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Performance Driven Design

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Abstract

There is an increased demand for designing more sustainable buildings. So, building performances become a driving force behind design decisions in the early stages. The goal of the research is to test how does the topological structure of architectural form for freeform buildings affect the daylighting and energy performance in parallel to the glazing ratio in the early design stage. The method of topological optimization of a building form is to adjust and modify the overall composition of the shape, and the glazing ratio to enhance the environmental performances of the building. Thus, to achieve the goal of energy savings. The aim is to prove that building geometry does not only determine the function and aesthetics of the building but also has a great impact on the energy and daylighting performance which will determine the overall thermal comfort of the user. The research follows an approach which takes a benchmark building the absolute tower by MAD architects and performs optimization using independent design variables. In order to test how geometry affects the environmental performance of the building.

Keywords: Optimization, Energy performance, Daylight, Radiation, Computational tools, Parametric design, Climate, Topological structure, Freeform, Comfort, Design variables

1. Introduction

With the increased demand for urbanization there is an increase in energy consumption. Because of the environmental crisis there is a growing interest and demand for more sustainable buildings. Built environments affect both indoor and outdoor comfort. This has led architects and engineers to be more energy conscious and aim towards a more sustainable and ecofriendly approach in their design. The aim is to decrease the energy consumption but keeping the users comfort satisfied. Most building authorities in many countries have started implementing new rules which require the building to be built more energy consciously and comply with energy efficiency certificates and certifications like LEED, BREEAM etc.

During the past it was hard for engineers or designers to estimate the energy consumption of a building in the early design stages. Today, with the continuous advancement in computation tools designers and engineers can evaluate building performances at any stage of the design process; however, these simulation technologies are not adopted and implemented as needed due to their complexity and time consuming. During this research, the use of Honeybee and Ladybug for daylight simulations and Energy+ for energy simulations while Galapagos and Biomorpher are adopted and used for optimization purposes.

Most of the design decisions are made during the initial stage of design, that is why there is a great potential to maximize the efficiency of the building if designers made rough environmental analysis during this stage (Miles, Sisk, & Moore, 2001). Thus, it is important to optimize the design process and define the right fitness and the right objectives to increase the efficiency of the optimized design options.

Due to the time constraint, the study focused on an existing building that falls under the freeform category. Rebuilding the geometry parametrically then identifying different parameters to study the building performance and apply different optimization. The objective of this study is to create a tool with the use of advanced computational aids, to find out the most optimal solution from the generated pool of geometry which will in terms reduce the overall energy consumption and increase the performance of the building.

2. Literature Overview

The number of building performance optimization papers has increased significantly in recent years.

- 38% of the reviewed work focused on the optimization of building envelop
- 21% focused on building form
- 17% focused on HVAC systems
- 16% focused on renewable energy generation
- and the others focused on controls and lighting strategies (Evins, 2013)

The common objectives to be optimized are energy found in 60% of the studies, and the other common objectives are cost, daylight performance, comfort, and CO2 emission, etc. Most of the precedent studies that performed building performance optimization usually used fixed building form while the variables to be optimized were limited to the building systems or the properties of the materials. Very few studies who used radiation as a strategy to optimize a building shape. Thus, there are minimal studies oriented towards combining building form, radiation optimization, energy optimization and daylighting optimization (Fang,2017).

3. Methodology

The primary goal of the research is to test the impact of geometry on the building performances ensuring the users comfort by having enough daylighting and minimizing the energy consumption especially during the heating period.

The approach taken to test the hypothesis was to take an existing building, use it as a benchmark to extract the different parameters that could affect the overall performance of the building.

First, importing the context as per the location of the building, and understanding the climate by analyzing the weather data to identify what is beneficial and what is harmful and at what time of the year.

Second, was to apply different simulations including radiation, energy and daylighting for the benchmark building so that the results can be compared later to the optimized result options.

Third, selecting three different geometries as an initial study to understand the impact of geometry and later when adding the parameters (Floor Rotation, Cantilever Overhang, Global Rotation) and applying them to the optimization how will it affect the building performance.

Fourth, introducing the independent variables to the proposed geometry and applying a radiation optimization using different engines like Galapagos and Biomorpher. The aim is to maximize the radiation during the heating period and minimize it during the cooling period. In addition to applying an optimization for the energy consumption focusing on minimizing the heating energy.

Fifth, evaluating the results whether they meet the expectations or not and then doing the comparison between the benchmark building and the optimized result options, as shown in Fig (1).

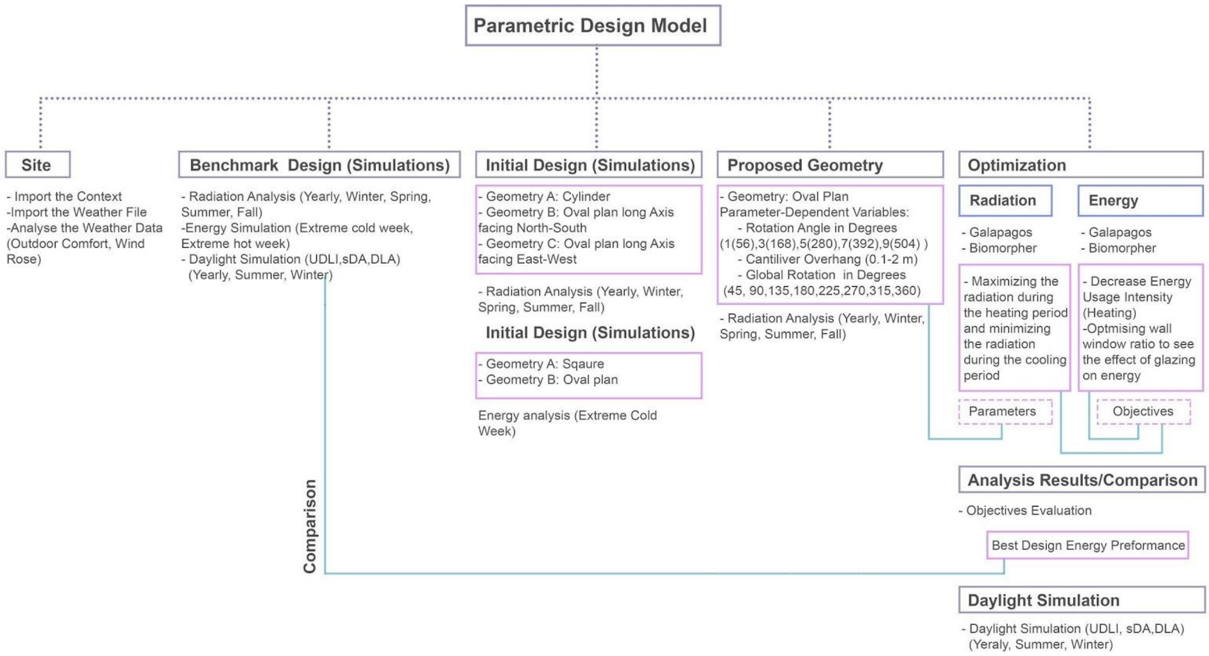


Figure 1: Design process

2.1. Building Selection

As a benchmark, the Absolute tower by MAD Architects Fig(2), a residential tower, located in Toronto, Canada was selected for the study and the optimization purposes; because of its topological structure and it's ease to apply different parameters to change the environmental performance of the building.

The site comprises two towers one of which has 56 floors (h. 170 m) and the other one 50 floors (h. 150 m). The chosen tower is the one with the highest number of floors (56) while the other one was used as a shading context. The skyscraper has a continuous platform cantilevered out from the façade around the entire structure creating a set of balconies. The structure takes a different rotation angle at each level to provide a 360 view to each of its units.

Figure 2: Absolute tower by MAD Architects [www.urbanismo.com]

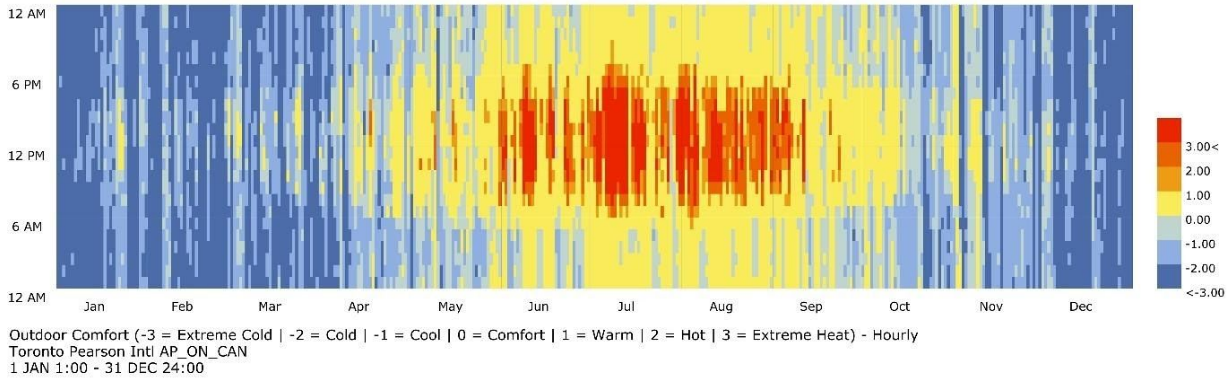
2.2. Site

Toronto, Canada experiences a continental climate (Köppen climate classification Dfa). The winters are extremely cold and long and summers are short, warm, and humid. The site context and Weather file is imported using plugins for grasshopper in Rhino such as Elm for context and Ladybug for weather file. Further, data like Dry bulb temperature, outdoor comfort, wind etc. are studied.

2.2.1. Outdoor Comfort Analysis

An outdoor comfort study was conducted to further understand the weather and the climate in Toronto. The percent of cold stress is 7 times more than the percent of heat stress, that means the energy used for heating is much more than the one needed for cooling. That would be the key reason why it is mandatory to optimize the building having the objective of minimizing the energy usage during the heating period.

Percent of Time Comfortable (9°-26°): 28.41%
Percent Comfort for Short Period (0°-9) and (26°-28°): 19.13%
Percent Heat Stress: 6.48%
Percent Cold Stress: 45.62%
Total Comfort: 47.55%   Fig (3)



Outdoor Comfort (-3 = Extreme Cold | -2 = Cold | -1 = Cool | 0 = Comfort | 1 = Warm | 2 = Hot | 3 = Extreme Heat) - Hourly
Toronto Pearson Intl AP_ON_CAN
1 JAN 1:00 - 31 DEC 24:00

Figure 3: Outdoor Comfort Study UTCI no Protection: Exposed to wind and sun

2.2.2. Wind Analysis

According to the wind rose analysis the highest wind pressure is mainly during the winter and they are coming from the west and west-south Fig (4). Decreasing the comfort zone and increasing the percent of cold stress.

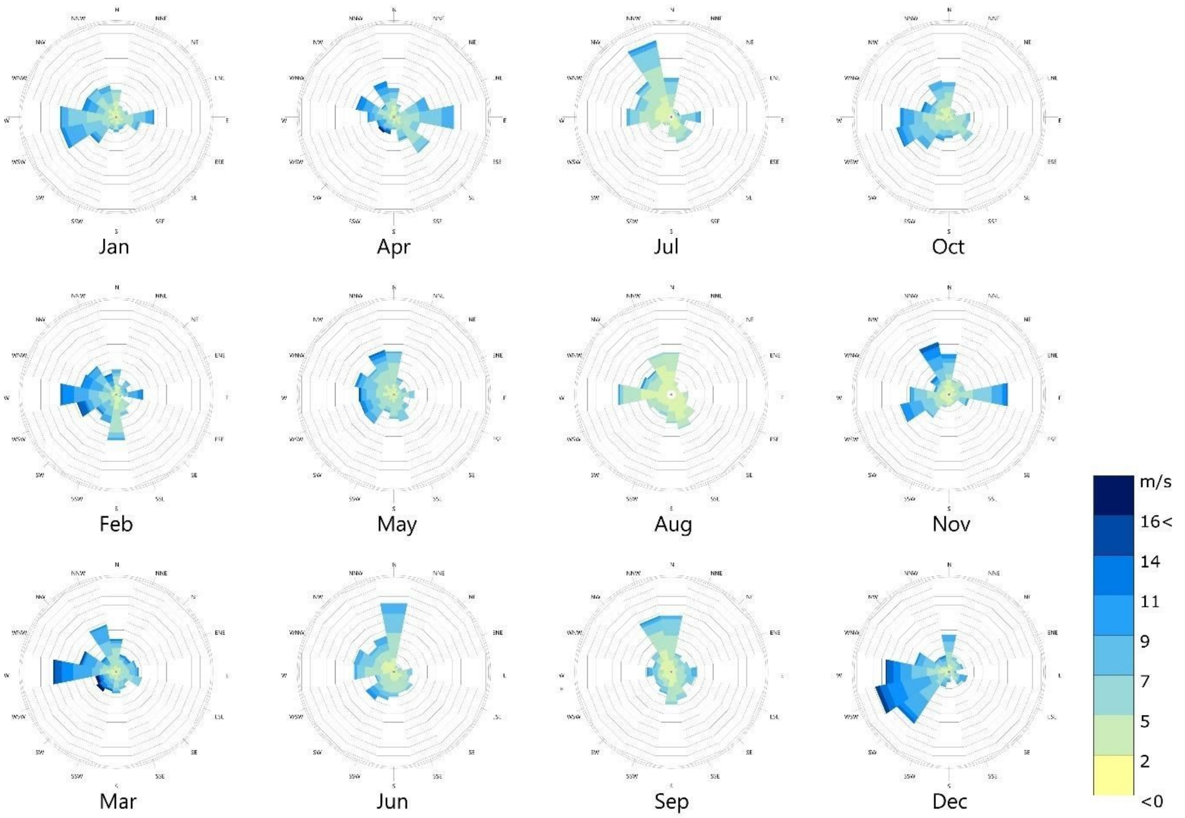


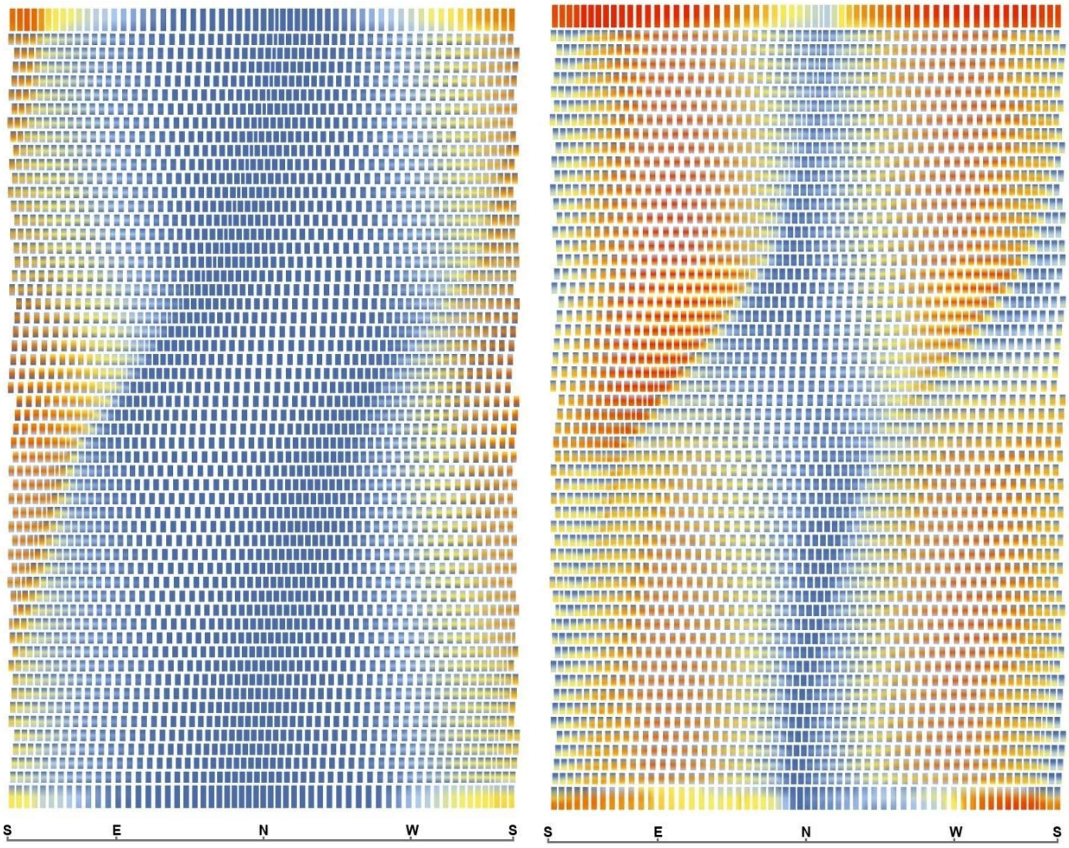
Figure 4: Wind Rose

2.3. Benchmark design simulations

2.3.1. Radiation Analysis

It is beneficial to conduct a radiation analysis in the early analysis steps to detect the harmful radiation during the cooling period and the beneficial radiation during the heating period, including the time of the year it occurs. The panels get squeezed in the peak of the rotation angle toward a specific orientation. So, it can be used as a strategy to maximize the number of panels towards where they can get the most radiation in winter.

A radiation analysis is conducted for the Absolute tower, further referred to as benchmark design, for analysis periods such as Winter and Summer Fig (5).



Radiation in Winter: 1.816 kWh

Radiation in Summer: 3.440 kWh

Figure 5: a.Radiation in Winter, b.Radiation in Summer.

2.3.2. Energy Analysis

Energy analysis is conducted for the benchmark design, for analysis periods of extreme cold week (Fig 6.a) and extreme hot week (Fig 6.b).

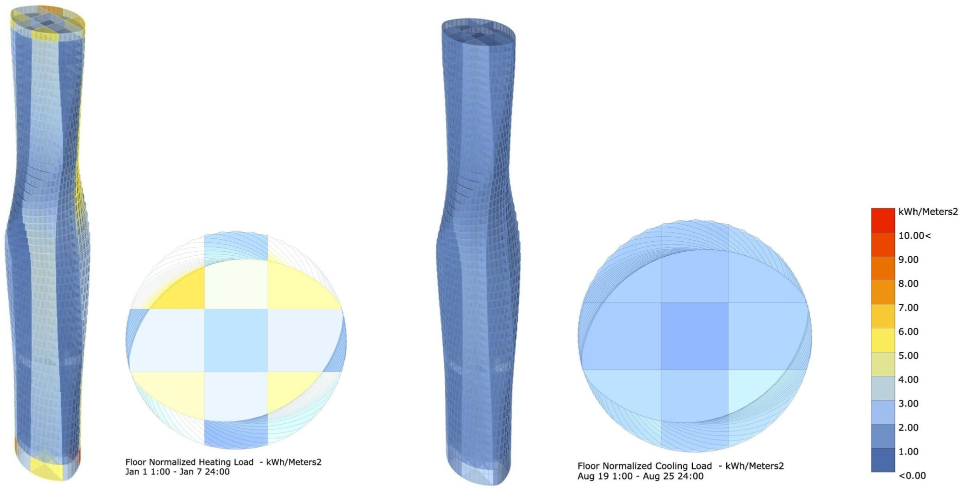


Figure 6: Total floor normalized heating load in a. extreme cold week, b. extreme hot week.

2.3.3. Daylight Analysis

Having good daylight performance is proven to be in correlation with the comfort and the productivity of the user. Researches on the effect of daylight on the occupants found that having enough daylight increases the productivity and financial savings, reduces Absenteeism in the Office and turnover (Edwards and Torcellini, 2002). The measures say that 15% of absenteeism was decreased in the Lockheed Martin company when they moved some of their employees to a building that receives sufficient daylight in 1983 (Romm and Browning 1994). One of the major benefits is the energy savings, it is found that artificial lighting systems consume about 25% to 40% of the total energy of a building The optimal alternative is the daylighting that can save part of this energy by having sensors that detects the level of the daylight to switch off or on the artificial lighting accordingly.

A daylight simulation is conducted in order to understand the daylight performance of the absolute tower where UDLI (Useful Daylight Illuminance), sDA (spatial daylight autonomy) and DLA (Direct Light Access) are studied for an analysis period of Yearly, Summer and Winter.

Daylight Autonomy (DLA) is the percentage of time during the active occupancy hours that the test points receive more daylight than the illuminance threshold. DLA is a dynamic daylighting metric which is based on time series of illuminance that are based on annual solar radiation (Reinhart, Mardaljevic, & Rogers, 2006). According to the international recommendations at least 40% of the yearly daylight the building receives should be useful. The typical floor of the Absolute Tower receives a minimum daylight of 57% and the maximum is 69% during winter. The percent of the daylight in each floor is differing in this case between 1.5% to 12% which means that the form of the building has an impact on the building performances Fig (7).

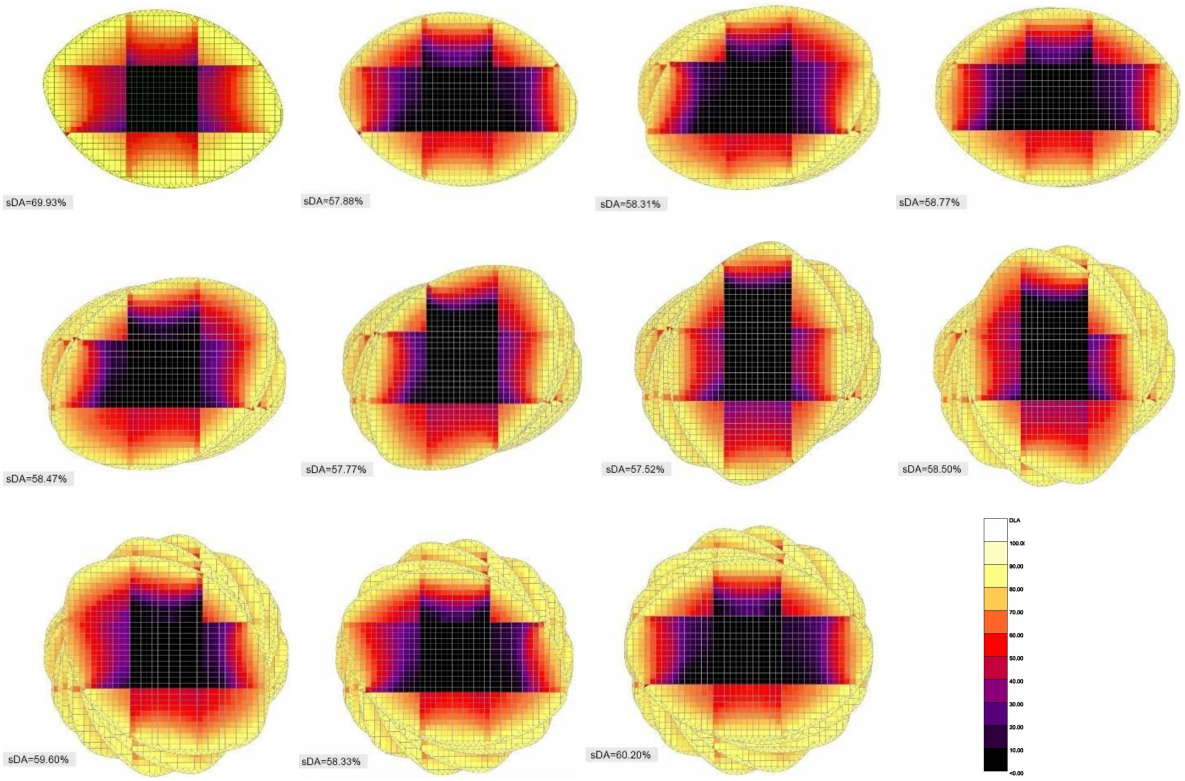


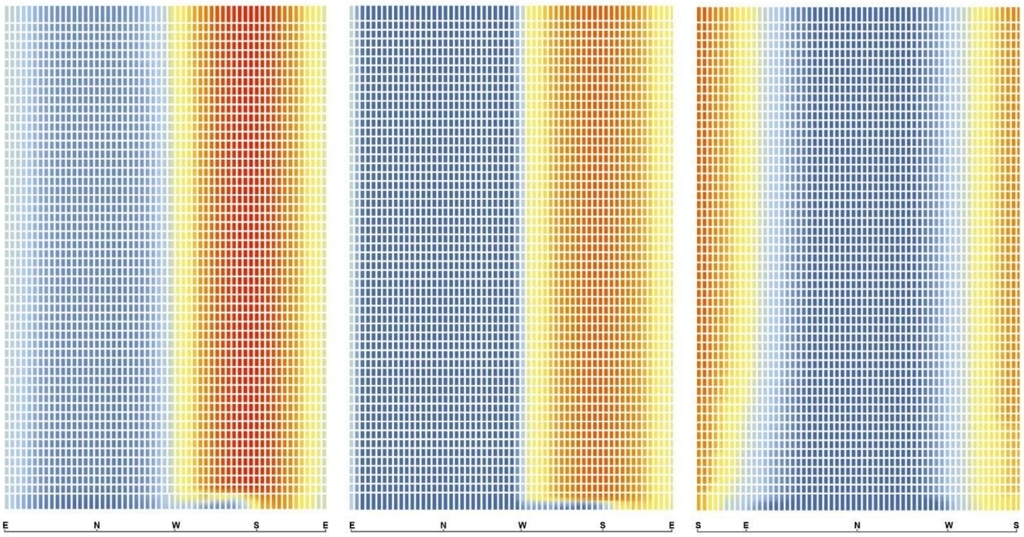
Figure 7: Daylight Autonomy in Winter

Typical Floor Plans: Level 0, Level 5, Level 10, Level 17, Level 20, Level 25, Level 29, Level 32, Level 36, Level 39, Level 45, Level 51

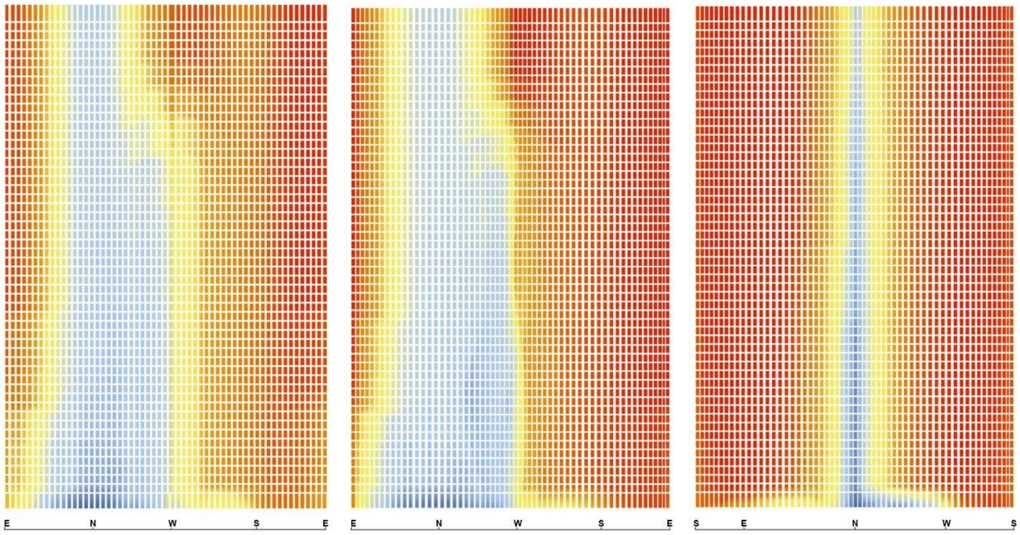
5. Initial Design Study

5.1. Radiation Analysis

As an initial step of understanding the geometry and its impact on the performance of the building, three different forms with the same area were selected for the study named a). Circular plan, b). Oval plan orienting the long axis to face East-West direction, and c). The same oval plan oriented in the North-South direction. A radiation analysis was conducted for the three forms for two different seasons Fig (8). Geometry C receives the most radiation in summer because of its elongated façade that is oriented to the south and has the least radiation in winter. Thus, geometry C is eliminated from the study because it is not working for Toronto's Climate as the building needs to receive the maximum radiation in winter and a minimum radiation in summer. While geometry A and B receives almost the same radiation in summer but with B receiving more radiation in winter.



a). Radiation in Winter: 2.649 kWh b). Radiation in Winter: 2.882 kWh c). Radiation in Winter: 2.623 kWh



a). Radiation in Summer: 4.915 kWh b). Radiation in Summer: 4.939 kWh c). Radiation in Summer: 5.845 kWh

Figure 8: Winter and Summer Radiation Panel Plot for a.Circular plan, b.Oval Plan facing East-West, c. Oval Plan facing South-North.

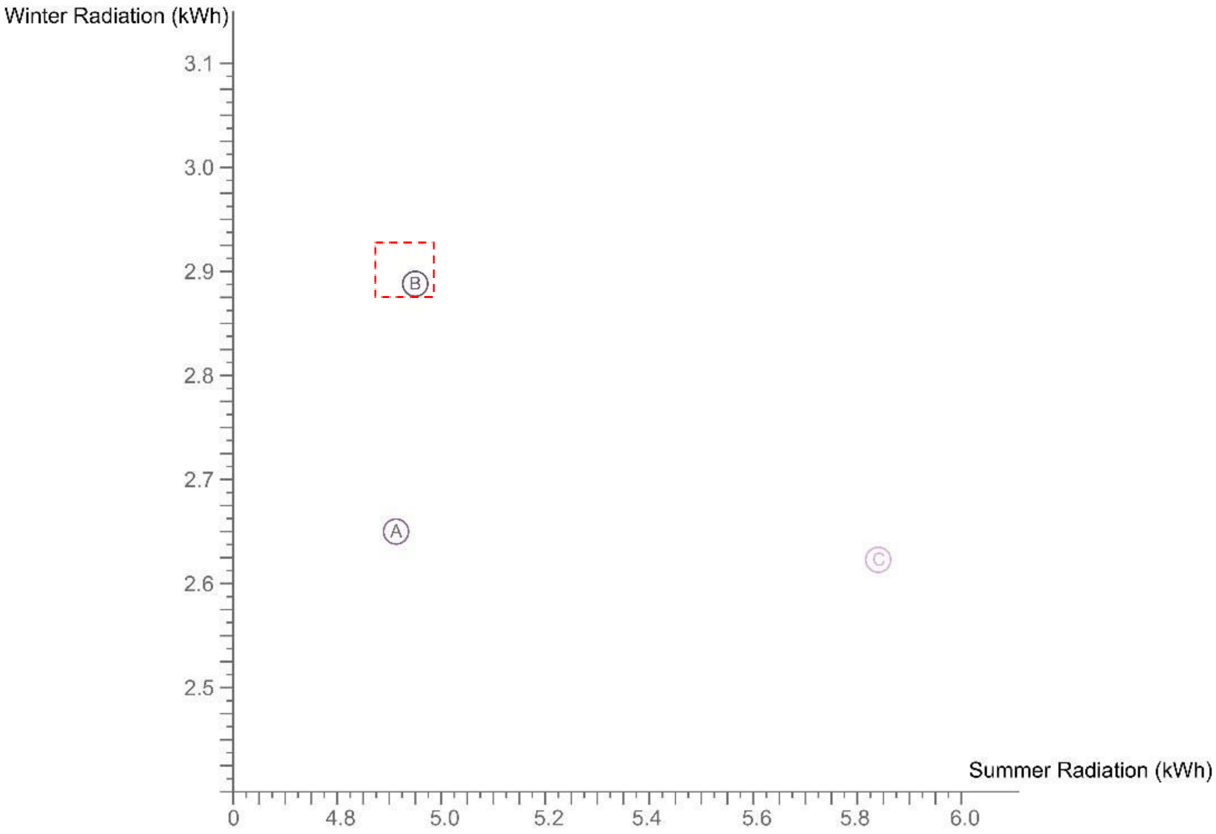


Figure 9: Radiation Analysis Comparison for 3 Geometries

5.2. Energy Analysis

Further, to study the energy performance, two geometries with different forms with the same area were considered namely, building with

a). Square plan,

b). Square plan rotated,

c). Oval plan and

d) Oval plan rotated (Fig 10).

As winter is the longest season in Toronto, lasting from November till April, in order to reduce the computational time for the form optimisation further in the study, only the coldest week is considered as the analysis period. Graph 10e below shows the heating load requirement of different forms in peak winter (Fig 10. e).

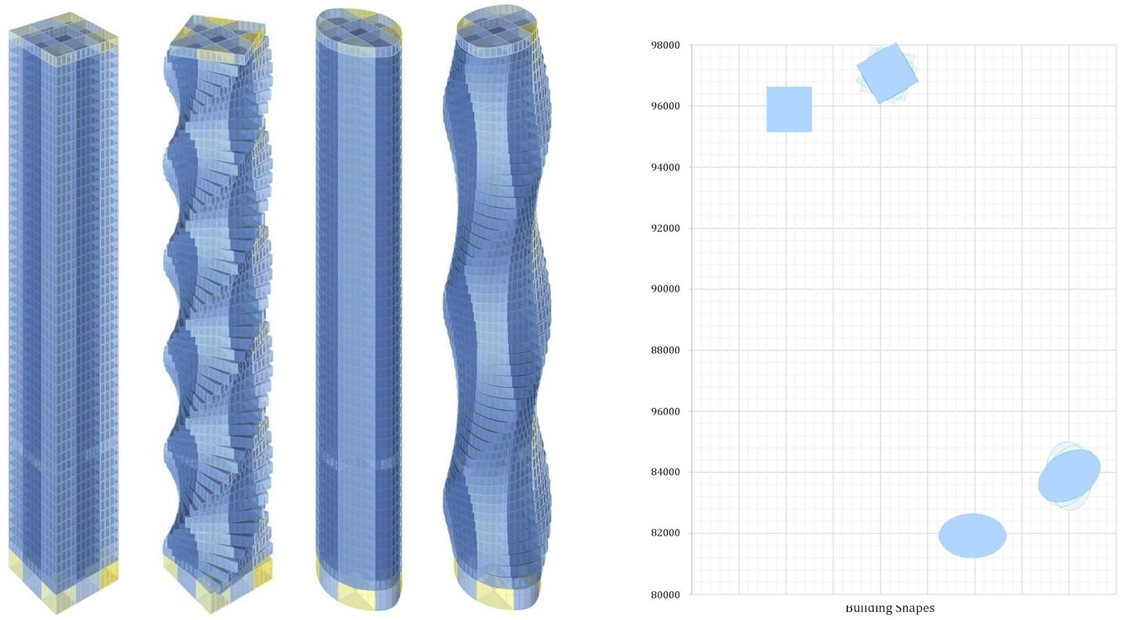


Figure 10: a). Square plan, b). Square plan rotated, c). Oval plan, d). Oval plan rotated and e). Comparison graph.

6. Optimization

For form optimization, radiation and energy simulations were considered as primary factors. As daylight simulations are computationally very expensive to run, the study was limited to optimization of the form with radiation and energy usage using three different parameters. And further trying to optimize the building using varying wall window ratio and conducting a daylight analysis on the optimized form.

6.1. Independent Variables-Parameters

There are three main parameters that were used to study further the impact of geometry in building performances. The three parameters are floor rotation, cantilever overhang, and global rotation. Due to the computational time required to run the radiation and energy optimization, the interval of the parameters were reduced to 1 to 9 degrees odd numbers for the floor rotation, global rotation was limited to multiples of 45 degrees and the cantilever overhang was from 0.0 to 2.0 m.

6.2. Radiation Optimization

6.2.1. Radiation Optimization Biomorpher

Two different engines (Biomorpher and Galapagos) were tested to optimize the forms based on radiation where the objectives are to maximize the radiation during the heating period and minimize it during the cooling period Fig (11). The results of the design options given by Galapagos are plotted in a 2D graph winter radiation vs summer radiation to evaluate the best option Fig (12). The results show that design option 8 and 9 have a balance of a maximum radiation in winter and a minimum radiation in summer while 2 and 4 have the maximum radiation in winter and maximum radiation in summer. Since the cold stress accounts for 46%, to choose the best option out of these 4 options will depend on the energy analysis.

Design Options	0	1	2	3	4	5	6	7	8	9	10	11
Fitness Value	0.360	1.379	1.171	0.825	1.172	0.758	1.135	0.771	0.689	0.857	0.611	0.715
Radiation in Winter kWh	1.712	2.245	2.529	1.752	2.555	1.979	2.126	2.202	2.104	1.942	1.606	1.814
Radiation in Summer kWh	2.432	5.004	4.871	3.402	4.899	3.136	4.397	3.745	3.485	3.656	2.828	3.245
Rotation Angle (Degree)	7	7	5	1	7	3	3	3	9	9	3	5
Balcony Projection (m)	2	0.2	0.4	1.4	0.3	1.5	0.6	1	1.3	1.1	1.8	1.4
Global Projection (Degree)	180	225	135	315	135	90	315	135	90	225	270	315

Generation 0

Select parents whose genes will be used to create the next design generation via the checkboxes

Design Properties

Double click a design to diplay its Rhino/ Grasshopper instance and review performance data below.

Use the radio buttons below to optimise for criteria using the whole population (artificial selection can also be used).

Design 0:

● Num = 0.36 ○ ● ○

Figure 11: Radiation Optimization using Biomorpher

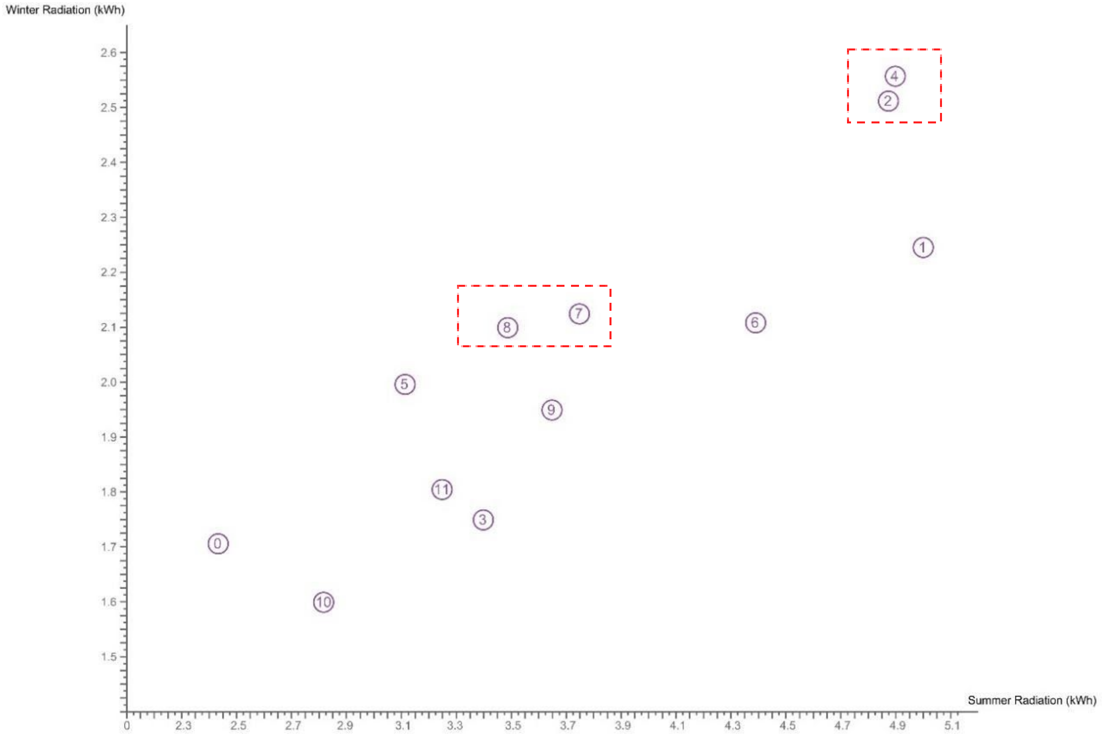
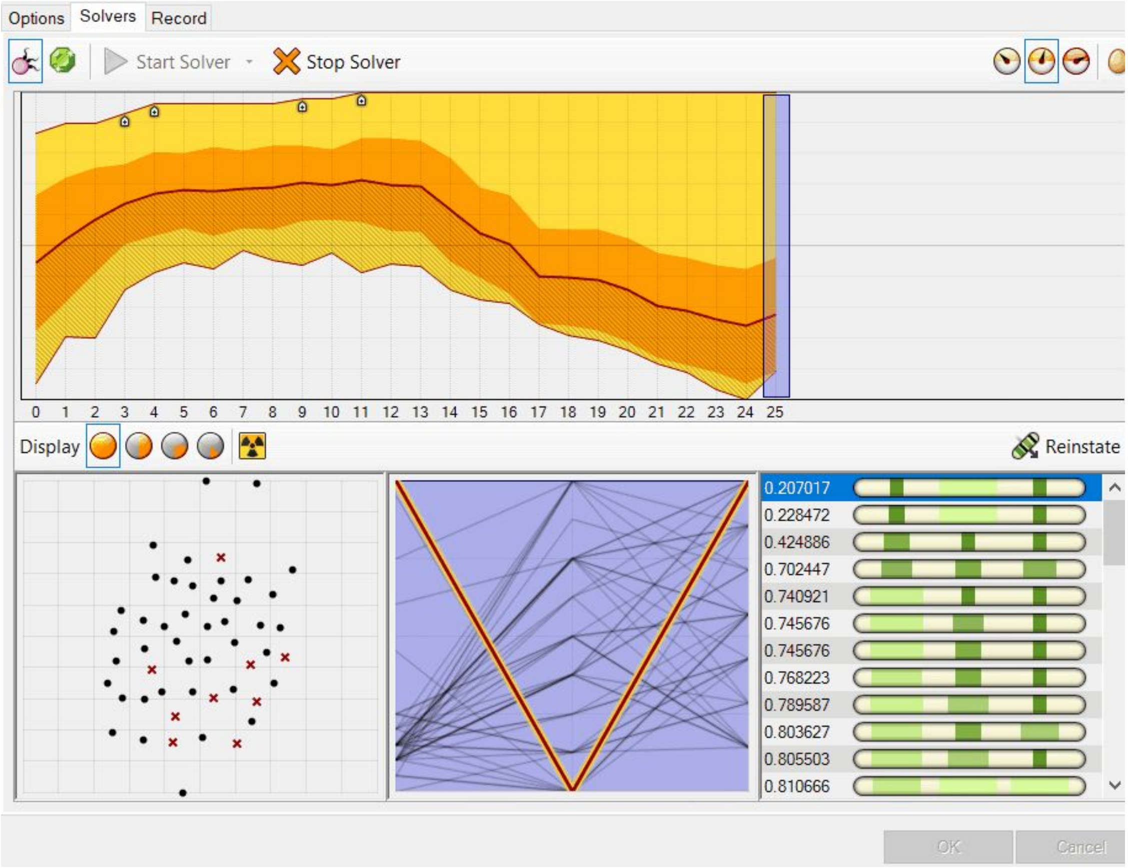


Figure 12: Radiation Optimization Comparison of the Design Options

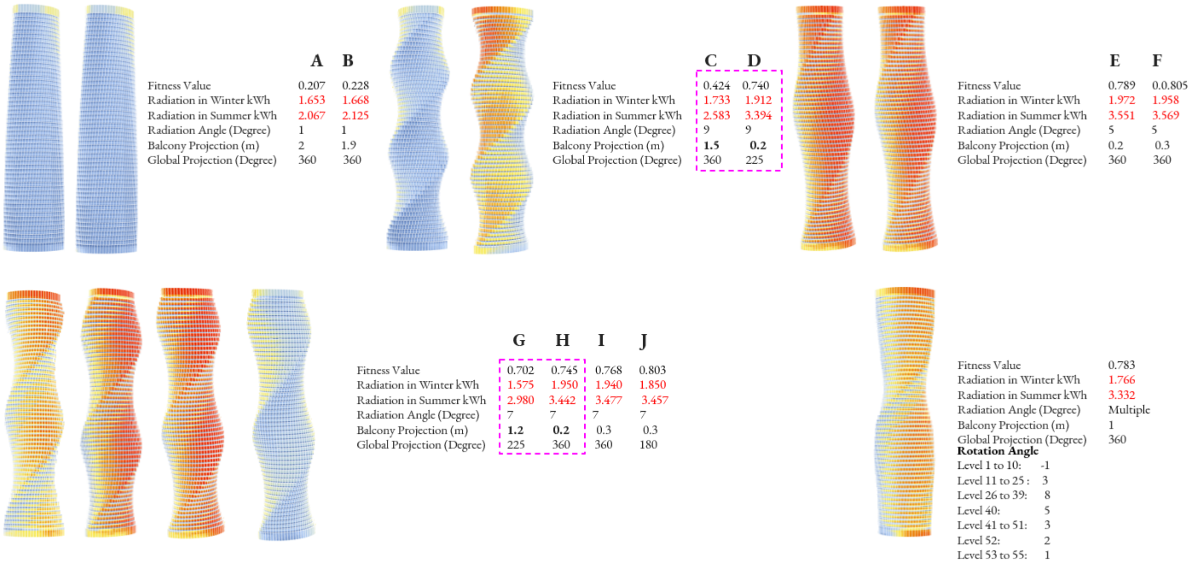
6.2.2. Radiation Optimization Galapagos

Galapagos is another optimization tool that was used in optimizing the radiation. In the same way the aim is to maximize the radiation in winter and minimize it in the summer Fig (13). The optimization was run till the 25th generation and that took 3 days but that is not necessarily telling that it reached the optimal option which makes this type of simulations hard to count and use. From figure 14, the impact of each of the different parameters in the radiation is shown, for example option C and D have the same rotation angle but just changing their balcony projection and their global rotation their radiation differs both in summer and winter. Option C has less radiation in winter and summer than option D where when we decrease the balcony projection the radiation increases in both seasons for the rotation angle 9 degree. The same scenario happens with the rest of the options, but the ratio of change is different from one rotation angle to another when the rotation angle is the same and when the rotation angle changes. In the first case scenario the ratio of change between C and D is 1.7 time while between I and J is almost the same ratio. In addition on the second scenario, the ratio of the optimal option A and the 10th option J is 4 times more, however it will all depends on finding a relationship between the ratio difference between the radiation in winter and summer after applying energy analysis to these design options, as the cold stress is more than the heat stress in Toronto’s climate. When the results are plotted in a 2D graph radiation in winter vs the radiation in summer the best design options are grouped together (D, E, F, H , I) where those have the highest radiation in winter but they have different parameters Fig (14). So, to select the best design option from those 5 options it will depend on other parameters that designer’s control could be the daylighting, the structure, the view or for esthetics reasons etc.



0.207017
0.228472
0.424886
0.702447
0.740921
0.745676
0.745676
0.768223
0.789587
0.803627
0.805503
0.810666

Figure 13: Radiation Optimization using Galapagos



	A	B
Fitness Value	0.207	0.228
Radiation in Winter kWh	1.653	1.668
Radiation in Summer kWh	2.067	2.125
Radiation Angle (Degree)	1	1
Balcony Projection (m)	2	1.9
Global Projection (Degree)	360	360

	C	D
Fitness Value	0.424	0.740
Radiation in Winter kWh	1.733	1.912
Radiation in Summer kWh	2.583	3.394
Radiation Angle (Degree)	9	9
Balcony Projection (m)	**1.5**	**0.2**
Global Projection (Degree)	360	225

	E	F
Fitness Value	0.789	0.0.805
Radiation in Winter kWh	1.972	1.958
Radiation in Summer kWh	3.551	3.569
Radiation Angle (Degree)	5	5
Balcony Projection (m)	0.2	0.3
Global Projection (Degree)	360	360

	G	H	I	J
Fitness Value	0.702	0.745	0.768	0.803
Radiation in Winter kWh	1.575	1.950	1.940	1.850
Radiation in Summer kWh	2.980	3.442	3.477	3.457
Radiation Angle (Degree)	7	7	7	7
Balcony Projection (m)	**1.2**	**0.2**	0.3	0.3
Global Projection (Degree)	225	360	360	180

Fitness Value	0.783
Radiation in Winter kWh	1.766
Radiation in Summer kWh	3.332
Radiation Angle (Degree)	Multiple
Balcony Projection (m)	1
Global Projection (Degree)	360
Rotation Angle	
Level 1 to 10:	-1
Level 11 to 25 :	3
Level 26 to 39:	8
Level 40:	5
Level 41 to 51:	3
Level 52:	2
Level 53 to 55:	1

Figure 14: Radiation Optimization using Galapagos Top Ten

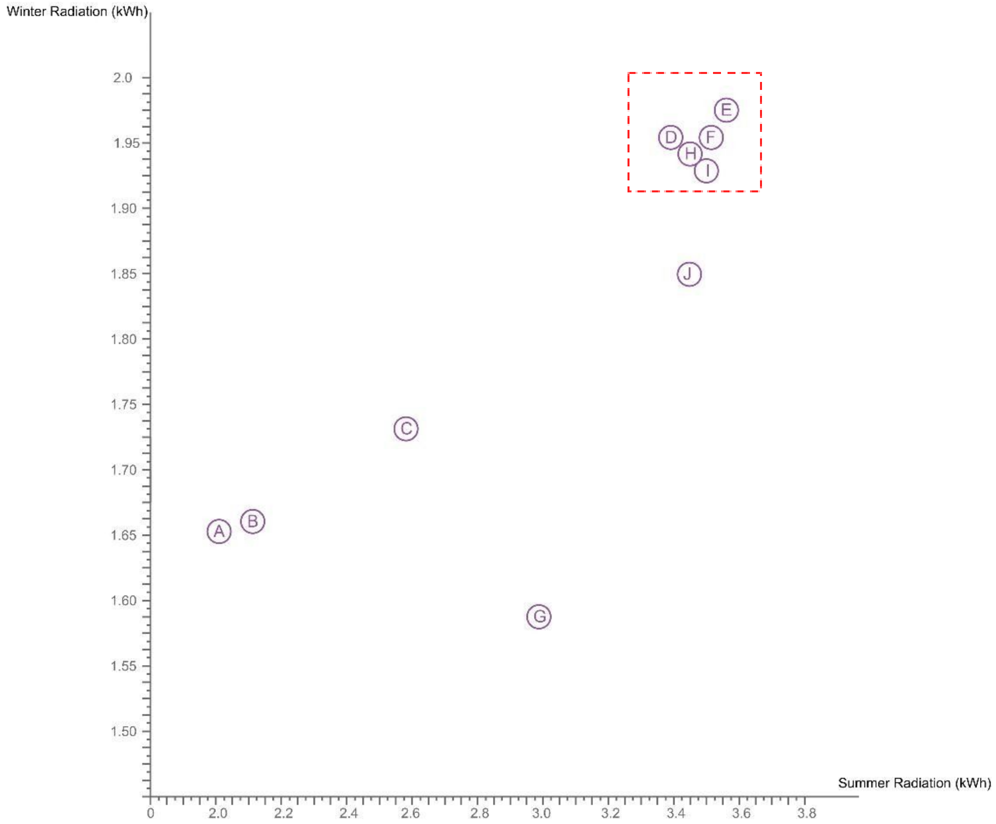


Figure 15: Radiation Optimization Comparison of the Design Option

7. Analysis results

7.1 From optimization using Energy usage

As the heating load is the main factor affecting energy performance, and heating load consumption is projected to be the highest in extreme cold weeks, form optimisation was conducted to reduce this heating load. The table below depicts the effect of the three main parameters on the heating load (Table 1).

The best solutions are chosen by a dynamic optimisation solver on the basis of forms that require the least heating energy.

Table 1: Best results for energy optimisation

	Absolute Tower	**Opt 1**	**Opt 2**	**Opt 3**	**Opt 4**	**Opt 5**	**Opt 6**	**Opt 7**	**Opt 8**	**Opt 9**	**Opt 10**	**Opt 11**
Coldest Week (1st Jan - 7th Jan)	*kWh/m2*	*kWh/m2*	*kWh/m2*	*kWh/m2*	*kWh/m2*	*kWh/m2*	*kWh/m2*	*kWh/m2*	*kWh/m2*	*kWh/m2*	*kWh/m2*	*kWh/m2*
Parameter 1	360	315	180	90	90	270	180	270	135	135	45	315
Parameter 2	Varying	3	9	1	3	3	3	5	3	5	3	5
Parameter 3	1.0	1.3	1.0	1.2	1.4	1.0	1.2	1.0	1.3	1.3	1.2	1.2
Heating Load	**83953.33**	**83582.08**	**83856.04**	**85151.37**	**83522.02**	**85027.01**	**85380.04**	**84303.74**	**84785.79**	**83735.56**	**83853.76**	**83391.38**

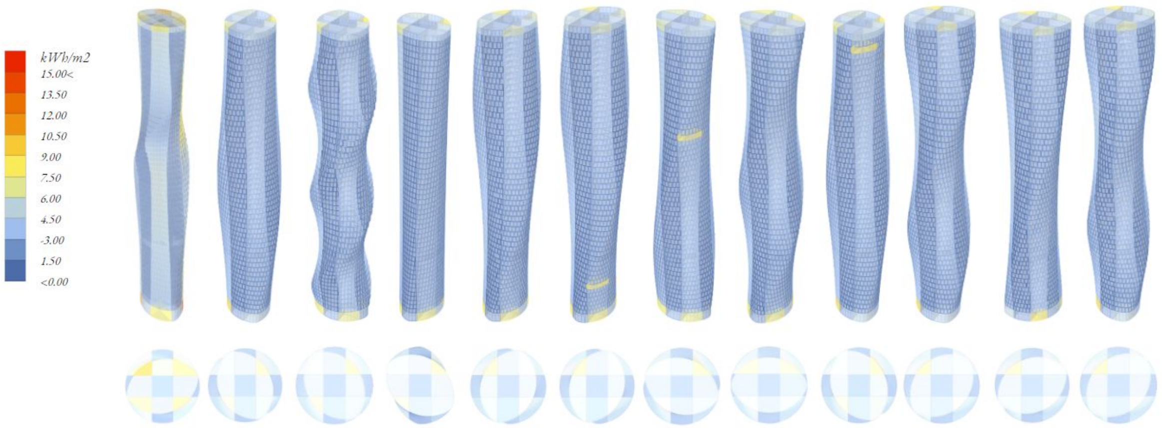


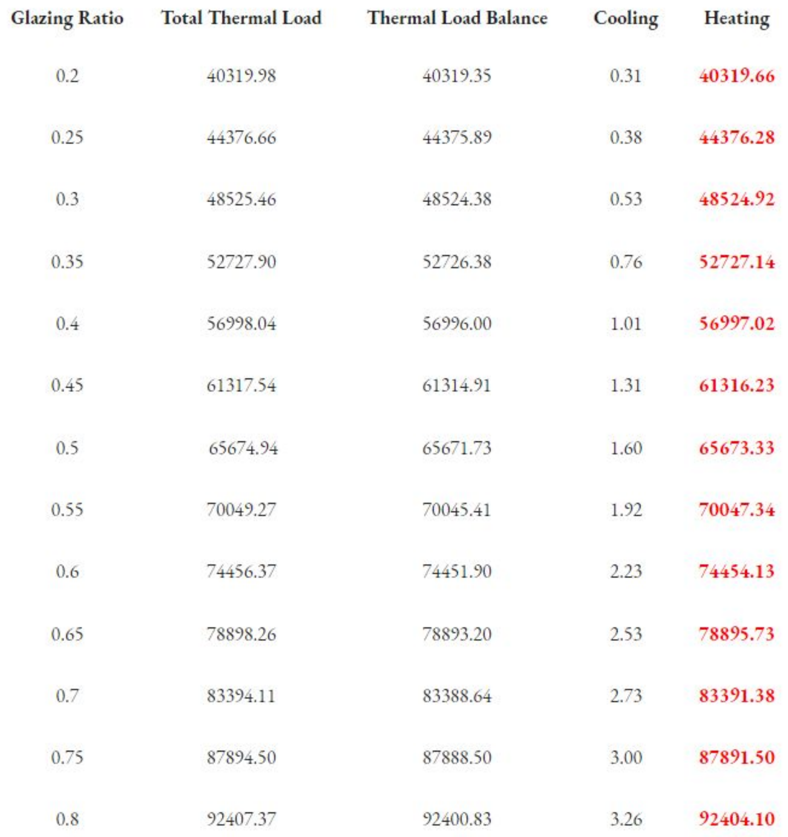
Figure 16: Views and plans of optimised forms

Further analysis was conducted to optimise the wall-window ratio in order to reduce the heating requirement in the peak winter week.

7.1.1. Wall window optimization

The results of energy optimisation were analysed and the best performing form (Fig7. Opt 11) was selected for a secondary optimisation study. The aim of this study was to analyse the effect of glazing ratio for the energy performance of the building as glazing ratio plays a major role in conduction and convection.

Table 1: Glazing ratio optimisation along with main parameters



Glazing Ratio	Total Thermal Load	Thermal Load Balance	Cooling	Heating
0.2	40319.98	40319.35	0.31	40319.66
0.25	44376.66	44375.89	0.38	44376.28
0.3	48525.46	48524.38	0.53	48524.92
0.35	52727.90	52726.38	0.76	52727.14
0.4	56998.04	56996.00	1.01	56997.02
0.45	61317.54	61314.91	1.31	61316.23
0.5	65674.94	65671.73	1.60	65673.33
0.55	70049.27	70045.41	1.92	70047.34
0.6	74456.37	74451.90	2.23	74454.13
0.65	78898.26	78893.20	2.53	78895.73
0.7	83394.11	83388.64	2.73	83391.38
0.75	87894.50	87888.50	3.00	87891.50
0.8	92407.37	92400.83	3.26	92404.10

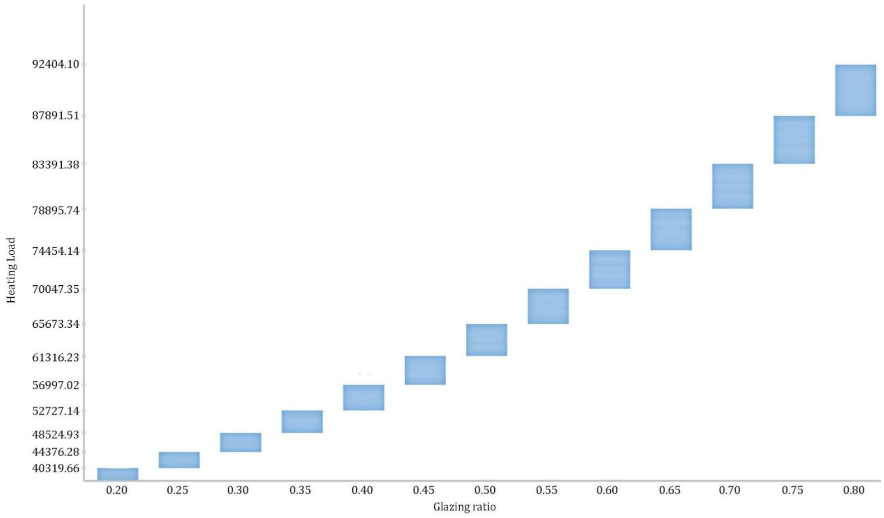


Figure 17: The heating load rises proportional to the glazing ratio

7.2 Daylight Simulation of The Optimized Form

According to the international recommendations at least 40% of the yearly daylight the building receives should be useful. The typical floor of the optimized form receives a minimum daylight of 56% and the maximum is 70% during winter. The percent of the daylight in each floor is differing in this case between 1% to 14% which means that the form of the building has an impact on the building performances Fig (18). So, in comparison with the absolute tower there is no much difference in the total daylight received in each tower however each typical floor receives different percentages of daylight because of their rotation angle and global rotation.

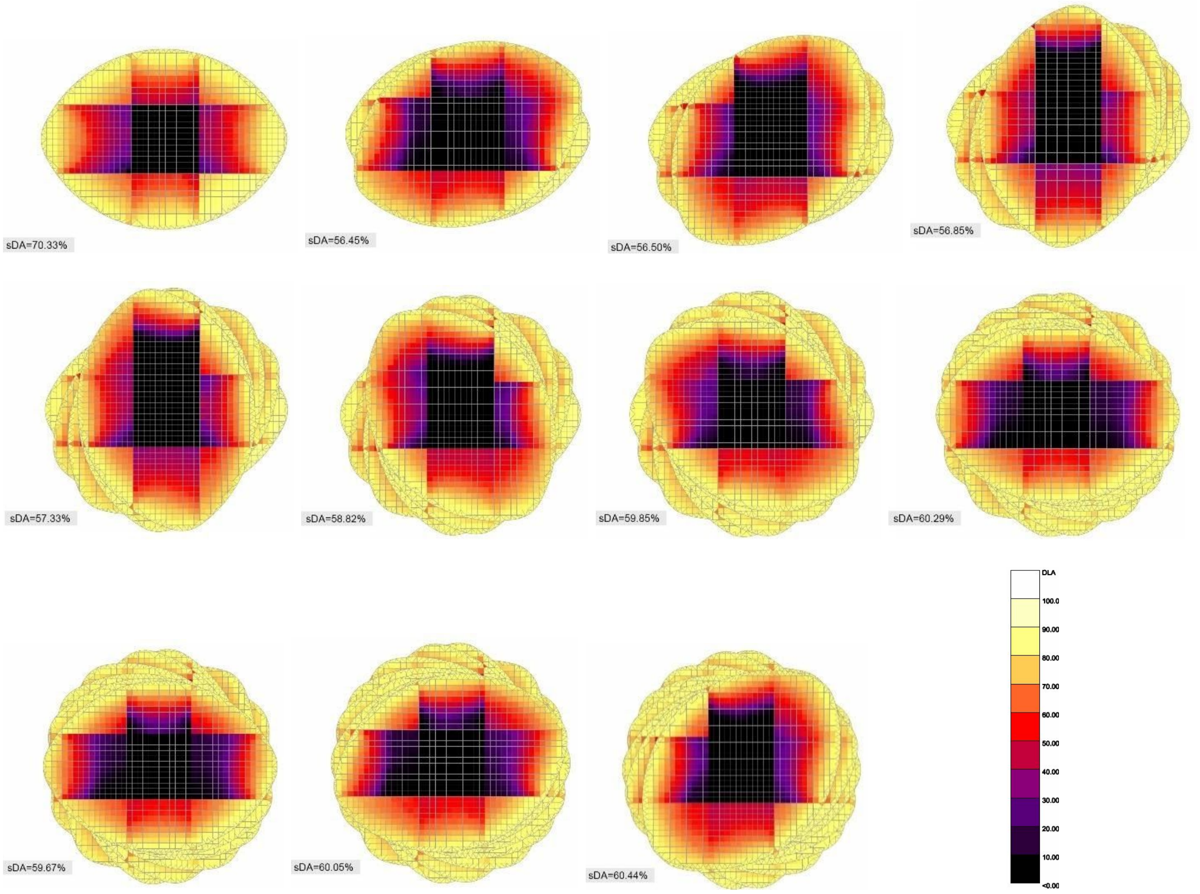


Figure 18: Daylight Autonomy in Winter

Typical Floor Plans: Level 0, Level 5, Level 10, Level 17, Level 20, Level 25, Level 29, Level 32, Level 36, Level 39, Level 45, Level 51

8.Conclusion: submission of contributions

Optimising a form for best energy performance can be done using factors like glazing and multiple independent parameters. Due to the structural limitation there are certain factors to be considered and should go hand in hand in the optimisation process. There is a possibility the optimisation might suggest a specific number, without keeping in mind the external loads for structural performance. The point of the study was to identify different parameters which could be optimised to perform the best within the limitations assigned by the designer. We were exploring the tools to run the optimization and analyse the effects of free form architecture in energy and radiation performance.

9. Further Scope/ Future works:

We conclude that this topic could benefit from further research in the following areas:

a) a broader study of the current building in different climate conditions to find out which parameters affect the performance in different climatic conditions.

b) adding more than one fitness (in this case only heating energy) to optimise the building form.

c) find better ways to minimise computational time required for the process.

d) conducting a thorough study on the effect of materials which can be modified for better performance.

e) further comparison with a building with the same area but different user activity.

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