PROGRAMMATIC MODELING OF SHELTERS USED IN THE FORWARD OPERATING BASES

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SUMMARY

The rising cost of sending military troops overseas has been a significant issue for the Department of Defense (DOD). Mission supplies such as liquid fuel, battery, diesel generator, the heating, ventilation and air conditioning (HVAC) system, and other equipment need to be transported from the source location to the destined operating base. To reduce energy consumption and unnecessary transfer of supplies, it is important to develop a programmatic modeling framework to predict energy consumption of an operating base depending on the mission needs and the local environment conditions. The research develops a modeling framework which will allow energy consumption estimation of shelters in a programmatic way for a large set of parameters using simulation tools OpenStudio and EnergyPlus and high level programming language Ruby. The programmatic framework considers different variables such as shelter types, construction components, number of personnel, electric equipment loads, the HVAC systems, the duration of operation, schedules, and the location of operation. The thesis developed measures to perform parametric analysis and sensitivity analysis of shelters. The analysis can be further used for the optimization of the energy consumption of an operating base. A better estimation of supplies needed in a mission can be provided from the simulation database to reduce unnecessary transportation and energy usage.

CHAPTER 1

INTRODUCTION

In 2014, about 17% of the federal spending in United States is used in national defense. The number is relatively small compared to 26.3% in health care, 24.3% in social security, and 19% in income security. However, compared to only 7% net interest paid toward national debt, 3% in transportation, and 1% in education, the percentage used in national defense seems comparably large and could be better relocated. Although the defense spending is declining since 2010, this is mostly due to pulling out military troops overseas [1]. The cost of sending a single military troop overseas has nevertheless still increasing and has been a significant issue for the Department of Defense (DOD). As shown in Figure 1, the cost of sending one service member to Afghanistan costs around 1-1.5 million. By 2014, the cost has increased to 2.1 million. This is because a clear guideline of what mission supplies are needed, in its most energy efficiency way, for a particular mission has not been established. To better understand the mission supplies needed in the outpost, simulations of the shelters would provide a database of energy consumption for comparison.

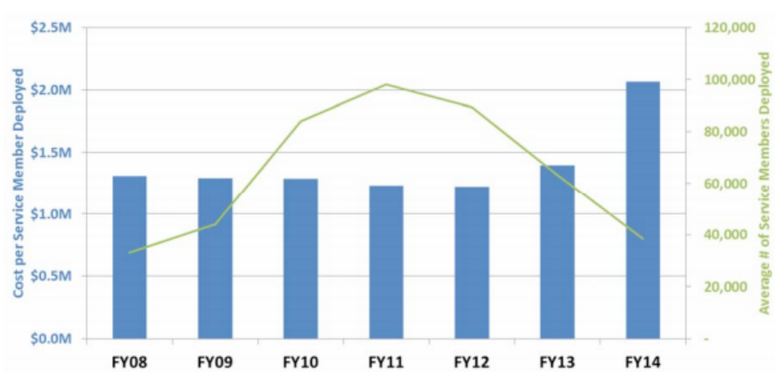


Figure 1: Cost Per Service Member Deployed in Afghanistan [2]

The ultimate goal of the project is to develop an application tool that would help in taking decision about the optimal numbers, types, and size of the energy-related equipment prior to the deployment. The project is pursued in collaboration with National Renewable Energy Laboratory (NREL), Communications-Electronics Research, Development and Engineering Center (CERDEC), U.S. Army Construction Engineering Research Laboratory (CERL), and Colorado School of Mines. The team from Georgia Institute of Technology is responsible for the modeling of the shelters and the heating, ventilation and air conditional (HVAC) systems, typically employed in a forward operating base, using OpenStudio and EnergyPlus applications. The overall architecture of primary application is shown in Figure 2. The different components of architecture will be addressed by the different organizations described above. This thesis focus on developing shelter models using the Building Component Library (BCL), OpenStudio, and DEnCity shown in Figure 2. The BCL is an online repository created by NREL that serves as a center for building/storing modeling data with citation and source verification. OpenStudio is a graphical user interface (GUI) of EnergyPlus for developing energy models. DEnCity is a database created by NREL for storing EnergyPlus results. The automated transfer of data from the BCL into the simulation tools, and then automated storing of the results into DEnCity has not been developed before. This thesis developed a programmatic workflow using Ruby scripts to develop this connection for various shelters used at forward operating bases.

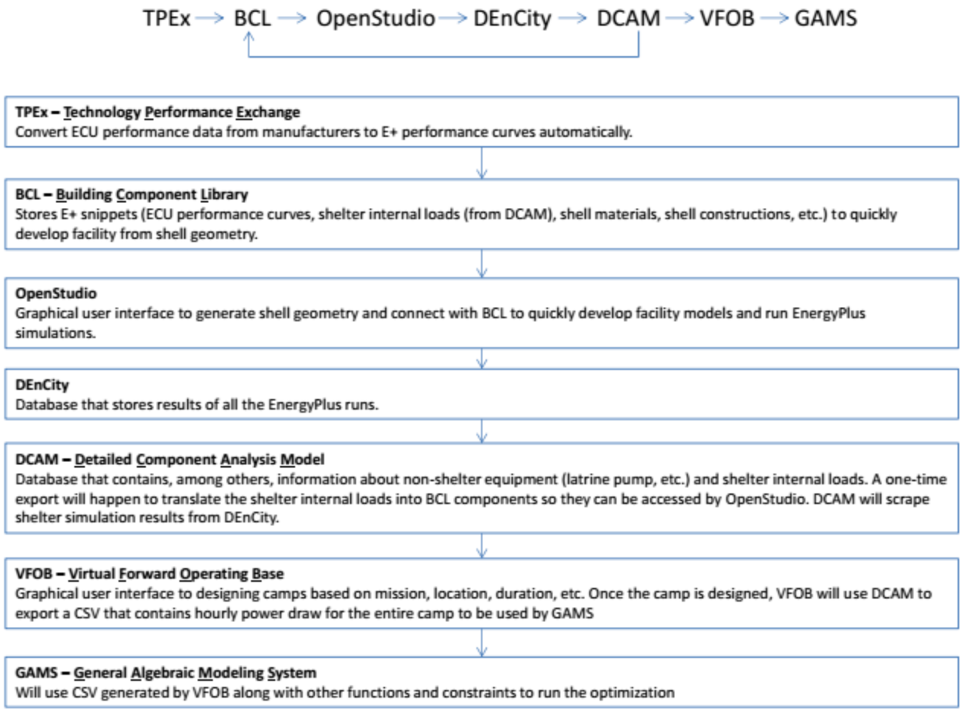


Figure 2: Application Architecture of the Project

Mission supplies such as liquid fuel, battery, diesel generator, HVAC system, and other equipment required transportation from the source location to the destined forward operating base. To reduce unnecessary transfer of supplies as well as energy consumption, it is important to analyze different shelters, and the required supplies for a forward operating base for a specified mission. There are numerous parameters to consider due to the variation in schedules, number of personnel, internal loads, etc. So it is important to develop a programmatic modeling framework to predict energy consumption of a forward operating base depending on the mission needs and the local environment conditions.

The thesis develops a load generation tool to calculate the energy consumption of shelters in a programmatic way using simulation tools OpenStudio, EnergyPlus, and high-level programming language Ruby. The large set and variation of parameters in the simulation process make manual modeling of shelters using OpenStudio and EnergyPlus inefficient. There are numerous shelter types to be considered in an outpost, such as AIRBEAM, Military Van (MILVAN), Container Living Unit (CLU), and Bhutan (B-hut). Numerous HVAC units such as HDT F100, HDT USMC 60K, HDT E2CU, and Carriers units are used in the outposts. Other parameters need to be considered in the model are the construction components, the number of personnel, electric equipment loads, the HVAC systems, duration of operation, schedules, and the location of operation. It is important to consider all these factors in models to give the most accurate site energy load and upload them into the DEnCity database.

When considering the variation of parameters, some parameter does not have significant impact on the total site energy compared to the others. Sensitivity analysis studies are required to understand the impact of the different factors to eliminate the unnecessary sets of simulations. For this purpose, a guideline for performing the sensitivity analysis is provided in the thesis.

In Chapter 2, a detailed literature review of the simulation tools, shelters, infiltration modeling, and sensitivity analysis methods are described. The simulation tools include OpenStudio, EnergyPlus, Ruby, Measures, and DEnCity. This chapter also describe the MILVAN and CLU shelter models, its construction and materials, and the modeling method for the entry and exit infiltration. At the end, the chapter provide details of the sensitivity analysis method, Morris Method, used in this research.

In Chapter 3, the computational methodology used in the thesis is presented. In this chapter, a detailed explanation on the programmatic workflow modeling is discussed. It explains how multi-dimensional matrix interface, OpenStudio measures, EnergyPlus measures, and Reporting measures should be used to build a model. At last, it provides a detailed explanation of the methodology for the sensitivity analysis.

In Chapter 4, the completed Ruby workflow and measures for the shelter simulations are presented. In this chapter, a detailed explanation is given on the multi-dimensional input matrix and the workflow modeling development. The workflow is composed of numerous measures that considered the different parameters in the shelter modeling. These parameters are shelter geometry types, construction components, people load, light load, electric equipment load, schedules, HVAC system, thermostat-set point, building rotation, and infiltration. The chapter explains the measures in detail and how each measure works side by side with each other.

In Chapter 5, the results of the sensitivity analysis is presented. The sensitivity analysis considered parametric studies which provide information about the importance of the parameters. These studies are required to provide a guideline to select the important parameters to be included in the DEnCity database for shelter modeling.

Chapter 6 presents the conclusion of this work and a discussion of possible future work.

CHAPTER 2

LITERATURE REVIEW

In this chapter, a detailed literature review of the EnergyPlus, OpenStudio, Ruby measures, DEnCity, shelter types, and sensitivity analysis method are described. The chapter is split into three parts: a discussion of simulation tools for building energy modeling, followed by MILVAN and CLU shelter information and infiltration, and then the sensitivity analysis by Morris Method.

2.1 Simulation Tools

2.1.1 EnergyPlus

EnergyPlus is an energy analysis and thermal load simulation program released by U.S. federal agency in early 2001 to replace US government supported building energy simulation programs, BLAST (Building Loads Analysis and System Thermodynamics) and DOE-2. BLAST and DOE-2 are two 20+ year old hourly building energy simulation programs written in Fortran. BLAST uses a heat balance approach while DOE-2 uses a room weighting factor approach in their simulation process [3]. DOE-2 is widely used to design energy-efficient building by given building's climate, architecture, materials, operating schedules, and HVAC equipment [4]. BLAST contains subprograms: Space Loads Prediction, Air System Simulation, and Central Plant that calculate hourly loads with given weather data, building construction, and operation details. BLAST also considers the radiant, convective, and conductive heat balance for all surface and space in a building energy model [5]. However, the Fortran code structure have become too expensive to maintain and modify, which lead to termination of support by Department of Defense (DoD) in 1995 and 1998 respectively. The initial concept of creating EnergyPlus is to merge the two programs into one. In 1996, U.S. Department of Energy (DOE), CERL, University of Illinois, Lawrence Berkeley National Laboratory (LBNL), Oklahoma State University, and Gaud Analytics initialized the creation of the program. In 1999, the beta version of EnergyPlus was released for testing and in 2001 the first version of EnergyPlus was released. [3]

The simulation code of EnergyPlus was initially written in Fortran 90 Standard. As the Fortran programming language becomes outdated, the decision to convert the code to C++ was made. By 2014, the program had been fully converted to C++ for better maintenance [1, 6]. EnergyPlus calculates the cooling and heating loads necessary to maintain thermostat set-points based on the building's physical make-up, mechanical system, and surrounding environment. Other features include integrated and simultaneous solution for coupled systems and building responses using iterative calculations. The software allows user to define time steps in hourly or sub-hourly manner. The solution techniques of EnergyPlus use heat balance approach considering the radiant and convective effects in both interior and exterior surface at each time step. Other functionalities of EnergyPlus includes transient heat conduction, three-dimensional finite difference ground analytical techniques, layer-by-layer integration of moisture adsorption/desorption into conduction transfer functions, and effective moisture penetration depth model (EMPD). The thermal comfort models are based on the activity, inside dry bulb, and humidity in the environment. It uses anisotropic sky model, considering atmospheric pollution calculation that predict CO_2, SO_x, NO_x, CO and particulate matters on the site. Daylighting controls can also be specified in the simulation engine. The ability to configure HVAC systems makes EnergyPlus a good simulation tool for easy modification and consideration of different mechanical systems [6].

The intent of using EnergyPlus is to be able to calculate thermal loads and energy consumption of different types of buildings and HVAC design systems. EnergyPlus do not have a user friendly interface; it is a simulation engine that uses simple ASCII format for inputs and outputs. Because EnergyPlus code are written in modules, it makes it easy to link new programming elements into the existing ones. Figure 3 shows the big picture of EnergyPlus. EnergyPlus does not provide temperature and flow distribution compared to computation fluid dynamics as it is based on heat balance model. There are major assumptions in heat balance models such as uniform surface temperatures, uniform wave irradiation, and one dimensional heat condition [3]. The majority heat balance codes are originated back from the parent programs, BLAST and DOE-2. EnergyPlus has been exhaustive tested and there is high confidence in the results obtained from EnergyPlus simulations [6].

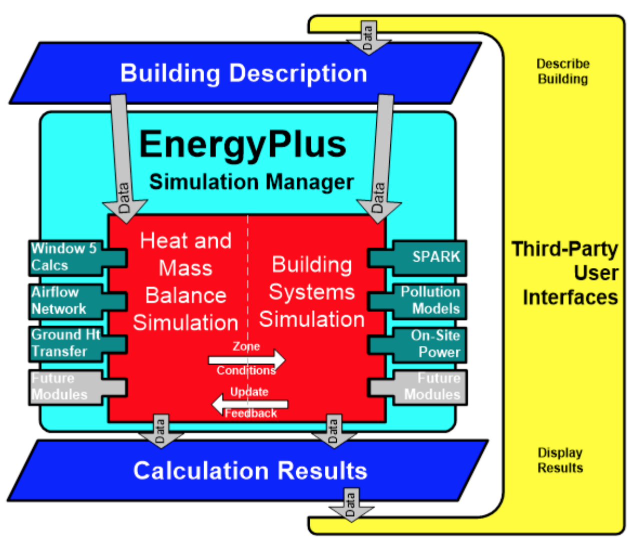


Figure 3: Big Picture of EnergyPlus [6]

2.1.2 OpenStudio

OpenStudio is an open source integrated analysis platform developed by NREL, LBNL, Oak Ridge National Laboratory (ORNL), Pacific Northwest Laboratory (PNNL), and Argonne National Laboratory (ANL) to support whole building energy simulation for the U.S. Department of Energy. The software incorporates two simulation tools: EnergyPlus and Radiance, an advanced daylight analysis simulation tool. OpenStudio is a graphical user interface (GUI) of EnergyPlus, whose application interface is shown in Figure 4 [7]. OpenStudio application is a graphic energy modeling tool for EnergyPlus [8]. It is a cross-platform software that can be used in Windows, Mac, and Linux. OpenStudio is written in object-oriented programming language C++ [10]. The application has extensions such as OpenStudio SketchUp Plug-in, ResultsViewer, and the Parametric Analysis Tool [7,8].

The basic modeling workflow of OpenStudio starts with OpenStudio SketchUp Plug-in to allow user to create 3D geometry building envelope. The Plug-in allows SketchUp geometry to load into OpenStudio. OpenStudio provides the interactive setup in creating a building energy model, including setting up the site weather profile, the schedules, the constructions, the internal loads, the space type, the facility, the spaces, thermal zone, HVAC systems, and measures which are shown on the left menu in Figure 4. The application allows users to switch between SI and IP units. It automatically scans for tools such as Ruby, EnergyPlus, and Radiance that work interactively in the OpenStudio application [7].

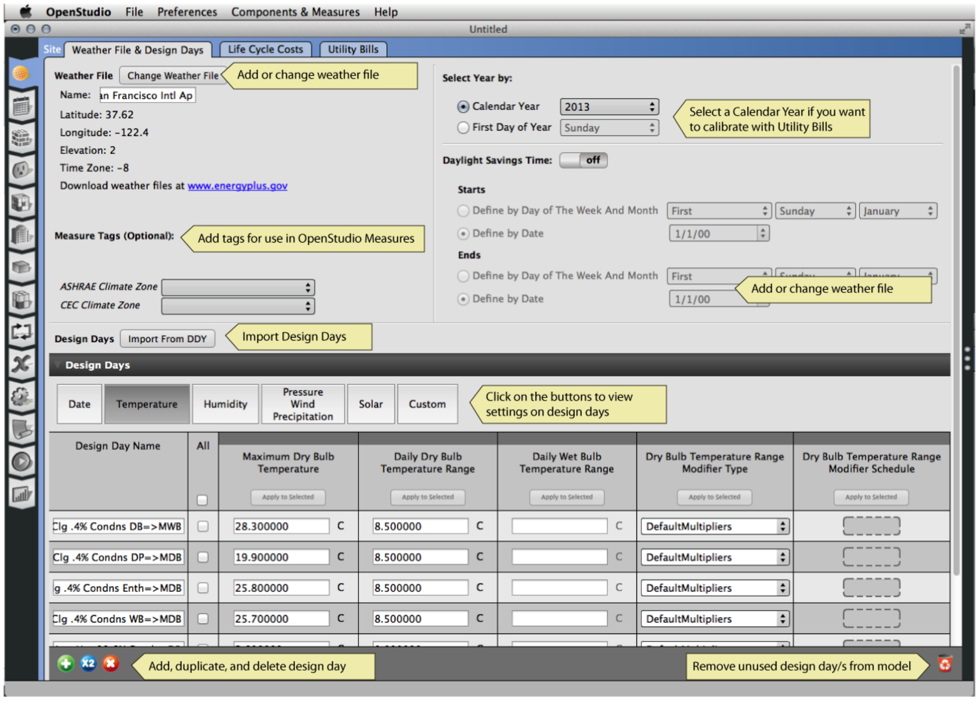


Figure 4: OpenStudio Application Interface [6]

An OpenStudio model can be a whole single building energy model that can be simulated with EnergyPlus or just a component of the building energy model. OpenStudio model is hierarchical and object-oriented that serves as a container for Model Objects. A Model Object is an OpenStudio class that represent an input data dictionary (IDD) object in EnergyPlus [9]. There are different classes that make up the foundation of the OpenStudio model, including Model Component, Model Object, Parent Object, and Resource Object. A typical Model is composed of Model Objects. A Component is a partial model that cannot be run on EnergyPlus where it only has one or few Model Objects. A Parent Object is a high hierarchy Model Object which can have children. An example is building, which is the parent of story and space. A Resource Object is object that can be referenced multiple time by the Parent Object, including schedule, construction, material, internal load, and space type objects. Overall, OpenStudio Model Objects can be broken down into these categories: simulation settings, output data, resources, site and location, geometry, building loads, advanced daylighting, HVAC systems, and economics [10].

Once the model has been created in OpenStudio, the model is translated from OpenStudio model object format into EnergyPlus' IDD format. The simulation only run after the translation takes place. Once the simulation has completed running, the ResultsViewer enable browsing, plotting and comparing of the simulation result [10].

As mentioned, Model Object in OpenStudio represents an IDD object in EnergyPlus. IDD object is composed of numerous ASCII string fields that configures a module in EnergyPlus. Yet, not all the module of EnergyPlus is converted from IDD objects into Model Objects in OpenStudio. Then the importance of EnergyPlus measure comes in to place. Measure is a programmatic instructions written in Ruby script that alters a model. If any EnergyPlus measure is applied into the model, it will be added after the translation happens [7].

OpenStudio has a Software Development Kit (SDK) that provides pointer to the public class that holds the model object data and methods for implementation. The high-level Ruby programming language can then be used to access these pointers to interact with the C++ modules in the OpenStudio software. The SDK documentation is accessible to the public in the OpenStudio website (*https://www.openstudio.net/*) [10].

Parametric Analysis Tool (PAT) is an extension of OpenStudio that enable parametric studies for a model. PAT removes the need of manually editing each model for different architectures, mechanical systems, loads, and other measures. PAT allows user quickly compare alternatives compared with a baseline model. The tool operates with

OpenStudio workflow to allow customized parametric analysis to perform in reasonable time using a cloud computing services [7].

2.1.3 Ruby 2.0

Ruby is an object-oriented, dynamic programming language that was first released in 1995. It was created by Yukihiro Matsumoto as a combination of Perl, Smalltalk, Eiffel, Ada, and Lisp programming languages. Since 2006, Ruby has become one of most popular programming languages worldwide. Ruby is a high-level scripting language, which unlike C++, that requires less lines for the same programmatic instruction. This make developing a Ruby program faster. It is common to have an application that is written in C++, which has better performance, to have Ruby or Python script to call the C++ parts outside the application [12].

Ruby is a scripting language that is more powerful than Perl and more object-oriented than Python. Everything is an object to Ruby, where each object has a given methods and instance variables. This makes the language very flexible. There are five major classes in the root hierarchy of Ruby: Basic Object, Object, Kernel, Module, and Class as shown in Figure 5. Everything is defined as a Basic Object in Ruby and Object is the superclass for all classes and module. Module mainly provides reflection mechanisms like gathering methods and variables to be called within a class. Classes define the name of the program and are used to gather all the methods and variables that can be called by class instance using “new” in a script. Other commonly used Ruby objects are String, Array, and Hash. The benefits of Ruby include exceptional handling, easy C extensions interaction by using API, a true make-sweep garbage collector for all objects, and portable to be used in all operating systems [12,13].

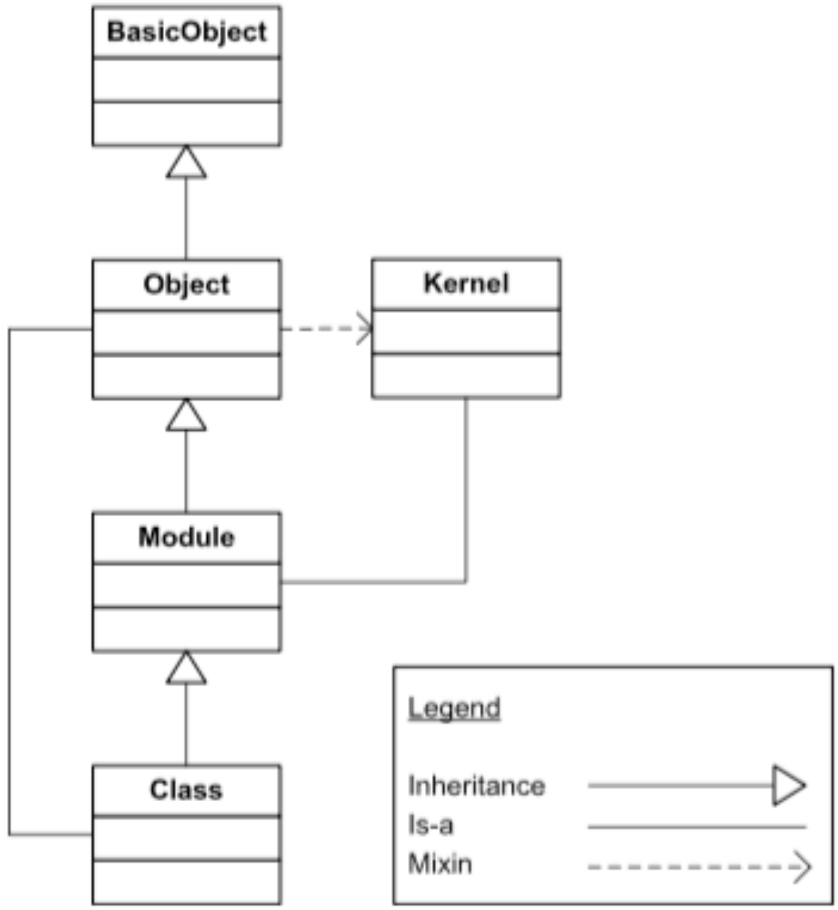


Figure 5: Ruby Hierarchy Classes [13]

Gem is a software package library in Ruby that is shared among programmer. There are 7.8 billion Ruby gems published online today. The functionalities of gems are to modify Ruby applications and to distribute reusable function to the public developers for use in their application. All gem has the following components: code, documentation, and gemspec. The gemspec contains the information of the author and description of the gem's function [14]. Once Ruby is installed in the platform properly, user can install any gem using command prompt by typing *"gem install -"*. Some gem can calculate the days from a given date, reading excel file, and even sending text to mobile devices from command line. To find out the list of gems installed in the platform, user can type *"gem list"* on command prompt. To use the gem package, user should include the "require *gem name*" in the Ruby script [15].

2.1.4 Measures

The SDK is a library of OpenStudio and EnergyPlus functions that are accessible with Ruby 2.0 and C++. These functions include importing 3D geometry, modifying internal loads, configuring standard HVAC systems, etc. The library allows the establishment of Measure, which is a powerful platform to work with EnergyPlus models. The relationship of measure, OpenStudio, and EnergyPlus is comparable to Visual Basic Marco in Microsoft Excel [16].

A measure is a set of programmatic instructions that can be used to make changes in a building energy model. Measure is flexible and can be designed to be generic where it will work on any building energy model. Their flexibility allows effortless parametric analysis, uncertainty studies, and sensitivity analysis studies as the input values of the simulation model can be easily modified. The benefits of using measures are reduction in modeling time and cost, lower administrative and training costs, and ability to maintain quality and consistency in energy modeling. There are three types of measures: OpenStudio, Workspace, and Reporting measures. Each type of measures can be used to represent the stage of model from constructing objects in OpenStudio, to EnergyPlus translation, and finally the simulation output report. NREL has published the Building Components Library (*http://bcl.nrel.gov*), which is a public repository that contains more than 190 measures and thousands of components. The public can easily access the library for these measures as well as writing their own measure [16].

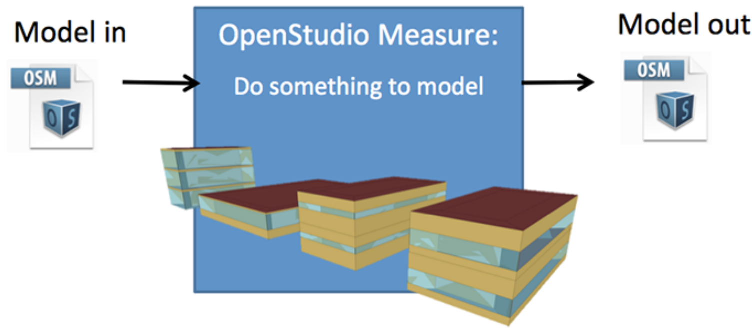


Figure 6: Measure Usage [15]

OpenStudio measure takes in an OpenStudio model and produces a transformed OpenStudio model as an output showed in Figure 6. Each OpenStudio measure contains their own folder with two key files: *measure.rb* and *measure.xml*. The folder can also contain a resources folder and a tests folder. The resources folder includes any component or library that is accessible to the measure. The tests folder contains a ruby script that tests the *measure.rb* in the parent folder because *measure.rb* requires another script to call its instance. The folder structure is shown in Figure 7 [15].

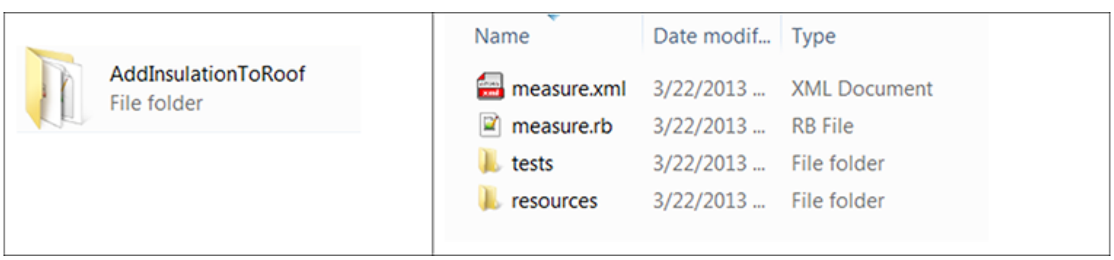


Figure 7: Measure File Directory [15]

Measures can add, replace, and remove objects in an OpenStudio model. For examples, adding a geometry structure, replacing construction layers on a surface, and removing an internal load. Measures are written in Ruby 2.0. The structure of a measure is shown in Figure 8, where each contains five basic methods that define the description and the instruction of the measure. The first three methods classify the name, the description, and the modeler description of a measure. The description should include the functionality of the measure and its purpose. The fourth method classify the arguments needed for the measure to run. Arguments are user-specified inputs which play an important role in automation of the project. The fifth method is the run method, which takes in an OpenStudio model, arguments, and a runner as inputs. This method includes the programmatic instructions that alter the model. It is where the transformation of model happens [15].

```ruby
measure.rb
class ChooseGeometry < OpenStudio::Ruleset::ModelUserScript

  # human readable name
  def name
    return "Choose Geometry"
  end

  # human readable description
  def description
    return "This measure will allow user to choose the geometry / structure type localed in the local resource file.
  end

  # human readable description of modeling approach
  def modeler_description
    return "This measure will allow user to choose the geometry / structure type localed in the local resource file.
  end

  # define the arguments that the user will input
  def arguments(model)
    args = OpenStudio::Ruleset::OSArgumentVector.new

    #make an argument for the geometry
    geometry = OpenStudio::Ruleset::OSArgument.makeStringArgument("geometry", true)
    geometry.setDisplayName("Choose Geometry to Import.")
    geometry.setDefaultValue("MILVAN")
    args << geometry
  # the name of the building to add to the model
    building_name = OpenStudio::Ruleset::OSArgument.makeStringArgument("building_name", true)
    building_name.setDisplayName("New building name")
    building_name.setDescription("This name will be used as the name of the building.")
    args << building_name

    return args
  end

  # define what happens when the measure is run
  def run(model, runner, user_arguments)
    super(model, runner, user_arguments)

    # use the built-in error checking
    if !runner.validateUserArguments(arguments(model), user_arguments)
```

Figure 8: Ruby Measure Layout

Workspace measure, also known as EnergyPlus measure, is an alternative way to modify a building energy model. However, EnergyPlus measure uses ASCII format for input, output, and modification which make it less flexible to be used in all type of building energy model. Unlike OpenStudio measure, EnergyPlus measure does not crosscheck the objects linked as it is simply modifying the string fields in the IDF input file. User has to ensure the particular usage of EnergyPlus module is fitted to the input building energy model while writing the measure. EnergyPlus measures are used mostly for the IDD objects that have not been translated into OpenStudio SDK model objects. These include modification of surface boundary conditions and Energy Management System (EMS). The measure scripting format is similar to OpenStudio measure except the class is directed to WorkspaceUserScript [15].

Reporting measure takes in models and transform representation of simulation results. The measure allows users to generate custom reports, table, and charts. Some example of reporting measures is space type summary report, zone conditions and humidity report, and the way to view model and data. The view model and data measures are still under development but this would be a powerful interactive visualization platform for the future [16]. The measure scripting format is similar to OpenStudio measure except the class is directed to ReportingUserScript [15].

OpenStudio application allows users to attach any OpenStudio, EnergyPlus, and Reporting measures using the measure tab as shown in Figure 9. A more effective way for large scale modeling is linking the measures in a workflow formulation using OpenStudio workflow-gem and analysis-gem. Ruby scripting provides a powerful tool for large volume parametric studies [6].

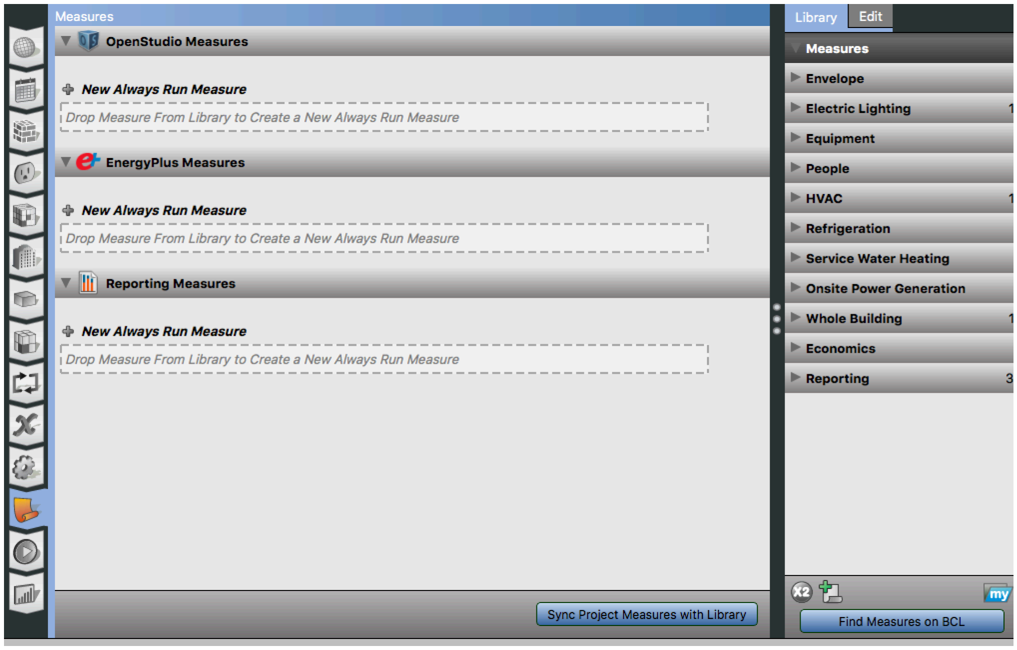


Figure 9: Measure Tab to Apply Measures in OpenStudio Application

The OpenStudio Server is a vagrant or cloud instance that allows large scale parametric analysis of building energy models. The server is a private source code created by NREL. By proper installation of Vagrant, Virtual Box, and ChefDK, an OpenStudio Server can be setup locally in the computer. A machine image of OpenStudio Server is also located on Amazon EC2 to be setup on the cloud at any instance with account access key and secret access key. The OpenStudio Server provides a smart and clean interface for comparison of the simulation results. As shown in Figure 10, datapoints can be compared in parallel with each other in an analysis. The top row of Figure 10 represents the different variables for each simulation and each column represents the variance of each variable. [16]. As shown in column 1 of Figure 10, the weather filename is varied with three locations: Chongjin, Kharga, and Singapore. Colunm 2 is the building rotation variable, where four rotations varied are 0,90,180, and 270. The third column is the total electricity intensity calculated from the simulation. User can select a range of total electricity intensity as shown in the figure to see which parameters give the following results. As shown, a MILVAN shelter in Chongjin has highest total electricity load where the parameter on building rotation does not have huge impact compared to location.

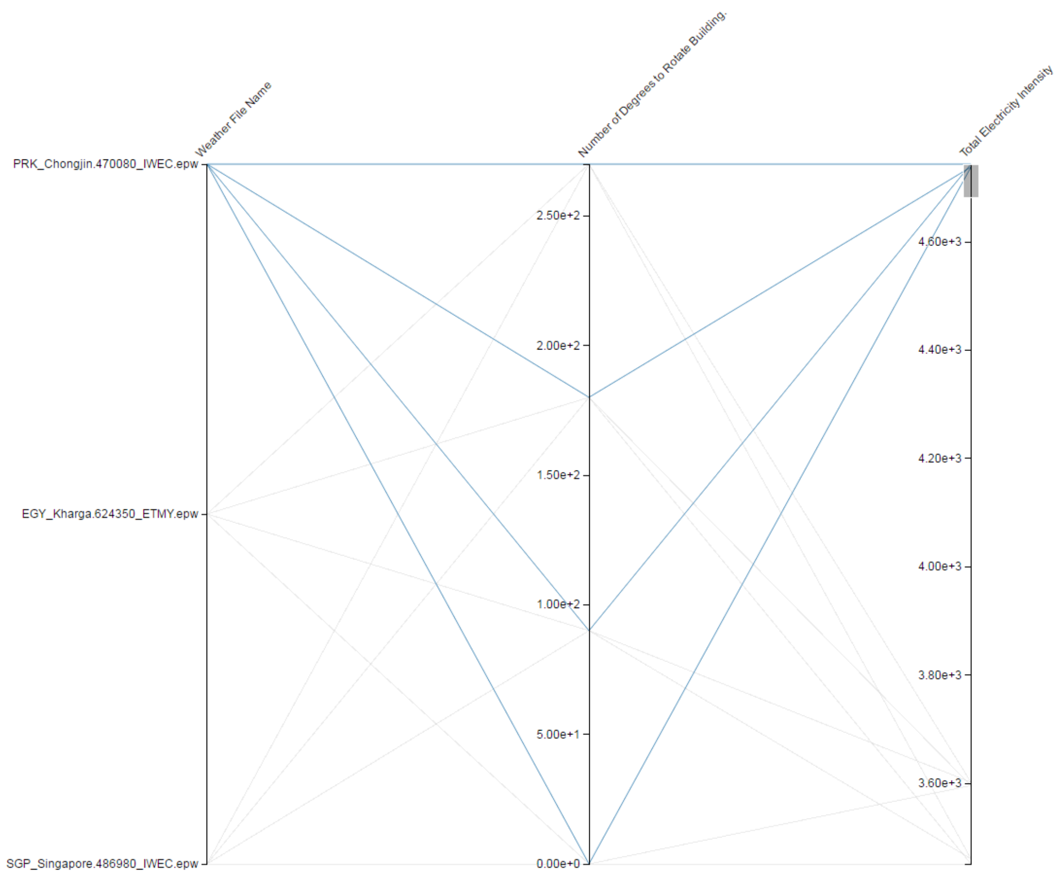


Figure 10: Multi-datapoints Result from OpenStudio

2.1.5 DEnCity

DEnCity, also known as DOE's Energy City, is a multi-purpose, open, and dynamic database to place building energy simulation inputs and results. A public DEnCity database created by NREL has been setup to be shared for general purpose to the public. The goal of the public DEnCity database is to reduce cost and increase resolution of a given analysis by comparing with relevant data points contributed by other building modeler. The online database is implemented in mongoDB, which is an open source database that support document storage, can be hosted locally or on the web. The advantages of DEnCity database are it can store full model input file, its attributes for fast lookup, and hourly simulation data in CSV format. Therefore, providing a better platform for building data management [17].

The objective of DEnCity is to facilitate storage of all possible shelter design and load simulation data as energy simulation require time and expertise to set up. By developing a location for big data, it could open up revolutionizing analytics in the future where simulations can be re-purposed and reused in the future. DEnCity is implemented based on DOE's Building Performance Database (DBPD). DBPD is a database of real building consumption data and its building characteristics information can be used in the simulation models.

DEnCity has an application program interface (API). API is a set of routines that specifies how software components should interact. It provides the building blocks for users to interact the application programmatically. DEnCity API provides searching and uploading structures for the database as shown in Figure 11 [17].

Resources

Api

Resource	Description
POST /api/login	Credential check
POST /api/search	Search for structures
POST /api/search_by_arguments	Search for structures within an analysis by arguments
GET /api/retrieve_analysis	Retrieve an analysis.
POST /api/analysis	Add or update an analysis
POST /api/structure	Add or update a structure
POST /api/related_file	Add a related file to a structure
POST /api/remove_file	Remove a related file from a structure
POST /api/meta_upload	Add one metadatum
POST /api/meta_batch_upload	Add multiple metadata

Figure 11: DEnCity API

2.2 Shelter Types

A forward operating base contains many different shelters for different facility purpose, e.g., MILVAN, CLU, AIRBEAM, B-hut, and etc. [18]. Shelters used in the forward operating bases are broken down into two categories: hard shelter and soft shelter. MILVAN, CLU, and B-hut are hard shelters. AIRBEAM is a soft shelter. MILVANs are used as aid station, billeting structure, command structure, network communication hub, and laundry station. CLU is used as billeting structure for visitor or service member.

2.2.1 MILVAN and CLU Shelters

MILVAN and CLU are modified 20-foot shipping containers that are commonly used as shelter units for different mission type. Shipping container has the benefit of carrying up to 20 tons of general cargo, which provides space for supplies transportation as well as housing purpose on-site. The MILVAN and CLU are climate-controlled 20-ft ANSI/ISO standards shipping container that has been used in the military since 1978. Two common dimensions of shipping container used by the Department of Defense are 20x8x8 ft. and 20x8.5x8 ft. [19].

The 20x8x8 ft. dimension ISO shipping container is the most common MILVAN used by the military, which weighted around 4,770 pounds and has a volume of 1,060 cubic feet. A 20x8x8ft MILVAN unit has typical internal length of 19ft.4in., width of 7ft.6in., and height of 7ft.1in. as shown in Figure 12. It has a 0.0787 in. thick corrugated steel walls and a hardwood floor. The material of typical 20-foot shipping container structure is made of Cor-Ten A steel. It is a weathering steel material that has higher resistance to atmospheric corrosion than common steel [20,21].

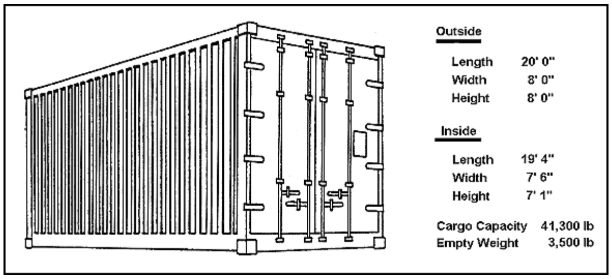
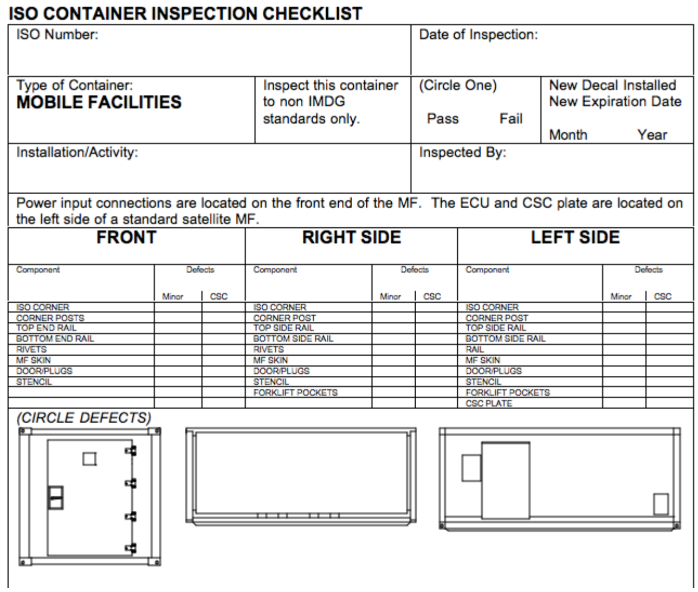


Figure 12: Dimension of ISO Shipping Container [21]

The 20-foot shipping container requires modification before usage in the operating base. These includes addition of personnel doors, windows, and insulations. The modification of shipping container highly depends on the operating base's location and its purpose. MILVAN shelter is used as command structure, laundry, medical aid center, maintenance building, and climate-controlled-lighted shelter. CLU is used as a billeting structure, which typically requires windows. Each has different power loads and should be modeled [19]. A DTIC document used for ISO shipping container inspection by the army has shown mobile facilities used in camp have two doors on the two ends as shown in Figure 13. The ECU and electronic panels are located on the left side of the shipping container as shown below. The MILVAN shelter model is based on the diagram in Figure 13 with standard exterior doors on the front and back end [22]. The windows shown on the doors are negligible in modeling due to its small dimension. CLU is similar to MILVAN in its dimension and vendor's modification, except it has two additional 0.91ft x 0.91ft windows as shown in Figure 14 [23].



ISO CONTAINER INSPECTION CHECKLIST

ISO Number:		Date of Inspection:	
Type of Container: **MOBILE FACILITIES**	Inspect this container to non IMDG standards only.	(Circle One) Pass Fail	New Decal Installed New Expiration Date Month Year
Installation/Activity:		Inspected By:	
Power input connections are located on the front end of the MF. The ECU and CSC plate are located on the left side of a standard satellite MF.			

FRONT			RIGHT SIDE			LEFT SIDE		
Component	Defects		Component	Defects		Component	Defects	
	Minor	CSC		Minor	CSC		Minor	CSC
ISO CORNER			ISO CORNER			ISO CORNER		
CORNER POSTS			CORNER POST			CORNER POST		
TOP END RAIL			TOP SIDE RAIL			TOP SIDE RAIL		
BOTTOM END RAIL			BOTTOM SIDE RAIL			BOTTOM SIDE RAIL		
RIVETS			RIVETS			RAIL		
MF SKIN			MF SKIN			MF SKIN		
DOOR/PLUGS			DOOR/PLUGS			DOOR/PLUGS		
STENCIL			STENCIL			STENCIL		
			FORKLIFT POCKETS			FORKLIFT POCKETS		
						CSC PLATE		

(CIRCLE DEFECTS)

Figure 13: Mobile Facility Diagram from DITC [22]

Figure 14: Container Living Unit [23]

2.2.2 Construction and Materials

The MILVAN and CLU shelters used in army camp are climate-controlled [19]. This required modification with insulation and flooring of the shipping container. Without modification, these shelters would not be applicable in harsh environment. The insulation materials used in the modification of shipping container may vary with different vendor. ContainerTech, Inc. suggested three types of commonly used insulations in modification of shipping container: fiberglass, rigid polystyrene foam paneling, and closed cell spray foam. Two types of interior walls are suggested, including fiberglass reinforced panel (FRP) and Hardie paneling. Building material and thermal insulation play a significant role in reducing energy consumption of a HVAC system. R-value is a measurement unit commonly used in construction industry that defines the thermal resistance of an insulation material. The recommended R-value in units of BTU/(h^{o}F$\cdot$ft^2) for shipping container's thermal insulation are R-30 for the roof, and R-20 forthe floor and walls. However, the R-value of insulation also depends on the operating base location [24]. Three initial locations that represent three extreme climate profile are selected for modeling. These include Kharga, Egypt as desert climate, Singapore as tropical climate, and Chongjin, North Korea as temperate climate [9]. The EnergyPlus temperature profile for each location is shown in Figure 15.

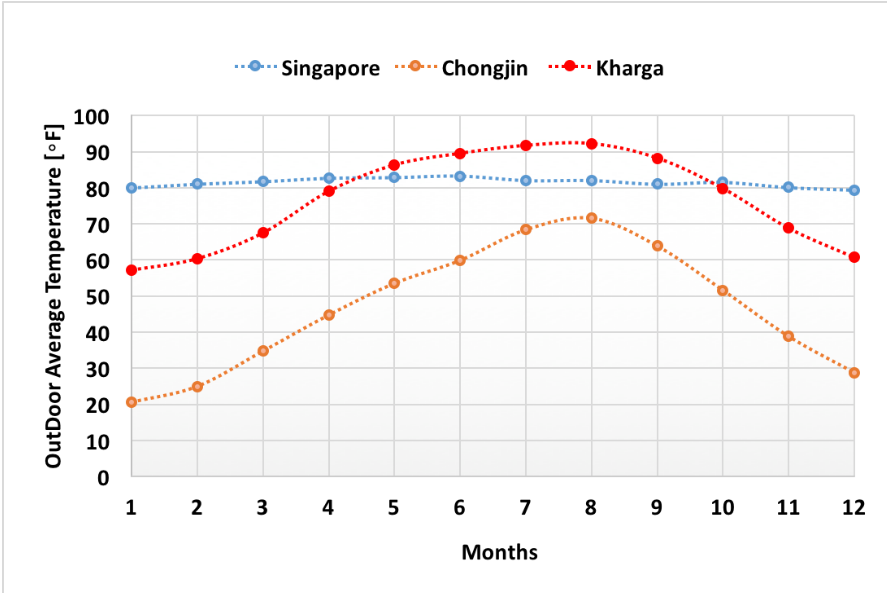


Figure 15: EnergyPlus Weather Data

In 2012, Naval Facilities Engineering Command (NAVFAC) started a project to make CLU more energy efficient. Camp Lemonnier, Djibouti is a U.S-Africa command combined joint task located at the east Africa region. The mission of the camp is to promote regional security and stability, prevent conflict, and protect US and coalition interests. The region has a humid environment with average temperature reaching up to 125˚F. The CLUs use 40% of the operating base energy load in Camp Lemonnier. The goals of the project are to reduce energy load, and easier set-up and tear-down of CLU with new design of the super energy efficient containerized living unit (SuperCLU). The CLU featured high R-value insulation and reflective coating on the walls. By considering all type of insulation in shelter modeling simulations, MILVAN and CLU can be constructed to increase energy efficiency [23].

Table 1: Shipping Container Insulation Types [25-27]

Insulation Material	Thermal Conductivity (W/mK)	Heat Capacity (J/kgK)	Density (kg/m^3)	R-value per inch	Estimate Price per square foot	R13 inches required	R20 inches required	R30 inches required
Fiberglass	0.038	843	150	3.7	0.50-1	3.514	5.405	8.108
Expanded Polystyrene (EPS)	0.035	1500	22.5	4	1.628	3.250	5.000	7.500
Extruded Polystyrene (XPS)	0.028	1500	35	5	3.6	2.600	4.000	6.000
Polyisocyanurate (ISO)	0.022	1370	40	6.5	5-6	2.000	3.077	4.615
Closed Cell Spray Foam	0.023	1400	36.8	6	5-6	2.167	3.333	5.000
Mineral Wool	6.024	840	48	4.3	1.7-3.2	3.023	4.651	6.977

Six common insulation materials are considered as shown in Table 1. The choice of insulation materials depends on the cost of the material and the required internal volume of the shelter. For example, even the estimate price for fiberglass is $ 0.50 per square foot, a R-30 fiberglass roof is unreasonable as it requires 8 inches of fiberglass insulation. Closed cell spray foam and polyisocyanurate (ISO) are the highest R-value per inch insulating materials but the price per square foot can be too expensive. Expanded polystyrene (EPS), extruded polystyrene (XPS), and Polyisocyanurate (ISO) are three types of rigid foam insulations. The price listed in the table are estimation and should only be used for relative price reference. There are recommended levels of insulation in United States depending on the climate zone as shown in Table 2. The R-value of insulation range from R-13 to R-20 for walls and R-20 to R-30 for roof. Depending on the R-value per inch, the thickness of each insulation is shown in Table 1 [24,28].

Table 2: R-Value for Different Climate [28]

Climate Required Insulation	Roof	Walls	Floor
Tropical	R30-R49	R13-R15	R13
Desert	R30-R38-R60	R13-R21	R25-R30
Temperate	R38-R60	R13-R21	R25-R30

2.2.3 Infiltration

In all building structure, there are air exchange by ventilation, infiltration, and exfiltration. Infiltration is flow of outdoor air into the structure through unintentional openings based on construction error or through door opening event. Envelope infiltration is caused by pressure differences created from stack effect, wind effect, mechanical systems [29].

The stack effect, also known as buoyancy effect, is caused by the temperature difference in a building. Temperature difference in the air causes cool-higher density air to be at lower part of the building and warm-lower density air to be pressurizing the top of the building. In all building envelope, there are cracks and leakage area for these pressurized air to leak outside the building. The pressure difference depends on the height of the building and air temperature difference. The taller the building, the greater the stack effect [29].

Wind effect is caused by the pressure difference between the windward and leeward sides of the building. As wind flow through sharp edges of the building, it would create negative pressure on the leeward side of the. The pressure difference is proportional to the square of wind speed [29].

In an operating base, it is common to have air supply ducts running exteriorly in unconditioned space. Depending on the mechanical system, there might be leakage which cause pressure difference that could led to increase in envelope infiltration. To estimate the air infiltration in a shelter, the blower door method is commonly used. The method uses the blower to measure the quantity of air that leak out of the house based on the pressure difference in indoor and outdoor [29].

There are three types of infiltration modeling methods in EnergyPlus: "Design Flow Rate", Sherman and Grimsrud's "Effective Leakage Area", and Walker and Wilson's "Flow Coefficient" model. Infiltration is caused by unintentional openings around doors and windows, opening and closing of doors, and other building elements. User can define the design flow rate which is used to calculate the infiltration based on the temperature difference and wind speed based on Equation 1. The question originated by Coblenz and Achenbach in 1963. The EnergyPlus default constant values for A, B, C, D in Equation are 1,0,0,0. The BLAST method uses constant values of 0.606, 0.03636, 0.1177, 0 based on ASHRAE journal articles and other outdoor weather data. The DOE-2 method uses constant values of 0,0,0.224,0 based on the ASHRAE Handbook of Fundamentals. For Equation 1, I_{design} is design flow rate in unit of m^3/s, $F_{schedule}$is the user-defined factorial infiltration schedule, $T_{zone}$is the interior shelter temperature, $T_{out}$is the outside shelter temperature, and windspeed is the local wind speed obtained from the weather profile.

$$Infiltration = I_{design}F_{schedule}[A + B|T_{zone} - T_{out}| + C * Windspeed + D * Windspeed^2] \qquad (1)$$

Sherman-Grimsrud's effective leakage area model is referred to the basic model in ASHRAE Handbook of Fundamentals. The model is based on user-defined effective area of leakage (A_L) in the building. The model is mostly used for building envelope infiltration. The equation considers the stack (C_s) coefficient in unit of $(L/s)^2/(cm^4K)$ and wind coefficient (C_w) in unit of $(L/s)^2/(cm^4(m/s)^2)$, schedule ($F_{schedule}$), local wind speed, and temperature difference (ΔT) to define the infiltration of the building as shown in Equation 2.

$$Infiltration = F_{Schedule}\frac{A_L}{1000}\sqrt{C_s\Delta T + C_w * WindSpeed^2} \qquad (2)$$

Walker-Wilson's flow coefficient model is referred as the enhanced model in the ASHRAE Handbook of Fundamentals. The model is based on user-defined flow coefficient (c) in unit of $m^3/(s\ Pa^n)$ as shown in Equation 3, where n is the pressure exponent, s is the shelter factor, stack coefficient in $(Pa/K)^n$, and wind coefficient in $(Pa \cdot s^2/m^2)^n$.

$$Infiltration = F_{Schedule}\sqrt{c * C_s \Delta T^{n^2} + c * C_w * s * WindSpeed^{2n^2}} \tag{3}$$

Entry and exit infiltration through the door can be modeled using the first method by specifying the air flow rate. The calculation of air flow rate is based on the air flow coefficient (C_A), the pressure factor (R_p), and the area of the door opening (A). The coefficient and the pressure factor are different based on the windspeed and the pressure difference across door. The values can be founded in the ASHRAE Handbook of Fundamentals. The schedule for the entry and exit infiltration is defined by the number of occupants and occupancy schedule [30].

$$Q = C_A A R_p \tag{4}$$

The ASHRAE Handbook of Fundamentals provides suggestion on modeling entry and exit infiltration through commercial building. To calculate the average airflow rate through an automatic door, the variables including area of the door, the pressure across the door, the discharge coefficient of the door, and the number of door opening events in the building. The discharge coefficient is a complex variable to consider since it changes as the door opens and closes. The ASHRASE research project RP-763 developed a graph for the airflow coefficient depending on the occupancy schedule as shown in Figure 16. The airflow coefficient is used to obtain the average infiltration rate as shown in Equation 5, where N is total number of door opening event and R_p is pressure factor from Figure 17.

The pressure factor is the square root of the pressure difference across the door. The pressure difference across an automatic door depends on the external temperature and building height as shown in Figure 17 and has unit in inches of water. An inch of water is equaled to 248.84 Pascal (Pa). For most shelter in a forward operating base, the building height is within 10ft and has Rp of 0.3 [29].

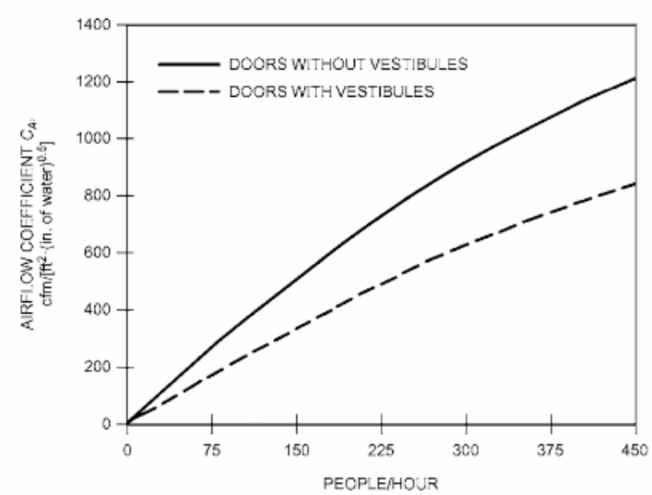


Figure 16: Airflow Coefficient for Automatic Doors [29]

$$Q = N * C_A * A * R_p \quad (5)$$

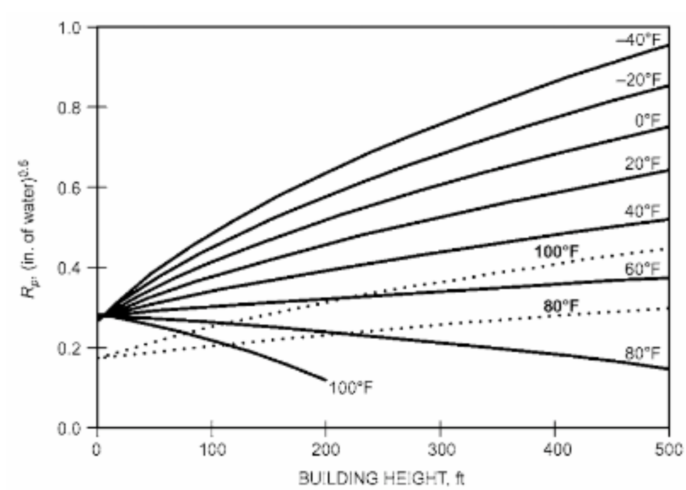


Figure 17: Pressure Factor for Automatic Doors [29]

2.3 Sensitivity Analysis

Uncertainty and sensitivity analysis are important in all modeling process as it helps decision-making to consider the influence of an individual parameter in the model [31]. There are primarily two techniques of sensitivity analysis, local sensitivity and global sensitivity. The local sensitivity method is based on calculation on the partial derivatives to measure the importance of parameter to its output. The global method is used to evaluate large number of parameters to consider the overall importance of each factor on its output [32].

2.3.1 Morris Method

Morris Method is a common global sensitivity analysis method that is derived from One-factor-at-a-time (OAT) screening technique. The OAT method is based on simply varying one factor at a time and estimate the variance in its outputs. In 1991, Morris proposed the Morris Method to better consider models with high uncertainty. The method characterizes sensitivity of a model with basic statistics, Elementary Effects (EE). The elementary effects are approximations of the first order partial derivatives of the model. It randomly selects start sample points and compares the points with changes of a p-values regular grid. The average and standard derivations of elementary effects can indicate the importance and the linear impact in the model. The method has been used in numerous fields such as Environmental Modeling, Agriculture, Biophysics, and Nuclear Engineering for large data analysis. There are other methods that could provide better information but computational cost. Such as the variance-based sensitivity indices (VBM) would requires 14,000 datapoint runs for just 12 input variables while Morris Method only requires 130 datapont runs [32].

The method has been tested in building energy simulation for sensitivity analysis. In an article by Corrado and Mechri [32], a sensitivity analysis was performed to analyze HVAC loads in a house using the Morris method. The sensitivity analysis shows the most influence parameters are the indoor temperature, the air change rate, the number of occupants, the metabolism rate, and the equipment heat gains [32].

CHAPTER 3

COMPUTATIONAL METHODOLOGY

In this chapter, a detailed computational methodology section on the workflow development process and sensitivity analysis method is described. The chapter is split into two parts: the methodology of workflow development process, followed by the sensitivity analysis methodology.

3.1 Workflow Development Process

The project objective is to generate a database of total electricity load data for all shelter type considering the variation in different parameters. These parameters include shelter geometry type, the different construction materials, internal loads and their schedules, the different HVAC systems, thermostat-set point, locations, building rotations, and infiltration. The large number of variation make modeling of all shelter type using OpenStudio Application and EnergyPlus interface ineffective. Up to 30% of HVAC system load can be occupancy-driven and yet, the occupancy schedule is one parameter that can vary in hundreds of ways. The PAT can be used in parametric studies but it is inefficient for large scale and evolving parameter values for consideration as user still have to interact with a GUI interface. In the future, more parameters would be considered to accurately model the different conditions of shelters in a forward operating base. For this reason, modeling the shelters based on Ruby scripting and measures seem more reasonable and effective.

As mentioned, measures can be gathered in a workflow to transform an OpenStudio model one step at a time. The goal of the workflow is to generate hundreds of simulations based on a matrix that considers all the parameters. The best way is to write one measure for each parameter. These measures include selection of geometry type, construction materials, number of people, number of lights, internal electric equipment load, schedules, location, HVAC system, thermostat-set points, building rotation, and infiltration information as shown in Figure 18. The breakdown of these different measure would make modification of any element in the model at anytime easier.

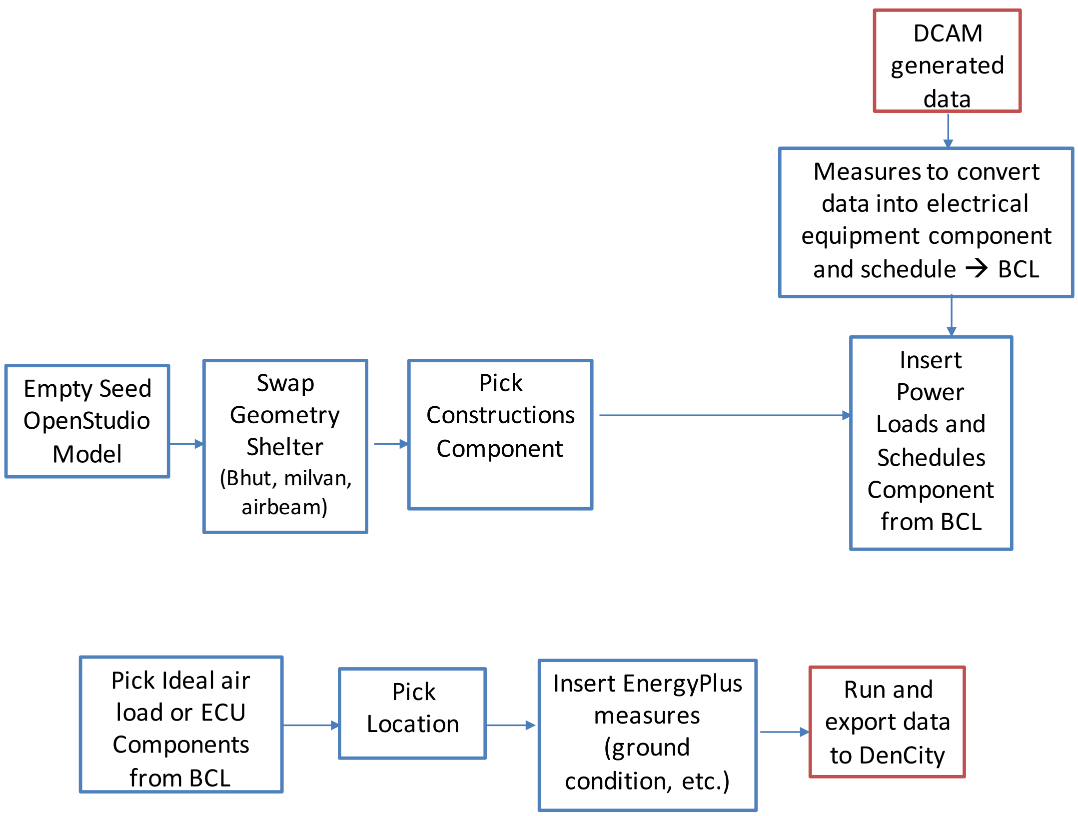


Figure 18: Initial Attempt Flowchart for Programmatic Modeling Process

There are numerous soft shell shelters and hard shell shelters with different geometry and dimension to be considered in a forward operating base. The workflow starts with an empty OpenStudio seed model to be exchanged by the shelter geometry desired for the facility. These geometries have a default construction modeled in the OpenStudio Model (OSM). The next step in the modeling process is to modify the construction (roof, floor, and etc.) of the shelter. MILVAN and CLU would have many insulation types based on the location. It is important to model all these insulation types to consider what type of insulation increase energy efficiency of the shelter. These constructions component would be pre-defined as OpenStudio component (OSC). As described in Chapter 2, constructions, schedules, and loads are resource objects. Initially, all resource objects would be placed in a private BCL and the measure would link to the private BCL to obtain the components. These resource objects are kept locally in the resources file of a private Github repository, because of the security reason, for extraction. The next step is to set the internal loads, including occupancy schedule, light definition and schedules, and electric equipment loads and schedules. These components are generated from another measures that convert the spreadsheet data of the power load profile to electrical equipment and schedule (.osc) component file. The next step is to consider the selection of HVAC system. Then, location selection and inputs of infiltration information. For function not available in OpenStudio, EnergyPlus measures are needed to input into the model. EnergyPlus measures are applied after all OpenStudio measures. This is because OpenStudio model is translated into EnergyPlus format before simulation runs. The EnergyPlus measures can only be added after the translation.

Each shelter geometry has infiltration and boundary conditions that can only be modeled in EnergyPlus. For this reason, each shelter type has a unique set of EnergyPlus measures to construct these shelters' conditions. That means the workflow would be composed by different set of measures. However, to make the workflow more effective, it is very important to generate a single workflow that would consider all the shelter types and its variable. This responsibility lies upon the input variable known as argument and is the reason for building a multi-dimensional matrix.

NREL provides gem packages called OpenStudio workflow-gem, aws-gem, and analysis-gem on Github for developers to run modeling simulation process programmatically. Gems are libraries or packages in the Ruby Programming language. The OpenStudio workflow-gem is a package needed to run an EneryPlus simulation using a file-based workflow that is read from the local drive. The gem has dependencies on Ruby 2.0, OpenStudio, EnergyPlus, and MongoDB. The gem read the analysis.json generated from the analysis-gem that states the analysis to be run. It includes exception classes to better consider the errors. It also implements logger of runs in the adapters and hook up all the measures in the workflow. The OpenStudio analysis-gem creates the analysis.json and analysis.zip files needed for the OpenStudio Distributed Analysis. The OpenStudio aws-gem allows user to connect serve on Amazon EC2 cloud. These gem packages can be referenced with proper Ruby scripting to customize a programmatic modeling workflow.

The purpose of a multi-dimensional matrix is to allow users to run the workflow using a simple Excel matrix interface. This process required a Ruby script to read the multi-dimensional matrix and translate the values into the workflow inputs. After the model has been created and ran, reporting measures are needed to push the completed simulation datapoints into the DEnCity database created by NREL.

3.2 Sensitivity Analysis Methodology

The objective of the sensitivity analysis study is to determine which variables are most influential in electric consumption of the shelter. This would provide guidelines for what models should be included in the DEnCity database. This initial sensitivity analysis study does not only provide the sensitivity analysis results of the AIRBEAM and MILVAN, but it also provides the guidelines to perform sensitivity analysis study of other shelters in the future.

Two methods are used in the sensitivity analysis. The first method uses one at a time (OAT) sampling of variables to understand the difference in total site electricity influenced by varying the different parameters. The method will calculate a range of output total site electricity load and will be shown in tornado graphs for different locations. The OAT method is used to get the interactive effects. The second method uses Morris Method. The method is commonly used for large data sensitivity analysis and better capture the impact of a variable than method one. Since some variables are dependent on other variables, which first method could not capture.

3.2.1 Morris Method

The first step of Morris Method is calculating the elementary effects for each factor (i). In building energy model, the energy consumption is the output variable of interest where it can be represented by a function of y(x) with x as a vector of input variables. The input variables used in calculation of elementary effect are reduced dimensionless variables calculated by the maximum (x_{max}) and minimum (x_{min}) values of the variable in Equation 5 [32]. For k number of factors in the model, there will be k number of reduced dimensionless variables, each identified as x_i' in Equation 5.

$$x_i' = \frac{x_i - x_{min}}{x_{max} - x_{min}};\ x_i' \in [0,1] \tag{5}$$

The elementary effects are calculated in Equation 6, which is comparable to the first order partial derivatives equation for each variable. A simulation trajectory has a sequence of (k+1) datapoints, where k is the number of variables. In a trajectory, each input parameter only changes once with pre-defined step (Δ_i) and y(x) is evaluated for every parameter (i). In Equation 6, e_i is the unit vector which equaled to 1 in this case.

$$EE_i = \frac{y(x \pm \Delta_i) - y(x)}{\Delta_i} \tag{6}$$

The Δ_i is a value in a uniform distribution in intervals [0,1], calculated using a grid value (p). The regular grid values are calculated as 0; $\frac{1}{p-1}$; $\frac{2}{p-1}$; ... ; 1. In Morris Method, to ensure equal probability for each value, p value is suggested to be even and has the pre-defined step , $\Delta_i = \frac{p}{2*(p-1)}$. The initial value of a single run is randomly selected. If initial value of x_i' is less than 0.5, the final value in Equation 6 is $x_i \ + \Delta_i$. Otherwise, $x_i \ - \Delta_i$ if initial value is greater than 0.5. The mean (μ) and standard derivation (σ) of elementary effects highlight the importance of each parameter and can be calculated using Equations 7 and 8. The calculation of mean and standard derivation depends on r-value, which specifies the number of runs/trajectories in elementary effects calculation. The r-value is user-defined value leads to a cost of r·(k+1) simulations; w is defined as a trajectory in r number of trajectories. One trajectory equaled to (k+1) simulations with each initial value selected randomly to be used in comparison. Higher number of r trajectories should be defined when analysis has large number of input variables. An example of morris method considering three variables and r-value of 2 is shown in Figure 19.

$$\mu_i \ = \frac{1}{r} \sum_{w=1}^{r} EE_{iw} \tag{7}$$

$$\sigma_i = \sqrt{\frac{1}{(r-1)} \sum_{w=1}^{r} (EE_{iw} - \mu_i)^2} \tag{8}$$

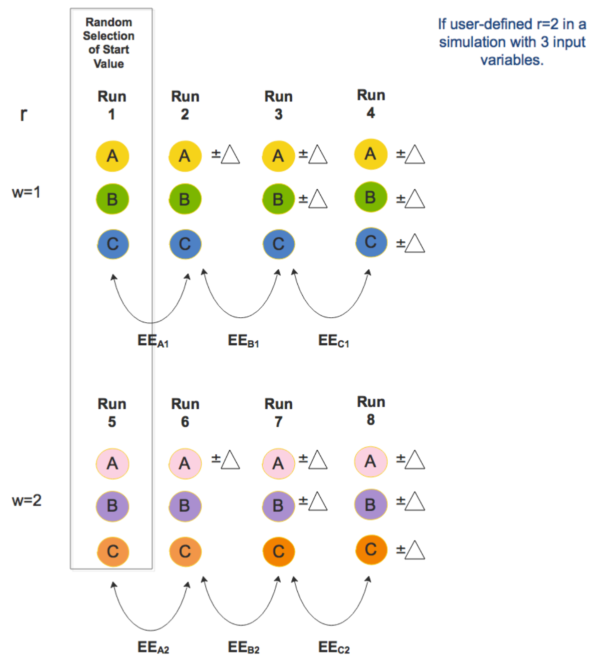


Figure 19: Example of Morris Method

As seen in Equation 6, the elementary effects could have a negative value based on the energy consumption output value calculated in the simulation. The mean predicted by Morris Method in Equation 9, is a better indicator to classify the order of importance of the input factors by considering the negative value. However, the sign of the elementary effects is lost in this case.

$$\mu_i^* = \frac{1}{r}\sum_{w=1}^{r}|EE_{iw}| \tag{9}$$

While the mean (mu) value shows the order of importance for the factors, the standard derivation is an indicator of linearity of the input factors. For low mean value and standard deviation value, the factor is identified to have negligible effect in the model. If the factor has a high mean value, the input factor has an importance influence in the model. For a factor that has a high standard deviation value, it indicates the factor has high dependence on other input factors. An example of the scatter plot of the mean and standard value is shown in Figure 20.

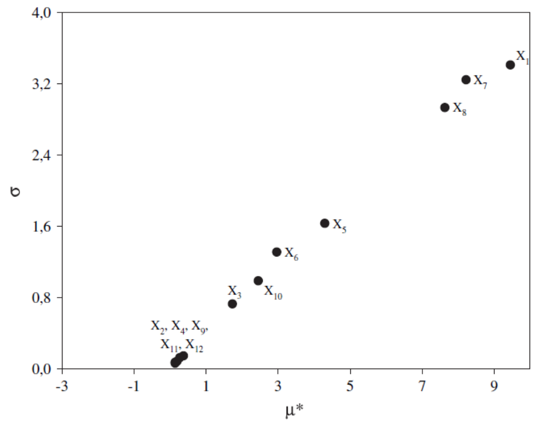


Figure 20: Example of Morris Method Scatter Plot [31]

An enhanced sampling strategy on the EE method has been developed for better scanning technique to minimize the number of sampling needed. In original EE method, the typical number of trajectories (r) is between 10 and 50. It is designed to have random starting point for each trajectory and randomly sample each factor at a time. However, this is inefficient if there are large number of input factors. The improved strategy is based on the concept of spread or distance (d_{ml}) between two trajectories m and l, which can be calculated by Equation 10, where X is the input parameters. The (d_{ml}) is the sum of the geometric distances between all the points in the two fixed trajectories.

$$d_{ml} = \begin{cases} \sum_{i=1}^{k+1} \sum_{j=1}^{k+1} \sqrt{\sum_{z=1}^{k} \left[X_i^m(z) - X_j^l(z)\right]^2} \; for\ m \neq l \end{cases} \tag{10}$$

First high number of randomly generated Morris trajectories, M, are generated. A d_{ml} (DM) matrix is generated based on Equation 10 for each trajectory. The r trajectories out of the M trajectories that has the highest d_{ml} are selected. The sum of all the d_{ml} (D) between couples of trajectories belonging to the combination is calculated as shown in Equation 11. The equation is based on an example with r=4 where the trajectories chosen are 4,6,7, and 9 out of M= {1,2,3,4,5,6,7,8,9,10}. After the computation of D value for the highest d_{ml} value of r trajectories, it will loop back to the DM matrix for the next highest d_{ml} value of r trajectories until the highest value of D is founded. The r trajectories that give the highest value of D is considered in the enhanced Morris Method [31,33].

$$D_{4,6,7,9} = \sqrt{d_{4,6}^2 + d_{4,7}^2 + d_{4,9}^2 + d_{6,7}^2 + d_{6,9}^2 + d_{7,9}^2} \tag{11}$$

3.2.2 Sensitivity Analysis Workflow

The sensitivity analysis study observes the total site energy load [GJ] based on changes of the variables. The variables considered the changes of light load, people load, electric equipment load, the different schedule, adjusting the thermostat-set point, building rotation, and entry infiltrations. The three locations used in the present study are Kharga (Desert), Singapore (Tropical), and Chongjin (Temperate). The mechanical system used for the study is HDT F100. Only Chongjin and Kharga locations use an internal heater based on the winter time specified in the workflow. Singapore has an average temperature of 80°F year round for which heater can be neglected.

Two facility equipment loads provided by CERL are also used to represent the range of low and high equipment loads. The low-ranged electric load used in modeling is VIP(0.2kW), a billeting facility load for visitors, equipped mostly in CHU shelter. The high-ranged electric load modeled is TAC (11.40kW), a command center facility load for AIRBEAM shelter. All of these facility loads are within peak sustained power shown in Table 3.

Table 3: Peak Sustained Power and Occupancy

Shelter Type	Peak Sustained Power (kW)	Peak Sustained Occupancy (ppl)
CHU	9.6	6
MILVAN	19.2	8
BHUT	19.2	24
	9.6 (if used for billeting)	
AIRBEAM	19.2	24
	9.6 (if used for billeting)	

The peak sustained power and peak sustained occupancy for each shelter are provided by USACE/CERL for the sensitivity analysis study, as shown in Table 3. The peak occupancy values shown in Table 3 stand for the peak number of people in a shelter at a time and is used to model the occupancy of people in the models.

A Ruby workflow is used in the sensitivity analysis. The workflow is composed of eleven OpenStudio measures as shown in Figure 21. Each measure is described in Chapter 4. The measures consider the impact of people, light, electric equipment load, schedules, location, building rotations, and infiltration. The focus of the sensitivity analysis is to understand what factor has the most impact in the energy consumption of the shelter. The energy consumption highly depends on the schedules in the shelter. For that, most variables are used to vary the schedules.

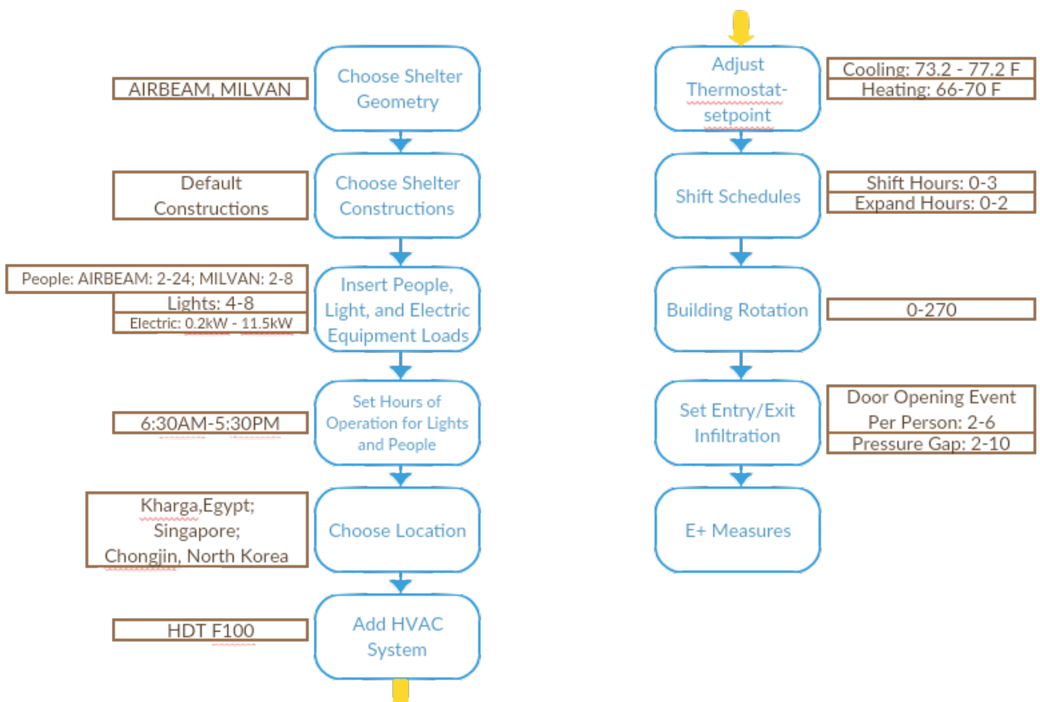


Figure 21: Flowchart of the Sensitivity Analysis

The sensitivity analysis workflow is constructed to work with all shelter geometry type. The first measure in Table 4 is used to select the shelter geometry type. In this study, two geometry type are used, which are AIRBEAM and MILVAN. The second measure is used to select the constructions for the shelter. These included materials for insulation and interior wall if shelter required that. The comparison of different constructions is not being studied in the report because all constructions are assumed to be modeled and pushed into DEnCity. The third measure changes the number of people, the number of light, and select the electric equipment load for the shelter. The number of people is a constant value that describe the peak number of people in the shelter over the schedule of time. The light equipment is a commonly used fluorescent light with model name, Jameson. The electric equipment load selected is based on a daily facility schedule provided by CERL. Measure 4 set the hours of operation based on a start time and end time as shown in Figure 22; the facility hours of operation is set at 6:30AM to 5:30PM. The people hours of operation is set similar to the facility hours of operation with fractional variation from 1, 0.5, and 0.8 as shown in Figure 22. The static value for activity level is 130 watts/person to represent a person's activity in office work as shown in Figure 22. Measure 5 chooses the location where the shelter would be located. Measure 6 select the HVAC unit for the shelter and the standard thermostat-set point at 72.5°F for cooling and 68°F for heating. Measure 7 adjust the thermostat-set points set by measure 6 to the desired temperature. Measure 8 would shift and expand the facility hours of operation, light schedule, electric equipment schedule, and occupancy schedules hourly as shown in Figure 23. The measure is to model the importance of the small changes in the schedules. Measure 9 set the building rotation in 0, 90, 180, and 270-degree coordinate. Measure 10 set the entry and exit infiltration by considering the number of people, the occupancy schedule, the door opening event per person, and the pressure gap across the door.

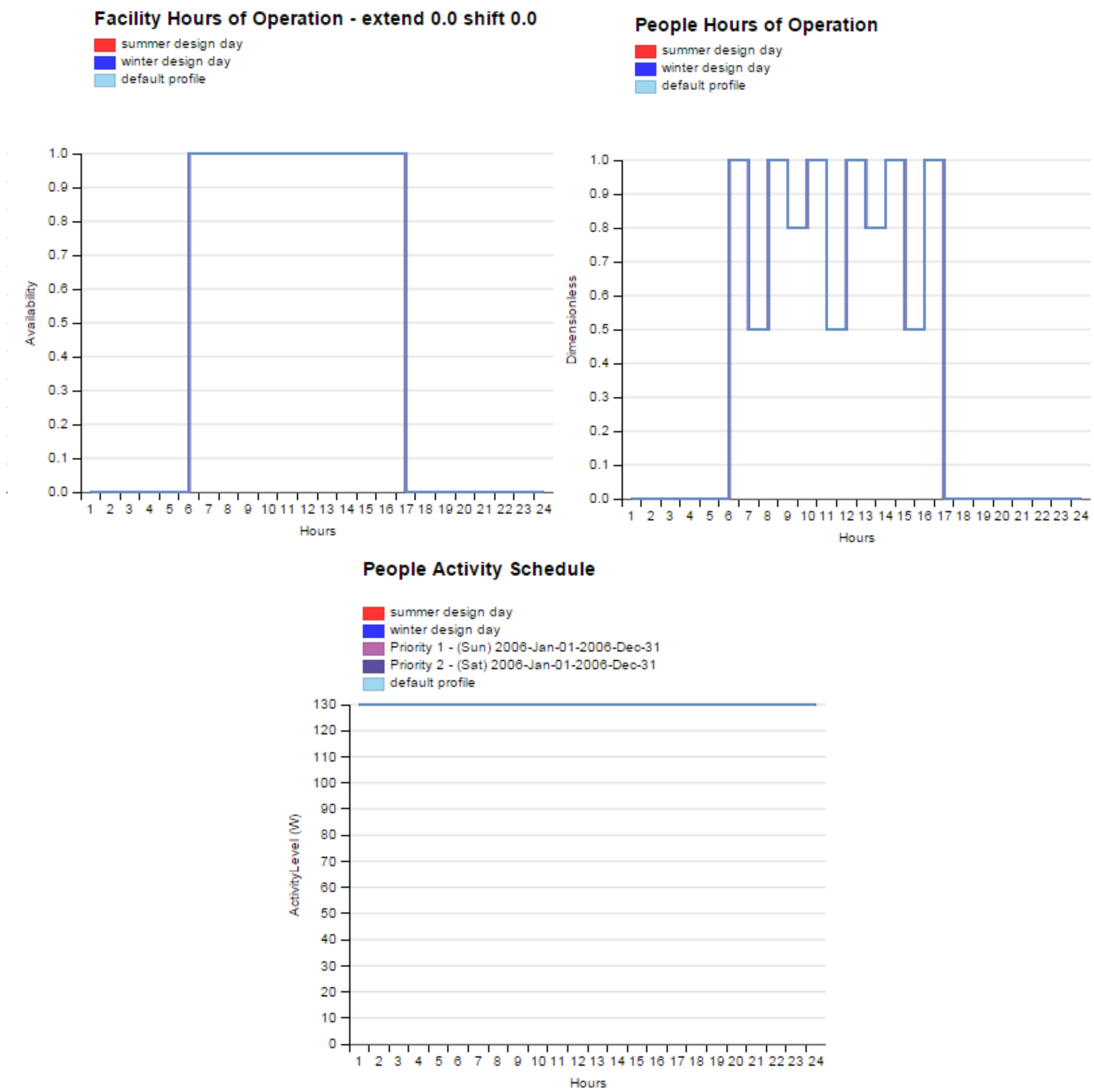


Figure 22: Hours of Operation, Occupancy, and People Activity Level Schedules.

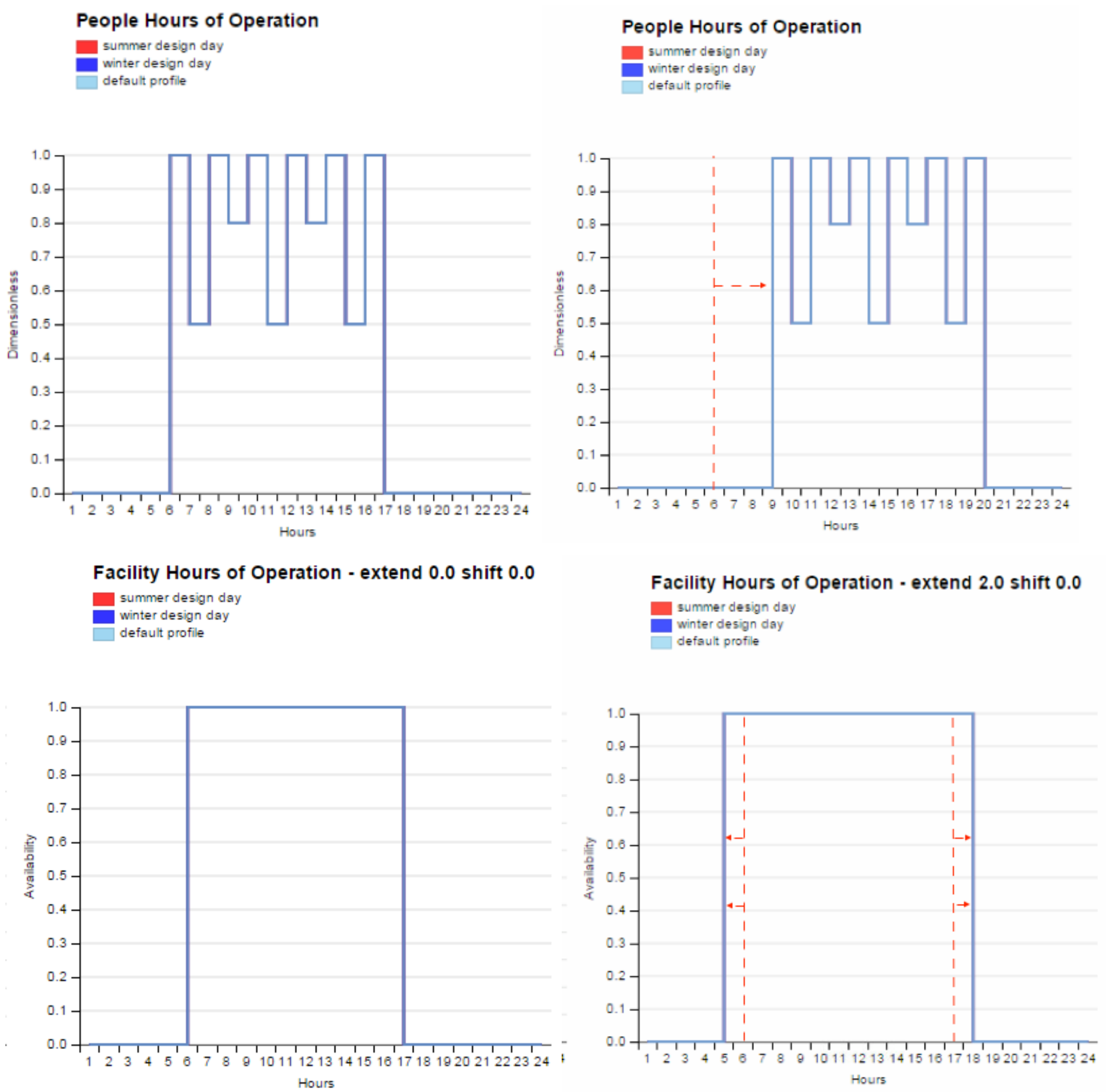


Figure 23: Shifting and Expanding Schedules

Table 4: Measures Used in the Sensitivity Analysis

Measures	Description
1. Choose Shelter Geometry	The measure import the components for the shelter geometry.
2. Choose Shelter Construction	The measure import the construction components into the shelter.
3. Insert People, Light, and Electric Equipment Load	The measure import the internal loads of people, light, and electric equipment into the shelter.
4. Set Hours of Operation for Lights and People	The measure set a default schedule. The start time and end time can be set by the user. The user can also select the light schedule and people schedule be the same of the hours of operation.
5. Choose Location	The measure will select the weather data based on location.
6. Add HVAC System	The measure will import the ECU loop into shelter. It also auto-setup the thermostat set points for heating at 20°C (68°F) and cooling at 24°C (75.2°F)
7. Adjust Thermostat set points	The measure adjusts the thermostat set point by number of degrees specified from the inputs.
8. Shift Hours of Operation	The measure will shift the schedules for lights and internal electric equipment loads.
9. Building Rotation	The measure will rotate the shelter based on specified degree.
10. Set Entry / Exit Infiltration	The measure calculate the entry / exit infiltration schedules based on the number of people schedule, the door opening event per person, and the pressure difference across door.

CHAPTER 4

WORKFLOW MODELING DEVELOPMENT

In this chapter, a detailed description on the workflow modeling development is described. The chapter is split into six parts: workflow overview, multi-dimensional matrix, script to export matrix data into inputs, OpenStudio Measures, EnergyPlus Measures, Reporting measures, and Helper Measure used in the workflow is discussed in details.

4.1 Workflow Overview

The goal of the load generation tool is to be able to generate detailed electrical energy load profiles for any given outpost configuration of interest based on a variety of inputs that include number and schedule of personnel, geographic location, number and types of Environmental Control Units (ECUs) and associated HVAC controls, shelter infrastructure type, number, composition and configuration, etc. A workflow is coded in Ruby 2.0 to generate all these possible shelter models to produce the detailed electrical energy load profiles.

The first part is a readable Excel matrix that composed variety of inputs for shelter configuration of interests. The second part is a ruby script that will extract matrix's data into hashes, and then import these hashes as inputs. The inputs will be used as arguments for the ruby measures. The third part of the ruby code is composed of numerous ruby measures that works inter-connected with OpenStudio and EnergyPlus to build and simulate the shelter models. The last part of the code is pushing output data into DEnCity database as shown in Figure 24.

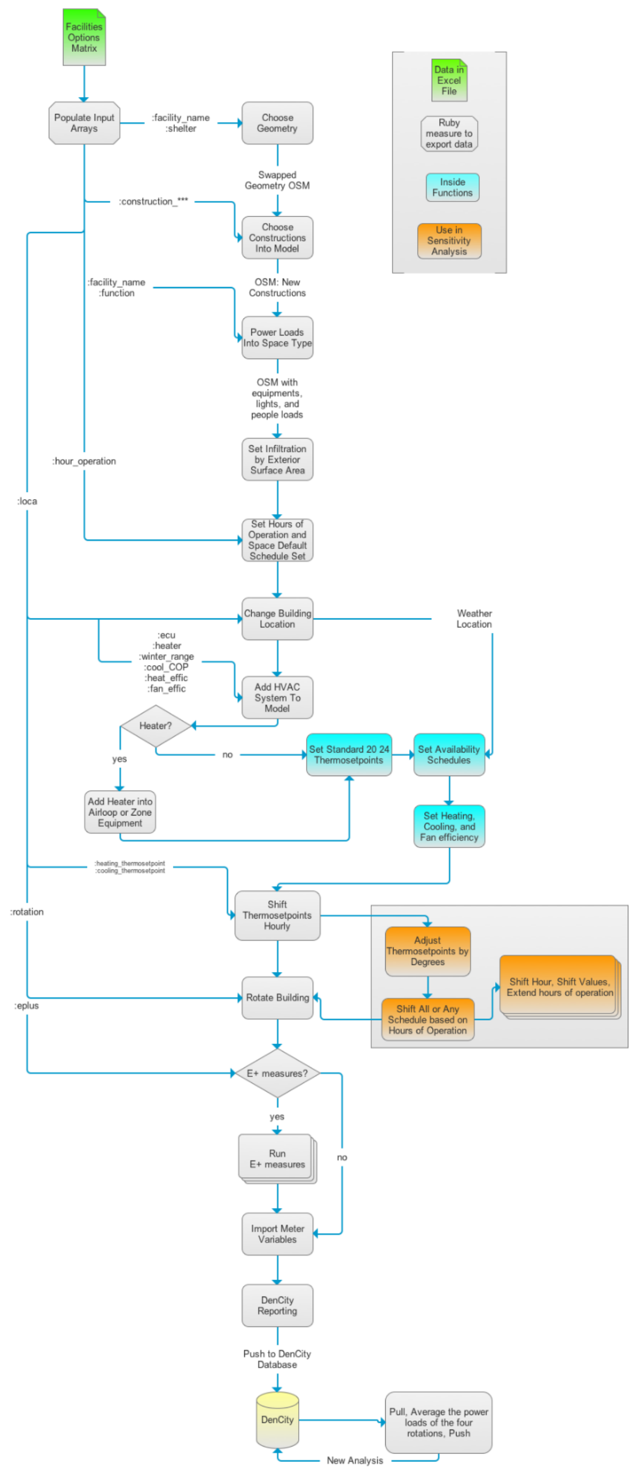


Figure 24: Workflow Development Overview

User of the workflow is required to have the following software to run the load generation tool workflow: Github, Ruby 2.0, OpenStudio Version 1.7.2 & above, EnergyPlus Version 8.3.0 & above. A local OpenStudio server or AWS account is required to run the multi-data points analysis. The user should have an understanding of Ruby 2.0, OpenStudio, and EnergyPlus before using the codes. The workflow also required Roo version 2.3.1, which is a Ruby gem for reading Excel file. The workflow of the load generation tool is located in the Github file in the link (https://github.com/satishkumar33/Shelter_Corso.git).

4.2 Multi-dimensional Matrix

For easier interface interaction, a multi-dimensional matrix of inputs is created. The multi-dimensional matrix is created using Excel that consider the input of facility type, shelter geometry type, construction type, schedules, locations, HVAC system selection, thermostat-set points, and E+ measures for different types of shelter. The matrix is easy to interact as shown in Figure 25. The Excel sheet have the following tabs: “Major”, “weather”, “AIRBEAM”, “BHUT”, “MILVAN”, “LAVMS”, “TRICON”, “LME”, “ECHS”, “milvaneplus”, “airbeameplus”, “bhutplus”, and “SensitivityAnalysis”.

The “Major” tab considered each unique facility instance name and the facility name in database on each row. Each column is an argument for each facility if the value is set to “1”. These arguments included selection of shelter type, HVAC system, heater, building rotation, hours of operation, and thermostat-setpoint. The cell that has the value of zero will be ignored when the matrix is being read. The input data in the matrix would be read from a Ruby script. With exception on the facility instance name, database name, and shelter type, and all other arguments can be selected more than once. Row 1 of the

Excel sheet is the hash key name to be read by the script. Row 3 is the hash value to be read by the script. A new column can be inserted by the user to consider additional choice of function, shelter, ECU, heater, EnergyPlus measure, and rotation. A new facility type can be added as new row in the "Major" tab.

	A	B	C	D	E	F
1			function	function	function	function
2		id	1	2	3	4
3	Facility Name in Database	Facility Instance Name / Load Profile Name	Enable Base Command and Control, Communications & Computing	Execute Protection	Mission Support	Provide Access to Maintenance/Repair
4	Airbeam Command Structure	Battalion TAC	0	0	0	0
5	AN-TSC-185 Satellite Transportable Terminal	STT	1	0	0	0
6	CHU Billeting Structure	Visitor CHU 1	0	0	0	0
7	Climate-Controlled, Lighted MILVAN Shelter	AAFES	0	0	0	0
8	Climate-Controlled, Lighted MILVAN Shelter	Chapel	0	0	0	0
9	Climate-Controlled, Lighted MILVAN Shelter	Key Leader Engagement Area	0	0	1	0
10	Climate-Controlled, Lighted MILVAN Shelter	Supply Office	0	0	0	0
11	Consolidated Supply Room	Consolidated Supply Room	0	0	0	0
12	Containerized Kitchen, NSN-7360-01-473-3408	CK	0	0	0	0
13	Entry Control Point	ECP	0	1	0	0
14	Expeditionary Containerized Batch Laundry, NSN-5419-01-539-7180	ET Batch Laundry	0	0	0	0
15	Expeditionary Latrine System, NSN-5419-01-539-7179	Latrine	0	0	0	0
16	Expeditionary Shower System, NSN-5419-01-539-7182	Shower	0	0	0	0
17	Expeditionary TRICON Kitchen System, NSN-5419-01-571-4107	ET Kitchen	0	0	0	0
18	Food Sanitation Center, FSC-2, NSN-7360-01-496-2112	Food Sanitation Tent	0	0	0	0
19	Forward Maintenance Assembly, M7 FRS, LIN-F64544	M7 Repair System	0	0	0	1
20	FP Billeting Tent	Billeting Tent	0	0	0	0
21	FP Billeting Tent	Transient	0	0	0	0
22	FP Changing Tent	Changing Tent	0	0	0	0
23	FP Dining Tent	Dining Tent	0	0	0	0
24	FP General Purpose Tent	QRF Staging Shelter	0	0	1	0

Major | weather | AIRBEAM | BHUT | MILVAN | LAVMS | Tricon | LME | ECHS | milvaneplus | airbeameplus | bhuteplus | SensitivityAnalysis | +

Figure 25: Matrix Interface

The "weather" sheet is used to specify the heater availability time for certain location. The first column listed out the weather file name for the desired location. The second column listed out the heater availability time that corresponded to the location on column 1. The format for the winter range input is start date to ending date, MM/DD-MM/DD. User can input "None" for location without the needs of heater.

If adding a new shelter type, a new Excel sheet with shelter structure name should also be added. The new Excel sheet should include a choice of constructions that could be used in the shelter structure. The user should consider what insulation should be used in certain climate or location on each row. The choice of construction includes the walls, roof, floor, and other (window, door, attic, and etc. constructions). User should input the filename of the OpenStudio components in the resource file of the construction selection measure.

Each shelter type might requires E+ measures in shelter modeling. A new sheet can be added if a new set of E+ measures are needed for specified facility. The E+ measure sheet should include the filename, arguments, and values of the measures used in the facility. The new sheet should be named lowercased in the following format: “name of shelter”+ “eplus.” The “SensitivityAnalysis” tab lists out all the arguments and values that would be needed in sensitivity analysis runs.

4.3 Export Input Data Script

The multi-dimensional matrix is easy to modify and to consider any new additional input variables in the future. Since the matrix is in Excel table format, a Ruby script is required for importing the data from the matrix into the input of the workflow. The inputs for each simulation run of the workflow is a hash of arrays. A hash of array is an array that uses string for indexing rather than index number. It is also known as associative array. The script should read the Excel sheets and translate the data into a set of hash of arrays.

The Ruby script written for this function is called “Export_Matrix.rb” with method called populate_arrays() in the script that read the Excel sheet one by one as shown in Figure 26. First, each row in the “Major” sheet is read for the facility instance and database name, the shelter type, HVAC system used for that facility type, and etc. as shown in Table 5. Once the shelter type name is read, it will automatically read the construction sheet and E+ sheet accordingly and create a simulation array.

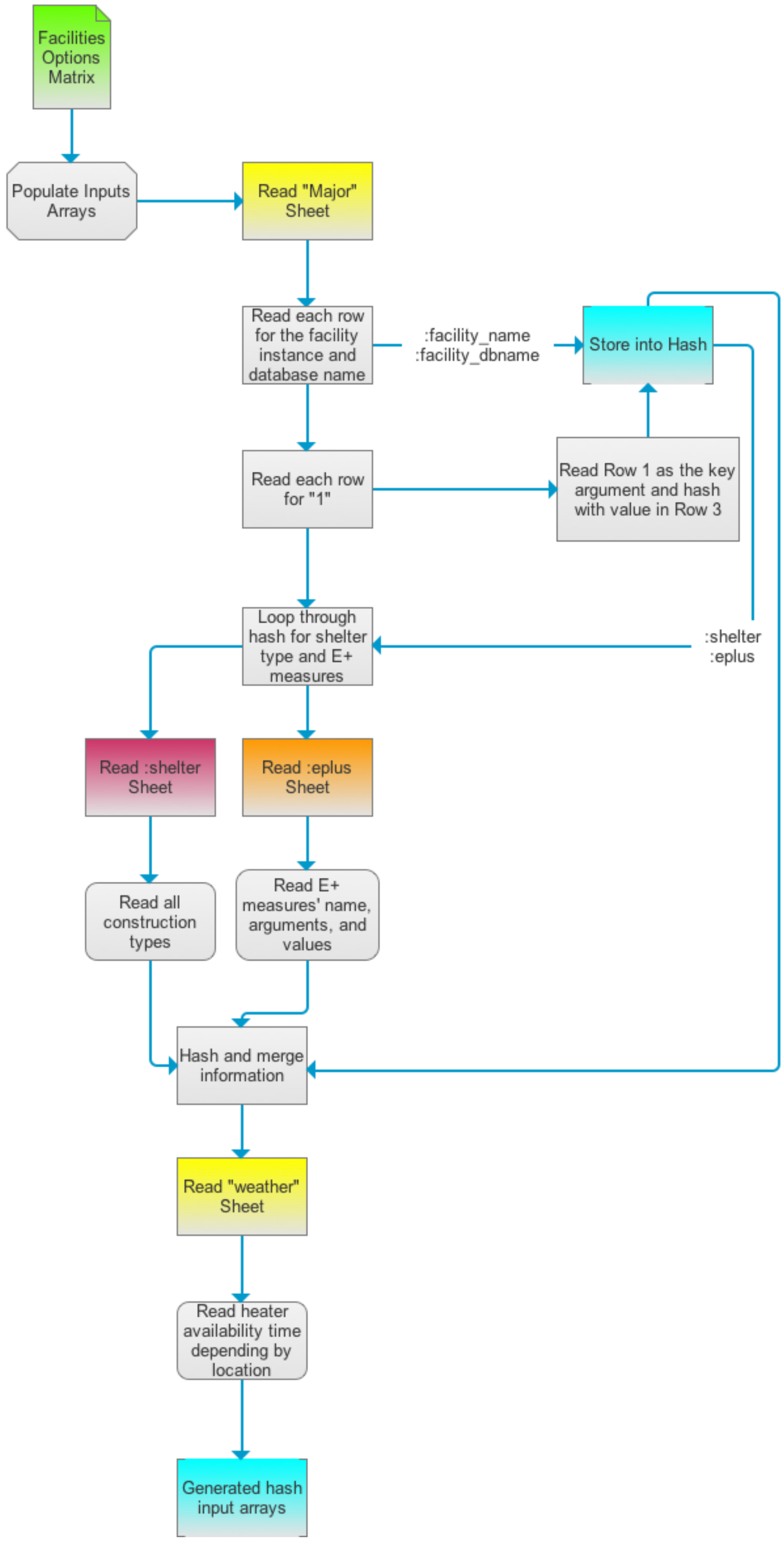


Figure 26: Flowchart of the Populate Array Method

Table 5: The Key and Value of Hash Arrays

Hash key	**Description**	**Arguments or Variables Type**
:facility_name	Facility Instance Name	Argument
:facility_dbname	Facility Database Name	Argument
:function	Function of the shelter	Argument
:shelter	Shelter geometry type	Argument or Variables
:ecu	ECU / HVAC System in OSM file	Variables
:heater	Heaters	Argument or Variables
:loca	Possible locations	Variables
:construction_walls	Required: An array of possible construction walls.	Variables
:construction_roof	Optional: An array of possible construction roofs.	Variables
:construction_floor	Optional: An array of possible construction floor.	Variables
:construction_doors	Optional: An array of possible construction doors.	Variables
:construction_windows	Optional: An array of possible construction windows.	Variables
:construction_other	Optional: An array of any other possible constructions.	Variables
:rotation	The building rotation to model	Variables
:hour_operation	The hours of operation defined in string as "24,1" as default, which means always on 24/7	Argument
:cooling_thermosetpoint	The cooling thermosetpoint for the HVAC system schedule in "time, value, time, value…" format.	Argument
:heating_thermosetpoint	The heating thermosetpoint for the HVAC system schedule in "time, value, time, value…" format.	Argument

4.4 OpenStudio Measures

As discussed in Chapter 2, OpenStudio Measures are programmatic instructions written in Ruby that alter a model. The SDK documentation provides pointers to Model Objects in OpenStudio Application for modification in Ruby measures interface. These includes the selection of geometry shelter type, construction component, number of personnel, light definition, electric equipment definition, schedules, location, HVAC system, thermostat-setpoint, building rotation, and geographic location.

4.4.1 Choose Geometry

Numerous shelter types are used in a forward operating base, including AIRBEAM, BHUT, MILVAN, CLU/CHU, LAVMS, Tricon, LME, ECHS, etc. All geometry type should be modeled in SketchUp with a default construction type. To ensure a single workflow runs all the simulation datapoint, the first measure should allow user to select the geometry shelter type. The concept of the Choose Geometry Measure is to transform an empty seed model into the desired geometry shelter type. The geometry shelter type is created in SketchUp with OpenStudio Plug-in. Figure 27 showed the MILVAN and CHU SketchUp model that are used in the measure.

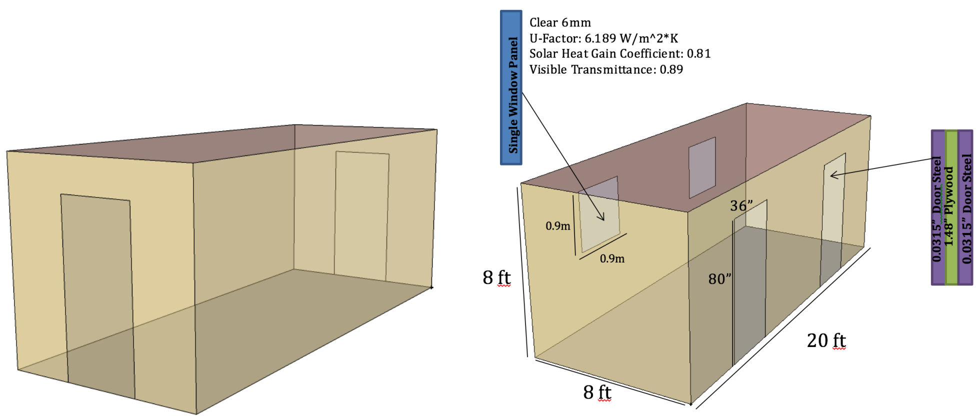


Figure 27: MILVAN and CLU SketchUp Model

Based on user input on *:shelter,* the measure would swap out the empty seed model with geometry type of choice. The measure also replaces the building name with facility instance name. The measure also create a space type named after the shelter name to be used as an identifier for the Choose Construction into Model measure. The list of arguments used for the measure is shown in Table 6.

Table 6: Argument for Choose Geometry Measure

Argument name	Type	Default Value
geometry	String	:shelter
building_name	String	:facility_name

The measure directory is shown in Table 7 where all geometry shelter model in the appropriate format should be placed in the local resource file. There are other limitations in the measure. All geometry shelter model filename in the resources file should have the same string value passed into argument name: *geometry*. These shelter models should be in OSM format with surfaces information and a default construction modeled in the file. For the measure to consider more geometry types, user should place new geometry model into the resources file.

Table 7: File Path for Choose Geometry Measure

Directory	https://github.com/satishkumar33/Shelter_Corso/tree/master/shelter_modeling/measures/ChooseGeometry/
Included:	./resources ./tests measure.rb measure.json measure.xml
./resources	CHU.osm MILVAN.osm AIRBEAM.osm BHUT.osm
./tests	choose_geometry_test.rb test.osm test_input.osm

4.4.2 Choose Construction Component Into Model

Each shelter type can have many different construction materials. Just MILVAN alone, there are six insulation types and two interior wall types. Considering all possible combination, twelve different constructions of MILVAN need to be model. The Choose Construction Into Model measure is used to replace an existing construction in the geometry model with construction specified by the user. If no change is desired, a simple

“No Change” can be feed into the arguments. The measure required the construction name string value in the ModelObject to be the same as the ModelObject name value in the OpenStudio component OSC file. That is the key connection for replacing the shetler’s constructions.

The arguments for the measures allow user to replace constructions for walls, roof, floor, doors, windows, and others as shown in Table 8. Only the argument for construction walls is required for input. For B-hut, the construction for attic can be replaced by using other constructions. The input arguments are not tie to only the surface it specified, but the concept is to replace the construction layers if ModelObjects of the input component have the same string name as those ModelObjects in the model. If there are no window in the shelter, user can still use the argument to exchange for other construction component.

Table 8: Argument for Choose Construction Into Model Measure

Argument name	**Type**	**Default Value**
construction_walls	String	:construction_walls
construction_roof	String	:construction_roof
construction_floor	String	:construction_floor
construction_doors	String	:construction_doors
construction_windows	String	:construction_windows
construction_others	String	No Change

There are limitations in the measure. Only existing construction in the model can be replaced with the OpenStudio component (osc) of user’s choice. To insert or delete a layer of new material onto a construction surface, user is required to build the construction component first to be used in this measure. The function for inserting and deleting a layer material is not in this measure. The OpenStudio construction component file is required to run this measure. The filename of these components should be the same as the input values and should be placed in the resources file as shown in Table 9. The EnergyPlus (.idf) and the OpenStudio model (.osm) is included for possible future reference.

Table 9: File Path for Choose Construction Into Model Measure

Directory	https://github.com/satishkumar33/Shelter_Corso/tree/master/shelter_modeling/measures/ChooseConstructionIntoModel/
Included:	./resources ./tests measure.rb measure.json measure.xml
./resources	*.osc (See Appendix) *.idf *.osm
./tests	choose_construction_into_model_test.rb test.osm test_input.osm

4.4.3 Add Electric Equipment Definition and Schedule

There are three types of internal loads in each shelter of an operating base. These include the electric equipment load, occupancy load, and light load. The electric equipment load depends on facility type. TECD document listed out most of the facility types used in a forward operating base. CERL also provides a 24-hour electric load for each facility type they measured in Excel format. To insert these electric equipment load into the shelter mode, the information from Excel should be transformed into OpenStudio component format. A helper measure would be used for the generation.

The electric equipment load measure imports the electric equipment definition and schedule into the model. The measure first creates a space type named after the function of the shelter. The electric equipment load components (.osc) are named after the facility instance name to be inserted into the created space type. The facility instance name would automatically use an argument for the measure to clone the equipment load into the model. At last, the created space type would be attached to the “Main_Zone” in the model. The argument for the measure is shown in Table 10. There are limitations in the measure as all schedule and power load components should be located in the local resource file.

Table 10: Arguments for Electric Equipment Definition and Schedule Measure

Argument name	Type	Default Value
function	String	:function
npeople	Integer	-
nlight	String	-
powerload	String	:facility_name

Table 11: File Path for Electric Equipment Definition and Schedule Measure

Directory	https://github.com/satishkumar33/Shelter_Corso/tree/master/shelter_modeling/measures/ add_electric_equipment_into_space_type /
Included:	./resources ./tests measure.rb measure.json measure.xml
./resources	*.osc (See Appendix)
./tests	add_electric_equipment_into_space_type_test.rb test.osm test_input.osm

4.4.4 Add People Definition and Schedule

The function of the measure allows user to add the occupancy schedule and people activity level into the shelter model. The measure set the people definition by defining the peak number of people in the shelter at the duration of the mission. The occupancy schedule can be imported from an OpenStudio component from the local resource file. If user desired to create an occupancy schedule based on hours of operation, user can specify “hoo” as value for the people_schedule_filename argument. User is also required to input the space type name, which is the function of the facility as specified in previous measure. If a space type has not been initialized by previous measure, it would be created in this measure. The arguments information of the measure is shown in Table 12. The measure file directory is shown in Table 13.

Table 12: Arguments for People Definition and Schedule Measure

Argument name	Type	Default Value
spacetype_name_people	String	:function
people_schedule_filename	String	hoo
number_of_people	Double	2

Table 13: File Path for People Definition and Schedule Measure

Directory	https://github.com/satishkumar33/Shelter_Corso/tree/master/shelter_modeling/measures/add_people_into_space_type/
Included:	./resources ./tests measure.rb measure.json measure.xml
./resources	*.osc
./tests	add_people_into_space_type_test.rb test.osm test_input.osm

4.4.5 Add Light Definition and Schedule

The function of the measure adds the light definition and schedule into the space type of the shelter. The light definition components should be placed inside the resources file. There are numerous light models used in a forward operating base. Jameson 31-502SK is an electromagnet interference (EMI) protected fluorescent stringable light that is commonly used in the shelters as shown in Figure 28. It is the only light that has been modeled in the resources file but this will change in the future as the library of light definition expands.

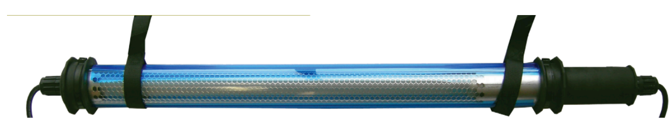


Figure 28: Jameson 20-502SK Light

Jameson 31-502SK light has power consumption of 36 Watts that operate independently with on/off switches. As shown in Table 14, the measure allows user to define the number of light, choice of light definition, and light schedule filename. The light schedule can be imported from OpenStudio components located in the resources file. If user desired, the light schedule can also follow the hours of operation by specifying “hoo” as string value of light schedule filename.

Table 14: Arguments for Light Definition and Schedule Measure

Argument name	Type	Default Value
spacetype_name	String	:function
light_filename	String	jameson_lightdefinition
number_of_lights	Double	4
light_schedule	String	hoo

From TECD document, the number of light used in the shelter range from 4 Jameson in a MILVAN shelter to 8 Jameson in an Airbeam shelter. All OpenStudio component should be placed in resources file as shown in Table 15.

Table 15: File Path for Light Definition and Schedule Measure

Directory	https://github.com/satishkumar33/Shelter_Corso/tree/master/shelter_modeling/measures/add_lights_into_space_type/
Included:	./resources ./tests measure.rb measure.json measure.xml
./resources	jameson_lightdefinition.osc
./tests	add_lights_into_space_type_test.rb test.osm test_input.osm

4.4.6 Set Hours of Operation and Default Schedule Set

The function of the measure will let user defines the hours of operation of the facility type. The hours of operation schedule will be used within a default schedule set that includes all schedules in the building. The measure would also predefine an infiltration schedule, occupancy schedule, people activity level schedule, and light schedule. The measure will help set up platform for the sensitivity analysis. If schedule has been setup in previous measures or to its individual load, then the default schedule set would just act as dummy and do not contribute to the simulation result.

The arguments for the measure are shown in Table 16. User has to input a start time and end time for the hours of operation. The input values are in double format where 6.30 would be equaled to 6:30 AM in the morning. The measure also set the people activity level per person in the shelter. The occupancy and light schedules can be set to follow the hours of operation schedule using the measure.

Table 16: Arguments for Hours of Operation Measure

Argument name	Type	Default Value
start_hour	Double	6.5
end_hour	Double	17.5
people_activity_level	Double	170
people_occ	String	yes
light_occ	String	yes

Table 17: File Path for Hours of Operation Measure

Directory	https://github.com/satishkumar33/Shelter_Corso/tree/master/shelter_modeling/measures/temp_assign_schedules/
Included:	./tests ./resources measure.rb measure.json measure.xml
./tests	temp_assign_schedules.rb example_model.osm ./output/test_output.osm
./resources	OsLib_Schedules.rb

4.4.7 Select Building Location

The function of the measure is to set the location and weather profile for the shelter model. The measure is developed by NREL to load the EPW and DDY file, which are the weather profile format that is acceptable for EnergyPlus. The measure is required to consider in early step of the workflow as the ground boundary condition measure and the

HVAC system measure depends on the weather profile data. The required arguments are weather directory and weather filename. The weather filename is loaded directly from the multi-dimensional matrix. The description on the argument and measure directory is shown in Table 18 and 19.

Table 18: Arguments for Select Building Location Measure

Argument name	Type	Default Value
weather_directory	String	.../../weather
weather_file_name	String	-

Table 19: File Path for Select Building Location Measure

Directory	https://github.com/satishkumar33/Shelter_Corso/tree/master/shelter_modeling/measures/ChangeBuildingLocation/
Included:	./tests ./resources measure.rb measure.json measure.xml
./tests	change_building_location_test.rb test.osm ./output/test_output.osm
./resources	stat_file.rb

4.4.8 Add HVAC System to Model

The function of the add HVAC system to model measure is to import the HVAC airloop premade in (.osm) format into the model in the workflow. The measure makes a new airloop in the workflow model and simply import all components in the airloop from the HVAC model located in the resources file. The thermal zone "Main_Zone" will be set to connect to the newly made airloop. The standard cooling thermostat-setpoint of 24°C and heating thermostat-setpoint of 20°C are used for the thermal zone. If an extra heater is needed in the operation duration, the measure will import the heater components into the airloop and uses availability schedules to set the operation time of the ECU system and the heater system. The schedules are based on the winter time of the shelter location. The measure can also set the cooling COP, the heating efficiency, and the fan efficiency. The option to adjust this thermostat-setpoint will be in a separated measure. The measure also has an option to set the zone into Ideal Air Load. The arguments required for the measure is shown in Table 20.

Table 20: Arguments for HVAC System Measure

Argument name	**Type**	**Default Value**
hvacsystem	String	:ecu
schedulechoice	String	Always on 20 24 Schedule
zones	String	Main_Zone
heater_name	String	:heater
cooling_COP	Double	:cooling_COP
heating_effic	Double	:heating_effic
fan_effic	Double	:fan_effic
winter_ranges	String	:winter_ranges

There are limitations in the measure. The HVAC system and the heater system must be in OSM format for now. OSC format does not work in this measure. The measure is not meant to adjust the thermostat-setpoint. It sets a standard heating and cooling thermostat-setpoints to be modified in later steps of workflow. If no heater is used in shelter at the certain location, "No Heater" can be specified by the user in the matrix inputs. The winter range is also defined in the matrix for each different location. The cooling COP, heating COP, and fan efficiency are not required to be defined in the measure. The measure directory is shown in Table 21.

Table 21: File Path for HVAC System Measure

Directory	https://github.com/satishkumar33/Shelter_Corso/tree/master/shelter_modeling/measures/AddHVACSystemToModel/
Included:	./resources ./tests measure.rb measure.json measure.xml

Table 21 Continued …

./resources	OsLib_Schedules.rb MTH150.osm LCFH.osm HDT F100.osm HDT F100.osc thermostat.osc
./tests	AddHVACSystemToModel_test.rb test.osm test_input.osm

4.4.9 Shift Thermostat-Setpoints by Time

The function of the shift thermostat-setpoints by time measure is to set the dead bandwidth gap, the until time, and the value of the heating and cooling thermostat-setpoints schedules. The measure will take in a string argument defined as "dead bandwidth gap, time, value, time, value." Previous measure set a standard constant 20°C heating thermostat-setpoints and a constant 24°C cooling thermostat-setpoints. The dead bandwidth gap would be constant value between the cooling and the heating thermostat-setpoints. This gap can be changed in the next measure if constant gap is not desired. The inputs values are based on the heating thermostat-setpoints value. The cooling thermostat-setpoints values would be a simple addition of the bandwidth gap value and the value at the certain time. If the schedule is constant 24/7, an input of "4, 24, 20" can be set to be equal to 20°C heating thermostat-setpoints and a 24°C cooling thermostat-setpoints. The arguments required for the measure and file directory information are shown in Table 22 and 23.

Table 22: Arguments for Shift Thermostat-Setpoint Measure

Argument name	Type	Default Value
thermosetpoints	String	"dead bandwidth gap, time, value, time, value…"

Table 23: File Path for Shift Thermostat-Setpoint Measure

Directory	https://github.com/satishkumar33/Shelter_Corso/tree/master/shelter_modeling/measures/ShiftThermosetpointByTime/
Included:	./tests ./resources measure.rb measure.json measure.xml
./tests	shift_thermosetpoint_by_time_test.rb example_model.osm ./output/test_output.osm
./resources	OsLib_Schedule.rb

4.4.10 Adjust Thermostat-setpoints by Degrees

The function of the adjust thermostat-setpoints by degree measure is to adjust the heating and cooling thermostat-setpoint by a delta value. The measure is created by NREL and is mainly used in the sensitivity analysis but it can be used in the regular workflow when desired. The purpose is to understand the effects on the facility energy load based on changes in thermostat-setpoints. The arguments required for the measure and file directory information are shown in Table 24 and 25.

Table 24: Arguments for Adjust Thermostat-Setpoint Measure

Argument name	Type	Default Value
cooling_adjustment	Double	1.0
heating_adjustment	Double	-1.0
alter_design_days	Boolean	False

Table 25: File Path for Adjust Thermostat-Setpoint Measure

Directory	https://github.com/satishkumar33/Shelter_Corso/tree/master/shelter_modeling/measures/AdjustThermostatSetpointsByDegrees/
Included:	./tests measure.rb measure.json measure.xml
./tests	AdjustThermostatSetpointsByDegrees_Test.rb seed_model.osm ThermostatTestModel.osm

4.4.11 Shift and Expand Schedules

The function of the shift schedule by hours of operation is to be able to shift all schedule or any single schedule based on a shift in the hours of operation. The purpose of this measure is to be used in the sensitivity analysis. The measure has the options to shift the schedules by defined hours and to expand the hours of operation by defined delta hours. Other options included setting a double value for multiplier on the power loads and setting an integer value as multiplier for number of people in the shelter. The arguments required for the measure and file directory information are shown in Table 26 and 27.

Table 26: Arguments for Shift Schedules Measure

Argument name	Type	Default Value
shiftHofO	Boolean	True
shiftPeople	Boolean	True
shiftElectric	Boolean	True
shiftThermostat	Boolean	True
start_end_time	String	Auto
shift_hour	Double	0.0
delta_hour	Double	0.0
value_mult	Double	0.05
people_mult	Integer	1

Table 27: File Path for Shift Schedules Measure

Directory	https://github.com/satishkumar33/Shelter_Corso/tree/master/shelter_modeling/measur es/ShiftScheduleByHOO/
Included:	./resources ./tests measure.rb measure.json measure.xml
./resources	OsLib_Schedules.rb
./tests	shift_scheduleby_hoo_test.rb example_model.osm ./output/test_input.osm

4.4.12 Rotate Building

The function of the rotate building measure is to rotate the building at certain degree. The measure is created by NREL is to consider the effects of the solar radiation based on different orientation of the shelter. Four rotations (0, 90, 180, 270 degree) would be considered in most shelter. The arguments required for the measure and file directory information are shown in Table 28 and 29.

Table 28: Arguments for Rotate Building Measure

Argument name	Type	Default Value
relative_building_rotation	Double	90

Table 29: File Path for Rotate Building Measure

Directory	https://github.com/satishkumar33/Shelter_Corso/tree/master/shelter_modeling/measures/RotateBuilding/
Included:	measure.rb measure.json measure.xml

4.4.13 Entry and Exit Infiltration

The function of the measure is to consider the entry and exit infiltration of the shelter depending on the door size, pressure across the door, occupancy schedule, and door opening event per person. Infiltration contributed large part of total space-conditioning load, representing 20 to 50% of building thermal load. There are numerous types of door activities, including swing, slide, rotate, and overhead doors. For facility type used in a forward operating base, there would be large number of door opening events. The ASHRAE Handbook of Fundamentals 16.26 describes the air leakage through exterior doors. Air exchange associated with infrequent door openings can be simply modeled based on air leakage through cracks between the door and frame. For frequent use of door, the air leakage should be modeled based on the door opening events.

This measure is developed by NREL and is used to calculate the average airflow rate in a small commercial building office as discussed in Chapter 2. The measure calculates the entry and exit infiltration information based on Equation 5. User is required to provide the building story name, the door area, the door operating event per person, and pressure difference across door in Pa as shown in Table 30. As discussed in Chapter 2, the pressure factor for most shelter under 10ft is 0.3 (in. of water) $^{(0.5)}$, which is equaled to 23 Pa in pressure difference across door. The file directory of the measure is shown in Table 31.

Table 30: Arguments for Entry and Exit Infiltration Measure

Argument name	**Type**	**Default Value**
story	String	Building Story 1
door_area_ftsqt	Double	21
doorOpeningEventsPerPerson	Double	3
pressureDifferenceAcrossDoor_pa	Double	23

Table 31: File Path for Entry and Exit Infiltration Measure

Directory	https://github.com/satishkumar33/Shelter_Corso/tree/master/shelter_modeling/measures/AedgSmallToMediumOfficeEnvelopeAndEntryInfiltration/
Included:	./resources ./tests measure.rb measure.json measure.xml
./resources	OsLib_Schedules.rb OsLib_AedgMeasures.rb OsLib_HelperMethods.rb OsLib_OutdoorAirAndInfiltration.rb
./tests	AedgSmallToMediumOfficeEnvelopeAndEntryInfiltration_Test.rb

4.5 EnergyPlus Measures

The workflow modeling development focus majorly with usage of OpenStudio measures as it provides pointers to model objects. For EnergyPlus functions not applicable in OpenStudio Application, EnergyPlus measures are required. These include consideration of boundary condition, EMS codes, and meter variable selection. EnergyPlus measures are applied after OpenStudio model objects have been translated into EnergyPlus IDF format.

To insert an EnergyPlus measure into the workflow, the user will input the filename, argument, and value of the E+ measures in separate sheet that corresponded to the selected geometry type inside the multi-dimensional matrix. The format to insert EnergyPlus measures required for AIRBEAM in the matrix is shown in Figure 29.

A	B	C	D
filename	AssignAnyNumberToScheduleTypeLimitsName	# of arguments	0
filename	AddObjectsToAirBeam	# of arguments	7
argument	ask_ZoneCapacitanceMultiplier		
value	TRUE		
argument	ask_OtherSideCoefficients		
value	TRUE		
argument	ask_ConvectionCoefficients		
value	TRUE		
argument	ask_Ventilation		
value	TRUE		
argument	ask_ZoneMixing		
value	TRUE		
argument	ask_EMS		
value	TRUE		

Figure 29: E+ measure Input User-Interface

4.5.1 Input Meter Variables

The function of this measure is to set the time series data by setting the total site electricity as a meter variable. Only time series data classified in this measure would be pushed into DEnCity database. The measure is used for all the shelter type, setting the variable “Electricity:Building” as the hourly output meter variable. If user desired to consider other output meter variable, the measure can be easily modified with additional any of these variables: “InteriorEquipment:Electricity”, “Electricity:HVAC”, “Cooling:Electricity”, “Heating:Electicity”, “Fan:Electricity”, “Heating:DistrictHeating”, and “Cooling:DistrictCooling”. The input value for the argument shown in Table 32 should not be changed as the time step for energy consumption data uploaded to DEnCity is hourly. The measure directory is shown in Table 32.

Table 32: Arguments for Rotate Building Measure

Argument name	Type	Default Value
meter_format	String	Hourly

Table 33: File Path for Input Meter Variable Measure

Directory	https://github.com/satishkumar33/Shelter_Corso/tree/master/shelter_modeling/measures/ ImportMeterVariable/
Included:	measure.rb measure.json measure.xml

4.5.2 On Grade Ground Domain Slab Measure

The function of the on grade ground domain measure is to add an on-grade ground domain slab object onto the floor using weather file’s ground temperature as the initial guess points. The measure is specified to be used in the shelters where floor construction included insulation already. The measure will look up the location of the model and load the initial guess temperature directly from the weather file directory to generate a boundary condition for the ground. A pre-process would run to develop the average ground temperature on the floor based on the initial guess temperatures from the weather file. The measure is specified to be used in shelter models where floor construction include insulation; these shelters include MILVAN and CLU. The input value for the argument shown in Table 34 should not be changed. The measure directory is shown in Table 35.

Table 34: Arguments for On Grade Ground Domain Slab Measure

Argument name	Type	Default Value
weather_directory	String	../../weather

Table 35: File Path for On Grade Ground Domain Slab Measure

Directory	https://github.com/satishkumar33/Shelter_Corso/tree/master/shelter_modeling/measures/OnGradeGroundDomainSlab/
Included:	./tests measure.rb measure.json measure.xml
./tests	on_grade_ground_domain_slab_test.rb test.idf test.osm

4.6 Reporting Measures

Reporting measures provides the platform to detailed model and simulation result data desired by the energy modelers. A customized reporting measure can be created to present data in charts, plots, tables, or any other formats. The final objective of the workflow is to push the model and simulation result into DEnCity database. The reporting measures are used to ensure the hourly total electricity consumption is pushed into the DEnCity. Three reporting measures were created by NREL to incorporate into the workflow: the DEnCity report measure, the DEnCity datapoint upload measure, and the DEnCity file upload measure. The DEnCity reporting measure generates data that are required for the DEnCity API. The DEnCity datapont upload measure is a reporting measure that push analysis and structures hash into the DEnCity server. The measure required arguments such as the hostname, user ID, and authorization code of the DEnCity server. The DEnCity file upload measure is used to upload a CSV file that contains the hourly electricity load of the shelter. The measure used the provided DEnCity API to add a related file to each structure being uploaded into DEnCity database. A private DEnCity server has been setup on Georgia Tech's Amazon account (http://52.11.23.255:8080/). The server will be used to store all the simulation results for the shelter modeling.

4.7 Helper Measure

CERL provides Georgia Tech the data of the different internal loads for shelter modeling. These internal loads included light, people, and electric equipment. A helper measure is need to import these load from an Excel format into OpenStudio components. These OpenStudio components should contain the load definition and its schedule. The measure imports the load profile provided by CERL and creates the OpenStudio components to be used in the workflow. The measure will directly generate these components into the resources file of the Add Electric Equipment Definition and Schedule measure. The argument required for the measure as shown in Table 36 and is the Excel filename provided from CERL. The measure directory is shown in Table 37.

Table 36: Arguments for Electric Load and Schedule Generator Measure

Argument name	Type	Default Value
equip_filename	String	-

Table 37: File Path for Electric Load and Schedule Generator Measure

Directory	https://github.com/satishkumar33/Shelter_Corso/tree/master/shelter_modeling/measures/ElecLoadandSchGenerator/
Included:	./tests ./resources measure.rb measure.json measure.xml
./tests	elec_equipand_sch_generator_test.rb example_model.osm ./output/test_output.osm

4.8 Application of Workflow on Shelters

The workflow has been tested with AIRBEAM and MILVAN shelter models. The result for MILVAN with low internal equipment load is shown in this section. A performance comparison for different locations and insulation materials are shown in the section. Three locations modeled are Kharga, Singapore, and Chongjin as mentioned in Chapter 2. The six type of insulation materials and two types of interior walls are also modeled in R-13, R-20 for walls and floor, R-30 for roof.

The result of MILVAN with low internal equipment load for different types of insulation materials and interior walls is shown in Figure 30. Figure 30 is based on the result of 95 simulations of different combination of insulation materials and interior walls. The interior wall does not have an impact in the energy model compared to the insulation materials. As predicted, low thermal insulated MILVAN with R-13 construction walls required higher total electricity intensity (EUI) to cool the shelter in a desert climate where outdoor heat can easily transfer through the building structure. In contrast, if MILVAN has high internal equipment load where large amount of wasted heat is generated inside the shelter, the R-13 is favorable to be used in a desert climate.

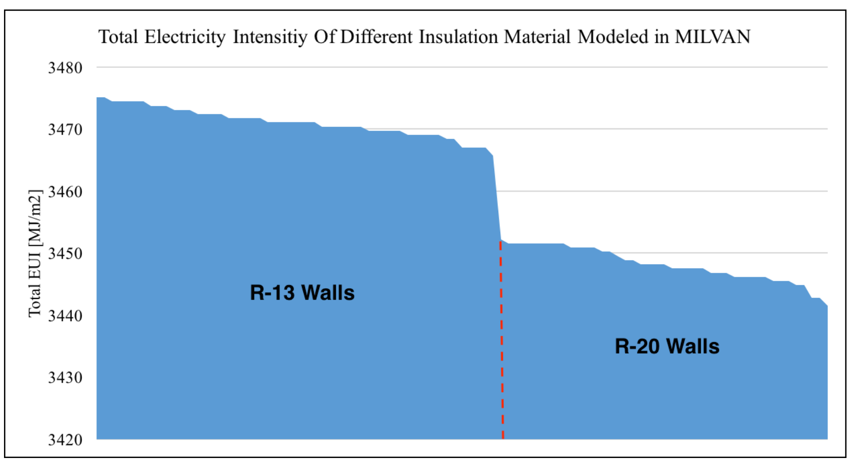


Figure 30: Comparison of Different R-Value of Walls used in MILVAN

The result of MILVAN with low internal equipment load for the three locations are shown in Figure 31. As predicted, the location affects the HVAC load greatly. In cold temperate weather of Chongjin, 88% of total site electricity is used in HVAC system where 60% is used in heating. In tropical Singapore with average outdoor temperature at 80ºF, 52% of total site electricity is used in cooling. In desert Kharga, 46% of total site electricity is used in cooling with only 3% used in heating. Even with the nighttime average outdoor temperature drops sharply in Kharga, the cooling still dominates the HVAC load in a well-insulated MILVAN shelter.

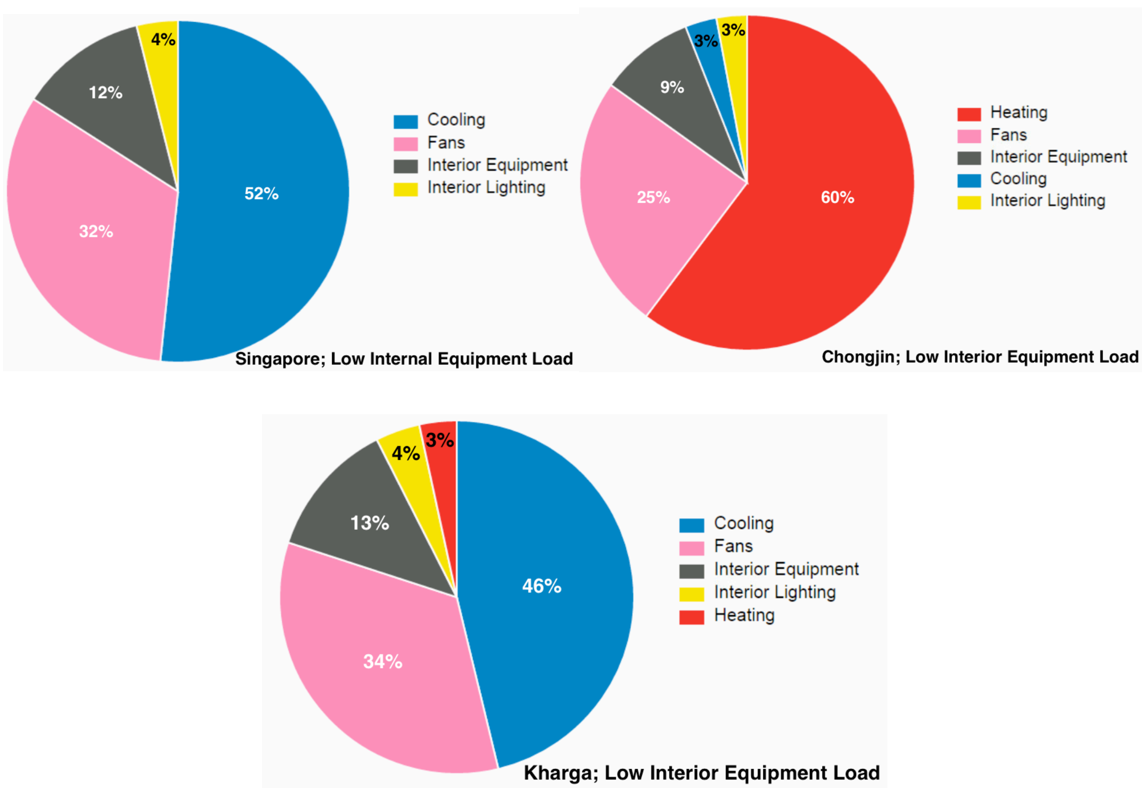


Figure 31: MILVAN in Three Climate Locations

Building rotation was also taken into consideration as shown in Figure 10 in Chapter 2. As shown in Figure 10 and later on Chapter 6, building rotation is not a important variable to be considered in MILVAN modeling as the total electricity variance generated is small.

4.9 Summary

This chapter provides details of the workflow and associated measures. The workflow has been tested with the different shelter types and HVAC system available. The shelters included B-hut, AIBEAM, CLU, and MILVAN. The HVAC system included HDT F100 and Carrier units. User can also change schedule, construction, and internal loads variables mentioned in this chapter. Continuous maintenance of the workflow is required as SDK objects can be changed due to OpenStudio updates where these objects might not be supported anymore. The workflow enable easier data analysis and a path to populate simulation datapoint into DEnCIty database.

CHAPTER 5

SENSITIVITY ANALYSIS RESULT

In this chapter, the result of the AIRBEAM and MILVAN sensitivity analysis is described. The chapter is split into five parts: first an overview of the sensitivity analysis, followed by the results of AIRBEAM shelter with high electric equipment load, AIRBEAM shelter with low electric equipment load, MILVAN shelter with high electric equipment load, and MILVAN shelter with low electric equipment load.

5.1 Sensitivity Analysis Overview

Each shelter has its unique geometry and construction. Without data analysis, it would be difficult to understand how a shelter would react in different environments and different internal loads. The sensitivity analysis would sample the key parameters in shelter modeling to determine the impact of the parameter on its total electricity load. Two methods are used in the sensitivity analysis. The first method uses one at a time (OAT) sampling of variables to understand the difference in total site electricity influenced by varying the different parameters. The results are graphed in tornado graphs. The second method uses Morris Method and is plotted in scatterplots. The method is commonly used for large data sensitivity analysis and better capture the impact of a variable than method one.

Two shelter types are used in the sensitivity analysis: AIRBEAM and MILVAN. AIRBEAM is a soft canvas tent shelter commonly used as a command center, a dinning hall, a billeting structure, and etc. in an operating base. The volume of AIRBEAM is three times that of MILVAN. The shelter can have peak occupancy up to 24 people and uses 8

Jameson lights as mentioned in the TECD document. Because of its volume, the peak occupants for MILVAN is only 8 people and only needs 4 Jameson lights. For different shelter type, the input values used for workflow arguments are different as shown in Table 38 and 39.

The chapter describes the result of twelve sensitivity analysis simulations based on the different shelter type, locations, and electric equipment load used. Three locations that represent the temperate, tropical, and desert climate are used in the analysis as described in Chapter 3. Two facility loads provided by CERL are used in the analysis for the representation of high internal electric equipment load (11.4 kW) and low internal electric equipment load (0.2kW). The high electric equipment load is TAC, a AIRBEAM command center facility load obtained from CERL. The low electric equipment load is VIP, a CLU billeting structure facility load.

The workflow for running the sensitivity analysis is located in the private Shelter_Corso repository. The sensitivity analysis methodology and measures used in the workflow are discussed in Chapter 3. The variables, static values, and discrete values used for each variable are listed in Table 38 and 39 for anyone who would like to repeat the study. Since values for the peak occupant, number of lights, and constructions for MILVAN and AIRBEAM are different, they are showed in two tables.

The results determined by the Morris Method would be used to determine the importance of the variables. The OAT method is only used to understand the interactive effect of the variables and the variance of the total site energy generated. After discussion with NREL, a good mean value of elementary effects that determine the importance of the factors in the model is 75. This means variables with a mean value of elementary effects greater than 75 dominates the influence in the energy model.

Table 38. AIRBEAM Static Values and Discrete Values Used in OAT Method

Variable	*Argument name*	*Units*	*Type*	*Static Values*	*Discrete Values*
Choose Geometry Type	geometry	N/A	String	AIRBEAM	-
Choose construction for the walls	construction_walls	N/A	String	No Change	-
Choose construction for the roof	construction_roof	N/A	String	No Change	-
Choose construction for the floor	construction_floor	N/A	String	No Change	-
Number of people	npeople	N/A	Double	12	[2,8,12,24]
Number of lights	nlight	N/A	Double	8	[4,8]
Choose electric equipment load	powerload	N/A	String	VIP; or TAC	-
The start time for hours of operation	start_hour	hour	Double	6:30 AM	-
The end time for hours of operation	end_hour	hour	Double	17:30 PM	-
People Activity Level	people_activity_level	Watt/person	Double	130	[100,130,170]
Weather location file	weather_file_name	N/A	String	Chongjin, North Korea; Singapore; Kharga, Egypt	-
HVAC System Unit	hvacsystem	N/A	String	HDT F100	-
Adjust cooling thermostat-setpoint	cooling_adjustment	Fahrenheit	Double	0	[-2,0,2]
Adjust heating thermostat-setpoint	heating_adjustment	Fahrenheit	Double	0	[-2,0,2]
Shift the light and electric equipment schedule	shift_hour	Hour	Double	0	[0,1,2,3]
Expand the light and electric equipment schedule	delta_hour	Hour	Double	0	[0,2]
Shift the occupancy schedule	ppl_shift_hour	Hour	Double	0	[0,1,2,3]
Expand the occupancy schedule	ppl_delta_hour	Hour	Double	0	[0,2]
Building rotation	relative_building_rotation	Degree	Double	0	[0,90,180,270]
Door Opening Event Per Person	doorOpeningEventsPerPerson	N/A	Double	3	[2,4,6]
Pressure Difference Across Door	pressureDifferenceAcrossDoor_pa	Pa	Double	4	[4,20]

Table 39. MILVAN Static Values and Discrete Values Used in OAT Method

Variable	*Argument name*	*Units*	*Type*	*Static Values*	*Discrete Values*
Choose Geometry Type	geometry	N/A	String	MILVAN	-
Choose construction for the walls	construction_walls	N/A	String	milvanCHU_R20SFFRP_Walls	-
Choose construction for the roof	construction_roof	N/A	String	milvanCHU_R30SFFRP_Roof	-
Choose construction for the floor	construction_floor	N/A	String	milvanCHU_R20SFPlywood_Floor	-
Number of people	npeople	N/A	Double	4	[2,8]
Number of lights	nlight	N/A	Double	4	[4,8]
Choose electric equipment load	powerload	N/A	String	VIP; or TAC	-
The start time for hours of operation	start_hour	hour	Double	6:30 AM	-
The end time for hours of operation	end_hour	hour	Double	17:30 PM	-
People Activity Level	people_activity_level	Watt/person	Double	130	[100,130,170]
Weather location file	weather_file_name	N/A	String	Chongjin, North Korea; Singapore; Kharga, Egypt	-
HVAC System Unit	hvacsystem	N/A	String	HDT F100	-
Adjust cooling thermostat-setpoint	cooling_adjustment	Fahrenheit	Double	0	[-2,0,2]
Adjust heating thermostat-setpoint	heating_adjustment	Fahrenheit	Double	0	[-2,0,2]
Shift the light and electric equipment schedule	shift_hour	Hour	Double	0	[0,1,2,3]
Expand the light and electric equipment schedule	delta_hour	Hour	Double	0	[0,2]
Shift the occupancy schedule	ppl_shift_hour	Hour	Double	0	[0,1,2,3]
Expand the occupancy schedule	ppl_delta_hour	Hour	Double	0	[0,2]
Building rotation	relative_building_rotation	Degree	Double	0	[0,90,180,270]
Door Opening Event Per Person	doorOpeningEventsPerPerson	N/A	Double	3	[2,4,6]
Pressure Difference Across Door	pressureDifferenceAcrossDoor_pa	Pa	Double	4	[4,10,20]

5.2 AIRBEAM with High Electric Equipment Load

The result from the OAT runs on AIRBEAM with high electric load in Chongjin is shown in Table 40. A tornado graphs has been generated to better represent the data in Figure 32. The three parameters with highest total site variance are adjusting the cooling thermostat-setpoint, number of people, and number of lights. Chongjin has a cold-temperate climate and a heater is needed where it is assumed adjusting the heating thermostat-setpoint would make the most impact in the shelter. However, as shown in Figure 32, adjusting the cooling thermostat-setpoint has the largest variance in the total site electricity. The reason is the high internal electric equipment load in the shelter would generate high volume of wasted heat. The simulation result showed the heater only turns on occupational and the cooler is used most of the time even during the winter to cool the wasted heat generated from equipment in the shelter.

Table 40: Total Site Energy of AIRBEAM with High Electric Load in Chongjin

Variable Display Name				**Total Site Energy [GJ]**			
	Static Value	MIN Value	MAX Value	Static Result	MIN Result	Max Result	Variance
Adjust the Cooling Thermostat Setpoint	0	-2	2	420.9	415.34	426.04	10.7
Number of People	12	2	24	420.9	418.16	423.96	5.8
Number of Light	8	4	8	420.9	418.23	420.9	2.67
Adjust the Heating Thermostat Setpoint	0	-2	2	420.9	420.12	422.08	1.96
People Activity Level	130	100	170	420.9	420.38	421.49	1.11
Expand Hours of Operation	0	0	2	420.9	420.9	421.98	1.08
Building Rotation	0	0	270	420.9	420.28	421.11	0.83
Door Event Per Person	3	2	6	420.9	420.44	421.13	0.69
Pressure Difference Across Door	4	4	20	420.9	420.46	420.9	0.44
Expand Occupancy Schedule	0	0	2	420.9	420.9	421.34	0.44
Shift Hours of Operation	0	0	3	420.9	420.77	420.9	0.13
Shift Occupancy Schedule	0	0	3	420.9	420.82	420.9	0.08

The variable that controls the peak number of people has the second most impact in the shelter. The door opening event per person, the occupancy schedule, and people activity level highly depends on this variable. The result shows occupancy schedule is an important parameter in shelter modeling.

The variable that controls the number of light has the third most impact in the shelter. Each Jameson light has power consumption of 36 Watts as mentioned in Chapter 4 and it is assumed to be on during the hours of operation. The number of lights varies from 4 to 8 in the simulations. Since OpenStudio models light in a similar fashion as electric equipment load, the variable also showed the importance of adding/removing electric equipment load in the shelter.

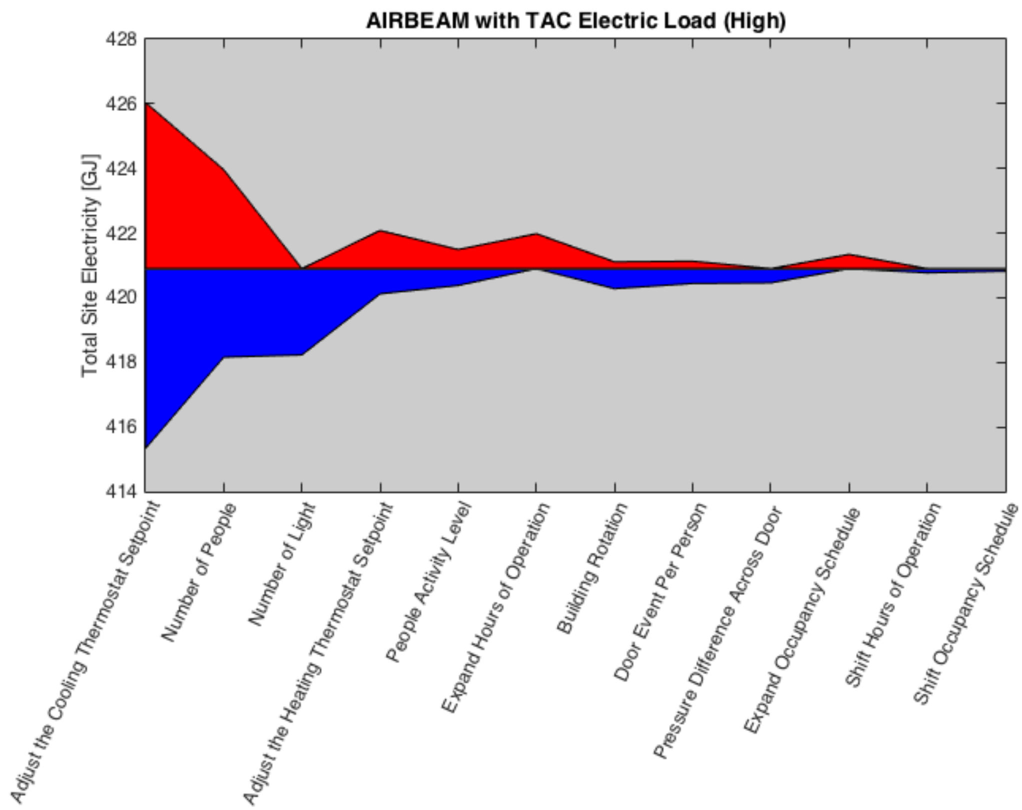


Figure 32: Tornado Graph AIRBEAM with High Electric Load in in Chongjin

The result from the Morris Method for the AIRBEAM with high electric equipment load in Chongjin is consistent with the OAT method. The three highest mean values of elementary effects are adjusting the cooling thermostat-setpoint, number of people, and number of lights as shown in Table 41 and Figure 33. As mentioned in Chapter 2, the mean value indicates the order of importance for the factors and the standard derivation is an indicator for the linearity of the input factor. As shown in Figure 33, the variables that have dependence on other input factors are shifting and expanding the hours of operation in AIRBEAM. However, these variables have low mean value of elementary effects and have small impact in the model. For the rest of the variables with low mean and standard deviation value, their impact is small.

Table 41: Morris Method Result for AIRBEAM with High Electric Load in Chongjin

Importance Order	**Variable**	**Min Input Value**	**Max Input Value**	**μ**	**μ***	**σ**
1	Adjust the Cooling Thermostat Setpoint	-2	2	-212.86	212.86	9.33
2	Number of People	2	24	120.36	120.36	15.43
3	Number of Light	4	8	115	115	3.97
4	Shift Hours of Operation	0	3	-26.07	49.29	50.57
5	Expand Hours of Operation	0	2	6.61	48.39	56.97
6	Adjust the Heating Thermostat Setpoint	-2	2	33.93	33.93	8.03
7	Building Rotation	0	270	8.39	28.04	32.59
8	People Activity Level	100	170	17.5	17.5	6.56
9	Shift Occupancy Schedule	0	3	-2.86	12.5	17.19
10	Expand Occupancy Schedule	0	2	7.32	12.32	16.35
11	Door Event Per Person	2	6	-11.96	11.96	5.52
12	Pressure Difference Across Door	4	20	-9.11	9.11	7.78

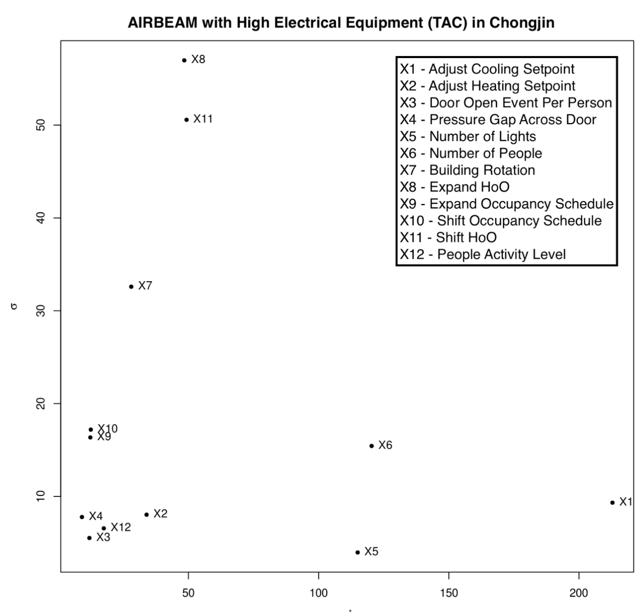


Figure 33: Morris Method Result for AIRBEAM with High Electric Load in Chongjin

The result from the OAT runs on AIRBEAM with high electric load in Singapore is shown in Table 42. A tornado graph has been generated to better represent the data in Figure 34. The three parameters with highest total site variance are adjusting the cooling thermostat-setpoint, number of people, and number of lights, which are the same as previous runs in Chongjin location. Unlike Chongjin, Singapore has a tropical climate with an average temperature of 80°F year round. The interior and exterior condition highly demand HVAC system for cooling which led to adjusting the cooling thermostat-setpoint to have the most influence in the model. Heater is not available in Singapore for which the total site energy variance showed in Table 42 is zero.

Table 42: Total Site Energy [GJ] of AIRBEAM with High Electric Load in Singapore

Variable Display Name				**Total Site Energy [GJ]**			
	Static Value	MIN Value	MAX Value	Static Result	MIN Result	Max Result	Variance
Adjust the Cooling Thermostat Setpoint	0	-2	2	542.62	537.64	547.54	9.9
Number of People	12	2	24	542.62	537.52	547.29	9.77
Number of Light	8	4	8	542.62	540.07	542.62	2.55
People Activity Level	130	100	170	542.62	541.66	543.8	2.14
Expand Occupancy Schedule	0	0	2	542.62	542.62	544.22	1.6
Pressure Difference Across Door	4	4	20	542.62	542.62	544.01	1.39
Door Event Per Person	3	2	6	542.62	542.32	543.62	1.3
Expand Hours of Operation	0	0	2	542.62	542.62	543.89	1.27
Building Rotation	0	0	270	542.62	542.22	542.62	0.4
Shift Occupancy Schedule	0	0	3	542.62	542.62	542.85	0.23
Shift Hours of Operation	0	0	3	542.62	542.62	542.84	0.22
Adjust the Heating Thermostat Setpoint	0	-2	2	542.62	542.62	542.62	0

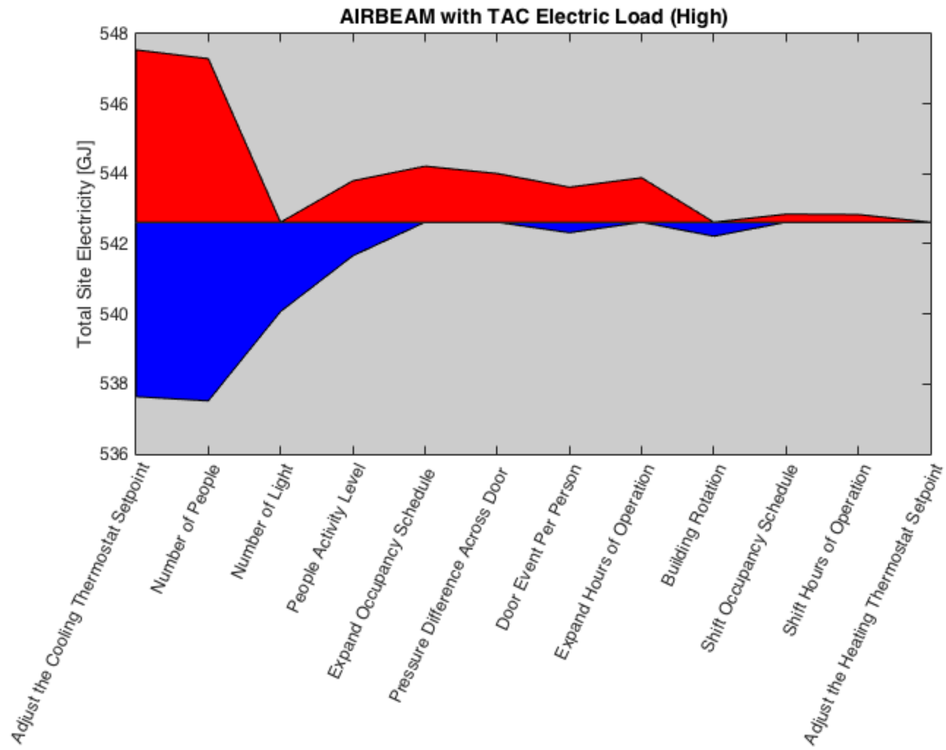


Figure 34: Tornado Graph of AIRBEAM with High Electric Load in Singapore

The result from the Morris Method in Singapore for AIRBEAM with high electric load is consistent with the OAT method. The three highest mean values of elementary effects are number of people, adjusting the thermostat-setpoint, and number of lights as shown in Table 43 and Figure 35. As mentioned, the variable with mean value of elementary effects greater than 75 are important in the model, which includes shifting the occupancy schedule. As shown in Figure 35, the variables that have dependence on other input factors are shifting the occupancy schedule and changing the number of people in the AIRBEAM. For the rest of the variables with low mean and standard deviation value, their impact is small.

Table 43: Morris Method Result for AIRBEAM with High Electric Load in Singapore

Importance Order	Variable	Min Input Value	Max Input Value	μ	μ*	σ
1	Number of People	2	24	296.07	296.07	82.19
2	Adjust the Cooling Thermostat Setpoint	-2	2	-203.04	203.04	10.48
3	Number of Light	4	8	109.29	109.29	7.66
4	Shift Occupancy Schedule	0	3	-54.11	79.82	89.5
5	Shift Hours of Operation	0	3	12.32	49.82	57.03
6	Expand Hours of Operation	0	2	12.86	48.93	59.33
7	Door Event Per Person	2	6	45.71	45.71	15.95
8	People Activity Level	100	170	44.46	44.46	17.61
9	Pressure Difference Across Door	4	20	41.61	41.61	21.38
10	Expand Occupancy Schedule	0	2	23.04	23.04	43.45
11	Building Rotation	0	270	0.54	21.25	23.91
12	Adjust the Heating Thermostat Setpoint	-2	2	0	0	0

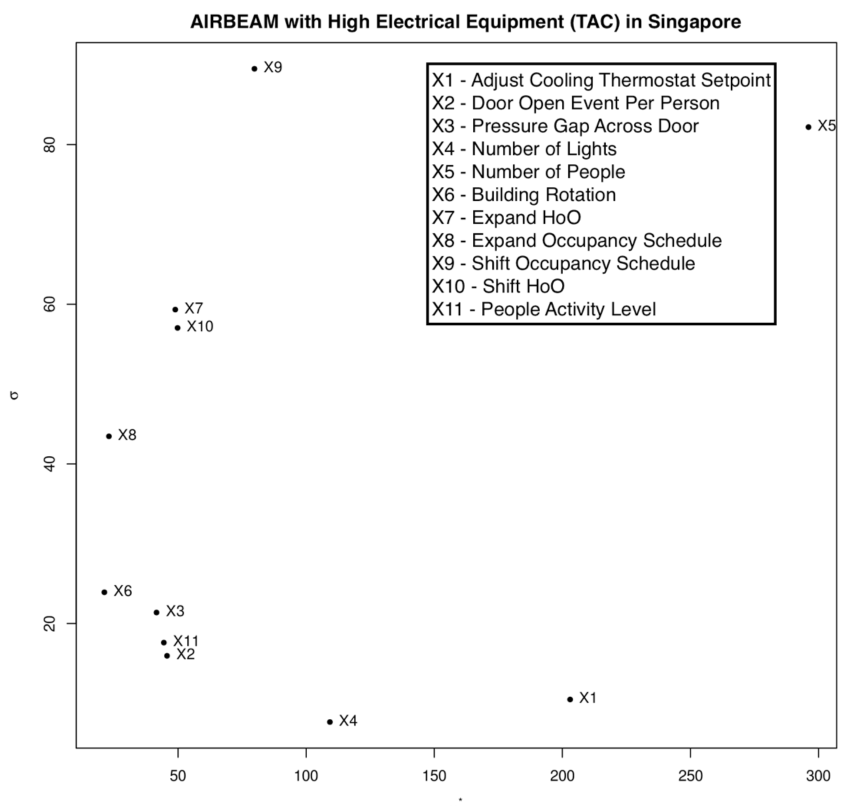


Figure 35: Morris Method Result for AIRBEAM with High Electric Load in Singapore

The result from the OAT runs on AIRBEAM with high electric load in Kharga, Egypt is shown in Table 44. A tornado graph has been generated to better represent the data in Figure 36. The three parameters with highest total site variance are adjusting the cooling thermostat-setpoint, number of people, and number of lights which are the same result as Chongjin location. Unlike Chongjin and Singapore, Kharga has a desert climate with high average temperature at daytime and low average temperature at night. The heater is applied in this model but as shown in Table 44, adjusting the heating thermostat-setpoint does not cause an energy variance in the total site load, which means the heater does not have a large impact in the shelter model. Similar to Chongjin and Singapore location, adjusting the cooling thermostat-setpoint has the largest variance in the total site energy. The result shows if high internal load is applied in the shelter, the loads from the inside the shelter dominate the HVAC performance where exterior environment became less important.

Table 44: Total Site Energy [GJ] of AIRBEAM with High Electric Load in Kharga

Variable Display Name				**Total Site Energy [GJ]**			
	Static Value	MIN Value	MAX Value	Static Result	MIN Result	Max Result	Variance
Adjust the Cooling Thermostat Setpoint	0	-2	2	517.06	510.96	522.96	12
Number of People	12	2	24	517.06	514.01	520.53	6.52
Number of Light	8	4	8	517.06	514.53	517.06	2.53
People Activity Level	130	100	170	517.06	516.4	517.98	1.58
Expand Hours of Operation	0	0	2	517.06	517.06	518.25	1.19
Building Rotation	0	0	270	517.06	516.03	517.12	1.09
Expand Occupancy Schedule	0	0	2	517.06	517.06	517.92	0.86
Shift Occupancy Schedule	0	0	3	517.06	517.06	517.25	0.19
Shift Hours of Operation	0	0	3	517.06	517.06	517.22	0.16
Door Event Per Person	3	2	6	517.06	517.06	517.08	0.02
Pressure Difference Across Door	4	4	20	517.06	517.06	517.08	0.02
Adjust the Heating Thermostat Setpoint	0	-2	2	517.06	517.06	517.06	0

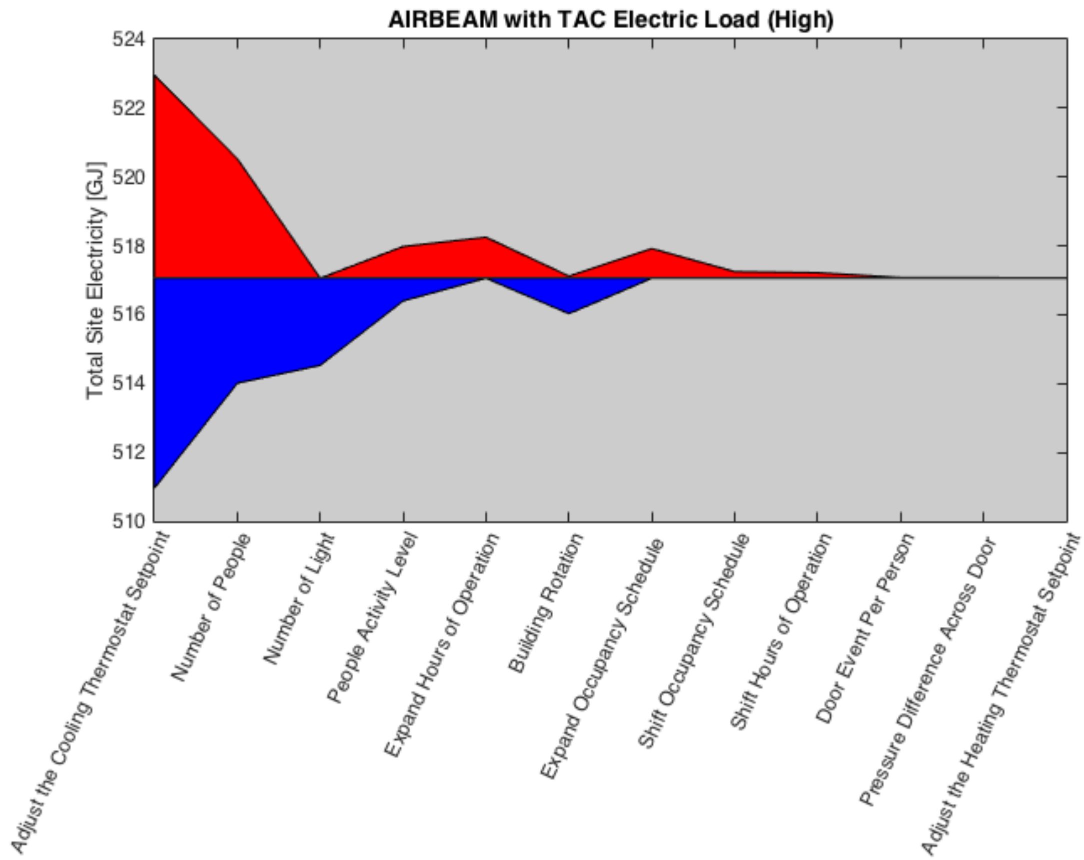


Figure 36: Tornado Graph of AIRBEAM with High Electric Load in Kharga

The result from the Morris Method in Kharga with high electric load is consistent with the OAT method. The three highest mean values of elementary effects are adjusting the thermostat-setpoint, number of people, and number of lights as shown in Table 45 and Figure 37. As shown in Figure 37, the variables that have dependence on other input factors are building rotation, shifting and expanding the occupancy schedule and hours of operation. However, their mean value of elementary effects are relatively small and does not dominate the impact in the energy model. For the rest of the variables with low mean and standard deviation value, their impact is small.

Table 45: Morris Method Result for AIRBEAM with High Electric Load in Kharga

Importance Order	Variable	Min Input Value	Max Input Value	μ	μ*	σ
1	Adjust the Cooling Thermostat Setpoint	-2	2	-238.04	238.04	5.4
2	Number of People	2	24	152.5	152.5	24.17
3	Number of Light	4	8	112.14	112.14	4.11
4	Shift Occupancy Schedule	0	3	-60.43	60	42.1
5	Expand Hours of Operation	0	2	8.57	48.57	56.95
6	Shift Hours of Operation	0	3	-40.35	48.04	52.36
7	Building Rotation	0	270	10	39.64	50.28
8	Expand Occupancy Schedule	0	2	26.94	32.32	49.41
9	People Activity Level	100	170	27.68	27.68	11.49
10	Pressure Difference Across Door	4	20	1.96	2.32	1.56
11	Door Event Per Person	2	6	1.25	1.61	1.47
12	Adjust the Heating Thermostat Setpoint	-2	2	0	0	0

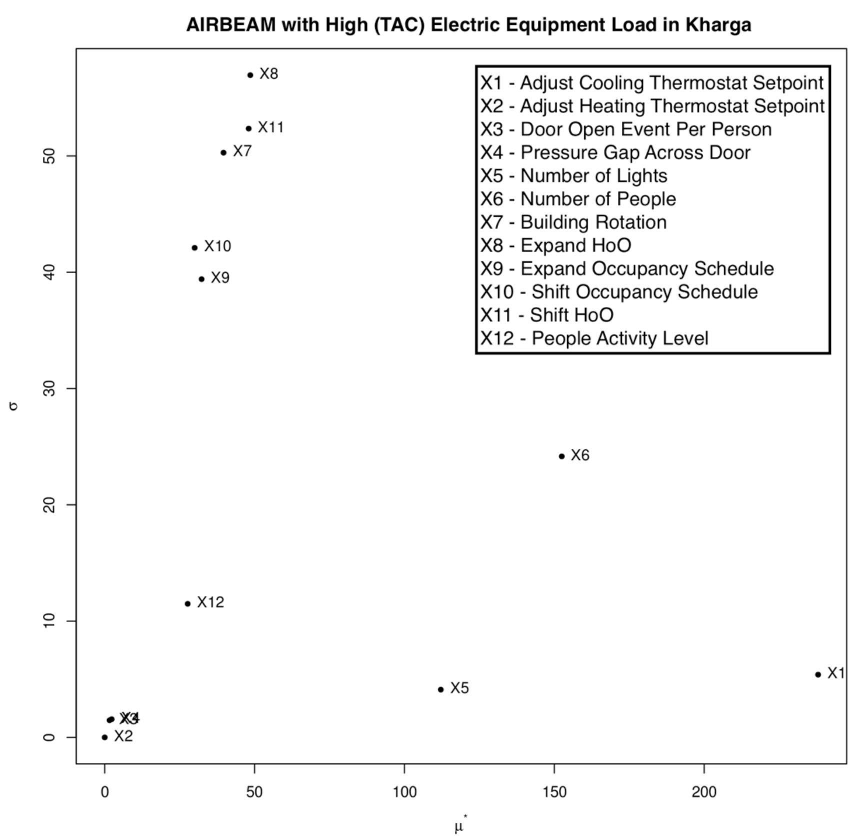


Figure 37: Morris Method Result for AIRBEAM with High Electric Load in Kharga

5.3 AIRBEAM with Low Electric Equipment Load

The result from the OAT runs on AIRBEAM with low electric load in Chongjin is shown in Table 46. A tornado graphs has been generated to better represent the data in Figure 38. The three parameters with highest total site variance are adjusting the heating thermostat-setpoint, number of people, and adjusting the cooling thermostat-setpoint. The total site energy variance measured by adjusting the heating thermostat-setpoint by 2°C negatively and positively is 11.93 GJ; changing the peak number of people in the shelter at anytime from 2 to 24 is 3.55 GJ; and adjusting the cooling thermostat-setpoint by 2°C negatively and positively is 2.53 GJ. Compared to AIRBEAM with high electric equipment load in Chongjin, the variable for adjusting the thermostat-setpoint have the greatest variance in the total site energy. With low electric equipment load as little as 0.2kW, the wasted heat generated from equipment inside the shelter is small. And the outdoor environment dominated the HVAC performance in the model.

Table 46: Total Site Energy [GJ] of AIRBEAM with Low Electric Load in Chongjin

Variable Display Name				Total Site Energy [GJ]			
	Static Value	MIN Value	MAX Value	Static Result	MIN Result	Max Result	Variance
Adjust the Heating Thermostat Setpoint	0	-2	2	122.96	116.74	128.67	11.93
Number of People	12	2	24	122.96	121.04	124.59	3.55
Adjust the Cooling Thermostat Setpoint	0	-2	2	122.96	121.65	124.18	2.53
Number of Light	8	4	8	122.96	121.23	122.96	1.73
Door Event Per Person	3	2	6	122.96	122.52	124.18	1.66
Pressure Difference Across Door	4	4	20	122.96	122.96	124.39	1.43
Building Rotation	0	0	270	122.96	121.96	123.27	1.31
Expand Occupancy Schedule	0	0	2	122.96	122.48	122.96	0.48
Expand Hours of Operation	0	0	2	122.96	122.96	123.34	0.38
People Activity Level	130	100	170	122.96	122.65	122.97	0.32
Shift Occupancy Schedule	0	0	3	122.96	122.95	122.96	0.01
Shift Hours of Operation	0	0	3	122.96	122.96	122.96	0

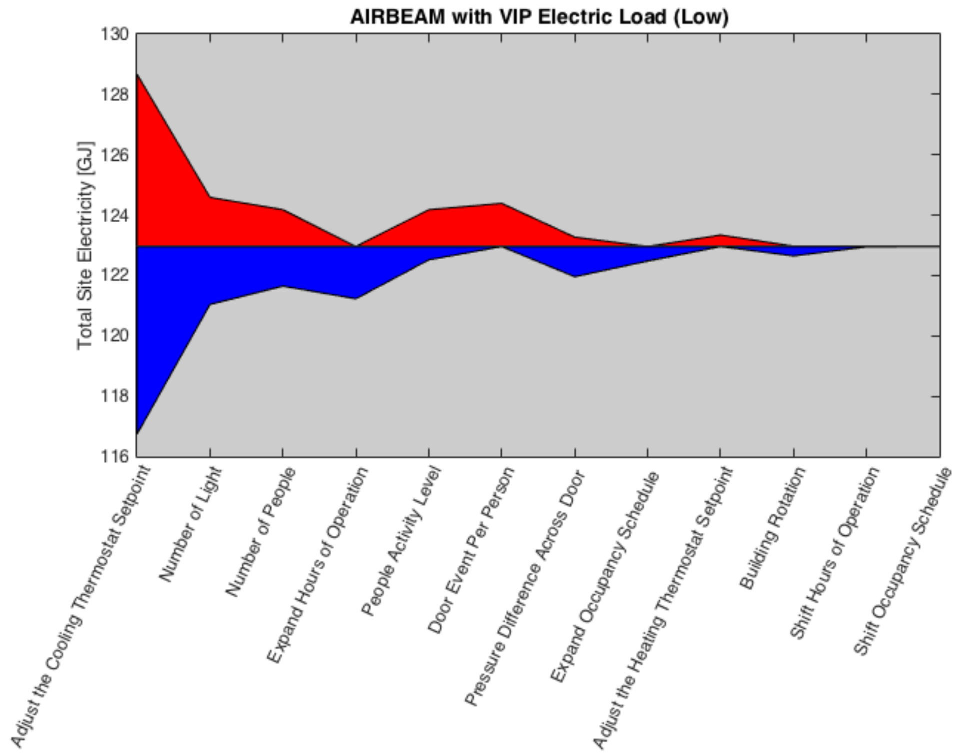


Figure 38: Tornado Graph of AIRBEAM with Low Electric Load in Chongjin

The result from the Morris Method on AIRBEAM with low electric load in Chongjin is inconsistent with the OAT method. The three highest mean values of elementary effects are adjusting the heating thermostat-setpoint, number of light, and building rotation as shown in Table 47 and Figure 39. As mentioned, only variables with the mean value of elementary effects greater than 75 is important. The mean value calculated from the Morris Method for building rotation is only 65.36, meaning the impact is there but it does not dominate the energy model compared to the mean value of 240 calculated for adjusting the heating thermostat-setpoint. As shown in Figure 39, the variable that have dependence on other input factors is building rotation. More studies are needed to determine the impact of building rotation as this analysis only consider the two shelters. With more parameters in energy model in the future, the building rotation might show a larger impact.

Table 47: Morris Method Result of AIRBEAM with Low Electric Load in Chongjin

Importance Order	Variable	Min Input Value	Max Input Value	μ	μ*	σ
1	Adjust the Heating Thermostat Setpoint	-2	2	240	240	6.8
2	Number of Light	4	8	70.71	70.71	3.06
3	Building Rotation	0	270	-10.36	65.36	71.96
4	Number of People	2	24	-55.36	55.36	24.02
5	Adjust the Cooling Thermostat Setpoint	-2	2	-49.64	49.64	4.82
6	Door Event Per Person	2	6	32.5	32.5	13.28
7	Pressure Difference Across Door	4	20	27.32	27.32	17.62
8	Expand Occupancy Schedule	0	2	-14.643	16.43	20.79
9	Shift Occupancy Schedule	0	3	5.71	16.07	22.97
10	People Activity Level	100	170	-6.07	6.07	2.55
11	Expand Hours of Operation	0	2	4.11	4.11	4.38
12	Shift Hours of Operation	0	3	0.71	0.071	1.73

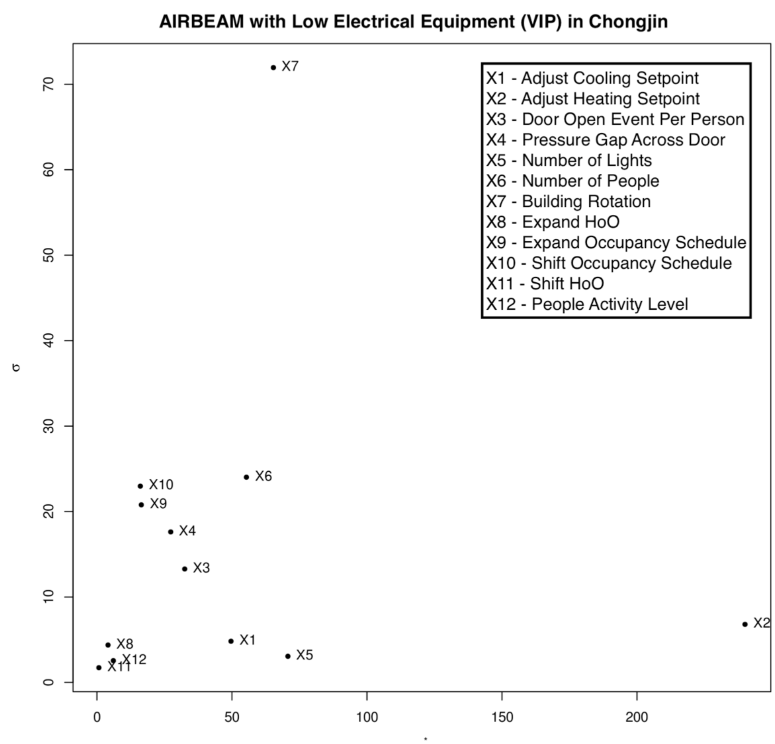


Figure 39: Morris Method Result for AIRBEAM with Low Electric Load in Chongjin

The result from the OAT runs on AIRBEAM with low electric load in Singapore is shown in Table 48. A tornado graphs has been generated to better represent the data in Figure 40. The three parameters with highest total site variance are changing the number of people, adjusting the cooling thermostat-setpoint, and varying the door opening event per person. The total site energy variance measured by changing the number of people from 2 to 24 person is 1.18 GJ; adjusting the cooling thermostat-setpoint by 2°C negatively and positively is 13.66 GJ; and varying the door opening event per person from 2 to 6 is 0.85 GJ. As mentioned, the average outdoor temperature in Singapore is 80°F and with low internal electric load, more cooling would be needed from the HVAC system in the model. Since the shelter has low electric load, the outdoor environment dominates the shelter's HVAC system. The entry and exit infiltration variables: number of people and the door opening event per person, created a greater variance in AIRBEAM with low electric load as shown in the OAT method.

Table 48: Total Site Energy [GJ] of AIRBEAM with Low Electric Load in Singapore

Variable Display Name				**Total Site Energy [GJ]**			
	Static Value	MIN Value	MAX Value	Static Result	MIN Result	Max Result	Variance
Number of People	12	2	24	73.31	66.07	82.25	16.18
Adjust the Cooling Thermostat Setpoint	0	-2	2	73.31	66.77	80.43	13.66
Door Event Per Person	3	2	6	73.31	72.75	74.54	0.85
People Activity Level	130	100	170	73.31	71.71	75.47	3.76
Number of Light	8	4	8	73.31	70.35	73.31	2.96
Pressure Difference Across Door	4	4	20	73.31	73.31	74.56	1.25
Expand Occupancy Schedule	0	0	2	73.31	73.31	74.37	1.06
Expand Hours of Operation	0	0	2	73.31	73.31	74.16	0.85
Building Rotation	0	0	270	73.31	72.65	73.31	0.66
Shift Occupancy Schedule	0	0	3	73.31	73.21	73.31	0
Adjust the Heating Thermostat Setpoint	0	-2	2	73.31	73.31	73.31	0
Shift Hours of Operation	0	0	3	73.31	73.24	73.31	0

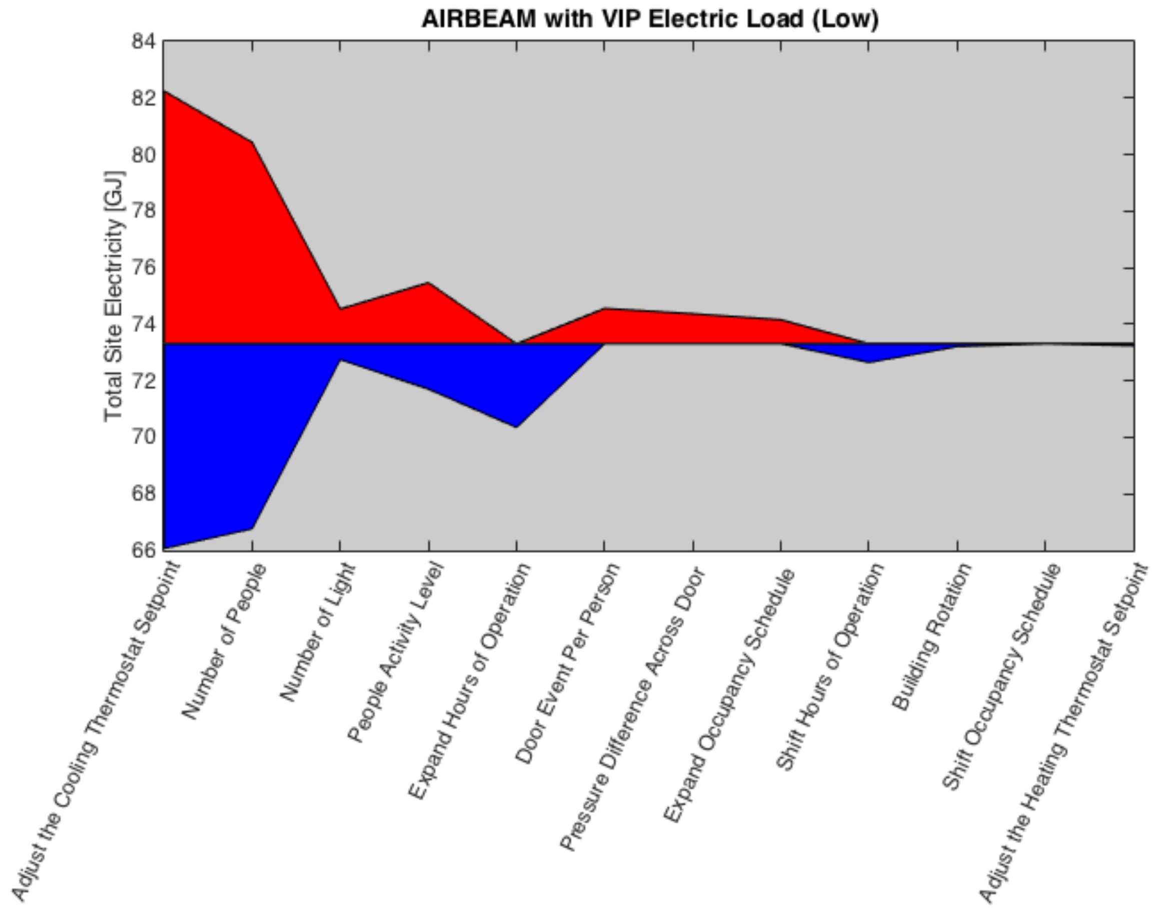


Figure 40: Tornado Graph of AIRBEAM with Low Electric Load in Singapore

The result from the Morris Method in Singapore is somewhat inconsistent with the OAT method. The highest mean values of elementary effects are number of people, adjusting the heating thermostat-setpoint, and number of light as shown in Table 49 and Figure 41. Nevertheless, both methods showed that people activity is important in the energy model as the variables related to door opening event per person, number of people, and people activity level have moved up in the lists. As shown in Figure 41, the variables that have dependence on other input factors are number of people, the people activity level, and the occupancy schedule. For the rest of the variables with low mean and standard deviation value, their impact is small.

Table 49: Morris Method Result of AIRBEAM with Low Electric Load in Singapore

Importance Order	Variable	Min Input Value	Max Input Value	μ	μ*	σ
1	Number of People	2	24	375	375	56.09
2	Adjust the Cooling Thermostat Setpoint	-2	2	-279.64	279.64	21.25
3	Number of Light	4	8	125.54	125.54	5.26
4	People Activity Level	100	170	71.61	71.61	37.22
5	Door Event Per Person	2	6	52.68	52.68	24.88
6	Pressure Difference Across Door	4	20	32.14	32.14	20.34
7	Building Rotation	0	270	-1.61	30.18	33.2
8	Shift Occupancy Schedule	0	3	-20.71	25.36	29.66
9	Expand Occupancy Schedule	0	2	16.79	16.79	44.99
10	Shift Hours of Operation	0	3	0.89	6.25	9.68
11	Expand Hours of Operation	0	2	4.46	4.46	6.26
12	Adjust the Heating Thermostat Setpoint	-2	2	0	0	0

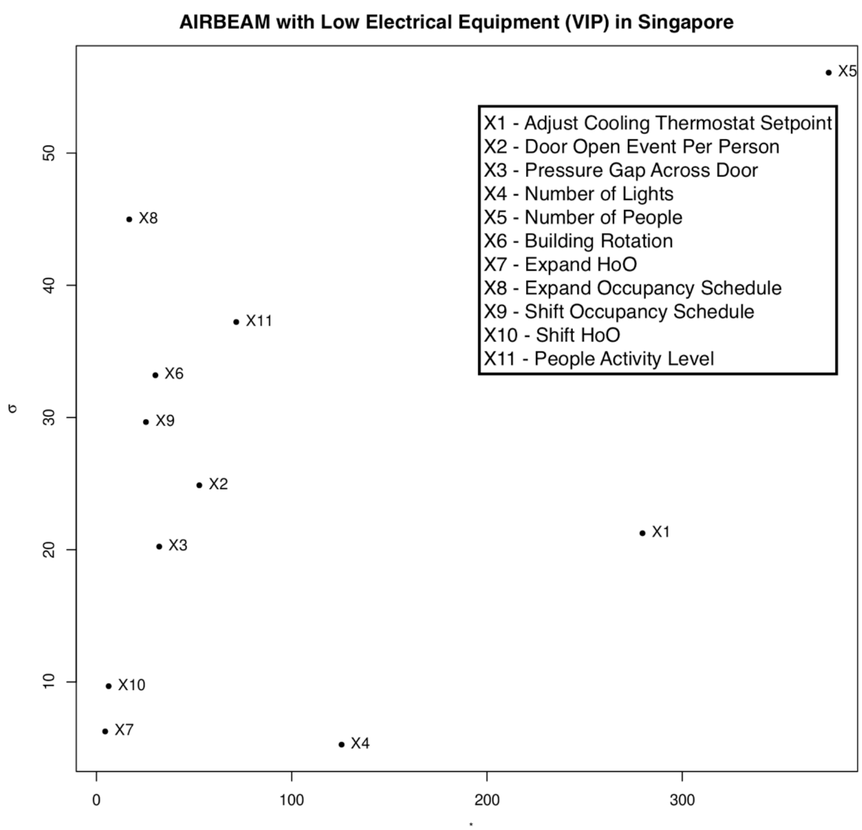


Figure 41: Morris Method Result for AIRBEAM with Low Electric Load in Chongjin

The result from the OAT runs on AIRBEAM with low electric load in Kharga is shown in Table 50. A tornado graphs has been generated to better represent the data in Figure 42. The three parameters with highest total site variance are adjusting the cooling thermostat-setpoint, changing the number of people, and adjusting the heating thermostat-setpoint. The total site energy variance measured by adjusting the cooling thermostat-setpoint by 2°C negatively and positively is 10.79 GJ; changing the number of people from 2 to 24 person is 9.06 GJ; and adjusting the heating thermostat-setpoint by 2°C negatively and positively is 6.49 GJ. Since the shelter has low electric load, the outdoor environment dominates the shelter's HVAC system. In Kharga where the temperature would drop sharply at night, heating and cooling from the HVAC system are needed. Adjusting the thermostat-setpoint have the most influence in the energy model.

Table 50: Total Site Energy [GJ] of AIRBEAM with Low Electric Load in Kharga

Variable Display Name				**Total Site Energy [GJ]**			
	Static Value	MIN Value	MAX Value	Static Result	MIN Result	Max Result	Variance
Adjust the Cooling Thermostat Setpoint	0	-2	2	99.96	94.57	105.36	10.79
Number of People	12	2	24	99.96	96.03	105.09	9.06
Adjust the Heating Thermostat Setpoint	0	-2	2	99.96	96.81	103.3	6.49
Number of Light	8	4	8	99.96	97.33	99.96	2.63
People Activity Level	130	100	170	99.96	99.12	101.13	2.01
Building Rotation	0	0	270	99.96	98.04	99.96	1.92
Door Event Per Person	3	2	6	99.96	99.7	100.54	0.84
Expand Hours of Operation	0	0	2	99.96	99.96	100.67	0.71
Pressure Difference Across Door	4	4	20	99.96	99.96	100.63	0.67
Expand Occupancy Schedule	0	0	2	99.96	99.96	100.26	0.3
Shift Occupancy Schedule	0	0	3	99.96	99.96	100.07	0.11
Shift Hours of Operation	0	0	3	99.96	99.96	100.07	0.11

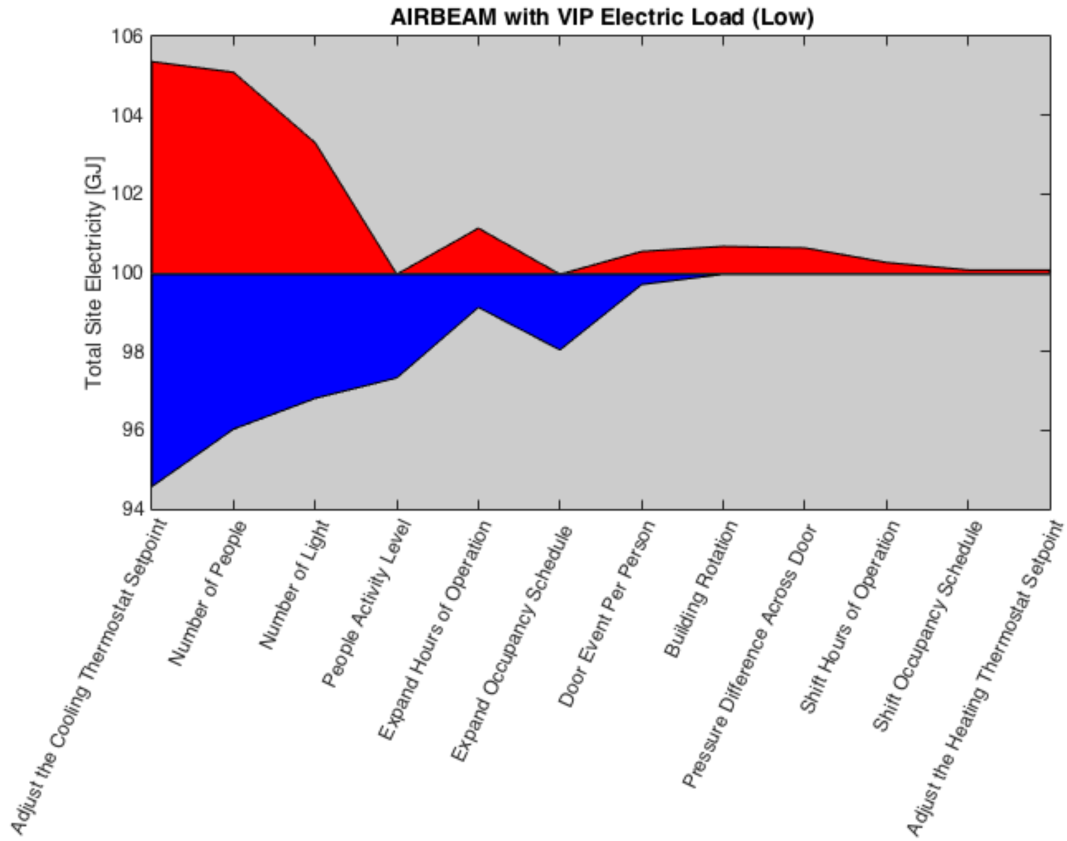


Figure 42: Tornado Graph of AIRBEAM with Low Electric Load in Kharga

The result from the Morris Method in Kharga is consistent with the OAT method. The four mean values of elementary effects greater than 75 are adjusting the cooling thermostat-setpoint, changing the number of people, and adjusting the heating thermostat-setpoint. As shown in Figure 43, the variable that have dependence on other input factors is building rotation. For the rest of the variables with low mean and standard deviation value, their impact is small.

Table 51: Morris Method Result of AIRBEAM with Low Electric Load in Kharga

Importance Order	Variable	Min Input Value	Max Input Value	μ	μ*	σ
1	Number of People	2	24	226.43	226.43	36.6
2	Adjust the Cooling Thermostat Setpoint	-2	2	-223.39	223.39	11.71
3	Adjust the Heating Thermostat Setpoint	-2	2	126.25	126.25	4.04
4	Number of Light	4	8	116.79	116.79	4.31
5	Building Rotation	0	270	11.42	50.36	62.5
6	People Activity Level	100	170	32.68	32.68	14.82
7	Pressure Difference Across Door	4	20	24.11	24.11	14.39
8	Door Event Per Person	2	6	22.86	22.86	9.81
9	Shift Occupancy Schedule	0	3	15.18	19.11	22.39
10	Expand Occupancy Schedule	0	2	-12.68	12.68	19.42
11	Expand Hours of Operation	0	2	6.07	6.07	6.023
12	Shift Hours of Operation	0	3	1.96	1.96	3.09

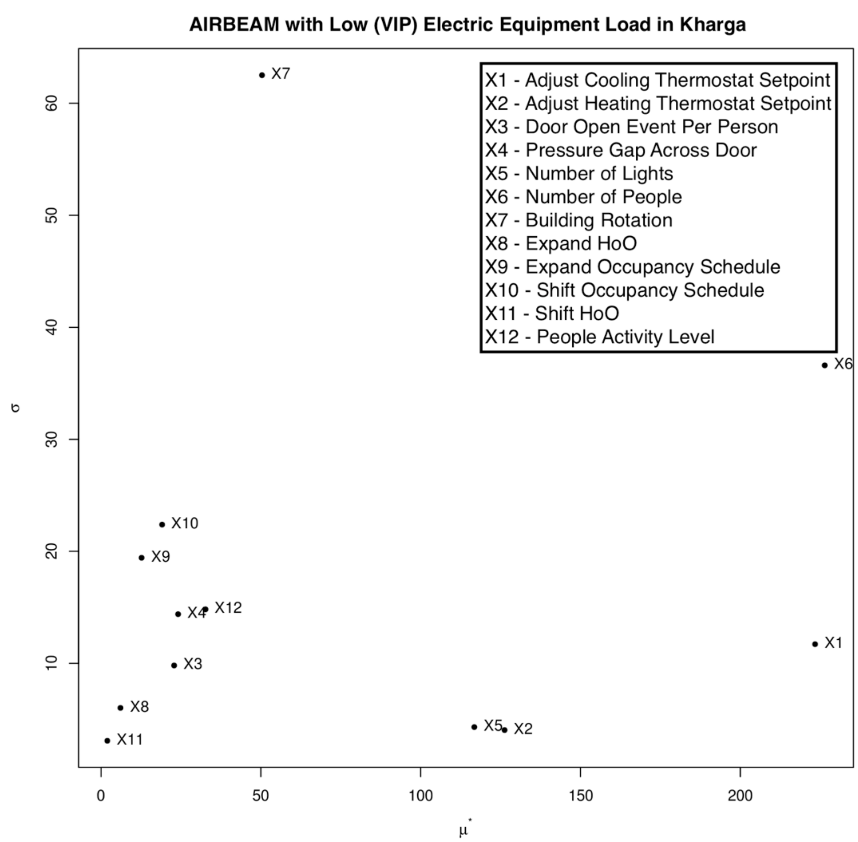


Figure 43: Morris Method Result for AIRBEAM with Low Electric Load in Kharga

5.4 MILVAN with High Electric Equipment Load

Compared to AIRBEAM, MILVAN is better insulated and is only 1/3 of AIRBEAM's volume. The result from the OAT runs for a MILVAN with high electric equipment load in Chongjin is shown in Table 52 and Figure 44. The three parameters with highest total site variance are adjusting the cooling thermostat-setpoint, number of light, and number of people. The total site energy variance measured by adjusting the cooling thermostat-setpoint by 2°C negatively and positively is 5.63 GJ; changing the number of lights from 4 to 8 person is 2.77 GJ; and changing the number of people from 2 to 8 is 1.99 GJ. The high electric equipment load generated large amount of wasted heat to be cooled by the HVAC system. Since MILVAN is better insulated, adjusting the heating thermostat-setpoints just generated a variance of 0.01 GJ in a cool temperature climate.

Table 52: Total Site Energy [GJ] of MILVAN with High Electric Load in Chongjin

Variable Display Name				Total Site Energy [GJ]			
	Static Value	MIN Value	MAX Value	Static Result	MIN Result	Max Result	Variance
Adjust the Cooling Thermostat Setpoint	0	-2	2	447.09	444.21	449.84	5.63
Number of Light	4	4	8	447.09	447.09	449.86	2.77
Number of People	4	2	8	447.09	446.43	448.42	1.99
Expand Hours of Operation	0	0	2	447.09	447.09	447.79	0.7
People Activity Level	130	100	170	447.09	446.88	447.4	0.52
Door Event Per Person	3	2	6	447.09	446.91	447.15	0.24
Pressure Difference Across Door	4	4	20	447.09	446.86	447.09	0.23
Expand Occupancy Schedule	0	0	2	447.09	447.09	447.31	0.22
Adjust the Heating Thermostat Setpoint	0	-2	2	447.09	447.09	447.1	0.01
Building Rotation	0	0	270	447.09	447.08	447.09	0.01
Shift Hours of Operation	0	0	3	447.09	447.09	447.09	0
Shift Occupancy Schedule	0	0	3	447.09	447.09	447.09	0

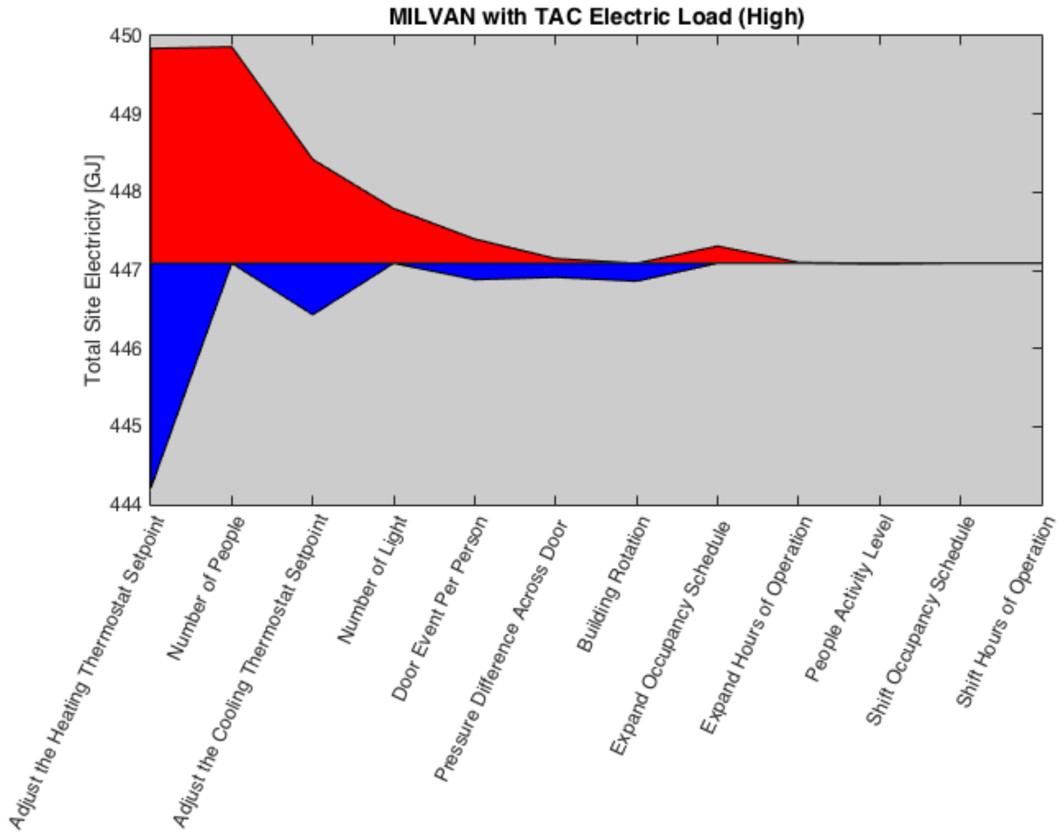


Figure 44: Tornado Graph of MILVAN with High Electric Load in Chongjin

The result from the Morris Method for MILVAN with high electric equipment load in Chongjin is consistent with the OAT method. The six mean values of elementary effects that are greater than 75 are number of lights, adjusting the cooling thermostat-setpoint, number of people, expanding the hours of operation, and people activity level as shown in Table 53 and Figure 45. As shown in Figure 45, the variables that have dependence on other input factors are expanding the hours of operation and occupancy schedule. For the rest of the variables with low mean and standard deviation value, their impact is small.

Table 53: Morris Method Result of MILVAN with High Electric Load in Chongjin

Importance Order	Variable	Min Input Value	Max Input Value	μ	μ*	σ
1	Number of Light	4	8	454.24	454.24	77.61
2	Adjust the Cooling Thermostat Setpoint	-2	2	-394.28	394.28	56.05
3	Number of People	2	24	152.02	152.02	75.13
4	Expand Hours of Operation	0	2	11.51	103.57	120.1
5	People Activity Level	100	170	76.92	76.92	66.04
6	Expand Occupancy Schedule	0	2	16.95	76.31	100.77
7	Shift Occupancy Schedule	0	3	-15.75	59.35	79.29
8	Shift Hours of Operation	0	3	27.25	58.75	90.57
9	Building Rotation	0	270	-44.82	46.03	68.18
10	Adjust the Heating Thermostat Setpoint	-2	2	15.75	44.82	82.31
11	Door Event Per Person	2	6	-33.31	33.31	41.99
12	Pressure Difference Across Door	4	20	-4.24	29.68	47.52

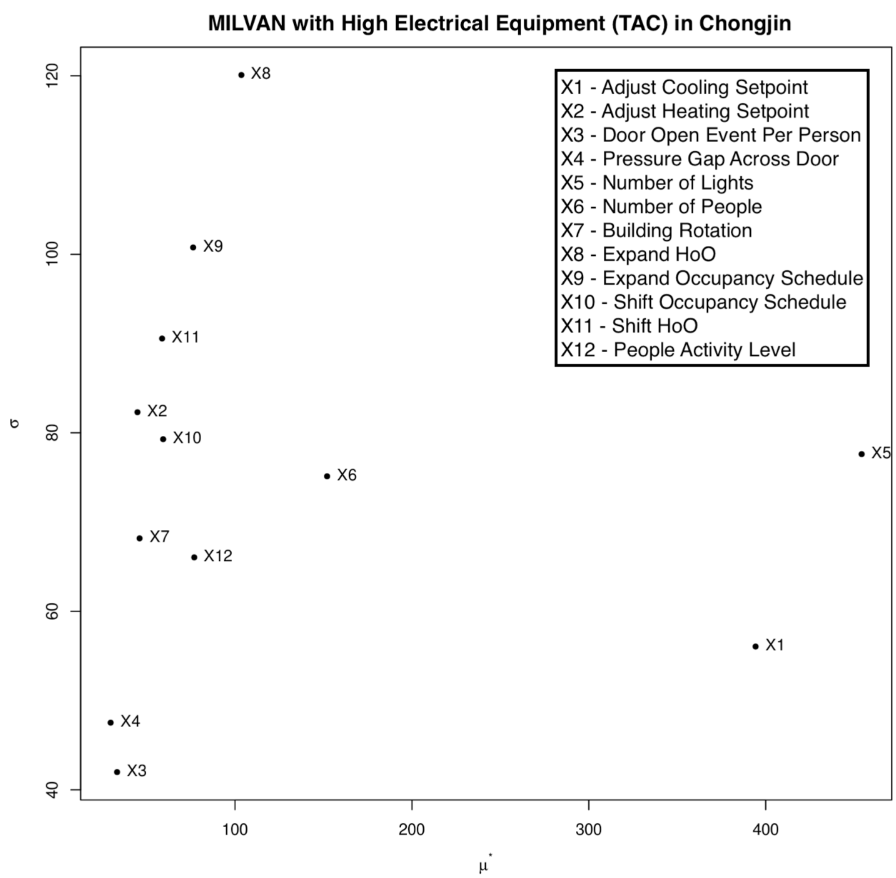


Figure 45: Morris Method Result for MILVAN with High Electric Load in Chongjin

The result from the OAT runs for a MILVAN with high electric equipment load in Singapore is shown in Table 54 and Figure 46. The three parameters with highest total site variance are adjusting the cooling thermostat-setpoint, number of people, and number of lights. The total site energy variance measured by adjusting the cooling thermostat-setpoint by 2°C negatively and positively is 11.77 GJ; changing the number of people from 2 to 8 person is 4.53 GJ; and changing the number of lights from 4 to 8 is 2.97 GJ. The outdoor hot environment and high electric equipment load required cooling from the HVAC system, which is consistent with the expected result.

Table 54: Total Site Energy [GJ] of MILVAN with High Electric Load in Singapore

Variable Display Name				**Total Site Energy [GJ]**			
	Static Value	MIN Value	MAX Value	Static Result	MIN Result	Max Result	Variance
Adjust the Cooling Thermostat Setpoint	0	-2	2	551.63	545.69	557.46	11.77
Number of People	4	2	8	551.63	550.06	554.59	4.53
Number of Light	4	4	8	551.63	551.63	554.6	2.97
People Activity Level	130	100	170	551.63	551.01	552.32	1.31
Expand Hours of Operation	0	0	2	551.63	551.62	552.41	0.79
Door Event Per Person	3	2	6	551.63	551.42	552.2	0.78
Pressure Difference Across Door	4	4	20	551.63	551.63	552.31	0.68
Expand Occupancy Schedule	0	0	2	551.63	551.63	552.15	0.52
Shift Hours of Operation	0	0	3	551.63	551.63	551.73	0.1
Building Rotation	0	0	270	551.63	551.63	551.7	0.07
Shift Occupancy Schedule	0	0	3	551.63	551.63	551.69	0.06
Adjust the Heating Thermostat Setpoint	0	-2	2	551.63	551.63	551.63	0

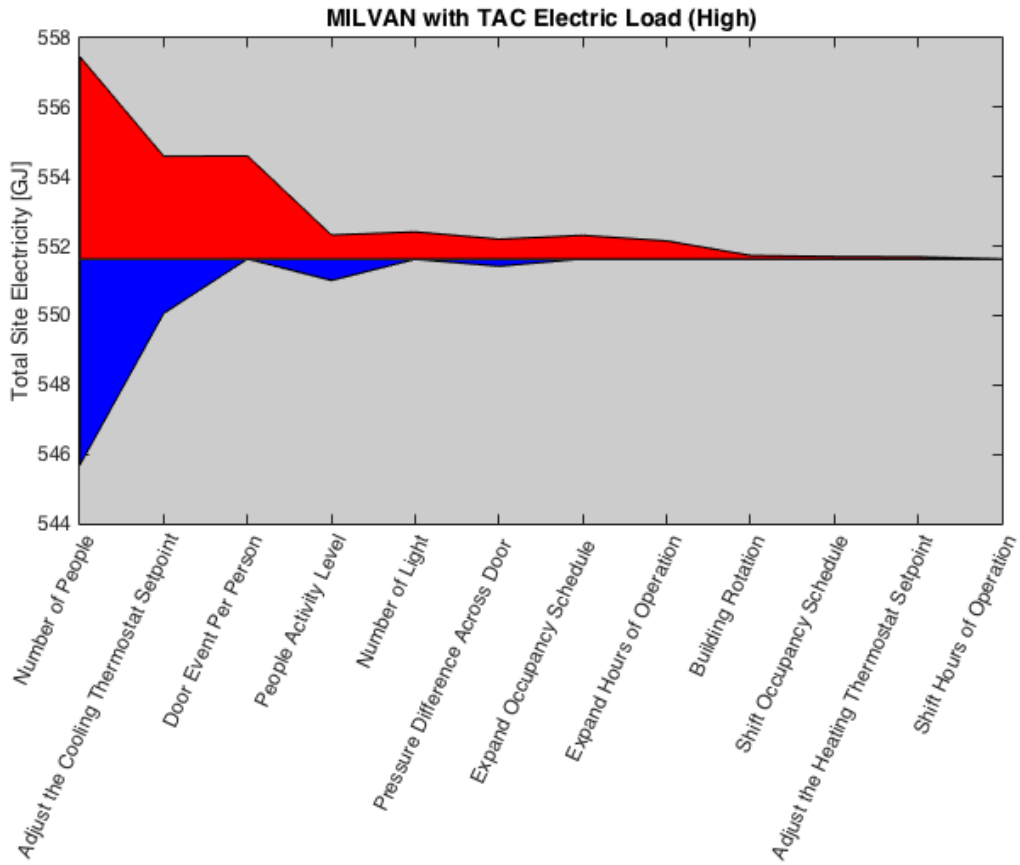


Figure 46: Tornado Graph of MILVAN with High Electric Load in Singapore

The result from the Morris Method for MILVAN with high electric equipment load in Singapore is consistent with the OAT method. The four mean values of elementary effects greater than 75 are number of lights, adjusting the cooling thermostat-setpoint, number of people, and expanding the hours of operation as shown in Table 55 and Figure 47. As shown in Figure 47, the variables that have dependence on other input factors are expanding the hours of operation and occupancy schedule. For the rest of the variables with low mean and standard deviation value, their impact is small.

Table 55: Morris Method Result of MILVAN with High Electric Load in Singapore

Importance Order	Variable	Min Input Value	Max Input Value	μ	μ*	σ
1	Number of Light	4	8	374.9	374.9	58.47
2	Adjust the Cooling Thermostat Setpoint	-2	2	-353.7	353.7	61.18
3	Number of People	2	8	169.58	169.58	79.72
4	Expand Hours of Operation	0	2	13.32	95.69	120.31
5	Pressure Difference Across Door	4	20	-43.61	71.47	95.51
6	Shift Occupancy Schedule	0	3	-36.94	70.86	94.84
7	Door Event Per Person	2	6	36.34	59.35	71.89
8	People Activity Level	100	170	49.06	49.06	45.9
9	Building Rotation	0	270	-42.4	46.03	68.46
10	Expand Occupancy Schedule	0	2	10.3	38.16	69.41
11	Shift Hours of Operation	0	3	15.14	15.14	45.8
12	Adjust the Heating Thermostat Setpoint	-2	2	0	0	0

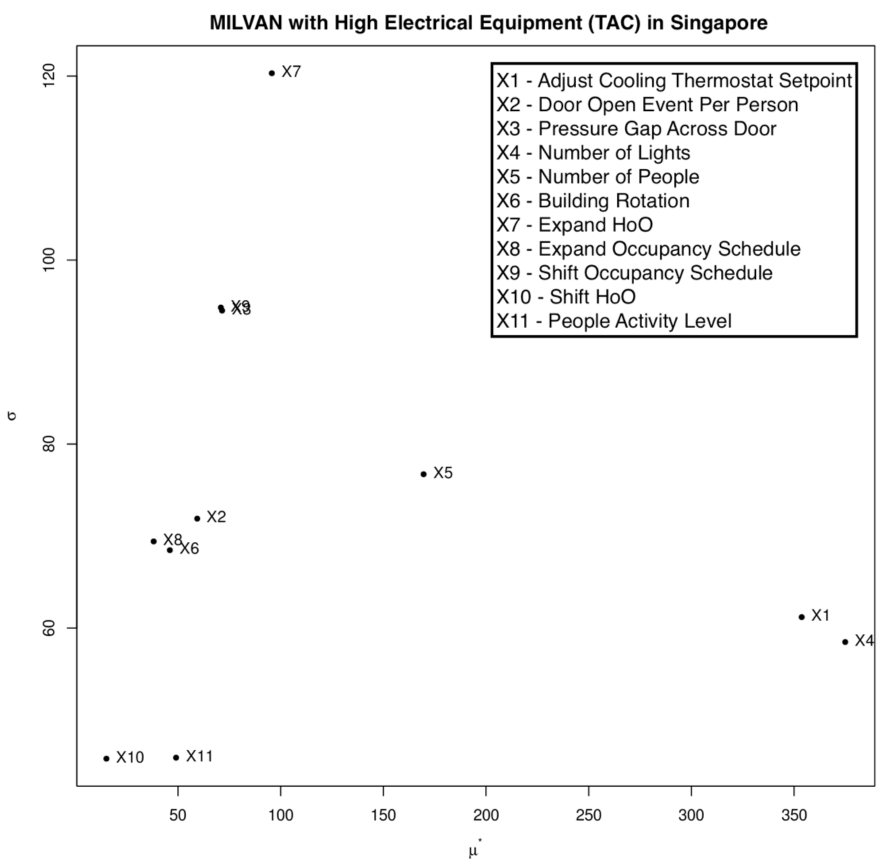


Figure 47: Morris Method Result for MILVAN with High Electric Load in Singapore

The result from the OAT runs for a MILVAN with high electric equipment load in Kharga is shown in Table 56 and Figure 48. The three parameters with highest total site variance are adjusting the cooling thermostat-setpoint, number of people, and number of lights. The total site energy variance measured by adjusting the cooling thermostat-setpoint by 2°C negatively and positively is 7.95 GJ; changing the number of people from 2 to 8 person is 3.12 GJ; and changing the number of lights from 4 to 8 is 2.9 GJ. Since MILVAN is better insulated, even with the temperature at Kharga drop sharply at night, adjusting the heating thermostat-setpoint has small influence in the model. The outdoor environment and high electric equipment load required cooling from the HVAC system, which is consistent with the expected result.

Table 56: Total Site Energy [GJ] of MILVAN with High Electric Load in Kharga

Variable Display Name				**Total Site Energy [GJ]**			
	Static Value	MIN Value	MAX Value	Static Result	MIN Result	Max Result	Variance
Adjust the Cooling Thermostat Setpoint	0	-2	2	522.18	518.16	526.11	7.95
Number of People	4	2	8	522.18	521.13	524.25	3.12
Number of Light	4	4	8	522.18	522.18	525.08	2.9
People Activity Level	130	100	170	522.18	521.83	522.67	0.84
Expand Hours of Operation	0	0	2	522.18	522.18	522.92	0.74
Expand Occupancy Schedule	0	0	2	522.18	522.18	522.55	0.37
Door Event Per Person	3	2	6	522.18	522.13	522.29	0.16
Building Rotation	0	0	270	522.18	522.18	522.3	0.12
Pressure Difference Across Door	4	4	20	522.18	522.18	522.29	0.11
Shift Hours of Operation	0	0	3	522.18	522.18	522.27	0.09
Shift Occupancy Schedule	0	0	3	522.18	522.18	522.25	0.07
Adjust the Heating Thermostat Setpoint	0	-2	2	522.18	522.18	522.18	0

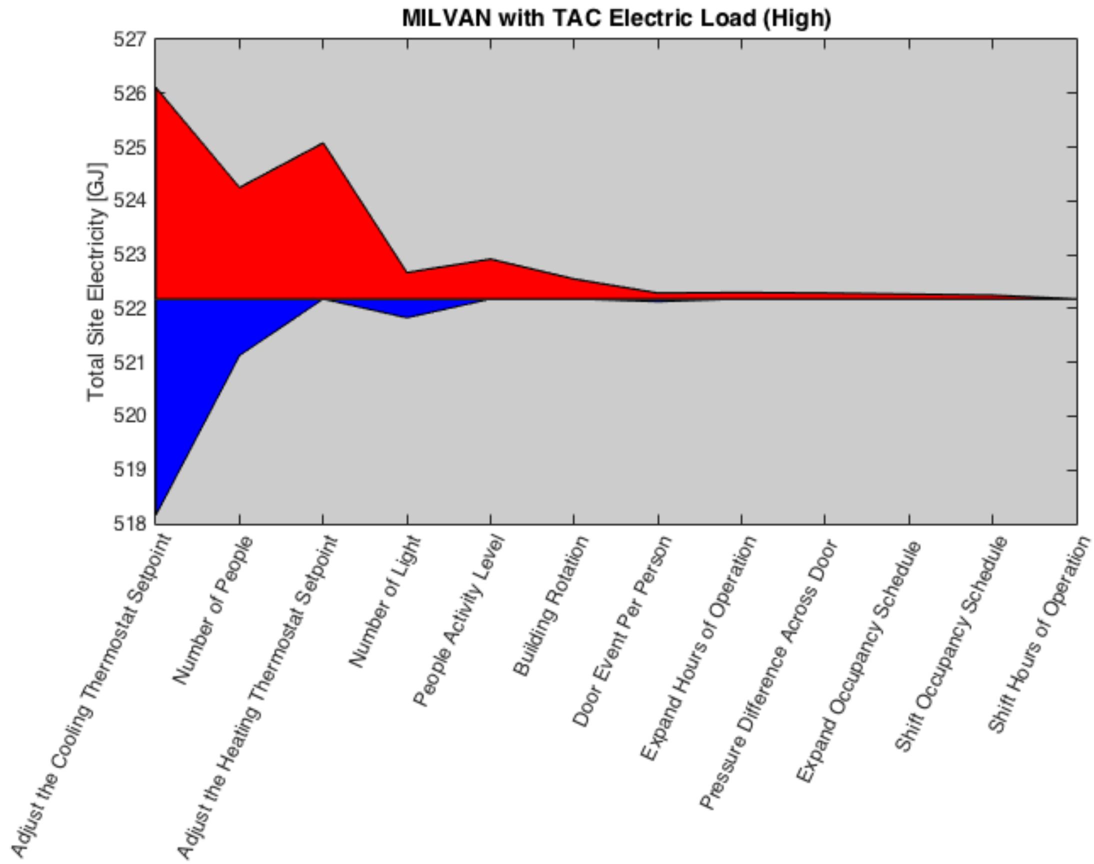


Figure 48: Tornado Graph of MILVAN with High Electric Load in Kharga

The result from the Morris Method for MILVAN with high electric equipment load in Kharga is consistent with the OAT method. The highest mean values of elementary effects are number of lights, adjusting the cooling thermostat-setpoint, number of people, and expanding the hours of operation and occupancy schedule as shown in Table 57 and Figure 49. As shown in Figure 49, the variables that have dependence on other input factors are expanding the hours of operation and occupancy schedule. In a smaller volume shelter like MILVAN with high electric equipment load, the occupancy schedule should be carefully considered in the modeling process. For the rest of the variables with low mean and standard deviation value, their impact is small.

Table 57: Morris Method Result of MILVAN with High Electric Load in Kharga

Importance Order	Variable	Min Input Value	Max Input Value	μ	μ*	σ
1	Number of Light	4	8	396.7	396.7	76.68
2	Adjust the Cooling Thermostat Setpoint	-2	2	-396.7	396.7	85.71
3	Number of People	2	8	136.27	136.27	70.82
4	Expand Hours of Operation	0	2	12.72	93.88	113
5	Expand Occupancy Schedule	0	2	59.96	90.24	108.77
6	Pressure Difference Across Door	4	20	-62.38	62.38	74.78
7	People Activity Level	100	170	53.9	53.9	46.08
8	Shift Hours of Operation	0	3	13.93	45.42	82.8
9	Door Event Per Person	2	6	-12.11	37.55	49.7
10	Adjust the Heating Thermostat Setpoint	-2	2	-29.07	29.07	61.28
11	Shift Occupancy Schedule	0	3	-2.42	25.44	34.99
12	Building Rotation	0	270	-15.75	16.96	45.7

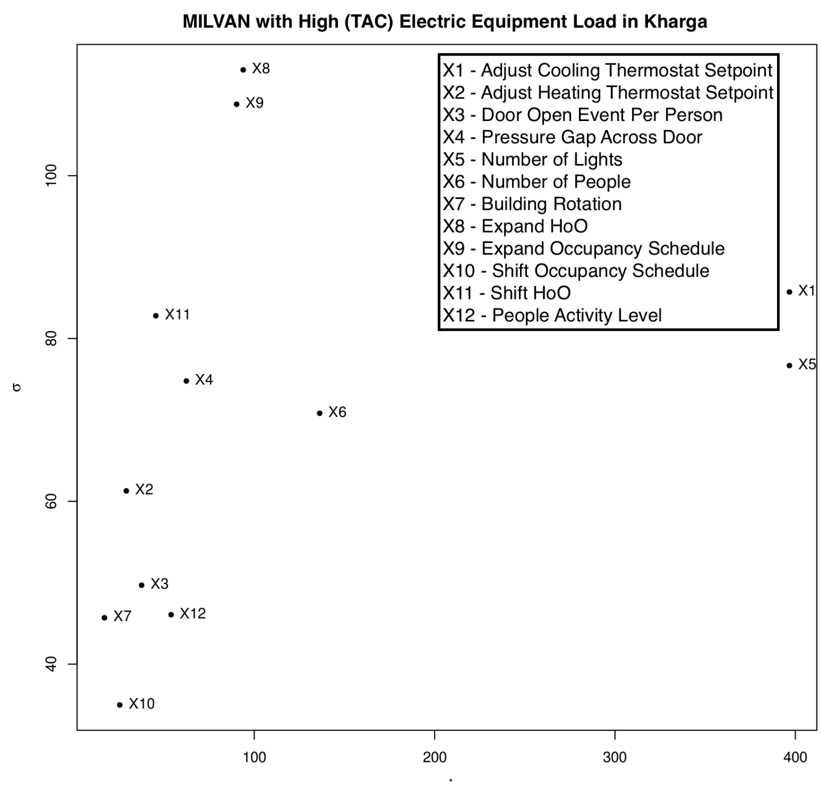


Figure 49: Morris Method Result for MILVAN with High Electric Load in Kharga

5.5 MILVAN with Low Electric Equipment Load

The result from the OAT runs for a MILVAN with low electric equipment load in Chongjin is shown in Table 58 and Figure 50. The three parameters with highest total site variance are adjusting the heating thermostat-setpoint, the number of light, and the number of people. The total site energy variance measured by adjusting the heating thermostat-setpoint by 2°C negatively and positively is 7.81 GJ; changing the number of lights from 4 to 8 person is 1.57 GJ; and changing the number of people from 2 to 8 is 1.16 GJ. Even through MILVAN is better insulated than AIRBEAM, the low electric equipment load does not generate enough wasted heat to warm the shelter in a cold temperate climate. Adjusting the heating thermostat-setpoint creates the highest total site variance in the study as expected.

Table 58: Total Site Energy of MILVAN with Low Electric Load in Chongjin

Variable Display Name				**Total Site Energy [GJ]**			
	Static Value	MIN Value	MAX Value	Static Result	MIN Result	Max Result	Variance
Adjust the Heating Thermostat Setpoint	0	-2	2	69.98	66.13	73.94	7.81
Number of Light	4	4	8	69.98	69.98	71.55	1.57
Number of People	4	2	8	69.98	69.23	70.39	1.16
Adjust the Cooling Thermostat Setpoint	0	-2	2	69.98	69.56	70.47	0.91
Door Event Per Person	3	2	6	69.98	69.84	70.41	0.57
Pressure Difference Across Door	4	4	20	69.98	69.98	70.51	0.53
Expand Hours of Operation	0	0	2	69.98	69.98	70.23	0.25
People Activity Level	130	100	170	69.98	69.85	70.08	0.23
Expand Occupancy Schedule	0	0	2	69.98	69.83	69.98	0.15
Building Rotation	0	0	270	69.98	69.98	70.07	0.09
Shift Occupancy Schedule	0	0	3	69.98	69.98	70.01	0.03
Shift Hours of Operation	0	0	3	69.98	69.98	69.98	0

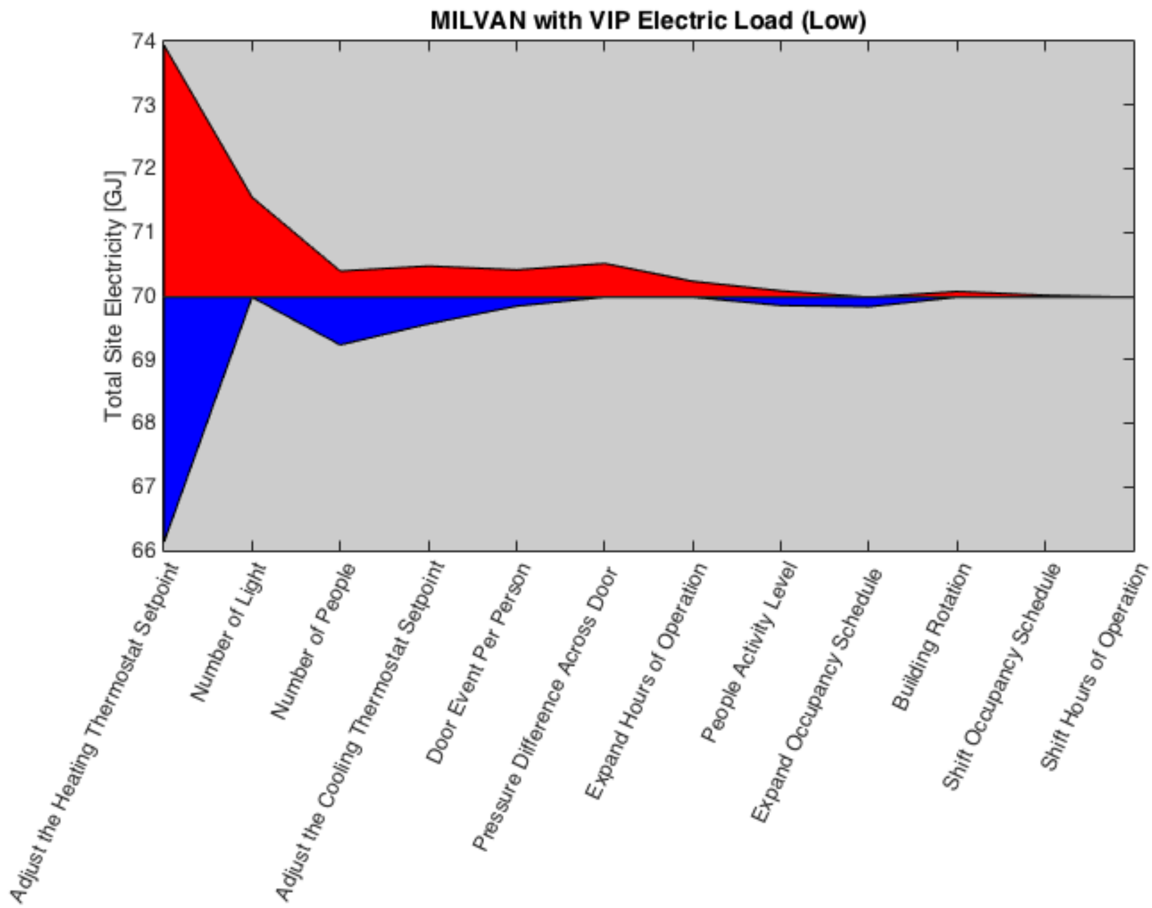


Figure 50: Tornado Graph of MILVAN with Low Electric Load in Chongjin

The results from the Morris Method for MILVAN with low electric equipment load in Chongjin is somewhat consistent with the OAT method. The two mean values of elementary effects that are greater than 75 are adjusting the heating thermostat-setpoint and the number of lights, as shown in Table 59 and Figure 51. As shown in Figure 51, the variables that have dependence on other input factors are shifting and expanding the occupancy schedule. For the rest of the variables with low mean and standard deviation value, their impact is small.

Table 59: Morris Method Result of MILVAN with Low Electric Load in Chongjin

Importance Order	Variable	Min Input Value	Max Input Value	μ	μ*	σ
1	Adjust the Heating Thermostat Setpoint	-2	2	525.1	525.1	5.75
2	Number of Light	4	8	233.18	233.18	9.99
3	Adjust the Cooling Thermostat Setpoint	-2	2	-66.02	66.02	6.67
4	Number of People	2	24	-65.41	65.41	20.75
5	Door Event Per Person	2	6	47.85	47.85	12.91
6	Pressure Difference Across Door	4	20	39.97	39.97	19.82
7	Shift Occupancy Schedule	0	3	4.84	21.8	29.23
8	Expand Hours of Operation	0	2	21.2	21.2	18.56
9	Expand Occupancy Schedule	0	2	-14.53	20.59	24.26
10	Building Rotation	0	270	4.24	16.35	20.4
11	People Activity Level	100	170	-14.54	15.54	5.11
12	Shift Hours of Operation	0	3	-0.61	1.82	3.44

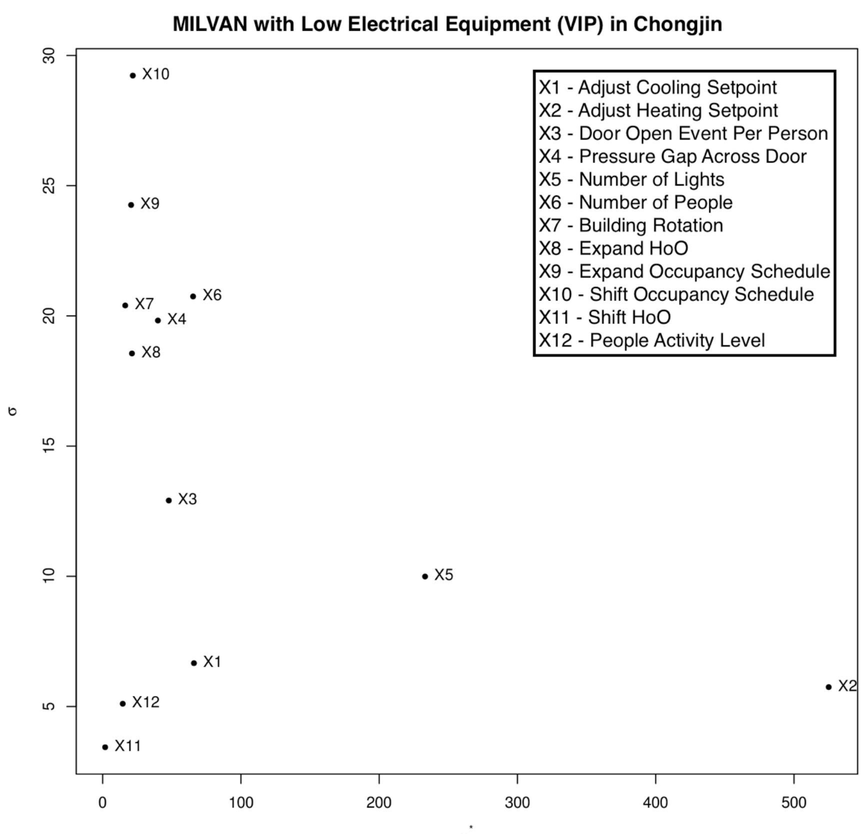


Figure 51: Morris Method Result for MILVAN with Low Electric Load in Chongjin

The result from the OAT runs for a MILVAN with low electric equipment load in Singapore is shown in Table 60 and Figure 52. The three parameters with highest total site variance are adjusting the cooling thermostat-setpoint, the number of people, and the number of lights. The total site energy variance measured by adjusting the heating thermostat-setpoint by 2°C negatively and positively is 11.02 GJ; changing the number of people from 2 to 8 is 4.29 GJ; and changing the number of lights from 4 to 8 person is 3.08 GJ.

Table 60: Total Site Energy [GJ] of MILVAN with Low Electric Load in Singapore

Variable Display Name				Total Site Energy [GJ]			
	Static Value	MIN Value	MAX Value	Static Result	MIN Result	Max Result	Variance
Adjust the Cooling Thermostat Setpoint	0	-2	2	50.38	45.3	56.32	11.02
Number of People	4	2	8	50.38	48.95	53.24	4.29
Number of Light	4	4	8	50.38	50.38	53.46	3.08
People Activity Level	130	100	170	50.38	49.87	51.07	1.2
Expand Hours of Operation	0	0	2	50.38	50.38	50.88	0.5
Expand Occupancy Schedule	0	0	2	50.38	50.38	50.82	0.44
Door Event Per Person	3	2	6	50.38	50.29	50.61	0.32
Pressure Difference Across Door	4	4	20	50.38	50.38	50.63	0.25
Building Rotation	0	0	270	50.38	50.38	50.46	0.08
Shift Occupancy Schedule	0	0	3	50.38	50.38	50.42	0.04
Shift Hours of Operation	0	0	3	50.38	50.38	50.39	0.01
Adjust the Heating Thermostat Setpoint	0	-2	2	50.38	50.38	50.38	0

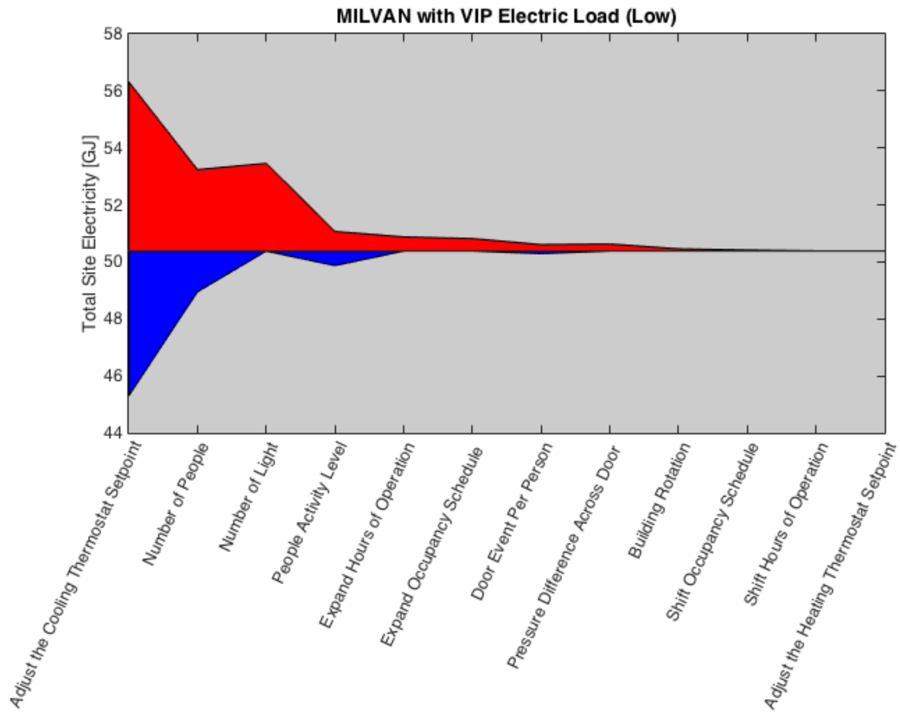


Figure 52: Tornado Graph of MILVAN with Low Electric Load in Singapore

The result from the Morris Method for MILVAN with low electric equipment load in Singapore is consistent with the OAT method. The four mean values of elementary effects greater than 75 are adjusting the cooling thermostat-setpoint, the number of lights, the number of people, and people activity level as shown in Table 61 and Figure 53. For the rest of the variables with low mean and standard deviation value, their impact is small.

Table 61: Morris Method Result of MILVAN with Low Electric Load in Singapore

Importance Order	Variable	Min Input Value	Max Input Value	μ	μ*	σ
1	Adjust the Cooling Thermostat Setpoint	-2	2	-757.67	757.67	65.32
2	Number of Light	4	8	450	450	22.67
3	Number of People	2	8	312.52	312.52	38.22
4	People Activity Level	100	170	80.55	80.55	27.39
5	Shift Occupancy Schedule	0	3	-36.34	50.87	53.79
6	Door Event Per Person	2	6	30.89	30.38	13.53
7	Expand Hours of Operation	0	2	30.28	30.28	29.25
8	Expand Occupancy Schedule	0	2	26.04	26.04	48.8
9	Pressure Difference Across Door	4	20	15.75	15.75	5.85
10	Building Rotation	0	270	3.73	14.5	16.89
11	Shift Hours of Operation	0	3	0.61	0.61	1.92
12	Adjust the Heating Thermostat Setpoint	-2	2	0	0	0

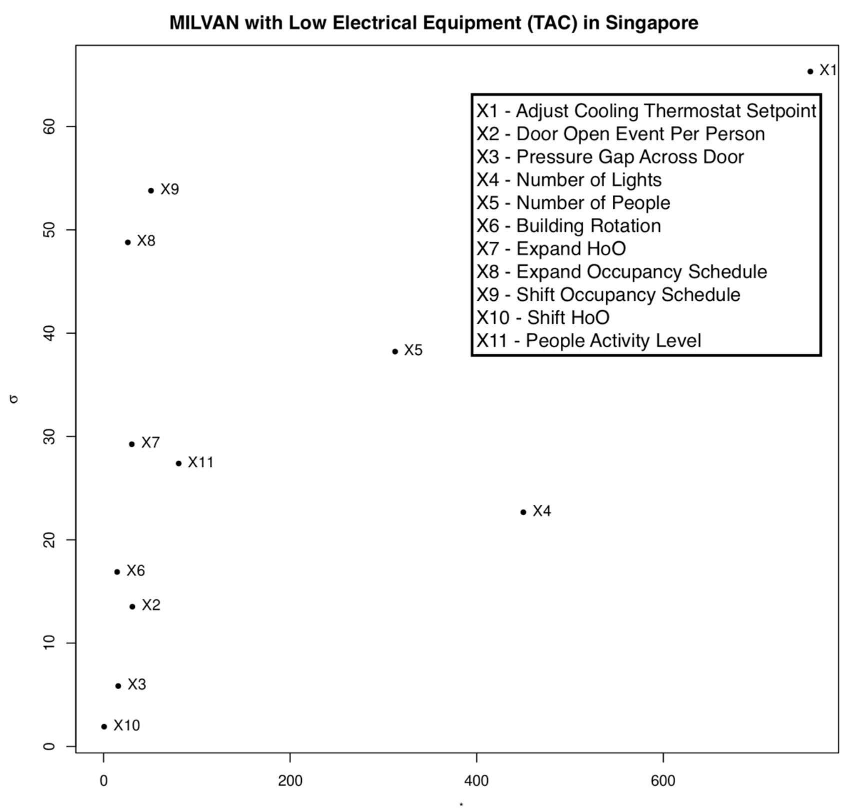


Figure 53: Morris Method Result for MILVAN with Low Electric Load in Singapore

The result from the OAT runs for a MILVAN with low electric equipment load in Kharga is shown in Table 62 and Figure 53. The three parameters with highest total site variance are adjusting the cooling thermostat-setpoint, the number of people, and the number of lights. The total site energy variance measured by adjusting the heating thermostat-setpoint by 2°C negatively and positively is 5.01 GJ; changing the number of people from 2 to 8 is 1.77 GJ; and changing the number of lights from 4 to 8 person is 2.75 GJ.

Table 62: Total Site Energy [GJ] of MILVAN with Low Electric Load in Kharga

Variable Display Name				**Total Site Energy [GJ]**			
	Static Value	MIN Value	MAX Value	Static Result	MIN Result	Max Result	Variance
Adjust the Cooling Thermostat Setpoint	0	-2	2	49.71	47.31	52.32	5.01
Number of Light	4	4	8	49.71	49.71	52.46	2.75
Number of People	4	2	8	49.71	49.14	50.91	1.77
Adjust the Heating Thermostat Setpoint	0	-2	2	49.71	49.16	50.44	1.28
Expand Hours of Operation	0	0	2	49.71	49.71	50.13	0.42
Door Event Per Person	3	2	6	49.71	49.65	49.87	0.22
Expand Occupancy Schedule	0	0	2	49.71	49.71	49.93	0.22
Shift Occupancy Schedule	0	0	3	49.71	49.71	49.92	0.21
Pressure Difference Across Door	4	4	20	49.71	49.71	49.89	0.18
Building Rotation	0	0	270	49.71	49.71	49.86	0.15
Shift Hours of Operation	0	0	3	49.71	49.71	49.8	0.09
People Activity Level	130	100	170	49.71	49.69	49.76	0.07

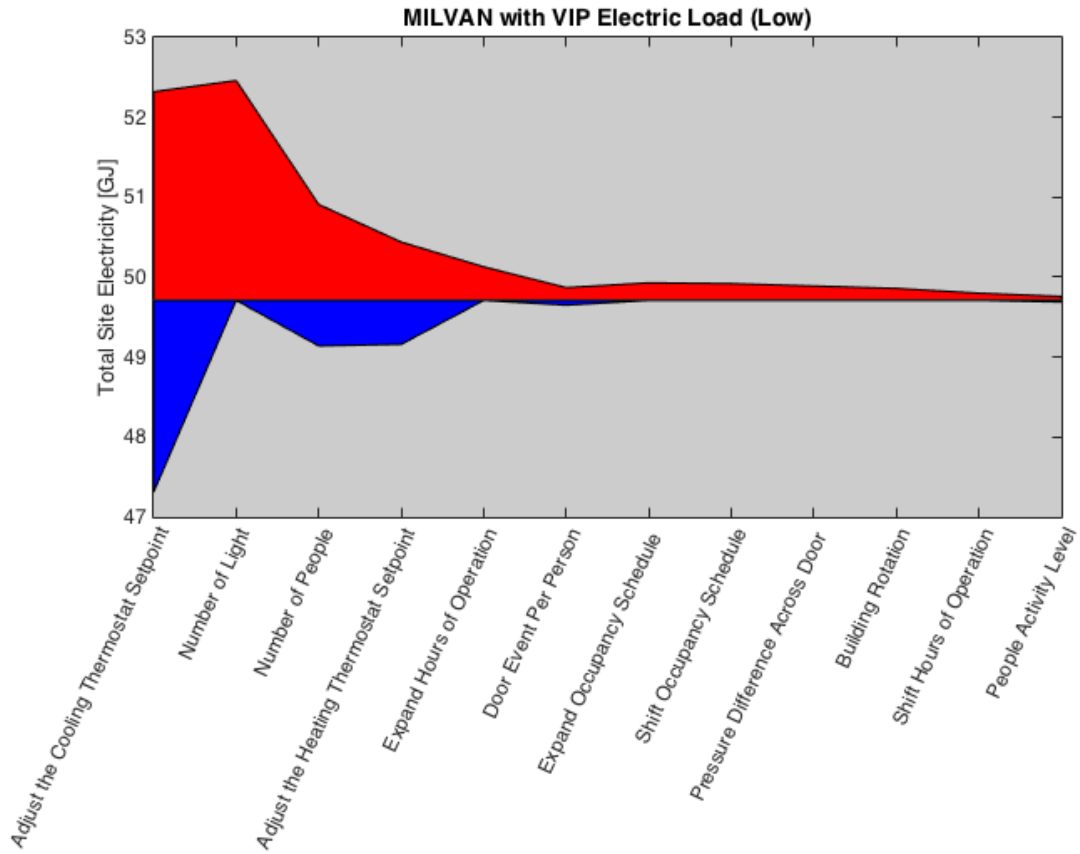


Figure 54: Tornado Graph of MILVAN with Low Electric Load in Kharga

The results from the Morris Method for MILVAN with low electric equipment load in Singapore is consistent with the OAT method. The highest mean values of elementary effects are adjusting the cooling thermostat-setpoint, the number of lights, and the number of people as shown in Table 63 and Figure 55. As shown in Figure 55, the variable that have dependence on other input factors is building rotation. For the rest of the variables with low mean and standard deviation value, their impact is small.

Table 63: Morris Method Result of MILVAN with Low Electric Load in Kharga

Importance Order	Variable	Min Input Value	Max Input Value	μ	μ*	σ
1	Number of Light	4	8	417.3	417.3	18.6
2	Adjust the Cooling Thermostat Setpoint	-2	2	-354.91	354.91	20.23
3	Number of People	2	8	158.68	158.68	27.65
4	Adjust the Heating Thermostat Setpoint	-2	2	79.95	79.95	9.81
5	Expand Hours of Operation	0	2	39.37	39.37	32.71
6	Building Rotation	0	270	9.08	33.31	40.4
7	Shift Occupancy Schedule	0	3	26.68	29.68	30.28
8	Door Event Per Person	2	6	26.04	26.04	9.05
9	Pressure Difference Across Door	4	20	26.04	26.04	12.78
10	Expand Occupancy Schedule	0	2	15.14	26.04	34.53
11	People Activity Level	100	170	8.48	8.48	5.11
12	Shift Hours of Operation	0	3	7.27	7.27	5.57

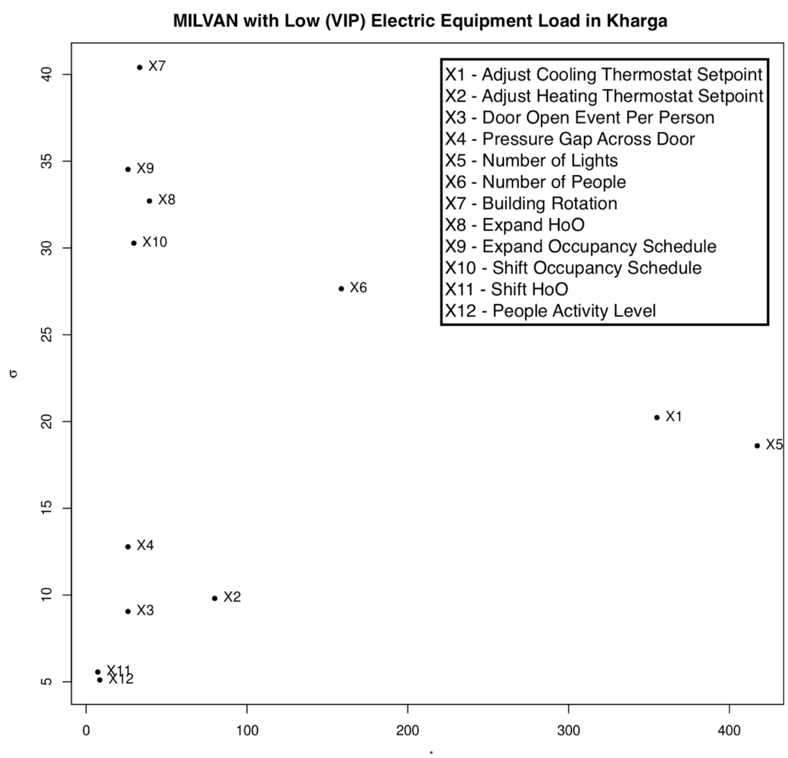


Figure 55: Morris Method Result for MILVAN with Low Electric Load in Kharga

5.6 Summary

Table 64: Important Variables for AIRBEAM and MILVAN

			Variables with Mean Value of Elementary Effect > 75				
			1	2	3	4	5
Airbeam	High	Chongjin	Adjust Cooling Thermostat setpoint	Number of People	Number of Lights	-	-
		Singapore	Number of People	Adjust Cooling Thermostat setpoint	Number of Lights	Shift Occupancy Schedule	-
		Kharga	Adjust Cooling Thermostat setpoint	Number of People	Number of Lights	-	-
	Low	Chongjin	Adjust Heating Thermostat setpoint	-	-	-	-
		Singapore	Number of People	Adjust Cooling Thermostat setpoint	Number of Lights	-	-
		Kharga	Number of People	Adjust Cooling Thermostat setpoint	Adjust Heating Thermostat setpoint	Number of Lights	-
MILVAN	High	Chongjin	Number of Lights	Adjust Cooling Thermostat setpoint	Number of Lights	Expand Hours of Operations	People Activity Level
		Singapore	Number of Lights	Adjust Cooling Thermostat setpoint	Number of People	Expand Hours of Operations	
		Kharga	Number of Lights	Adjust Cooling Thermostat setpoint	Number of People	Expand Hours of Operations	Expand Occupancy Schedule
	Low	Chongjin	Adjust Heating Thermostat setpoint	Number of Lights	-	-	-
		Singapore	Adjust Cooling Thermostat setpoint	Number of Lights	Number of People	People Activity Level	-
		Kharga	Number of Lights	Adjust Cooling Thermostat setpoint	Number of People	Adjust Heating Thermostat setpoint	-

Based on the results of the Morris Method shown in Table 64, the most important factor in both MILVAN and AIRBEAM shelter modeling are the thermostat-setpoint, the peak number of people, and the number of lights. Expanding the hours of operation, expanding the occupancy schedule, and adjusting the people activity level are important factors for MILVAN as well. In cold temperate Chongjin location, AIRBEAM with low internal electric equipment energy model is dominated by the impact of adjusting the heating thermostat-setpoint. Even though there is increase of importance in building rotation and door opening event per person for shelter with low internal electric equipment load in Chongjin and Kharga, their mean value of elementary effects never reached greater than 75. The entry and exit infiltration information should still be carefully modeled in shelters as the number of door opening event is multiplication of peak number of people and door opening event per person. The studies did show occupancy schedule is an important factor to model which is expected from the literature review. As shown in this study, the smaller volume and more insulated MILVAN is sensitivity to occupancy schedule and changes in the hours of operation. Nevertheless, the analysis shows the workflow of load generation tool is developed successfully and working properly. The sensitivity analysis workflow is located in the Shelter CORSO repository and can be run with different shelter type by changing the input value in the matrix.

CHAPTER 6

CONCLUSION

The thesis has developed a workflow that automates shelter energy modeling process using OpenStudio and EnergyPlus. The workflow modeling process is composed of measures that considers the shelter geometric type, constructions, materials, schedules, mechanical system, and infiltration in a shelter in a forward operating base. The workflow is created from Ruby scripting, OpenStudio, EnergyPlus, and Reporting measures. It can easily be modified to consider additional variables in the future. The workflow has been tested and has successfully push simulation inputs and results into the DEnCity database. The sensitivity analysis results have been reviewed and accepted by NREL. There are more tasks to be considered in the project as the thesis only provides the framework from input data in Excel interface to EnergyPlus simulation inputs and result on the DEnCity database. More shelter type, construction, and materials have to be considered. Calibration is needed for shelter model to ensure it captures the energy consumption of shelters realistically in a forward operating base.

6.1 Future Works

Beside the calibration and validation of MILVAN shelter models, there are more future works to be considered in the workflow and sensitivity analysis. These included a post-DEnCity script to average building rotations, continuous refinement of workflow, and uncertainty analysis, and automation of sensitivity analysis process.

The sensitivity analysis result has shown the building rotation variable might be an important factor in shelter modeling with mean value of elementary effects around 60. In the future when more shelter geometries and locations are being considered, the building rotations would factor into modeling concerns. To consider the different building rotations of each shelter type, a post-DEnCity script is proposed to calculate the average energy consumption of all building rotations model. The concept is shown in Figure 56. The script should pull out all the models with same specification but different rotation in the DEnCity database. The hourly facility power loads of these models would be averaged. Then a new analysis should be generated and pushed the average load calculated into DEnCity database.

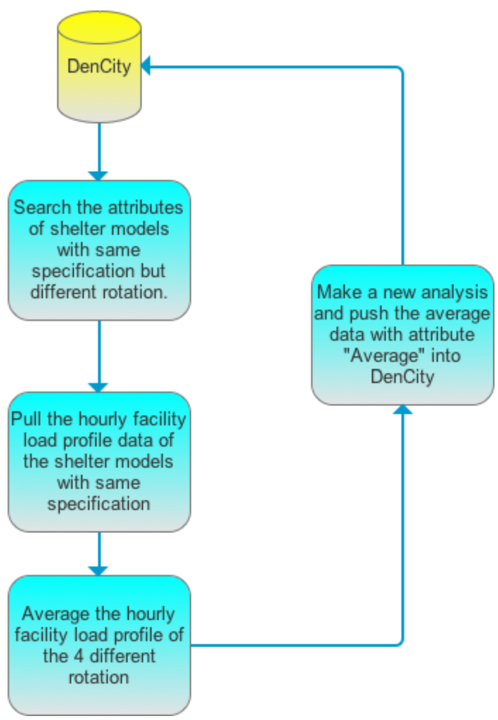


Figure 56: Flowchart for Post-DEnCity Script

Other future works included continuous refinement of the workflow. As more information is obtained on the parameters of the shelter, the workflow and measures have to be modified to fit its changes. For example, when a new HVAC system is proposed, user have to test the HVAC components in the HVAC OpenStudio measure to ensure the unit is imported into the shelter model properly. User can use the test file provided in the HVAC measure for this purpose. However, the workflow is aimed to work with different geometry shelter type and HVAC models. The thesis has provided the required naming method and format for importing any new HVAC system and geometry type.

Performing uncertainty analysis is important because there will always be uncertainty in the electric equipment load measured, occupancy schedule, and other parameters in modeling. OpenStudio has common functions such as uncertainty analysis, optimization, and model input calibration. With powerful cloud computing such as Amazon AWS, user can consider the Latin hyercube sampling method (LHS) integrated in OpenStudio to run uncertainty analysis. User can specify the normal distribution, minimum value, maximum value, and standard deviation for the variables of interests. LHS would generate outputs that can be expressed as probability distribution based on the model runs to evaluate uncertainty in outputs [34].

Automation of the sensitivity analysis run has been discussed with NREL to provide a bridge from the OpenStudio Server to data analysis or plotting tools, such as Matlab. This could reduce the cost and time spent in searching to insert the hundreds of simulation results manually by hand. The provided sensitivity analysis results and guidelines is only initial attempt to understand the importance of occupancy in shelter modeling. In the future, the sensitivity analysis workflow can be modified to consider any variable of interests and automation of the data collecting process can make it more efficient.

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