Multi-Objective Optimization for Structure and Energy in the Case of Multistory Buildings with Atriums

by

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Submitted to the Department of Civil and Environmental Engineering on May 19, 2016 in Partial Fulfillment of the Requirements of the Degree of Master of Engineering in Civil and Environmental Engineering

ABSTRACT

This research shows that a successful workflow exists that compares structural efficiency with operational energy efficiency for buildings that incorporate natural ventilation practices. The parametric model successfully generates floor-framing plans with atriums that are similar to industry standards. Furthermore, this research follows a workflow that allows one to search through a series of building designs to find options that minimize embodied energy while maintaining a minimum usable square footage. The models generated in Rhino can then quickly be analyzed in SimCFD to find the cooling and natural lighting potentials.

A review of the results generated in this thesis answers the questions: "How far can we push structural optimization while designing for occupant comfort using natural ventilation and buoyancy effects? And 2) What constraints are put on a building's global design when cooling and heating is accomplished with natural air flows?"

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CONTENTS

CHAPTER 1: PROBLEM STATEMENT

1.1 Introduction

Building energy use is an increasingly important topic as the world attempts to reduce greenhouse gas emissions from the construction, operation, and destruction of buildings. Currently, the operation of buildings consumes 41.7% of all the energy used in the United States (Architecture 2030, 2015). Heating and cooling commercial buildings requires 36% of this total building energy and totals over 2,200 trillion BTUs per year (U.S. Energy Information Administration, 2016). This energy usage converts to nearly 200 million tons of CO_2 pollution released into the atmosphere annually. With advances in heating and cooling technologies, it makes sense that the United States government is targeting building operational energy use to decrease carbon pollution (Silverman, 2016).

According to Executive Order 13693, by 2020, all newly constructed Federal buildings greater than 5,000 gross square feet must be designed to achieve net-zero energy usage in the United States. The order specifies that priority should be placed on reducing energy use first. Once energy usage is reduced as much as possible, then energy sources utilizing fossil fuels should be replaced with renewable and alternative energy sources (Secretary, 2015). One of the ways building energy use can be reduced is by implementing atriums in new construction projects.

Before cheap energy became available in the 1950s, most building designs in the United States relied on open courts, lightwells and atriums to provide natural lighting and natural ventilation (Wood & Salib, 2013). Within the past ten years, trends have turned back to using natural lighting and natural ventilation in office spaces. Atriums can significantly reduce the operational energy required in tall buildings because they are able to provide an abundance of natural light, and encourage airflow via stack effect. Pressure differences between the indoor and outdoor spaces allow air to move through building openings, to the atrium and up to a specified number of floors (Moosavi, Mahyuddin, Ghafar, & Azzam Ismail, 2014). The Post Tower in Bonn Germany is a good example of successful natural ventilation strategies. The building utilizes cross ventilation and stack ventilation to effectively cool the office building. The atrium system is 42 stories high, located in the center of building and has "wing" extensions at key floors to ensure air movement across the entire building footprint (see Fig 1.1). Utilizing a double-skin façade and atrium, the total annual energy consumption is 75 kWh/m^2 (Post Turm, 2015). The Post Tower uses 71% less energy than the typical American office building (U.S. Department of Energy, 2010 Buildings Energy Data Book, 2011).

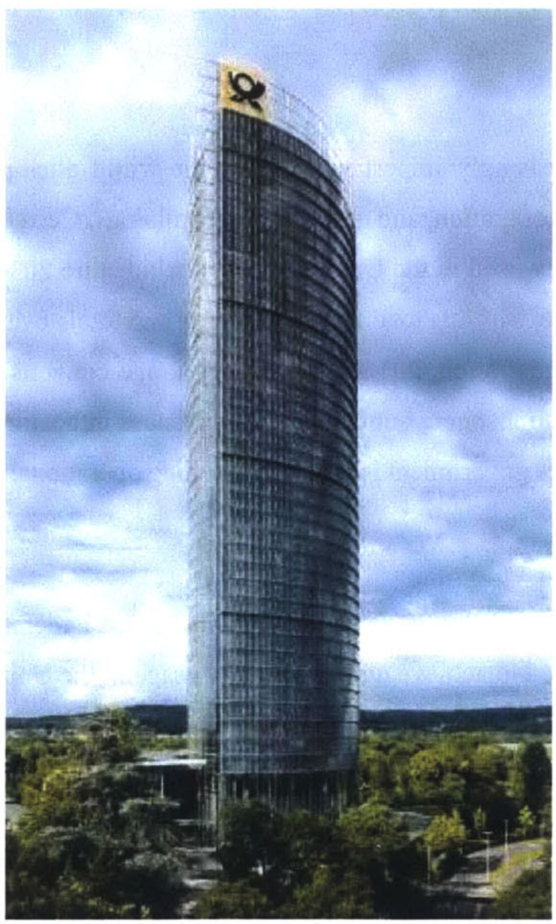


Figure 1.1: Post Tower in Bonn, Germany (Jahn, 2002)

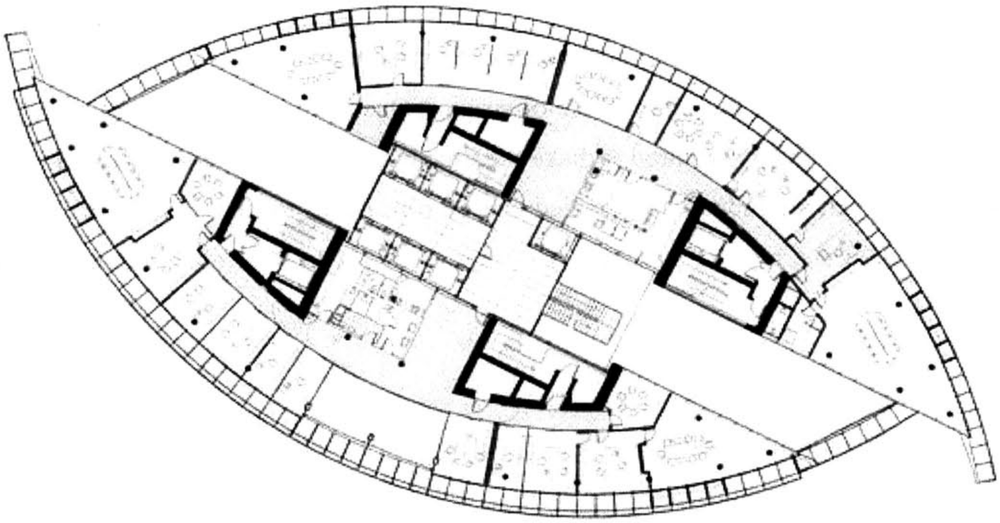


Figure 1.2: Post Tower Floor Plan (Post Turm, 2015)

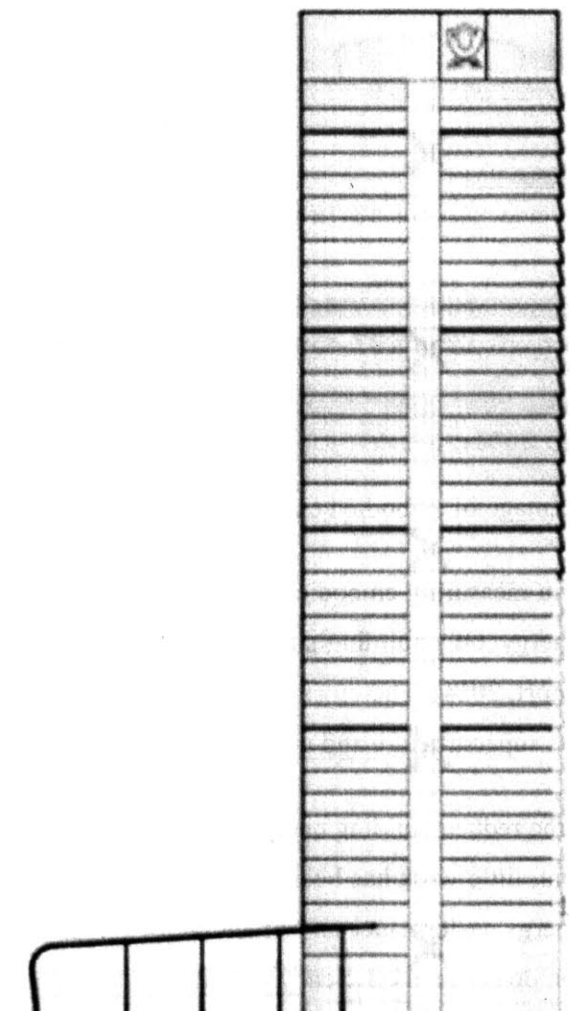


Figure 1.1: Post Tower Elevation showing central atrium (Post Turm, 2015)

Following the example of the Post Tower, new construction buildings in the United States will be able to greatly reduce operational energy through the use of atriums. Once building operational energy is reduced, the next step is to reduce the energy required to make the structure (embodied energy). Currently there is little consensus about how much a structure's embodied energy contributes to total lifetime energy use. Power highlights how embodied energy in a structure can range from 2% to 80% of the total life-cycle energy demand (2014).

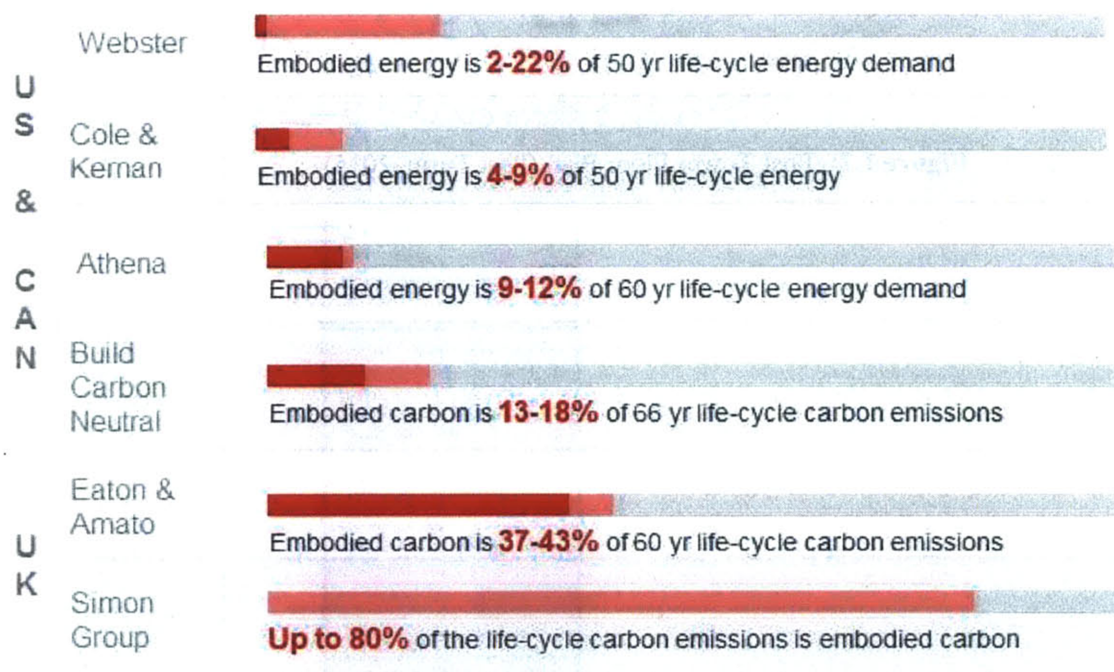


Figure 1.2: Estimated percentage of embodied energy vs total building lifetime energy use (Power, 2014).

Despite these discrepancies in measuring embodied energy, it is clear that reducing operational energy puts the spotlight on embodied energy. Of a building's total embodied energy, 42% lies within the superstructure (De Wolf, Iuorio, & Ochsendorf, 2014). Therefore, further efforts to reduce energy use of the building sector should reduce material in the superstructure and utilize materials with a lower energy demand.

It is clear that the best way the reduce building energy usage is to reduce operational energy and embodied energy. While this is apparent, little work has been done that evaluates tradeoffs (if there are any) between optimizing for operational energy performance and structural performance. As of now, it is unknown whether the focus should be placed on operational efficiency or structural efficiency given a building's size, location and environment.

1.2 Literature review

Researchers have looked into optimizing building operational energy through various optimization techniques. Asadi et al. (2012) studies a multi-objective approach using TRNSYS (an energy simulation program) and GenOpt to find the optimal solution for retrofit cost, operational energy savings and thermal comfort of a residential building. In this instance, thermal comfort and operational energy efficiency are directly related, while cost is inversely related to operational energy efficiency. Therefore, it is difficult to generate meaningful results showing the trade-offs between the three objectives (Asadi, Gameiro da Silva, Antunes, & Dias, 2012). Similarly, Diakaki et al. (2008) uses a multi-objective optimization (MOO) approach to evaluate high-performing building designs that weigh operational energy versus lifetime cost. The model looks at changing the window type, wall insulation material and the thickness of the wall insulation material versus the cost of the item and material selection. Trubiano et al. (2013) utilizes parametric optimization to minimize operational energy usage in an office building through shading techniques and atrium design for an existing exterior architecture. Rogler (2014) looks at the work flow engineers and architects could use to set up a model to analyze operational building energy use without having finalized dimensions.

Furthermore, substantive research has been performed in optimizing structural efficiency associated with topology selection, geometry selection and member sizing. Mueller and Ochsendorf (2013) presents three unique methods to making structural design decisions. The three methods are interactively evolutionary exploration utilizing design parameters, trans-typological grammars to define structural types, and surrogate modeling. In all three instances Mueller et al. evaluates architectural success versus structural performance. Chen (2014) uses topology optimization techniques to minimize the acoustic response of a structure for a given frequency. The research utilizes evolutionary multi-objective optimization methods to find the most acoustically stable structure with the smallest structural weight. Hu and Chang (2014) also uses evolutionary structural optimization to evaluate the truss topology and geometry for a specific member size. Again, this research optimizes structural performance versus total structure weight. Iyengar (2004) looks at using evolutionary mutli-objective optimization methods to evaluate structural performance based on minimum weight design, buckling stresses, structural natural frequencies and fatigue life of the structure. This research evaluates structural performance under a series of failure criteria and provides a more comprehensive structural design performance metric than what is being evaluated in this paper.

Very little work has been completed which evaluates the tradeoffs associated with optimizing both structural efficiency and operational energy efficiency. Flager et al. (2008) uses multi-objective optimization techniques to analyze the structural integrity, operational energy consumption, daylighting, initial capital costs and life-cycle costs for a particular classroom design. The overall geometry of the classroom is a rectangular box. Flager et al. does not consider architecturally diverse geometries when generating the design space for their research. Brown et al. (2015) uses MOO techniques to determine the optimal design for trading-off structural efficiency (embodied energy) and operational energy for long-span roof structures in different climates. The research focuses on placing the same general building geometry within a heating-dominate climate, temperate climate, and cooling-dominate climate. Brown's results show that the pareto-optimal results for structural efficiency and operational efficiency vary based on the type of climate the building is in. This research does not look at passive heating and cooling strategies. This work also does not evaluate how designing a building for occupant comfort can affect the structural performance of the building.

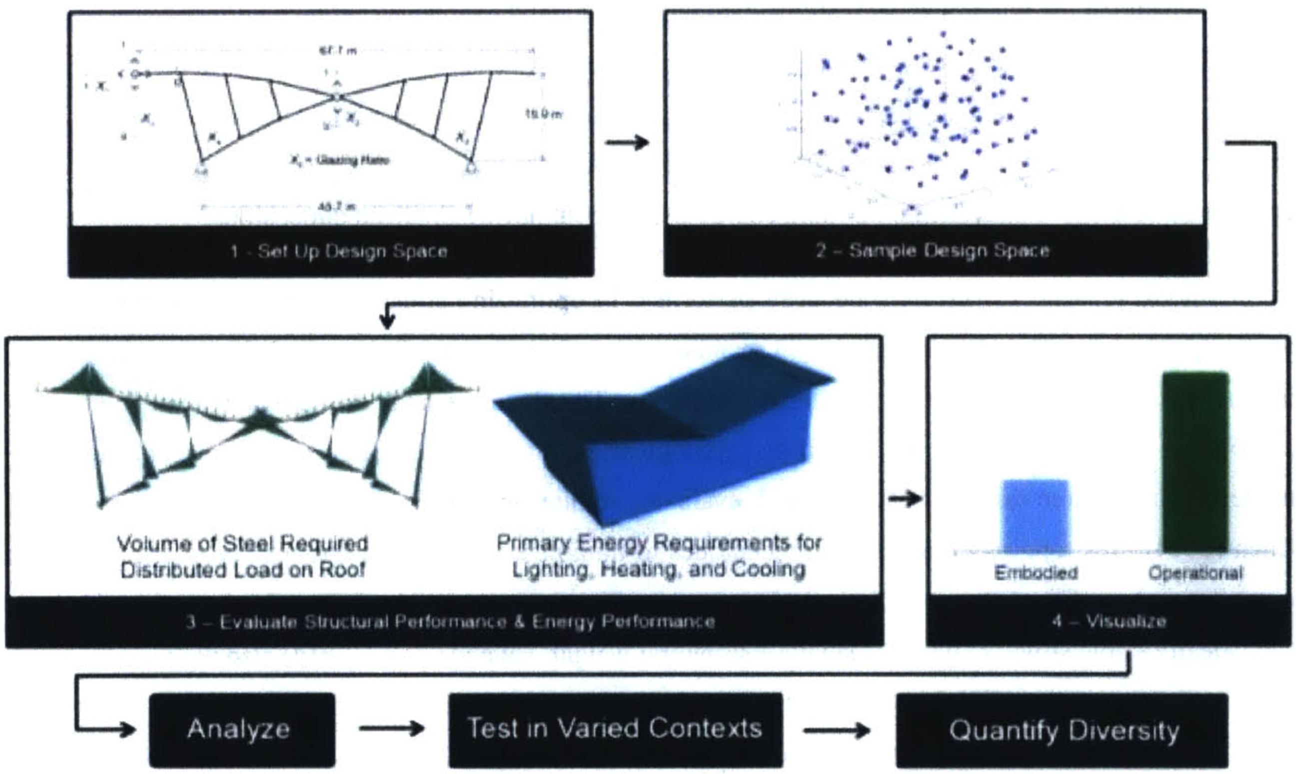


Figure 1.1: Conceptual MOO process flowchart to compare structural efficiency and operational efficiency (Brown, Tseranidis, & Mueller, 2015).

1.3 Research Questions

With the effectiveness of atriums in reducing operational energy in tall office buildings, it is now important to analyze how implementing atriums affects structural performance. This thesis looks to answer the questions: 1) How far can we push structural optimization while designing for occupant comfort using natural ventilation and buoyancy effects? And 2) What constraints are put on a building's global design when cooling and heating is accomplished with natural air flows? The research sets up an analysis that looks at how atriums affect building operational energy and embodied energy for a parameterized building geometry.

1.4 New Contributions

This thesis provides original contributions to the integration of two important objectives in design: operational energy efficiency and structural efficiency. This thesis outlines how adding an atrium affects the structural performance of a 25-story moment frame building with cross bracing. It also provides some guidance on the best location and size of atriums to reduce operational energy.

This chapter has introduced the purpose of designing buildings for operational energy and structural efficiency. It highlights some of the previous work done by other scholars and professionals that look at these topics.

Chapter 2 provides the methodology used to set up the analysis and collect data. It also provides background on the many tools used in this thesis.

Chapter 3 evaluates the data collected from the structural analysis, energy analysis and computational fluid dynamics analysis.

Chapter 4 summarizes the results of the multi-objective optimization process and discusses the potential impact of these results in designing efficient tall office buildings in the future.

CHAPTER 2: METHODOLOGY

Typical steel-framed, tall office buildings utilize a one-way floor system, with beams running to girders and then connecting to columns which run to the foundation. The methodology for developing the analysis for this thesis follows typical structural layouts of moment frame steel office buildings. The goal is to match the parameterized analysis as closely with what is typically done in the field when establishing a building's superstructure.

2.1 Conceptual overview

To determine optimal building geometry for structural efficiency and operational energy, simplified structural and energy models are developed within Rhino (Robert McNeel & Associates, Rhinocerous 5.0, 2016) and Grasshopper (Robert McNeel & Associates, Grasshopper 0.9.0076, 2016). This parametric design space is rigorously sampled, each design is evaluated and the results are plotted. A Pareto front is generated from these results using a multi-objective tool. Six of these optimal solutions are then modelled using a computational fluid dynamics commercial software tool to find the total amount of thermal comfort the atrium is able to provide. From here, the total operational energy and embodied energy are compared against the total building energy to determine which value controls building energy usage.

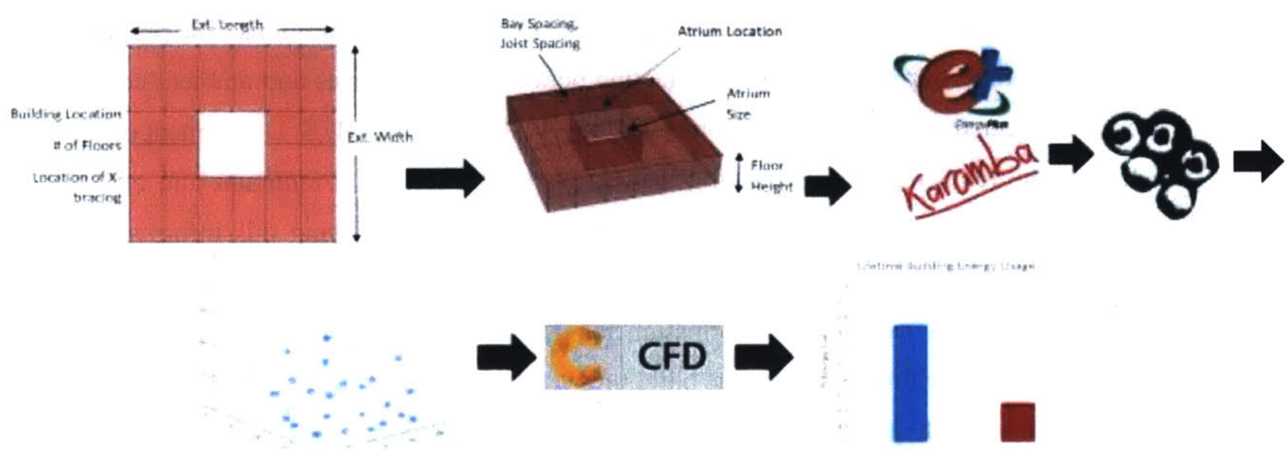


Figure 2.1: Conceptual MOO process flowchart to compare structural efficiency and operational efficiency for tall buildings with atriums

2.2 Implementation details

This research utilizes Rhino (Robert McNeel & Associates, Rhinocerous 5.0, 2016) and Grasshopper (Robert McNeel & Associates, Grasshopper 0.9.0076, 2016) to develop a parametric model of a 25-story office tower with an atrium. The building is square with a side dimension of 240 ft. Excluding the atrium, the office building has a total of 134,000 sq. ft. The model is parameterized by adjusting the bay size (i.e. the beam and column spacing), the floor height, and the atrium size and location. Once the parameterized building is established, the annual heating, cooling and lighting loads are calculated using EnergyPlus (U.S. Department of Energy, 2016) through the Archsim platform (Dogan, 2016). This parameterized building is also analyzed using a finite element analysis program called Karamba (Preisinger C. , 2015). The total embodied carbon of the structure and the total lifetime building operational energy usage is calculated. Octopus (Vierlinger R. , 2016) generates iterations of designs which are analyzed to find the building with the lowest embodied energy, operational energy and largest net building square footage. After generating a Pareto front outlining these best designs, the top five most diverse designs are analyzed using Autodesk's Sim CFD (Autodesk, 2014) to analyze how much operational energy the atrium saves. The embodied energy and the total operational energy are compared to find the building geometries which require the least amount of energy and maximize usable space.

EnergyPlus is an energy analysis and thermal load simulation program. It calculates the heating, cooling and lighting loads necessary to meet specified set-points and occupancy schedules based on a user-defined building geometry. The program can also calculate coil loads and the energy use of boiler equipment, although these functions are not used in this analysis. To calculate the heating, cooling and lighting loads of the building, EnergyPlus requires a TMY3 weather file with hourly environmental conditions. The program also requires a user-defined time step to look at the interaction between thermal zones and ambient conditions, and the interaction between the defined thermal zones and the HVAC equipment (U.S. Department of Energy, 2016). To calculate the total heating and cooling loads, EnergyPlus calculates radiation and convection through each zone, and transient heat conduction through walls and floors. Using this information with thermal comfort models, EnergyPlus gives the user total heating and cooling loads for the specified time period. The program also uses daylighting information for the specified location and daylighting control models to calculate the total lighting loads for the building over the specified time period (U.S. Department of Energy, 2016). The EnergyPlus software runs through Archsim to allow the user to parameterize the model within Grasshopper. Archsim Energy Modeling includes DIVA 4.0, software that calculates annual daylight availability within the building, and EnergyPlus (Archsim Energy Modeling for Grasshopper, 2015). Only the EnergyPlus component of Archsim is used in this analysis.

Karamba 1.1.0 is a finite element (FE) modeling program that works in the parametric environment of Grasshopper. It is an easy-to-use program that allows users to change the structure and receive immediate feedback. It is regarded as a good first step at structural analysis while global geometries are explored

(Preisinger C. , 2013). To use Karamba, one first creates a wire-frame, point geometry or mesh and convert these elements into Karamba beams and/or shells. Then, one defines which points are supports and apply loads to the structural members. Finally, attach material and cross section properties to the Karamba elements. Once the model is assembled, analyze the structure as elastic-linear or non-linear (Preisinger C. , 2015). Only the elastic-linear analysis is used in this research.

The "Optimize Cross Section" (OptiCroSec) component automatically selects the most appropriate cross sections for beams and shells based on the procedure outlined in Eurocode 1993-1-1 (Preisinger C. , 2015). Eurocode 1993-1-1 outlines the equations used to design steel structures (Standardization, 2005). First, the component determines the cross section of each structural member given the user-defined allowable stress and the member buckling capacity for each load case. Then the component searches to see if there is a lighter structural element that also will not fail under the same conditions (Preisinger C. , 2015). This search lasts for 5 iterations to reduce computation time.

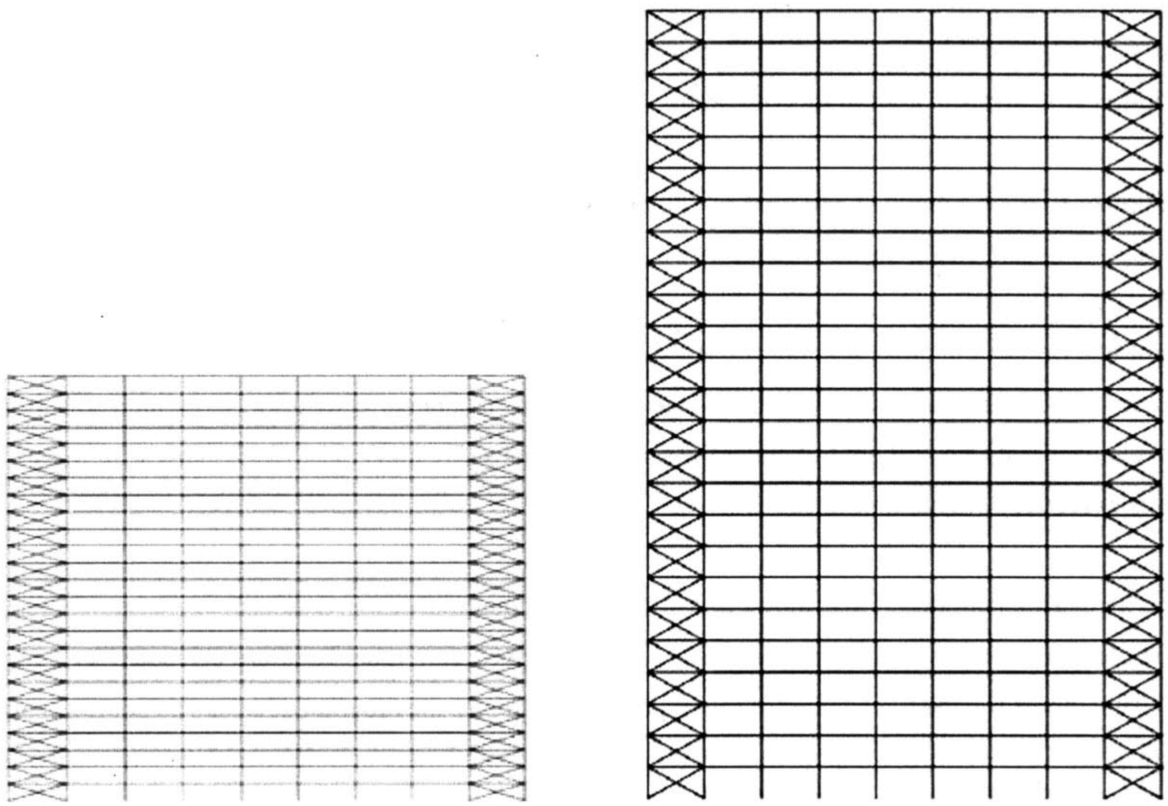
Octopus is a grasshopper plug-in that shows tradeoffs between multiple design options by generating a Pareto front. The component takes in variables as sliders and objectives as numbers that are calcuated by various models. Using inputs for and the number of samples and generations, the program develops an approximation of a Pareto front. The sampling component of Octopus utilizes evolutionary principles to find optimized trade-off solutions (Vierlinger R. , 2016).

Autodesk SIM CFD is a computational fluid dynamics (CFD) software that also simulates thermal environments. Because of the capabilities of SIM CFD, the program is useful at modeling natural ventilation and buoyancy flows within buildings. The program calculates the stack effect by calculating the indoor and outdoor pressures, and includes wind effects through all described openings (Autodesk, 2014).

2.3 Design variables and scope/assumptions

To set up the parameterized model, the location of the building would be located in Boston, the building would be square with a side length of 240 ft and would have 25 total floors and a roof. Unlike the work done by Brown, et al. the location of the building is to remain constant to better determine the effects that the atrium has on the entire building structure and energy usage. Parameters for this analysis include the floor height, number of bays per floor, atrium x-location, atrium y-location, atrium width and atrium length.

The available floor heights for the model range from 8 ft to 15 ft in 1ft increments. This range of floor heights covers typical floor heights employed in office buildings in the Boston area. Figure 2.2 shows the range of total building heights for the model.



a) b)

Figure 2.2: Structural elevation showing model with a) 8 ft height and b) 15 ft height

The number of bays per floor range from 5 to 10 and are available in increments of 1. This gives a bay spacing that ranges of 48 ft to 24 ft between columns. Figure 2.3 shows the smallest and largest framing plans without atriums.

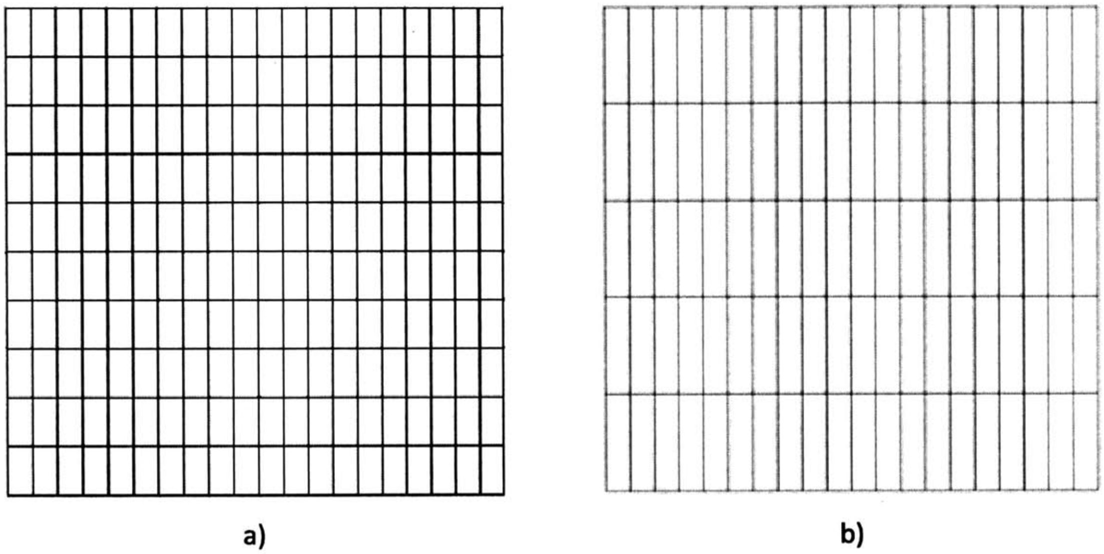


Figure 2.3: Structural framing plan showing model with a) 24 ft bays and b) 48 ft bays

The atrium location is able to move in the x-location and y-location between bays. Therefore, as the slider moves the atrium, the atrium itself jumps from bay to bay to ensure that the floor framing for the atrium is accurate. The atrium is able to move fully across the structure in both x and y directions. Figure 2.4 gives a sample of an atrium moving across the plan in the x and y directions.

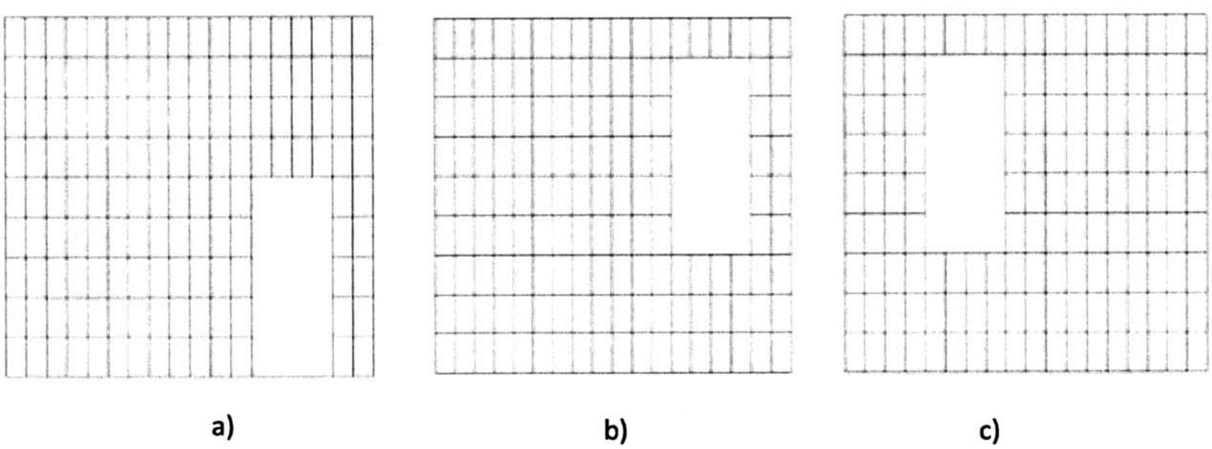


Figure 2.4: Structural framing plan showing a) original atrium location, b) atrium moved in y-direction and c) atrium moved in x-direction

The atrium width and length are adjustable by adding or removing a bay from the atrium. This ensures that the floor framing for the atrium remains accurate. The total size of the atrium is not allowed to exceed 50% of the total building footprint. A floor-framing plan without an atrium is also a possibility. Figure 2.5 gives an example of an atrium increasing in width from one bay to four bays.

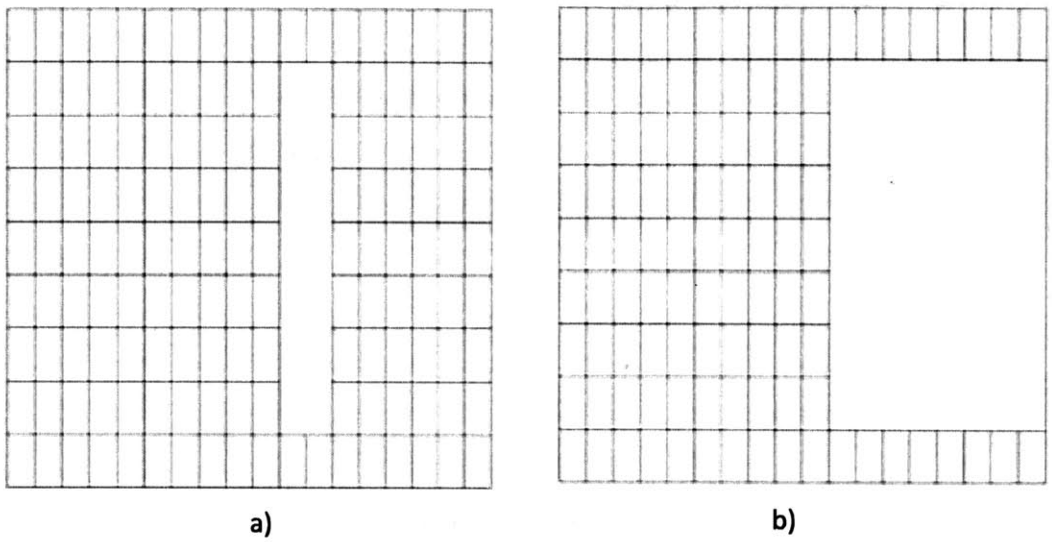


Figure 2.5: Structural framing plan showing a) original atrium size and b) atrium with larger width

A summary of these variables and their bounds are presented in Table 2.1.

Table 2.1:
Model variables, their bounds and increment size

Variable	Lower Bound	Upper Bound	Increment
Bay Size (ft)	24	48	1
Floor Height (ft)	8	15	1
Atrium X-location (% of total bays)	0%	100%	1/ total # of bays
Atrium Y-location (% of total bays)	0%	100%	1/ total # of bays
Atrium Width (% of total bays)	0%	100%	1/ total # of bays
Atrium Length (% of total bays)	0%	100%	1/ total # of bays

2.4 Structural analysis and sizing

The structural system is set up to ensure that all beam spacings and slab spans are reasonable and produce stress and deflections that are within ASCE 7-10 requirements without utilizing non-standard steel sections.

2.4.1 Overview of Structural System

The selected building structure is a braced moment frame. In a rigid frame system, the lateral force is resolved through portal frame action. It consists of horizontal and vertical members rigidly connected together in a planar grid form. In other words, through the flexural and shear deformation of both the columns and beams. The size of the columns is typically controlled by the gravity loads, while the size of the beams is typically controlled by the lateral load acting on the building. The rigid frame by itself is only economical for structures under 25 stories (Eisele, 2003). Therefore, cross bracing is added to the system to improve the lateral performance of this model.

Using a braced frame system, the lateral forces are resolved axially through tension and possibly compression of the bracing members. This system is used in conjunction with the rigid frame system to lower the bending stresses in the columns and beams as the total building height is increased. The x-bracing system consists of two main diagonal systems (Eisele, 2003). These diagonals behave as a tension-compression system. Care must be exerted when designing the system for lateral events, such as earthquakes, where the direction of the load changes frequently (Eisele, 2003). As Boston typically has only small earthquake events, x-bracing is considered an adequate bracing pattern for the building's structure.

2.4.2 Model Generation

To begin the model, the footprint of the building is established by drawing a 240 feet by 240 feet square. In the x-direction beam-lines are filled in as indicated by the number of bays slider. For 10 bays, 10 beams are drawn in every 24 feet, for 5 bays, 5 beams are drawn in every 48 ft. In the y-direction, filler beams are drawn in to reduce the span of the composite slab system. The span of the filler beams ranges from 12 feet to 15 feet to ensure that the deflection of the composite slab remains within building codes limit. Columns are positioned at the given bay spacing in both x and y-directions. The columns are drawn in the negative z direction with a magnitude equal to the value in the floor height slider. Figure 2.6 shows this progression in model generation.

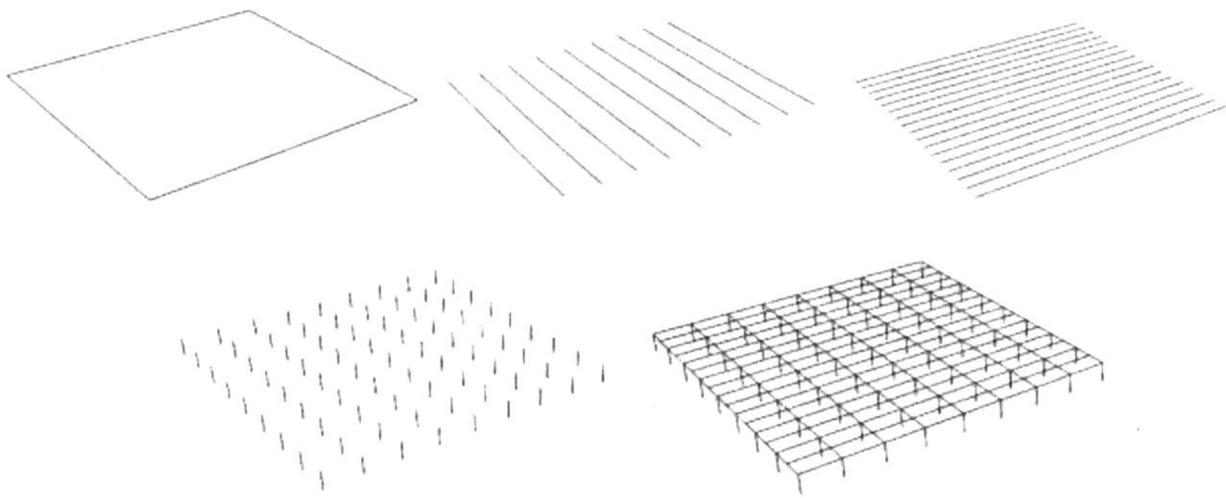


Figure 2.6: Framing definition process showing exterior footprint, girder beams, filler beams and columns.

The atrium is defined as a certain number of bays. The size of the atrium is altered by a slider and controls the atrium size by increasing or decreasing the number of bays allotted to the atrium. The location of the atrium is also controlled by sliders in order to move the atrium a certain number of bays in the x and/or y-direction. Defining the atrium as a certain number of bays ensures that the structural framing plan is accurate. Otherwise a new framing plan would have to be established for only around the atrium. All structural elements located within the atrium area are deleted with the exception of exterior beams. Figure 2.7 shows the structural framing definition including the atrium over two stories.

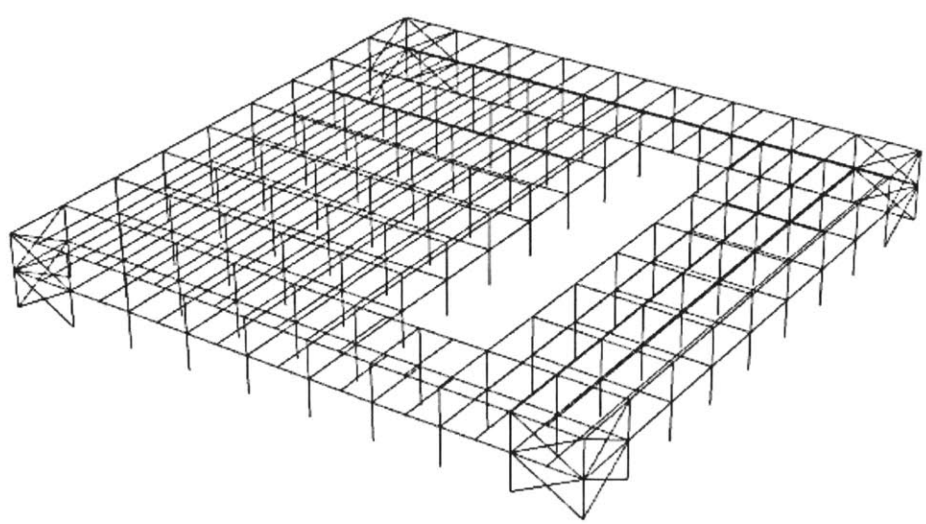


Figure 2.7: Atrium definition showing deleted elements within defined area (two floors shown for clarity)

A slab system is defined to ensure diaphragm action within the braced moment-frame structure. This is accomplished using a surface grid to mesh with points defined at the column locations. Figure 2.8 shows a sample slab definition. The x's mark the location of the columns.

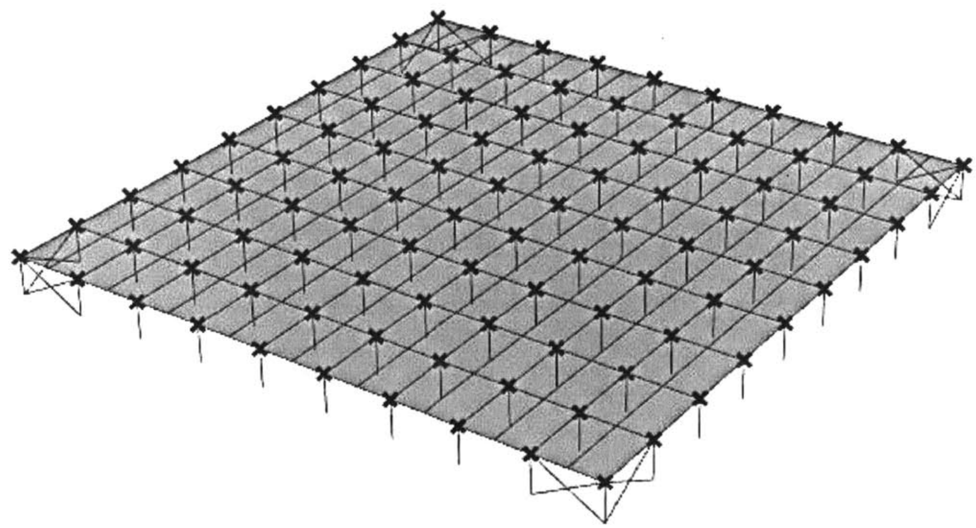


Figure 2.8: Slab definition using a surface grid to mesh (one floor shown for clarity)

Cross bracing is added to the four corners of the building as shown in Figure 2.9. Each cross brace is a single story and runs diagonally from the top of a column to the bottom of the adjacent column to the right and left of the building corner. The cross bracing was divided in two so that both members within the cross bracing would act together – with one brace in tension and the other brace in compression.

Figure 2.9: Elevation view of cross bracing definition for single floor

Once the general floor framing plan and the bracing is defined, the model is arrayed 25 stories to complete the final structural geometry. Figure 2.10 gives a sample of the final arrayed framing geometry.

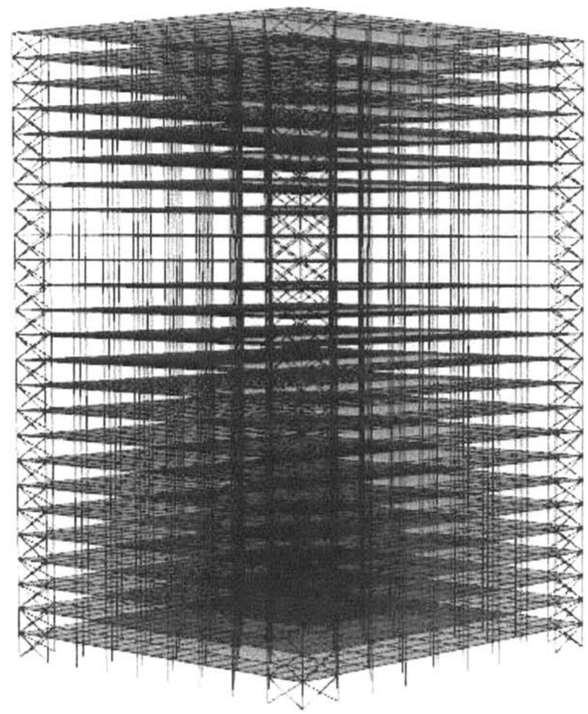


Figure 2.10: Grasshopper stick model to be utilize in structural analysis

2.4.3 FE Analysis

Once the stick model is developed, the Karamba FE model is generated. The building's filler beams, girders, columns and cross bracing lines were passed into Karamba's "Line to Beam" component and the defined slab mesh was passed into Karamba's "Mesh to Shell" component. Releases were defined connecting the filler beams to girders as the filler beams do not carry moment in the structure. Pinned supports were defined at the base of the columns at the ground floor of the structure. A36 steel was defined for all of the filler beams, girders, columns and cross bracing. This steel has a young's modulus of 20,000 kN/cm^2, a shear modulus of 7700 kN/cm^2, density of 78.5 kN/m^3 and a yield stress of 24.8 kN/cm^2. Concrete is applied to all of the floor slabs. The material properties of the concrete assume a young's modulus of 3100 kN/cm^2, and shear modulus of 1291 kN/cm^2 and a density of 0 kN/m^3. The density is listed as zero as the weight of the slabs is accounted for the structural loads. The concrete slabs are given a shell cross section 15.2 cm thick.

The structural loads a defined in concordance with ASCE 7-10. The gravity loading follows the equation (ASCE, 2013):

$$1.2D + 1.6L + 1.0W$$

The gravity loading assumes a 20 psf superimposed dead load and a 50 psf live load. The loading also assumes a 70 psf dead load to account for the weight of the 5" composite concrete slab on steel deck. Once the load factors are applied, the total gravity load is 188 psf or 9 kN/m^2. Because the slab system is one-way, this gravity load is applied to the filler beams and not the slab. A gravity load is applied to the entire structure in order to account for the self-weight of the steel. Figure 2.11 shows a sample of this gravity loading on the structure.

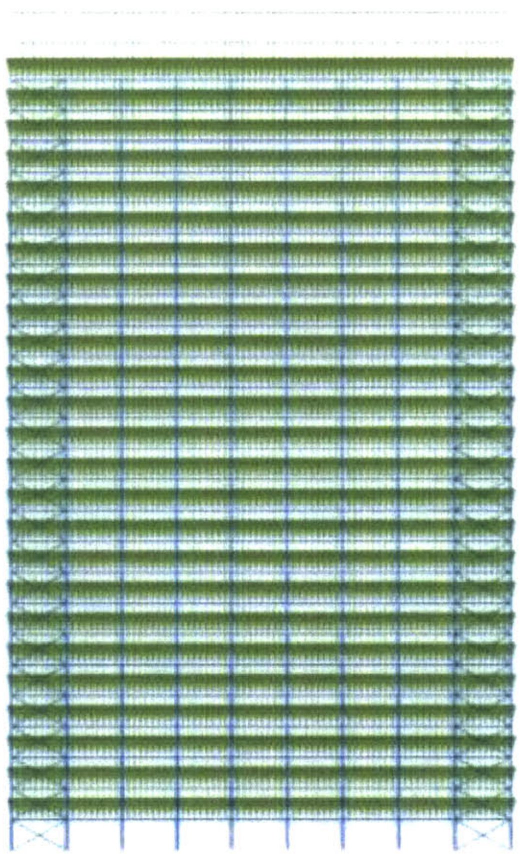


Figure 2.11: Gravity Loading

The lateral loading applies a wind pressure of 35 psf along the southern face of the building. The wind is placed on the south face because the typical wind direction in Boston is North-east. This analysis could be expanded to look at wind loading in both orthogonal directions, but the single load case was considered sufficient for this study. This load is multiplied by the floor height, the length of the side of the building and by 1.3. The 1.3 factor accounts for the windward and leeward effects of the wind (i.e. suction effects). This load is then applied to the top of the columns at each floor (see Figure 2.8 for column definitions). The magnitude of the load is converted to metric and has a final value of 0.79 kN/m/col (different per floor height and total number of columns).

Next, each of these model components are passed through Karamba's "Assemble Model" component. This model then undergoes a linear-elastic analysis via "AnalyzeThI." "AnalyzeThI" calculates the deflections of the model using the theory of small deflections (Preisinger C. , 2015). This model is then passed into the "OptiCroSec" component in order to auto-size all of the steel members. "OptiCroSec" requires the "Cross Section Range Selector" and the "Read Cross Section Table from File" component. Figure 2.12 shows the required "OptiCroSec" components and their connectivity.

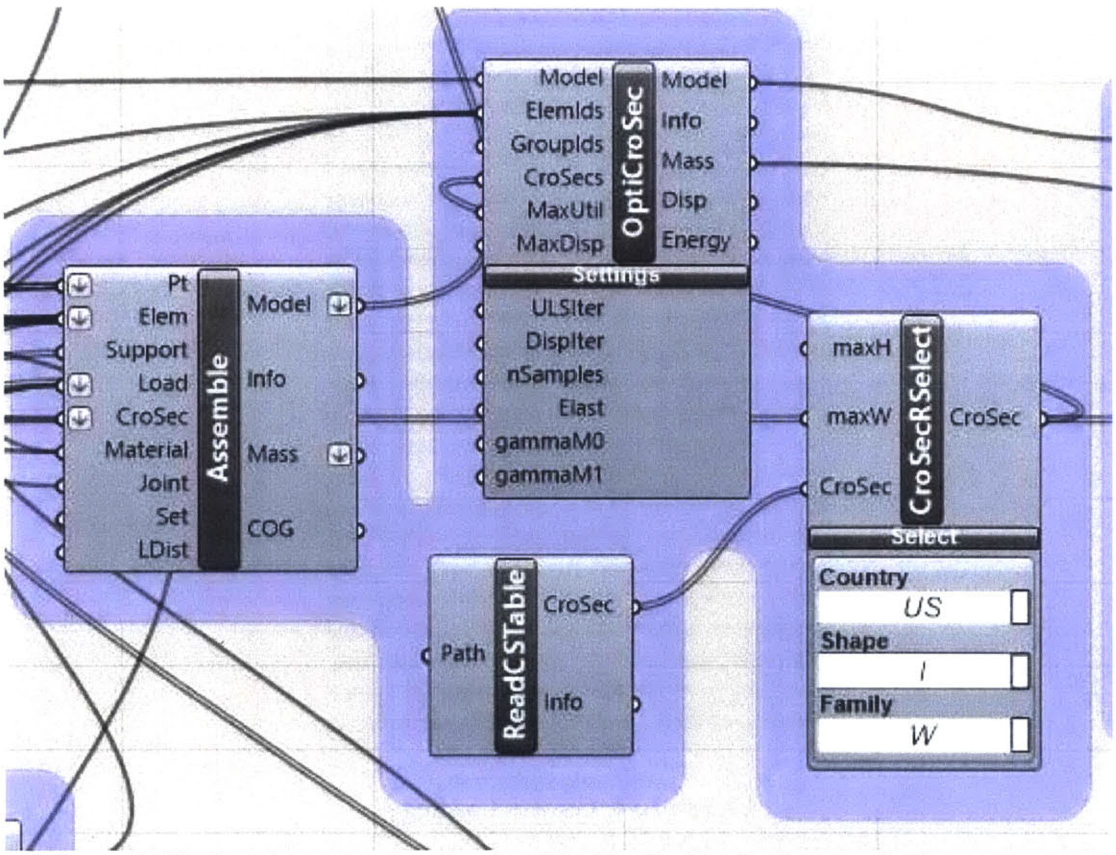


Figure 2.12: Grasshopper script showing "OptiCroSec" and other required components

To calculate the embodied energy of the structure, the total building mass, in kg, is read out from the "OptiCroSec" component. This total structure weight is multiplied by the embodied carbon coefficient for imported, recycled steel. This research assumes an embodied carbon coefficient of 35 MJ/kg as outlined by the Victoria University of Wellington in New Zealand (Embodied Energy Coefficients, 2003). This embodied carbon value is then converted to kWh as it is a commonly used metric for measuring energy efficiency in the United States. This energyusage, in kWhh, is the lifetime embodied energy used for the structure.

2.5 Energy modelling

Energy plus requires BRep geometries made up of a series of joined surfaces in order to define each of the zones of the building. For the case of this model, one zone is equivalent to one floor. The BRep geometry includes the top and bottom floors and the walls on all four sides. The energy modeling within EnergyPlus does not account for natural ventilation effects connected to the atrium. Therefore, no atrium BReps are defined in this energy model. 8 windows are defined on the corners of the building. The effect of the windows are further evaluated in the CFD models. Figures 2.13 and 2.14 show a sample BRep geometry utilized in the EnergyPlus analysis.

Figure 2.13: Zone BRep geometry for a single floor

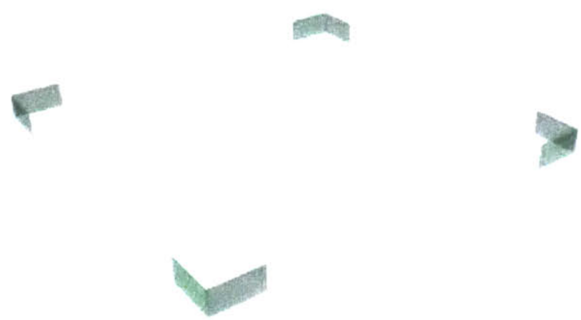


Figure 2.14: Window BRep geometry for a single floor

The zone BRep geometry is arrayed for 25 floors and then is passed into the Archsim "Zone" component where heating, cooling and lighting loads are defined for the building. This model assumes a 0.2 persons/m^2, open office loads, a lighting power density of 12 W/m^2, a target lux of 500, dimming on and an all on schedule to reduce the model runtime. The domestic hot water heater has a peak flow rate of 0.003 m^3/sec and supply temperature of 65°C and a mains temperature of 10°C. The flow rate fraction is assumed at 100% or all on.

The heating set point for the energy model is 23°C, assumes an occupancy schedule for an open office and does not have a limit. The cooling set point is 25°C, assumes an occupancy schedule for an open office and does not have a limit. The mechanical ventilation requires 0.001 m3/sec/person of fresh air and enthalpy heat recovery is turned on. None of the ventilation components are turned on as this is explored in the CFD model.

The building materials assume a roof with an R-value of 30 °F*ft^2/BTU, default construction for the interior partitions, slab material for the slab/ceiling construction, a slab on grade ground construction and a façade construction with an R-value of 19.5 °F*ft^2/BTU. Internal mass is turned off for this model.

After the zones and windows are defined, the geometries are plugged into the Archsim "Networker" component. This model is connected to the "Run EnergyPlus" component. The simulation runs from January 1 to July 1 in order to increase the speed of the model. With monthly ground temperatures of 20°C for every month. The airflow simulation runs as a simple airflow object. The EnergyPlus simulation outputs zone lights electric energy usage, zone loads total heating energy and zone loads total cooling energy.

The load results file for heating, cooling and lighting are read out to calculate total building operational energy usage. Each of the loads for the six months is summed and multiplied by two. It is assumed that the lights are all LEDs and have an efficiency of 100%, the cooling system has a coefficient of performance of 3.2 and the heating system has an efficiency of 85%. The energy output from the lighting, cooling and heating systems are divided by these respective efficiencies. Furthermore, an electric efficiency of 33% and a thermal efficiency of 90% is accounted for in the operational energy usage. The total operational energy use is the summation of the lighting, heating and cooling energy multiplied by the lifetime of the building. For this analysis it is assumed that the building lifetime is 50 years. The total operational energy in MJ is then converted to kWhh in order to better compare it to the building's embodied energy.

2.6 Square footage

The total building usable square footage is measured by taking the area of the entire building footprint per floor, subtracting out the area of the atrium and then multiplying this value by the total number of floors (25).

2.7 Optimization

Octopus inputs the sliders defining the number of bays, floor height, atrium x-location, atrium y-location, atrium width and atrium length and searches for the optimum solutions to maximizing the building square footage, and minimizing the building's operational energy and embodied energy. In order to accomplish maximizing square footage while minimizing building energy, the total building square footage is input into octopus as a negative value. Figure 2.14 shows the grasshopper code for setting up the Octopus component.

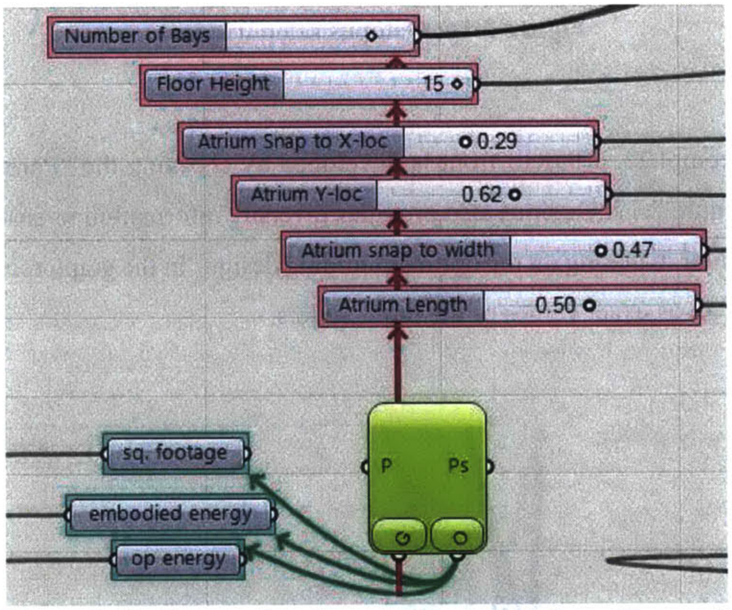


Figure 2.15: Octopus input parameters and optimization goals

To evaluate the design space, octopus runs 1000 iterations calculating building structural energy, lifetime operational energy and useable floor space. 500 of the most diverse solutions are kept and plotted on a 3-D scatter plot. To set up the Octopus simulation, elitism is set to 0.5, mutation probability is set to 0.543, the mutation rate is set to 0.74 and the crossover rate is set to 0.663. The mutation rates are large to ensure that the sampler gets a wide range of values from the inputted sliders. Figure 2.16 shows the Octopus setup window.

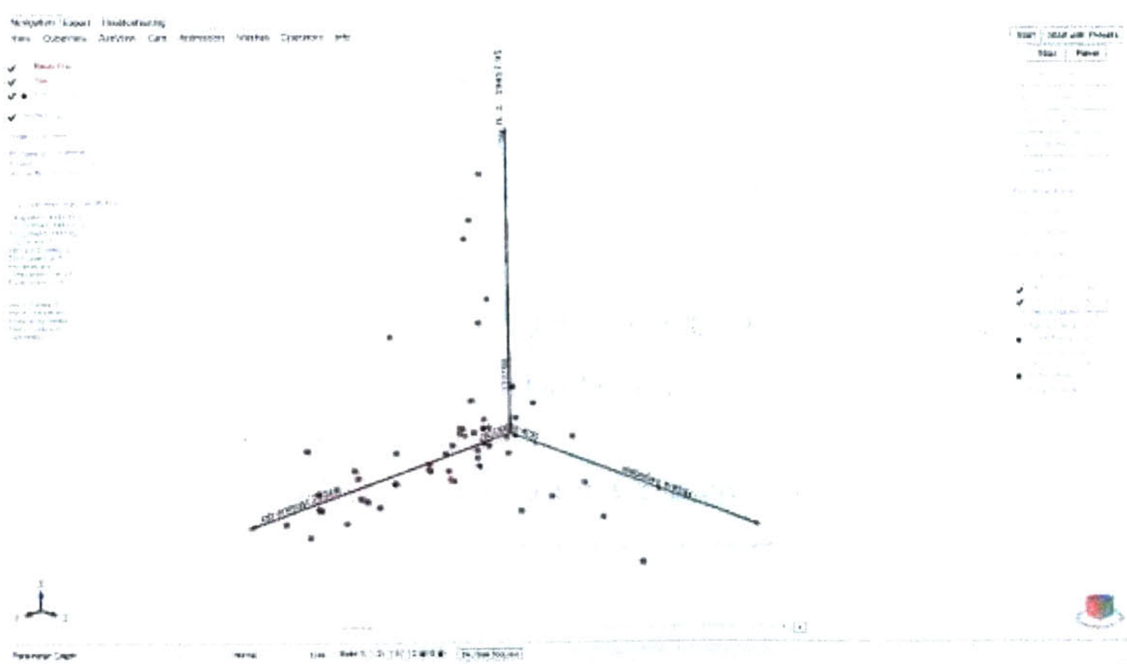


Figure 2.16: Octopus setup window

After the simulation is complete, a Pareto front is developed by checking the "Pareto Front" view port in Octopus. As shown in Figure 2.17, Octopus also provides diversity information to ensure that final geometry selections are not too similar. Clicking on the optimal building designs in the graph reinstates the grasshopper state of the model which gives exact values of the input sliders.

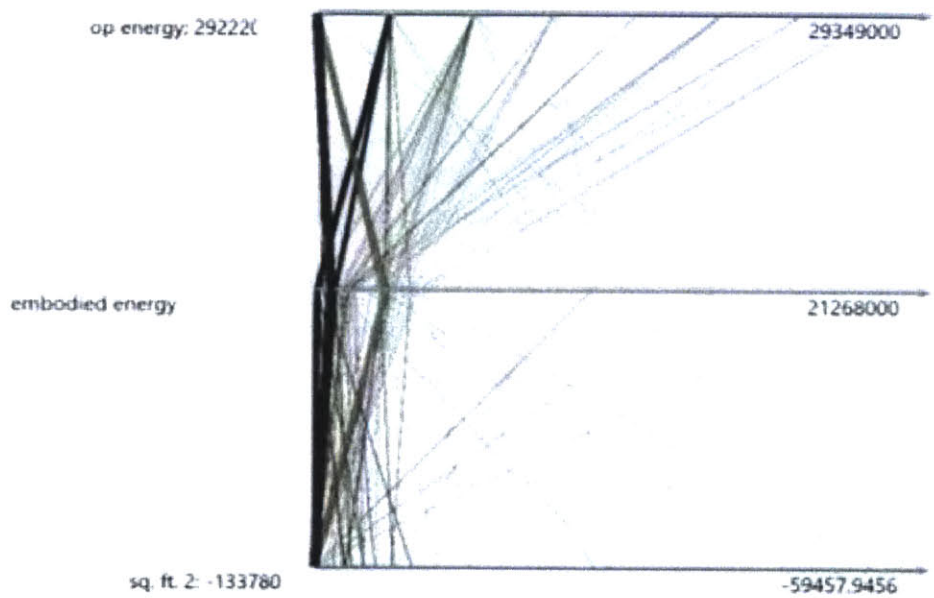


Figure 2.17: Sample diversity graph

Based on the output from Octopus, five models were selected for further evaluation. These five models were then modeled in SimCFD to sample how much energy is saved through natural ventilation.

2.8 Computational Fluid Dynamics (CFD)

To generate the model used in the CFD the slabs and building exterior are turned into boundary volumes. Figure 2.18 shows a generated sample boundary volume. The top floor is given a cap equal to one floor height tall and with the width and length of the atrium over the atrium to designate the exit point of the buoyancy flow. This model is then baked and saved as a Rhino file and imported into Simulation CFD 2015 (SimCFD). This buoyancy flow model follows the procedure outlined in the Autodesk Knowledge Network: Natural Ventilation (Autodesk, 2015).

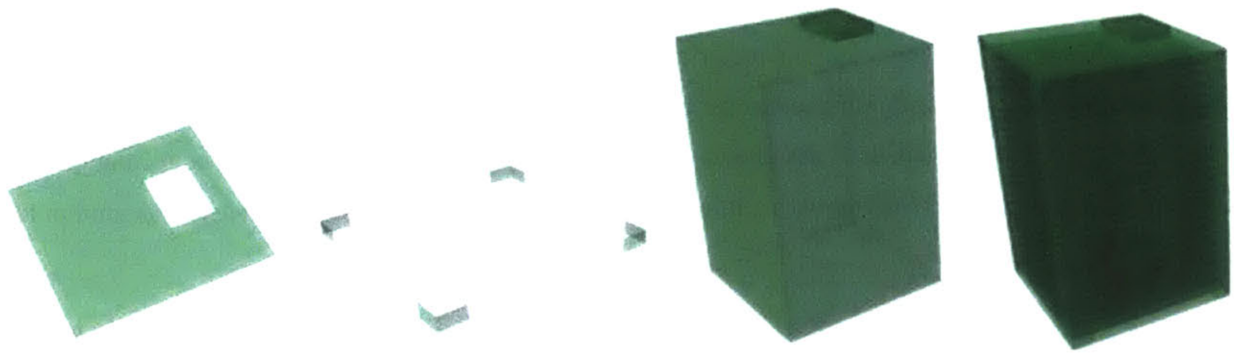


Figure 2.18: Boundary volume generation to be used in the SimCFD model

Once imported into SimCFD, an external volume is generated using the "External Volume" tool. This volume is generated to be 1.5 times the height of the building, and three times the width and depth (as shown in figure 2.19). Generating an external volume allows natural ventilation through wind effects to be modelled in the building.

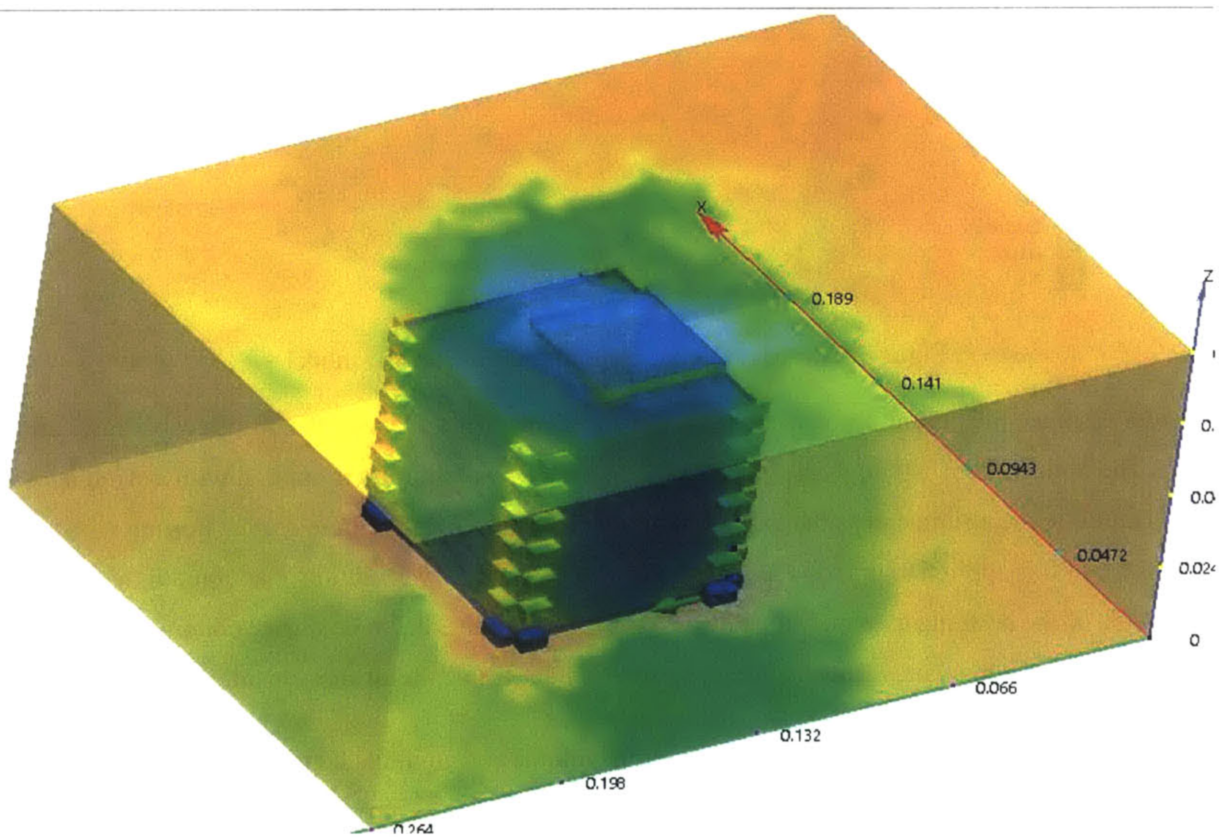


Figure 2.19: External volume generated in SimCFD

Next, materials are assigned to each part of the model. Air is assigned to all air regions, including the total building volume (places that do not contain building structure) besides the window openings and the atrium cap. The "Environment" setting under the material "air" is changed to variable to perform a transient analysis of the model. Materials are then assigned to the rest of the model. The slabs are assigned a concrete material with a depth of 13 cm. The façade is assigned a glass material with an R-value of 5.4). The roof and ground slab are assigned a concrete material with a thickness of 20 cm. Figure 2.20 shows material assignment for a sample SimCFD model.

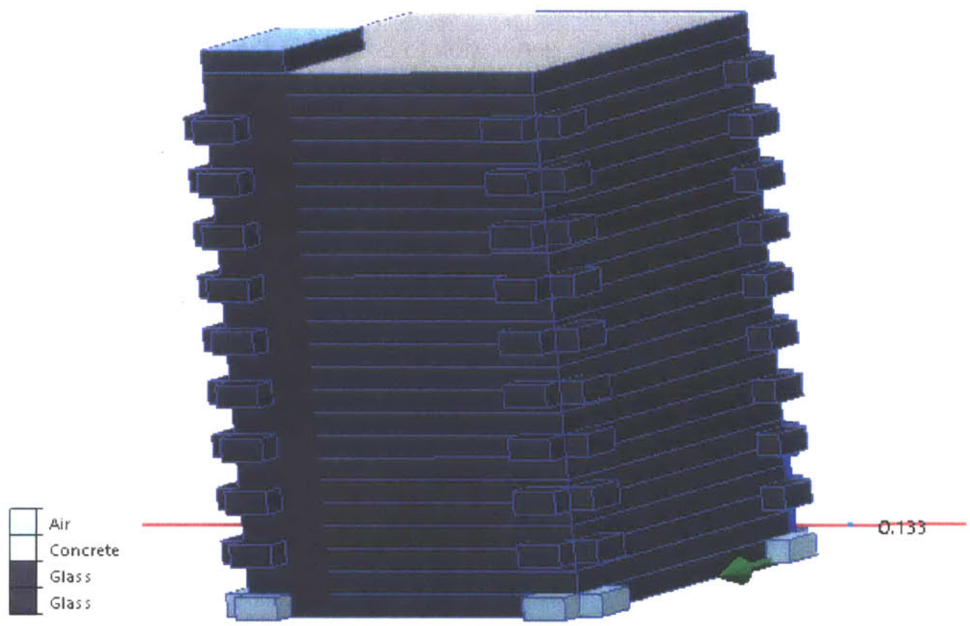


Figure 2.20: Material assignment in the SimCFD model

This model assumes the bottom floor windows allow air in and the top face of the atrium cap allows air out. To define the bottom floor windows as open, a velocity boundary condition is applied with a wind speed of 2.5 m/s. To define the atrium cap as the exit point of the building, a pressure boundary condition with a static gage pressure of 0 is applied to the top face. A slip/symmetry boundary condition is applied to the remaining exterior walls of the building to signify air flow in an open environment. No boundary conditions are applied to the windows as the buoyancy flow and cross ventilation determine the air movement.

An initial condition of 30.6°C is applied to the external volume and an initial condition of 23°C is applied to the building volume. The scenario environment temperature is also set to 30.6°C. By setting these initial conditions, the model simulates a hotter-than average summer day. Initial conditions also help reduce the model run time, as otherwise the analysis begins with volume temperatures of 0°C.

The model is then meshed using the "Manual Mesh" option. Figure 2.21 shows the meshed geometry of a sample SimCFD model. Windows are meshed with a mesh size of 0.004, the slabs are meshed with a mesh size of 0.007, the walls are meshed at a size of .006, and the top and bottom slabs are meshed at a size of 0.015. Meshing by hand assures that the meshes aren't too small to find convergence. Also, it ensures that there is not any mesh overlap between the different building surfaces.

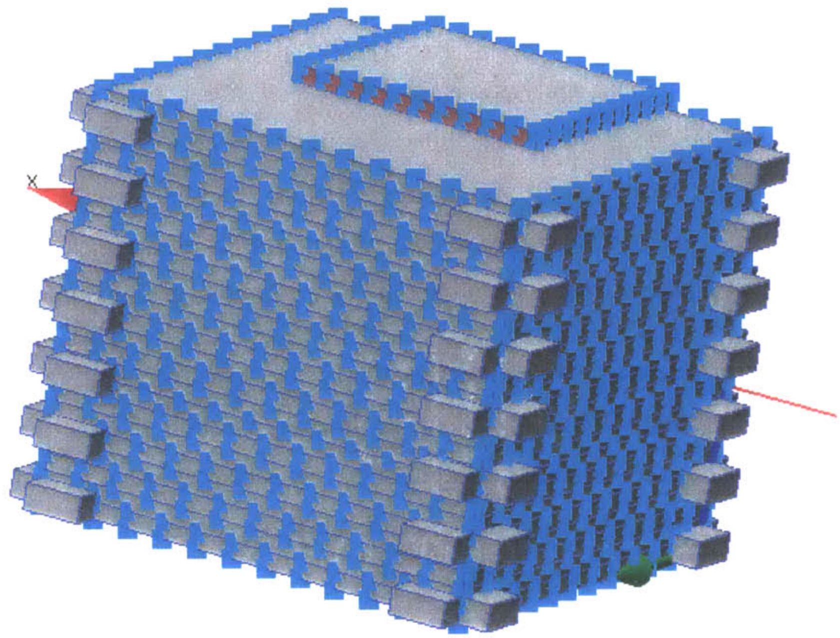


Figure 2.21: Generating mesh geometry in SimCFD

To set up the analysis the following parameters are specified. Flow is turned on, heat transfer is turned on, the gravity vector is set towards earth, iterations are set to 500, radiation is enabled, solar heating is enabled, scalar mixing is turned off, the humidity solver is turned off and the thermal comfort solver is enabled. The location specified for each of these parameters is Boston, MA, zipcode 02108. Once all of these parameters are defined, the model runs.

Once the model runs, the percentage of thermal comfort in the summer months due to natural ventilation and buoyancy flows is collected. One minus the percent of time occupants are comfortable gives the percent of time cooling equipment needs to run to keep the building around 25°C. This value multiplied by the calculated total cooling load gives the total cooling demand in kWhh. This new cooling load is added to the calculated heating and lighting loads to get the total lifetime operational energy demand of the building.

Additionally, the percentage of natural lighting is collected from the model. One minus this natural lighting percentage multiplied by the calculated lighting load gives the actual lighting load for each model.

2.9 Data Collection & Expectations

With the data collected from the structural analysis, EnergyPlus analysis and the computational fluid dynamics models, it will be possible to determine how atriums affect total building operational energy of a 25-story office building.

First, the models are generated without analyzing natural buoyancy effects. Data from Karamba analyses are collected to measure embodied energy of 500 samples. Operational energy of each model is first calculated assuming mechanical heating, cooling and lighting only. The total building square footage is obtained for every sample run in Octopus. After 500 geometries are evaluated, a Pareto front is found outlining the most optimal designs for embodied energy, mechanical operational energy and usable floor space.

Five of the top performing models are then analyzed to calculate the effectiveness of the building design. One of these five models is a building without an atrium to define a baseline of effectiveness. SimCFD then performs a transient analysis on each model. The output of this analysis provides information on each models' thermal comfort and average interior building temperature during the cooling season. Each SimCFD model also produces natural lighting potential for the entire year.

Once the atrium effectiveness is calculated for each of the five models, the final operational energy accounting for natural ventilation and natural lighting can be found. This then lets one compare the lifetime building operational energy to the embodied energy of the structure.

CHAPTER 3:
DATA COLLECTION AND ANALYSIS

Overview of results

After running Octopus for 500 samples of the building geometry, following results were received:

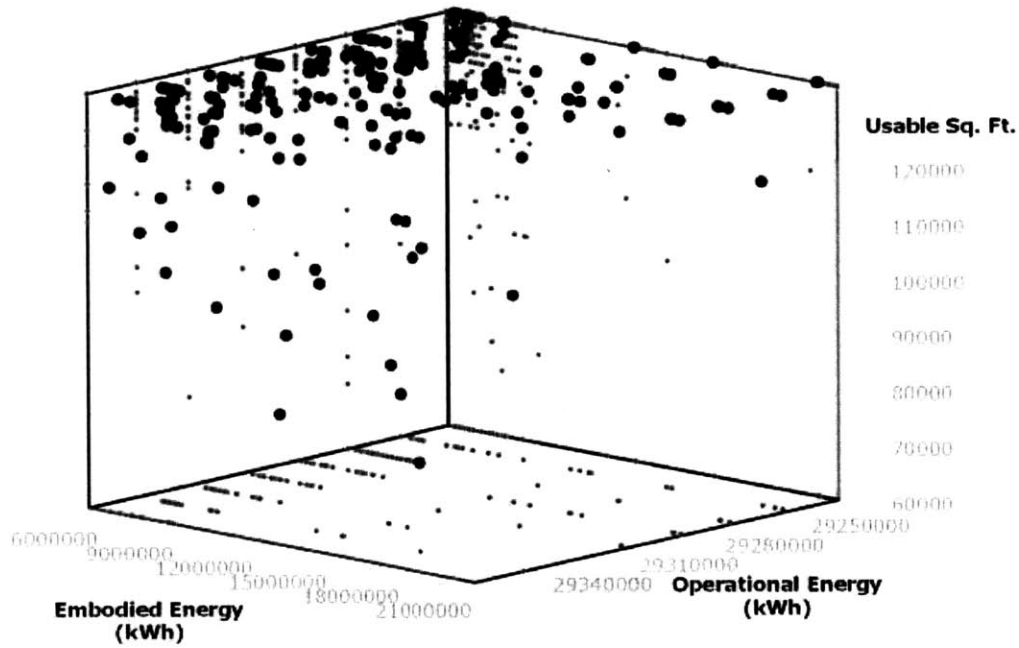


Figure 3.1: Operational Energy vs Embodied Energy vs Usable Sq. Ft

The following plots show the 2D comparison of embodied energy to operational energy, operational energy to usable square footage, and embodied energy to usable square footage.

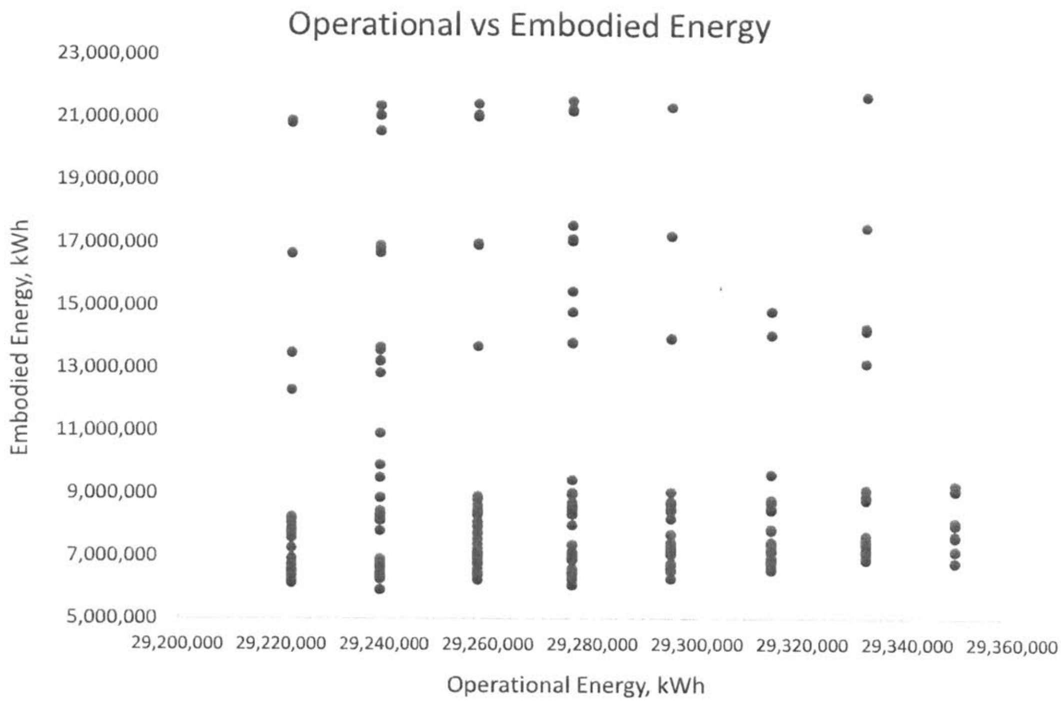


Figure 3.2: Operational Energy vs Embodied Energy projected

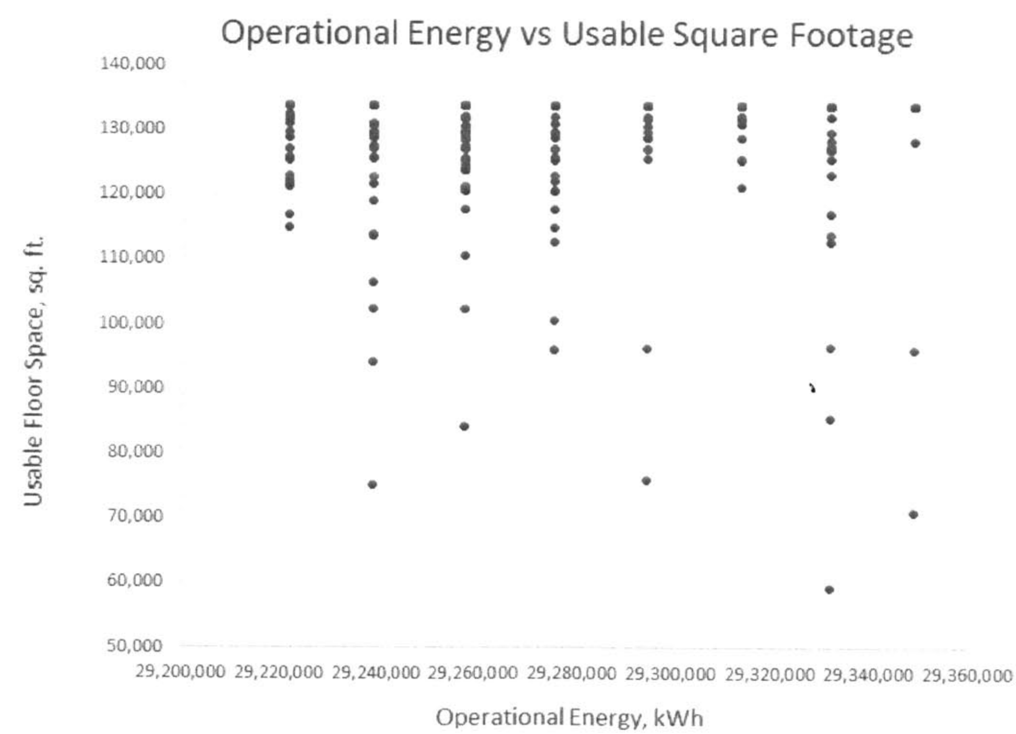


Figure 3.3: Operational Energy vs Usable Square Feet projected

Figures 3.2 and 3.3 show that the operational energy increases step-wise depending on the floor height. Table

3.1 gives the total operational energy of the building per floor.

Table 3.1:
Operational Energy Per Given Floor Height

Floor Height (ft)	Operational Energy (kWh)
8	29,222,000
9	29,239,000
10	29,258,000
11	29,276,000
12	29,295,000
13	29,314,000
14	29,332,000
15	29,349,000

The structure with the lowest operational energy usage has a floor-to-floor height of 8 ft. Therefore, without considering the effects of natural ventilation, the optimal building design would have this minimum floor height.

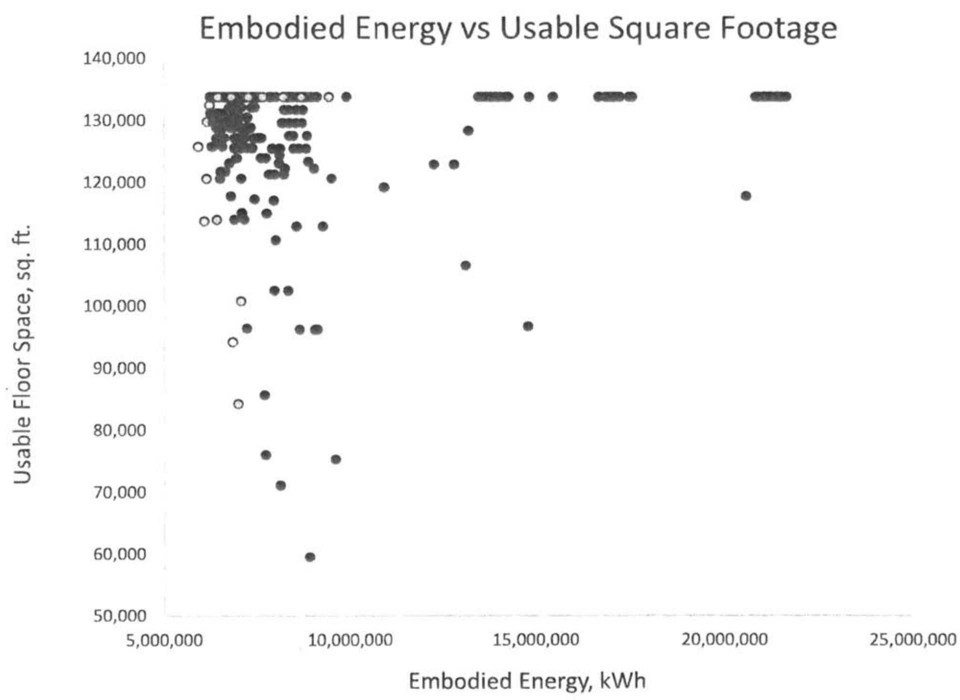


Figure 3.4: Embodied Energy vs Usable Square Feet projected

Figure 3.4 shows that there is a Pareto front of optimal designs for optimizing usable square footage and embodied energy. Unexpectedly, models without atriums tend to perform well structurally. However, as can be seen in figure 3.4, there are many models with low embodied energy and large atriums. Also, while looking at the same figure, it can be seen that there are many models with large embodied energy and no atriums. The trade-offs between usable square footage and embodied energy are the most interesting.

Evaluating the full 3D scatterplot shows there is a "best" design. This design has the minimum embodied energy, minimum operational energy and maximum amount of square footage. This design is shown in Figure 3.5.

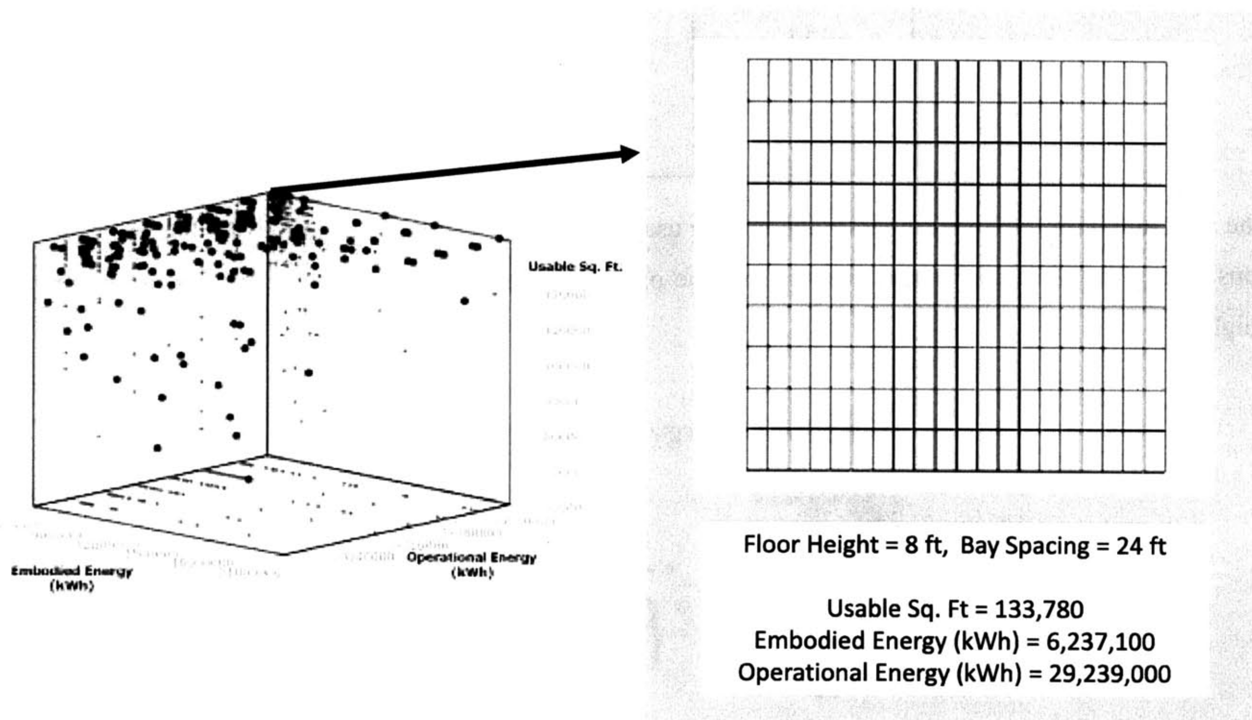


Figure 3.6: "Best" design: minimizes embodied and operational energy, and maximizes usable square feet

Despite being the "best" design, the framing plan is uninteresting. The building has a floor height of the minimum 8 ft, a bay size of 24 ft, and does not contain an atrium. The total lifetime energy of the model is 35,459,000 kWh. Even though this framing plan reduces the total operational and embodied energy, and maximizes floor framing, it is unknown how well the building will perform once natural ventilation is taken into account. Therefore, five models with varying operational energy and usable square footage, and low embodied energy are selected for further evaluation. Figure 3.7 shows the region of best fit to choose these designs.

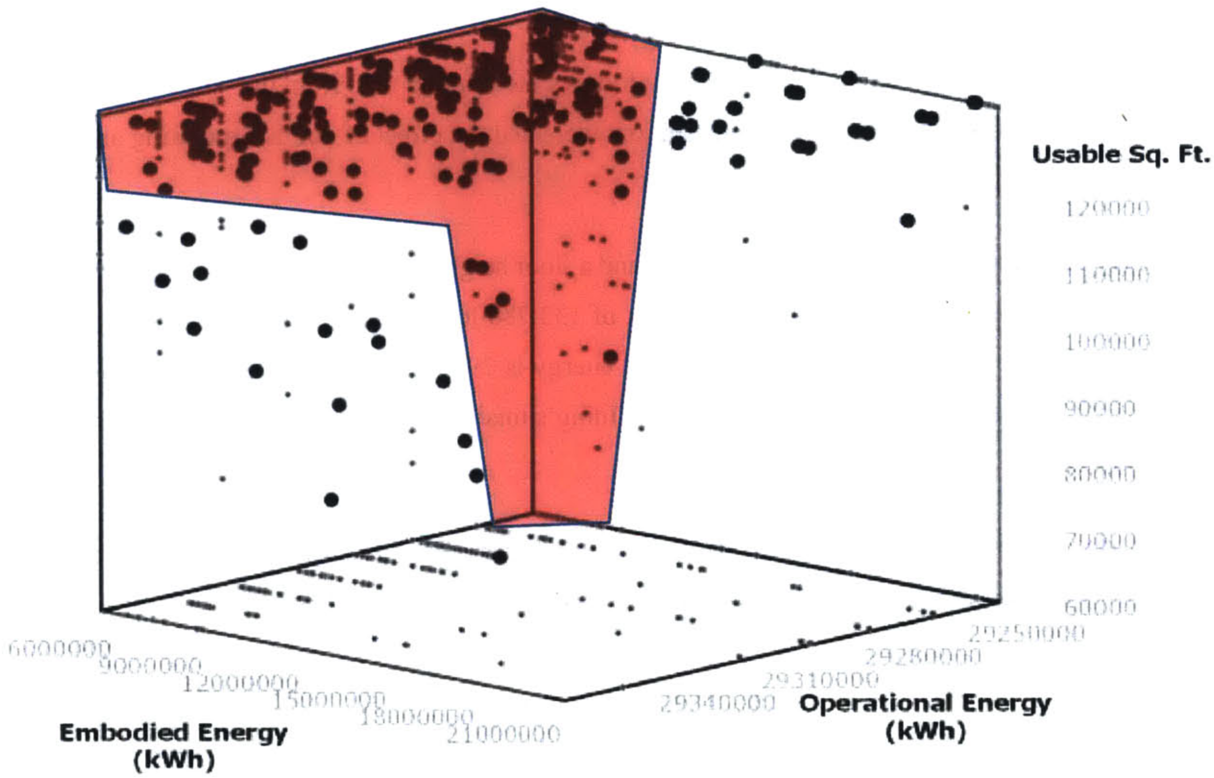


Figure 3.7: Region of favored designs that have low embodied energy, variable usable sq. ft and variable operational energy

Analysis of specific designs (without CFD analysis)

The five designs that are evaluated were selected because of their low embodied energies and differing global geometries. The models cover a range of floor heights and a range of atrium sizes. All models have a bay sizing of either 24 ft or 26.7 ft. This bay size is selected because evaluation of the most efficient structural systems shows that a smaller bay size produces a more efficient framing system.

The analysis of each model looks at the total structure embodied energy, lifetime operational energy and usable floor space. The models' operational energy is further broken down into respective lighting, cooling and heating loads of the system. These values are utilized in the next section, which explores the effects of natural ventilation.

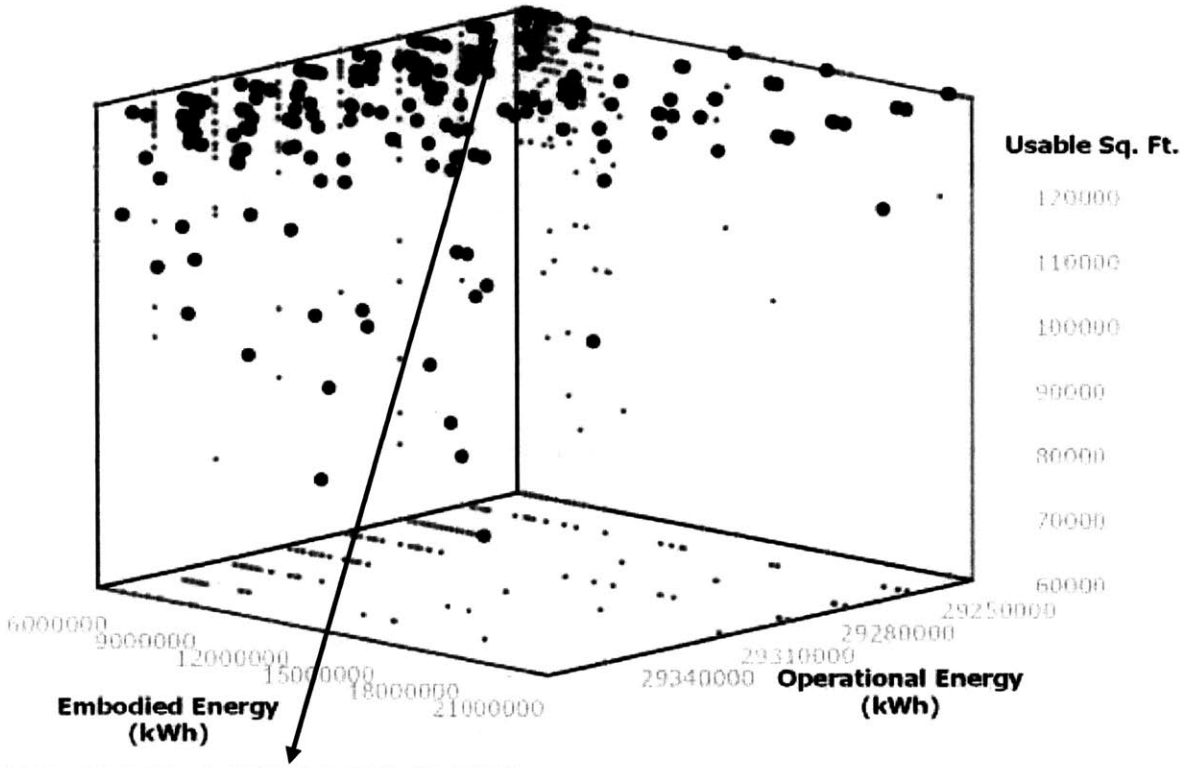
3.2.1 Building model #1

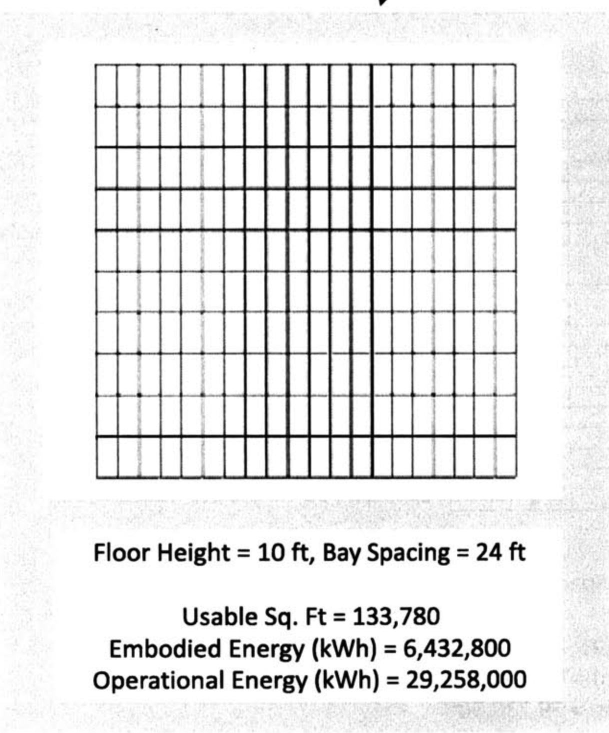
Building model #1 was selected because it closely follows the framing plan from the "best" design shown in Figure 3.6. Additionally, this model was selected to understand the effect of not incorporating an atrium into the building design.

The framing plan consists of a bay spacing of 24 ft and a floor height of 10 ft. There is no defined atrium. The total usable square footage is the maximum amount of 133,780 ft^2. The total building's embodied energy is 6,432,800 kWh. The building's lifetime operational energy is 29,258,000 kWh. Assuming a lifespan of 50 years, the embodied energy makes up 18% of the building's total lifetime energy, and the operational energy makes up 82%.

Figure 3.8 shows how the model performs compared to the other samples. This spacific model ranks first in usable floor space and 29th in total building energy.

Building model #1:





Energy Loads (kWh)	
Lighting	19,676,574
Cooling	482,880
Heating	9,283,243

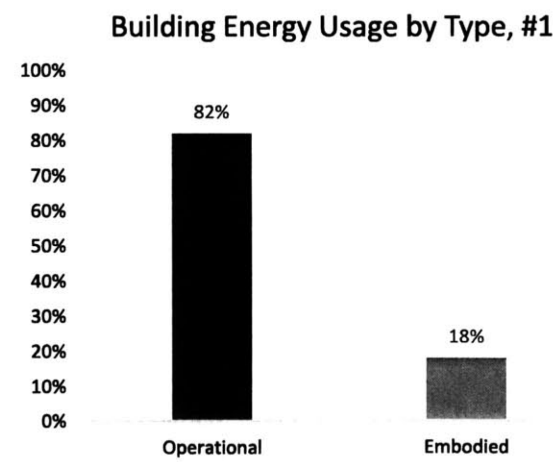


Figure 3.8: Numerical results from building model #1

3.2.2 Building model #2

Building model #2 was selected because it has the lowest embodied energy of the 500 sampled designs. This atrium size and location is typical of many office spaces that utilize central atriums.

The framing plan consists of a bay spacing of 24 ft and a floor height of 9 ft. The atrium is located two bays in the y-direction and four bays in the x-direction. It is almost perfectly centered in the framing plan.The atrium is two bays wide and four bays long. It takes up 6% of the floor plan. The total usable square footage is 125,750 ft^2. The total building's embodied energy is 5,925,400 kWh. The building's lifetime operational energy is 29,239,000 kWh. Based on these values, the embodied energy makes up 17% of the building's total lifetime energy, and the operational energy makes up 83%.

Figure 3.10 shows how the model performs compared to the other samples. This spacific model ranks 269th in usable floor space and 1st in total building energy.

This model is the most structurally efficient out of the 500 framing designs. This atrium reduces the embodied carbon of the system by nearly 1,000,000 kWh compared to the same system without an atrium. Furthermore, the central atrium reduces the embodied energy by 175,000 kWh (or 2.9%) when compared to a framing plan with the same-sized atrium shifted to the edge of the structure (see Figure 3.9).

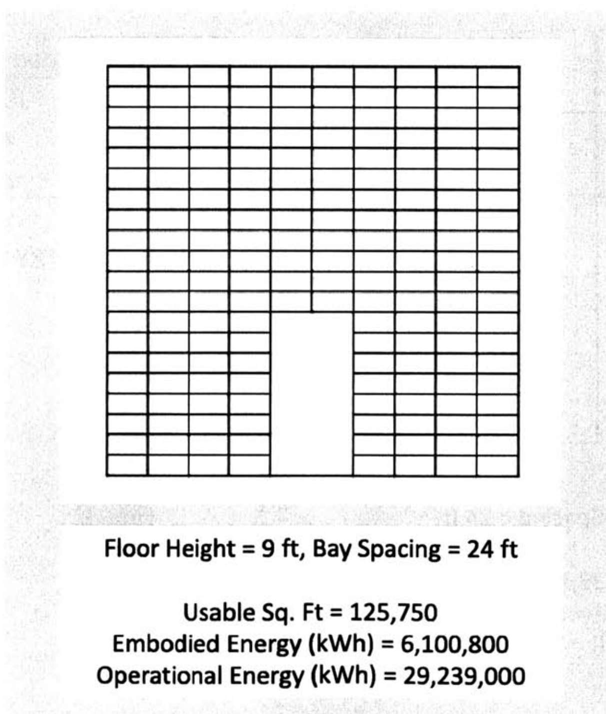
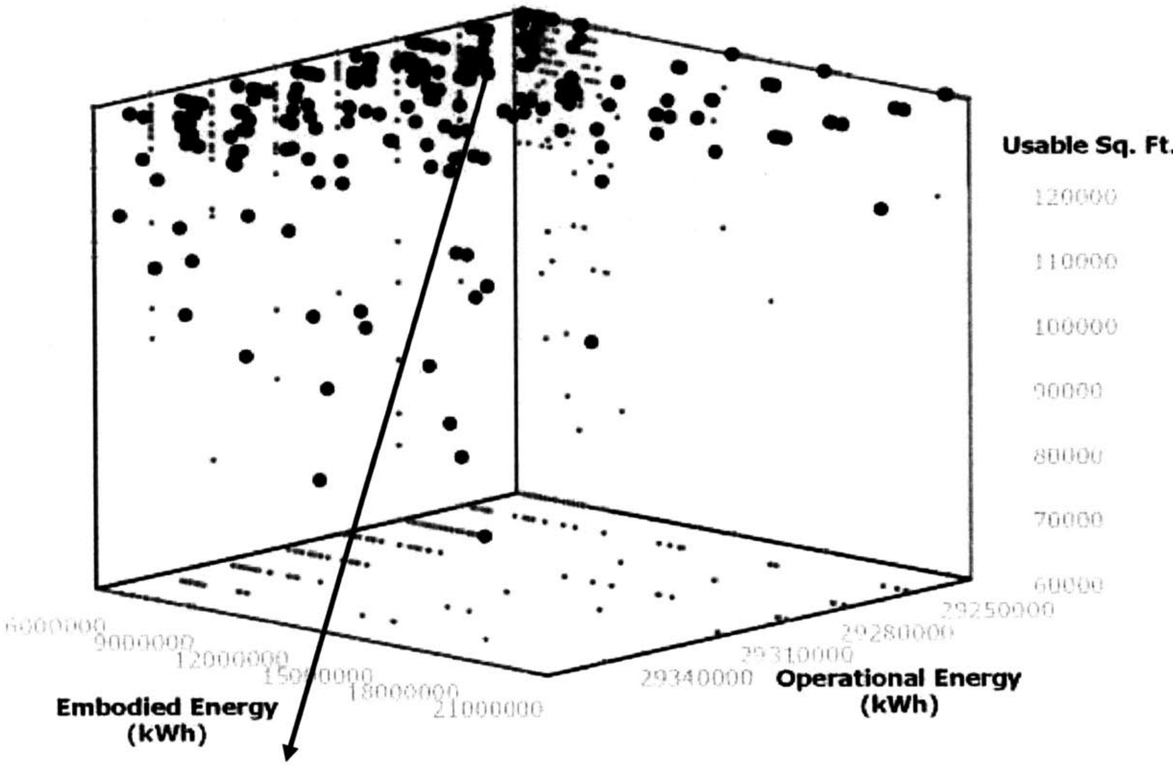
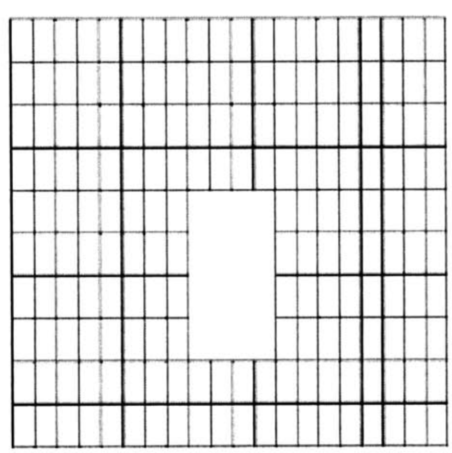


Figure 3.9: Numerical results from comparable model with shifted atrium

Building model #2:





Floor Height = 9 ft, Bay Spacing = 24 ft

Usable Sq. Ft = 125,750
Embodied Energy (kWh) = 5,925,400
Operational Energy (kWh) = 29,239,000

Energy Loads (kWh)	
Lighting	19,676,574
Cooling	454,600
Heating	9,299,911

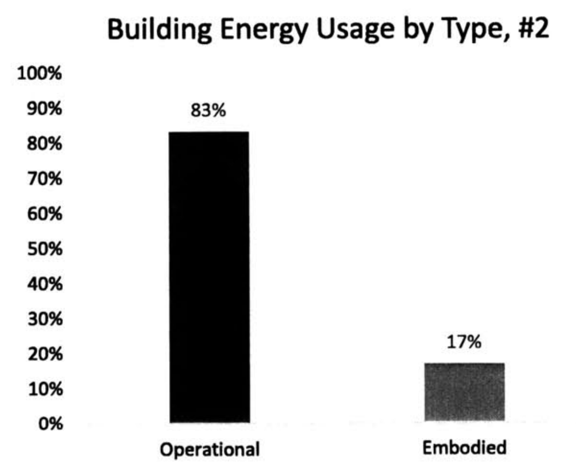


Figure 3.10: Numerical results from building design #2

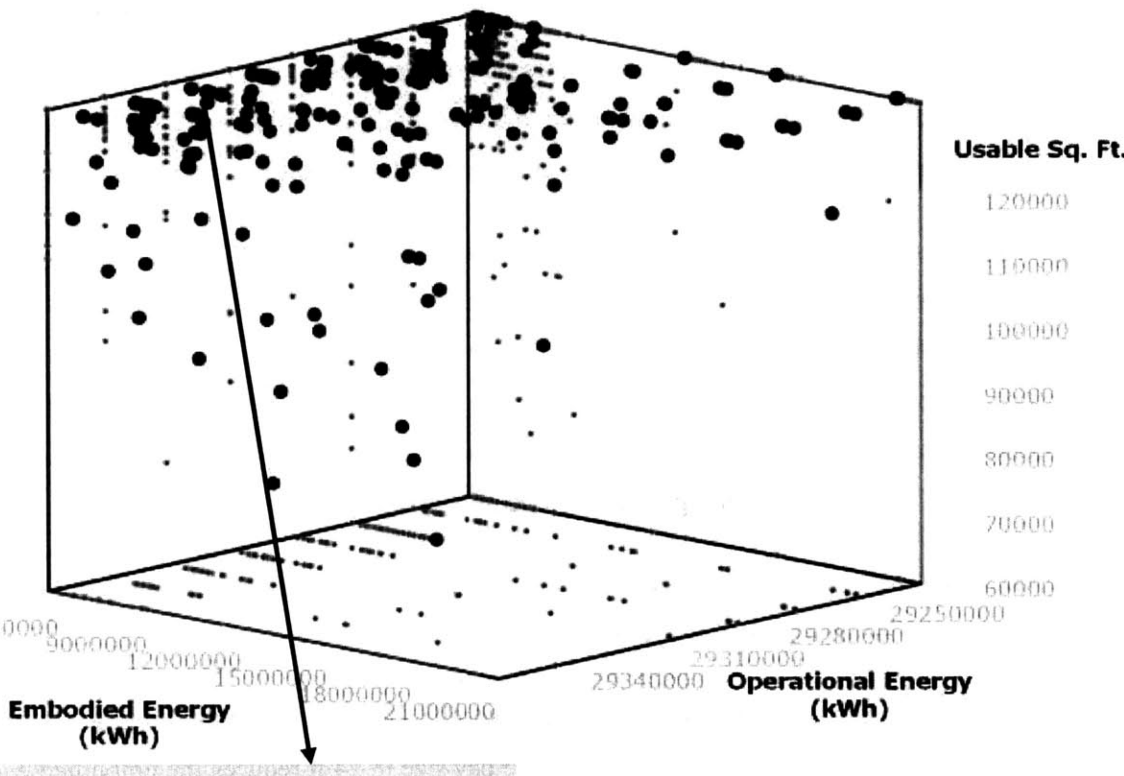
3.2.3 Building model #3

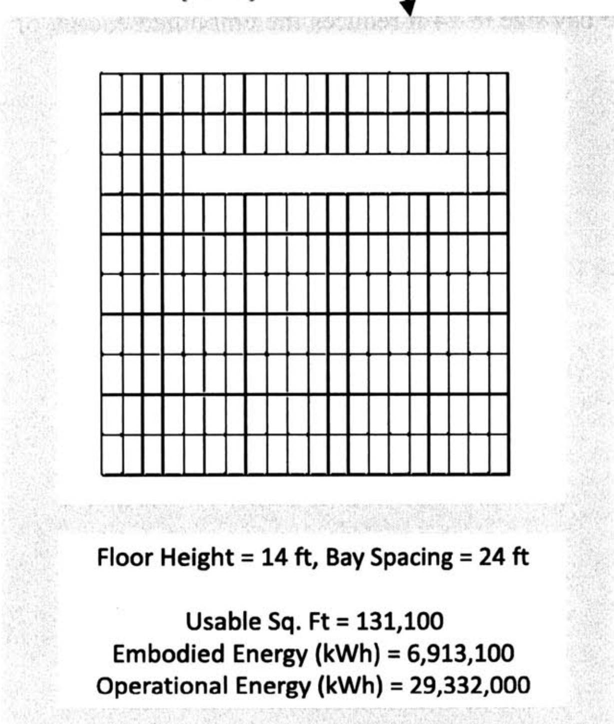
Building model #3 was selected because it incorporates a larger floor height and has an atrium geomtry that is atypical of atirums used in real office buildings.

The framing plan consists of a bay spacing of 24 ft and a floor height of 14 ft. The atrium is located eight bays in the y-direction and two bays in the x-direction. It is located off-center in the y-direction, but is almost centered in the x.The atrium is seven bays wide and one bay long. It takes up 2% of the floor plan. The total usable square footage is 131,100 ft^2. The total building's embodied energy is 6,913,100 kWh. The building's lifetime operational energy is 29,332,000 kWh. Based on these values, the embodied energy makes up 19% of the building's total lifetime energy, and the operational energy makes up 81%.

Figure 3.11 shows how the model performs compared to the other samples. This spacific model ranks 217th in usable floor space and 101st in total building energy.

Building model #3:





Energy Loads (kWh)	
Lighting	19,676,574
Cooling	596,000
Heating	9,210,459

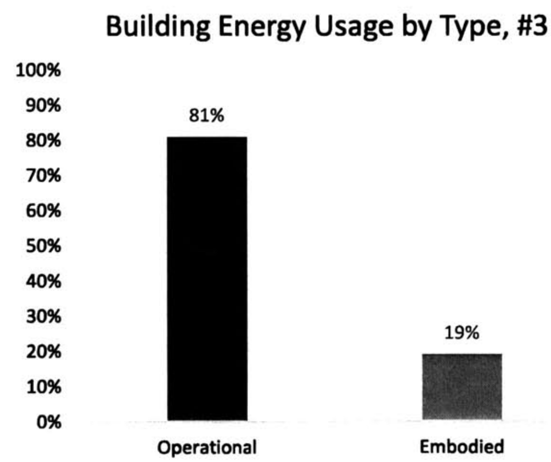


Figure 3.11: Numerical results from building design #3

3.2.4 Building model #4

Building model #4 was selected because it incorporates one of the largest atriums of the models sampled. Additionally, this type of side atrium is commonly used in office buildings. Unlike some of the other samples, which also had large atriums, this model split up the floor plan to allow usable space on either side.

The framing plan consists of a bay spacing of 26.7 ft and a floor height of 9 ft. The atrium is located zero bays in the y-direction and two bays in the x-direction. It is located at the bottom of the framing plan, but is centered to the building's width.The atrium is five bays wide and five bays long. It takes up 30% of the floor plan. The total usable square footage is 94,141 ft^2. The total building's embodied energy is 6,844,100 kWh. The building's lifetime operational energy is 29,239,000 kWh. Based on these values, the embodied energy makes up 19% of the building's total lifetime energy, and the operational energy makes up 81%.

Figure 3.13 shows how the model performs compared to the other samples. This spacific model ranks 328th in usable floor space and 74th in total building energy.

Additionally, this model is one of few models with a bay spacing of 26.7 ft that is within the top 100 most energy efficient building designs. However, decreasing the bay size to 24 ft reduces the embodied energy of the structure by 173,000 kWh (see Figure 3.12).

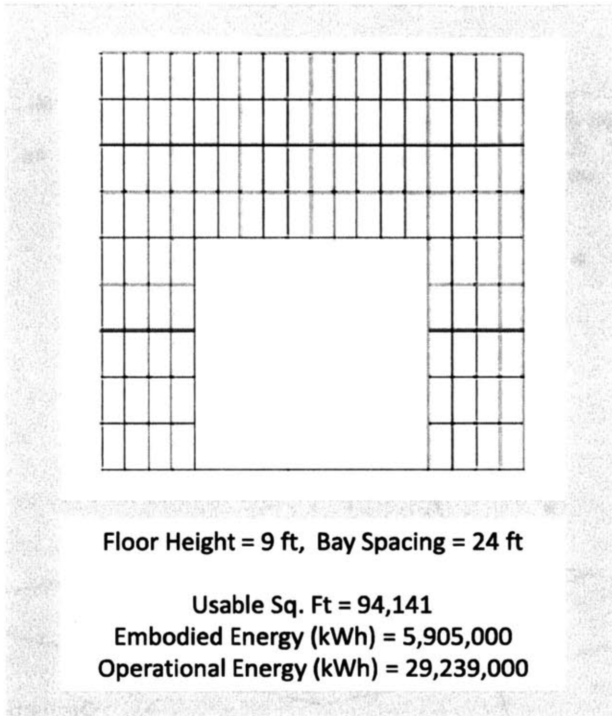
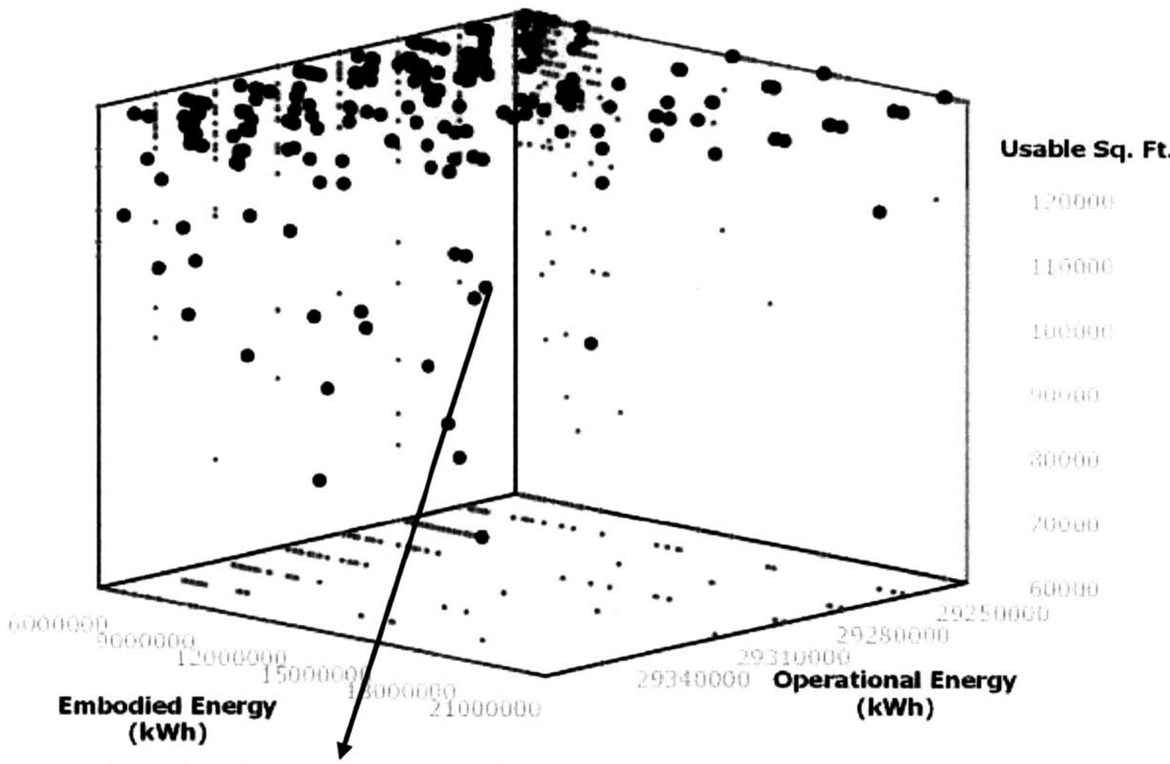
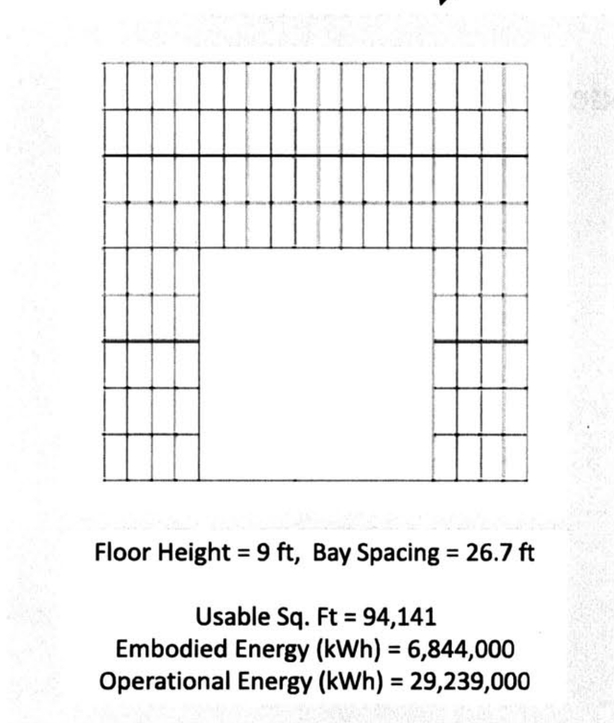


Figure 3.12: Numerical results from comparable model with reduced bay sizes

Building model #4:





Energy Loads (kWh)	
Lighting	19,676,574
Cooling	454,600
Heating	9,299,911

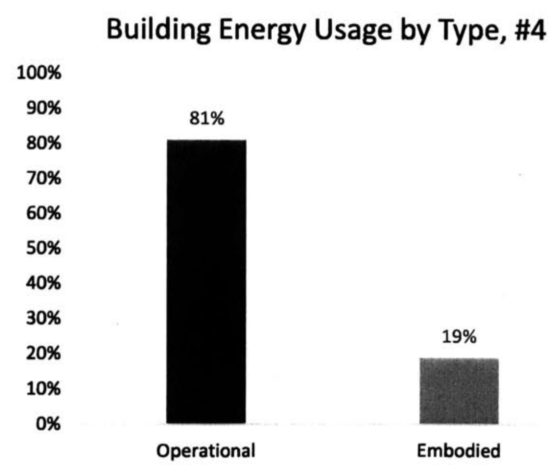


Figure 3.13: Numerical results from building design #4

3.2.5 Building model #5

Building model #5 was selected because it incorporates a small side atrium and has the largest possible floor-to-floor height. A model with a small side atrium will be useful in evaluating how atirum size affects natrual ventilation performance.

The framing plan consists of a bay spacing of 26.7 ft and a floor height of 15 ft. The atrium is located six bays in the y-direction and eight bays in the x-direction. It is located on the right edge of the framing plan, slightly and slightly above the frame's centerline. The atrium is two bays wide and two bays long. It takes up 5% of the floor plan. The total usable square footage is 127,170 ft^2. The total building's embodied energy is 7,599,700 kWh. The building's lifetime operational energy is 29,349,000 kWh. Based on these values, the embodied energy makes up 21% of the building's total lifetime energy, and the operational energy makes up 79%.

Figure 3.14 shows how the model performs compared to the other samples. This spacific model ranks 265th in usable floor space and 177th in total building energy.

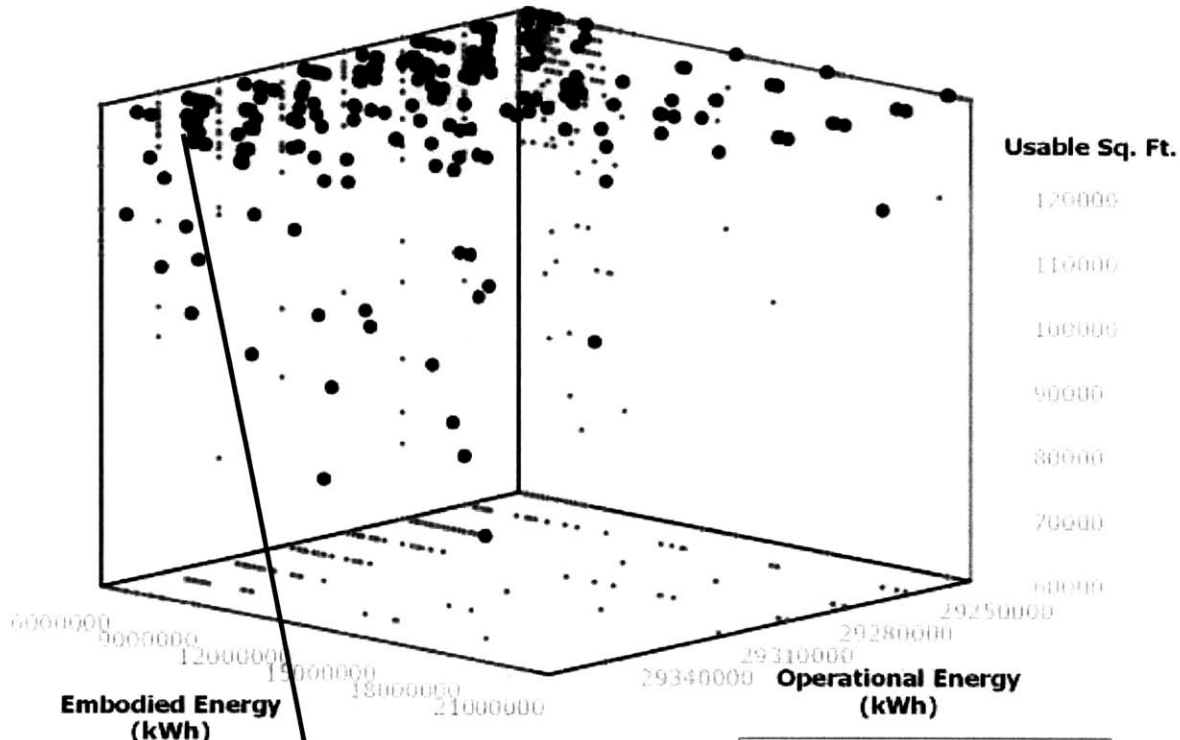
Additionally, this model is one of few models with a height of 15 ft. Reducing the structure height to 14 ft reduces the embodied energy by nearly 500,000 kWh. Table 3.2 shows the embodied energy for the same floor plan at different floor heights. It also gives the percent reduction in embodied energy as the floor height is reduced by one foot.

Table 3.2:
Reduction in Embodied Energy Per Given Floor Height for Model #5

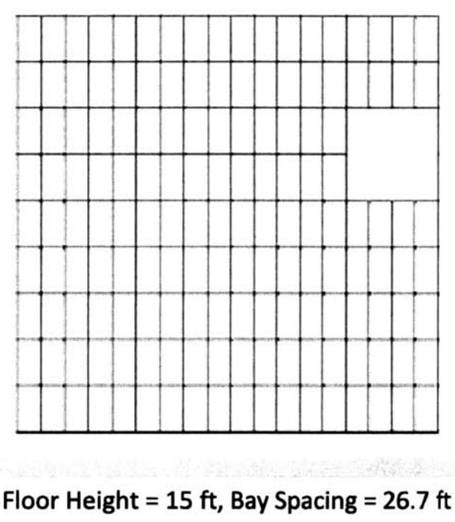
Floor Height (ft)	Embodied Energy (kWh)	Reduction in Embodied Energy (%)
15	7,599,700	-
14	7,105,300	6.5%
13	6,851,900	3.6%
12	6,697,500	2.3%
11	6,558,100	2.1%
10	6,433,000	1.9%
9	6,343,600	1.4%
8	6,246,000	1.5%

It should be noted that floor heights of 8 ft and 9ft are small when compared to industry standards. These two values were included in the analysis to see the affect building height has on embodied energy. As embodied energy is only reduced by 2.9% from 10 ft to 8 ft, it is improbable that any office building would employ floor heights less than 10 ft.

Building model #5:



Energy Loads (kWh)	
Lighting	19,676,574
Cooling	623,640
Heating	9,192,124



Floor Height = 15 ft, Bay Spacing = 26.7 ft

Usable Sq. Ft = 127,170
Embodied Energy (kWh) = 7,599,700
Operational Energy (kWh) = 29,349,000

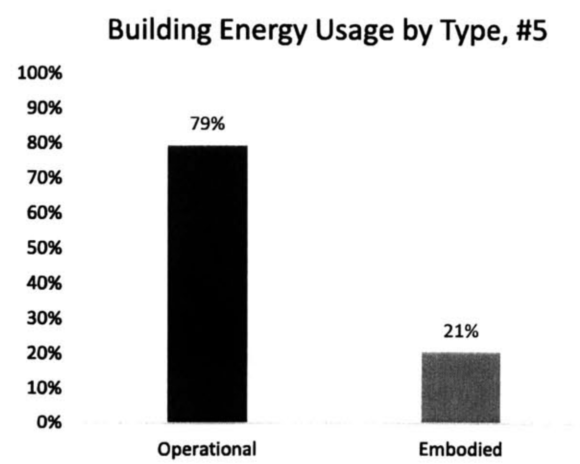


Figure 3.14: Numerical results from building design #5

Analysis of specific designs with CFD

Each building model is inputted into Simulation CFD to calculate natural ventilation cooling potential and natural lighting potential. Cooling potential is calculated by looking at the percentage of dissatisfied occupants and the building temperature per floor. The models do not account for mechanical cooling equipment. Furthermore, the models perform a transient analysis on the solar gains of each building. Every building has a fully glass façade, as is typical with office builings. While solar heat gain and natural lighting are not the same metric, areas with high solar heat gain receive a lot of natural light, while areas with low solar heat gain receive little light. Shading coefficients on the glass façade can be changed to increase or decrease solar heat gain. For this model, the shading coefficient is constant at 0.91.The percentage of solar gain is then used to calculate the natural lighting potential for the entire year.

Modeling the atriums in CFD gives an estimate of the cooling load and lighting load savings for a building over its entire lifetime. This information can then be used to determine where the focus should be placed on reducing total building energy for new construction projects.

3.3.1 Building model #1

Percent satisfied over entire building = 12%

Average interior building temperature = 34°C

Percent natural lighting over entire building = 45%

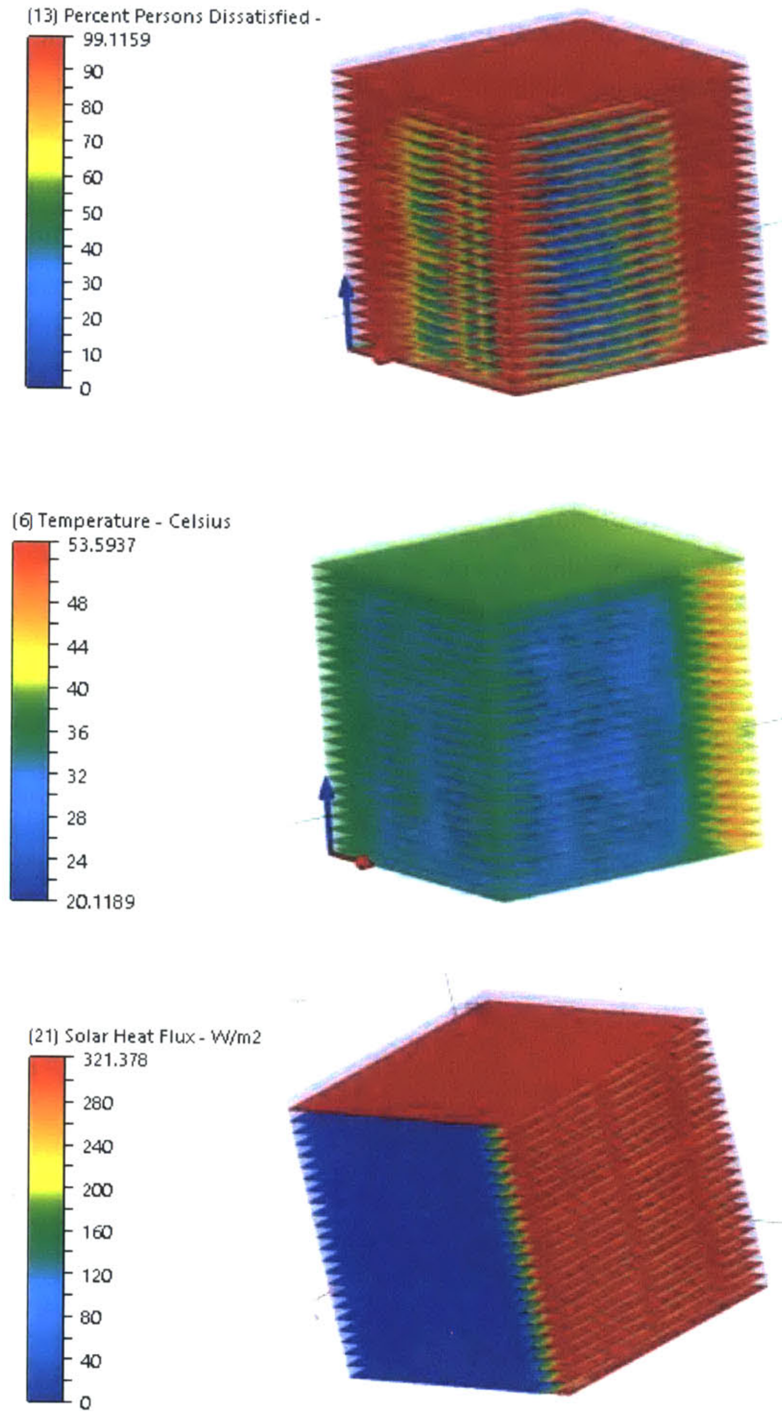
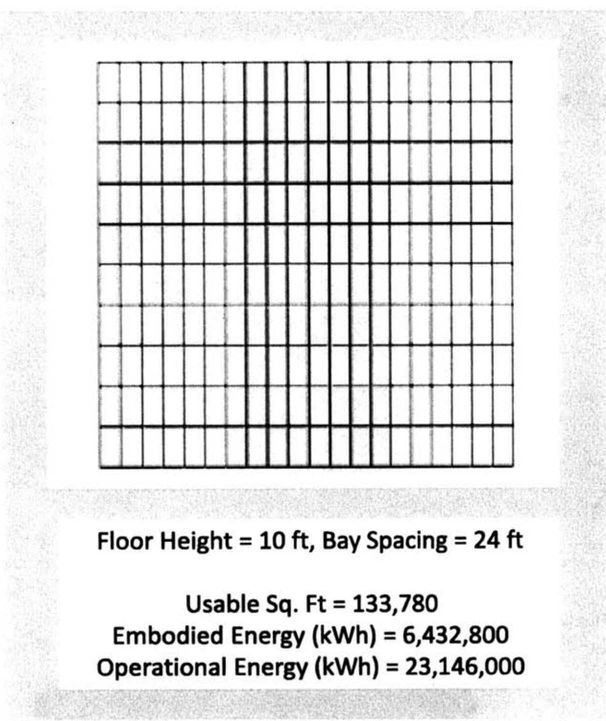


Figure 3.15: CFD results for building design #1

Without an atrium, the only energy savings that are calculated are from natural lighting within the building. As seen in Figure 3.15, evaluating the CFD model shows that natural light reaches about 45% of the entire building. Accounting for reduced sunlight during the winter, the total natural lighting potential for building model #1 is 32%. Because lighting is the highest load for an office building, reducing lighting loads equates to 6,300,00 kWh saved for this model.

The final lifetime operational energy usage of model #1 is 23,146,000 kWh. This reduction in operational energy increases the impact of embodied energy by 4%. Figure 3.16 gives an overview of the total energy usage for the model.



Energy Loads (kWh)	
Lighting	13,380,070
Cooling	482,880
Heating	9,283,243

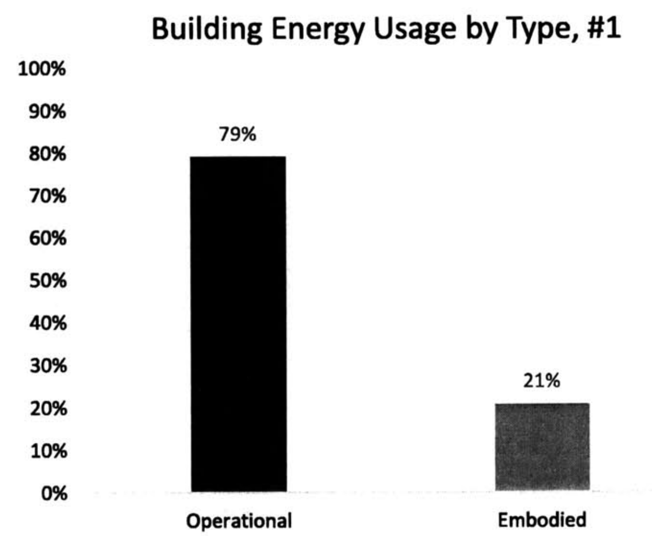


Figure 3.16: Overview of total lifetime energy use for model #1

3.3.2 Building model #2

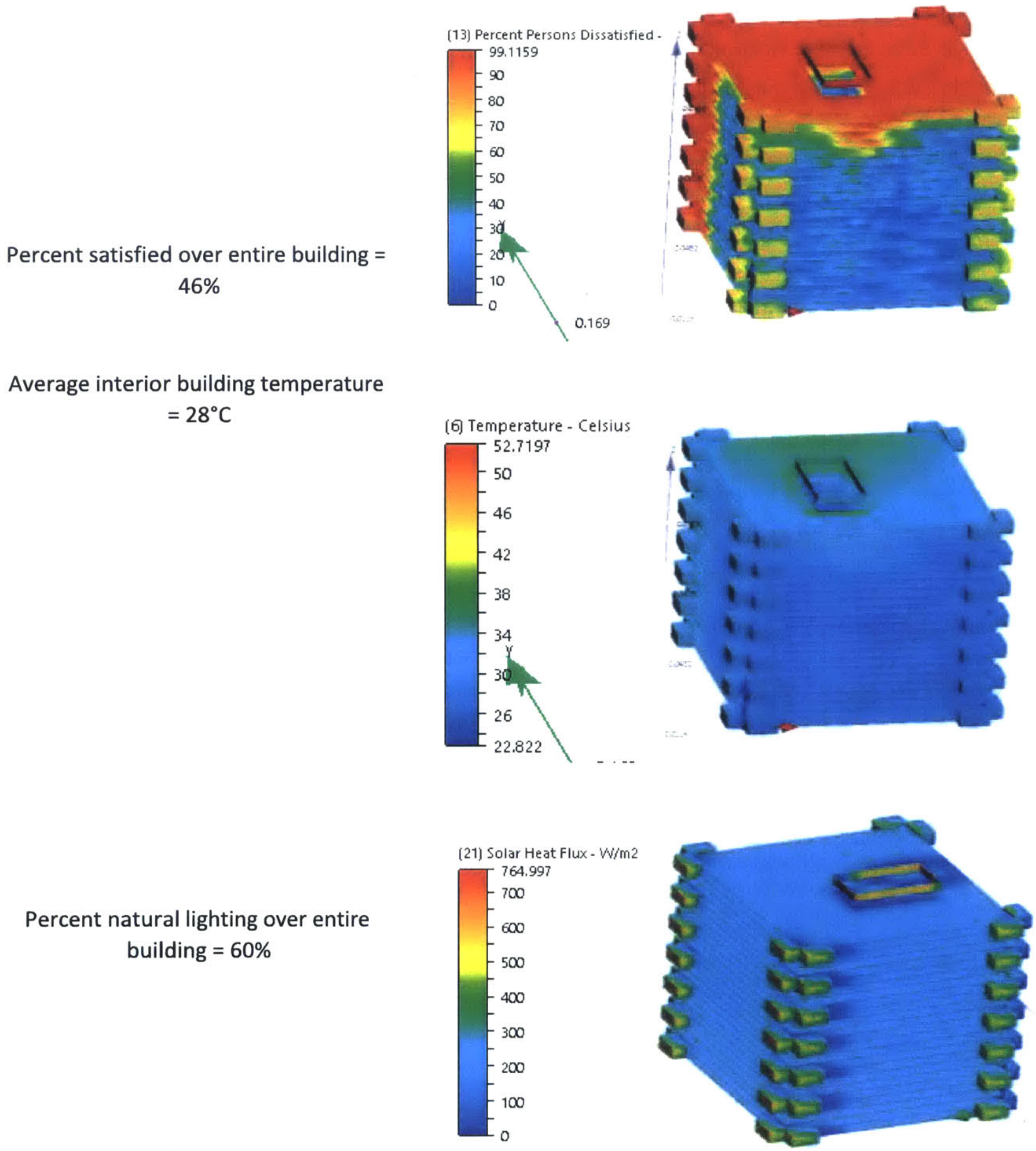
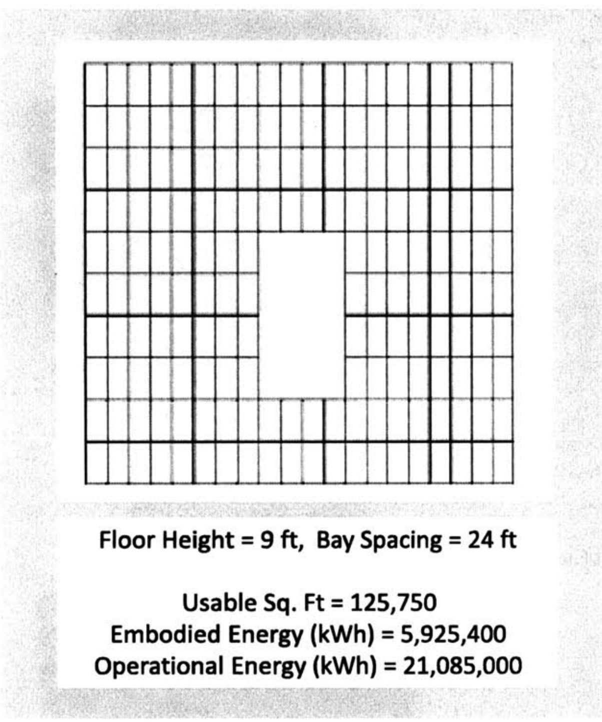


Figure 3.17: CFD results for building design #2

It can be seen in Figure 3.17 that with a central atrium, air is able to move from the ground floor windows to and to the central atrium. This air movement reduces the internal temperature of the building. This effect leads to an 18% reduction in cooling loads. This equates to an energy savings of 81,800 kWh. Additionally, the central atrium provides a small amount of natural lighting to the center of all of the floors. Evaluating the CFD model shows that natural light reaches about 60% of the entire building. Accounting for reduced sunlight during the winter, the total natural lighting potential for building model #2 is 42%. Because lighting is the highest load for an office building, reducing lighting loads equates to 8,260,00 kWh saved for this model.

The final lifetime operational energy usage of model #2 is 21,085,000 kWh. This reduction in operational energy increases the impact of embodied energy by 5%. Figure 3.18 gives an overview of the total energy usage for the model.



Energy Loads (kWh)	
Lighting	11,412,413
Cooling	372,772
Heating	9,299,911

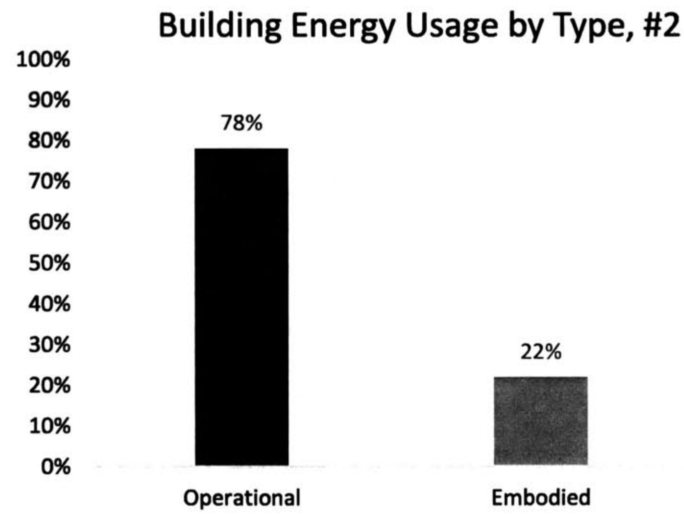


Figure 3.18: Overview of total lifetime energy use for model #2

3.3.3 Building model #3

Percent satisfied over entire building = 0%

Average interior building temperature = 38°C

Percent natural lighting over entire building = 64%

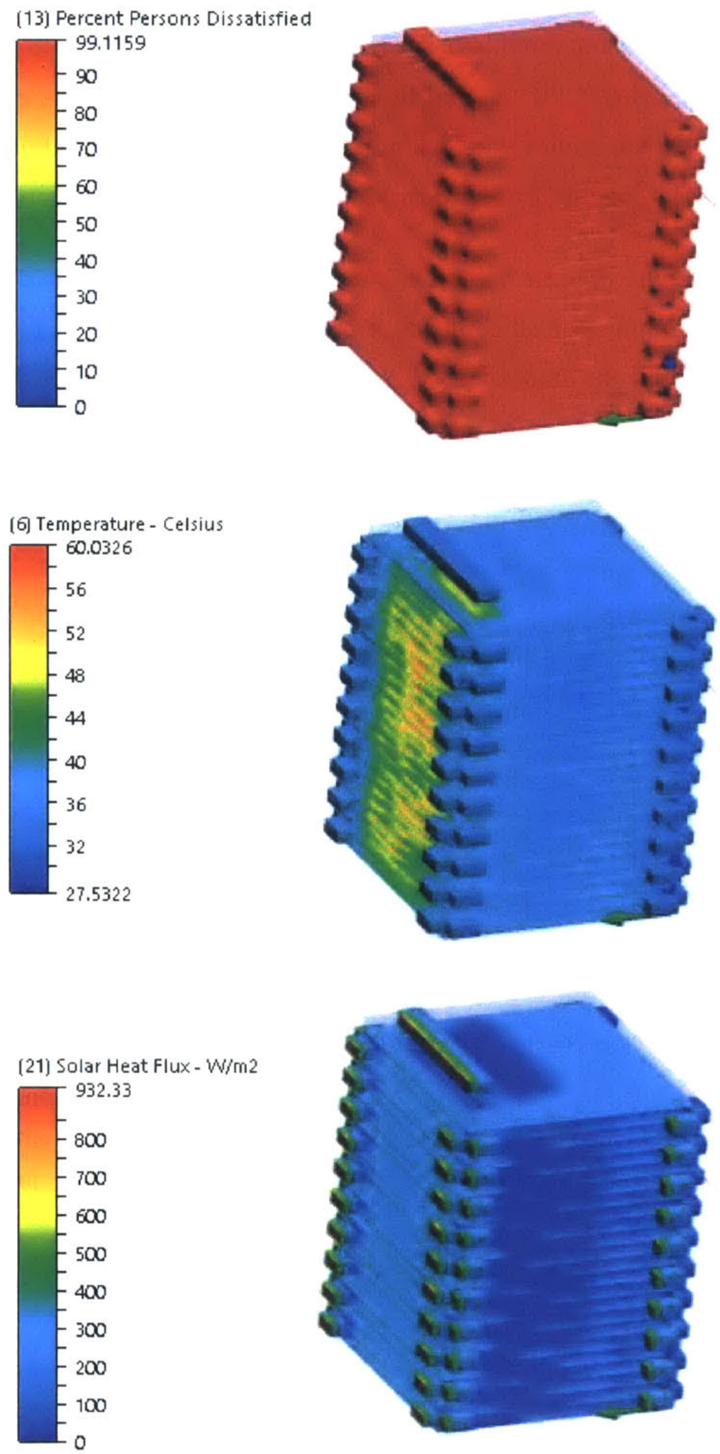
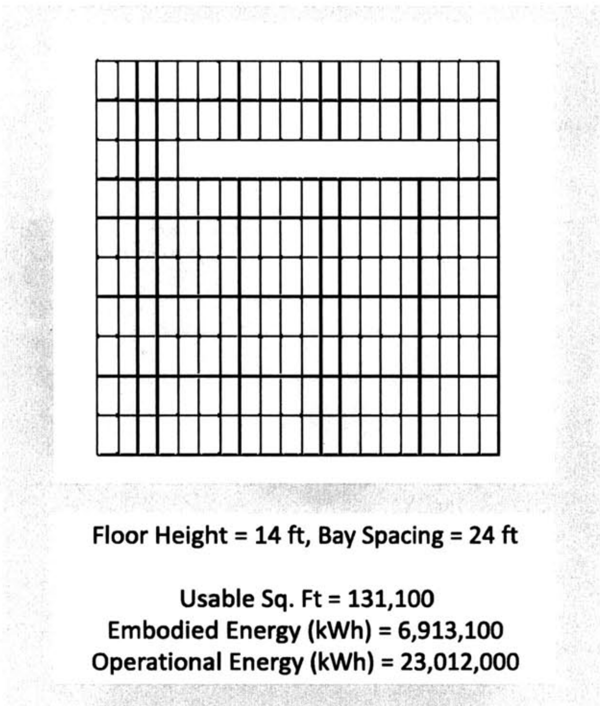


Figure 3.19: CFD results for building design #3

As can be seen in Figure 3.19, this model's atrium design was not successful in providing cooling. The atrium was too thin to effectively move air throughout the building. Instead, because windows are open on the bottom floors, hot air travels in, but does not travel out. Therefore, the cooling potential for model #3 is 0%. This atrium is able to provide a small amount of natural light to the left side of the building. However, the taller floors are the reason this building has a larger natural lighting potential. Including the effects of the atrium, this building reduces the lighitng load by 45%. This equates to a reduction of 8,850,00 kWh for this model.

The final lifetime operational energy usage of model #3 is 20,630,000 kWh. This reduction in operational energy increases the impact of embodied energy by 3%. Figure 3.20 gives an overview of the total energy usage for the model.



Energy Loads (kWh)	
Lighting	10,822,116
Cooling	2,980,000
Heating	9,210,459

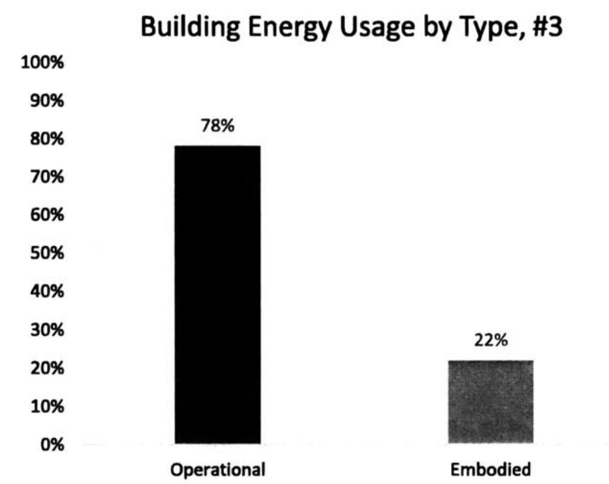
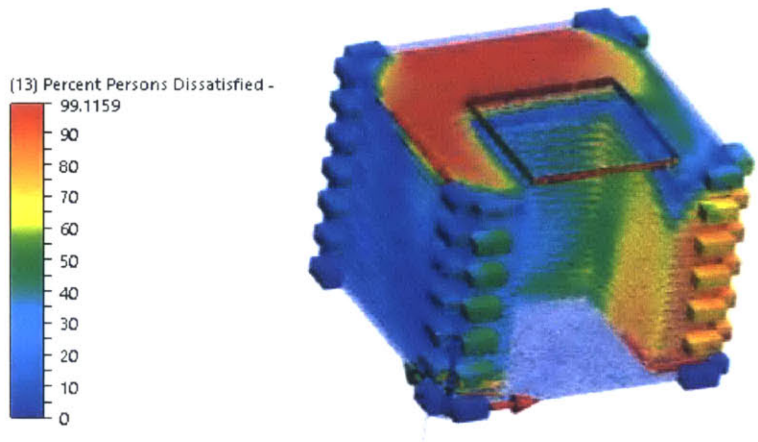


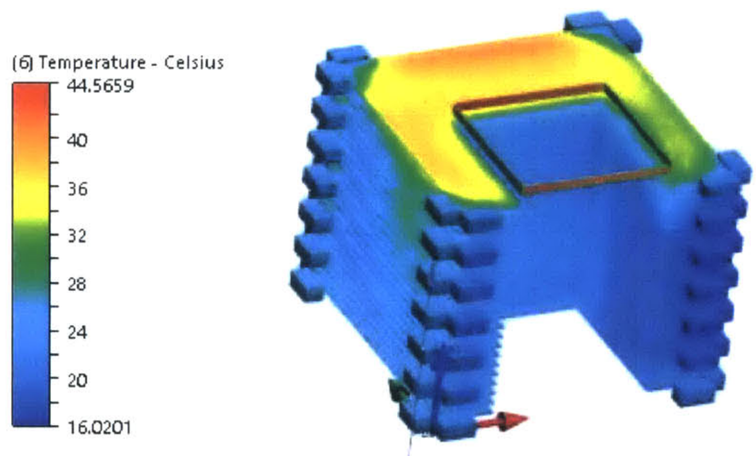
Figure 3.20: Overview of total lifetime energy use for model #3

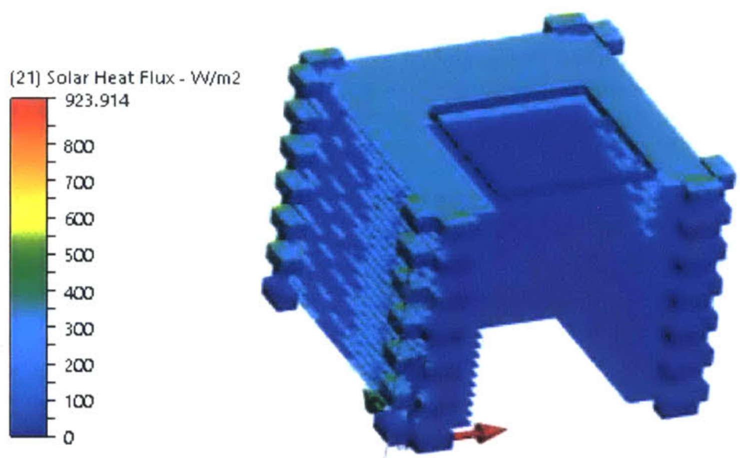
3.3.4 Building model #4



Percent satisfied over entire building = 69%

Average interior building temperature = 27.5°C



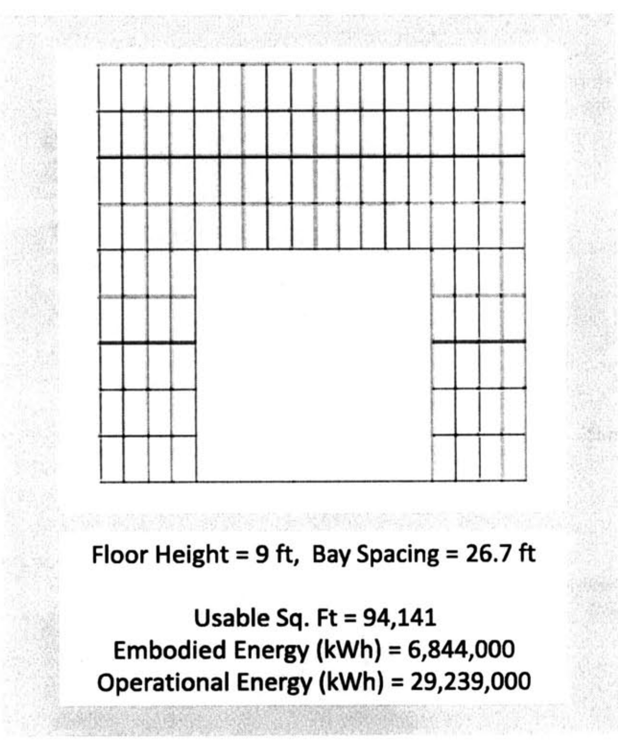


Percent natural lighting over entire building = 72%

Figure 3.21: CFD results for building design #4

Figure 3.21 shows that the atrium design for model #4 was successful in providing cooling to the space. This atrium is faced North-East and therefore does not experience a lot of solar gain. This shadowing mixed with the size of the atrium provides comfortable temperatures to 69% of the building occupants. This atrium is also able to provide a small amount of natural light to the front of the building. However, the floors are too short to effectively move light to the center of the floors. Despite this, the atrium reduces the total amount of floor space, resulting in a natural lighting potential of 50%. This equates to a reduction of 9,840,00 kWh for this model.

The final lifetime operational energy usage of model #4 is 19,497,000 kWh. This reduction in operational energy increases the impact of embodied energy by 7%. Figure 3.22 gives an overview of the total energy usage for the model.



Energy Loads (kWh)	
Lighting	9,838,287
Cooling	359,134
Heating	9,299,911

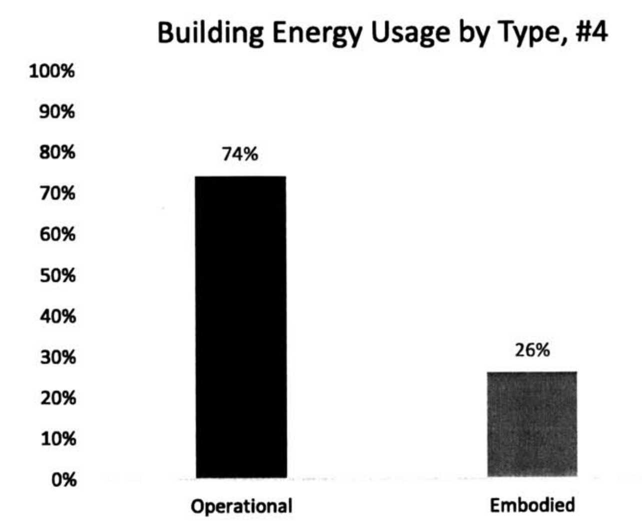


Figure 3.22: Overview of total lifetime energy use for model #4

The while the embodied energy of this design follows the same methodology of the other models, the embodied energy of the structure most likely is higher than what is calculated. This is because there is a large section of façade that is not able to rely on diaphram action to resist wind loading. Further analysis could be done to see how an atrium this large at at the edge of the floor plan further increases the embodied energy of the structure.

3.3.5 Building model #5

Percent satisfied over entire building = 5%

Average interior building temperature = 31°C

Percent natural lighting over entire building = 78%

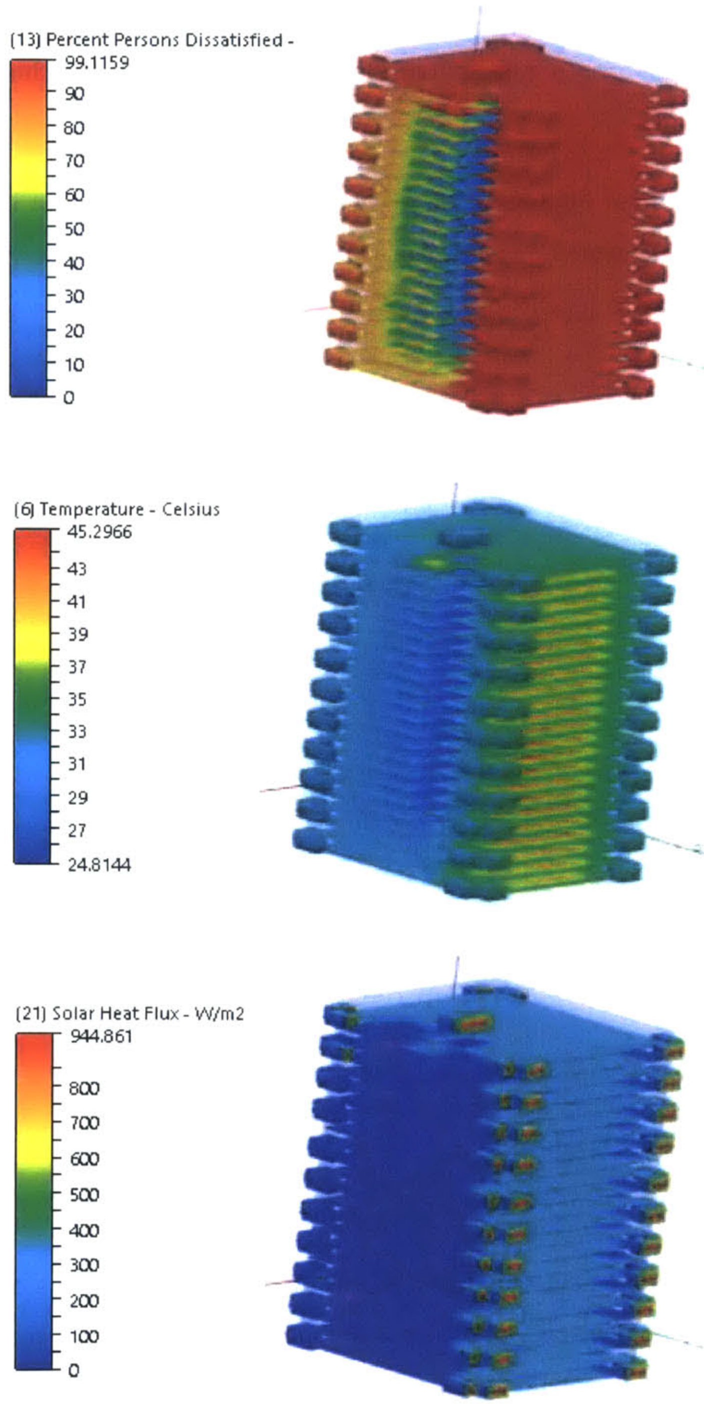
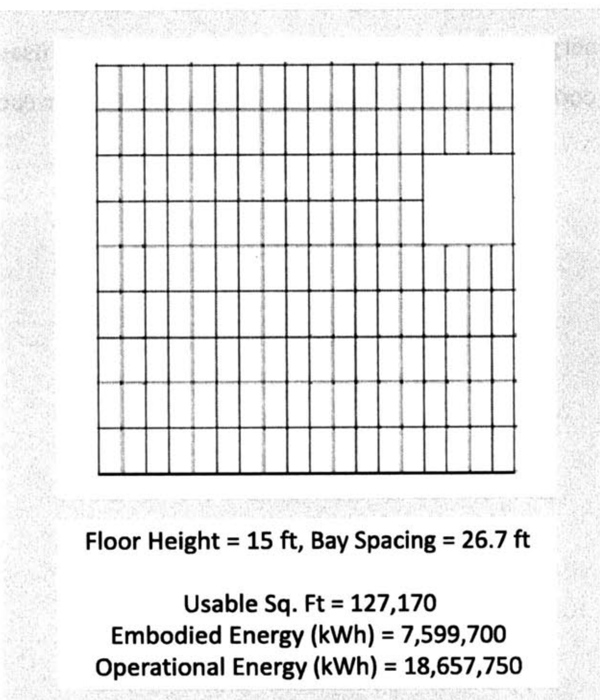


Figure 3.23: CFD results for building design #5

As can be seen in Figure 3.23, the atrium design provides very little cooling to the building. Unlike model #3, the width and depth of the atrium are wide enough to create a stack effect. However, the atrium is too small to provide air flow for the entire area of the floors. As can be seen from image of internal building temperatures, the atrium was able to reduce the average building temperature from 34°C to 31°C. The cooling potetional of this atrium design is 2%. This cooling reduction equates to an energy savings of 12,500 kWh.

Natural lighting reaches 75% of this building design despite the small atrium. This occurs because the 15 ft floors allow more light to permeate the center of the building. The natural lighitng potential for model #5 is 55%. This equates to a reduction of 10,820,00 kWh for this model.

The final lifetime operational energy usage of model #4 is 18,660,000 kWh. This reduction in operational energy increases the impact of embodied energy by 8%. Figure 3.24 gives an overview of the total energy usage for the model.



Energy Loads (kWh)	
Lighting	8,854,458
Cooling	611,167
Heating	9,192,124

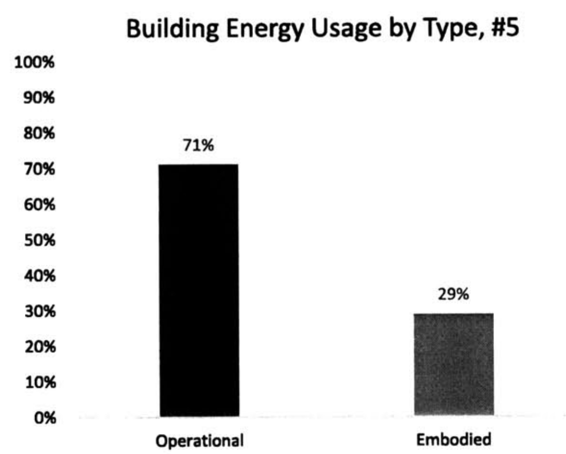


Figure 3.23: Overview of total lifetime energy use for model #5

3.3 Summary of results

Looking at the five design models shows that bay size, floor height, atrium location and atrium size impacts the final embodied and operational energy of a building. Model #2 shows that reducing the bay size from 24 ft to 26.7 ft saves 173,000 kWh of embodied energy. Similarly, reducing the floor height of the structure has the greatest impact on embodied energy when the original height is large. An analysis of Model #5 as 15 ft and 14 ft shows that nearly 500,000 kWh of energy can be saved in a 1 ft height reduction per floor. Additionally, the size and location has a large impact on the structural system and on the effectiveness of natural ventilation and lighting. Model #2 shows that a structure with an atrium reduces the total embodied energy. Furthermore, a central atrium is structurally more efficient. However, after reviewing the computational fluid dynamics models, a larger atrium at the edge of the building tends to be more effective it takes advantage of solar heat gains. Additionally, a structure with a large floor height (14 ft or 15 ft) provides the most natural lighting to the entire building.

Figure 3.24 gives a summary of the lifetime operational energy, embodied energy, percentage of energy usage by type, persons satisfied, average internal temperature, cooling potential, natural lighting potential for each of the five designs.

CHAPTER 4:
CONCLUSIONS

4.1 Summary of Contributions

This research shows that a successful workflow exists that compares structural efficiency with operational energy efficiency for buildings that incorporate natural ventilation practices. The parametric model successfully generates floor-framing plans with atriums that are similar to industry standards. Furthermore, this workflow allows one to search through a series of building designs to find options that minimize embodied energy while maintaining a minimum usable square footage. The models generated in Rhino can then quickly be analyzed in SimCFD to find the cooling and natural lighting potentials.

A review of the results generated in this thesis shows that my initial questions could be answered using this workflow. The structural models, operational energy models and computational fluid dynamics models helped answer: "How far can we push structural optimization while designing for occupant comfort using natural ventilation and buoyancy effects? And 2) What constraints are put on a building's global design when cooling and heating is accomplished with natural air flows?"
Results from this research shows that designing a building with natural ventilation and natural lighting has an effect on its structural efficiency. From Table 3.2 it is clear that there is large embodied energy savings from reducing the floor-to-floor height from 15 ft to 14 ft, 15 ft to 13 ft, or 15 ft to12 ft. This results in embodied energy savings of 6.5%, 10.1% and 12.4% respectively. Because large floor heights increase the amount of natural light the structure gets, a marrying of the two concepts should occur to find a design that has high levels of natural lighting and low embodied energy.

Further results from this research shows that smaller bay sizes with more filler beams performs better in tall buildings than buildings with less framing. Reducing the bay sizing from 26.7 ft to 24 ft saves about

2% of the structure's embodied energy.

Additionally, this research shows that atrium size and location affects structural performance and natural ventilation performance. Structurally, an atrium should be medium-sized and placed in the center of the floor plan. However, when designing for the summer climate of Boston, the atrium should be medium sized to large and placed in a location with low solar gains or in the center of the building. Therefore, changing the parameters in the Rhino/Grasshopper model generation would allow a person to figure out which design reduced total building energy more.

It should be noted that this research would not have been possible without the development of the parameterization environment utilized within Rhino and Grasshopper. As short as ten years ago a parameterized model with 25 stories would require too much computational power to be analyzed using a personal laptop. It should be expected that another 10 years into the future there will be ways to generate more sophisticated models than the ones implemented in this research.

4.2 Potential Impact

Very little work has been done to analyze the affects reducing operational energy has on the structural performance of a building. As reducing total energy of buildings becomes more important so does understanding how different building systems interact. Eventually, as operational energy becomes almost null, the focus will turn to the structural performance of buildings. This research sheds some light on how structural performance changes when different atrium geometries are employed.

4.3 Future Work

Future work can be done on evaluating the trade-offs associated with different structural systems and total building energy. This research assumes a braced moment-frame structure based on the height and aspect ratios of the model. However, different structural systems might give different results than what was found in this paper. Other structural systems that may be added to this research include core wall systems, outrigger systems, braced core wall systems, tube systems and braced tube systems. By evaluating different structural systems, the total building height could be increased beyond the maximum height of 375 ft used in this research.

Further work could also look into how different natural ventilation systems affect the model's total building energy. This work could incorporate double-skin façades, multiple atriums, building reheat from stack flows (to reduce heating loads) and additional cross-ventilation systems.

4.4 Concluding Remarks

It is my hope that these results help marry the fields of architect and engineer as we push efficiency in buildings. It is clear in this research that operational energy has a substantial effect on the building's embodied energy. Therefore, when seeking the most efficient building designs, it becomes impossible to design one system without considering the other.

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