Building Energy Performance of Complex Forms

Test simulation of minimal surface-based form optimization

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Many optimization tools are developed in line with the form-energy relationship to ensure energy efficiency in buildings. However, such studies with complex forms are very limited. Therefore, the MSO-2 model was developed. In this model, on the roof of the conceptual form, minimal surface is used, thus complex forms can be created. In this model, the conceptual form can be optimized (for one day) according to these objectives: increasing daylight in the space with maximum value limitation, reducing radiation on the roof, and enlarging floor surface area of the conceptual form with minimum value limitation. A test simulation was performed with this model. Thus, in order to find the most optimized form in multi-objective optimization, more generations could be produced in a short time and optimized conceptual forms, which were produced, could be tested for energy efficiency.

Keywords: *Multi-Objective Optimization, Radiation Analysis, Building energy performance, Daylighting Analysis*

INTRODUCTION

The vast majority of the related studies on the relationship between building energy performance and form are made using forms in Euclidean geometry. The studies of Caldas (2008), Flager et. al. (2009) and Jalali et al. (2020) can be given as examples of this. This type of study, which has been done with complex form is very rare (Yi and Malkawi, 2009; Lin and Gerber, 2014). The forms in these optimization studies may be complex to a certain extent during the optimization process. So, in other words, in these cases, forms can move as limited by the optimization process. On the other hand, when we look at designs in the world of contemporary architecture, we see that the use of forms in Euclidean geometry is diminishing, and complex forms are beginning to be used instead (Burry and Burry, 2012; Helenowska-Peschke, 2012; Bellone et. al., 2017).

In our previous study, we developed Minimal Surface based Form Optimization Model (MSO) (Agirbas, 2018). This model leads the conceptual form to behave freely during the optimization. It was aimed to test optimization of the complex building form, according to determined criteria, in order to achieve an optimum energy performance. During the study minimal surface geometry was used. Optimization objectives for the minimal surface based form were defined as: increase daylighting, enlarging the ground floor surface area of the conceptual form and reducing radiation. However, in our previous study (creation of MSO model), simulation took too long, because of the use of annual daylight and radiation in the optimization. Therefore, few generations were created, and the conceptual form options produced were also limited.

In this study, it was aimed to reduce the limitation of the previous study (Agirbas, 2018) (creation of few generations) and to test the production of forms. For this, the MSO model was modified to run for a day. Also, min and max value limitations (min value limitation to floor area, max value limitation to daylighting) were brought to the objectives.

BACKGROUND

Multi-objective optimization in the field of architecture

There are many parameters that affect the performance of the building. For example, the designer can make the windows wider to get more daylight into the room and to reduce the use of artificial light, but broad windows increase heat transfer and can cause the increase of energy used for heating. Therefore, because of this conflict, to produce alternatives in the direction of parameters, the use of multi objective optimization algorithms was started. Multi-optimization studies have been mostly conducted with Euclidean form. Evins (2013), Attia et al. (2013), Nguyen et al. (2014), Machairas et al. (2014), and Shi et al. (2016) made extensive reviews about optimization studies.

Some of these multi-objective optimization tools are done with GAs (Goldberg and Holland 1988; Bentley and Wakefield 1997; DeLanda 2002). Octopus (Vierlinger, 2013) used in this study is an add-on to Grasshopper is based on the SPEA-2 algorithm (based on GA algoritm) (Zitzler, 2001).

Minimal Surface as a complex form

In the optimization process, the minimal surface form was chosen to be used to make the conceptual form behave more freely. Minimal surface geometries are the surfaces formed by covering least area within the given boundaries in 3D space (Velimirovic et al. 2008; Emmer 2013).

In his "Contemporary Geometry for the Built Design" article, Hyde (2010) associates non-Euclidean forms with "curvature" and in this sense focuses on minimal surfaces. Furthermore, Gawell (2013) categorizes non-Euclidean geometries (used in modeling contemporary architectural forms) as elliptic geometry, hyperbolic geometry and fractal geometry, and he includes the Hyperbolic paraboloid [which is actually a kind of ruled minimal surface (Shin et al., 2013)] under the heading of Hyperbolic geometry. The minimal surface, which was first mentioned in the context of Frei Otto's buildings, is now widely used in contemporary architecture (Keller, 2017).

RESEARCH METHOD

Computer Software

In this study, Rhino (3D modeling environment) and Grasshopper (visual programming language) were used. In addition, various add-ons to Grasshopper, were used. These include: Ladybug for radiance simulation, Honeybee for daylighting simulation, and Octopus as a GA based multi-objective optimization simulation tool.

Objectives, Variables and Constraints

The objectives of the model are increasing daylighting (max 300 lux), decreasing radiation on the roof surface and enlarging ground surface area (min 500 m2) of the form. The variables are the values of the parametric geometry with minimal surface. The constraints are the parcel dimensions, height of the building form and program of the building (Table 1).

Model Set-up (MSO-2)

It is possible to examine this created script in 5 pieces as the set up of the creation of general geometry, the set up of leaving the gap in geometry, daylighting set up, radiation set up and optimization set up.

Set up of the Creation of Main Geometry. This section describes how parametric geometry is modeled with visual programming language.

Table 1
Objectives and constraints in the MSO-2 model

Assumptions of Site constraints	Site	Hudson Street, St Luke's Pl, Clarkson Street, 7 Avenue, NY			
	Parcel	65 m x90 m			
	Height	20 m			
	Program	Office			
Objectives	**Properties**	**Minimum**	**Maximum**	**Unit**	**Increase / Decrease**
	Daylight	-	300	lux	Increase
	Radiance	-	-	kWh/m^2	Decrease
	Ground floor surface	$500m^2$	approx. $5850m^2$	m^2	Increase

- The points were created using the "Construct point" component. The "series" component was connected to each of the x, y, z inputs of this component. The amount of points, the spacing between the points and the first point's position were defined. This process was done twice.
- From 2 sets of points (created by using "Construct point" component), 2 curves were created by using "Nurbs Curve" component.
- These curves were used to create Minimal surface form.
- These curves were also projected to the ground floor level (z axis:0) by using the "project" component. The curves used to produce minimal surface geometry were lofted with the projected curves. The projected curves were made a ground level surface with "edge surface" component. So, a volume was created.
- The created surfaces were turned into a whole with the help of "Brep join" component (Figure 1).

The set up of leaving the gap in geometry. This section describes how parametric gaps in parametric geometry are modeled with visual programming language.

- The last created 2 curves and 2 curves projected onto the floor were offset. Offset new curves were lofted between them (ie, the loft process was performed between the offset curve and the projected curve on the offset floor). Thus, a surface was created in a surface previously created by the loft. The offset distance was determined with number sliders.
- Using the "surface split" component, these two lofted surfaces on top of each other were separated.
- Using the "List item" component, the parts, which were separated from each other, were provided being selected. Thus, the areas, which were determined as window openings, could be selected (the openness was left at the 2 edges of the whole form) (Figure 1).

Daylighting set up. At this stage, the Honeybee, which is a Grasshopper add-on, was used. The model produced through the script was improved by Roudsari and Pak (2013).

- First, for determining the zone, the created geometry was defined to "Honeybee_-Masses2Zones" component. The other inputs in this component were left as default set. "Zone programs" were left as Open Office. "IsConditioned" was left as True (conditional output zones with an Ideal Air Loads System). "MaxRoofAngle" was left at 30 degrees (the maximum angle from z vector that the surface would be assumed as a roof).

- The "Honeybee_addHBGlz" component was used to add a custom glazing surface to the specified zone (to define the window opening). The specified zone was connected to the input "HBObj" of this component. And the surfaces

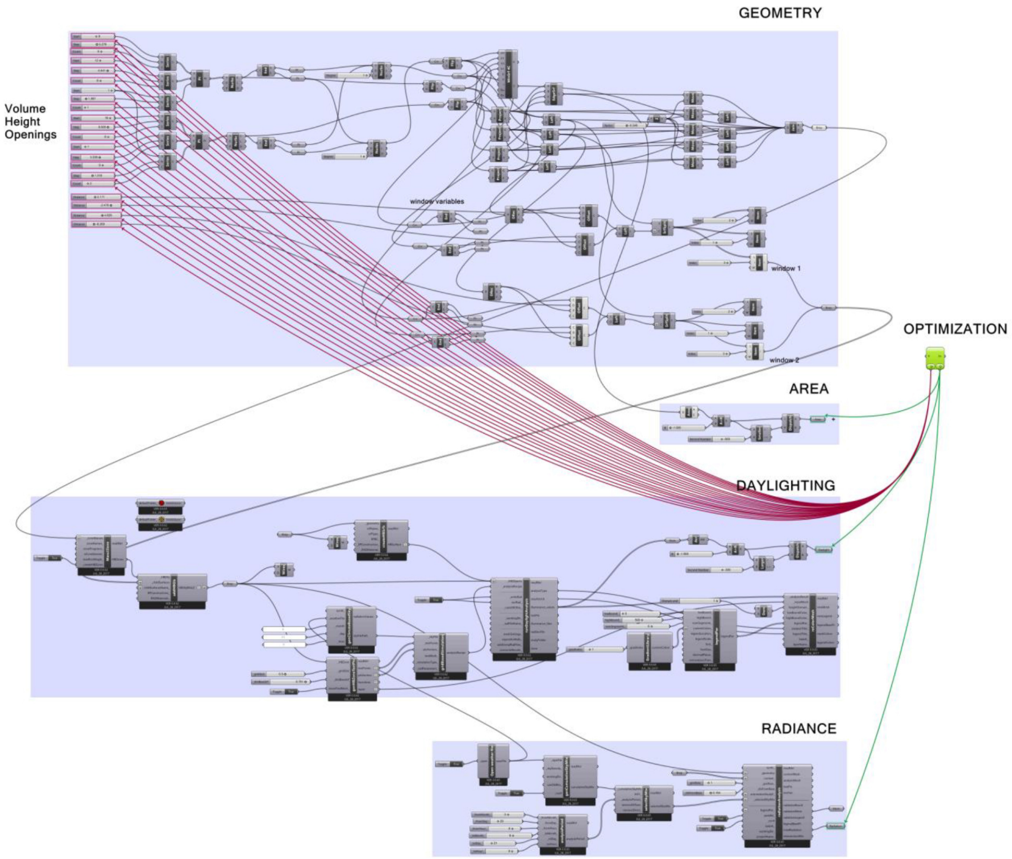


Figure 1
Script prepared by the author for multi-objective optimization simulation

specified as windows were connected to "childSurfaces" input. The Optional "EPConstructions" and "RADMaterials" inputs were left to default settings.

- The "Honeybee_Generate Zone Test Points" component was used to create test points on the floor surface in the space, which is necessary for grid based daylighting simulation. To this component as an input, a zone with windows defined was assigned, and the size of the test grid and distance from the base surface values were also assigned.
- "TestPoints" and "ptsVectors", which were the outputs of the "Honeybee_Generate Zone Test Points" component, were connected to the inputs of corresponding "Honeybee_Grid Based Simulation" component. "SimulationType", which was another input of the "Honeybee_Grid Based Simulation" component, was defined as illuminance (lux).

- Another required input for the "Honeybee_Grid Based Simulation" component is the radiance sky file. For this, the "Honeybee_Generate Climate Based Sky" component was used. This component generates a 'climate based sky' at any time of the year. The related values were given to the inputs of this component (for this study, the time was set as 9 o'clock of 21st day of 6th month). Via the "open weather file" component, the weather file of a determined city (New York City in this study) in epw format (New York City, 94728) was defined to "weatherFile", which is another input of this component. The "north", the other input of the "Honeybee_Generate Climate Based Sky" component, was left at default sets (Y axis shows north).
- "AnalysesRecipe" (the input of the "Honeybee_-Run Daylight Simulation" component, which is used to perform daylight simulation), was connected to the output of the "Honeybee_Grid Based Simulation" component. "HBObjects", which is the other input of the "Honeybee_-Run Daylight Simulation" component, was connected to the zone with defined windows.
- With the output of the "Honeybee_Run Daylight Simulation" component, the legend was created using the components "Ladybug_Recolor Mesh", "Ladybug_Legend Parameters" and "Ladybug_Gradient Library".

Radiation set up. At this stage, the Ladybug, which is a Grasshopper add-on, was used. The model produced through the script was improved by Roudsari and Pak (2013).

- The "Ladybug_Radiation Anaysis" component is the main component used for radiation analysis. "GridSize" input of this component was defined as 1 unit and "disFromBase" input of this component was defined as 0.1 unit. The zone with defined windows was assigned to the "geometry" input. The buildings that can block sunlight in the environment of the selected area were defined to the "Context" input.
- An important input of the "Ladybug_Radiation Anaysis" component is "selectedSkyMtx". "Ladybug_selectSkyMtx" component, which determines the specific sky matrix and the analysis period, was connected to this input.
- The "Ladybug_GenCumulativeSkyMtx" component, which calculates the sky's radiation for each hour of the year, was connected to the "cumulativeSkyMtx" input of the "Ladybug_selectSkyMtx" component. Via the "open weather file" component, weather file in the epw format (New York City, 94728) of the designated city (New York City in this study) was defined to this component.
- The "Ladybug_Analysis Period" component was connected to the "analysisPeriod" input of the "Ladybug_selectSkyMtx" component and the analysis period (month: from 5 to 6, day: from 20 to 21, hour: from 8 to 9) was determined.

Optimization set up. This section describes how the set up of optimization is done.

- The number sliders (16 pieces), which are used when creating the "Construct point" component, were connected to Octopus' input for use in the optimization process. These (16 number slider) affect the size of the volume of the geometry (Figure 1).
- The site's parcel border was accepted as 65 meters by 90 meters. Since 12 of 16 number sliders are related to the area of the conceptual form, the value ranges of these sliders were limited with the direction of the parcel boundaries. The max values of 'number of points', 'starting point' and 'distance between the points', which are the variables in the X and Y inputs of the point components that make up the curves in the form, were determined according to the size of the parcel. Accordingly, the starting point in the X coordinate of the first point component as min value 0, max value 20 (as only integer value); number of points, min value 1, max value 9 (as only integer value); the distance between

points, min value 1, max value 10 (including decimal values), the starting point in Y coordinate of the first point component as min value 0, max 20 (as only integer value); number of points, min value 1, max value 13 (as only integer value); the distance between points, min value 1, max value 5 (including decimal values), the starting point in the X coordinate of the second point component as min value 0, max value 20 (as only integer value); number of points, min value 1, max value 9 (as only integer value); the distance between points, min value 1, max value 10 (including decimal values), the starting point in the Y coordinate of the second point component as min value 0, max value 20 (as only integer value); number of points, min value 1, max value 13 (as only integer value); the distance between points, min value 1, max value 5 (including decimal values) were determined.

- The 4 number sliders of “Construct point” components connected to Z inputs affect the height of the form. For this study, the maximum building height was assumed to be 20 meters. Therefore, the maximum values of the distance between the points and the number of points and were set according to this. In Z coordinates of first and second point components, ‘the number points’ as min value 1, max value 10 (only integer values); the distances between the points as min value 1, max value 2 (including decimal values) were set.
- The number sliders in the distance parameters (determined when the curves are offset) were connected to Octopus’ input. These 4 number sliders affect the dimensions of window openings. The value of range of these offset values is 10 units.
- For the purpose of increasing daylighting (since Octopus focuses on minimizing the values, this value of the number was multiplied by -1 and connected to Octopus), the result values obtained from the daylight analysis simulation (“results” output of “Honeybee_Run Daylight Simulation” component) was connected to the multi-objective search input of Octopus. At this stage, with the help of the “dispatch” component, the

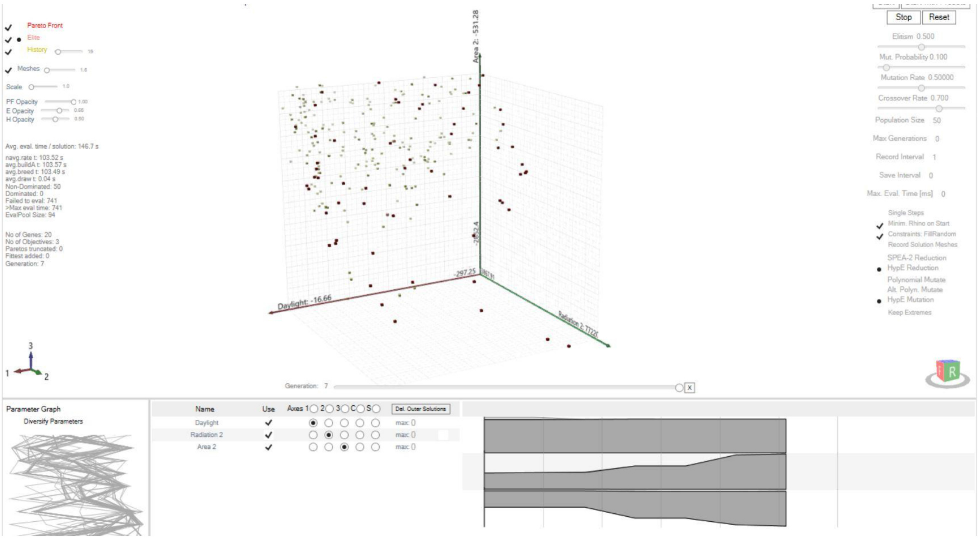


Figure 2
The optimization results in the Octopus

max lux value was set to 300 lux. The daylighting values above 300 lux were left out of the optimization simulation.

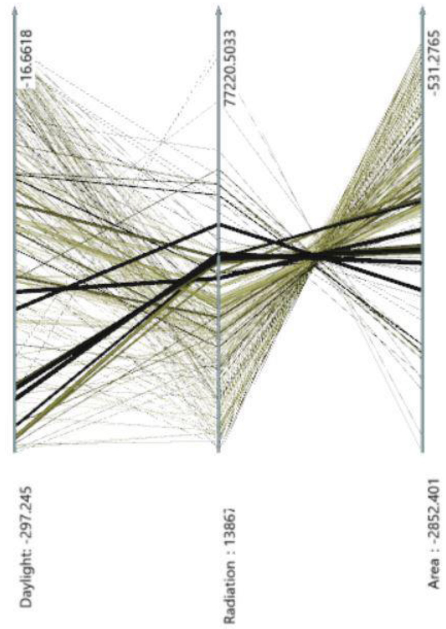


Figure 3
Max and min values of the objectives obtained as a result of optimization

- For the purpose of reducing the radiation, the total radiance value found was connected to the Octopus's multi-objective search input.
- In order to enlarging the floor surface area of the conceptual form, the value of the ground floor surface area of the form was connected to the Octopus's multi objective search input (since Octopus focuses on minimizing the values, this value of the number was multiplied by -1 and connected to Octopus). Based on the data of the geometry creation part, the value of ground floor surface area of the conceptual form was calculated with the help of the "area" component. For optimization simulation, the floor surface area value of the conceptual form was constrained to minimum 500 m2. During performing this limitation, the "dispatch" component was used, and the lower values were left out of the optimization simulation (Table 1).

RESULTS

Presets were determined as Elitism: 0.5, Mut.Probability: 0.1, Mutation Rate: 0.5, Crossover Rate: 0.7, Population Size: 50 for the optimization simulation. As a result of the optimization with 3 objectives, 7 generations were produced and several values were obtained (Figure 2). As understood from the obtained values of Pareto Front (optimized solutions) results of each generation, the simulation was attempting to increase daylight values and the floor surface area, while it was attempting to reduce the radiance value. Dark lines in graphic (Figure 3) show the closest value options to the desired values, obtained from the combinations of daylight, radiance and area values of the optimization result.

From the optimization results obtained, some combinations of values, which are seen to be closely related to the target by the author, were reconsidered to see the form that they created. In doing so, first a combination was determined (a combination of area, daylight and radiance values obtained as a result of optimization). Simulation, which can create this combination of values, was created with the help of the "reinstate solution" option in Octopus. When we create this simulation, the form, which was created by the combination of these values, can be seen on the Rhino screen. Also, the values in the Grasshopper script change accordingly. So, in other words, when we look back at the Grasshopper script, we see that the number slider parameters (value range of 20 variables connected to the Octopus Genome) came up to the values that can form the combination of them (daylight, area and radiance values).

The first combination (the combination of average daylight value: 257.754 lux, average radiance value: 27503.110 kWh/m2, and the floor surface area of the form: 974.202 m2) (Table 3), the second combination (the combination of average day-

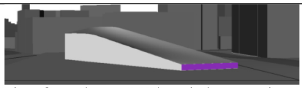
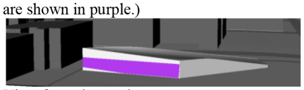
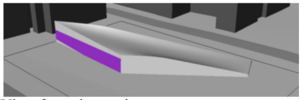
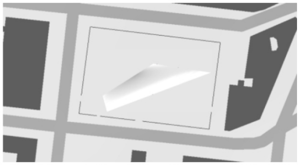
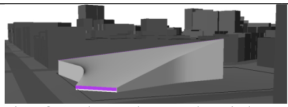
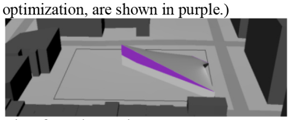
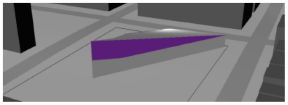
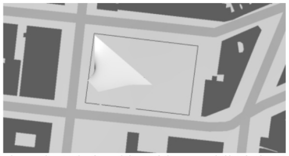
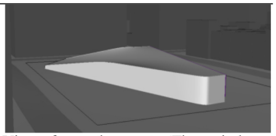
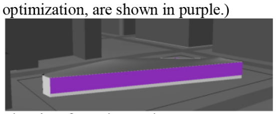
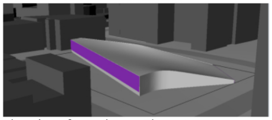
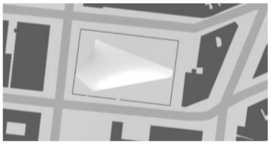
	The first optimized form	The second optimized form	The third optimized form
Obtained values of objectives	Daylight: 257.754 lux Radiance: 27503.110 kWh/m^2 Area: 974.202 m2	Daylight: 290.704 lux Radiance: 35209.431 kWh/m^2 Area: 1200.970 m2	Daylight: 177.806 lux Radiance: 58023.222 kWh/m^2 Area: 2289.674 m2
Obtained values of the form	Volume: 5256.971 m^3 Max height: 9.27 m Window area (north): 195.64m^2 Window area (south): 11.40m^2	Volume: 8597.975 m^3 Max height: 14.94 m Window area (north): 293.264m^2 Window area (south): 13.453m^2	Volume: 11216.823 m^3 Max height: 6.79 m Window area (north): 411.552m^2 Window area (south): 21.931m^2
The obtained form	 View from the west (The window openings, which were obtained after the optimization, are shown in purple.)  View from the north  View from the northwest  Plan (the relationship with parcel limit is seen)	 View from the southwest (The window openings, which were obtained after the optimization, are shown in purple.)  View from the north  View from the northeast  Plan (the relationship with parcel limit is seen)	 View from the east (The window openings, which were obtained after the optimization, are shown in purple.)  The view from the northeast  The view from the northwest  Plan (the relationship with parcel limit is seen)

Table 2
The first, second and third optimized forms

light value: 290.704 lux, average radiance value: 35209.431 kWh/m2, and the floor surface area of the form: 1200.970 m2) (Table 4), third combination (the combination of average daylight value: 177.806 lux, average radiance value: 58023.222 kWh/m2, and the floor surface area of the form: 2289.674 m2) (Table 5) and the forms obtained from these combinations can be seen in Table 2. It can be observed that, the first form was positioned in the south, the second form was positioned in the west and the third form spread widely within the parcel area.

LIMITATIONS AND FUTURE WORK

During the optimization process in this study, the annual daylighting analysis was not performed since the simulation takes too long time. However, to perform such a study will be efficient in terms of making the conceptual level optimization of the building form according to the data obtained throughout the year.

This model can be used by designers. Since the visual programming language is used while this model is being developed, it will be easier for other designers to modify the script according to other parameters. It is important to integrate various parameters into the script to make case studies and evaluate the results.

In this study, floor slabs were not considered and only conceptual mass was emphasized. In addition, the minimal surface geometry, which provides complex conceptual form formation, was used only on the roof. Minimal surfaces can also be used in lateral surfaces and the forms, which were formed at the end of optimization, can be examined. Optimization studies can be done via using other complex geometries.

Since the objectives of this optimization are related to daylighting and radiation, the materiality is excluded. But, in an optimization model including energy efficiency parameters such as acoustics and heat, the materiality should also be included in the process.

CONCLUSION

In our MSO study (Agirbas, 2018), fewer generations could be produced due to annual analysis. MSO model was developed for conceptual form creation from complex forms in the direction of the relationship between the energy performance of the building and the building form. In this study, the code was modified (MSO-2) and a case study was performed with analyzing on a daily basis. With this modification, more generations could be produced in the multi-objective optimization process and the more optimized conceptual form possibilities could be created. As a result, it was observed that the script also works effectively in this way.

At the end of the case study carried out, it has been seen that this model is capable of optimizing the complex form in the direction of the determined objectives, constraints and variables. Thus, by using this model, steps can be taken to design more energy efficient buildings in complex forms.

Although there are many optimization studies done in this respect in Euclidean geometry, very few studies are done in complex form. Research on complex forms, which have a great potential for energy efficiency, should also be carried out.

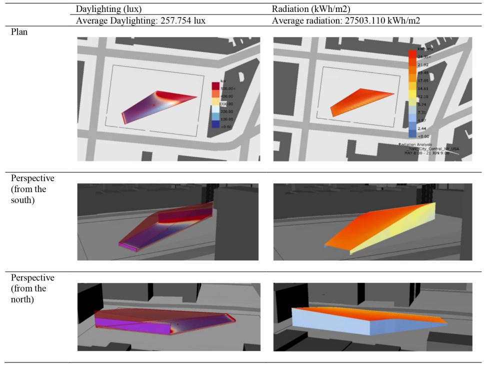


Table 3
The analysis of the form in specific that was obtained in the end of the simulation which was done with the first combination of values (the places shown in purple colour are window openings)

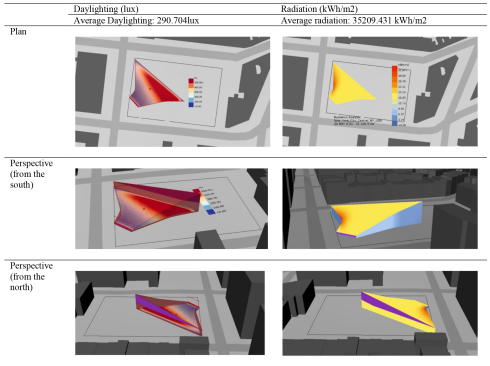


Table 4
The analysis of the form in specific that was obtained in the end of the simulation which was done with the second combination of values (the places shown in purple colour are window openings)

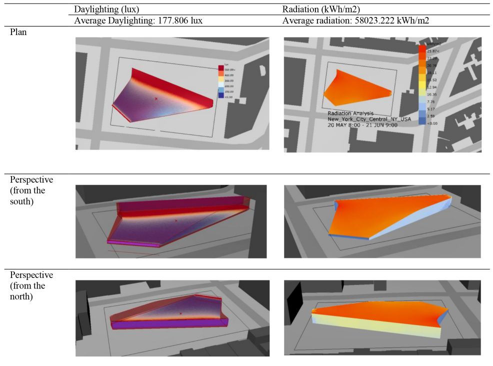


Table 5
The analysis of the form in specific that was obtained in the end of the simulation which was done with the third combination of values (the places shown in purple colour are window openings)

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