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Generative Design in Energy Efficient Buildings

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GENERATIVE DESIGN IN ENERGY EFFICIENT BUILDINGS

By

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Abstract

This is an investigative report on the use of generative design and genetic algorithms in the design of energy-efficient buildings. It focuses on a workflow using Project Refinery© and Dynamo© in Revit® for multi-objective optimization and visualization, and Honeybee© for daylighting analysis. The workflow was not about to run completely due to instability in Dynamo, however daylighting analysis and visualizations were produced separately from demonstrations of Refinery. It concludes that while genetic algorithms have potential to be useful in energy-efficient building design, these programs are not yet fully developed and difficult to use without extensive background knowledge and fluency in Python, due to issues regarding incompatibility between software versions.

1 Background

This is an investigative report on the use of generative design and genetic algorithms in the design of energy-efficient buildings. It focuses on a workflow (see Table 1) using Project Refinery© [1] and Dynamo© [2] in Revit® for multi-objective optimization and visualization, and Honeybee© [3] for daylighting analysis. This workflow begins with Revit®, which is a building information modeling (BIM) software. Unlike standard computer-aided design (CAD), BIM software is intended specifically for buildings, with groups of people working on the same project. Dynamo© is an open source visual programming tool within Revit® that allows users to analyze and manipulate nearly any object in Revit®, including windows, floors and walls. Visual programming works similarly to standard text-based coding. Instead of lines of code, “nodes” are selected from a library, placed in the Dynamo© environment, and connected to each other to demonstrate the workflow. This is intended to make coding more accessible to a wide variety of people who may not have computer science backgrounds. Dynamo© is a dynamic, community driven software that is constantly evolving, and is especially useful in generative design and automating repetitive tasks in Revit®. Honeybee© is an energy analysis tool that is also open source and dynamic. While there are many energy analysis programs, Honeybee© is unique because it is designed with interoperability in mind and intended to be used with many different software platforms, including Dynamo©. Project Refinery© is another Dynamo© tool that works with given inputs and outputs to find optimal solutions to architecture and engineering problems using genetic algorithms. Genetic algorithms begin with a random set of values within a user-defined range and “evolve” by identifying the best performing solutions and creating new generations using the characteristics of those solutions. This process requires many iterations, making Project Refinery© and Dynamo© excellent tools for the job. In this report, Project Refinery© and Dynamo© were used to identify the top performing solutions in a system attempting to achieve maximize natural lighting and minimum window area in a Revit® building by varying window dimensions and modeling lighting performance with Honeybee©.

Table 1. Software List

Program	Description
Revit®	BIM Software
Dynamo©	Open source visual programming tool within Revit® that allows users to analyze and manipulate Revit objects. Especially helpful for repetitive processes.
Optimo	A Dynamo© plugin which uses a Multi-Objective Optimization algorithm to find solutions to problems with conflicting objectives, using the Pareto front.
Project Refinery©	A Dynamo© tool that works with user defined inputs and outputs find optimal solutions using genetic algorithms.
Honeybee©	Daylighting tool within Dynamo©. Also available on other platforms.
Ladybug©	Energy Analysis tool within Dynamo©. Also available on other platforms. Must be installed with the following instructions: https://github.com/ladybug-tools/ladybug-legacy/wiki/Installation-Instructions
Rhythm	An add-on script for Dynamo© that allows users to manipulate Type Parameters in Revit®
Radiance©	Part of Honeybee Daylighting Analysis which must be installed separately

1.1 Motivation

According to a 2018 survey by the World Green Building Council [4], global green building activity is rising and expected to grow substantially by 2021. 47% of respondents said they planned to build more than 60% green projects in 2021, which was up from 27% in 2018. This comes from recent realizations that climate change is a more imminent threat than was originally thought, but it is also a sound financial decision, as the additional investment made into a green building has a payback period that is continuously shrinking. The same report stated that 30% of respondents expected an over

10% increase in asset value for green buildings in 2018. Countries in the survey currently leading in percentage of green building construction are Australia, China (Hong Kong), and Ireland. The UAE claims it will be at the top in 2021, with Australia, Norway, and Spain close behind. Only 17% of respondents expect to have little to no green involvement by 2021. Most of these environmentally friendly projects will be new commercial construction, but more than half of green projects in the U.S are retrofits of current buildings. This increase in green building intent can be attributed to increased awareness, environmental regulations, and lower operating costs. Healthier buildings are another aspect of sustainability that has been recently identified. According to the U.S. Green Building Council (USGBC) [5], buildings with better light, ventilation, views, and occupant controls result in significantly healthier and more productive occupants, as well as attracting better employees and giving them another reason to stay at a company longer and be more productive.

In 2012, 76% of respondents cited higher first costs as the biggest obstacle to building green. This number dropped to 49% in 2018, showing that we are nearing a tipping point where it becomes widely accepted that building green is a financially as well as environmentally sustainable decision. In addition to concerns about first costs, some major barriers are lack of political support, lack of educated green professionals, and lack of public awareness.

While energy efficient buildings are securing their place in new technology throughout developed countries, they are even more important in the developing world. Many energy saving strategies involve passive heating, cooling, and ventilation, as well as employing natural light. Energy saving strategies in modern buildings often come from traditional techniques for occupant comfort that have been employed for centuries. This report aims to explore how these techniques can be best used with modern computation for use in different climates.

As the building industry shifts to more sustainable construction, energy modeling has become a more common step in the design process. In the past, this was done near the end of the process because it was too time consuming to model many iterations of the same design concepts. With generative design, models are driven by equations and relations so that they can be easily adjusted and updated, making energy analysis feasible and useful throughout the entire design process even as the model changes. Generative design has been greatly supported by genetic algorithms, which essentially provide a survival of the fittest selection process and combine variations within user set parameters across a certain number of "generations" to arrive at an optimal solution or solutions. This can be done with one variable or many, which is known as multi-objective optimization (MOO).

1.2 Generative Design

Generative design covers a wide area of methods which use automation to help designers and engineers make better and faster decisions. The use of parameters is the driving factor and allows users to easily update and improve models by relying on dynamic, interrelated equations rather than static numbers. Parameters used in this way can generate thousands of possible solutions and the user can see how one variable affects the entire system. This helps manage complex systems, optimize specific criteria, and combine human creativity with computational power. This is especially useful early in the design process with problems that are complex or not yet well defined. It also helps demonstrate tradeoffs in order to initiate and direct discussion between stakeholders on a project. In the past it would have been a huge time sink to complete calculations and then go back and make a significant design change, but with generative design, major alterations can be completed and evaluated with just a few clicks.

This technology has been in use for decades, but recent developments have made it more accessible and useful to many industries. AutoCAD® was one of the early pioneers of generative design with AutoLISP®, which allowed the user to write simple functions and have design parameters interact with each other. Since then, the plugin by Autodesk called Dynamo© has been developed for Revit®. This open source plugin allows users to perform complex calculations, optimizations, and visualizations of their designs, all using visual based programming. As generative design progresses, it has been able to manage increasingly larger and more complex portions of the design process, allowing companies to automate otherwise tedious tasks and keep up with growing demand for new buildings, while keeping prices low. This is especially important now, as a survey by the USG Corporation and the U.S. Chamber of Commerce reported in 2018 that 57% of construction contractors want to hire more workers in the next six months, but face challenges with respect to availability and cost. [6] In addition to freeing up time that would otherwise be spent on tedious tasks, generative design can also be used with optimization functions to find the most efficient designs for any given situation. This could involve any set of design metrics, such as minimization of energy use, materials, or distance from a certain point, or maximization of natural lighting and ventilation. For example, the Dutch construction company Van Wijnen used generative design to test 15,000 possibilities for a new land development project, with the goals of maximizing solar energy collection to meet net-zero energy goals, while also maximizing yard size and views. Generative design tools also allowed the company to include cost and profit in their analysis, leading them to designs which were good for the company, the customers, and the environment. According to "Leading the Future of Building, Connecting Design Insight", only 46% of design firms are aware of generative design, and 37% of those are actually using it. [6] The exploration of multi-objective optimization as a visual tool is the main goal of this report and will be discussed more further on.

Phil Bernstein, a lecturer from the Yale School of Architecture elaborated on the freedom of design that stems from integrating computers into the building design process.

"Architects have been using scripting for decades to take the geometry created by a computer and manipulate it in new ways, and a new generation of building design and construction was born. Computers overruled the tyranny of the right angle, and shapes and curves became possible not to just draw but to build." Phil Bernstein, Associate Dean and a Senior Lecturer at the Yale School of Architecture; Autodesk Fellow [6]

Generative design allows for the use of complex geometric features that would have been prohibitively complex without the help of computer models made with parameters and algorithms. It also offers an avenue to combine architecture and engineering into a true work of art, like the Heydar Aliyev Centre in Baku, Azerbaijan [7]. This building made critical use of generative design and 3D CAD programs to incorporate sweeping and elaborate curves into its construction and won the Design of the Year award in 2014. The architect, Dame Zaha Hadid was the first woman to win this award, and was selected from over 70 nominations in architecture, digital, fashion, furniture, product, and transport design.

Achieving curved, organic shapes in architecture has been attempted without generative design, but the process is extremely arduous. Antonio Gaudi, for example, is famous for his works in Barcelona imitating and inspired by nature. La Sagrada Familia, shown in Figure 1 is one of his most well-known projects.

Figure 1. La Sagrada Familia (Johanna Thill)

While he achieved great beauty and international acclaim for his architectural designs that were laden with Catholic symbolism and forms found in nature, his most famous work, the Sagrada Familia has been in construction since 1882. This is a clear indication that this style of design is incredibly time consuming without the proper technology. CAD models are now being used to complete the basilica, and it is projected to be finished in 2026 [8].

In a report by Catarina Rocha [9], the author highlights the importance of using building energy analysis throughout the entire design process, rather than only at the end. This is made possible by generative design, which allows designers to explore many avenues without spending all their time evaluating how basic changes affect the final product. She describes generative design as a process that produces various design solutions from a set of rules and constraints defined by algorithms. Lars Hesselgren, Director of KPF Research is quoted, saying:

"*Generative design is not about designing a building. It's about designing the system that designs a building."* In the system studied in this report, generative design was used to create many variations from a case concept, and then the top performing solutions were evaluated. She also emphasizes the increase in interest in energy efficient buildings and discusses how energy efficiency brings an entirely new aspect to building design. Incorporating energy efficiency into building systems and architecture creates an even more complicated design problem with multiple conflicting factors that feed in to producing the best possible solution and means that generative design is more necessary than ever in the evolving field of building design.

1.3 Building Information Modeling

Another key element to modern day building design is Building Information Modeling, commonly known as BIM. It is a 3D design process used by architecture, engineering, and construction professionals which allows users to efficiently design, plan, build, and manage buildings and infrastructure. It has a much higher level of detail and emphasis on construction than many 3D design software such as Autodesk Inventor® or Solidworks® and should not be confused with standard 3D CAD. Unlike most 3D CAD software, BIM is meant to be collaborative, and can be easily worked on by many people at the same time. It is also intended to be used as an integrated workflow and passed on from one phase of a project to the next, from design into construction and operation. For example, while a wall drawn with a line in AutoCAD® may just be a line, this same wall represented in Revit®, a software commonly used in the BIM process, will always have properties, schedules, and type information included. There are other useful functions that come into play while editing designs, such as corners of walls staying connected no matter how the edge is dragged around. Revit® also bases design off specific levels in a building, and views or drawings can be easily switched between floors. In conclusion, the BIM process is vastly better to use for designing buildings than traditional CAD because it is designed specifically for buildings and large projects with many team members, rather than all-purpose, mostly single-user CAD programs such as AutoCAD®, Inventor®, or Solidworks®.

1.4 Multi-Objective Optimization (MOO)

In most architecture, there are many more objectives to consider than just beauty and symbolism. The U.S. Green Building Council has created a rating system called Leadership in Energy and Environmental Design that includes lighting, energy use, material sustainability, and ventilation, and other factors to evaluate the sustainability and quality of a building. As in many complex systems, sometimes improving one aspect of a design makes performance worse in another. This is where multi-objective optimization (MOO) comes in. MOO can be applied manually by finding local maxima and minima of a design function, but it is much more useful as a computational tool. In complex systems, automated MOO is usually the only practical strategy. There is rarely one perfect solution, but generative design in combination with MOO can allow users to model and visualize the tradeoffs between the top performing design options. It must be noted that this process does not start or end with optimization. Parameters need to be carefully chosen and goals defined. After running an optimization, the designer should thoroughly examine results and choose the best design to refine further, possibly even with additional design criteria.

Two common strategies with MOO problems are simple aggregation, and Pareto Optimality [10, as first documented by Fonseca and Fleming in 1993 [11]. Simple aggregation involves creating a composite objection function that is a combination of all individual objective functions in the system. Importance of each function is determined with a weighting factor. This is useful for general or preliminary design, but often a more precise method is needed, especially with systems as technical and complex as energy efficient buildings. The Pareto Optimality approach seeks a set of high performing solutions which have arrived at the point where a single objective cannot be improved without causing a worse outcome in other objectives. The designer can then manually search through this set of optimal solutions in order to find the one that best suits their needs, or to simply find inspiration and strategies that they might not have thought of otherwise.

1.5 Genetic Algorithms

Genetic algorithms (GAs) are a "heuristic search and optimization technique inspired by natural evolution.", first proposed by John Holland in 1975. [12] They use a Darwinian approach to find optimal solutions through mutations of user driven parameters. The user parameters are like chromosomes, and each combination represents a possible solution. Each combination has a "fitness", which is a metric of how well the solution performed. The search for an optimal solution begins with a random list of values within a user defined range of values. The solutions which provide the highest fitness functions are passed on to the next generation for their characteristics to be recombined with those of the other highest performing solutions, as many times as the user wishes, or until certain criteria are met. Working with more generations requires more time or computational power, but better results may be achieved.

Genetic algorithms enable designers from many fields to automate tedious tasks, as well as efficiently create, explore, and document more design options that result in solutions with higher quality, sustainability, and creativity. While genetic algorithms involve a "bottom up" method, which begins with random values and combines the top performing solutions to eventually arrive at a set of optimal and sometimes unexpected solutions, generative design is considered to be "top down". This means that the end goal must be defined with equations, and this method relies less on randomness to arrive at the desired goal. Combing the two with human oversight and innovation has opened an entirely new chapter of design.

Although the theory behind genetic algorithms has been around for a long time, they have only recently become more common in industry and have lately provided some fascinating design solutions to complex problems. They were first used in HVAC s-ystems and controls in 1986 in the form of the Direct Search Method by Wright.[13] Three variables were minimized in this thesis: first cost, operating cost, and lifecycle cost. Factors such as price of manufactured components, controller setpoints, mass flow rates and temperature were considered. It also predicted the use of the technology explored in this report, stating, "*Exploitation of this power is expected to reach a level where computers will produce integrated building designs from a minimum of human input*." It also described the formulation of an optimization problem as containing 3 elements: variables, the objective function (also known as a fitness function), and system constraints.

In 2001, Wetter released GenOpt, a program with new algorithms that significantly contributed to optimization solutions in building engineering. [14] One of the greatest advantages of genetic algorithms is their adaptability to different situations; if there are parameters to be optimized, genetic algorithms can be applied. For example, in January 2007, two researchers published an article on the optimization of a bicycle frame using genetic algorithms. [15] The goal was to minimize weight, while considering the stresses on five critical rods in the frame, as well as a safety factor. This study also explored the effects of the crossover rate and number of generations on the fitness value.

Luckily, people who want to use genetic algorithms no longer need to have a profound understanding of the math behind optimization in order to find interesting and valuable results. Dynamo©, the open source visual programming language used as a plugin in Revit and other modeling software, allows those who are less familiar with coding to perform MOO with genetic algorithms, among many other things. This is especially useful in the field of energy efficient buildings, because designers and architects often do not have strong coding backgrounds. Dynamo© works with blocks or nodes that connect to each other and allow for easier visualization of functions, if/for loops, etc. Custom blocks can also be created and shared within this plugin. The most interesting capability of Dynamo© is its ability to interact with a variety of programs and plugins, including Revit®. In Revit®, elements and parameters can be manipulated via Dynamo© with a series of blocks linked together. This can include standard blocks as custom ones written by users with Python code and shared within Dynamo©. The example code in Figure 2 shows how to edit elements in Dynamo© with a numerical slider.

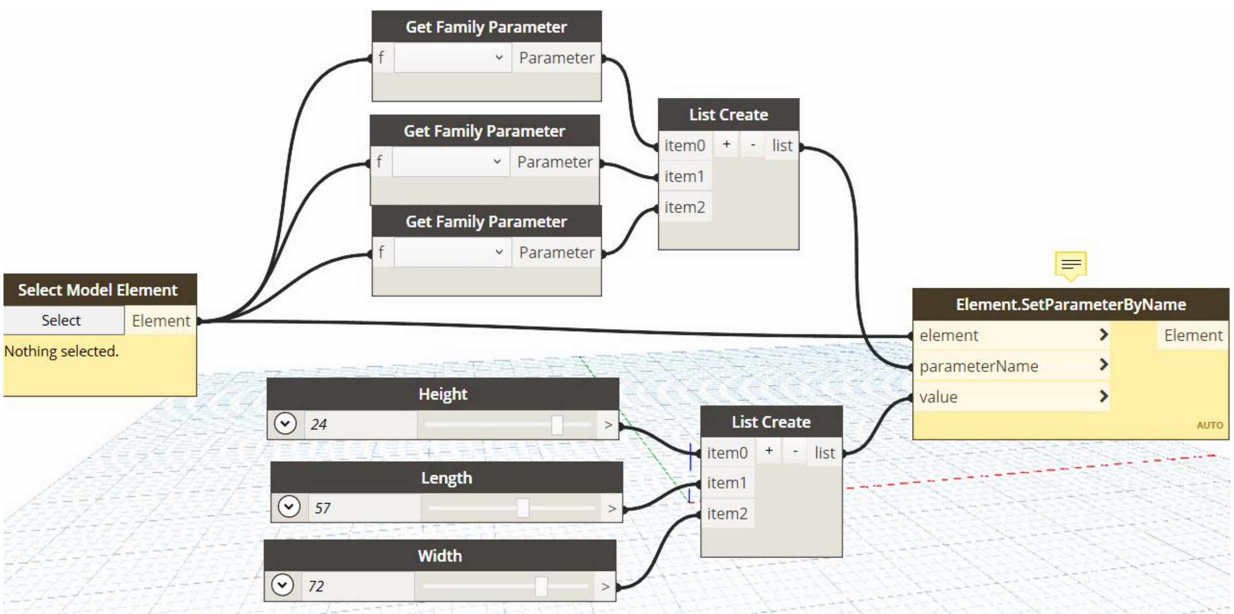

Figure 2. Basic Dynamo© Blocks

The steps taken in Figure 2 are as follows, beginning with the node name:

1. Select Model Element: Place this node, and then select mass by clicking on it in Revit®. A Model Element is a Revit® object that contains a geometric definition and parameters used by the element. This includes walls, windows, doors, roofs, etc. The model element carries physical dimensions and can also have thermal and structural information.

2. Get Family Parameter: This allows the user to select a family parameter from a Revit® model element in a dropdown list. A Family Parameter contains variables such as dimensions or materials.
3. Slider (Height, Length, Width): Set numerical values for the corresponding Family Parameters.
4. List Create: Combine all parameters and values into lists, for a more compact and organized code. Lists are a crucial element of Dynamo©, and function like vectors or matrices in text-based programming.
5. Set Parameter by Name: This node assigns values from the sliders to the Family Parameters selected in the Get Family Parameter nodes. It has three inputs: the element, list of parameter names, and list of parameter values, all which were assembled in steps 1-4.

2 Previous Work

Due to their extremely modular nature, generative design genetic algorithms have been used in a variety of fields, including architecture, automotive, and even immunology. In [9], Catarina Rodrigues Ferreira da Rocha demonstrated a workflow that uses generative design to create a parametric model in a BIM environment. It provided high performing solutions to one variable at a time and did not use MOO. Since only one variable was tested at a time, the process was highly manual and time consuming, and an optimal solution could have been missed.

2.1 Optimo

M. Rahmani Asl took this strategy another step, creating a tool which uses a MOO algorithm to "*investigate a systematic integration of BIM, parametric modeling, and building performance analysis to provide a new workflow that makes the parametric building energy performance study more accessible for innovative energy efficient building design*." [11] His team worked with open source software to create the Dynamo© plugin Optimo that would allow integration of an entire BIM model and energy simulation with the optimization code. They ran a case study that attempted to maximize the number of rooms in a building, satisfy daylighting requirements for LEED IEQ Credit 8.1, and minimize expected energy use. The team later completed a similar project with Optimo and Revit® which optimized daylighting and energy use.

Optimo uses a MOO algorithm called Non-dominated Sorting Genetic Algorithm-II (NSGA-II) to find solutions to problems with conflicting objectives [16], using the Pareto Frontier. The Pareto Frontier is the set of solutions where a single objective cannot be improved without causing a worse outcome in other objectives. Optimo is made up of four main nodes, explained below. The four main code blocks are used in every Optimo application, but custom nodes must be added for analyzing specific functions. These can be as simple as x^2 and (x-2)^2, or it could involve information from models in other programs that work with Dynamo©, such as Revit® or Grasshopper©.

1. Initial Solution List: This is a list of random variables within a user defined range and length. In order to run an efficient study, ranges should be selected reasonably, and some background knowledge of the variable is required. Physical constraints may also affect this range. For example, if the variable is window height, the window obviously can't be taller than the wall, so the range should be limited by wall height. In this way, generative design works hand in hand with genetic algorithms, because some geometric constraints will need to evolve and be constrained by an equation, rather than a constant. This node outputs a list of variables generated by the initial solution and objectives, which are first created as null in this step and assigned a value in the next node. The size of this initial solution is called the population size. A larger size may arrive at more precise results but will also take up more computational power and time.
2. Assign Fitness Function Results: Retrieves a list of objective values and assigns them to the population list. This allows Optimo to work with objective functions that are built into nodes or packages of nodes.
3. Generation Algorithm: Gets the initial solution list in each generation and generates the children solution list through a genetic algorithm. The objectives are set again using the Assign Fitness Function Results node.
4. Sorting: Uses Pareto Frontier sorting to sort the solutions based on their fitness, with the best result first. A solution in a multi-objective optimization problem is considered optimal if no objective can be improved without worsening another.

Optimo was originally built to be used with the Autodesk Green Building Studio, which is a cloud-based platform to evaluate energy and lighting performance in Revit® models. The web application also allows users to edit parameters to modify building energy performance. Making changes this way updates the building performance calculations shown in Insight 360, but not the actual BIM model in Revit®. Performance can be demonstrated in Energy Use Intensity (kWh/m^2/yr,), or $/m^2/year spent on heating, air conditioning, and lighting. Some of the variables include window properties on specific sides of the building, window to wall ratio on all sides, wall and roof construction, infiltration (unintended leaking of air in or out of conditioned spaces), lighting efficiency, daylighting controls (if occupants can control their spaces or not), and operating schedule. Solar panels are also an option, and users can change the efficiency of the panels, payback period limit, and percent of rooftop surface area covered. There is a "model history" tab which gives a summary of how the model changes based on adjusting one parameter. This is useful, however finding an optimal solution one parameter at a time is very time consuming, and some combinations that lead to greater energy efficiency could be missed.

Situations with many conflicting factors affecting greater overall design metrics, like the one described above, are perfect candidates for genetic algorithms. Unfortunately, Optimo's connectivity with Green Building Studio it has since been discontinued and functionality is now focused on a new program called Project Refinery©, which will be explained later in this report.

2.2 Optimization in Developing Countries

Another report, titled "Optimum design of low-cost housing in developing countries using nonsmooth simulation-based optimization" [17] was published in 2018. It documents the design of low-cost housing in developing countries using Particle Swarm Optimization (PSO), as opposed to genetic algorithms. PSO is inspired by the behavior of birds in a flock and schools of fish, focusing more on the interactions between solutions, rather than a single point. This was done with GenOpt, coupled with EnergyPlus for dynamic energy analysis. Three functions were included in the optimization: construction cost, indoor thermal comfort, and 50-year operating cost. These were applied in both naturally ventilated and air-conditioned scenarios. There were 18 building parameters and 6 ventilations strategies considered. The results showed that optimal building strategies for naturally ventilated and air-conditioned scenarios are drastically different, and even sometimes contradictory. Potential for these optimization techniques in energy efficient buildings was shown in improvements to occupant comfort, energy savings, and life cycle costs.

3 Design of Energy-Efficient Buildings

While there are many programs that can calculate nearly everything we need to know about a building, it is still important for architects and engineers to be aware of the factors that affect energy performance. Most energy use in a building comes from heating, cooling, ventilation, and lighting, which are all affected by the heat and light transferred to or generated from within a building. The four types of heat transfer are convection, conduction, thermal radiation, and evaporative cooling. Conduction and thermal radiation have the most prominent effects on modern buildings, but convection and evaporative cooling have some weight as well, especially in some traditional buildings with passive cooling techniques. A New Orleans shotgun house, for example, takes advantage of the humid air in Louisiana that might otherwise cause occupants to be uncomfortable by aligning all rooms in a long building with large open windows to allow fresh air to freely pass through. The entrance is typically facing the closest body of water, and the house is cooled by convection as cooler air rushes into the house, and the humidity brings evaporative cooling in to play as well.

Another traditional method of keeping occupant comfort at its best is building with adobe, or other thick-walled constructions in extreme climates. In regions that experience large variations in temperature, like New Mexico and Arizona, the high heat capacity of thick adobe walls helps regulate the indoor temperature by keeping buildings cooler during the day, and then at night slowly releasing the heat it has absorbed. Windows are typically small and deep set within the thick walls, allowing only indirect sunlight into the building. This type of building relies on insulation to take advantage of conduction and radiation, exactly opposite of how a shotgun house operates. Examples like these demonstrate how sustainable buildings do not have a one-size fits all solution, and the best strategies must account for the location and use of a building.

One of the biggest design decisions in modern energy-efficient building is the glazing, or windows. Depending on the geographic location, northern windows may be preferred over southern, and windows on eastern or western walls may have a more moderate effect on heating and cooling loads. Windows in general offer much less insulation than walls, but they also let in sunlight, and therefore heat. In a cooling dominated system, northern windows may improve performance by letting in light and reducing lighting cost, but not causing excess heat addition to the system by the sun's radiation. Natural light, in addition to cutting lighting costs, has also been proven to improve occupant mood and comfort, and could boost productivity in workplaces. [5] One common way to take advantage of indirect sunlight that illuminates a room but does not overheat it is with window shading. In northern climates where buildings tend to be heating dominated, more direct sunlight is desired, but large windows on all sides would lose a great deal of heat through conduction.

3.1 Energy Efficient Design in Developing Countries

Energy-efficient buildings are particularly important in developing countries. While energy efficiency may only offer a slight economic advantage for homeowners in developed countries, it can account for a significant portion of family spending in other parts of the world. For example, in Managua, the capital of Nicaragua, electricity costs $0.19/kW-hr [18], but the average annual income is only $370 [19]. In comparison, electricity in the US costs an average of $0.12/kw-hr [20] and the average annual income is $46,800 [21]. Additionally, electricity is often simply not available in Nicaragua and other developing countries, so passive heating, cooling, ventilation, and lighting methods may be the only option and should be used to the highest extent possible. The strategies such as thick adobe walls in desert climates or the New Orleans shotgun house were formulated out of necessity before central heating and air conditioning were widely available and could be easily implemented in developing countries with similar climates. While different climates have different building requirements, all can benefit from natural lighting from glazing that is efficiently placed and sized, which was the goal of the simulation run for this report.

3.2 Project Refinery©

While Optimo, the Dynamo© plug-in by M. Rahmani Asl is highly customizable, it is still not very user friendly. This is where Project Refinery©, a new plug-in for Revit® has advantages. Originally released in July 2016 as Project Fractal, Project Refinery© came out in November 2018 and features advanced features and improved stability from the original program. It is a beta project working to advance the possibilities of generative design in architecture, engineering, and construction. One of the most important updates is the ability to run custom Python nodes within Refinery©, which allows users nearly infinite customizability.

4 Methods

4.1 Refinery

A simple analysis was conducted to demonstrate some basic functions in Project Refinery©. Although this study could be performed without Refinery©, it is presented here to clarify how the program is used. Three rectangles drawn in Dynamo© represented the outer walls of a building. For the purpose of this study, Cube 1 (C1) had a fixed location, but varied in height. C2 and C3 were varied in both location and height. With these options, Refinery© was used to find the maximum volume which corresponds with the minimum surface area. This could be useful to any building with project specific restrictions, as surface area to volume ratio has a significant effect on heating/cooling loads, depending on the environment. One could rearrange or display other variables used in a study by selecting another variable from the dropdown menus, shown in Figure 3. The resulting plot, Figure 4, shows the relationship between four variables: total surface area, total volume, height of C1, and height of C2. Users can demonstrate the effect of up to four variables at once by using the X and Y-Axes as well as colors and sizes of data points. There is not a specific scale provided for the colors and sizes, so this only serves to visually demonstrate correlation or lack thereof. Larger numbers are represented by larger circles, and smaller circles are smaller numbers. Variables demonstrated by color are shown in blue when they are large, going through the color spectrum from green to yellow, then orange and red for smaller numbers.

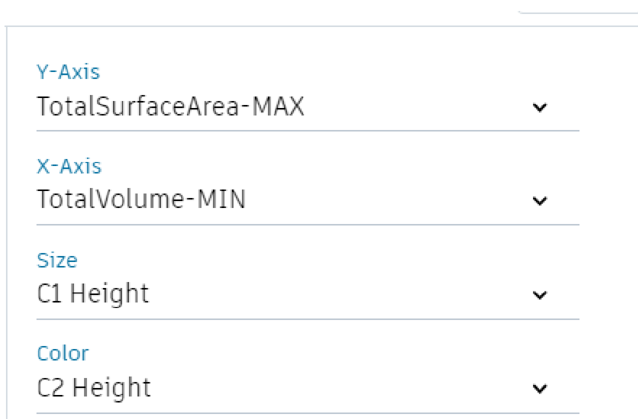

Figure 3. Plotting Options

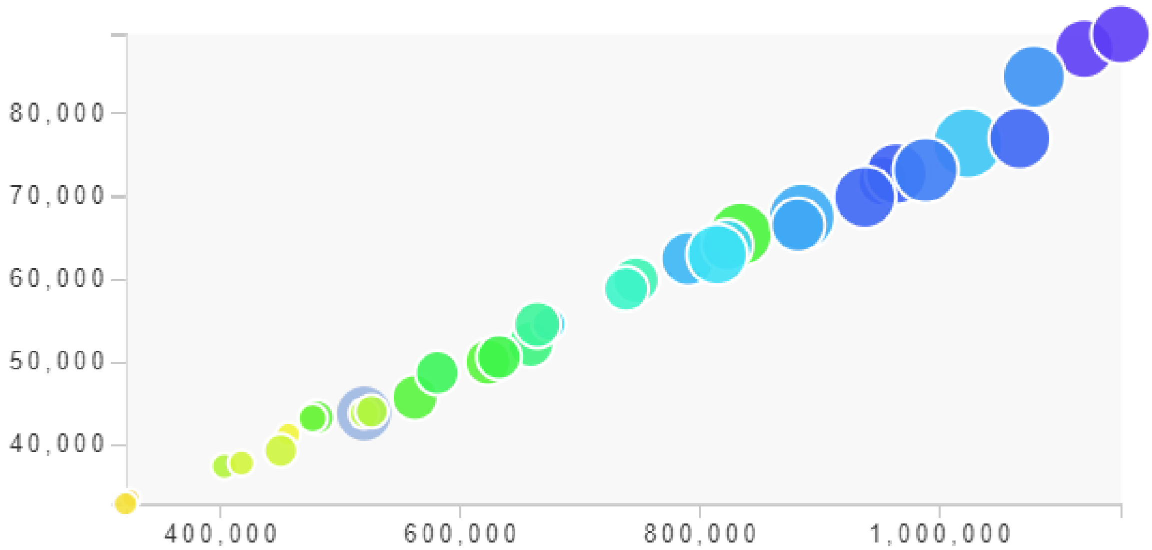

Figure 4. Data points on X and Y-Axes shown with colors and point sizes representing additional variables

In this case, there was a correlation between the total surface area on the Y-axis and the volume on the X-axis as shown by the data points increasing along both axes. The C1 height values are shown by the size, and C2 height shown by the color of the data points. These points show that increasing the height also increases the volume and surface area of the building. Refinery© has several options to view results and help users come to a conclusion about their data. A visualization of the best performing solutions is also generated with this study in Project Refinery©, shown in Figure 5. Users can choose between this view, which shows the shape and size of C1, C2, and C3 as they would be built, and the numerical solutions in Figure 4, which are helpful showing trends and relationships between different variables.

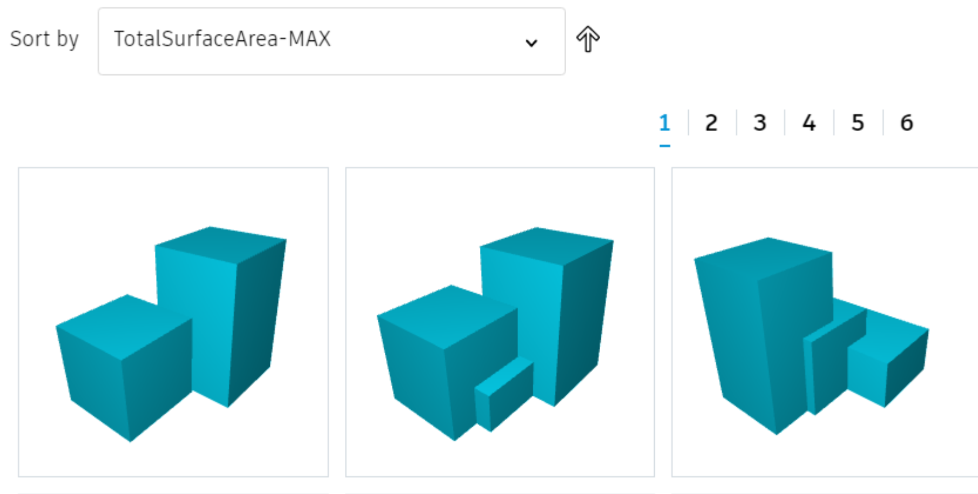

Figure 5. Visualization of Solutions

Figure 6 is from the same study, but instead of a visualization of a few top performing solutions, this shows numerical values of the user defined variables, as well as the outputs (Total Surface Area and Total Volume)

TotalSurfaceArea-MAX	TotalVolume-MIN	C3 X-Location	C2 Y-Location	C2 X-Location	C1 Height
36610.859	343791.282	23.933	36.034	26.470	83.225
36636.722	346111.412	24.132	35.597	14.410	79.989
36864.683	361953.498	34.020	30.820	27.865	31.725
38362.654	370546.978	23.302	36.634	38.870	78.156
38645.061	397119.397	31.666	27.382	12.620	89.075
40778.652	401969.118	23.840	36.187	38.904	92.632

Figure 6. Numerical Description of Solutions

These studies can be conceptually useful, but they use simple geometry created in Dynamo©, not actual Revit® geometry. The final goal was to create Revit® geometry that could be modified by Dynamo©, and then perform a daylighting analysis with Honeybee©. Rhythm, a package for Dynamo©, was used for its ability to set Revit®

Parameters (in this case, window dimensions) of a model element (the window) by name. Honeybee© also requires an additional package called Radiance© to run this code, which was installed. With all components downloaded and installed correctly, the daylighting analysis produced a grid within the building, color coded in a gradient based on the percentage of lux from outdoor light which reaches each square, also known as a Daylight Factor. This model used the CIE (Commission Internationale d'Eclairage - International Commission on Illumination) Overcast Sky, which does not include direct light from the sun. This means that it can be characterized with just the diffuse horizontal illuminance, which is set to 10,000 lux in the source code of Honeybee©. [22] In effect, the model is run at full daylight with a bright, overcast sky but no direct sunlight. Because of this, the orientation and location of the building are not necessary. This is a simplification, however stability issues in Dynamo© with weather files made analysis with a specific location and orientation impossible. [23] Daylight factors are also significantly simpler to calculate than actual lux based on a sky model, making this strategy more appropriate for genetic algorithms performed on a personal computer with relatively low computational power.

In order to apply genetic algorithms to this daylighting analysis, first a simple building with windows was created in Revit®. The Dynamo© sample code for Honeybee© was modified so that the user could change the height, width, and vertical position of the windows via slider in Dynamo©. These variables were set as inputs in Refinery©. An example from this part of the code can be seen in Figure 7, where a parameter, "Width" is set to 1500mm. Units in Dynamo correspond to what the user has selected in Revit. Millimeters were used throughout this report.

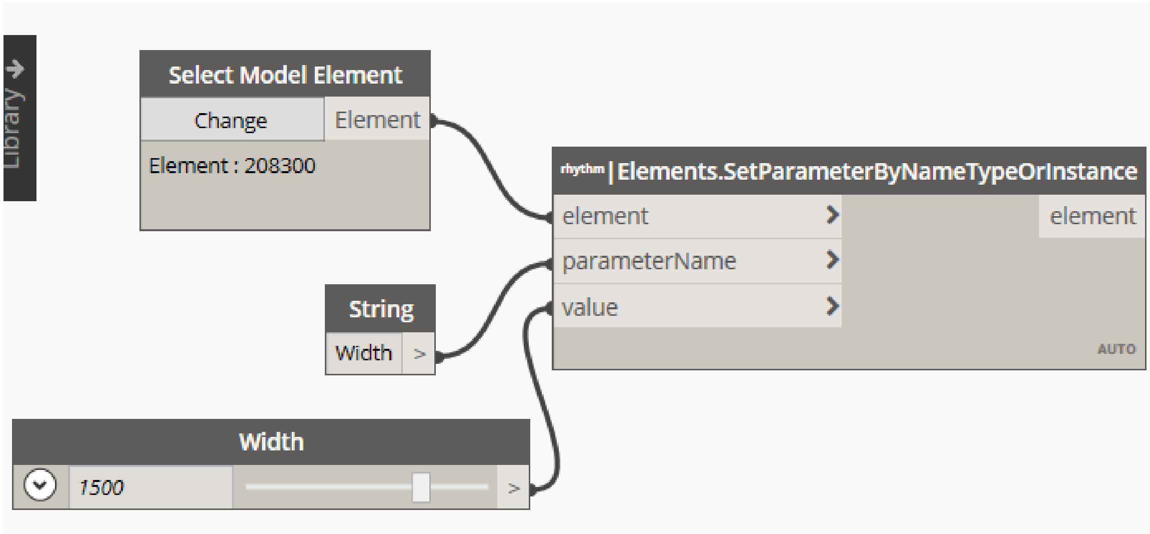

Figure 7. Setting parameters by name

Results from the lighting analysis were then used as an objective in Project Refinery© to design a building with maximum spaces lit naturally to an acceptable level, while keeping the area of the windows as small as possible to minimize heating and cooling costs in extreme climates. This was done with a code that counted the number of grid points with a daylight factor above 2% and setting the result of this count as an output to be maximized by Refinery©. This value was chosen because BREEAM (Building Research Establishment Environmental Assessment Method), a sustainability code similar to LEED, requires a 2% daylight factor in most spaces. [24]

4.2 Dynamo

When this project was begun, it was expected to use Dynamo© with the Optimo plugin, and another plugin called Energy Analysis for Dynamo©. However, Energy Analysis also worked with Green Building Studio in the cloud to compute energy use and stopped working after updates were made to both Dynamo© and Energy Analysis. On the advice of an Autodesk representative on the Dynamo© forums, the strategy changed to use the newly released Project Refinery© and Honeybee© instead of Optimo and Green

Building Studio, for optimization and energy use computation, respectively. More progress was made on this route, with a narrowed focus on natural lighting and ventilation. A Dynamo© script for grid-based daylight factor analysis was modified to allow a user to change the geometry of the windows in a simple building in Revit® using Type parameters. Code was added to count the number of grid spaces above a certain level of natural lighting. Window height and width were then set as an input, and the number of low light grid spaces and total area of the windows were set as the output in Refinery©. Minimizing the window area while maximizing grids with acceptable lighting would lower electricity costs and make the building more thermally efficient due to lower insulation values in windows than walls, especially in cold climates like Minnesota and Michigan, where the building would hypothetically be placed. It would also help in hot climates, where excessive glazing could cause a building to perform like a greenhouse and become uncomfortably hot. Several plugins for Dynamo© including Rhythm for accessing Revit® Type Parameters, and Radiance, which runs the lighting analysis for Honeybee© were installed, and the simulation ran as expected.

5 Results

The initial values for window height and width were set very high at 1500mm and 1000 mm, for demonstration purposes. The window parameters to reflect and produced the expected window dimensions in the Revit® models shown in Figure 8, and a nice visualization, shown in Figure 9. The dark blue squares in Figure 9 represent areas that have low levels of natural lighting, and the red squares have the highest levels, as shown in the legend. The lighting simulation appears to be successful, as the spaces closet to the windows are red and yellow, and the space in the middle of the room where less natural light would reach is shown in blue. A counter showed that 231of the 432 grid spaces had a daylight factor of 2% or higher. The goal was to maximize the number of these squares with a 2% or higher daylight factor, while keeping the total window area as small as possible.

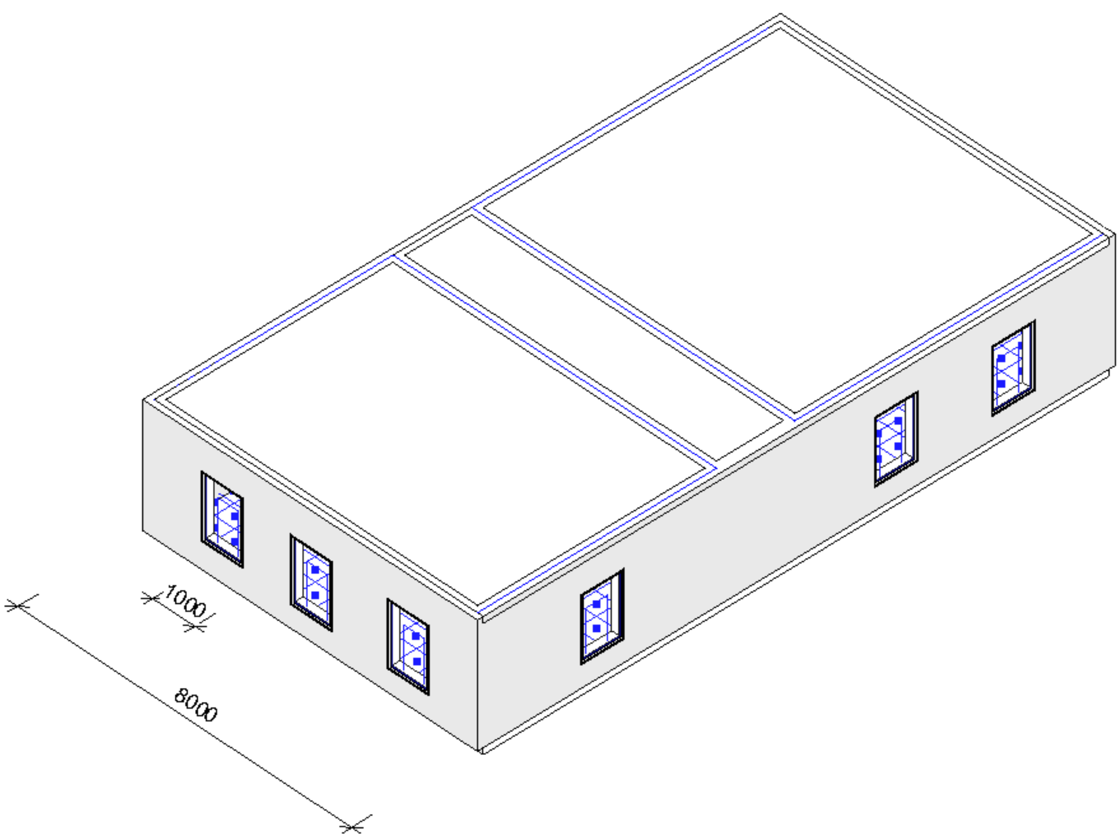

Figure 8. Revit® Model with 1m x 1.5m Windows

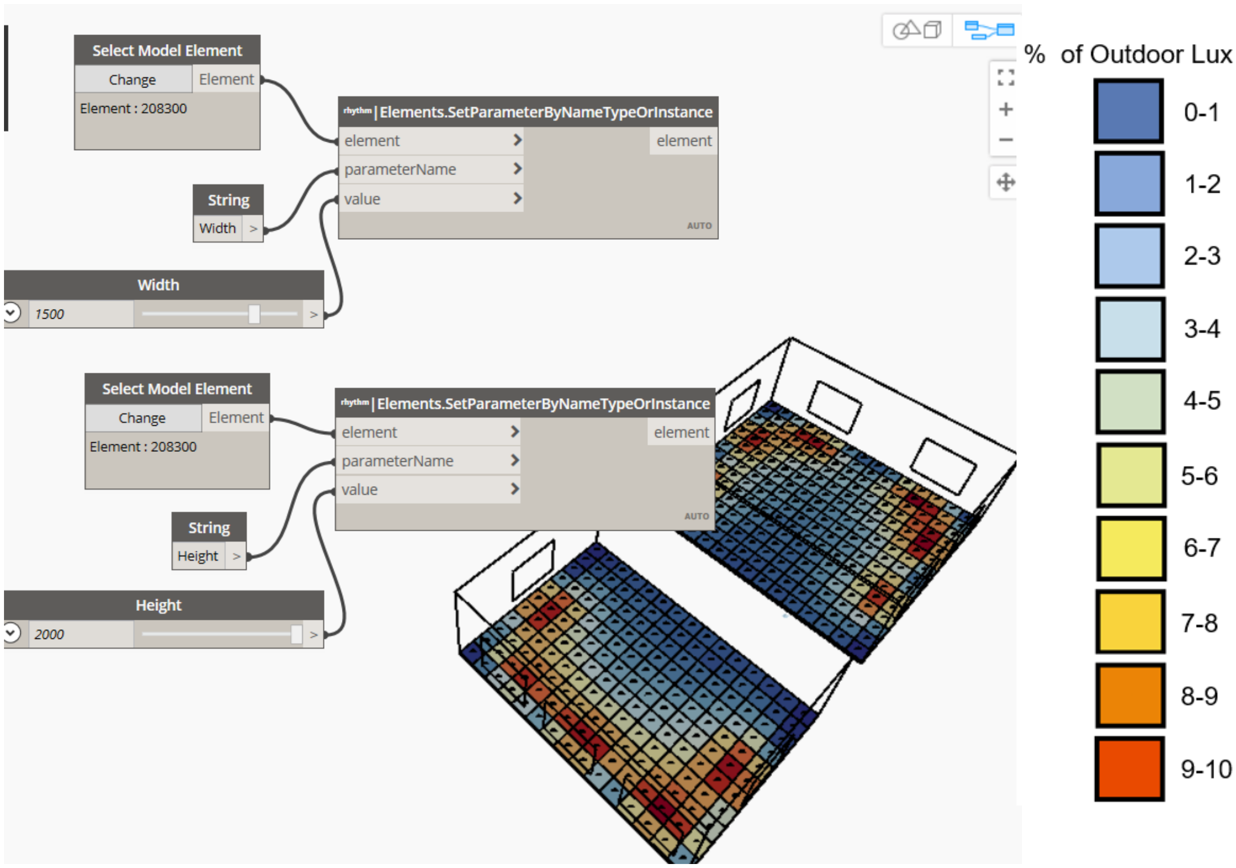

Figure 9. Simulation Results with 1m x 1.5m Windows

In the next step, the window height and width were set in Dynamo to 1000mm and 500mm, respectively. The change can be seen in the Revit® model (Figure 10), but the lighting simulation did not run again with the rest of the code. (Figure 11).

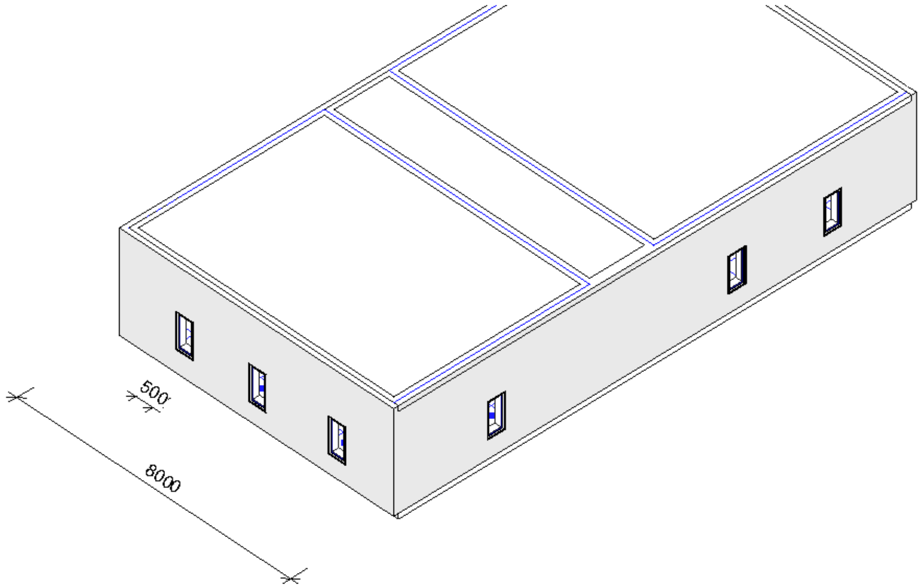

Figure 10. Revit® Model with 1m x 0.5m Windows

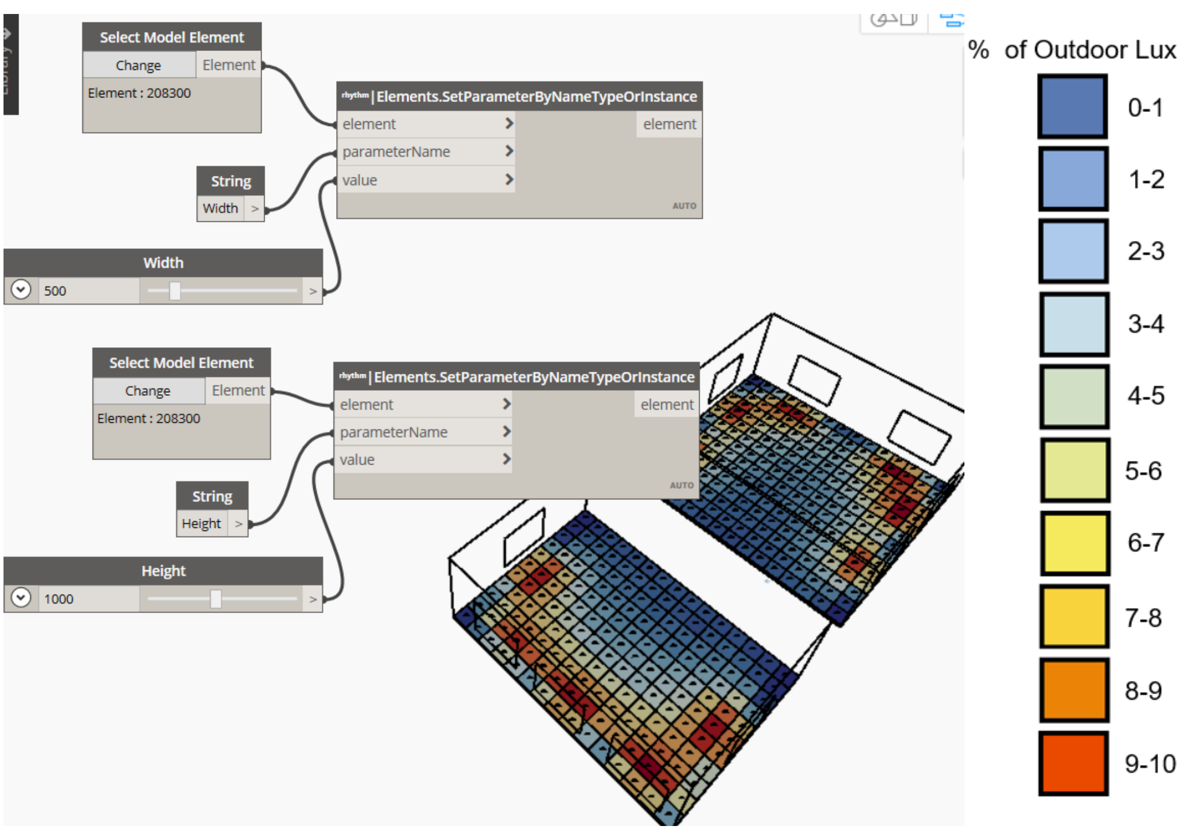

Figure 11. Lighting Simulation does not change from “1.5m x 1m Window” results

The simulation would, however, run as expected and reflect the change in window height and width when Dynamo© was closed and opened again. The results can be seen in Figure 12, where the color-coded grid shows less well-lit squares, corresponding to the smaller window size. The output was 56 grid spaces with a daylight factor above 2%. The simulation was also run with 0.5m x 0.5m windows, which resulted in 24 grid spaces at or above the desired daylight factor.

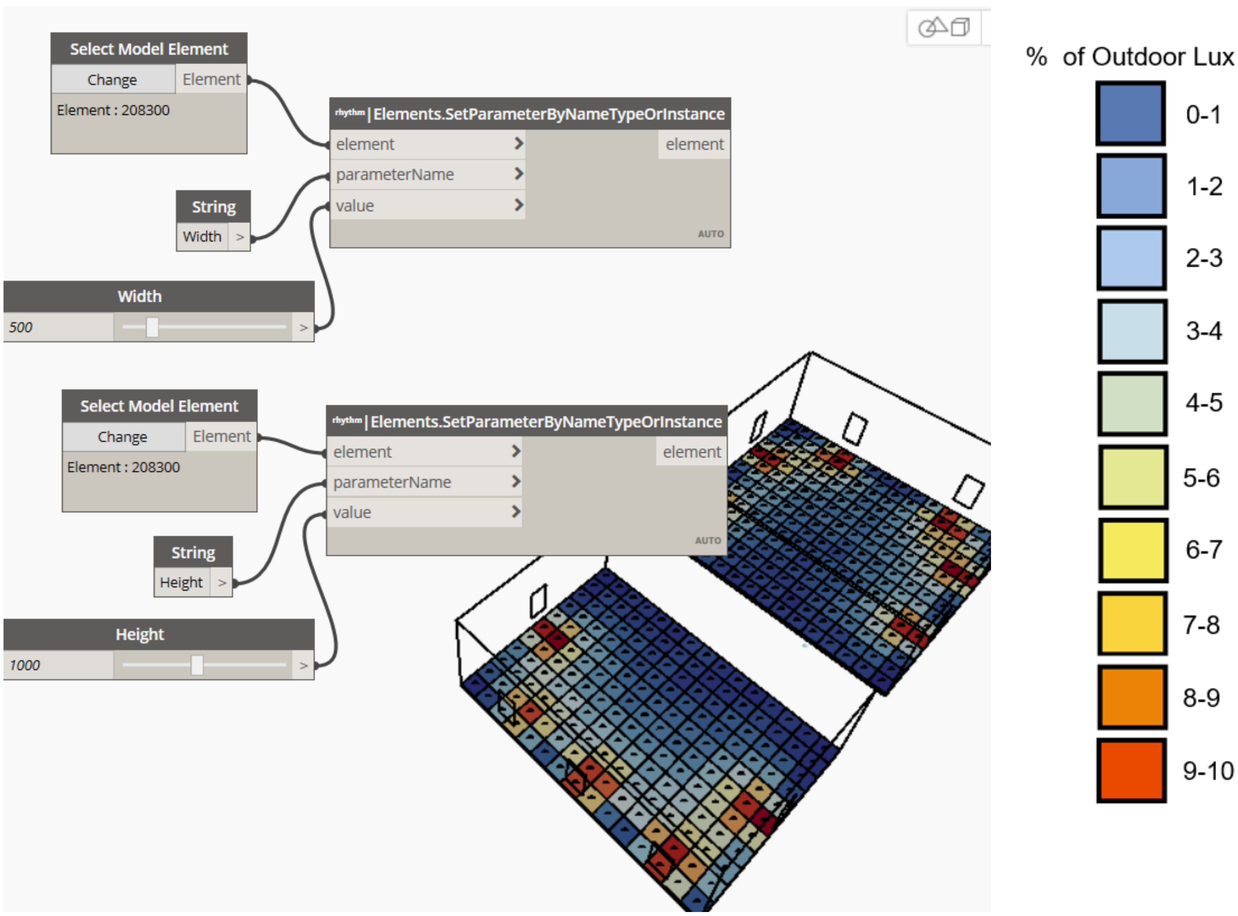

Figure 12. Lighting simulation reflects smaller window size after restarting Dynamo©

The lighting simulation would never run twice to update changes made in Dynamo© without closing and reopening, even with different buildings or using the code from an example file to simply run a lighting analysis, without the changes made for this report. Ideally, this program would be run repeatedly by Refinery to find the optimal window dimensions for this building, but it is not useful if Revit must be manually opened and closed between each iteration. There is great potential to using these three programs together, if the developers could make Honeybee© for Dynamo© more robust, and it could be a useful tool in industry or for students if it were offered in a polished package that could be downloaded as one streamlined program, making sure the entire analysis can be run reliably. Honeybee© and Ladybug have made great progress with Dynamo©, but it would be in users' best interest to have one stable package released with all necessary plugins, but still allow changes to be made to a flexible beta version of the software.

6 Conclusion

This process is demonstrated with window sizing but can be applied to any family parameter within any Revit® building model. Although it is cumbersome for the design of just one building, the advantage is that once set up, it can run a similar analysis to find top performing solutions in other aspects of building design. This modular approach which allows design decisions to be made early in the process is the core of generative design.

Some of the beauty of collaborative, open source software is also its greatest setback. Many of the programs and plugins used in this report are still in beta releases, and sometimes when updates come out for one, it causes compatibility issues. The workflow discussed in this report reaches will reach its full potential when a balance is found between flexibility and robustness of a system. It is useful to have access to code and plugins written by researchers all over the world, but it is highly difficult to keep all the necessary components working together smoothly without a governing body to ensure all components are compatible in each release. This report found that genetic algorithms in energy efficient buildings are a potentially useful design tool, but also indicates that a more polished and robust program needs to be released before this technology can offer real results. Revit® 2020 was recently released with Refinery built in, and the developers working on Honeybee© are currently working on a release which will also be integrated directly in Revit®, so this will soon be a reality.

7 Future Work

Many of the programs and plugins discussed in this report could be useful to a wide range of people if produced in an integrated package of lighting and energy analysis along with optimization components which would only be updated in unison. Since this process uses mainly open source add-ons to an industry standard software, it would be particularly useful to smaller companies and startups with lower spending power and more flexible design processes. As of now, Dynamo© is quite difficult to use with Honeybee© without an extensive knowledge of both programs and ability to write in Python when issues arise due to incompatibility between updates. It would also be interesting to see a genetic algorithm component written into a user-friendly version of Ladybug and Honeybee©. In a less demanding endeavor, Honeybee© code could be improved to allow for more stable analysis without having to restart Dynamo© every time. This would allow users and researchers to use genetic algorithms on their own to find optimal solutions to the multifaceted design problems they are faced with in sustainable building design.

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