse was minimized.

Five sets of trials were conducted with the decision support tool, and these trials proved that the decision support tool is adaptable and efficient. First, the decision support tool was used to study the NZE warehouse for two different construction techniques. The construction methods were used to represent construction for both a developing country and a developed country. The optimum results had a 58.41% energy saving for the developed country construction and 55.67% energy savings for the developing country construction when compared to a reference case. Then, the highly energy efficient NZE design solution, which uses the best technology available, was compared to the cost-optimal optimal result. For both construction cases, the highly energy efficient NZEB design solution was at least 1.15 times more expensive ($30,000) than the optimal design solution. This result shows the cost savings that can be achieved by using the decision support tool compared to only designing a building to be energy efficient.

The influences of different climates on the economic-efficient design of NZEB were investigated. The results show that the overall investment cost to accomplish NZE was similar for all climates. The climates with a high number of HDDs required solutions that were more energy efficient, which lead to increased investment in materials. The climates with a significant amount of cloud coverage and high number of CDDs required a larger PV system to offset the energy usage. The difference in cost between the optimal solution and highly energy efficient solution ranged from $47,000 to $69,000. These results illustrate the importance of an economic analysis of NZEBs in order to reach the energy goals with economic efficiency. The results obtained from the five sets of trials were used to make recommendations for each of the building parameters.

The results for five of the parameters - roof insulation thickness, external wall insulation thickness, cold room floor insulation thickness, freezer room floor insulation thickness, and the air infiltration reduction - were directly correlated to the climatic conditions. If the climate has a high number of HDDs, then investments should be made to increase the freezer room floor insulation thickness and to reduce the air infiltration rate. If the climate has a high number of CDDs, then investments should be made to increase the external wall insulation thickness and the cold room floor insulation thickness. The suggested roof insulation thickness was found to correlate to two climatic conditions, HDDs and the cloud coverage.

The other four parameters - COP value for the HVAC system, the cold storage insulation thickness, the roof reflectivity, and the efficiency of the windows - correlated to climatic conditions and other building parameters. The suggested COP value of the HVAC system correlated to HDDs, CDDs, the roof reflectivity, and the air infiltration rate. The cold storage insulation correlated to HDDs, CDDs, the cold room floor insulation thickness and the roof insulation thickness. The roof reflectivity correlated to CDDs and cold storage insulation. The suggested window efficiency correlated to CDDs, HDDs, the exterior wall insulation thickness, the COP value of the HVAC system, and the roof insulation thickness.

This thesis provides a decision support tool and generalized construction recommendations to aid in the design of an economically feasible NZE vaccine warehouse for the developing world. The work performed in this thesis is useful to those interested in designing an energy efficient building for a developing country or those who are interested in an easy and proven method to integrate an optimization technique with an energy simulation program.

5.2 Possible Future Research

Future research related to this thesis may involve applying this tool to different situations. It would be interesting to see the effect of different cost data on the construction recommendations. This thesis used cost data from Tunisian government reports; using cost data from actual contractors make the parameter recommendations more accurate. Also, a different building layout for a vaccine warehouse could be investigated to see if the parameters have the same suggested investment. Tests could be completed for more climates in order to improve the recommendations presented. If more climates are investigated, then the breaks in the recommendations can be accurate. Also, if more construction techniques are studied, the recommendations can become more generalized.

APPENDIX A

This appendix shows the final drawings of the vaccine warehouse designed for Tunisia. The vaccine storage facility will be located on an Access Street off Rue Mongi Slim in the capital city of Tunis. Figure 56 shows the site plan for the warehouse. The proposed project is located on an empty plot of land adjacent to the existing DSSB warehouse and vehicle repair shop. The proposed building is located in the southeast corner of the plot, to allow for vehicle access. This layout also allows space for the addition of an injection waste disposal facility without disrupting the administration building or the electrical transformer currently located on the land. Figure 57 shows the ground floor plan of the warehouse. The building is oriented so that the shipping and receiving docks and areas are located on the north side of the building, which is closest to the street from where the trucks will come. An office is located in the northeast corner of the building and provides an efficient way to view the warehouse operations; in addition, it allows the warehouse manager to view all incoming and outgoing trucks. The refrigerated storage is located in the middle of the warehouse, with only one wall adjacent to an external wall, minimizing the transmission of heat from the outside. The plant area is located along the entire south wall of the building. Figure 58 shows the ground floor plan of the warehouse. Offices are located on the second floor of the building in its northeast corner. Expansion of the building will be on the west side of the building. The west wall will be constructed to be able to tear down for future expansion, opening up towards the second, larger empty land plot on the DSSB site. Figure 59 shows the roof plan of the warehouse.

NZE project		Project: DSSB central vaccine store, Tunis		Title: Site plan	
Scale: 1:500 @ A4	Date: 6 Jun 2013	Drawn: -	Checked: -	SK01	C

Do not scale from drawing. Check all dimensions and levels on site. Unless otherwise noted, all dimensions are in millimetres and are taken to structural surfaces. If in doubt, ASK.

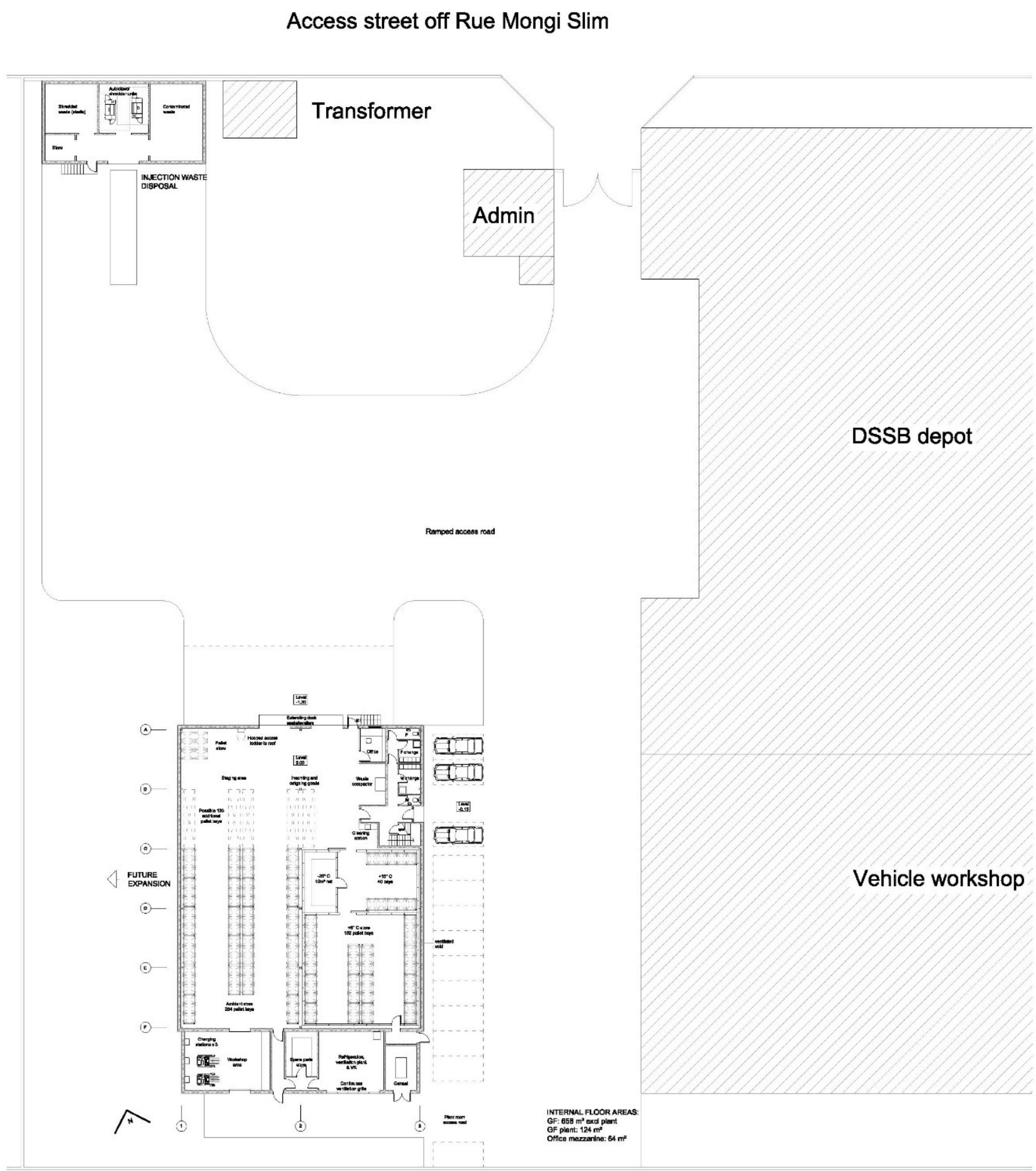


Figure 56: Tunisian Vaccine Warehouse Site Plan

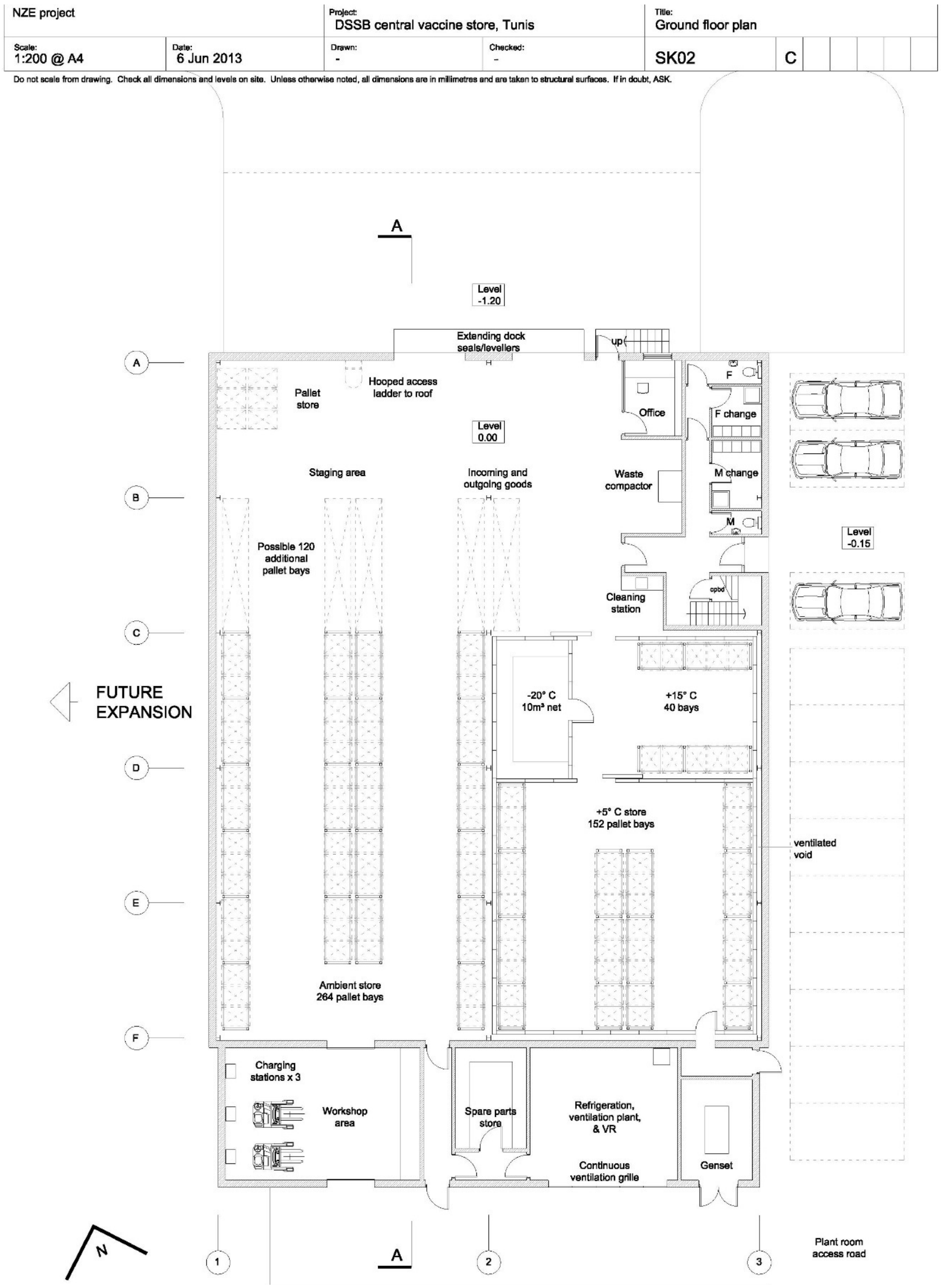


Figure 57: Ground floor plan of Tunisian Vaccine Warehouse.

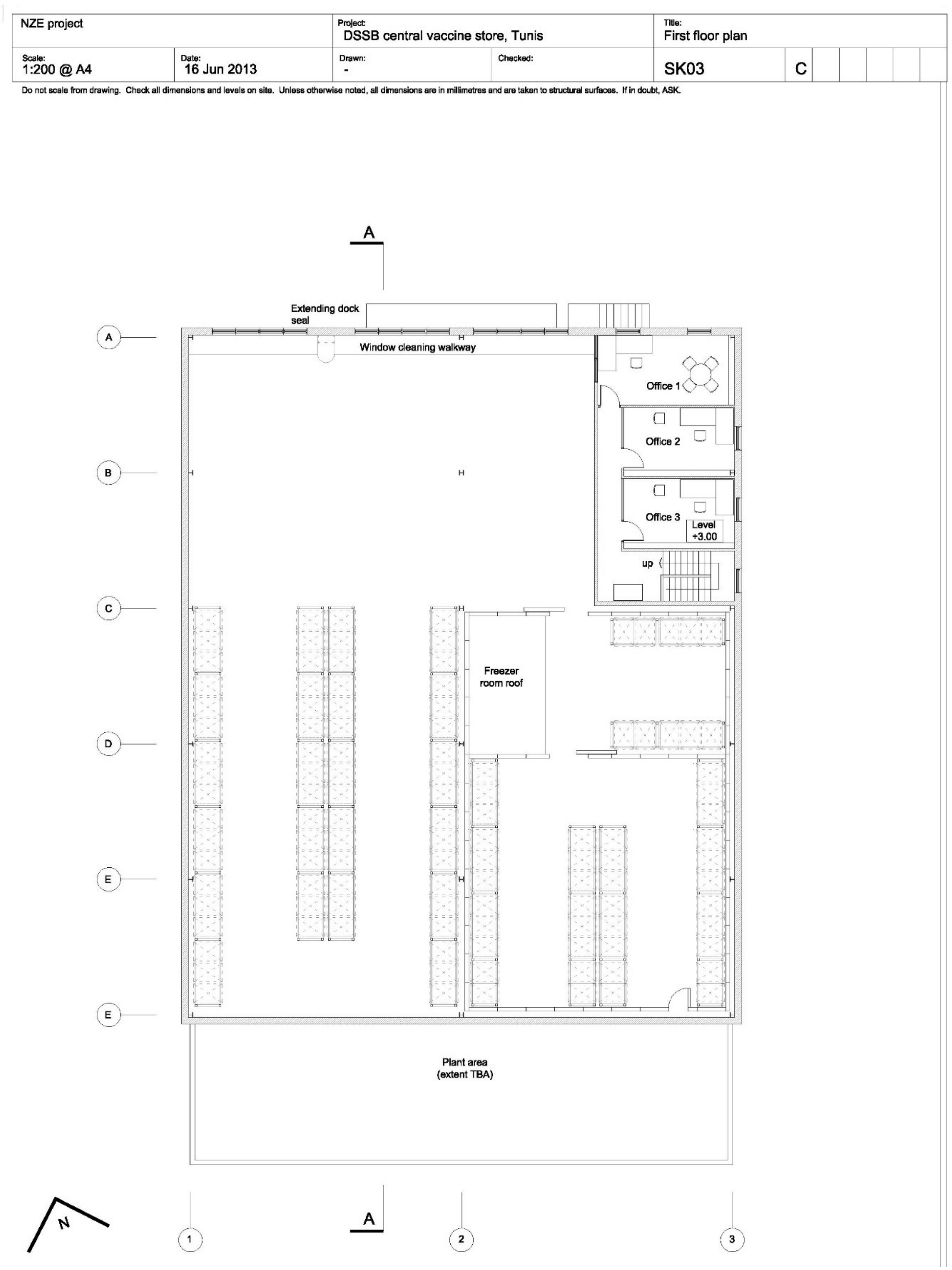


Figure 58: First Floor Plan of Tunisian Vaccine Warehouse.

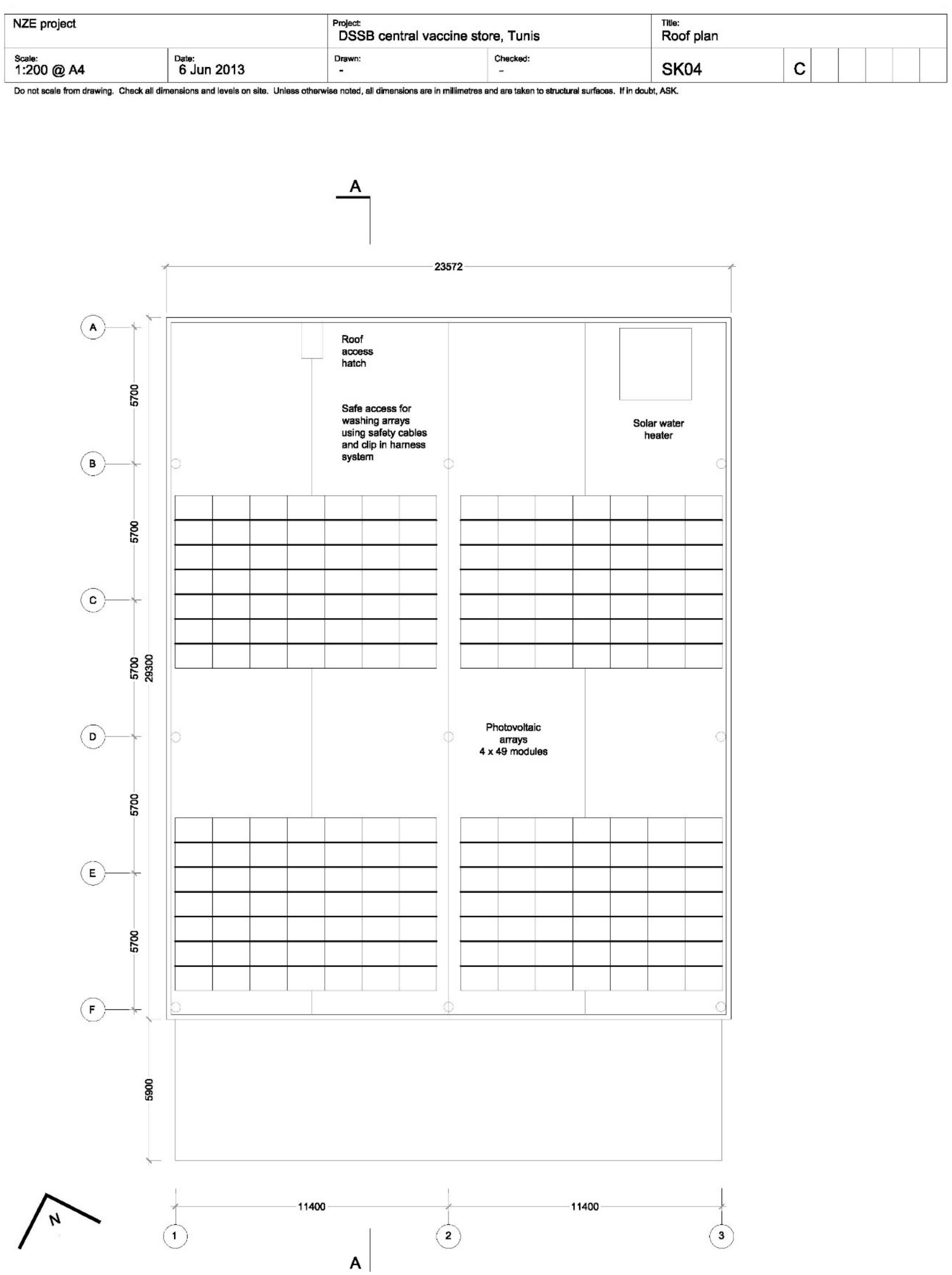


Figure 59: Roof Plan of Tunisian Vaccine Warehouse.

The roof slab will be 130 mm composite profiled steel and reinforced concrete. On top of the concrete will be a vapor barrier, insulation, two layers of high performance membranes with a mineral finish, and a non-penetrative support system for PV array. Figure 59 shows the layout with four Photovoltaic Arrays. The roof will also provide space for a solar water heater. Figure 60 provides the west and east elevations of the warehouse.

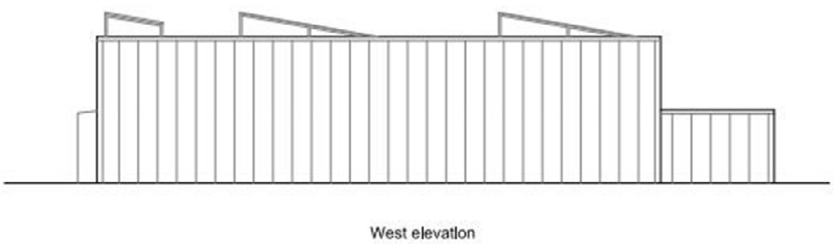


Figure 60: East and West elevation of Tunisian Vaccine Warehouse

The east elevation shows the access door to the back of the warehouse and the windows that are in the office areas. The back of the warehouse includes the workshop for mechanical maintenance and the plant area. This workshop is for servicing equipment and to support any general manual tasks for maintenance, such as repairing broken equipment such as reach trucks and pallet jacks. The plant area will have sufficient space for refrigeration and mechanical ventilation systems equipment, and a separate room for the backup generator. Figure 61 provides the south and north elevations of the warehouse.

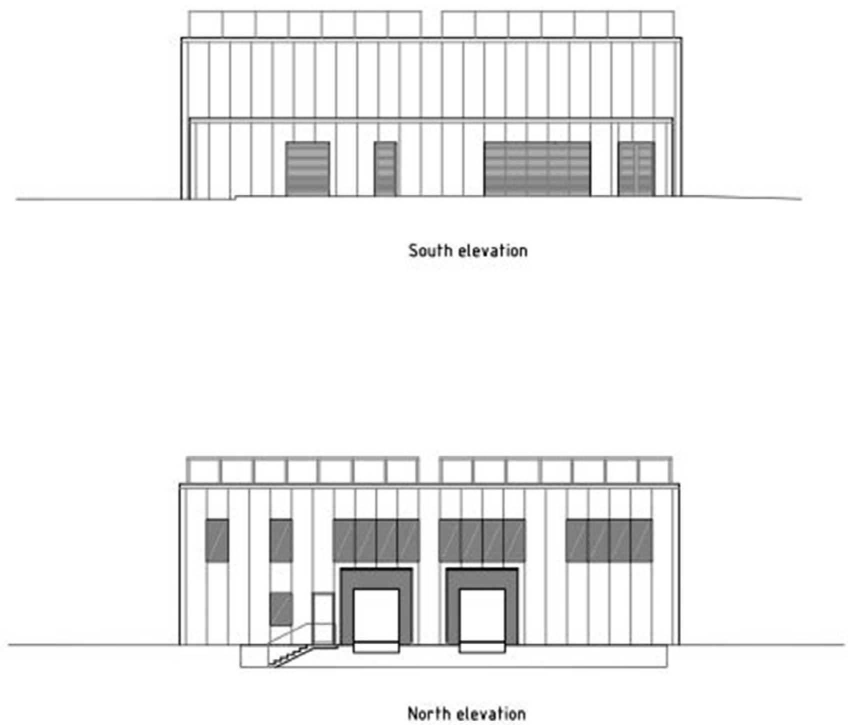


Figure 61: North and South elevation of Tunisia Vaccine Warehouse

The north elevation shows the entrance to the shipping and receiving area. This area will have two docking bay doors fitted with dock shelters and insulated roller shutter systems to minimize energy loss and for weather protection of facilities and products. Both bays will be fitted with dock leveling equipment to accommodate a range of vehicles. A pallet store will be located adjacent to loading/unloading area for easy and quick access. This adaptable space will be used for receiving, for order assembly and for shipping. This area will be equipped with work tables that are 900 mm high, space for assembling orders onto pallets, space for storing packaging materials and packaging tools, filing trays for storing order vouchers and packing lists, and space for the storage of assembled pallets that are awaiting shipping.

APPENDIX B

The main three economic equations used in building design optimization are initial investment costs, net present value, and life cycle cost. The net present value can only be used when there will be future cash flows. Since this thesis is investigating net zero energy, there will be no future cash flows because the building is designed to offset as much energy as it uses on an annual basis, meaning that no money will be spent or gained on energy. Also, this thesis does not include the maintenance and upkeep costs associated with the building. Therefore, net present value will not be used for this project. Life cycle cost was investigated. Life cycle cost (*LCC*) is calculated using Equation 16.

$$LCC = \sum_{j=1}^{N} IC_j + \sum_{j=1}^{N} RC_j \tag{16}$$

IC is the initial investment cost of the investigated design variables and *RC* is the replacement cost of the replaced building elements and systems. *i* denotes indexes for the design solutions and *j* is an index for the design parameters. In most studies, the life-cycle cost analysis is performed for a 30-year calculation period. Longer calculation periods are not recommended, as beyond a 30-year timeframe assumptions on interest rates and forecasts for energy prices become very uncertain (Hamdy, Hasan et al. 2013). The replacement cost (RC_k) is calculated for the building elements and systems that have lifespans shorter than the calculated period (30 years). Some typical building elements that need to be replaced are windows, shading elements, heat recovery unit, cooling unit, hot water heater, and the inverter of the photovoltaic system. The replacement costs are discounted, assuming the replacement will take place in the middle of the calculation period. *k* is the subscript of the replaced building element, *r* is the real interest rate, and *n* is the lifespan. A real interest rate of 3% is used (Hamdy, Hasan et al. 2013). Replacement costs are calculated using Equation 17.

$$RC_k = IC_k \times (1 + r)^{-n/2} \tag{17}$$

Since only a few of the building elements that need to be replaced are considered in this thesis, a test is performed to determine how much the replacement costs affect the accuracy of the model. The results from the test are shown in Table 58. LCC accounts for life cycle cost; IC only investigates the initial investment cost.

Table 58: Results comparing function value of computing LCC and IC

	x1	x2	x3	x4	x5	x6	x7	x8	x9	Function value	Difference IC and LCC
IC	3	4	1	4	4	6	4	1	3	-2.3811100e+05	
LCC	3	4	1	4	4	6	4	1	3	-2.3794411e+05	0.071%
IC	5	3	3	3	6	7	4	1	4	-2.1841200e+05	
LCC	5	3	3	3	6	7	4	1	4	-2.1783304e+05	0.265%
IC	2	1	6	2	8	4	2	2	2	-1.0198900e+05	
LCC	2	1	6	2	8	4	2	2	2	-1.0184586e+05	0.140%

The results show a negligible difference between the life cycle cost and the initial investment cost. Since the replacement cost makes a very small effect on the model, only the initial investment in construction costs for the objective function will be used.

APPENDIX C

The input data file (idf) from EnergyPlus outputs the heating and cooling energy as an ideal load. In order to make these values realistic, they need to be multiplied by a system coefficient of performance (COP). A review of products currently available on the market was done in order to determine ranges of COP values. The ranges can be seen in Table 59.

Table 59: Ranges of COP values studied

	Cold Room	Freezer Room	Controlled Temp Room	Split system for the offices and ambient portion of the warehouse
Low Efficiency	1.1	0.9	1.3	2
Average Efficiency	1.45	1.35	2.4	3.5
High Efficiency	1.8	1.8	3.5	5

The COP values are used in the Tunisia construction model with Tunis, Tunisia for the climate. The optimum parameters for each efficiency range can be seen in Table 60.

Table 60: Optimum Results for three COP values

COP Efficiency	Roof (mm)	External Wall (mm)	Floor (mm)	Cold Wall (mm)	Cold Floor (mm)	Freezer Floor (mm)	Air Infiltration (L/s/m²)	Roof Reflect.	Window Type
Low Efficiency	40	0	0	279	100	250	0.175	0.90	3.163 W/m²K SHGC: 0.73
Average Efficiency	40	0	0	238	100	200	0.175	0.90	3.163 W/m²K SHGC: 0.73
High Efficiency	20	0	0	187	50	200	0.175	0.90	6.172 W/m²K SHGC: 0.83

The COPs of the systems have an impact on the external wall insulation thickness, cold room wall insulation thickness, cold room floor insulation thickness, freezer room floor insulation thickness, and window type. Since the efficiencies have an impact on many parameters, they are added to the optimization. However, cost data can only be found for the split system for the offices and ambient areas of the warehouse. So, an average efficient is used for the other rooms with the understanding on how the COP of these rooms does affect the building.

APPENDIX D

This appendix contains the tests performed to determine the optimum parameters for the Genetic Algorithm (GA). These tests were performed using the US construction parameters. Throughout the tests, the number of variables considered is increased. The GA needs to handle nine variables in order to investigate all the chosen parameters. Initially a three variable test was done to prove that the genetic algorithm code works. After proving that the code was successful, six variables and nine variables testing were completed. The goal of these tests was to reduce computing power while still converging to the correct optimum.

Initially, results were obtained using an exhaustive search method for three variables. The three variables were external wall insulation thickness, roof insulation thickness, and cold storage wall insulation thickness. The exhaustive search was used as a base of comparison for the genetic algorithm. The exhaustive search took 21,171 seconds (80 simulations) to reach the optimum point with a function value of -6.9975e+03.

The goal of the three variable tests was to significantly reduce computational time as compared to the exhaustive search method by reducing the necessary simulations while still finding the true optimum result. The built-in GA in Matlab was selected for this thesis. The GA is designed for continuous variables. For this first test, the GA is not modified and is tested using continuous variables. This test was performed to prove that the simulation-optimization approach would work and that the GA could converge to a result close to the optimum found by using discrete variables in exhaustive search. The results can be seen in Table 61.

Table 61: Results from varying population size and generations for continuous variable GA

Test Number	Population Size	Generations	Time(seconds)	Function Value
1	20	1	13051.644	-5.6810e+03
2	5	4	7676.895	1.8570e+03
3	5	7	13883.703	-163.0147
4	5	10	16922.932	-5.0944e+03
5	10	10		-5.7047e+03

These results show the importance of finding the correct ratio between the population size and generations. When the population size is too small, the result is a local minimum. This can be seen in Tests 2 and 3. When the generation size is too small, the algorithm does not have enough time to search the design space. However, increasing the population size too much will make it very time consuming to find the optimum result and therefore not meet the objective of reducing computational time. The best result, in terms of computation time and convergence, was found in Test 5, where the population size was 10 and the number of generations was 10.

The genetic algorithm was then modified the code to handle discrete variables instead of continuous ones. The combination of population size and number of generations was investigated. These tests looked at how much computational time is used and if the GA converges to the true optimal solution. The results from the tests can be seen in Table 62.

Table 62: Results from varying the population size and generations in discrete variable GA

Test Number	Population Size	Generations	Time (seconds)	Function Value
1	5	4	7092.352	-1.5395e+03
2	5	7	12486.867	-6.9975e+03
3	3	7	7295.948	-4.4543e+03
4	5	6	10828.036	-6.6011e+03
5	4	7	9773.093	-2.6646e+03

The exhaustive search that was initially performed with discrete values determined that the optimum function value was -6.9975e+03. Test 2 was the only test that successfully found this optimum. This test found the optimum by using 40 simulations compared to the 80 simulations of the exhaustive search. Test 3 came close to finding the optimal. Tests 2 and 4 had the same population size and the only difference was the number of generations. Tests 3 and 4 show how much of an impact the population size had on the results. Neither of the values was close to the true optimal, but instead converged to local minima. These tests show the importance of having a population size that is large enough and allowing the genetic algorithm a sufficient number of generations. After it was found that the genetic algorithm could successfully find the optimum point, the genetic algorithm was modified to vary six variables.

Next the six variable tests were conducted. These variables are the floor insulation for the ambient storage, floor insulation for the cold room, and floor insulation for the freezer room. The effect of population size of the optimal result was investigated. Table 63 shows the results from the tests.

Table 63: Effect of population size on optimum point for six variable tests

Population Size	Function Value
5	-2.4699210e+05
5	-2.4307855e+05
10	-2.5294030e+05
15	-2.5451652e+05
20	-2.5451652e+05

The results show that when six parameters are investigated, a population size of five would no longer works for the problem. When the same optimization was run two different times, it converged to different optima. The problem is that the GA converged too quickly. Therefore, the population size of the genetic algorithm was increased. The results showed a population size of 15 and 20 converging to the same point. For the three variable tests, a population of five was needed in order to assure convergence. When six variables were used with the same population size, the optimization converged too quickly and did not reach the optimum. The results from this test show that for six variables, a population size of 15 is needed. This shows an important relationship between variables and population. In order for the variables to have be able to properly search the design space the population size needs to be at least twice the variable size. However, making the population size too large will increase the computational time. These results show the importance of finding the right population size in order to prevent the optimization from getting stuck at a local minimum.

This thesis will investigate nine parameters. These parameters include the roof insulation thickness, the exterior wall insulation thickness, the floor insulation thickness, the cold storage insulation thickness, the cold room floor insulation thickness, the freeze room floor insulation thickness, the roof reflectivity, the air infiltration rate, and the roof reflectivity. Based on the six variables, it was decided to use a population size of 15. This test investigated the effect of the elite count and crossover fraction on the results. The elite count is the number of elite children that automatically survive to the next generation. Elite children are the individuals in the current generation with the best fitness values. The defualt value for elite children is determined by using the equation 0.05*min(max(10*nvars,40),100) are discrete problems and is 2 for continuous problems. If the default equation is used, then when nine variables are varied in the GA, there would be four elite clidren. The crossover fraction is the fraction of individuals in the next generation, other than elite children, that are created by crossover. The default for the crossover fraction is 0.8. With these parameters for a population of 15, in each generation there will be four elite children, eight crossover children, and three mutation children. The results from varying these two parameters can be seen in Table 64.

Table 64: Results from varying elite count and crossover fraction

Elite Count	Crossover Fraction	Number of Generation till converged	Function Value
4	0.8	18	2.7256200e+05
2	0.6	28	2.7473500e+05
2	0.8	29	2.7615600e+05

Table 64 shows that by using the default values for the elite count and crossover fraction, the problem converged too quickly. This test had four elite children and had a population size of 15.

As a result, the GA has 11 generations to create new children, which was not enough for the GA to truly explore the design space, so it converged too quickly. The optimization used for these tests has its maximum number of generations set to 35. This limited number of generations did not give the second test enough time to converge. This is due to the low elite count and crossover fraction. The low values resulted in six mutation children. Mutation children slow down the convergence but do help the problem to move the solution from a local minimum. In this situation, the mutation children population was too large. With an elite count of two and a crossover fraction of 0.8, the results seemed to converge at a reasonable speed. It was decided to have a small elite count of approximately 15% of the generation size. However, when looking at the result it was decided that the function values were too varied, and that the population needed to be increased again. Table 65 shows the results from increasing the population.

Table 65: Results from increasing population size on nine variable test

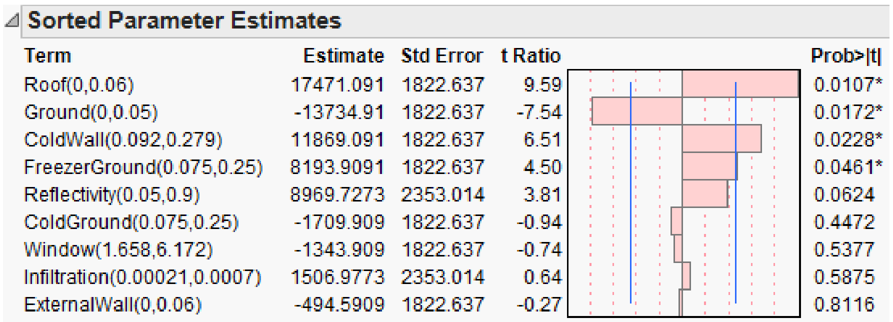
Population	Number of Generation till converged	Function Value
15	12	2.7557957e+05
20	23	2.7615600e+05
25	22	2.7615600e+05

In the end, it was decided that nine variables would be used for this thesis. To be safe, a population of 25 was used to make sure that the simulation does not converge too quickly and that it converges to the global optimum. The GA was set to have a maximum of 30 generations to make sure the optimal result is found and that excessive computational time is avoided. Since it was decided to have an elite count equal to approximately 15% of the generation size, the elite count was three. The crossover fraction was 0.8 in order to prevent the problem from converging too slowly.

APPENDIX E

This appendix shows the tests that were performed in order to find the DOE techniques that would be used in this thesis.

Based on a previous study reviewed, it was decided to investigate the D-Optimal method first (Plessis, Filfli et al. 2011). Using the ranges for the Tunisia construction, a D-Optimal test was conducted. The results from twelve runs can be seen in Figure 62.

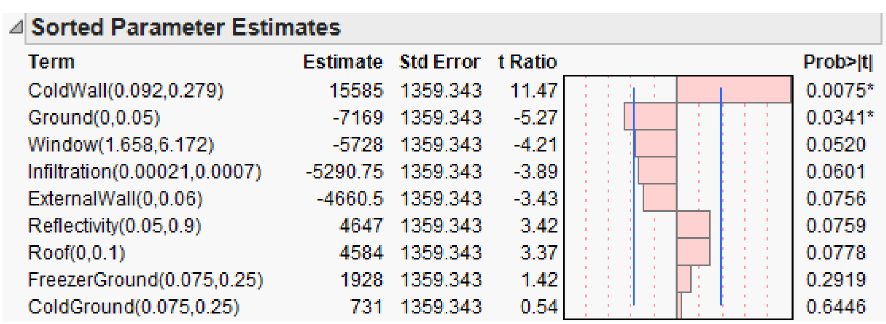


Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Roof(0,0.06)	17471.091	1822.637	9.59	0.0107*
Ground(0,0.05)	-13734.91	1822.637	-7.54	0.0172*
ColdWall(0.092,0.279)	11869.091	1822.637	6.51	0.0228*
FreezerGround(0.075,0.25)	8193.9091	1822.637	4.50	0.0461*
Reflectivity(0.05,0.9)	8969.7273	2353.014	3.81	0.0624
ColdGround(0.075,0.25)	-1709.909	1822.637	-0.94	0.4472
Window(1.658,6.172)	-1343.909	1822.637	-0.74	0.5377
Infiltration(0.00021,0.0007)	1506.9773	2353.014	0.64	0.5875
ExternalWall(0,0.06)	-494.5909	1822.637	-0.27	0.8116

Figure 62: Results from D-Optimal Test Run 1

During these tests, the roof insulation thickness was found to be the most important parameter. The range of the roof insulation thickness was changed from 0-0.06 m to 0-0.1 m to see how this affected the solutions. These results from this test can be seen in Figure 63.



Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
ColdWall(0.092,0.279)	15585	1359.343	11.47	0.0075*
Ground(0,0.05)	-7169	1359.343	-5.27	0.0341*
Window(1.658,6.172)	-5728	1359.343	-4.21	0.0520
Infiltration(0.00021,0.0007)	-5290.75	1359.343	-3.89	0.0601
ExternalWall(0,0.06)	-4660.5	1359.343	-3.43	0.0756
Reflectivity(0.05,0.9)	4647	1359.343	3.42	0.0759
Roof(0,0.1)	4584	1359.343	3.37	0.0778
FreezerGround(0.075,0.25)	1928	1359.343	1.42	0.2919
ColdGround(0.075,0.25)	731	1359.343	0.54	0.6446

Figure 63: Results fomr D-Optimal Test Run 2

The change of the importance of the roof insulation thickness was significant. The accuracy of the D-Optimal test then was investigated. Using the exact same ranges, two tests were performed. The results can be seen in Figure 64 and Figure 65.

Sorted Parameter Estimates

Term		Estimate	Relative Std Error	Pseudo t-Ratio	Pseudo p-Value
Ground(0,0.05)		-12728.37	0.306186	-25.20	<.0001*
ColdWall(0.092,0.279)		11300.625	0.306186	22.37	<.0001*
ExternalWall(0,0.06)		-5898	0.288675	-12.38	0.0002*
Reflectivity(0.05,0.9)		6072	0.322749	11.40	0.0003*
Roof(0,0.06)	Biased	13594.563	6.186245	1.33	0.2537
ColdGround(0.075,0.25)	Biased	-3562.312	2.08219	-1.04	0.3583
Infiltration(0.00021,0.0007)	Biased	54660.436	49.3433	0.67	0.5387
Infiltration*Infiltration*Infiltration	Biased	-58797.19	53.45563	-0.67	0.5415
FreezerGround(0.075,0.25)	Biased	-4043	4.130473	-0.59	0.5849
WindowU(1.658,6.172)	Biased	3496.1248	4.103908	0.52	0.6328
Infiltration*Infiltration	Biased	-4408.924	5.492674	-0.49	0.6521
WindowU*WindowU	Zeroed	0	0	.	.

Figure 64: Results from D-Optimal Test Run 3

Sorted Parameter Estimates

Term		Estimate	Relative Std Error	Pseudo t-Ratio	Pseudo p-Value
Roof(0,0.06)		17643.25	0.306186	2.94	0.0422*
ColdWall(0.092,0.279)		10963.125	0.330719	1.69	0.1655
Ground(0,0.05)		-8425.25	0.306186	-1.41	0.2324
Reflectivity(0.05,0.9)		5790.75	0.306186	0.97	0.3885
Infiltration(0.00021,0.0007)	Biased	-5487.625	0.330719	-0.85	0.4442
WindowU*WindowU		-8929.379	0.680609	-0.67	0.5393
FreezerGround(0.075,0.25)		3971.75	0.306186	0.66	0.5437
ExternalWall(0,0.06)		-2832.375	0.306186	-0.47	0.6610
ColdGround(0.075,0.25)		-2240.875	0.306186	-0.37	0.7274
Infiltration*Infiltration	Biased	6744.92	0.950018	0.36	0.7351
WindowU(1.658,6.172)		1415.75	0.353553	0.20	0.8479
Infiltration*Infiltration*Infiltration	Zeroed	0	0	.	.

Figure 65: Results from D-Optimal Test Run 4

The results from these two runs came out different even though they had the same initial ranges and nothing was changed in the model. Therefore, it was concluded that D-Optimal could not be used for this problems. Next, a full factorial DOE was investigated.

A full factorial DOE was performed on the ranges for the Tunisia construction in the Tunisia climate. The results can be seen in Figure 66.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Roof(0,0.06)	15641.102	87.92121	177.90	<.0001*
ColdWall(0.092,0.279)	14879.531	87.92121	169.24	<.0001*
Ground(0,0.05)	-8857.672	87.92121	-100.7	<.0001*
Roof*Reflectivity	-5203.125	87.92121	-59.18	<.0001*
Reflectivity(0.05,0.9)	4816.9219	87.92121	54.79	<.0001*
Infiltration(0.00021,0.0007)	-3105.789	87.92121	-35.32	<.0001*
Roof*Ground	2678.9063	87.92121	30.47	<.0001*
ExternalWall(0,0.06)	-2619.68	87.92121	-29.80	<.0001*
Ground*Reflectivity	2068.9453	87.92121	23.53	<.0001*
Roof*ExternalWall	1450.1953	87.92121	16.49	<.0001*
FreezerGround(0.1,0.25)	1244.3062	87.92121	14.15	<.0001*
ColdWall*Reflectivity	1031.8359	87.92121	11.74	<.0001*
ColdWall*ColdGround	1005.4687	87.92121	11.44	<.0001*
ColdGround(0.1,0.25)	-996.6266	87.92121	-11.34	<.0001*
ExternalWall*Reflectivity	931.64062	87.92121	10.60	<.0001*
ColdWall*FreezerGround	697.85156	87.92121	7.94	<.0001*
Infiltration*Reflectivity	-671.4844	87.92121	-7.64	<.0001*
Reflectivity*WindowU	370.89844	87.92121	4.22	<.0001*
Roof*Infiltration	370.89844	87.92121	4.22	<.0001*
WindowU(1.658,6.172)	-257.6875	87.92121	-2.93	0.0035*
Ground*Infiltration	225	87.92121	2.56	0.0108*
Ground*ColdWall	-212.6953	87.92121	-2.42	0.0159*
ColdWall*Infiltration	193.35938	87.92121	2.20	0.0284*
Roof*WindowU	-189.8437	87.92121	-2.16	0.0313*
ColdGround*FreezerGround	-186.3281	87.92121	-2.12	0.0346*
FreezerGround*Reflectivity	-166.9922	87.92121	-1.90	0.0581
ExternalWall*WindowU	-130.0781	87.92121	-1.48	0.1397
ExternalWall*Ground	91.40625	87.92121	1.04	0.2990
Infiltration*WindowU	77.34375	87.92121	0.88	0.3795
ColdWall*WindowU	-68.55469	87.92121	-0.78	0.4359
ColdGround*Reflectivity	56.25	87.92121	0.64	0.5226
Roof*ColdWall	52.734375	87.92121	0.60	0.5489
Roof*FreezerGround	45.703125	87.92121	0.52	0.6034
Roof*ColdGround	36.914062	87.92121	0.42	0.6748
FreezerGround*Infiltration	-24.60938	87.92121	-0.28	0.7797
ColdGround*Infiltration	22.851563	87.92121	0.26	0.7950
Ground*WindowU	22.851562	87.92121	0.26	0.7950
FreezerGround*WindowU	19.335937	87.92121	0.22	0.8260
ExternalWall*FreezerGround	-14.0625	87.92121	-0.16	0.8730

Figure 66: Results from Full Factorial

The Full Factorial method required 512 simulations. This method is very computationally expensive and is a proven to give accurate results. The Full Factorial results show both the main effects and the interactive effects. The results from the Full Factorial will be used as a comparison for other methods. If the other methods show the same effect from the parameters as seen above, then those methods are also accurate. Other methods will be investigated in order to reduce computational time.

Based on a previous study (Chlela, Riederer et al. 2009), it was decided to investigate the Taguchi method. The Taguchi 32 and Taguchi 64 tests were conducted. The results can be seen in Figure 67 and Figure 68.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Roof[0]	-15744.81	955.6236	-16.48	<.0001*
ColdWall[0.092]	-14914.69	955.6236	-15.61	<.0001*
Ground[0]	8790.875	955.6236	9.20	<.0001*
Reflectivity[0.05]	-4750.125	955.6236	-4.97	<.0001*
ExternalWall[0]	2874.5625	955.6236	3.01	0.0040*
Infiltration[0.00021]	2422	955.6236	2.53	0.0142*
FreezerGround[0.1]	-1251.338	955.6236	-1.31	0.1959
ColdGround[0.1]	1072.2125	955.6236	1.12	0.2668
Window[1.658]	257.6875	955.6236	0.27	0.7885

Figure 67: Results from Taguchi 64

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	105978.6	799.5007	132.56	<.0001*
Roof[0]	-24538	1130.665	-21.70	<.0001*
Roof[0.02]	15064.5	1130.665	13.32	<.0001*
Roof[0.06]	9473.5	1130.665	8.38	<.0001*
ExternalWall[0]	2340.1667	1130.665	2.07	0.0531
ExternalWall[0.02]	1678.1667	1130.665	1.48	0.1550
ExternalWall[0.06]	-4018.333	1130.665	-3.55	0.0023*
Ground[0]	8944.6667	1130.665	7.91	<.0001*
Ground[0.025]	-5238.833	1130.665	-4.63	0.0002*
Ground[0.05]	-3705.833	1130.665	-3.28	0.0042*
ColdWall[0.092]	-13409	1130.665	-11.86	<.0001*
ColdWall[0.187]	1460.5	1130.665	1.29	0.2128
ColdWall[0.279]	11948.5	1130.665	10.57	<.0001*
ColdGround[0.1]	97.866667	1130.665	0.09	0.9320
ColdGround[0.2]	-3216.933	1130.665	-2.85	0.0107*
ColdGround[0.25]	3119.0667	1130.665	2.76	0.0129*
FreezerGround[0.1]	-941.9667	1130.665	-0.83	0.4157
FreezerGround[0.2]	-1434.367	1130.665	-1.27	0.2207
FreezerGround[0.25]	2376.3333	1130.665	2.10	0.0499*
Infiltration[0.00021]	1963.8633	1130.665	1.74	0.0995
Infiltration[0.00049]	2303.7733	1130.665	2.04	0.0566
Infiltration[0.0007]	-4267.637	1130.665	-3.77	0.0014*
Reflectivity[0.05]	-3372	799.5007	-4.22	0.0005*
Reflectivity[0.9]	3372	799.5007	4.22	0.0005*
WindowU[1.658]	1169.7	1130.665	1.03	0.3146
WindowU[4.27]	1466.6	1130.665	1.30	0.2110
WindowU[6.172]	-2636.3	1130.665	-2.33	0.0315*

Figure 68: Results from Taguchi 32

The Taguchi 64 results matched the results of the full factorial DOE. Based on this fact, it was decided that the Taguchi 64 method would be used to investigate main effects and that, if interactive effects were required, then the full factorial DOE would be used.

APPENDIX F

This appendix contains the DOE results for the US construction case from analysis performed in Section 4.4.1. These results are used in order to investigate the interactive effects between parameters. The DOE Results for Kenya can be seen in Figure 69 and Figure 70.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Infiltration[0.5]	-9128.906	930.205	-9.81	<.0001*
Reflectivity[0.05]	-7462.781	930.205	-8.02	<.0001*
Cold Wall Insulation[0.092]	-6369.656	930.205	-6.85	<.0001*
External Wall Insulation[0]	3118.9687	930.205	3.35	0.0015*
Window U-Value[1.6]	-2179.156	930.205	-2.34	0.0229*
Freezer Storage Ground[0.075]	-927.2188	930.205	-1.00	0.3233
Roof Insulation[0]	-591.8437	930.205	-0.64	0.5273
COP[2.6]	-404.2188	930.205	-0.43	0.6656
Cold Storage Ground[0.075]	391.65625	930.205	0.42	0.6754

Figure 69: Main Effects from US Construction for Kenya

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Infiltration[4]	9179.0039	47.1318	194.75	<.0001*
Reflectivity[0.05]	-7465.418	47.1318	-158.4	<.0001*
Cold Storage Insulation[0.092]	-6370.535	47.1318	-135.2	<.0001*
Roof Insulation[0]*Reflectivity[0.05]	-6357.129	47.1318	-134.9	<.0001*
External Wall Insulation[0]	3081.1758	47.1318	65.37	<.0001*
Window U-Value[5.1]	2176.5195	47.1318	46.18	<.0001*
Roof Insulation[0]*Cold Storage Insulation[0.092]	-934.2773	47.1318	-19.82	<.0001*
Freezer Room Ground Insulation[0.075]	-905.2461	47.1318	-19.21	<.0001*
Cold Storage Insulation[0.092]*Reflectivity[0.05]	-816.5039	47.1318	-17.32	<.0001*
COP[2.6]*Reflectivity[0.05]	-740.918	47.1318	-15.72	<.0001*
Roof Insulation[0]*Infiltration[4]	726.85547	47.1318	15.42	<.0001*
Roof Insulation[0]*External Wall Insulation[0]	653.02734	47.1318	13.86	<.0001*
Cold Storage Insulation[0.092]*Infiltration[4]	-602.0508	47.1318	-12.77	<.0001*
Roof Insulation[0]	-596.2383	47.1318	-12.65	<.0001*
Roof Insulation[0]*COP[2.6]	-521.1914	47.1318	-11.06	<.0001*
COP[2.6]*Infiltration[4]	-484.2773	47.1318	-10.27	<.0001*
External Wall Insulation[0]*Reflectivity[0.05]	457.91016	47.1318	9.72	<.0001*
COP[2.6]	-392.793	47.1318	-8.33	<.0001*
Cold Room Ground Insulation[0.075]	387.26172	47.1318	8.22	<.0001*
External Wall Insulation[0]*Infiltration[4]	348.92578	47.1318	7.40	<.0001*
Infiltration[4]*Reflectivity[0.05]	250.48828	47.1318	5.31	<.0001*
External Wall Insulation[0]*Cold Storage Insulation[0.092]	-211.8164	47.1318	-4.49	<.0001*
Cold Storage Insulation[0.092]*Cold Room Ground Insulation[0.075]	183.69141	47.1318	3.90	0.0001*
Roof Insulation[0]*Window U-Value[5.1]	164.35547	47.1318	3.49	0.0005*
Reflectivity[0.05]*Window U-Value[5.1]	155.56641	47.1318	3.30	0.0010*
COP[2.6]*Window U-Value[5.1]	-139.7461	47.1318	-2.97	0.0032*
External Wall Insulation[0]*Window U-Value[5.1]	53.613281	47.1318	1.14	0.2559

Figure 70: Top Interactive Effects from US Construction for Kenya

The DOE Results for Argentina can be seen in Figure 71 and Figure 72.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Infiltration[0.5]	31870.312	1353.051	23.55	<.0001*
Roof Insulation[0]	-12973.87	1353.051	-9.59	<.0001*
COP[2.6]	-7681.562	1353.051	-5.68	<.0001*
Cold Wall Insulation[0.092]	-6826.687	1353.051	-5.05	<.0001*
External Wall Insulation[0]	3688.5	1353.051	2.73	0.0086*
Window U-Value[1.6]	-2847.125	1353.051	-2.10	0.0400*
Reflectivity[0.05]	2669.25	1353.051	1.97	0.0537
Freezer Storage Ground[0.075]	-1229.563	1353.051	-0.91	0.3675
Cold Storage Ground[0.075]	-234.125	1353.051	-0.17	0.8633

Figure 71: Main Effects from US Construction for Argentina

Term	Estimate	Std Error	t Ratio	Prob>|t|
Infiltration[4]	-31771.87	89.92707	-353.3	<.0001*
Roof Insulation[0]	-12975.63	89.92707	-144.3	<.0001*
COP[2.6]	-7648.164	89.92707	-85.05	<.0001*
COP[2.6]*Infiltration[4]	-6934.57	89.92707	-77.11	<.0001*
Cold Storage Insulation[0.092]	-6828.445	89.92707	-75.93	<.0001*
Roof Insulation[0]*Infiltration[4]	-4656.445	89.92707	-51.78	<.0001*
External Wall Insulation[0]	3834.3984	89.92707	42.64	<.0001*
Window U-Value[5.1]	2869.9766	89.92707	31.91	<.0001*
Roof Insulation[0]*COP[2.6]	-2738.672	89.92707	-30.45	<.0001*
Reflectivity[0.05]	2729.0156	89.92707	30.35	<.0001*
Infiltration[4]*Reflectivity[0.05]	2566.4062	89.92707	28.54	<.0001*
Roof Insulation[0]*Reflectivity[0.05]	1868.5547	89.92707	20.78	<.0001*
Freezer Room Ground Insulation[0.075]	-1241.867	89.92707	-13.81	<.0001*
Roof Insulation[0]*External Wall Insulation[0]	907.03125	89.92707	10.09	<.0001*
Cold Storage Insulation[0.092]*Reflectivity[0.05]	-775.1953	89.92707	-8.62	<.0001*
COP[2.6]*Reflectivity[0.05]	725.97656	89.92707	8.07	<.0001*
Cold Storage Insulation[0.092]*Infiltration[4]	-490.4297	89.92707	-5.45	<.0001*
External Wall Insulation[0]*Reflectivity[0.05]	430.66406	89.92707	4.79	<.0001*
Cold Room Ground Insulation[0.075]	-248.1875	89.92707	-2.76	0.0060*
Roof Insulation[0]*Cold Storage Insulation[0.092]	-210.9375	89.92707	-2.35	0.0194*
Cold Storage Insulation[0.092]*Cold Room Ground Insulation[0.075]	181.05469	89.92707	2.01	0.0447*
COP[2.6]*Cold Storage Insulation[0.092]	-123.0469	89.92707	-1.37	0.1719

Figure 72: Top Interactive Effects from US Construction for Argentina

The DOE Results for Thailand can be seen in Figure 73 and Figure 74.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Reflectivity[0.05]	-17109.66	2263.509	-7.56	<.0001*
Roof Insulation[0]	-9423.094	2263.509	-4.16	0.0001*
Cold Wall Insulation[0.092]	-8493.094	2263.509	-3.75	0.0004*
External Wall Insulation[0]	3920.5312	2263.509	1.73	0.0890
COP[2.6]	-3230.781	2263.509	-1.43	0.1592
Window U-Value[1.6]	-2080.719	2263.509	-0.92	0.3621
Infiltration[0.5]	-1352.344	2263.509	-0.60	0.5527
Freezer Storage Ground[0.075]	-1011.594	2263.509	-0.45	0.6567
Cold Storage Ground[0.075]	138.53125	2263.509	0.06	0.9514

Figure 73: Main Effects from US Construction for Thailand

Term	Estimate	Std Error	t Ratio	Prob>|t|
Reflectivity[0.05]	-17076.26	161.9198	-105.5	<.0001*
Roof Insulation[0]*Reflectivity[0.05]	-15143.55	161.9198	-93.53	<.0001*
Roof Insulation[0]	-9421.336	161.9198	-58.19	<.0001*
Cold Storage Insulation[0.092]	-8496.609	161.9198	-52.47	<.0001*
External Wall Insulation[0]	3549.6328	161.9198	21.92	<.0001*
COP[2.6]	-3039.18	161.9198	-18.77	<.0001*
Infiltration[4]*Reflectivity[0.05]	-2105.859	161.9198	-13.01	<.0001*
Window U-Value[5.1]	2091.2656	161.9198	12.92	<.0001*
COP[2.6]*Reflectivity[0.05]	-2068.945	161.9198	-12.78	<.0001*
Roof Insulation[0]*COP[2.6]	-1822.852	161.9198	-11.26	<.0001*
Roof Insulation[0]*External Wall Insulation[0]	1738.4766	161.9198	10.74	<.0001*
Infiltration[4]	1563.2813	161.9198	9.65	<.0001*
External Wall Insulation[0]*Reflectivity[0.05]	1499.4141	161.9198	9.26	<.0001*
Roof Insulation[0]*Infiltration[4]	-1490.625	161.9198	-9.21	<.0001*
COP[2.6]*Infiltration[4]	-1420.313	161.9198	-8.77	<.0001*
Freezer Room Ground Insulation[0.075]	-1020.383	161.9198	-6.30	<.0001*
Cold Storage Insulation[0.092]*Infiltration[4]	-799.8047	161.9198	-4.94	<.0001*
Roof Insulation[0]*Cold Storage Insulation[0.092]	-632.8125	161.9198	-3.91	0.0001*
External Wall Insulation[0]*Infiltration[4]	558.98437	161.9198	3.45	0.0006*
Cold Storage Insulation[0.092]*Reflectivity[0.05]	-478.125	161.9198	-2.95	0.0033*
External Wall Insulation[0]*Cold Storage Insulation[0.092]	-281.25	161.9198	-1.74	0.0831

Figure 74: Top Interactive Effects from US Construction for Thailand

The DOE Results for Paraguay can be seen in Figure 75 and Figure 76.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Reflectivity[0.05]	-9319.031	1321.708	-7.05	<.0001*
Cold Wall Insulation[0.092]	-7705.594	1321.708	-5.83	<.0001*
Roof Insulation[0]	-5063.719	1321.708	-3.83	0.0003*
Infiltration[0.5]	-4164.844	1321.708	-3.15	0.0027*
External Wall Insulation[0]	4131.4688	1321.708	3.13	0.0029*
Window U-Value[1.6]	-2249.469	1321.708	-1.70	0.0945
COP[2.6]	-1515.156	1321.708	-1.15	0.2567
Freezer Storage Ground[0.075]	-1124.094	1321.708	-0.85	0.3988
Cold Storage Ground[0.075]	-16.15625	1321.708	-0.01	0.9903

Figure 75: Main Effects from US Construction for Paraguay

Term	Estimate	Std Error	t Ratio	Prob>|t|
Reflectivity[0.05]	-9267.176	72.44428	-127.9	<.0001*
Roof Insulation[0]*Reflectivity[0.05]	-8663.379	72.44428	-119.6	<.0001*
Cold Storage Insulation[0.092]	-7725.809	72.44428	-106.6	<.0001*
Roof Insulation[0]	-5066.355	72.44428	-69.93	<.0001*
Infiltration[4]	4283.4961	72.44428	59.13	<.0001*
External Wall Insulation[0]	4021.6055	72.44428	55.51	<.0001*
Window U-Value[5.1]	2253.8633	72.44428	31.11	<.0001*
Roof Insulation[0]*Infiltration[4]	-1642.676	72.44428	-22.68	<.0001*
COP[2.6]	-1405.293	72.44428	-19.40	<.0001*
Roof Insulation[0]*COP[2.6]	-1342.09	72.44428	-18.53	<.0001*
COP[2.6]*Infiltration[4]	-1329.785	72.44428	-18.36	<.0001*
Roof Insulation[0]*External Wall Insulation[0]	1261.2305	72.44428	17.41	<.0001*
Freezer Room Ground Insulation[0.075]	-1135.52	72.44428	-15.67	<.0001*
External Wall Insulation[0]*Reflectivity[0.05]	1023.9258	72.44428	14.13	<.0001*
COP[2.6]*Reflectivity[0.05]	-1009.863	72.44428	-13.94	<.0001*
Cold Storage Insulation[0.092]*Reflectivity[0.05]	-763.7695	72.44428	-10.54	<.0001*
Cold Storage Insulation[0.092]*Infiltration[4]	-528.2227	72.44428	-7.29	<.0001*
Roof Insulation[0]*Cold Storage Insulation[0.092]	-522.9492	72.44428	-7.22	<.0001*
External Wall Insulation[0]*Infiltration[4]	486.03516	72.44428	6.71	<.0001*
External Wall Insulation[0]*Cold Storage Insulation[0.092]	-194.2383	72.44428	-2.68	0.0076*
Cold Storage Insulation[0.092]*Cold Room Ground Insulation[0.075]	192.48047	72.44428	2.66	0.0082*
External Wall Insulation[0]*COP[2.6]	146.77734	72.44428	2.03	0.0433*
COP[2.6]*Window U-Value[5.1]	-115.1367	72.44428	-1.59	0.1127

Figure 76: Top Interactive Effects from US Construction for Paraguay

APPENDIX G

This appendix contains the DOE results for the Tunisian construction case from analysis performed in Section 4.4.2. These results are used in order to investigate the interactive effects between parameters. The DOE Results for Kenya can be seen in Figure 77 and Figure 78.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Reflectivity[0.05]	-8461.219	981.1433	-8.62	<.0001*
Cold Wall Insulation[0.092]	-5764.969	981.1433	-5.88	<.0001*
External Wall Insulation[0]	967.40625	981.1433	0.99	0.3285
Infiltration[0.000175]	959.15625	981.1433	0.98	0.3326
Freezer Storage Ground[0.075]	-870.9688	981.1433	-0.89	0.3786
Cold Storage Ground[0.075]	405.71875	981.1433	0.41	0.6809
Roof Insulation[0]	371.09375	981.1433	0.38	0.7067
Window U-Value[1.658]	335.53125	981.1433	0.34	0.7337
COP[2.6]	-94.84375	981.1433	-0.10	0.9233

Figure 77: Main Effects from Tunisian Construction for Kenya

Term	Estimate	Std Error	t Ratio	Prob>|t|
Reflectivity[0.05]	-8436.609	49.8638	-169.2	<.0001*
Roof Insulation[0]*Reflectivity[0.05]	-6699.023	49.8638	-134.3	<.0001*
Cold Storage Insulation[0.092]	-5754.422	49.8638	-115.4	<.0001*
Roof Insulation[0]*External Wall Insulation[0]	1219.9219	49.8638	24.47	<.0001*
Roof Insulation[0]*Cold Storage Insulation[0.092]	-1074.023	49.8638	-21.54	<.0001*
Cold Storage Insulation[0.092]*Reflectivity[0.05]	-950.9766	49.8638	-19.07	<.0001*
External Wall Insulation[0]	923.46094	49.8638	18.52	<.0001*
Infiltration[0.0007]	-895.875	49.8638	-17.97	<.0001*
Freezer Room Ground[0.075]	-885.0313	49.8638	-17.75	<.0001*
External Wall Insulation[0]*Reflectivity[0.05]	829.6875	49.8638	16.64	<.0001*
COP[2.6]*Reflectivity[0.05]	-696.0937	49.8638	-13.96	<.0001*
External Wall Insulation[0]*Cold Storage Insulation[0.092]	-608.2031	49.8638	-12.20	<.0001*
Roof Insulation[0]*COP[2.6]	-464.0625	49.8638	-9.31	<.0001*
Cold Room Ground[0.075]	428.57031	49.8638	8.59	<.0001*
Infiltration[0.0007]*Reflectivity[0.05]	420.11719	49.8638	8.43	<.0001*
Roof Insulation[0]*Infiltration[0.0007]	391.99219	49.8638	7.86	<.0001*
Roof Insulation[0]	388.67188	49.8638	7.79	<.0001*
Window U Value[6.172]	-298.6172	49.8638	-5.99	<.0001*
Cold Storage Insulation[0.092]*Infiltration[0.0007]	-251.3672	49.8638	-5.04	<.0001*
Roof Insulation[0]*Window U Value[6.172]	182.8125	49.8638	3.67	0.0003*
External Wall Insulation[0]*Window U Value[6.172]	163.47656	49.8638	3.28	0.0011*
Cold Storage Insulation[0.092]*Cold Room Ground[0.075]	151.17188	49.8638	3.03	0.0026*
Reflectivity[0.05]*Window U Value[6.172]	151.17188	49.8638	3.03	0.0026*
COP[2.6]*Infiltration[0.0007]	-144.1406	49.8638	-2.89	0.0040*
COP[2.6]*Window U Value[6.172]	-135.3516	49.8638	-2.71	0.0069*
COP[2.6]	-100.1172	49.8638	-2.01	0.0452*
External Wall Insulation[0]*COP[2.6]	-89.64844	49.8638	-1.80	0.0728

Figure 78: Top Interactive Effects from Tunisia Construction for Kenya

The DOE Results for Argentina can be seen in Figure 79 and Figure 80.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Cold Wall Insulation[0.092]	-6334.5	389.0531	-16.28	<.0001*
Roof Insulation[0]	-4881.25	389.0531	-12.55	<.0001*
External Wall Insulation[0]	1776	389.0531	4.56	<.0001*
Freezer Storage Ground[0.075]	-1215.5	389.0531	-3.12	0.0029*
Reflectivity[0.05]	-1127.625	389.0531	-2.90	0.0054*
COP[2.6]	-481.5625	389.0531	-1.24	0.2212
Window U-Value[1.658]	-416.8125	389.0531	-1.07	0.2888
Cold Storage Ground[0.075]	-220.0625	389.0531	-0.57	0.5740
Infiltration[0.000175]	108.375	389.0531	0.28	0.7816

Figure 79: Main Effects from Tunisian Construction for Argentina

Term	Estimate	Std Error	t Ratio	Prob>|t|
Cold Storage Insulation[0.092]	-6331.863	41.62966	-152.1	<.0001*
Roof Insulation[0]	-4910.254	41.62966	-118.0	<.0001*
External Wall Insulation[0]	1799.7305	41.62966	43.23	<.0001*
Roof Insulation[0]*COP[2.6]	-1797.363	41.62966	-43.18	<.0001*
Freezer Room Ground[0.075]	-1225.168	41.62966	-29.43	<.0001*
Reflectivity[0.05]	-1128.504	41.62966	-27.11	<.0001*
Roof Insulation[0]*Infiltration[0.0007]	-1067.871	41.62966	-25.65	<.0001*
Cold Storage Insulation[0.092]*Reflectivity[0.05]	-876.2695	41.62966	-21.05	<.0001*
External Wall Insulation[0]*Reflectivity[0.05]	593.26172	41.62966	14.25	<.0001*
Infiltration[0.0007]*Reflectivity[0.05]	573.92578	41.62966	13.79	<.0001*
COP[2.6]	-500.0195	41.62966	-12.01	<.0001*
Window U Value[6.172]	421.20703	41.62966	10.12	<.0001*
Roof Insulation[0]*Reflectivity[0.05]	-398.1445	41.62966	-9.56	<.0001*
Roof Insulation[0]*Cold Storage Insulation[0.092]	-387.5977	41.62966	-9.31	<.0001*
Roof Insulation[0]*External Wall Insulation[0]	-380.5664	41.62966	-9.14	<.0001*
COP[2.6]*Reflectivity[0.05]	304.98047	41.62966	7.33	<.0001*
COP[2.6]*Infiltration[0.0007]	-290.918	41.62966	-6.99	<.0001*
Cold Room Ground[0.075]	-227.9727	41.62966	-5.48	<.0001*
External Wall Insulation[0]*COP[2.6]	-211.8164	41.62966	-5.09	<.0001*
Cold Storage Insulation[0.092]*Cold Room Ground[0.075]	160.83984	41.62966	3.86	0.0001*
External Wall Insulation[0]*Cold Storage Insulation[0.092]	-137.9883	41.62966	-3.31	0.0010*
Roof Insulation[0]*Window U Value[6.172]	137.98828	41.62966	3.31	0.0010*
Reflectivity[0.05]*Window U Value[6.172]	-132.7148	41.62966	-3.19	0.0015*
Cold Storage Insulation[0.092]*Infiltration[0.0007]	-125.6836	41.62966	-3.02	0.0027*
External Wall Insulation[0]*Infiltration[0.0007]	-122.168	41.62966	-2.93	0.0035*
Infiltration[0.0007]	-68.82422	41.62966	-1.65	0.0990

Figure 80: Top Interactive Effects from Tunisia Construction for Argentina

The DOE Results for Thailand can be seen in Figure 81 and Figure 82.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Reflectivity[0.05]	-15710.44	1857.294	-8.46	<.0001*
Cold Wall Insulation[0.092]	-7487.625	1857.294	-4.03	0.0002*
Roof Insulation[0]	-6456.25	1857.294	-3.48	0.0010*
Infiltration[0.000175]	3399	1857.294	1.83	0.0728
COP[2.6]	-1817.5	1857.294	-0.98	0.3322
Freezer Storage Ground[0.075]	-1004.562	1857.294	-0.54	0.5908
Window U-Value[1.658]	342.5625	1857.294	0.18	0.8544
Cold Storage Ground[0.075]	258.0625	1857.294	0.14	0.8900
External Wall Insulation[0]	-164.625	1857.294	-0.09	0.9297

Figure 81: Main Effects from Tunisian Construction for Thailand

Term	Estimate	Std Error	t Ratio	Prob>|t|
Reflectivity[0.05]	-15708.68	79.68988	-197.1	<.0001*
Roof Insulation[0]*Reflectivity[0.05]	-13088.67	79.68988	-164.2	<.0001*
Cold Storage Insulation[0.092]	-7496.414	79.68988	-94.07	<.0001*
Roof Insulation[0]	-6447.461	79.68988	-80.91	<.0001*
Infiltration[0.0007]	-3349.781	79.68988	-42.04	<.0001*
COP[2.6]	-1757.734	79.68988	-22.06	<.0001*
COP[2.6]*Reflectivity[0.05]	-1692.773	79.68988	-21.24	<.0001*
Roof Insulation[0]*External Wall Insulation[0]	1524.0234	79.68988	19.12	<.0001*
Roof Insulation[0]*COP[2.6]	-1443.164	79.68988	-18.11	<.0001*
Freezer Room Ground[0.075]	-1006.32	79.68988	-12.63	<.0001*
External Wall Insulation[0]*Reflectivity[0.05]	926.36719	79.68988	11.62	<.0001*
Roof Insulation[0]*Cold Storage Insulation[0.092]	-917.5781	79.68988	-11.51	<.0001*
External Wall Insulation[0]*Cold Storage Insulation[0.092]	-782.2266	79.68988	-9.82	<.0001*
Cold Storage Insulation[0.092]*Reflectivity[0.05]	-717.1875	79.68988	-9.00	<.0001*
Window U Value[6.172]	-358.3828	79.68988	-4.50	<.0001*
Cold Storage Insulation[0.092]*Infiltration[0.0007]	-311.1328	79.68988	-3.90	0.0001*
COP[2.6]*Infiltration[0.0007]	-302.3438	79.68988	-3.79	0.0002*
Infiltration[0.0007]*Reflectivity[0.05]	-297.0703	79.68988	-3.73	0.0002*
External Wall Insulation[0]	-252.5156	79.68988	-3.17	0.0016*
Cold Room Ground[0.075]	251.03125	79.68988	3.15	0.0017*
Roof Insulation[0]*Infiltration[0.0007]	-177.5391	79.68988	-2.23	0.0264*
Cold Storage Insulation[0.092]*Cold Room Ground[0.075]	170.50781	79.68988	2.14	0.0329*
COP[2.6]*Window U Value[6.172]	-166.9922	79.68988	-2.10	0.0367*
External Wall Insulation[0]*Window U Value[6.172]	159.96094	79.68988	2.01	0.0453*
External Wall Insulation[0]*COP[2.6]	-158.2031	79.68988	-1.99	0.0477*
External Wall Insulation[0]*Infiltration[0.0007]	144.14063	79.68988	1.81	0.0711

Figure 82: Top Interactive Effects from Tunisia Construction for Thailand

The DOE Results for Paraguay can be seen in Figure 83 and Figure 84.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Reflectivity[0.05]	-10500.28	1292.279	-8.13	<.0001*
Cold Wall Insulation[0.092]	-7100.906	1292.279	-5.49	<.0001*
Roof Insulation[0]	-1935.156	1292.279	-1.50	0.1401
External Wall Insulation[0]	1445.5312	1292.279	1.12	0.2683
Freezer Storage Ground[0.075]	-1124.094	1292.279	-0.87	0.3882
Infiltration[0.000175]	495.09375	1292.279	0.38	0.7031
COP[2.6]	-249.5313	1292.279	-0.19	0.8476
Window U-Value[1.658]	237.09375	1292.279	0.18	0.8551
Cold Storage Ground[0.075]	26.03125	1292.279	0.02	0.9840

Figure 83: Main Effects from Tunisian Construction for Paraguay

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Reflectivity[0.05]	-10487.1	58.97122	-177.8	<.0001*
Roof Insulation[0]*Reflectivity[0.05]	-9016.699	58.97122	-152.9	<.0001*
Cold Storage Insulation[0.092]	-7100.027	58.97122	-120.4	<.0001*
Roof Insulation[0]	-1962.402	58.97122	-33.28	<.0001*
External Wall Insulation[0]	1423.5586	58.97122	24.14	<.0001*
Freezer Room Ground[0.075]	-1126.73	58.97122	-19.11	<.0001*
Roof Insulation[0]*External Wall Insulation[0]	1122.3633	58.97122	19.03	<.0001*
Roof Insulation[0]*COP[2.6]	-990.5273	58.97122	-16.80	<.0001*
COP[2.6]*Reflectivity[0.05]	-974.707	58.97122	-16.53	<.0001*
External Wall Insulation[0]*Reflectivity[0.05]	965.91797	58.97122	16.38	<.0001*
Cold Storage Insulation[0.092]*Reflectivity[0.05]	-958.8867	58.97122	-16.26	<.0001*
Roof Insulation[0]*Cold Storage Insulation[0.092]	-675.8789	58.97122	-11.46	<.0001*
External Wall Insulation[0]*Cold Storage Insulation[0.092]	-522.9492	58.97122	-8.87	<.0001*
Infiltration[0.0007]	-408.082	58.97122	-6.92	<.0001*
Window U Value[6.172]	-243.2461	58.97122	-4.12	<.0001*
COP[2.6]	-232.832	58.97122	-3.95	<.0001*
Infiltration[0.0007]*Reflectivity[0.05]	217.08984	58.97122	3.68	0.0003*
Cold Storage Insulation[0.092]*Infiltration[0.0007]	-206.543	58.97122	-3.50	0.0005*
Cold Storage Insulation[0.092]*Cold Room Ground[0.075]	169.62891	58.97122	2.88	0.0042*
COP[2.6]*Infiltration[0.0007]	-152.0508	58.97122	-2.58	0.0102*
External Wall Insulation[0]*Window U Value[6.172]	137.98828	58.97122	2.34	0.0197*
Roof Insulation[0]*Window U Value[6.172]	132.71484	58.97122	2.25	0.0249*
COP[2.6]*Window U Value[6.172]	-125.6836	58.97122	-2.13	0.0336*
Cold Storage Insulation[0.092]*Freezer Room Ground[0.075]	79.980469	58.97122	1.36	0.1757

Figure 84: Top Interactive Effects from Tunisia Construction for Paraguay

APPENDIX H

This appendix contains the DOE and GA results for the Tunisian construction case from analysis performed in Section 4.5. These results are used in order to investigate the benefits of using a two-step process.

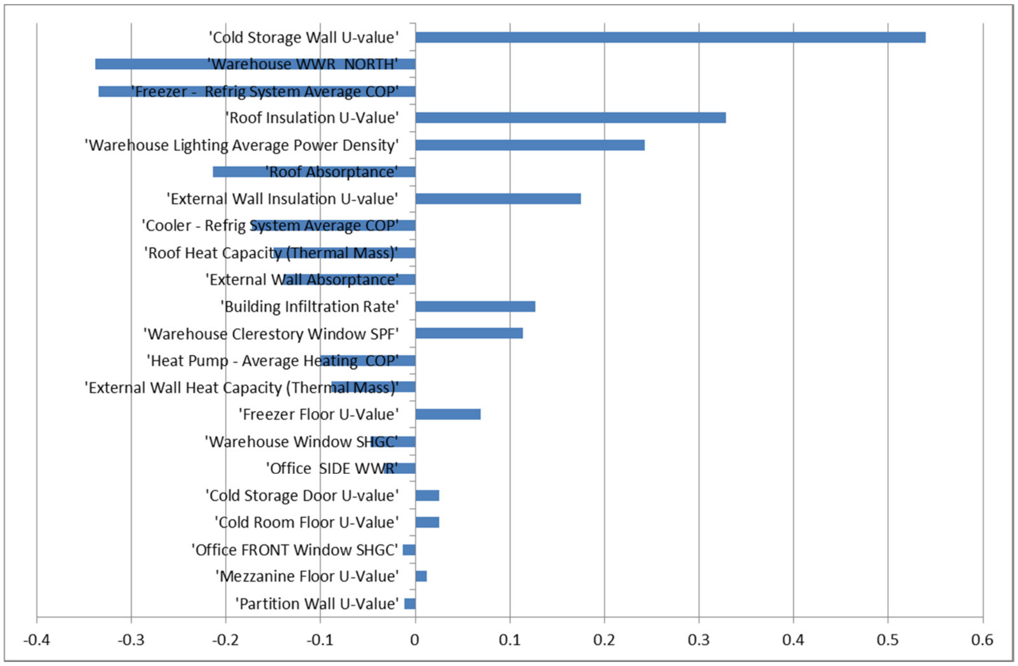


Figure 85: Main Affects from Latin Hypercube DOE for Argentina

For Argentina, the DOE gives main effects from the parameters and can be seen in Figure 85. The results from the GA can be seen in Table 66.

Table 66: Results from GA for DOE Energy Model for Argentina

Parameter	Roof	External Wall	COP	Cold Wall	Cold Floor	Freezer Floor	Air Infiltration	Roof Reflectivity	Window
Optimum Point	40 mm	40 mm	3.3	187 mm	50 mm	200 mm	0.7 L/s*m²	0.05	3.163 W/m²K SHGC: 0.73
Extra Cost (USD)	4,298	3,196	2,139	11,682	1,154	1,157	0	0	794

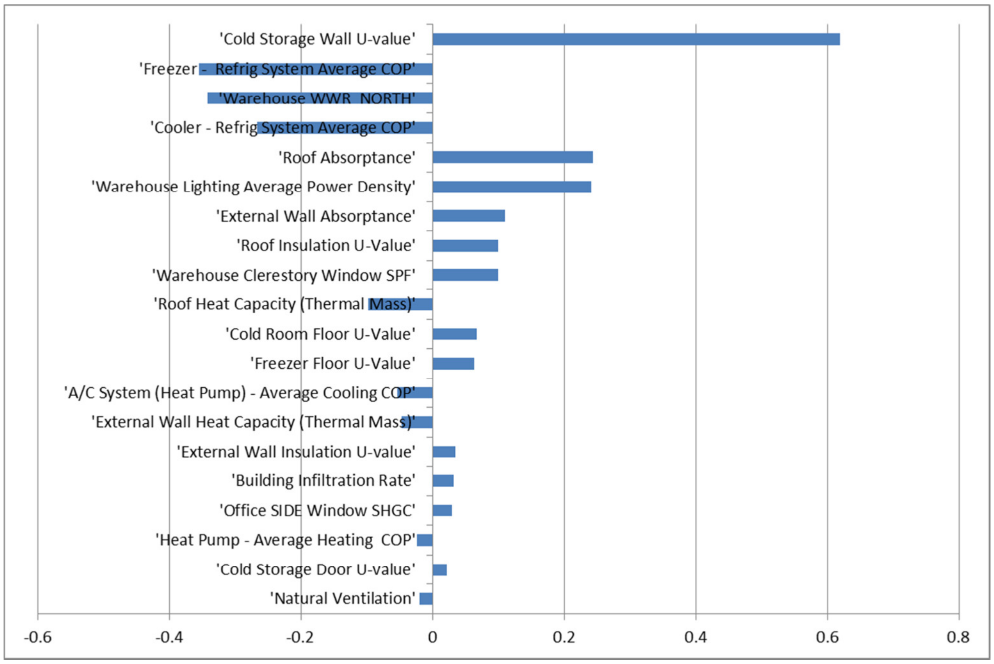


Figure 86: Main Affects from Latin Hypercube DOE for Kenya

For Kenya, the DOE gives main effects from the parameters and can be seen in Figure 86. The results from the GA can be seen in Table 67.

Table 67: Results from GA for DOE Energy Model for Kenya

Parameter	Roof	External Wall	COP	Cold Wall	Cold Floor	Freezer Floor	Air Infiltration	Roof Reflectivity	Window
Optimum Point	0 mm	0 mm	3.0	187 mm	50 mm	200 mm	0.7 L/s*m²	0.90	6.172 W/m²K SHGC: 0.68
Extra Cost (USD)	0	0	1,069	11,682	1,154	1,157	0	2,751	194

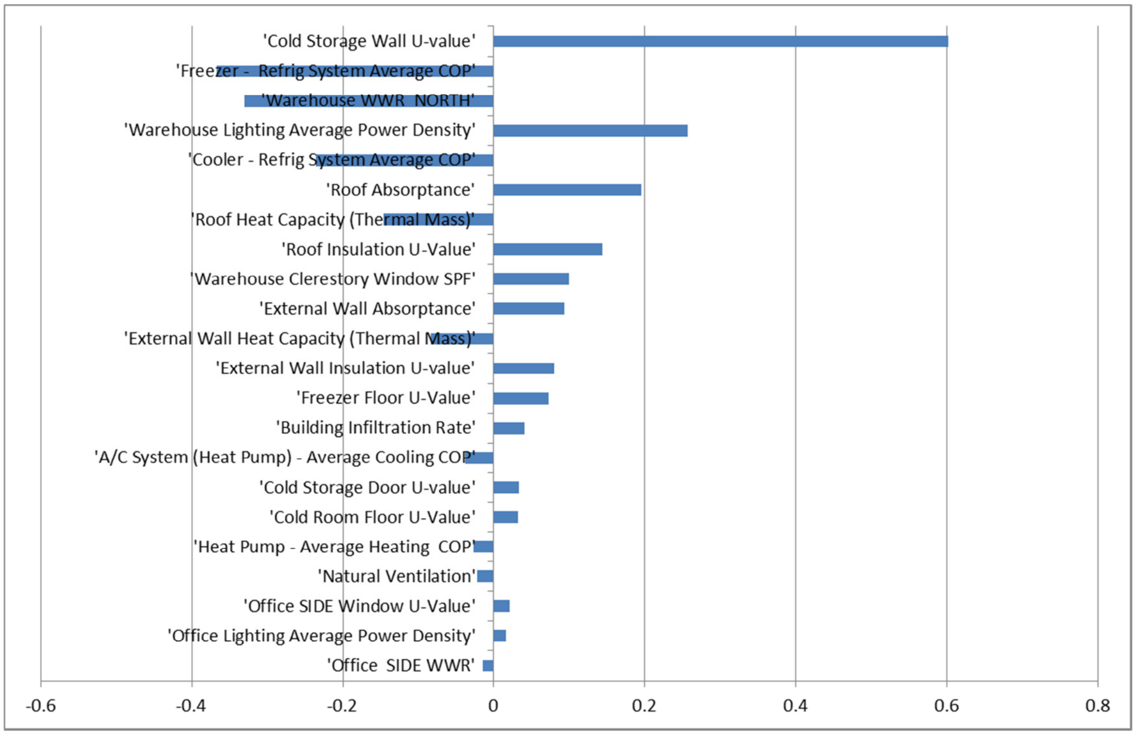


Figure 87: Main Affects from Latin Hypercube DOE for Paraguay

For Paraguay, the DOE gives main effects from the parameters and can be seen in Figure 87. The results from the GA can be seen in Table 68.

Table 68: Results from GA for DOE Energy Model for Paraguay

Parameter	Roof	External Wall	COP	Cold Wall	Cold Floor	Freezer Floor	Air Infiltration	Roof Reflectivity	Window Type
Optimum Point	20 mm	20 mm	3.0	187 mm	50 mm	200 mm	0.7 L/s*m²	0.90	3.160 W/m²K SHGC: 0.60
Extra Cost (USD)	2,391	1,936	1,069	11,682	1,154	1,157	0	2,751	1,052

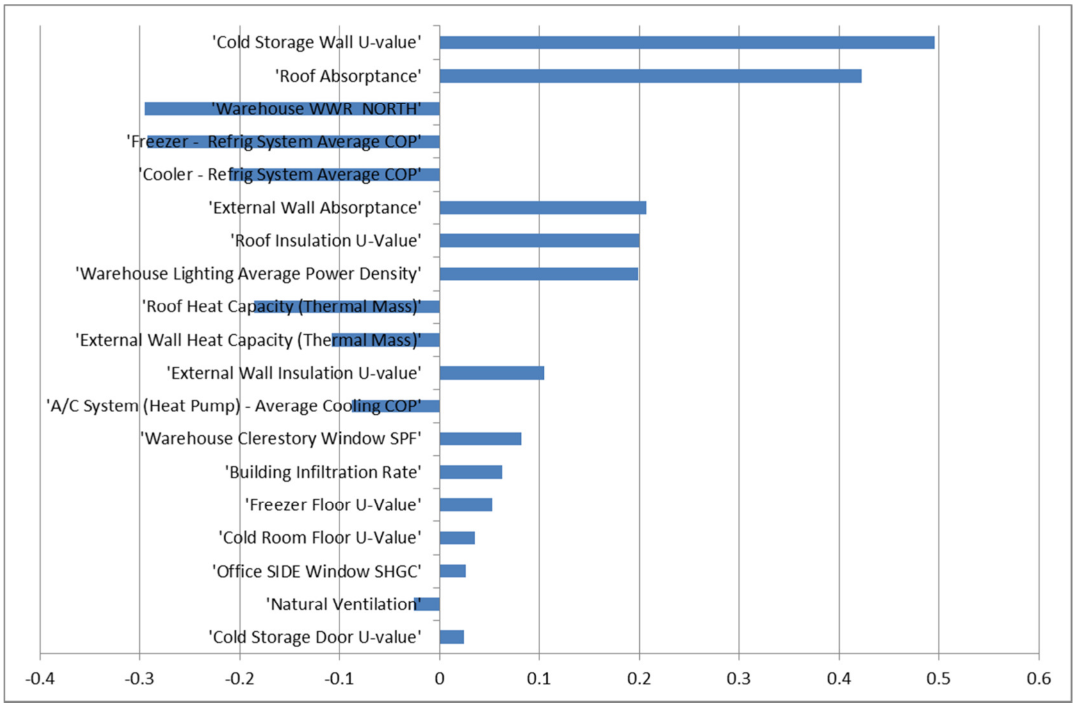


Figure 88: Main Affects from Latin Hypercube DOE for Thailand

For Thailand, the DOE gives main effects from the parameters and can be seen in Figure 88. The results from the GA can be seen in Table 69.

Table 69: Results from GA for DOE Energy Model for Thailand

Parameter	Roof	External Wall	COP	Cold Wall	Cold Floor	Freezer Floor	Air Infiltration	Roof Reflectivity	Window
Optimum Point	0 mm	20 mm	3.3	187 mm	50 mm	200 mm	0.7 L/s*m²	0.90	3.160 W/m²K SHGC: 0.60
Extra Cost (USD)	0	1,936	2,139	11,682	1,154	1,157	0	2,751	1,052

APPENDIX I

This appendix presents the framework of the code used to perform to perform the GA. Two codes will be needed in order to use the GA. First, the code to call the GA needs to be written. The options code is used to specify the number of generations, population size and the elite count. This code can be seen below:

```
ObjectiveFunction=@simple_fitness;
nvars=9;                         %Number of variables
LB=[1 1 1 1 1 1 1 1 1];          %Lower Bound of parameters level
UB=[8 4 4 5 8 8 5 2 5];          %Upper Bound of parameters level

IntCon=[1 2 3 4 5 6 7 8 9];      %Makes all the parameters be intergers
options = gaoptimset('Generations',30, 'PopulationSize', 25, 'EliteCount',
3);

GeneaticAlgorithm=ga(ObjectiveFunction,nvars,[],[],[],[],LB,UB,[],IntCon,opti
ons);
```

The GA calls simple_fitness in order to find the optimum results. The framework of the function can be seen below:

```
function y=simple_fitness

%Parameters with different levels and assosiated costs

if x(1)==1;          %Parameter 1

elseif x(1)==2;

end

if x(2)==1;          % Parameter 2

elseif x(2)==2;

end

if x(3)==1;          % Parameter 3

elseif x(3)==2;

end
```

```
if x(3)==1;          % Parameter 3

elseif x(3)==2;

end

if x(4)==1;          % Parameter 4

elseif x(4)==2;

end

if x(5)==1;          % Parameter 5

elseif x(5)==2;

end

if x(6)==1;          % Parameter 6

elseif x(6)==2;

end

if x(7)==1;          % Parameter 7

elseif x(7)==2;

end

if x(8)==1;          % Parameter 8

elseif x(8)==2;

end

if x(9)==1;          % Parameter 9

elseif x(9)==2;

end
cd C:\EnergyPlus
dos('copy reference.idf copiedreference.idf');

%Write to idf

%Code for Buliding Materials:
file_id=fopen('copiedreference.idf','A');
fprintf(file_id,'\n %s ', 'Material, MaterialName, roughness');

fprintf(file_id, '%s%f',',',matieral_thickness);
```

```
fprintf(file_id,'\n %s ', 'conductivity,density, specific heat, thermal
absorptance, solar absorptance, visible absorptance;');

fclose(file_id);


%Code for Infiltration
file_id=fopen('copiedreference.idf','A');
fprintf(file_id,'\n %s ', 'ZoneInfiltration:DesignFlowRate, Name, Zone Name,
Schedule Name, AirChanges/Hour,    ,   ,   ');


fprintf(file_id, '%s%f',',',air_changes_per_hour);

fprintf(file_id,'\n %s ', ' 1, 0, 0, 0;');
fclose(file_id);


%Code for Window Type
file_id=fopen('copiedreference.idf','A');
fprintf(file_id,'\n %s ', 'WindowMaterial:SimpleGlazingSystem, WindowName');

fprintf(file_id, '%s%f',',',window_u-factor);

fprintf(file_id, '%s%f',',',window_shgc);

fprintf(file_id,'\n %s ', 'visible transmittance;');
fclose(file_id);

%Run Energy Plus
dos('runeplus copiedreference Tunisia')

%Calculations
cost=

cd C:\EnergyPlus
energymonths(1,1:25)=[csvread('copiedreference.csv',1,1)]; %Read idf output


Tunisia=                  %Calculate energy usage from energymonths data


energy=Tunisia*2.77778*10^-7;  %Convert energy into KwH

%Enter PV data found from PV Watts
TunPVData=

%Determine PV System Size
low=energy-75;
high=energy+75;
xx=1;
tt=0;
```

```
Watts=TunPVData(xx,2); %Watts;
while tt<1

if Watts>low && Watts<high
PVNeeded=TunPVData(xx,1);       %System Size
tt=22525;

else
xx=xx+1;
Watts=TunPVData(xx,2);

end
end

CostofPVTunisia=PVNeeded*1000*4.50;     %Get into Watts and then $4.50 a Watt
Benefits=425700-CostofPVTunisia;        %Determine Benefits


%Calculate Objective Function
y=cost-Benefits
```

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