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Asli Agirbas

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Performance-based design optimization for minimal surface based form

Asli Agirbas

Department of Architecture, Fatih Sultan Mehmet Vakif University, Istanbul, Turkey

ABSTRACT
Currently, many studies are being done using optimization tools. However, optimization studies done with complex geometry are limited. Even so, the move toward complex geometric forms is a feature in the world of contemporary architecture. Hence, in this study, the minimal surface form, away from the Euclidean geometry, is considered as the roof cover of the building and optimization of the form is considered to be done according to the daylighting, radiation and covered area parameters. In this context, using a genetic algorithm based multi-objective optimization tool, a model is developed whose objectives are reducing radiation, increasing daylight in the space and increasing the floor surface area of the form. The results, which are obtained at the end of the optimization simulation, are evaluated. The complex forms, which are the result of optimization, are also modelled in the form of related Euclidean geometries and analyzed. The energy efficiency of the two forms is compared, and the complex forms are found to be more energy efficient than those with Euclidean geometry. When a complex form admits more daylight, a similar form made with a Euclidean geometry admits less daylight. Likewise, while the complex form is exposed to a lower radiation, a form of Euclidean geometry of similar form experiences a greater radiation.

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KEYWORDS
Minimal surface; multi-objective optimization; daylighting analysis; radiation analysis; conceptual design

Introduction

Buildings play an important role in global energy consumption. For example, the building sectors in the European Union, consume 40% of the total energy used, (OJEU 2010), and the figure is 47.6% in the United States (Architecture2030 2018). Therefore, in the field of architecture, studies are being carried out to reduce the energy use both by present buildings, and those to be constructed in the future. Currently, these studies are accelerated by the influence of computational tools which are undergoing progressive development. A variety of algorithm-based studies have been carried out for energy efficient building designs.

At present, creating complex form with up-to-date computer-aided design tools is easy. However, studies, which are carried out to make complex building forms according to building performance, are limited (Yi and Malkawi 2009; Lin and Gerber 2014). A few studies were able to carry their optimization studies forward by making optimization with complex geometry. However, the free-from experiments in these optimization studies are limited. The initial form, for example, can be complicated with creating fragments on the form in the optimization process (Yi and Malkawi 2009), or it can be complicated with changing some basic parameters such as twist and scale (Gerber and Lin 2014) during the initial form optimization process.

The hypothesis of this study is that complex forms can be more efficient in terms of energy performance, as they can formally offer more harmonious options to the conditions of the environment (eg climatic conditions). In order to test this, a model was first developed using multi-objective optimization to generate a complex form according to determined criteria. During this process, Grasshopper was used as a visual programming language platform and the Octopus (Vierlinger 2018) add-on was used as a multi-objective optimization tool. Then, a comparison between 3 optimized complex forms produced by using this model, and their approximate form in Euclidean geometry, was made in terms of their energy performance.

In the optimization model produced in this study, decreasing the radiation, increasing the daylight in the space and increasing the surface area of the form (to be limited with a min value) are determined as objectives. The creation of form was provided according to these objectives. In the direction of these objectives, through the optimization process, form alternatives were obtained according to the volume magnitude, the limit of the parcel, the form height and the window opening variables, which were limited to a certain value range as min and max. In addition, during the formation process of the form (the optimization process), a minimal surface geometry capable of creating curves and convoluted lines was used to enable the form to move as freely as possible. Thus, complex forms could be obtained. To test the hypothesis, a comparison was made of the energy efficiency obtained from the complex form in the case study with that from forms created in a similar Euclidean geometry. In order to do this, three complex building forms were used. To make this comparison, the mass was transformed into approximately Euclidean geometry while keeping the location and floor area constant (except changing the rounded corners to the right angles), without distorting the ratios of the window openings.

CONTACT Asli Agirbas asliagirbas@gmail.com Department of Architecture, Fatih Sultan Mehmet Vakif University, Istanbul, Turkey

Background and literature review

Building performance analysis and architectural design

Computer programmes used for building performance analysis have been developing very rapidly. In order to reduce the variety of problems which arise in data transfer and competition between the programmes, programmers aimed to reduce the transition between different kinds of software. However, with different add-ons and plug-ins, the desired operation began to be done using a single interface. This allows the programme user to reduce the transfer between various different programmes and to use the method more quickly. Therefore, the use of building performance tools increased in the conceptual design phase as a result of a user-friendly interface and the availability of many online training materials. In the conceptual design phase – i.e. in the ill-structured (Goel 1992) design phase – the designer is actually involved in a sketching process. In this process, the designer becomes aware of new relationships, and can refine and revise them (Schon 1983; Garner 1992; Suwa and Tversky 1996). By incorporating performance parameters into this conceptual design process, the designer's thoughts can be shaped in relation to energy performance and building form.

A secondary output of the energy performance of the building, which is to be made at the beginning of the design process, is the consideration of comfort in the final use of the building. Environmental factors such as solar radiation and outside temperature affect the interior spaces of the buildings. In order to provide the desired comfort in the places, air conditioning and artificial lights, which consume energy, are used. However, if the form of the building is designed by considering such environmental factors, the use of the factors causing energy consumption will be reduced while providing comfort in the spaces. Consequently, the energy consumption of the building can be seriously reduced (Sun, Han, and Feng 2015). In order to provide comfort to the interior of the space, the holistic form of the building must be designed in consideration of the environmental factors, in order to reduce the energy consumption to a minimum.

Optimization algorithms related to building performance

In building performance analysis, various optimization algorithms were used to find the optimal solution according to how the problem is defined, for example, the use of evolutionary algorithms. These evolutionary algorithms include genetic algorithms (GA) (Wright and Farmani 2001; Charron and Athienitis 2006; Znouda, Ghrab-Morcos, and Hadj-Alouane 2007; Pernodet, Lahmidi, and Michel 2009; Yi and Malkawi 2009; Rakha and Nassar 2011; Turrin, von Buelow, and Stouffs 2011), particle swarm optimization (PSO) (Rapone and Saro 2012), simulated annealing (SA) (Michalek, Choudhary, and Papalambros 2002) or ant colony optimization. In addition, according to the definition of the design problem, linear optimization (Bouchlaghem and Letherman 1990; Peippo, Lund, and Vartiainen 1999; Saporito et al. 2001; Eisenhower, Fonoberov, and Mezic 2012) or hybrid algorithms (Hasan, Vuolle, and Siren 2008; Juan, Gao, and Wang 2010; Hamdy, Hasan, and Siren 2011), may also be used (Machairas, Tsangrassoulis, and Axarli 2014).

A designer may want to reduce one parameter while another increases. Therefore, because of this inter-relationship, the use of multi-objective optimization tools began to be used. These tools are useful to make optimization towards many objectives. The basis of the multi-optimization tool (Octopus), which is used in the present study, is based on genetic algorithms (Goldberg and Holland 1988; Bentley and Wakefield 1997). Octopus (developed by Vierlinger (2013, 2018), and available online), is an add-on to Grasshopper (working as a plug-in to the Rhino program) and is based on the SPEA-2 (Zitzler, Laumanns, and Thiele 2001) algorithm.

Complex form optimization

Those, who do form optimization studies in relation to building performance (Caldas and Norford 2002; Caldas 2008; Flager et al. 2009; Welle, Haymaker, and Rogers 2011; Sun, Han, and Feng 2015), usually do experiments using forms in the Euclidean geometry. Euclidean geometries were used extensively in the building industry until now, not because they are better geometries, but easier to create and usable (Kotnik 2013). These forms usually consist of simple forms. Thus, the variables of geometry usually include parameters such as length, height and depth. However, a building with a more complex geometry may be a more energy efficient building. As a result of optimization of the geometry of the building, which may have many different complex form alternatives, the closest results can be obtained to the desired performance. Moreover, when we consider the practices of contemporary architecture, it is clear that they are directed toward the creation of complex geometries (Burry and Burry 2012; Helenowska-Peschke 2012; Bellone, Fiermonte, and Mussio 2017).

Minimal surface based form optimization (MSO)

Objectives, constraints, variables

In models developed with multi-objective optimization, it is useful to collectively define objectives, constraints, and variables, since their components will be run simultaneously in the script. In this study, it was intended to make a building form optimization study, following determined objectives, variables and constraints, by means of a complex form.

Minimal surfaces are able to depart from right angles being characteristic of Euclidean forms. Therefore, a minimal surface form was used because it can transform into curvilinear forms and thus create various spatial configurations, during the optimization process. Minimal surface is a branch of mathematics and exists in various forms (Figure 1). Minimal surfaces are surfaces that are formed by covering the smallest area within given boundaries in 3D space, and in mathematical terms, they are surfaces that minimize their areas on a local scale (Velimirović et al. 2008; Emmer 2013). In this work, while the curves basically create form, the minimal surface, which was connected with the curves, also shape the upper part of the form (roof). Thus, during the optimization process, the form occurs with curvilinear lines (i.e. more freely) instead of sharp lines. Thus, in this study, a model was created that allows the form to move more freely during the optimization process and can create more complex forms. The

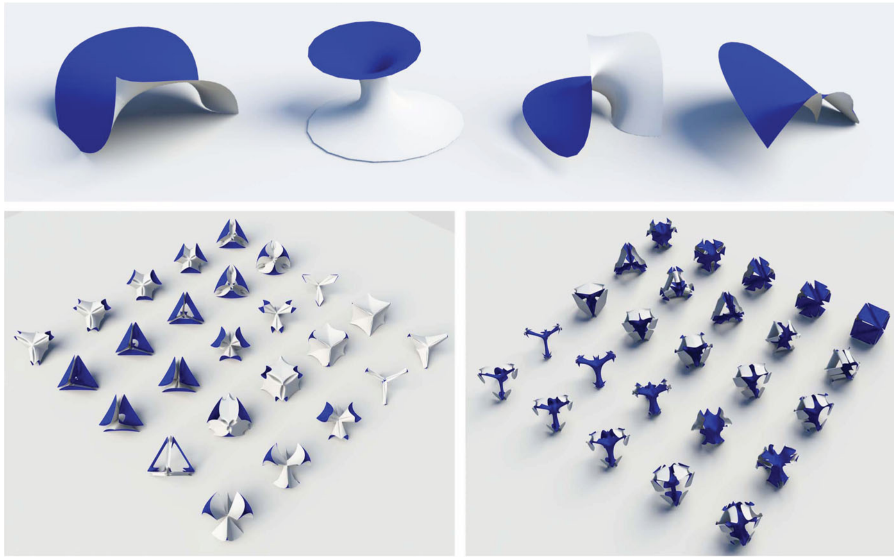


Figure 1. Various morphologies, which are based on minimal surface, were modelled by the author.

forms that were produced using the MSO model are referred to as complex forms in the inferences of this study.

As mentioned in the introduction, the design objectives of this form optimization study were defined as: maximizing the floor surface area, maximizing the daylighting and minimizing the radiation. According to this model, for which the minimal surface form was used, the form of building can be optimized more freely related to 3 objectives (daylighting, radiation, and floor area).

In this study, the site constraints were defined manually according to the width and height limits that can be attained by the form on the selected site. Thus, the maximum bounds, to which the form can reach in 2D and 3D, were determined. In addition, the designer also defines the function of building as a constraint, since its function will be an effective element in the daylighting objective. Variables are defined to be all geometric parameters that form the minimal surface based form.

Methodology

Computer software

In this work, various software and various simulation tools related to these software were used. The Grasshopper program, which basically works as a Rhino program plug-in and is a visual programming language, was the fundamental platform for the optimization simulation. In addition, many programmes, which work as an add-on to Grasshopper, were used. Octopus add-on as a GA-based multi-optimization tool, Honeybee add-on for daylight analysis (Honeybee connects Grasshopper to simulation engines such as EnergyPlus, Radiance, Daysim and OpenStudio), Ladybug add-on for radiation analysis (import and analyze standard weather data), MinSurf add-on for creating minimal surface geometry were used (Figure 2).

Model set up

The script used in this study was created by connecting the multi-objective optimization engine to the relevant add-ons according to the specified objectives. The Rhino platform (3D environment) for visual data, the Grasshopper platform (visual programming language) for visual coding data, and various other programmes running in the background (EnergyPlus, Radiance, Daysim and OpenStudio) were used in conjunction with Honeybee and Ladybug add-ons for simulation data (Figure 2). It is possible to examine this script in 2 parts: the design formulation part and the generative process part (Figure 3).

The parametric model was first produced in the design formulation part of the script. This parametric model is based on the creation of a minimal surface geometry over curves. Thus, the geometry to be formed during the optimization process can be shaped more freely, and more energy-efficient forms can be obtained. The MinSurf add-on was used to achieve this minimal surface form, since it is a suitable programme for producing many different types of minimal surface form (Figure 1). The variable ranges of the parametric model must be set according to the site constraints, and when generating this parametric model, the parcel area and altitude limit were taken into consideration, in relation to these. By doing this, the moving limit of the curves employed in the optimization process was determined according to these site constraints. The designer can change the minimum and maximum values of the variables of the parametric model by employing feedback according to the site constraints (Figure 3). In addition, parametric surface gaps were formed on the determined surfaces of the parametric model that was created, and which represent windows of the facade. Detailed descriptions of these stages can be found in Table 1. In order to discover the building form of best performance, variable ranges of all the parameters related to this geometry are defined as genes for the GA run.

In the design formulation section, the necessary components were added to the script following the specified objectives (maximizing the floor surface area, maximizing the daylighting and minimizing the radiation) (Figure 3). The Honeybee add-on, which acts as an add-on to the Grasshopper programming platform, is used to make a daylighting analysis of the created geometry, and was advanced over the script developed by Roudsari

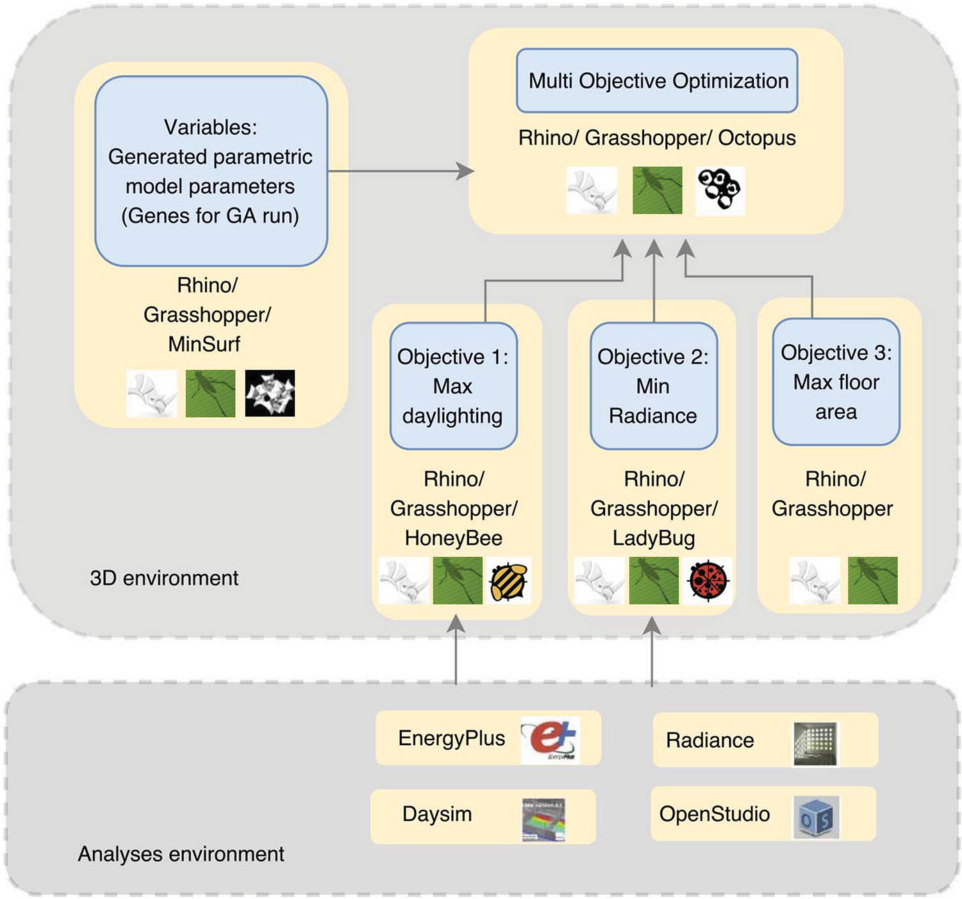


Figure 2. Software platforms for the generative process of minimal surface based form optimization.

and Pak (2013). Since the required daylighting level for each building function is different, the particular function must be specified in the script. Accordingly, in the present study, the function of the geometry was determined as being an office building, and additionally, a climate based daylighting model was used. Accordingly, the daylighting level was calculated on an annual basis. The operational hours of the office building were set to be 9 am and 6 pm, and the interior space of the office was analyzed using virtual sensor points. New York weather data (New York City, 94728 in epw format) was used for the annual daylight simulation.

Considerable savings in energy use can be achieved by means of well-designed lighting controls. The light levels preferred by office workers vary significantly from person to person. For example, Escuyer and Fontoynont (2001) found that people working with computers prefer light of intensity 100–300 lux, while those who spend less time on a computer prefer higher levels of 300–600 lux (Galasiu and Veitch 2006). In this study, Daylight Autonomy (DA), Daylit Area (DA300lx [50%]), Mean Daylight Factor (DF), Continuous Daylight Autonomy (cDA) and Useful Daylight Illuminance (UDI) data could be obtained as a result of the daylighting analysis, which was carried out in relation to the building form and its windows. The Daylight Factor (DF) measures the ratio of internal illumination to external illumination (Bian and Ma 2017). Daylight Autonomy (DA) measures the daylight performance (Reinhart and Walkenhorst 2001; Bian and Ma 2017) annually according to the facade orientation and location of the building. Yilmaz (2016) has expressed the following about DA, 'This metric is represented as a percentage of the annual hours that a given point in a space is above the required illumination level with the use of daylighting only.' Brembilla, Hopfe, and Mardaljevic (2018) have noted that, 'Useful Daylight Illuminance (UDI) predicts the occurrence of illuminance within ranges, and the occurrence of illuminances outside those ranges'. Accordingly, the illumination ranges are as follows: non-sufficient daylight illuminance ($<$ 100 lux), useful daylight illuminance (100–2000 lux), daylight illuminance that exceeds required levels ($>$ 2000 lux) (Nabil and Mardaljevic 2005; Yilmaz 2016). Continuous Daylight Autonomy (cDA) is a version of Daylight Autonomy (DA), and when this is used, if the illuminance level in the space is lower than the required illuminance level, partial credit is attributed to time-steps (Rogers and Goldman 2006; Carlucci et al. 2015). According to Brembilla, Hopfe, and Mardaljevic (2018),

> Daylit Area (DA300[50%]) is portion of the working plane that complies with DA requirements for more than 50% of the occupied time. The concept is similar to that of Spatial Daylight Autonomy (sDA), but without considering any model for the operation of dynamic shadings.

In the present study, no limit was set for the daylighting level. Together with the other objectives, the highest daylight value was searched for using the optimization process. However, if requested, the daylight level to be received can easily be limited.

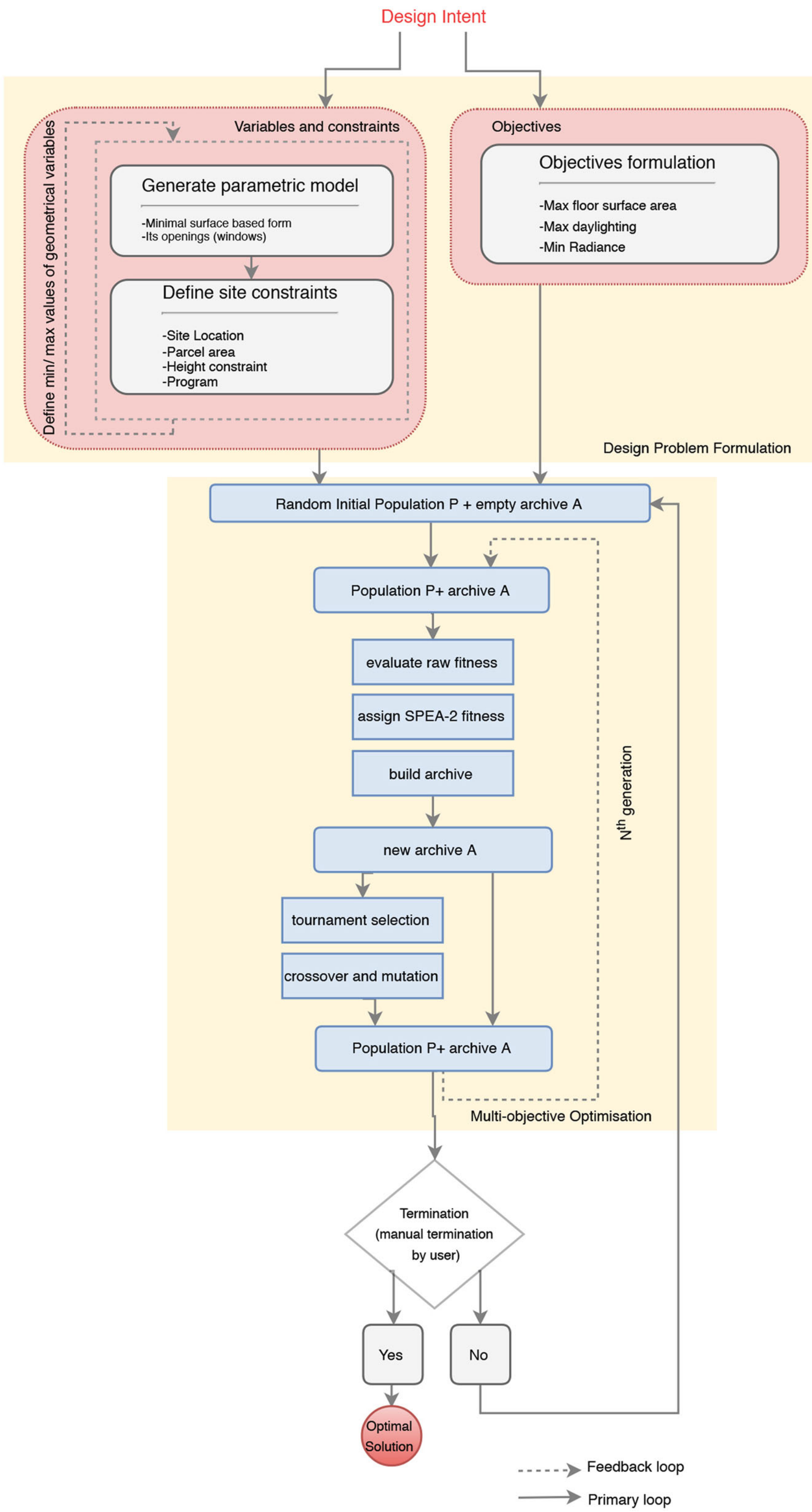


Figure 3. The algorithmic workflow of the multi-objective optimization for a minimal surface based form.

For the radiation analysis of the created geometry, the Ladybug add-on, was used, which acts as an add-on to Grasshopper. This was progressed over the script developed by Roudsari and Pak (2013). In order to simulate the annual radiation, New York weather data (New York City, 94728 in epw format) was used. In the optimization process, the script was arranged so to reduce the annual radiation received by the roof of the building in relation to the form. Detailed descriptions of these stages can be found in Table 2.

In order to maximize the floor area, which is a further objective, the floor area output obtained during the creation of the parametric geometric model was connected to the

Table 1. Creation of the parametric geometry.

	Creation process/ Definition	Variables	
Creation of the General Geometry	• First, a set of points was created. In this series, the number of points in each coordinate (X, Y, Z), and the distance between the points and the position of the starting point were defined parametrically. Thus, a parametric curve could be generated from this series of points. A second parametric curve was then formed by repetition of same procedure. • For the creation of the minimal surface, from the minimal surface component, 4 curves are required, which are related to the start and end points of each other as inputs. Thus, the starting and ending points of the 2 created curves were found, and these points were defined as the starting and ending points for the generation of the other 2 curves. From the points, which were obtained as output, new curves were obtained. 4 curves were used as inputs and a minimal surface was obtained. • 4 curves were projected to the ground level. These projected curves were lofted with 4 curves used to produce a minimal surface, and the projected curves were used to form a base surface (floor surface area). By this procedure, the sub-structure of the plan schema and the volume of the mass to be generated during the optimization simulation were determined. In addition, in this volume, parametric windows were added to the selected lateral surfaces with the offset of related curves. These windows were also included as variables in the optimization process.	1st curve	X starting point X number of points X distance between the points Y starting point Y number of points Y distance between the points Z number of points Z distance between the points
		2nd curve	X starting point X number of points X distance between the points Y starting point Y number of points Y distance between the points Z number of points Z distance between the points
		Area Offset distance of 1st curve Offset distance of projected curve of the 1st curve Offset distance of 2nd curve Offset distance of projected curve of the 2nd curve	

Table 2. Creation of optimization simulation.

	Creation process/ Definition	Simulation outputs	Output units
Daylighting Simulation	• Firstly, in order to determine the zone, where the daylight analysis is to be done, the created parametric geometry and its parametric window openings were defined in terms of the related Honeybee components. Later, other necessary data (weather data file, virtual sensor points, function of the building, operational hours of the building) were defined in terms of the related Honeybee components so that the annual daylighting simulation could be performed. These components were then connected to the main component of the Honeybee daylight simulation, in order to create the sub-structure of the simulation.	Daylight Autonomy (DA) Daylit Area (DA300lx [50%]) Mean Daylight Factor (DF) Continuous Daylight Autonomy (cDA) Occupancy Useful Daylight Illuminance (UDI)	% % % % hour per year three illumination ranges: 0–100 lux, 100–2000 lux, or over 2000 lux
Radiation Simulation	• In order to simulate the annual radiation flux, the necessary data (the created parametric geometry, weather data file, and surrounding building masses) were defined in terms of the related Ladybug components. The latter were connected to the main component of the Ladybug radiation simulation, in order to create the sub-structure of the simulation.	Radiation	kWh/m^2
Optimization Simulation	• All the values that affecting the volume (values in the parametric geometry) were connected to the Genome input of the Octopus programme. • For the purpose of increasing average daylighting (first objective) in the space, the values obtained from the daylighting simulation were used in Octopus's multi-objective search input (fitness value). In order to reduce the radiation input (secondary objective), the total radiation value obtained as a result of radiation analysis simulation was put into the multi-objective search (fitness value) of Octopus. For the purpose of increasing the area covered by the form (third objective), the value of its floor area was input to the multi-objective search (fitness value) of Octopus. In order to ensure that the volume of the form did not become overly decreased in the direction of the other parameters, the floor area value of the form was limited to occupy a minimum of 500 m^2.	The best solution space values: - the variables (distance based) - the variables (number based) - floor surface area - daylighting simulation results - and radiation simulation results	 m N/A m^2 % kWh/m^2

multi-objective optimization engine. When the initial optimization set up is generated, minimum and maximum values for these 3 objectives can be used by the designer as inputs.

After the designer has made a definition of constraints, variables and objectives, the initial solution space is automatically generated. To find the best building performance, the GA-based multi-objective optimization engine, Octopus, which is included in the script, is initiated by the designer, hence beginning the generative process. Thus, the simulation process begins, which employs the EnergyPlus, Radiance, Daysim and OpenStudio programmes via Honeybee and Ladybug add-ons to perform daylighting and radiation simulations. This generative process, acting in the direction of form-performance relationship, maximizes daylight-intake in the space as a first objective (via Honeybee), minimizes the flux of radiation on the roof as a second objective (via Ladybug), and maximizes the floor surface area as a third objective. The optimum solution is searched for in terms of the combination of the variable values of parametric geometry generated by using a minimal surface (via MinSurf) (Figure 2). While simulations are being made for forms created with different variable values (values related to parametric geometry), Octopus tries to find the best solution (in the direction of defined objectives) using the principles of genetic algorithm. In this multi-objective optimization process, the script produces a variety of alternatives for the designer (Figure 3).

The production of this variety of alternatives is related to the generations produced in the multi-optimization process, which in turn depend on the principles of the SPEA-2 algorithm. The Octopus add-on is based on the SPEA-2 (Strengh-pareto evolutionary algorithm for multi-objective optimization- core algorithm) algorithm. Vierlinger (2013) implemented the original state of the SPEA-2 algorithm published by Zitzler, Laumanns, and Thiele (2001) to Octopus add-on. As may be seen by Figure 3, when we consider the generative process of this algorithm (the process of creating the N^{th} generation), we immediately see that a random population is generated, and then an evaluation is made of 'raw fitness', which is the calculation of the objective value of each solution in the pool: then 'SPEA-2 Fitness' is assigned. Here, the Pareto-Principle goes into effect and a single fitness value is calculated, which is necessary for the genetic algorithm. It is then passed to the 'Build archive' process. The best solutions are kept in the archive. The solutions that are considered to be the best are transferred from each generation onto the next generation, hence becoming a process of 'Breeding a new population'. In order to be evaluated in the next generation, a new set of individuals is created. When this process is carried out in SPEA-2, Tournament Selection by Pareto-Principles is done in order to select mating individuals. Then, the genes of the selected individuals are exchanged with the 'crossover', and a single individual is mutated with 'mutation' (Vierlinger 2013) (Figure 3).

Finally, the designer stops the simulation and evaluates the results. If the results do not meet the designer's expectations (this could be particular daylighting, floor surface area or radiation value), the simulation can either be continued or restarted (Figure 3).

New York City office building studies

In this section, the Minimal Surface Based Form Optimization (MSO) script, the development of which was based on 3 objectives (reducing radiation, increasing daylight in the space and increasing the floor surface area), was tested. At the end of the simulation, 3 optimized conceptual forms were evaluated.

Later, by comparing the complex and Euclidean forms, the effect of the architectural form on daylighting was visualized, and this was determined quantitatively (DA, DF, cDA, UDI) simultaneously with the change in radiation values. On the basis of this comparison, although some prediction is possible of the variation of the daylight distribution, this cannot be predicted quantitatively because the detailed values also depend on other factors, as is mentioned in the previous section. Therefore, they must be calculated directly in order to understand the change.

Set-up

In this study, the site location of the form to be optimized was defined to be New York City (Hudson St, St Luke's Pl, Clarkson St, 7 Av) and its function was defined as an office (Table 3). The reason for choosing New York City for the case study is to include the shade effect of skyscrapers within the simulation. Hence, for this particular location, the effect of shading will be pronounced in the simulation analysis, and will vary over an annual period.

The maximum limit that the parametric model can expand to was determined by considering the site constraint. The parcel area with the site constraint was 65 metres by 90 metres in size; the height constraint of the area was assumed to be 20 metres, and variable ranges were defined according to these values. The limit of minimum value of the floor surface area was defined as 500 m^2, while a restrictive limit was not defined in maximizing daylighting and minimizing the radiation (Table 3). Thus, a very small-sized building was prevented from being formed during the optimization process. After the set-ups were made, the optimization simulation was started using the Octopus tool.

Optimization simulation

As a result of this optimization simulation, several values were obtained (Figure 4). With the specified objectives, 3 generations were produced during the optimization simulation. Accordingly, as understood from the result values of each generation, optimization simulation was trying to increase the area and daylight values, while it was trying to reduce the radiation value.

The graphical representation of a combination of alternative values which result from the optimization simulation is created at the Octopus interface. In the context of the present case study, the combination of those 3 objective values, which do not differ significantly between them, were selected. This leads the designer to focus on the combination of the values in the middle of the 3-axis graph (Figure 4). It was thought that a single form type would not be sufficient for evaluations, and it was considered appropriate to test other types of form. Therefore, the results of the 3 combination values were examined and the outputs are given below in separate sections. From the result of the examination of 3 forms created from these combination values, the same inferences related to the 3 forms were reached. Thus, the generalizations, which were mentioned in the following section, could be made.

Case 1

At the end of the optimization simulation, three combination values were chosen for evaluation, the first of which is termed

Table 3. 20 variables and 3 objectives connected to multi-objective optimization engine.

Constraints	Site location	Hudson St, St Luke's Pl, Clarkson St, 7 Av, New York
	Parcel area	65 metres to 90 metres = 5850 m^2
	Height constraint	20 metres
	Programme	Office building

Site Plan

Variables			Explanation of variable	No	Range		Unit	Type
					Min	Max		
	1st curve	X	starting point	1	0	20	m	integers
			number of points	2	1	9	N/A	integers
			distance between the points	3	1	10	m	including decimal values
		Y	starting point	4	0	20	m	integers
			number of points	5	1	13	N/A	integers
			distance between the points	6	1	5	m	including decimal values
		Z	starting point	-	1 (constant)		m	N/A
			number of points	7	1	10	N/A	integers
			distance between the points	8	1	2	m	including decimal values
	2nd curve	X	starting point	9	0	20	m	integers
			number of points	10	1	9	N/A	integers
			distance between the points	11	1	10	m	including decimal values
		Y	starting point	12	0	20	m	integers
			number of points	13	1	13	N/A	integers
			distance between the points	14	1	5	m	including decimal values
		Z	starting point	-	1 (constant)		m	N/A
			number of points	15	1	10	N/A	integers
			distance between the points	16	1	2	m	including decimal values
	offset distance of 1st curve			17	0	10	m	including decimal values
	offset distance of projected curve of the 1st curve			18	−10	0	m	including decimal values
	offset distance of 2nd curve			19	0	10	m	including decimal values
	offset distance of projected curve of the 2nd curve			20	−10	0	m	including decimal values
Objectives	**Explanation of objective**			**No**	**Min**	**Max**	**Unit**	**Increase / Decrease**
	Daylighting			1	-	-	%	Increase
	Radiation			2	-	-	kWh/m^2	Decrease
	Floor surface area			3	500 m^2	around 5850 m^2*	m^2	Increase

* This data was limited to the max values of the variables of the points forming the curves of the form in the direction of parcel width.

Case 1, and the form obtained from a combination of values for this, and the according changing of the variables can be seen in Table 4.

At the end of the optimization, the values of the variables in Case 1 are as follows: The start points of the 1st curve in the coordinate system are 9 m (X direction) and 18 m (Y direction). The number of points forming the 1st curve are 2 (X direction), 11 (Y direction), 5 (Z direction). The distance between these points are 5.408 m (X direction), 1.817 m (Y direction), 1.234 m (Z direction). The start points of the 2nd curve in the coordinate system are 8 m (X direction) and 3 m (Y direction). The number of points forming the 2nd curve are 6 (X direction), 9 (Y direction), 6 (Z direction). The distance between these points are 6.627 m (X direction), 2.785 m (Y direction), 1.515 m (Z direction). The distances of curves in the creating window openings are as follows: Offset distance of 1st curve is 9.102 m, offset distance of projected curve of the 1st curve is −0.686 m, offset distance of 2nd curve is 8.593 m, offset distance of projected curve of the 2nd curve is −9.662 m (Table 4).

Accordingly, the values that define parametric geometry appear to vary widely. For example, it appears that the start points (X starting point, Y starting point) of the curves in the coordinate system are positioned so to create the most optimized form. The number of points forming the curve (X number of points, Y number of points, Z number of points), the distance between these points (X distance between the points, Y distance between the points, Z distance between the points), the distances of curves creating window openings (Offset distance of 1st curve, Offset distance of projected curve of the 1st curve, Offset distance of 2nd curve, Offset distance of projected curve of the 2nd curve) seem to be differentiated again according to the same objective.

When we look at the form, which was created from the combination of daylight autonomy value: 71%, average radiation value: 832922 kWh/m^2, and the area covered by the form: 603.473 m^2, we see that the form was located in the south direction within the parcel area limits. A maximum height of 8.575 m and a volume of 3359 m^3 were found in the created form. The area occupied by the window opening created in the north (the big one): 189.59 m^2, and the area occupied by the window opening created in the south (the smaller one): 15.03 m^2 were found (Table 4). Thus, the conceptual form of the building was shaped according to the determined objectives and constraints of the optimization, and can be seen to

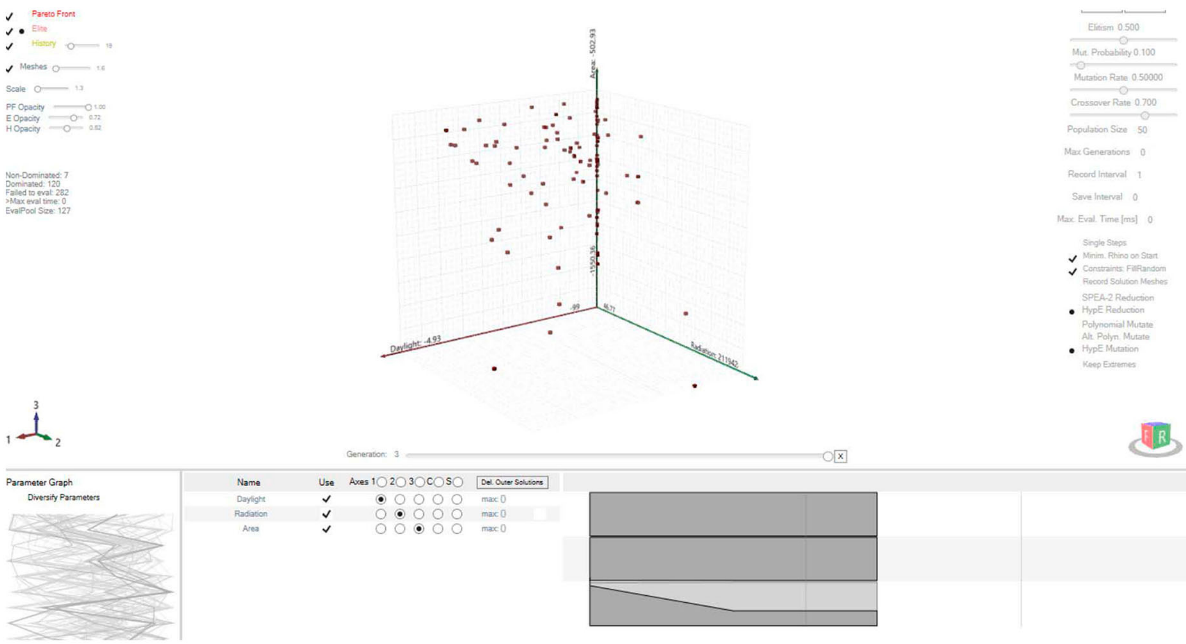


Figure 4. The graphical representation of optimization results in the Octopus interface.

depart from the right angles that are a feature of Euclidean geometry.

Case 2

The second combination of values selected for evaluation is termed Case 2, from which the form obtained, and the accordingly changed variables can be seen in Table 5.

At the end of the optimization, it can be seen that the variables in Case 2 are as follows: The start points of the 1st curve in the coordinate system are 5 m (X direction) and 4 m (Y direction). The number of points forming the 1st curve are 6 (X direction), 1 (Y direction), 6 (Z direction). The distance between these points are 7.522 m (X direction), 4.301 m (Y direction), 1.814 m (Z direction). The start points of the 2nd curve in the coordinate system are 7 m (X direction) and 18 m (Y direction). The number of points forming the 2nd curve are 9 (X direction), 7 (Y direction), 3 (Z direction). The distance between these points are 3.949 m (X direction), 3.081 m (Y direction), 1.195 m (Z direction). The distances of curves in the creating window openings are as follows: Offset distance of 1st curve is 8.297 m, offset distance of projected curve of the 1st curve is −7.505 m, offset distance of 2nd curve is 1.796 m, offset distance of projected curve of the 2nd curve is −1.273 m (Table 5).

Similarly to Case 1, in Case 2, the variable values of parametric geometry appear to be differentiated according to the objectives, although the actual variable values are completely different from those in Case 1.

When we look at the form, which was created from the combination of daylight autonomy value: 78%, average radiation value: 830206 kWh/m^2, and area covered by the form: 615.990 m^2, we see that the form was located in the west direction within the parcel area limits. A maximum height of 10.07 m and a volume of 3098 m^3 were found in the created form. The area occupied by the window opening created in the north (the big one): 238.73 m^2, and the area occupied by that in the south (the smaller one): 14.14 m^2 were found (Table 5). Thus, as in Case 1, the conceptual form of the building was shaped according to the determined objectives and constraints by means of the optimization procedure, and again departs from the Euclidean geometry, with its curved lines.

Case 3

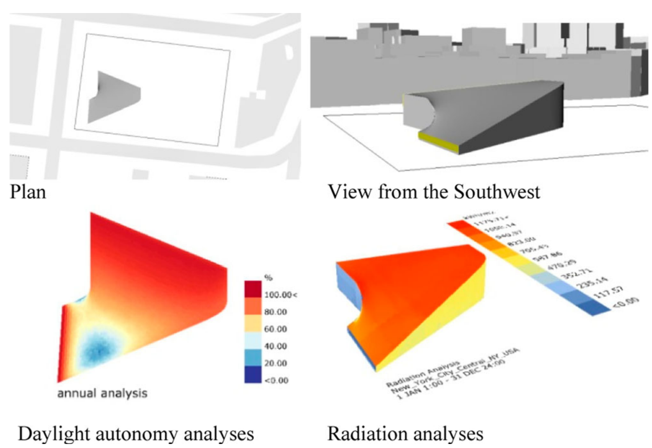
The third combination of values selected for evaluation is termed Case 3, for which the resulting form, along with the accordingly changed values of the variables can be seen in Table 6.

At the end of the optimization for Case 3, the following values were obtained: The start points of the 1st curve in the coordinate system are 9 m (X direction) and 14 m (Y direction). The number of points forming the 1st curve are 1 (X direction), 10 (Y direction), 10 (Z direction). The distance between these points are 4.935 m (X direction), 4.936 m (Y direction), 1.845 m (Z direction). The start points of the 2nd curve in the coordinate system are 17 m (X direction) and 5 m (Y direction). The number of points forming the 2nd curve are 5 (X direction), 1 (Y direction), 7 (Z direction). The distance between these points are 9.976 m (X direction), 2.214 m (Y direction), 1.945 m (Z direction). The distances of the curves employed in the creation of the window openings are as follows: Offset distance of 1st curve is 4.453 m, offset distance of projected curve of the 1st curve is −5.729 m, offset distance of 2nd curve is 2.521 m, offset distance of projected curve of the 2nd curve is −7.906 m (Table 6).

As in Case 1 and Case 2, in Case 3, the variable values of parametric geometry seem to be differentiated according to the objectives, although the values of the variables are completely different from those in both Case 1 and Case 2.

When we look at the form, which was created from the combination of daylight autonomy value: 74%, average radiation value: 2044900 kWh/m^2, and area covered by the form: 1243.611 m^2, we see that the form spreads widely within the

Table 4. The first selected combination of the values (Case 1), the obtained form from this combination, and the changed values of the variables accordingly (one of the dominated solutions that emerged as a result of the optimization).

Combination of the values of the objectives	Daylighting	Daylight Autonomy (DA)	71%
		Daylit Area (DA300lx [50%])	84% of floor area
		Mean Daylight Factor (DF)	4.1%
		Continuous Daylight Autonomy (cDA)	85%
		Useful Daylight Illuminance (UDI)	UDI $_{<100–2000\text{lux}}$
		Occupancy	2555 hours per year
	Radiance		832922 kWh/m^2
	Area		603.473 m^2
Values of the variables (genes)	Geometry generation	1st curve X starting point	9 m
		X number of points	2
		X distance between the points	5.408 m
		Y starting point	18 m
		Y number of points	11
		Y distance between the points	1.817 m
		Z number of points	5
		Z distance between the points	1.234 m
		2nd curve X starting point	8 m
		X number of points	6
		X distance between the points	6.627 m
		Y starting point	3 m
		Y number of points	9
		Y distance between the points	2.785 m
		Z number of points	6
		Z distance between the points	1.515 m
	Geometry openings generation	Offset distance of 1st curve	9.102 m
		Offset distance of projected curve of the 1st curve	−0.686 m
		Offset distance of 2nd curve	8.593 m
		Offset distance of projected curve of the 2nd curve	−9.662 m
Constraints	Site Locat.	Hudson St,St Luke's Pl, Clarkson St,7 Av, New York	
	Parcel area	65 metres to 90 metres = 5850 m^2	
	Height	20 metres	
	Programme	Office building	
The obtained form	Views		
	Geometric properties	Volume of the obtained form:	3359 m^3
		Max height of the obtained form:	8.575 m
		The occupied area of the obtained window opening in the north (the big one):	189.59 m^2
		The occupied area of the obtained window opening in the south (the small one):	15.03 m^2

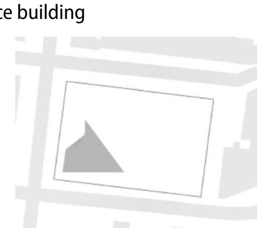
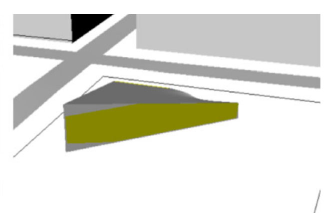
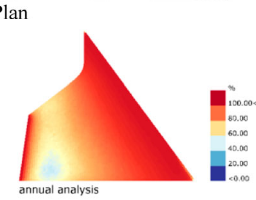
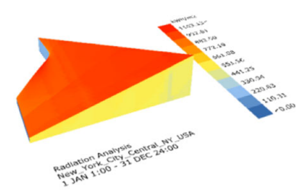
parcel area limits. A maximum height of 17.605 m and a volume of 12154 m^3 were found in the created form. The area occupied by window opening created in the north (the big one): 354.45 m^2, and the area occupied by that in the south (the smaller one): 12.04 m^2 were found (Table 6). Hence, as in Case 1 and Case 2, the conceptual form of the building was shaped according to the determined objectives and constraints by optimization, and which was once again removed from the right angles that are characteristic of an Euclidean geometry.

In these three types examined, we see that the forms differ from the Euclidean geometry and that the forms differ in the direction of the objectives given to the optimization simulation. Thus, the edges of the forms reached different heights. The window openings and their forms were differentiated. Floor surface areas of the conceptual mass in the site were obtained. In addition, minimal surface, which provides the roof surface, could be formed.

Discussion

The selected complex alternative forms that resulted from the optimization have also been modelled in terms of similar forms

Table 5. The second selected combination of the values (Case 2), the obtained form from this combination, and the changed values of the variables accordingly (one of the non-dominated solutions that emerged as a result of the optimization).

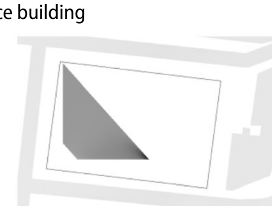
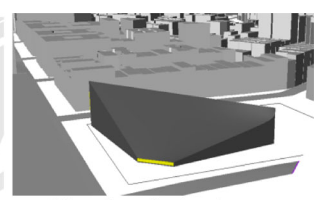
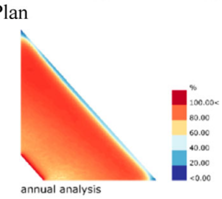
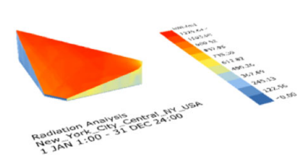
Combination of the values of the objectives	Daylighting	Daylight Autonomy (DA)	78%
		Daylit Area (DA300lx [50%])	95% of floor area
		Mean Daylight Factor (DF)	5.6%
		Continuous Daylight Autonomy (cDA)	88%
		Useful Daylight Illuminance (UDI)	UDI $_{<100\text{–}2000lux}$
		Occupancy	2555 hours per year
	Radiance		830206 kWh/m^2
	Area		615.990 m^2
Values of the variables (genes)	Geometry generation	1st curve X starting point	5 m
		X number of points	6
		X distance between the points	7.522 m
		Y starting point	4 m
		Y number of points	1
		Y distance between the points	4.301 m
		Z number of points	6
		Z distance between the points	1.814 m
		2nd curve X starting point	7 m
		X number of points	9
		X distance between the points	3.949 m
		Y starting point	18 m
		Y number of points	7
		Y distance between the points	3.018 m
		Z number of points	3
		Z distance between the points	1.195 m
	Geometry openings generation	Offset distance of 1st curve	8.297 m
		Offset distance of projected curve of the 1st curve	−7.505 m
		Offset distance of 2nd curve	1.796 m
		Offset distance of projected curve of the 2nd curve	−1.273 m
Constraints	Site Locat.	Hudson St,St Luke's Pl, Clarkson St,7 Av, New York	
	Parcel area	65 metres to 90 metres = 5850 m^2	
	Height	20 metres	
	Programme	Office building	
The obtained form	Views	 Plan  View from the Northwest  Daylight autonomy analyses  Radiation analyses	
	Geometric properties	Volume of the obtained form:	3098 m^3
		Max height of the obtained form:	10.07 m
		The occupied area of the obtained window opening in the north (the big one):	238.73 m^2
		The occupied area of the obtained window opening in the south (the small one):	14.14 m^2

with a Euclidean geometry, and comparisons made between the two.

The most prominent feature of many Euclidean geometries is that the surfaces are mutually connected at right angles. To do this, the mass was considered in 2 parts, taking into account the parts of the minimum height and the parts of the maximum height. In this way, both the minimum and maximum heights of the form are preserved and the roof surfaces are connected at right angles to the lateral surfaces. In the process of partitioning the form into two parts, the partition place is defined by taking into account the angularity in the plan form, or if there is no angularity in the plan form, then it is divided into 2 equal parts. The Rhino 3D modelling platform was used for this process.

It was determined that complex forms (forms in case 1, case 2 and case 3) received more daylight as a result of daylighting analysis, whereas those forms in the similar Euclidean geometry admitted less daylight. In Case 1, the daylight autonomy value for complex geometry was 71%, while the daylight autonomy value for the similar Euclidean geometry was 49% (Table 7). In Case 2, the daylight autonomy value for complex geometry was

Table 6. The third selected combination of the values (Case 3), the obtained form from this combination, and the changed values of the variables accordingly (one of the non-dominated solutions that emerged as a result of the optimization).

Combination of the values of the objectives	Daylighting	Daylight Autonomy (DA)	74%
		Daylit Area (DA300lx [50%])	89% of floor area
		Mean Daylight Factor (DF)	3.6%
		Continuous Daylight Autonomy (cDA)	85%
		Useful Daylight Illuminance (UDI)	UDI $_{<100–2000lux}$
		Occupancy	2555 hours per year
	Radiance		2044900 kWh/m^2
	Area		1243.611 m^2
Values of the variables (genes)	Geometry generation	1st curve X starting point	9 m
		X number of points	1
		X distance between the points	4.935 m
		Y starting point	14 m
		Y number of points	10
		Y distance between the points	4.936 m
		Z number of points	10
		Z distance between the points	1.845 m
		2nd curve X starting point	17 m
		X number of points	5
		X distance between the points	9.976 m
		Y starting point	5 m
		Y number of points	1
		Y distance between the points	2.214 m
		Z number of points	7
		Z distance between the points	1.945 m
	Geometry openings generation	Offset distance of 1st curve	4.453 m
		Offset distance of projected curve of the 1st curve	−5.729 m
		Offset distance of 2nd curve	2.521 m
		Offset distance of projected curve of the 2nd curve	−7.906 m
Constraints	Site Locat.	Hudson St,St Luke's Pl, Clarkson St,7 Av, New York	
	Parcel area	65 metres to 90 metres = 5850 m^2	
	Height	20 metres	
	Programme	Office building	
The obtained form	Views	 Plan  View from the Southwest	
		 Daylight autonomy analyses  Radiation analyses	
	Geometric properties	Volume of the obtained form:	12154 m^3
		Max height of the obtained form:	17.605 m
		The occupied area of the obtained window opening in the north (the big one):	354.45 m^2
		The occupied area of the obtained window opening in the south (the small one):	12.04 m^2

78%, while the daylight autonomy value for the similar Euclidean geometry was 45% (Table 8). In case 3, the daylight autonomy value for the complex geometry was 74%, while the daylight autonomy value for the similar Euclidean geometry was 54% (Table 9).

Hence, the radiation analysis showed that complex forms (forms in case 1, case 2 and case 3) received less radiation and that the similar Euclidean geometric forms were exposed to more radiation. In Case 1, the radiation value for the complex geometry was 832922 kWh/m^2, while the radiation value for the similar Euclidean geometry was 873981 kWh/m^2 (Table 7). In Case 2, the radiation value for complex geometry was 830206 kWh/m^2, while the radiation value for similar Euclidean geometry was 917506 kWh/m^2 (Table 8). In Case 3, the radiation value for complex geometry was 2044900 kWh/m^2, while for similar Euclidean geometry, the radiation value was 2308700 kWh/m^2 (Table 9).

Hence, from these results, where the objectives in the optimization process are to increase daylighting, reduce radiation, while the floor area, window openings and location are kept constant, we can deduce that complex geometries are more energy efficient than are those in the similar Euclidean geometry. The primary reason for this is that the building form in complex geometry has curvilinear lines. The curvilinear lines

Table 7. Comparison of the analysis of Case 1 form with the analysis of the form converted to Euclidean geometry.

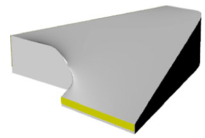
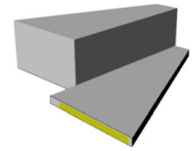
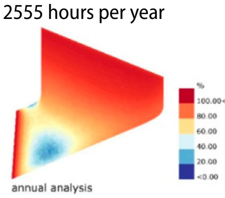
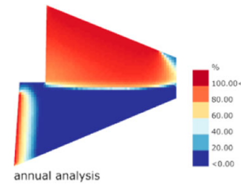
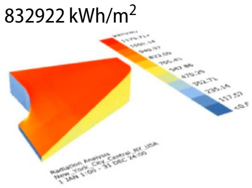
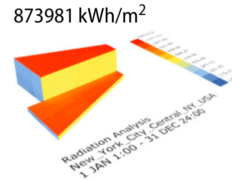
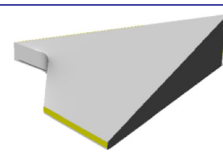
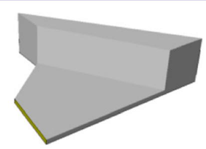
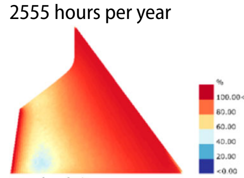
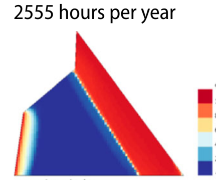
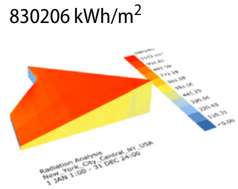
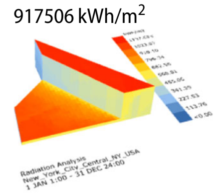
			Complex Geometry analyses results	Euclidean geometry analyses results
Case 1	Geometry			
	Daylighting	DA DA300lx[50%] DF cDA UDI Occupancy	71% 84% of floor area 4.1% 85% UDI $_{<100–2000lux}$ 2555 hours per year  Daylight autonomy analyses	49% 54% 4.6% 58% UDI $_{<100–2000lux}$ 2555 hours per year  Daylight autonomy analyses
	Radiance		832922 kWh/m^2  Radiation analyses	873981 kWh/m^2  Radiation analyses

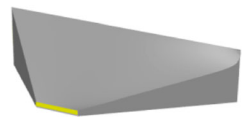
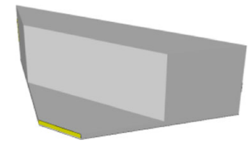
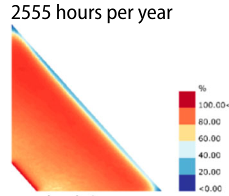
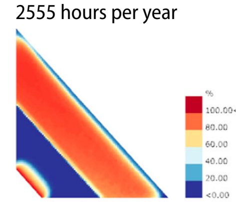
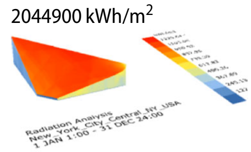
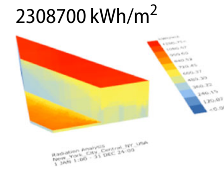
Table 8. Comparison of the analysis of Case 2 form with the analysis of the form converted to Euclidean geometry.

			Complex Geometry analyses results	Euclidean geometry analyses results
Case 2	Geometry			
	Daylighting	DA DA300lx[50%] DF cDA UDI Occupancy	78% 95% of floor area 5.6% 88% UDI $_{<100–2000lux}$ 2555 hours per year  Daylight autonomy analyses	45% 47% of floor area 5.5% 50% UDI $_{<100–2000lux}$ 2555 hours per year  Daylight autonomy analyses
	Radiance		830206 kWh/m^2  Radiation analyses	917506 kWh/m^2  Radiation analyses

can be shaped in various ways so that the mass can become more compatible with the determined building performance criteria.

In this study, the form limitation problem, which was encountered in previous form optimization studies related to the energy performance, has been largely eliminated. Thus, the complex

Table 9. Comparison of the analysis of Case 3 form with the analysis of the form converted to Euclidean geometry.

			Complex Geometry analyses results	Euclidean geometry analyses results
Case 3	Geometry			
	Daylighting	DA DA300lx[50%] DF cDA UDI Occupancy	74% 89% of floor area 3.6% 85% UDI <100–2000lux 2555 hours per year  Daylight autonomy analyses	54% 64% of floor area 3.2% 66% UDI <100–2000lux 2555 hours per year  Daylight autonomy analyses
	Radiance		2044900 kWh/m^2  Radiation analyses	2308700 kWh/m^2  Radiation analyses

form could be optimized in relation to the determined energy performance parameters.

Limitations and future work

In a study of this kind, the optimization process may be very time consuming, and so, in order to reduce the probability values in the process, minimum and maximum values can be determined for each objective, while keeping the interval between them small.

In this study, the minimal surface, which is a complex form, was used only as a roof cover. However, curved lines that can also show themselves on the lateral surfaces should also be investigated. Thus, it should be useful for this field of study to study different geometries including other curvilinear forms, as well as on the minimal surface.

Within the scope of this study (which focuses on form), floor surface area, daylighting and radiation parameters were investigated as objectives. However, different parameters (eg structure, acoustic parameters, etc.) can be included in the multi-objective optimization process. Thus, more parameters are employed in the early design process and design alternatives can be increased according to particular objectives.

This work focuses on finding the best conceptual mass form associated with the optimization of building performance. According to other parameters (e.g. the materials to be used, economic constraints etc.), objectives can be redefined, and accordingly the script can be modified. It should be noted that in this optimization study, it is neglected to create the floor slabs and those window openings, which are to be created according to these slabs. These parameters can also be included in the process in the next stage of the study. Also, studies of this kind for different sites with different weather data and site shading may be important for the comparison of the kind of forms that are created a as result of the optimization procedure.

Conclusion

Designing the holistic form of the building according to the environmental factors is a decision that must be given during the early design process. At this stage, many alternatives can be created for the form of the building, according to the determined environmental factors. Within these alternatives, the most optimal ones should be defined. For this, in this study, a model was developed using a multi-objective optimization tool. The results show that the model created in this study is capable of optimizing the minimal surface based form according to the determined objectives, constraints and variables. The developed model can provide a designer with many optimized complex alternative forms in relation to the building performance for the early design stage.

In contrast to the forms in the Euclidean geometry, the buildings having complex forms with their folds have the potential to be more harmonious with the environmental conditions. Thus we may conclude that, using this optimization model, more energy efficient building designs can be achieved. In addition, since the script was developed using a single interface and visual programming language, it allows users to easily optimize complex form in relation to its energy performance. It is also important for designers, and the scientific community more broadly, that other objectives can be included to this script using the same platform.

It should be noted that the limitations of the findings of the three cases include: to neglect the floor slabs in optimized conceptual forms, to provide the complexity only in the roofs of the conceptual forms, to limit the energy performance parameters with daylighting and radiation in the optimization process, and to study only on a specific site. These limitations must be considered in the future study to be done.

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