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Optimizing High rise Building form for energy performance using Generative Design Framework

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Abstract.

Knowing the significant impact of high-rise building form on solar heat gain, this paper proposes a generative design framework for finding the form achieving less solar heat gain in hot arid zone without detracting the functionality and aesthetic aspect. Among numerous design possibilities based on specific criteria, Generative design utilizing algorithms and optimization techniques can explore numerous design possibilities based on specific criteria. In this application, the goal is to identify building forms that reduce solar exposure while balancing functional and aesthetic needs. To achieve the work objective, Multi objective optimization (MOO) techniques like the Non-dominated Sorting Genetic Algorithm-II (NSGA-II) were used. The design parameters such as, orientation, plan shape …etc. will be inputs into generative design algorithms that will iteratively create and evaluate various design options to obtain the best possible design outcomes. The performance of each option will be verified using Solar exposure analysis, including sun path, shading, and energy simulation whilst the proposed design optimization focuses on two parameters, ie window-to-wall ratio (WWR), and energy use intensity (EUI). This paper illustrates how design of high-rise buildings can prioritize human well-being and environmental responsibility in addition to being landmarks.

Keywords: Generative design, solar heat gain, high-rise building, Form finding, design framework, Multi objective optimization.

1 Introduction

Building form, particularly high-rise building, is one of the most salient characteristics significantly affect environmental performance of a design solution. Environment. Preliminary architectural design is critical to the building's ultimate performance achieving a variety of goals [1]. High-rises envelop face numerous challenges, on the contrary low -rise ones, as, high-rise building are exposed

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to the solar radiation from all directions. That is leading to increasing building energy consumption related to cooling and discomfort for occupants, hindering their productivity and well-being.

Architectural Design Optimization workflow is used at early stage by decision-makers to guide the future evolution of architectural design [2]. The form-finding stage plays a crucial role in shaping the overall geometry and aesthetics of a high-rise building. Architectural Design Optimization (ADO) represents an energy-centric approach aimed at achieving high-performance objectives in design [3]. Consequently, there is a pressing need to develop innovative design strategies that mitigate the impact of solar radiation on high-rise buildings.

Traditionally, architects and engineers have relied on manual and intuition-driven methods to determine the form of a building. However, these approaches often neglect the complex interaction of environmental objectives and building geometry.

By leveraging generative design algorithms, architects and engineers can systematically explore a wide range of design options that consider solar radiation as a primary design constraint.

Building performance simulations and parametric modeling are combined by designers in simulation-based conceptual design of high-rise buildings to investigate efficient performance solutions [4]. In recent years, generative design has emerged as a promising approach in architecture and engineering. By utilizing algorithms and computational techniques, generative design enables architects and engineers to explore and generate countless design possibilities, leading to optimized design solutions.

This paper proposes a generative design framework for high-rise buildings. It optimizes building shape based on solar data to minimize energy use intensity (EUI) while prioritizing functionality. This reduces solar radiation exposure, leading to lower energy consumption and improved occupant comfort, promoting sustainable design.

2 Literature Review

Designing high-rise buildings is a complex architectural task due to the wide variety of design factors. Currently, parametric-based CAAD tools give architects the possibility of generating complex forms for tall buildings, the ability to monitor their responses to form changes, and finally generate the optimum form. [5].

Generative design has gained popularity in recent years due to its ability to optimize designs for specific criteria, including sustainability. Researchers have explored the use of generative design in creating sustainable high-rise buildings that respond to the environment. For example, researchers [6] are utilizing generative design to optimize the orientation and shape of a high-rise building in Seoul, Korea, to maximize solar energy generation while minimizing the building’s energy consumption, as, the optimized design resulted in a 30 % reduction in energy consumption compared to the baseline design.

“In supertall building design, early architectural form development is critical and can have substantial implications for the later stages of the design. Placing less emphasis on structural and aerodynamic concerns in the design process frequently yields ineffective design solutions that naturally lead to costly construction” [7].

2.1 Facade self-shading

Façade self-shading (FSS) is the aesthetic and functional skin of a building that explores their potential for reducing energy consumption in hot climates. By analyzing cumulative solar radiation on building surfaces [8]. As, in hot climate regions, shading design may be one of the most effective passive design solutions. It involves the exclusion of a large amount of direct solar radiation, emitted from the sun [9]. Also, cumulative annual irradiation analysis that integrate a cumulative irradiation value show an increase or decrease in the average irradiation levels for various twisting states [10] as shown in (Fig.1). As a result, twisting can minimize irradiation by up to 80kWh/m2 in most regions. Results from the self-shading benefit analysis display greater resolution. Results demonstrate significant levels of excessive irradiation in hot areas [10]

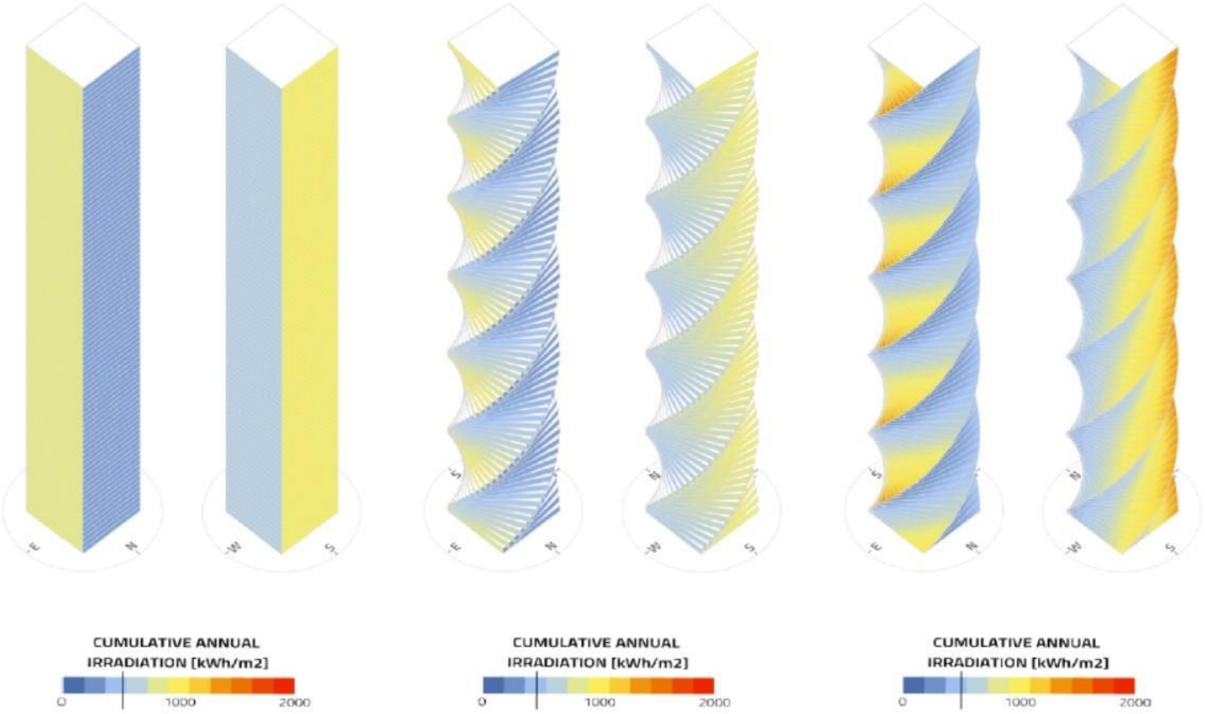


Fig. 1 Cumulative Annual Irradiation Analysis. Source: [10]

2.2 Generative Design Workflow:

A generative design workflow with multi-objective optimization proposed for architects. This tool facilitates qualitative and quantitative environmental performance evaluation during early design phases, applicable to diverse building forms as shown in (Fig.2). [11]

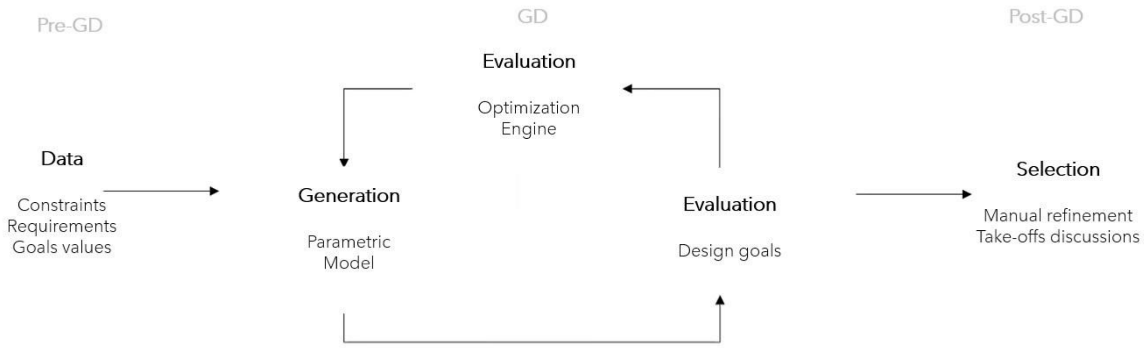


Fig. 2 Generative Design Workflow (modified by Authors), Source: [11]

2.3 Multi-objective optimization (MOO)

Evolutionary algorithms, inspired by natural selection, are gaining traction in architecture. By iteratively refining solutions. By maintaining a population of potential solutions (individuals) in parallel and enhancing their quality (fitness) through several rounds, an evolutionary algorithm attempts to solve a problem (generations). The individuals are subject to create a new generation. A fitness-based hiring method directs the population toward more qualified applicants. (Robert. vie linger) The architectural design of any building form especially high-rise buildings usually faces different objectives: to reduce environmental impact and energy consumption while improving the indoor thermal comfort[12] , reduce the energy consumption for cooling as well as for lighting by acting on solar shading [13]. To resolve these issues, truly multi-objective optimization solvers are created. MOPSO [14], SPEA2 [15], and NSGA-II [16].

NSGA-II and Pareto front optimization

NSGA-II is a solid multi-objective algorithm, NSGA-II generates offspring using a specific type of crossover and mutation and then selects the next generation according to non-dominated-sorting and crowding distance comparison. [16]

Finding a set of solutions that satisfy the optimal solution definition is crucial because there isn't just one global solution for multi-objective optimizations. [17]. several methods are available to optimize the trade-offs to evolve a population: Pareto optimal selection, tournament selection, Non-dominated Sorting Genetic Algorithm (NSGA), and Pareto optimality of an individual with assigning the same ranking to all non-dominated individuals [18]. NSGA is first introduced by Srinivas and Deb in 1994 NSGA uses a non-dominated sorting technique to highlight the more qualified solutions. [19]

Select Optimal Design:

Based on the evaluation, the optimal design represents the best meets the defined design objectives and environmental circumstances of the site. The optimal and minimize the building's impact on the environment.

Pareto-Optimal Front: "Pareto ranking refers to a solution surface in a multi-dimensional solution space formed by multiple criteria representing the objectives". The Pareto front is often used to explain the optimization results.[20] Many generations of genomes (solutions) must be produced to reach the Pareto front that is suitable for analysis.[21] Pareto front utilized in decision-making Once the set of Pareto-optimal solutions (or Pareto front) x opt 1; xopt2; …. ; x opt P (where P denotes the population size) is produced (using (using NSGA-II, for instance), for example), a choice had to be taken as to which solution is the ultimate optimal one. Such a choice is based on the relative significance of the objective functions, whose a priori evaluation relies on the user's knowledge. [22].

3 Methodology

The objective is to propose a generative design framework that can identify high-rise building form with reduced solar exposure while maintaining functionality and aesthetic appeal. The methodology utilizes algorithms and optimization techniques to explore numerous form design possibilities based on environmental parameters. The research objective is achieved through the following steps, as summarized in Figure. 3

Step 1 Generative model were defined, they included form parameters, curve plan shape with scale and rotational parameters getting a cylindrical -shape high rise building with a curved plan 50 floors.

Step 2 Define design objective and software plugins: optimizing solar radiation, window-to-wall ratio (WWR), and gross floor area (GFA) to get minimum energy use intensity (EUI)

Step 3 Performance simulation: define fitness values.

Step 4 generate design alternatives: by using multi-objective optimization.

Step 5 Evaluate design options finally, compare alternatives and decide.

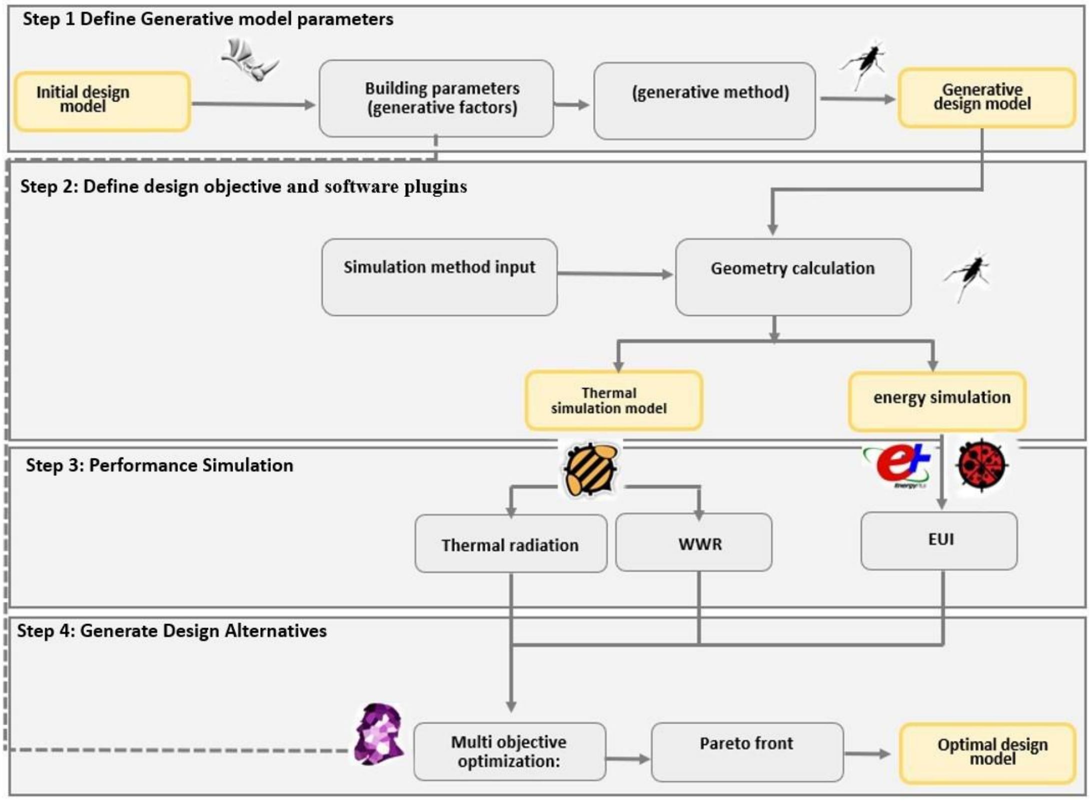


Fig. 3 The diagram shows the practical framework.

3.1 Inputs parameters of Generative model.

The initial form subjected to the optimization is a simple cylindrical shape 250m high consisting 50 storeys. The forms are generated by Grasshopper plugin. In Grasshopper, each architectural model identified as parameters. This process is automated using Wallacei plugin optimization. Table 1 shows a brief of form variables that are potentially affect building environmental performance.

Table 1. Form Parameters.

Form Parameters	
Plan shape	Curved plan shape
Proportion	Floor height 5m No. OF floors 50
3D transformation	Using scaling and rotation methods in flooring to get self-shading

The variable ranges of the parametric model must be set according to the site constraints, and when generating this parametric model, the area and altitude limit is taken into consideration, the moving limit of the curves used in the optimization process is established. In conjunction with the site limitations, the designer can adjust the parametric model's variables' minimum and maximum values by using feedback.

In addition, parametric surface curves are formed to determine the form of the parametric model that is created. To discover the building form of best performance, variable ranges of all the parameters related to this geometry as shown in Figure 4,5 script. represent the parameters of the plan shape and form and rotation transformation the red highlighted parameters are defined as genes for the GA run.

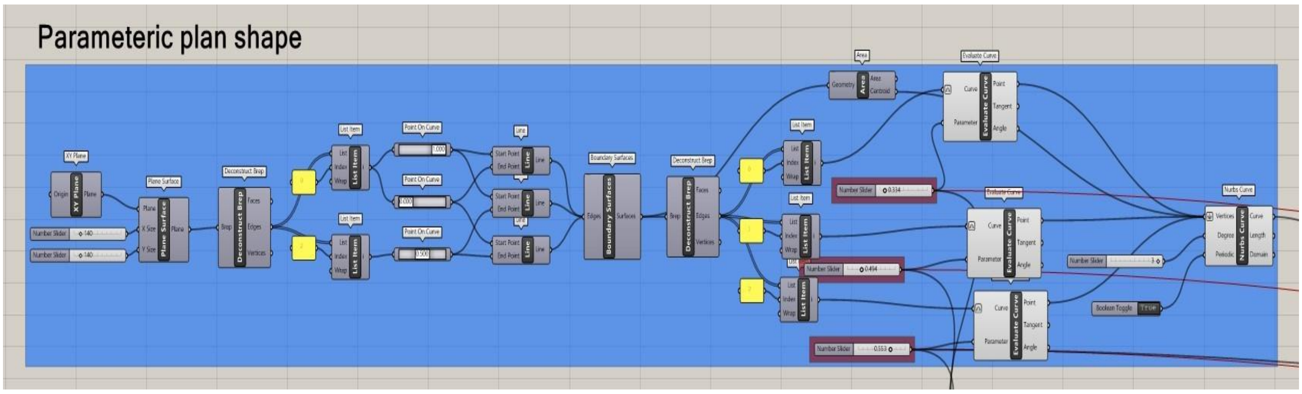


Fig. 4 The script shows the parameters of the plan shape.

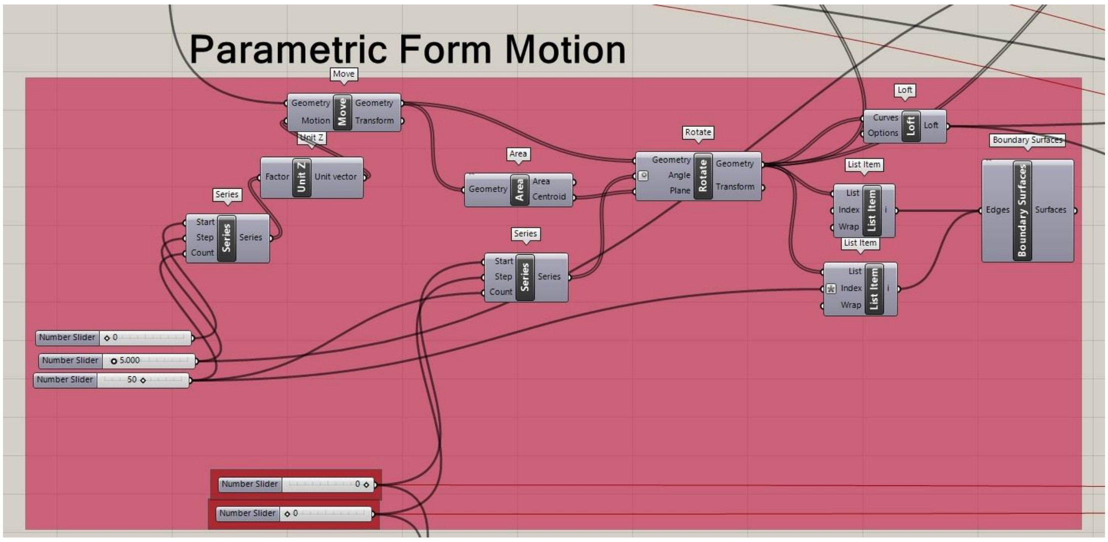


Fig. 5 Script shows form and rotation transformation parameters.

3.2 Define design objective and software plugins

In this framework, Various software and simulation tools linked to this software are employed As represented in figure 6. The optimization simulation is mostly built on the Grasshopper program, a visual programming language that functions as a Rhino program plugin. Additionally, Grasshopper is used in conjunction with several other applications. Ladybug add-on for radiation analysis (which imports and analyses common weather data), Wallacei add-on as a GA-based multi-optimization tool, and honey with energy plus.

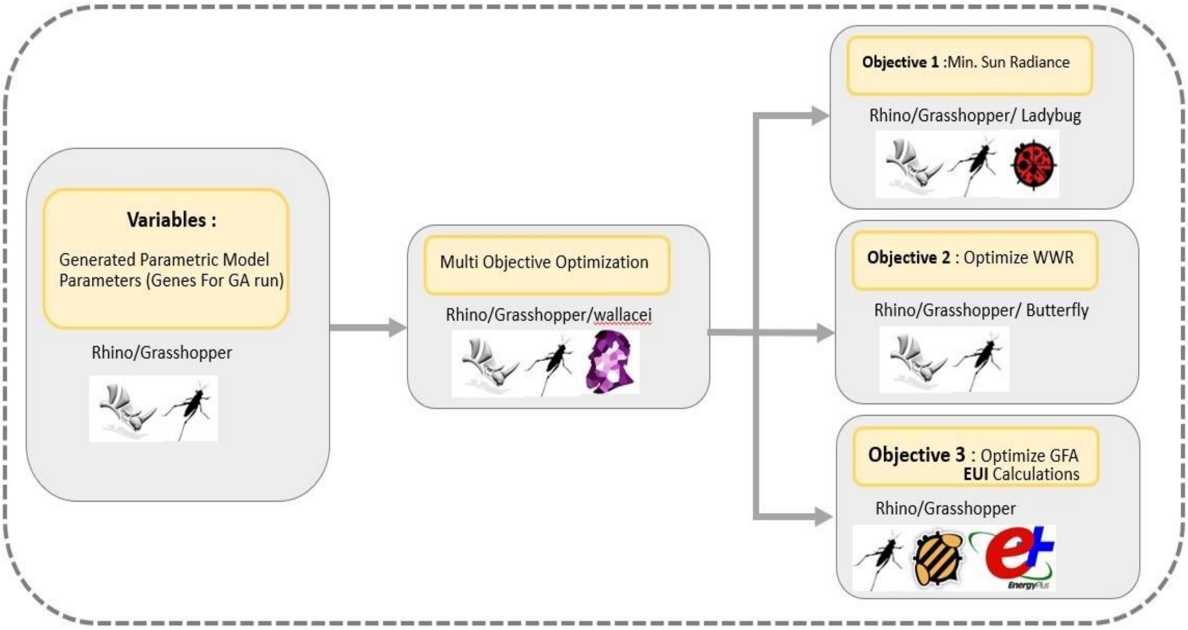


Fig. 6 The flow of the script shows the objectives and plugin used.

The multi-objective optimization engine relates to the appropriate add-ons by the predetermined objectives to build the script utilized in this investigation. The Ladybug add-ons are used in conjunction with the Rhino platform (3D environment) for visual data, the Grasshopper platform (visual programming language) for visual coding data, and several additional background applications (Honeybee, Radiance, and Energy Plus).

This script is divided into two sections as shown in Figure 7 and they represent the design formulation part and the generating process part. The design formulation part of the script is where the parametric model is initially created. The design of a curved surface geometry serves as the foundation for this parametric model. As a result, the geometry that will be created throughout the optimization process may be shaped more flexibly, leading to the creation of forms that are more climate efficient.

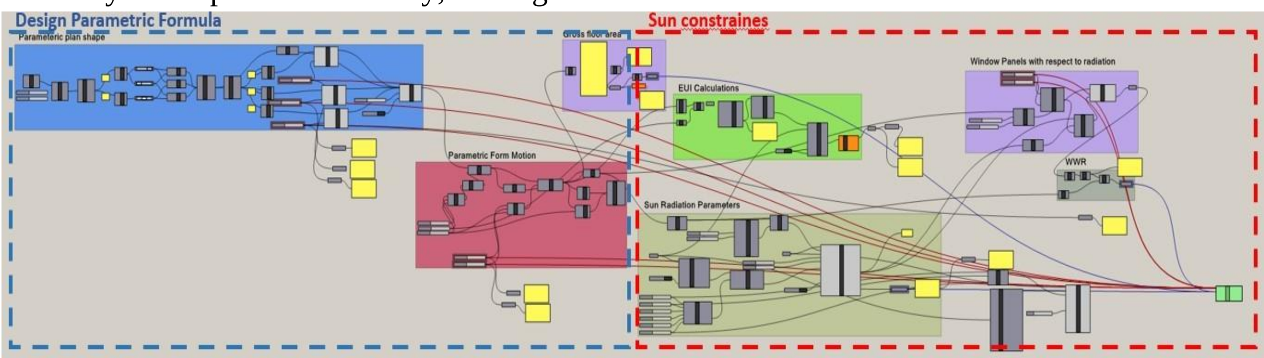


Fig 4: parametric plan shape — Fig 5: parametric form motion — Fig 8: Sun radiation parameters
Fig 9: window panels — Fig 10: EUI calculations

Fig. 7 script is divided into two sections.

3.3 Performance simulation

Fitness values can vary depending on the specific design problem or domain. They are defined based on the goals, constraints, and performance metrics relevant to the design problem. Generative design algorithms utilize fitness values to guide the search for optimal or near-optimal design solutions. By evaluating and comparing different design options based on their fitness values, the algorithm can iteratively generate and refine designs until the desired objectives are met. It's important to note that the definition and weighting of fitness values are typically defined by the designer or engineer and can be adjusted based on the specific project requirements and priorities.

Environmental Design and Climatic Analysis

This section defines the design criteria for the climatic analysis and performance evaluation, in the conceptual design stage." Performance-Based Environmental Design" (PBED) is an environmental design method based on climatic parameters (sun radiation). This approach requires a high-rise building to be formed to meet environmental performance objectives.

The ladybug add-on, which acts as an add-on to the Grasshopper programming platform, is used to simulate a radiance analysis of the created geometry. as represented in Figure 8 , part of the script shows the total annual solar radiation parameters.

Figure 8,9,10 shows main parameters result values, the components highlighted with purple in the script following the specified objectives (Minimizing the radiation, Maximizing the floor surface area, and Minimizing EUI), these objectives values connected with wallacie-x plugin optimization component.

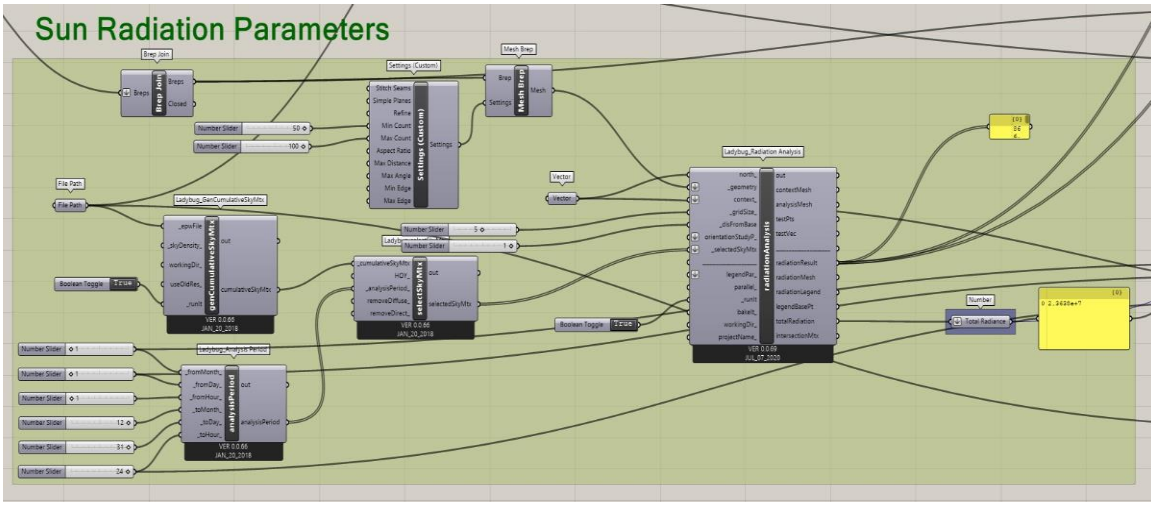


Fig. 8 The script part shows the total annual solar radiation parameters.

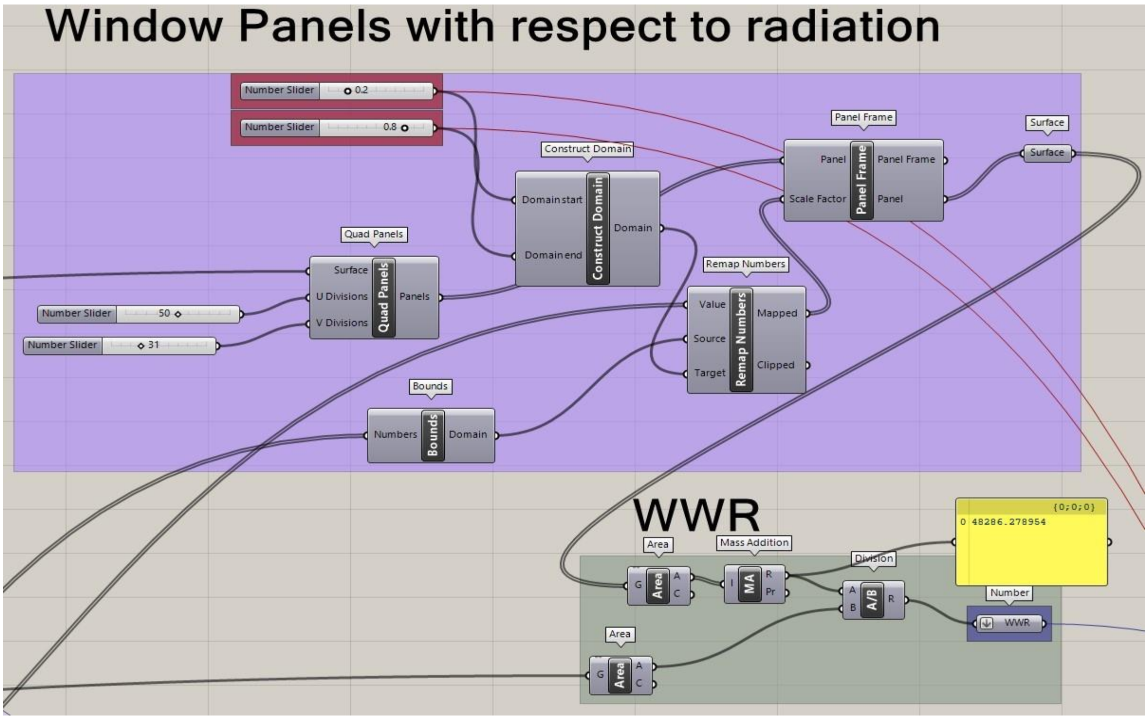


Fig. 9 The script part shows window panels and WWR calculation.

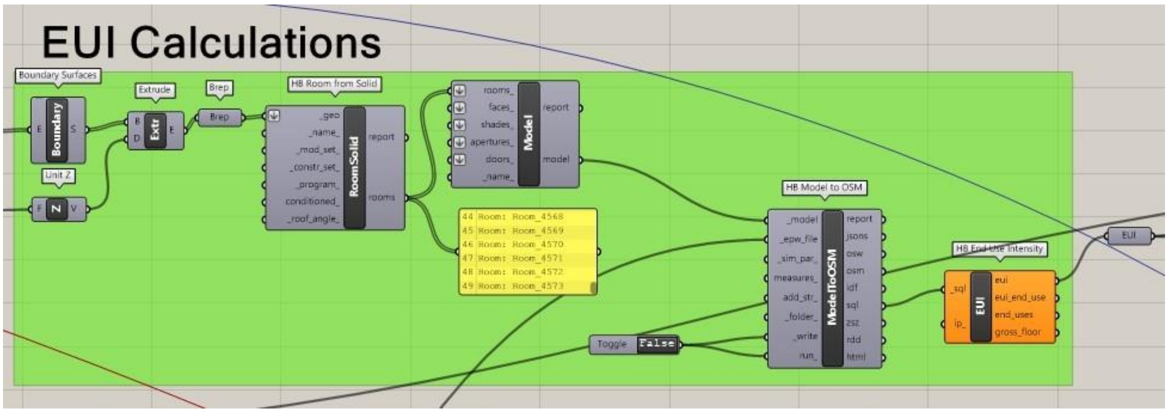


Fig. 10 The script part shows EUI calculations using Energy Plus and Honeybee plugins.

3.4 Generate Design alternatives.

Using generative design software, multiple design options can be generated based on the defined design objectives and collected data. The software can generate designs that respond to the environmental circumstances of the site, such as optimizing the building's form and orientation for solar exposure or wind resistance.

Optimization Problem Definition

Wallace X is an evolutionary multi-objective optimization engine that allows users to run evolutionary simulations in Grasshopper 3D by utilizing highly detailed analytic tools coupled with various comprehensive selection methods, including algorithmic.

Clustering, to assist users in better understanding their evolutionary runs, and make more informed decisions at all stages of their evolutionary simulations, including setting up the design problem, analyzing the outputted results and selecting the desired solution or solutions for the final output.

The production of following generations and finding the optimum solution depends on several settings which will be clarified in Table 2.

Table 2 Optimization setting in Wallacei-x window, Source: by Authors.

Generation	Generation count	Crossover probability	crossover DI	Mutation DI	No population
10	100	0.9	20	20	1000

3.5 The Generative Design Workflow

This thesis aims to explain a framework for architects to study the effect of their decisions on high-rise buildings' environmental performance. We concentrate on the conceptual phase of the design process due to the importance of early decisions. We propose" An environmental -Efficient Generative Design Workflow" as shown in Figure 12.

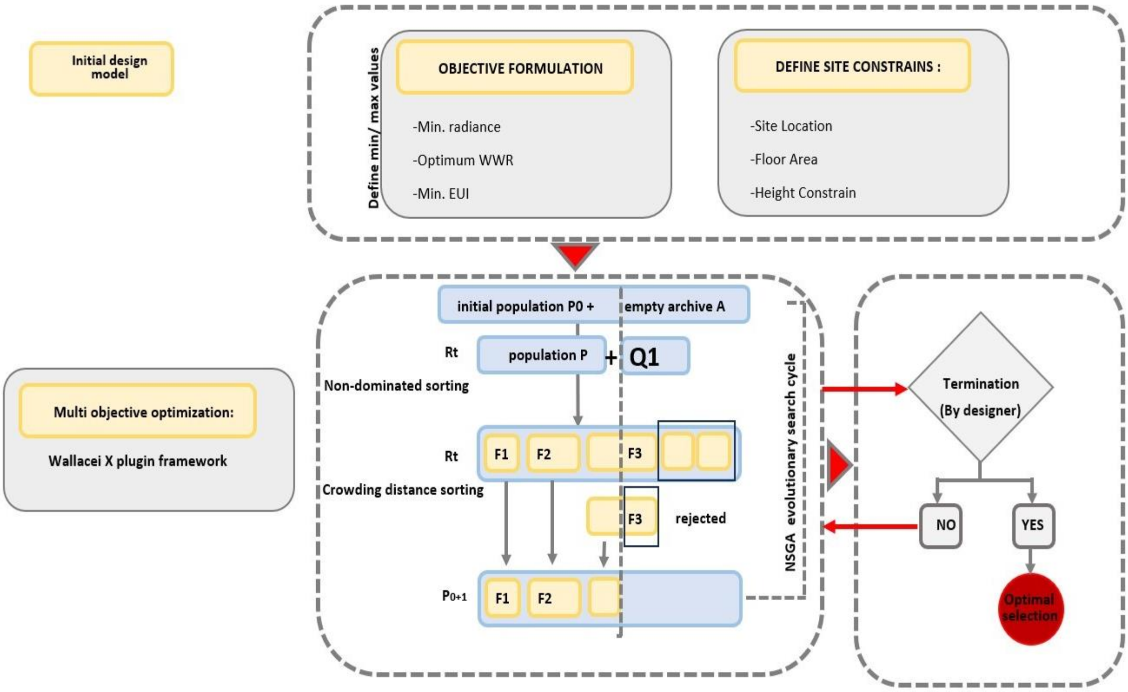


Fig. 12 workflow of the multi objectives optimization (MOO)

Design Generation (Multi-objective optimization)

In generative design studies, Geometry systems are a series of consecutive stages that, when carried out, can produce design options. Grasshopper's built-in geometry functions are used to preprogram the steps. After the design options are produced, the NSGA-II [23]. Previous geometry systems are constrained since they only consider alternatives for entire buildings rather than their key portions, and because they rely on orthogonal, square-like models. [24]. leaving out a major defining characteristic of high-rise buildings.

Evaluate Design Options

Once multiple design options have been generated, each design should be evaluated based on specific criteria, such as sun radiation impact, WWR, and energy use intensity. The evaluation can be conducted using simulation software. The goal of this process is to find the best (fittest) solutions as represented in Figure 14 Pareto frontier solutions three objectives' data optimization with NSGA-II , Figure. 13 shows standard deviation graph of the objectives during the optimization process ,Figure 15 shows Pareto front forms, Table 3 shows Pareto front solutions data and parameters.

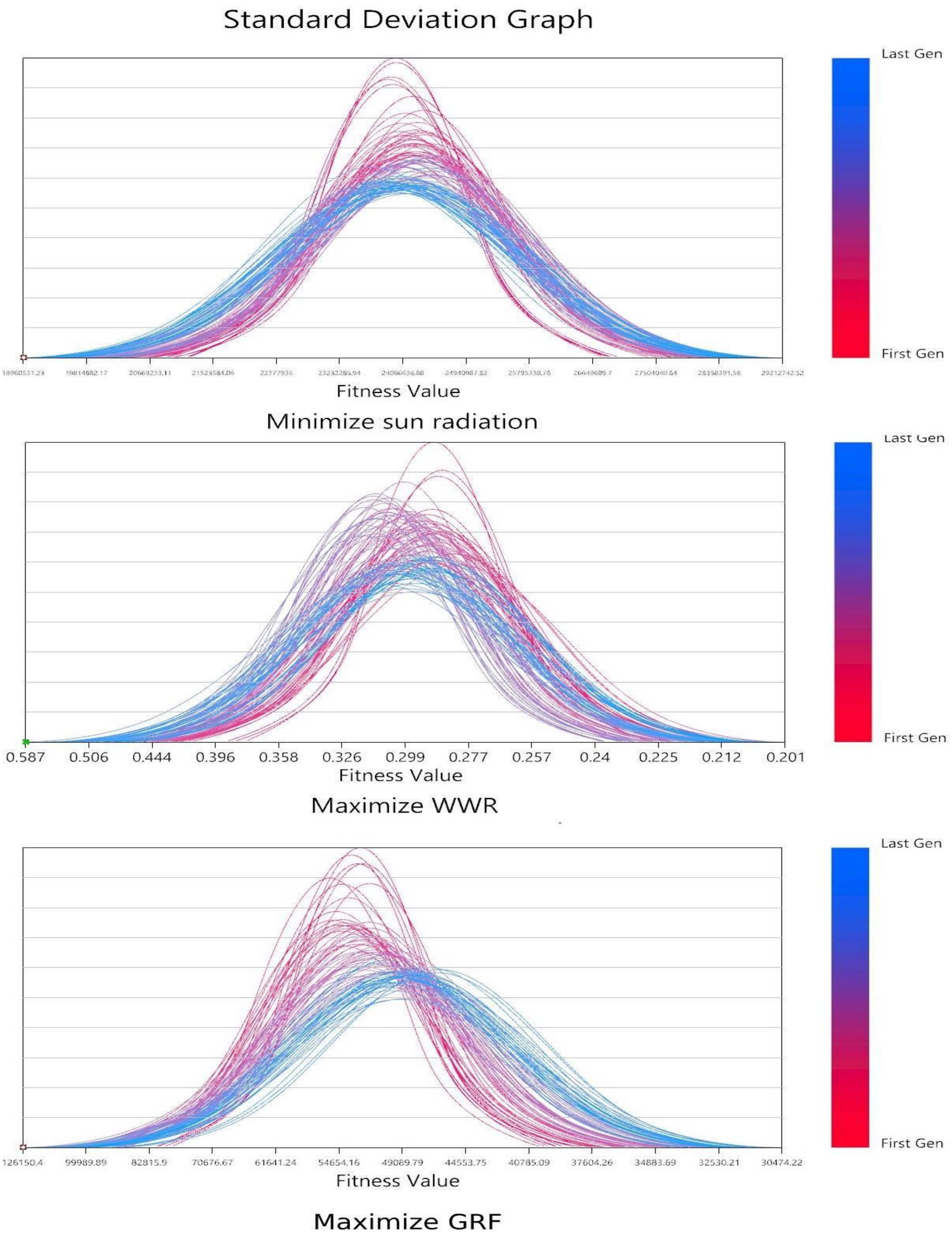


Fig. 13 standard deviation graph of the objectives, Source: by Authors.

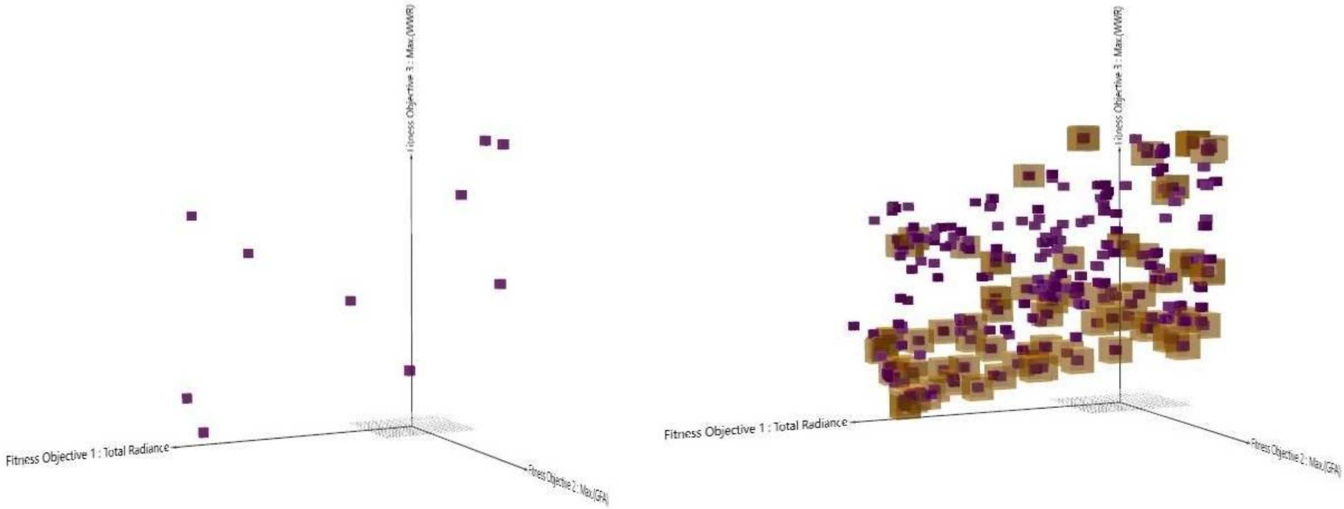


Fig. 14 Pareto frontier solutions three objectives' data optimization with NSGA-II, Source: by Authors.

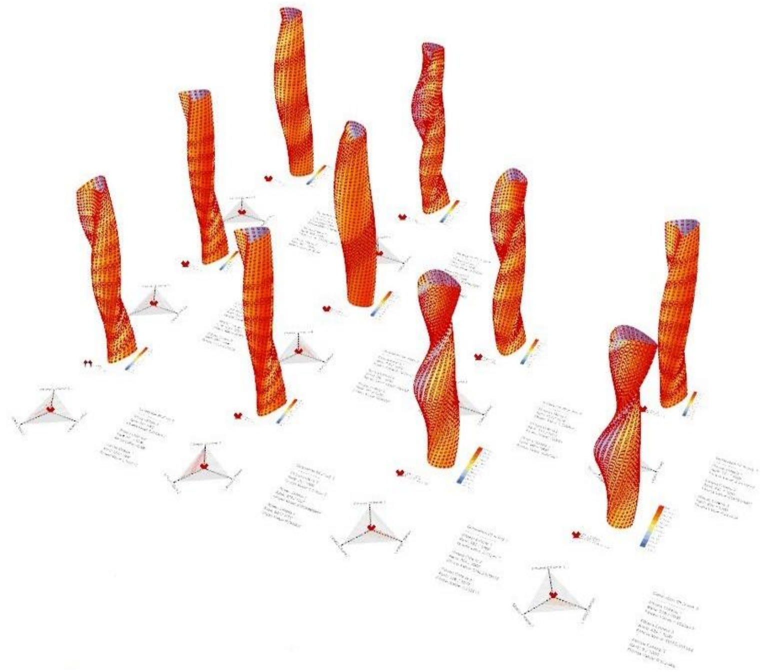
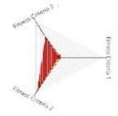
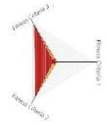
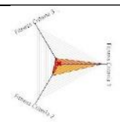
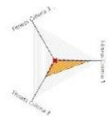
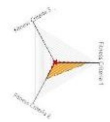
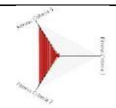
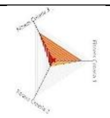
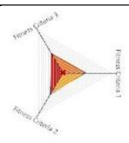
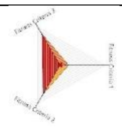
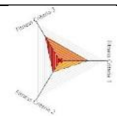
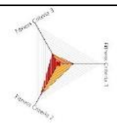


Fig. 15 Pareto front forms.

Table 3 Pareto front solutions data and parameters.

Gen.	No.	sun radia-tion	GFA	WWR	EUI	parameters	Diamond chart
99	0	22136000	40000	29%	142.6	(0.331,0.508,0.6, -4,4)	
99	1	22183000	41666.667	24.5%	142.58	(0.339,0.514,0.595, -4,3)	
99	2	26120000	58823.5	35%	139.1	(0.649,0.523,0.599, -25,5)	
99	3	25963000	55555.56	37%	139.65	(0.649,0.457,0.599, -25,5)	
99	3	25963000	55555.56	37%	139.65	(0.649,0.457,0.599, -25,5)	
99	4	22082000	40000	24.6	142.9	(0.331,0.514,0.6, -4,3	
99	5	25822000	66666.67	26.8	138.31%	(0.641,0.514,0.477, -28,3)	
99	6	23787000	50000	30	140.3%	(0.355,0.453,0.49, -1,4)	
99	7	22401000	43478.26	26	141%	(0.374,0.514,0.6, -4,3)	
99	8	25098000	58823.5	28	139.3%	(0.611,0.527,0.599, -1,3)	
99	9	23286000	43478.26	33.2	142.8%	(0.31,0.512,0.599, -4,5)	

Sun Radiation

Sun radiation can have a significant impact on the envelope of a high-rise building, leading to increased heat gain, discomfort, and increased cooling loads. Self-shading strategies can be employed to reduce the effects of sun radiation on the building envelope. Implementing self-shading strategies requires careful consideration of building design, climate, and site-specific factors. Figure 16 shows form with minimum sun radiation in pareto front solutions, Table 3 the form data and parameters for generation 99 number 4.

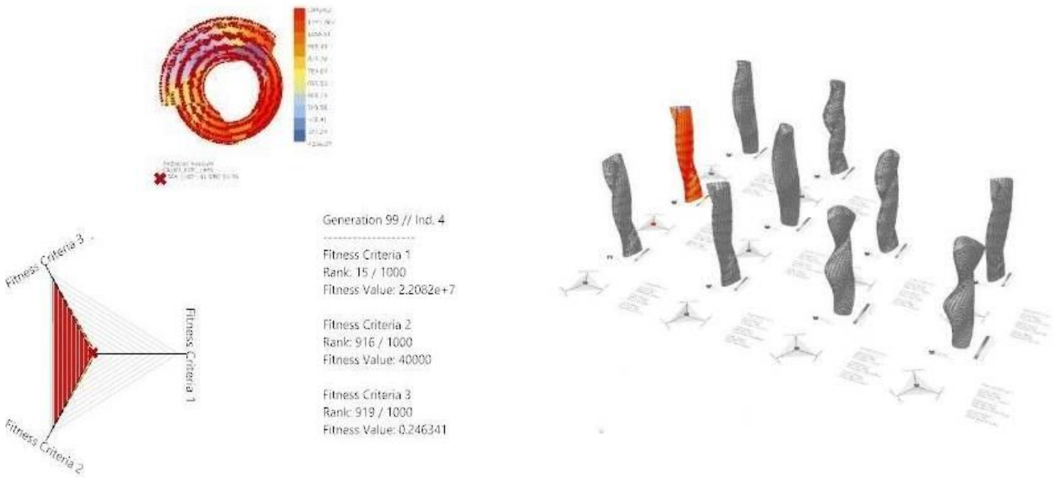


Fig.16 form with minimum sun radiation.

Window to Wall Ratio

Windows can lead to an increase in the amount of energy used for heating and cooling since they are a significant Source of heat loss in the winter and undesired heat gain in the summer. Large windows that let in enough natural light to either completely replace or enhance artificial lighting may also result in glare and increased energy use for air conditioning. Many studies have been conducted on these tradeoffs, usually with the intention of either reducing energy use without affecting visual or thermal comfort or enhancing the comfort and/or health of occupants. Figure 17 shows form with minimum WWR in pareto front solutions, Table 3 the form data and parameters for generation 99 gene number 1.

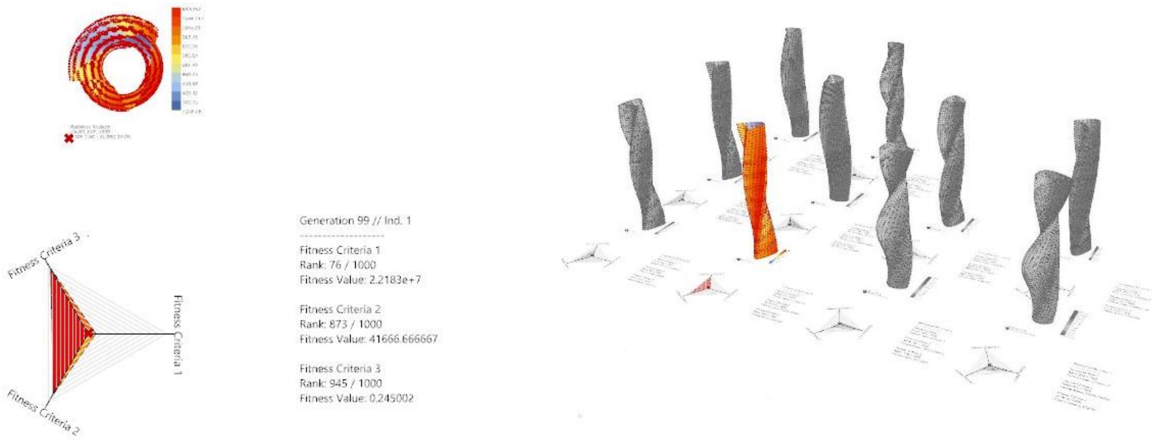


Fig. 17 form with minimum WWR.

Gros floor area

The gross floor area (GFA) of a building can have a significant impact on its annual energy use intensity (EUI). EUI is a measure of a building's energy consumption per unit of floor area over a given period, typically expressed as kilowatt-hours per square meter (kWh/m²) or British thermal units per square foot (BTU/ft²). GFA and the EUI of the sample buildings. To establish the EUI, the energy consumption was divided by the GFA as it had a significant relationship with energy consumption from the correlation analysis. Researchers and engineers often use GFA as a factor to normalize the EUI in the analysis of building benchmarking [25]. Figure 18 shows form with maximum GFA in pareto front solutions, Table 3 the form data and parameters for generation 99 gene number 5.

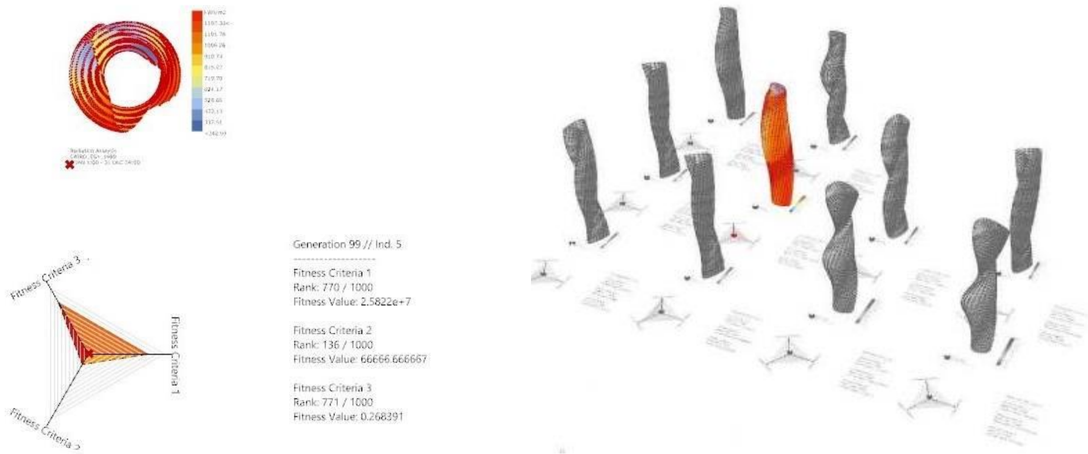


Fig. 18 form with maximum GFA.

Mean solution

Mean value is the average of a set of objective fitness values generated, Figure 19 shows mean fitness rank per solution, Table 6 the mean form data and parameters.

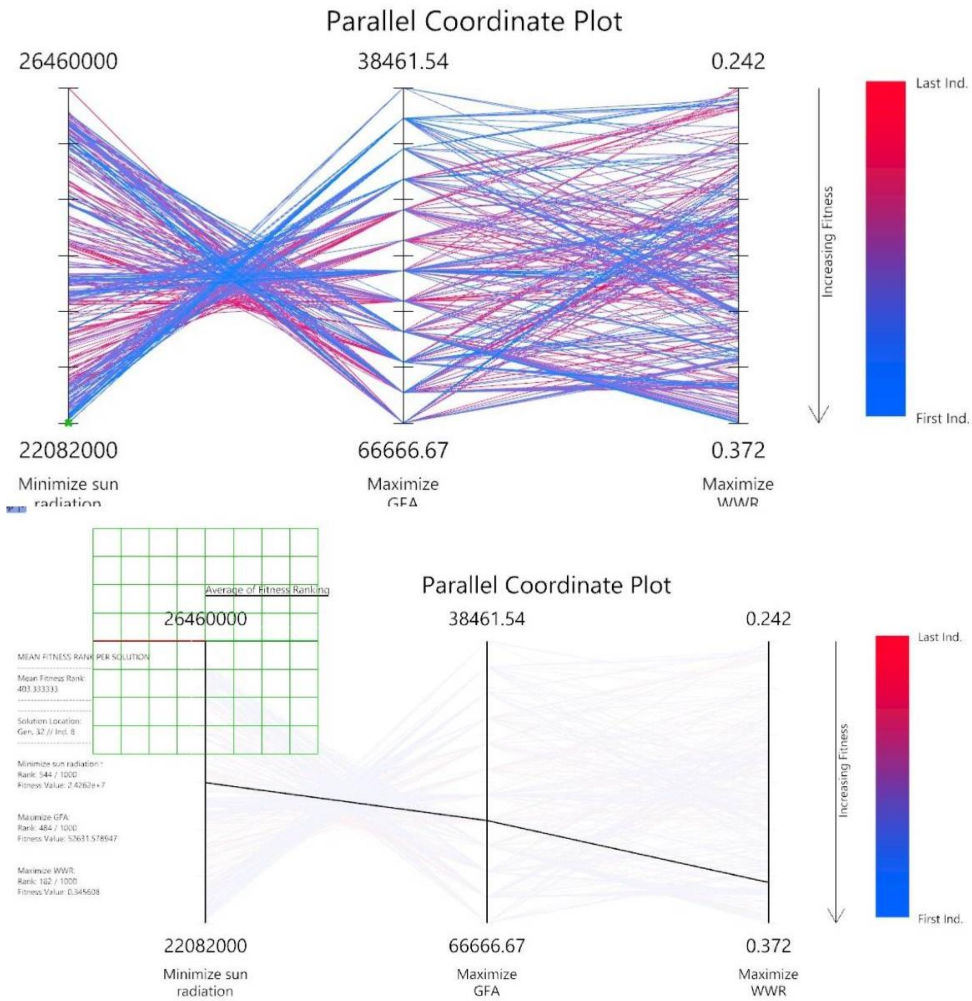


Fig. 19 mean fitness rank per solution.

Table 9 Mean values solution.

Gen.	No.	sun radiation	GFA	WWR	EUI	parameters	form
32	8	24262000	52631	34.5%	139.5	(0.564,0.472,0.595, -21,5)	

Select Design

After the Evaluation of design options, we need to select the optimal solution based on the energy use intensity of each form selecting the minimum EUI form. The Rhino and Grasshopper plug-in Honeybee tool is used to calculate energy use. An Open Studio and Energy Plus multi-simulation engine is used to achieve visualization. Energy Plus, an open-Source program created by Lawrence National Laboratory and the US Department of Energy, served as the main engine used to analyze energy use. EUI is expressed as energy per square meter per year. It’s calculated by dividing the total energy consumed by the building in one year (measured in kBtu or GJ) by the total gross floor area of the building (measured in square feet or square meters). Portfolio Manager automatically does the conversion to kBtu or GJ. Figure 20 shows part of script using Energy Plus and Honeybee plugins in EUI calculations , Figure 21 shows form with minimum EUI in pareto front solutions, Table 3 represent the form data and parameters for generation 99 gene number 5.

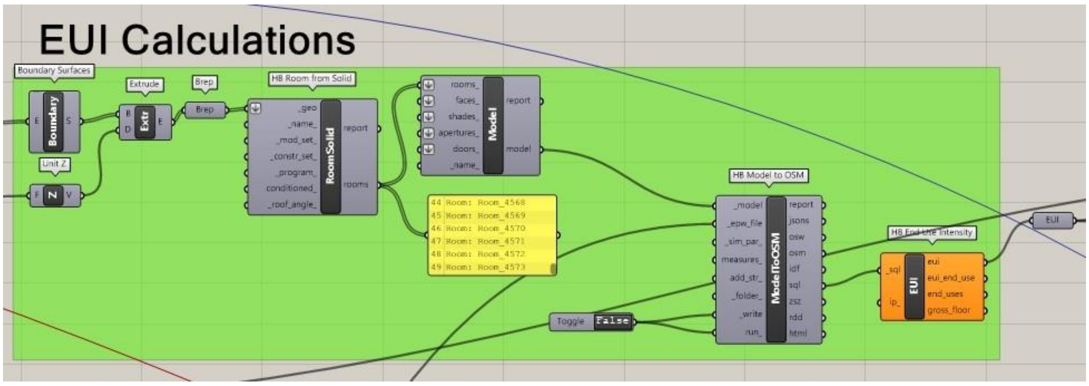


Fig. 20 The script part shows EUI calculations using Energy Plus and Honeybee plugins.

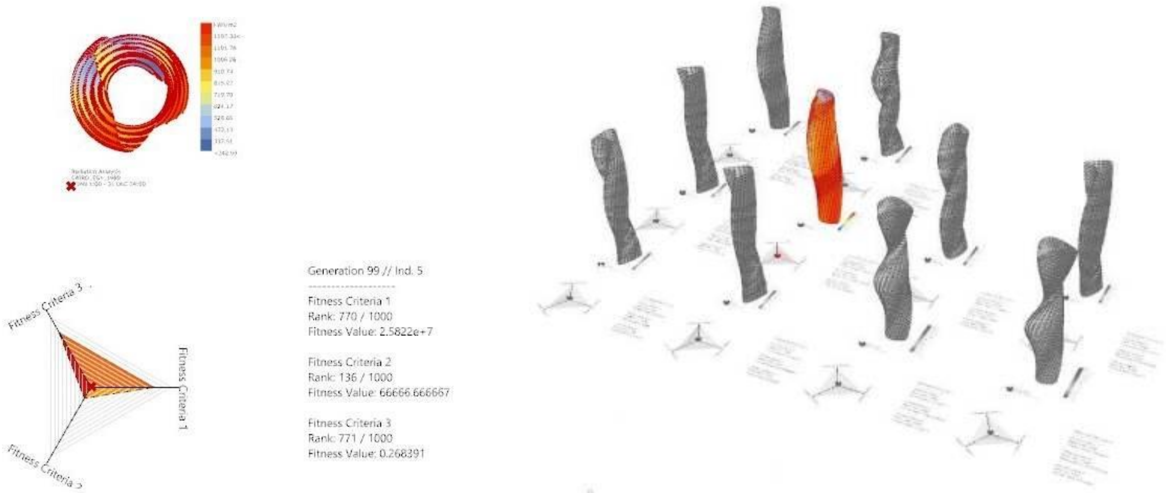


Fig. 21 form with minimum EUI, calculations using Energy Plus and Honeybee plugins.

Figure 22, 21 show fitness values of sun radiation, gross floor area respectively during the optimization process.

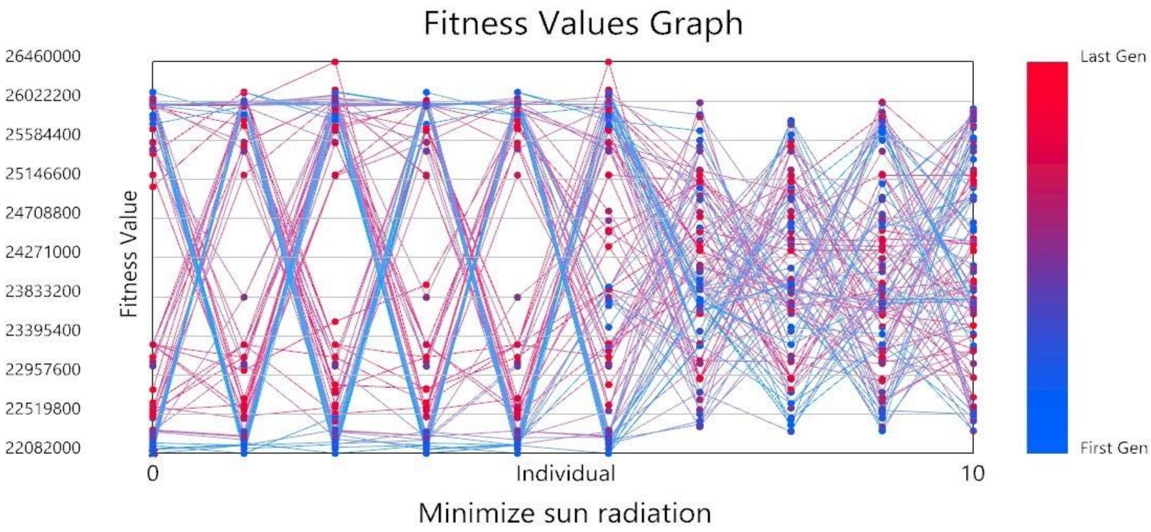


Fig. 22 graph shows fitness values of sun radiation.

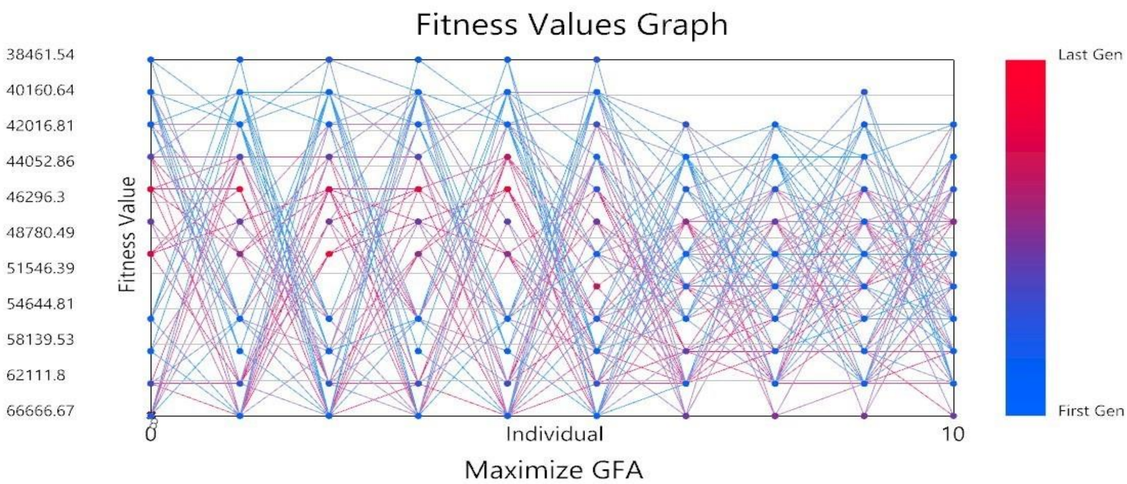


Fig. 23 graph shows fitness values of gross floor area.

Finalize Design: Once the early design stage has been finished it can be refined, and finalized, and detailed construction drawings can be produced. This workflow leads to getting a design that not only aligns with architects' design aspirations but also effectively enhances environmental performance and reduces energy demand.

4 Conclusion

This study proposes a generative design workflow to optimize high-rise building forms. A case study analysis is conducted to demonstrate the framework's effectiveness in optimizing high-rise building environmental benefits in the early-stage design scenario of a high-rise building aiming to increase the performance of the building by reducing the energy use intensity EUI of the building The main conclusions of this study are summarized as follows:

(1) Generative design plays a crucial role in developing the form-finding process in the conceptual design phase, aimed at establishing a set of applicable form deformations. Additionally, the generative design enables multi-objective performance optimization simulation objectives through parametric simulation models.

(2) The utilization of generative design has a notable impact on attaining environmental benefits in building design. In the case study conducted in this paper, the optimization of the sun radiation value on the envelope is reduced from 26460000 to 22082000 kw/h (decrease by 17%) in one of the solutions. while the improvement of increasing the gross floor area is a significant change from 38461.54 m2 to 66666.67 m2 this enhances the energy use intensity from 148.3 kw/h/m2 to 138.31 kw/h/ m2 (decrease by 7 %). The outcomes of the case study imply that the multi-objective optimization MOO method can improve the performance of the high-rise building forms and release the energy generation potential.

The proposed case study addresses the gaps between objective values and generalizability within generative-design-based building performance optimization problems. Specifically, the framework enables automated performance optimization and offers comprehensive form design concerning environmental circumstances; at the same time, the framework lays the foundation for generative study on environmental performance optimization.

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