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Performance-based Generative Shape Grammar Method: Energy Efficient Facade Design for Fully Glazed Multi-Storied Office Building - Hot and Humid Climate, Chennai, India

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Abstract: The traditional building form design or form-making is an intuitive design method that is neither efficient nor competent for energy-efficient façade design. The form-making design approach threatens sustainable development in India. This paper discusses the new tread of form-finding, a process in which the framework is set for parameters to interact. It suggests a performance-based shape grammar (PBSG) generative design method for façade finding and evaluates it as an energy-efficient facade design method for FGM office buildings for India's hot and humid climate. A research method to develop PBSG rules for a given project framework was demonstrated by redesigning a case sample site and evaluating the existing FGM office building in the sample site. The PBSG methods in two stages apply multiple rules, first for form-finding and later for façade plane-finding for energy efficiency. It was observed that the SG resultant generated form was 42% more energy-efficient than the existing design using the same envelope materials, HVAC equipment, development regulations, and context. The outcome of this study provides a framework for a generative design process using PBSG in the early design stages and proves to be an energy-efficient design method for India's hot and humid climate.

Keywords: Generative façade design, form- finding, performance-based shape grammar, energy-efficient fully glazed façade, hot and humid climate

1. Introduction

Sustainability is integral to development in today's built environment and is more needed for a developing country like India. In this 21st century, the façade design of office buildings with large glazed areas that give transparent architecture is the trend. However, these façade types have a challenging indoor climate and higher energy use. The FGM buildings with a window-to-wall ratio (WWR) of more than 70% influence more than 50% of the space cooling load [1]. The office building in the major cities of India with transparent glass designs influenced by the West does not account for the local climate and use over twice the energy of their international counterparts [2]. The growing magnitude of FGM office buildings with no mandatory compliance with green

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building regulations threatens sustainable development in India. This issue is due to the cost, construction methods, regulations, or design method. The research suggests an innovative form-finding design method to generate with the same constraints and context. This research is a generative design method for energy-efficient façade design for a redesign, with the same regulations and little more or the same cost for a given context.

Nomenclature and Abbreviations

AAI	: annual average solar insolation
AAIFA	: annual average solar insolation for the façade area per floor area
ASE	: annual solar exposure
API	: Application Programming Interface
BEE	: Bureau of Energy Efficiency
BIM	: Building information modelling.
CMDA	: Chennai metropolitan development authority
DA	: Daylight autonomy
EPI	: Energy performance Index -Annual energy consumption in kWh/ Total built-up area in m2 (excluding the inhabitable areas).
FGM	: Fully glazed multi-storied
FSI	: Floor space index
FA	: Façade area in m2
GRIHA	: Green rating for integrated habitat assessment
PHGE	: Peak heat gain from the envelope
PR	: Project Refinery – generative package by Autodesk
PGAD	: Performance-based generative architecture design
PBSG	: Performance-based shape grammar
SG	: shape grammar
SDA	: spatial daylight autonomy
SHGC	: solar heat gain co-efficient.

A conventional or intuitive design method is neither efficient nor competent for energy-efficient architecture design. Intuition and unpredictability are the essences of the form-making process. Form-making is a process of embodying ideas directly into forms. In a forming process characterized by coincidence and no logic or imitation and metaphor. Structural, constructional, economic, and environmental and other parameters once secondary concerns have become primary – are now being embraced as positive inputs within the design process from the outset."—Neil Leach [3]. In recent years, computational tools have introduced innovative form-finding techniques, revolutionizing architectural design and production. They shift the emphasis from 'form making' to 'form finding' [4]. Form making is often an intuitive process that is inspired and refined. Form-finding is a process in which the framework is set up for parameters to interact. Mathematical rules have played a significant role in the creation of form in art and architecture throughout history. The form-finding process uses a rule-based or constrained form-seeking methodology. The motivation for this research is to generate architectural forms using simulation results to examine performance criteria and quantitative data at the early design stage.

Previous research has pointed out a need to support the exploration aspect in the earlier design stages through generative design approaches ([5]. Generative design is a goal-driven approach that uses automation to give designers better Insight to make faster, more informed design decisions. Generative Design can offer advantages to traditional building design and the urban planning processes, given its capability to manage complexity by optimizing pre-selected criteria while still at the drafting stage [6]. Moreover, parametric modeling is increasingly accessible to the design practice via Visual programming software such as Grasshopper and Dynamo [7]. Performance-based Generative Architecture Design (PGAD) is a design approach based on coupling parametric modeling with performance simulation and optimization. In the early design stage, many critical decisions must be made to achieve the performance potential. With quick and easy software, it is possible to create an energy-efficient façade with a generative design method and tools at the early stage. SG is a generative design tool that predicts the design solutions by analyzing and optimizing early design alternatives through parameter control.

Previous research on performance-based shape grammar for structural components [8], indoor space planning [9], generate layouts for photovoltaic (PV) modules [10] or to achieve energy-efficient and sustainable architectural solutions [11,12 & 13]. Granadeiro et al. [14] integrated shape grammars as a generative envelope shape design and energy simulation to calculate the energy demand. Despite the growth and increase in popularity of SG generative design approaches in the past decade, the field has nevertheless been sparsely explored. Research on the performance-based SG Generative design approach is required for the growing new trend of transparent multi-storied office buildings in hot and humid climates for a developing nation like India.

The aim of this study is thus to investigate the potential use of PBSG generative design in a façade design context. The research design was based on a methodology from design science research by Pe_ers et al. [15]. In three stages, development, demonstration, and evaluation. It is done by iteratively developing PBSG algorithm rules within the contextual framework that is eventually demonstrated and evaluating its applicability for redesigning an FGM office building in a case sample site in Chennai, India. Shape grammar generative design solutions derived from Dynamo, the visual programming package. The Dynamo script is derived for performance criteria with simple geometrical rules to the form and the plane. Then the results are ranked for performance to green building performances. The SG process is demonstrated on the case sample site in two sections, first for form-finding and then for façade plane-finding. Furthermore, evaluate the SG resultant form by comparing it with the existing building built in the same case sample site.

This research approach uses a transparent energy-efficient façade with the climatic-based performance generative method, which could be applied to any context. The customized PBSG rules and techniques development allow designers to generate a form based on performance demands at the early design stage with simple and easy tools. The current research only scratches the surface of the potential of performance-based facade findings in architecture. We hope that this research, as an inclusive design approach, has the potential to improve the design and performance at multiple scales of future buildings, neighborhoods, and cities towards a more sustainable world.

2. Literature Review of Performance-based SG (PBSG)

Shape grammar is a generative design tool that predicts the design solutions by analyzing and optimizing early design alternatives through parameter control. SG has often been proposed as a possible support mechanism for architectural designers [16]. Architectural design knowledge is captured in ontology and processed by shape grammar, thus allowing for generation and analysis [17]. *Shape grammar* can be defined as a rule set deployed to form a design language. SG has been inspired by this first definition, as researchers have found practical applications in art, product design, engineering, architecture, and planning. One of the first applications of shape grammar in architecture was in work concerning Frank Lloyd Wright's prairie houses [18]. Here, shape grammars were used to generate new and different house plans in Wright's style. Another, more recent use of shape grammars in architecture can be seen in the work of Wonka et al. [19] towards rapid architecture generation.

A general discussion on performance and the shift to Performalism in architectural design can be found in Grobman & Neuman [20]. Performance criteria-based shape grammar helps us build a rule base for procedural facade modeling technology [21]. The first two decades focused almost exclusively on the analysis of shape grammar applications. Through this work, shape grammars became an established paradigm in design theory, computer-aided design, and related fields ([22]. George Stiny introduced the theory and idea behind shape grammar and James Gips in the seventies, with their early work on the composition of the form [23]. SGs are typically used for generating 2D shapes and compositions, space layouts, and in some cases, 3D compositions [22, 24, 25, & 26]. A shape grammar consists of shape rules and a generation engine that selects and processes rules recursively, starting from an initial shape [27]. Besides showing highly structured geometric forms, irregular fractals such as buildings and urban designs can also be efficiently described by shape grammar [28].

The language of a shape grammar is a potentially infinite set of finite shapes. The SG requires an initial shape, uses one rule at a time, is geometrically defined, is limited to constraints, and helps generate patterns incrementally and form-based. In the previous research, the analytical SG methods were developed and analyzed historical styles or designs by specific architects [22]. The form-finding area of research aims to identify optimal or effective forms given a specific objective. Ratti et al. [29] explore the effects of urban texture on building energy consumption through digital elevation models and assess the relationship between building forms and environmental performance through archetypes. Also falling in this area is the work done by Catalina et al. [30], who investigated the impact of building forms on energy consumption in the case of office buildings.

SG is a growing field of research in architectural design at the early stage. In this research, shape grammar rules are customized to this climate, site geometry, building typology, development regulations, and green building regulation was explored. They typically generate algorithms or rules for form-finding and façade plane-finding with performance-based criteria in each stage of the SG generative process.

3. Methodology

This research aims to develop a generative design method for energy-efficient façade design at the early stage by redesigning it with the same constraints and context. The research design was based on a methodology from design science research by Pe_ers et al. [15], where a problem drives a cycle of performance objectives to development, demonstration, and evaluation. The PBSG generative design method in three stages. At first, we understand and develop the framework for which the PBSG rule is generated. The second is to illustrate the SG process by redesigning a case sample site, and the final stage is to evaluate the SG's best results with the existing building on the same site through simulation methods. The PBSG redesign flowchart as in figure 1.

The three stages of the SG process:

1. Develop: Generative framework for SG
2. Demonstrate: Illustrate the SG process on a case sample site.
3. Evaluate the SG result with the existing case sample building design.

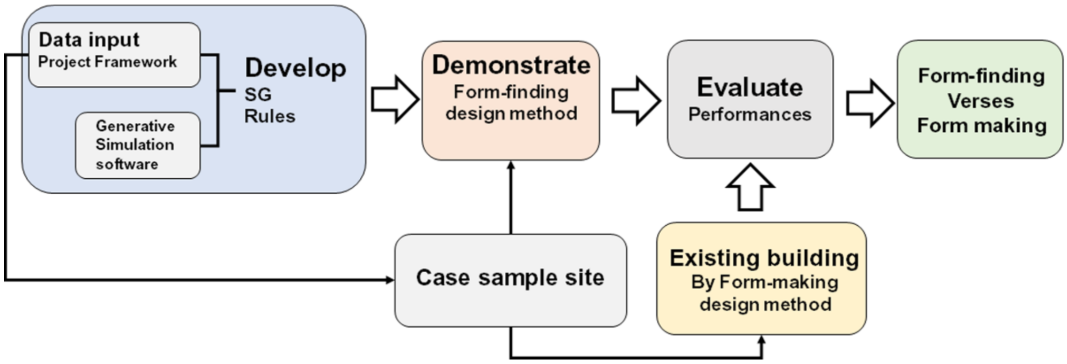


Fig. 1 - Three stages of the research design for PBSG generative design process for redesign

3.1 Develop: Generative Framework for SG

To derive SG rules, we must understand the project framework; a framework is created based on contextual limits data, understanding the tools for generative design, and the shape of grammar rules or algorithms that work within framework and simulation tools.

The generative research framework for shaping grammar in the following steps:

1) Contextual data: The project framework.
2) Tools: Formulate the design idea by breaking it into smaller parts to understand the generative software.
3) Develop rules: Formalise it clearly regarding algorithms or interactions between geometry and rules.

3.1.1 The Project Framework

The shape grammar framework is the contextual data or constraints in which the PBSG rules are developed. The following are the project framework to define the contextual constraints and variables to develop. Contextual information or the data input:

1) Climate & location
2) Development regulations
3) Building type and use: FGM office building typology.
4) Green building performance criteria for office use
5) facade cost and technology (curtain wall system)

The details of each contextual information are explained in section 4 as per the selected case sample site for a redesign.

3.1.2 Understand the Generative Software

For a long, engineers and architects have developed formulas and methods to evaluate the performance of buildings. These are now embedded in software analysis tools that save considerable time when analyzing the building's performance at the early design stage by reading geometry and adding materials and location. We are shaping the model based on its performance by using analysis tools and changing a project's design according to those analyses' results. In this research, the software packages are predominantly Autodesk products such as Revit, Dynamo, Project refinery, and E-Quest for energy analysis. The Dynamo, a visual programming tool that works with Revit, sets the geometry limits of max and minimum range to derive the desired output. The inputs and output results from the dynamo script are exported to the Project refinery (PR), and multiple options are generated. The options are then selected for the required performance output criteria. Section 4 explains in detail the simulation software for this redesign.

3.1.3 Algorithms or Rules and Interaction with Geometry

The study's objective is to generate designs for façades based on the performances. The algorithms or rules are based on the constraints and variables of the context. For a given context and site area, the permissible built-up area (FSI), plot coverage, permissible site setbacks, and building height are the fixed inputs or contextual geometry limits or the permissible volume for a given site as per the development regulations. The shape grammar generates a rule at a time based on the geometry limits. Different rules are applied in a sequence to select the best form. The starting to generate an SG rule is based on the data from contextual information or the data input applied to generate the geometry. Next, the generated solution is analyzed for thermal, daylighting, or energy performances, and the designer evaluates for set performance-based criteria. If the results pass the evaluation, it is ranked, and the solution is selected. If the results fail, the evaluation is sent to modify or evolve new algorithms to generate more solutions. This sequence repeats, and the results with multiple interactions with the designer for performance criteria to rank and select the shape. The flow chart of the PBSG rule generative design process is shown in figure 2. SG rules are applied for an energy-efficient form finding and façade plane-finding process; however, the order of these rules is as per the creation of the simulation model and the designer's choices.

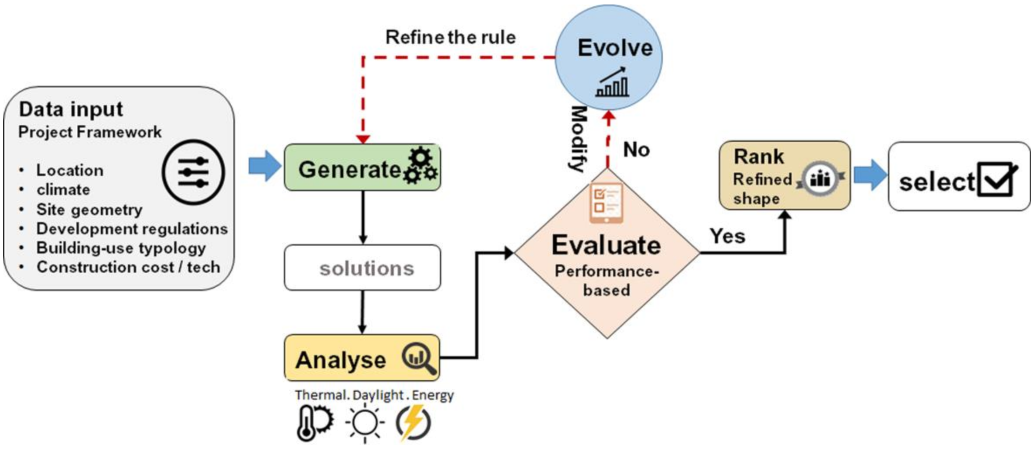


Fig. 2 - Overall process of PBSG rule for the generative design

3.2 Demonstrate: SG Process on A Case Sample Site

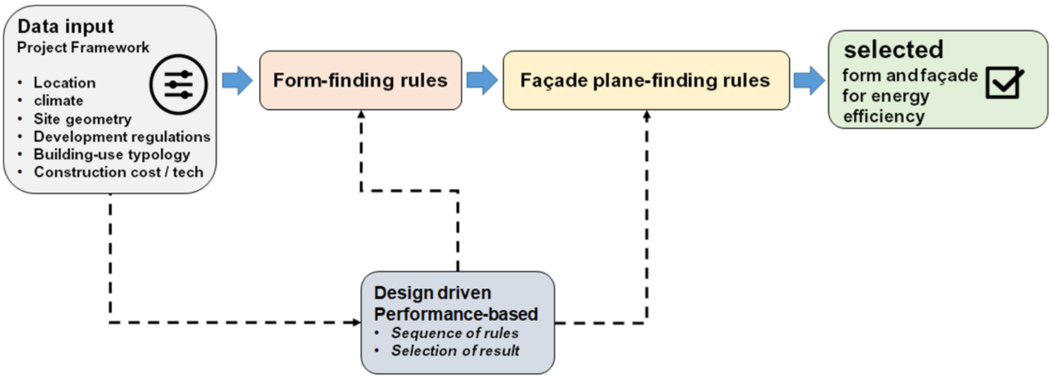


Fig. 3 - The overall process of form-finding and façade plane finding

It is applied to a case sample site to demonstrate the above methodology of shape grammar generative process. The demonstration flowchart of the SG process on a case sample is in figure 3. There are multiple rules developed and applied in each stage of the SG process. At first, there are 6 rules applied in a sequence for form-finding. The selected form is refined by 5 rules for the façade plane finding process. The designer for performance-based criteria evaluates each stage of the SG process. The final form with the façade plane is selected as the energy-efficient façade design for the FGM office building in the given context.

3.3 Evaluate: The SG Result with the Existing Building Design

The final resultant SG form is evaluated with the existing building in the same context and developed on the same project framework. The existing building simulation model is created with the same methods and assumptions used in the SG process with similar envelop materials. The case sample simulation results are compared with SG results for energy efficiency, Daylighting, and thermal performances. The overall process of the evaluation flowchart is as in fig 4.

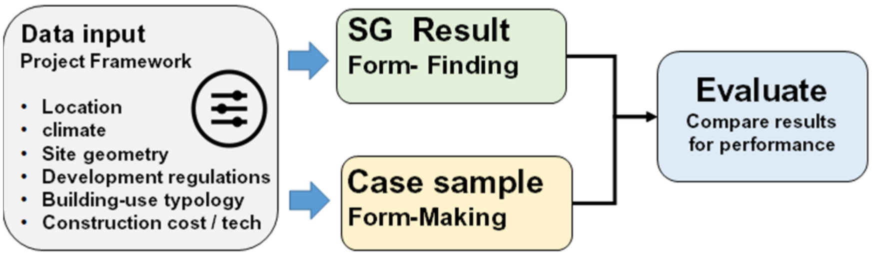


Fig. 4 - Evaluation process of the form-finding and form-making results for the case sample site

4. Demonstrate the PBSG Process for the Redesign

The first step of the SG process is to understand the project framework. This site is selected from case studies of 6 similar typologies of façade design in Chennai [31]. The project framework as mentioned in section 3.1. The next to understanding the simulation tools used for performance-based shape grammar generative design. And final stage to demonstrate the application of the peformance-based SG rules for form-finding and plane-finding process.

The following section, 4.1.1 to 4.1.5, explains the project framework for this research is the contextual limits to generate an energy-efficient FGM office building based on contextual information from Chennai, India.

4.1.1 Chennai Climate & Case Sample Site

Chennai is located at Lat. 13.0827°N Lon. 80.2707˚E has a hot and humid climate. The city lies on the thermal equator and coast, preventing extreme variation in seasonal temperature. The hottest part of the year is late May to early June, with maximum temperatures around 37–41 °C and the coolest part is January, with minimum temperatures around 19–25 °C. High solar radiation and high humidity are the most influential climatic factors in this climate. In these regions, the FGM office buildings have to deal with sun-glare and high cooling load energy use; the natural ventilation is insufficient or impossible as these buildings are fully air-conditioned for thermal comfort [32].

Case sample site: The area of 15,462 m^2 is accessible by the main road and is located within the city. The site is a rectangle of 114.8 m x 134.7 m in dimension. The permissible total built-up area of 38,653 m^2 of office space, excluding the underground parking and other utilities, as per CMDA rules of 2010 as in table 1. Google map of the site with surrounding built environment and key plan as in fig 5.

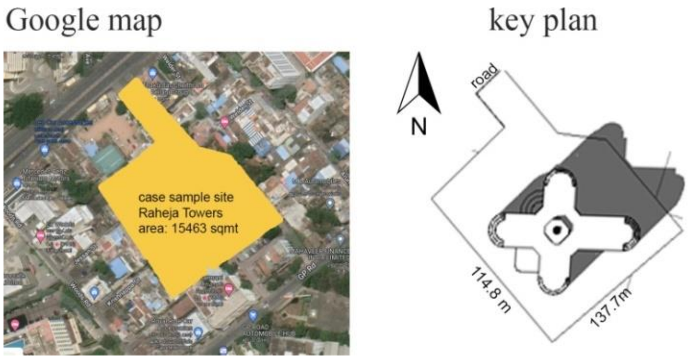


Fig. 5 - case sample site google image and key plan

4.1.2 Development Regulations

Every city has its own control rules for multi-storied commercial use development. The CMDA 2010 Development control rules for multi-storied commercial buildings are applied in this research. The CDMA 2010 rules are applied as the results are validated with the existing building developed per CMDA 2010 development rules [33]. The development control rules calculation for the selected sample site is shown in Table 1.

The building regulations for multi-storied commercial buildings are:

- Permissible FSI is 2.5

- Multi-storied: total building height of more than 18 meters
- Maximum plot coverage is 30% of the plot area.
- Minimum setbacks of 7 meters for a 30-meter height of the building and every increase in the height of 6m or part thereof above 30 meters additional setback of 1meter.
- The maximum height of the building is 60 meters.

Table 1 shows the permissible volume for a plot area of 15,462 m^2. The form can range from 4831 m^2 on 8 floors to 2577m^2 on 15 floors.

Table 1 - Development control rules calculations for sample site as per CMDA 2010

Development control rules calculations	values
plot area in m^2	15463
Floor space index (FSI)	2.5
TOTAL build-up area in m^2 (TFA)	38653
Maximum permissible plot coverage (% of site area)	30%
the coverage area for the plot area in m^2	4638
max - a minimum height in meters	60 - 30
min set back in meters	7
maximum setback for 60 meters Height	12
Maximum floor area in m^2 (coverage % of site area)	4638
Min number of floors (round off)	8
Maximum number of floor	15
Floor to Floor height in meters (FTF)	4

4.1.3 FGM Office Building Form Typologies

The two significant spaces for FGM office use are the air-conditioned office spaces and core/utility spaces. The form typology for office buildings has three major categories: point/block, court, and union [34]. Schematic images of the three categories of form typology as shown in Fig 6.

- ***Point/ Block:*** Compact shapes for office use are often organized with a core in the center or sides. This shape typology can be appointed on several scales.

- ***Court:*** These area subtractive forms of similar shapes with a space-efficient layout unifying different spatial qualities, well-lit office spaces, and naturally ventilated core areas.

- ***Union*****:** These are additive forms of similar shape/form or different forms. It is most responsive to the site and applicable for large floor depths. Core areas are located in the center or sides.

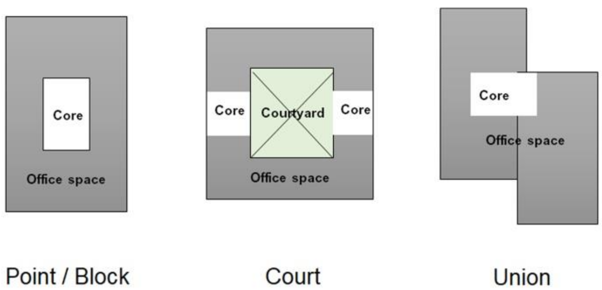


Fig. 6 - Schematic images of the three categories of office building typologies

The 13 forms were created from the three categories of typology of office building forms within the permissible volume. The types of shapes are simple geometric regular shapes such as square, rectangle, circle, ellipse & polygon, and free form with closed spline in the point/block typology. Rectangular, polygon, ellipse, and spline court in court typologies and polygon, curve, and spline union in union typology. The 13 types of form in three typology as in fig 7

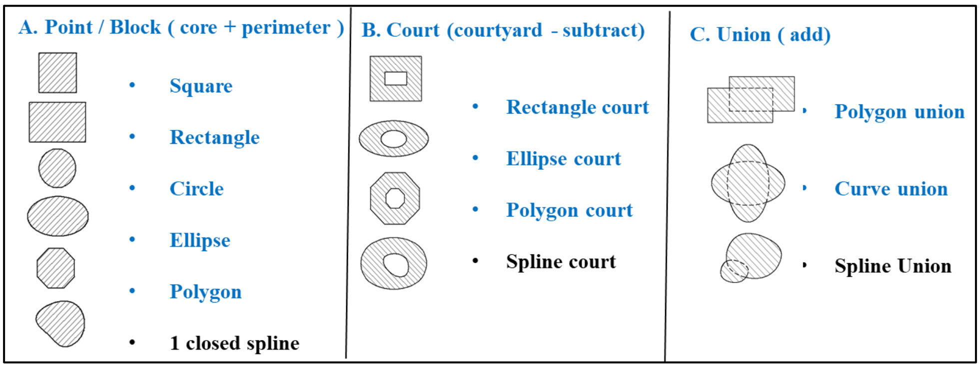


Fig 7 - 13 Types of massing shapes in three major categories 10 regular shapes and 3 splines free-form generated for the sample site

4.1.4 Green Building Performance Criteria for Office Use

India is still in the nascent stage of energy conservation for new buildings. To reduce energy and aim for positive economic development, BEE has formulated the energy-efficient building code initiated in 2002. The latest ECBC 2017 prescribes a minimum standard for energy use in new and major retrofits of buildings. Today designers can now use energy modeling workflows with minimum effort, and ECBC 17 explicitly endorses using energy simulations at the design stage [35]. While the GRIHA, like the US Green Building Council's LEED green building rating system, provides credit for energy-simulation informed massing design [35]. GRIHA v19 adapts the complaint of ECBC2017 as mandatory criteria.

The Green rating for integrated habitat assessment, version 2019 [36], is the national rating system of India. The building is assessed based on its predicted performance from inception through operation over its entire life cycle. By its qualitative and quantitative assessment criteria, this tool can 'rate' a building on the degree of its 'greenness' [36] with a benchmark for four different climate zone in India, including Chennai under the hot and humid zone.

The green building performance criteria used in this research for hot and humid climate zone at early design stage are:

a) ***Criteria 2- Low impact design*:** Building massing to reduce insolation as per passive design strategy no 5 of appendix 1c pg13 [35]. The analysis required to conduct solar insolation for the summer months (typically April to June) and demonstrate reduction against the base case of a cube created with the same surface area of the design case.

b) ***Criteria 7- Energy optimization*:** A building's EPI (Energy Performance Index**)** is its annual energy consumption per square meter of its usable spaces. The EPI benchmark is 121.5 kWh/m^2/year for warm and humid climate zone for daytime office working six days a week (pg 38-29, table 3.3 [36]).

c) **LEED v4.1 - *Visual comfort requirements:*** SDA % and ASE % of floor area is a Climate-based annual daylight simulation. With modeling for a grid size of 1m x 1m and analysis hours from 8 am to 6 pm for SDA% and ASE %. The target is 300 lux for 50% of the occupied period AND 40 % of the floor area as the threshold for SDA. ASE less than 20 percent of the floor area exceeding the threshold of 1000 lux for more than 250 occupied hours per year [37].

d) ***Criteria 8 - Peak heat grain from the envelope (PHGE):*** Peak heat gain from a building envelope provides designers with the flexibility to work with various materials and varying window-wall ratios, while limiting heat gain from the façade is crucial for a holistic green building design. The Sum of sensible heat by wall, roof, glazing frame, glazing, or windows conductions on the peak hour from the simulation data is divided by the total envelope area to calculate the building PHGE in W/m2. The Benchmark for PHEG is 35 W/m^2 for this climatic zone in a daytime office use building five days a week (pg 37, table 3.2, [36]).

4.1.5 Facade Cost and Technology

This research is for a redesign in a case sample site, and evaluation with the existing building in the same site with the same envelope materials is taken for cost calculations. Conventional construction with a typical frame structure RCC grade A up to 20 floors with single reflective glazing in an aluminum curtain wall system for Chennai is ₹30000/m^2 [38] The cost excluding professional fees, land cost, basements floors, and the cost associated with statutory approvals, equipment, fit-out, and other expenses. Curtain wall system comprises one of the elements of facade technology in high rise building. The stick-build glass system of curtain wall technology applicable to mid-rise buildings erected at site and it's economical. With aluminum frames and 6mm single reflective glazing glued to the metal frame, the curtain wall cost is ₹ 6000 to 8000 / m^2. The curtain wall cost for double glazing, triple glazing, curved glazing, or many custom panels is more than double compared to the conventional curtain panel cost.

4.2 Tools: Understand the Generative Software

The process starts from Revit for geometry creation according to contextual limits such as location, climate, site geometry, and permissible volume. Then with Dynamo for visual programming to create and set limits. It is exported to PR, the generative software by Autodesk. Revit-insight and E-Quest are the software for thermal, daylighting and energy analysis. The Dynamo with PR is the software for generative design.

4.2.1 Revit - BIM

The Revit for building massing modeling or the lightweight BIM model with building elements like floor, walls, curtain wall system, and roof. It is the base interface for Dynamo and Project refinery.

4.2.2 Insight - Solar Analysis

Insight is a plug-in with Revit for solar analysis. The analysis surface is selected, and the period in the sunsetting tab, the peak, cumulative, and average insolation results in kWh.

4.2.3 Insight - Daylighting

Insight is a plug-in with Revit for daylighting analysis in the cloud to perform the Griha Criteria10. The default annual analysis method in the Insight is as per LEED V4.1 of SDA, and ASE % [37] method is used in the research. The following daylighting metrics are used in this research:

- SDA%: Spatial Daylight Autonomy (SDA) assesses whether a space receives sufficient daylight on a work plane during standard operating hours on an annual basis. The target is 300 lux for 40% of the occupied period. Annual analysis as per LEED v4.1.
- ASE%: ASE (Annual Sunlight Exposure) identifies surfaces receiving too much direct sunlight that may cause visual discomfort or glare. ASE measures the percentage of the work plane exceeding the threshold of 1000 lux for more than 250 occupied hours per year.

This research simulation is based on the following input assumptions:

- Blinds, shades, or internal partitions are excluded from the model.
- Default surface reflectance of 80% for ceilings, 20% for floors, and 50% for walls.
- The analysis plane is at 0.8 meters.
- Analysis grid is 0.6 x 0.6 m
- 8 am to 6 pm – a total of 3650 hours.
- Sky Component: CIE uniform sky for Chennai location.

4.2.4 E-Quest – Energy Simulation

This research uses the E-Quest for EPI and PHGE results as it is the approved energy simulation software by GrihaV19 and ECBC17. A whole building energy simulation software runs on the DOE-2 platform. It has wizards to create projects in a simple menu and intellect dynamic defaults. The schematic design wizard is for massing analysis, and the design development wizard is for more detailed analysis. It is a quick and professional energy simulation software. To create the shell from default shapes or import a cadd file to create a floor plan with zones, wall, floor, ceiling, roof, doors, windows, glazing, shades, orientation, materials, types of equipment, and other inputs for energy analysis. Moreover, it also gives the output of annual, monthly, daily, and hourly energy use data for whole buildings, each zone, and each type of space.

The assumption and data inputs used in this study are as follows:

- Location : epw weather file for Chennai, India.
- Office space planning : 50%Open office plan, 25 % cubicles, 10% corridors, 5% lobby and 10%utilities.
- Floor to floor height : 4 meters
- Floor to false ceiling height : 3 meters

- Zoning pattern : perimeter and core
- A/C Zones : office area as air-conditioned and core area as non-air-conditioned
- Occupancy rate : 12.5 persons m^2
- Occupancy hours : 9 am to 6 pm (daytime)
- Walls : 150mm Aerated concrete block with no insulation.
- Glazing : single reflective clear glass 6mm thick in aluminium metal framework (as per existing case sample building)
- WWR % : 95 % for office area and 40% for core area.
- SHGC of glazing : 0.39
- Lighting load : 1 watt / m^2
- Power load : 2 watts/m^2
- Cooling set point : 23.3 ° C
- HAVC Type : VAV with a chilled water system
- Supply air temp : 12 ° C
- Relative Humidity (RH) : 50 %
- Latent Heat gain per person : 58 W
- Sensible heat gain per person : 73W

4.2.5 Dynamo – Visual Programming

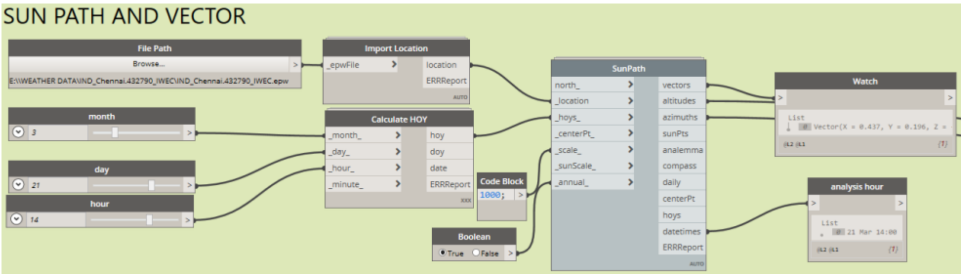


Fig 8 - Sun path node from Ladybug for Dynamo

Dynamo is a visual programming tool that works with Revit. Dynamo extends the power of Revit by providing access to the Revit API in a more accessible manner [39]. Rather than typing code, Dynamo creates programs by manipulating graphic elements called "nodes" and using a computational process to encode the workflow design. Each step with specific parameters becomes a series of instructions that can be evaluated, revised, and improved. With fixed or variable inputs, the Dynamo manipulates desired outputs that can be taken to Revit, making the design process a performance criterion rather than an intuitive or contextual-based design approach.

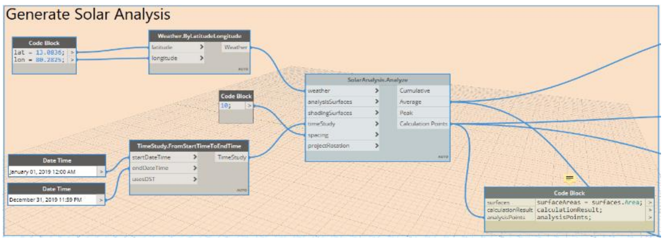


Fig. 9 - Solar analysis node

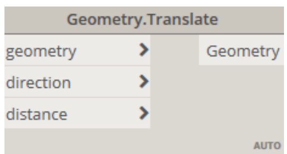


Fig. 10 - Geometry transpose node

The specific nodes used in the research are:

1) Lady Bug for Dynamo: The climatic data and sun vector generation node (Fig 8).
2) Solar analysis for Dynamo: To get the solar analysis results for the analysis area for the given analysis period and location (Fig 9).
3) Geometry Translate: moving the geometry in a specific direction and input distance on the same plane (Fig 10).

4.2.6 Project Refinery (PR) – Generative Design

Project Refinery is an Autodesk generative design data for the architecture, engineering, and construction industry. Project Refinery is the tool for generative design options used in this research. Project Refinery creates design options, sets goals, and optimizes those goals from the Dynamo design inputs and output data.

4.3 Form – Finding SG Rules

The façade design in two stages, first form-finding and then façade plane-finding. The rules for each stage are explained in the following sections. In both the sections, the generative design is applied for the thermal performance of the facade, as it has maximum impact on spce cooling energy saving for an FGM office building in a hot and humid climate. There are 6 rules applied for an energy-efficient form finding process. However, the order of rules is per the creation of the simulation model and the designer's choice for performances. The flowchart for the 6 rules is shown in fig 11. The rule is developed for this project redesign as per the flowchart shown in fig 2. The process is by creating a massing model with variable inputs for geometry limits in Dynamo and exporting them for generative selection from multiple options in PR. In the next stage, the selected results are created as a lightweight BIM model in Revit and E-Quest for performance analysis.

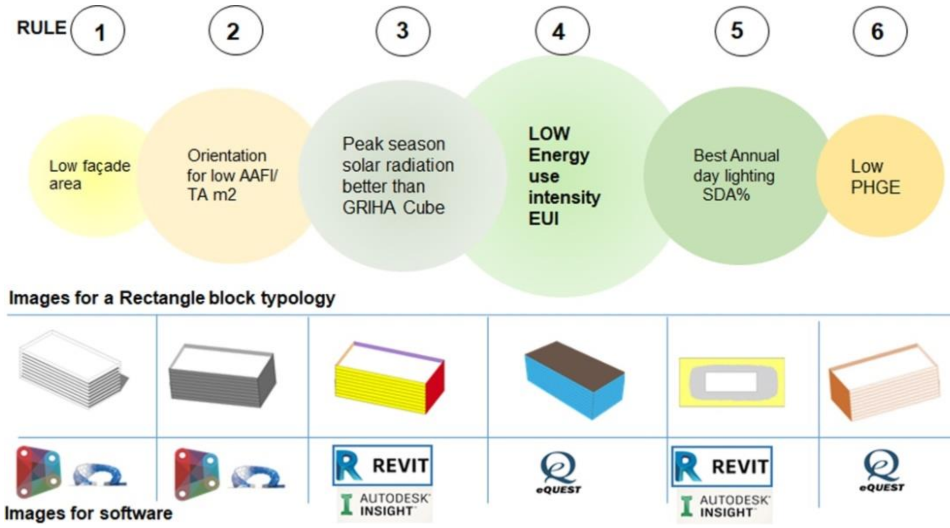


Fig. 11 - Six shape grammar rules process for form finding with case sample rectangle form generative process and software used

4.3.1 Form Rule 1

All the 13 typologies geometry created in Dynamo, for the dimension limits as per site are data, and calculating the façade area as output. Export these models to PR for each of the 13 typologies and evaluate for the lowest façade area as output criteria. The image of the dynamo script is shown in Fig 12. The image of PR options for spline union as in Fig13. The results are ranked for FA with no of floors as in rule 1 of table 2

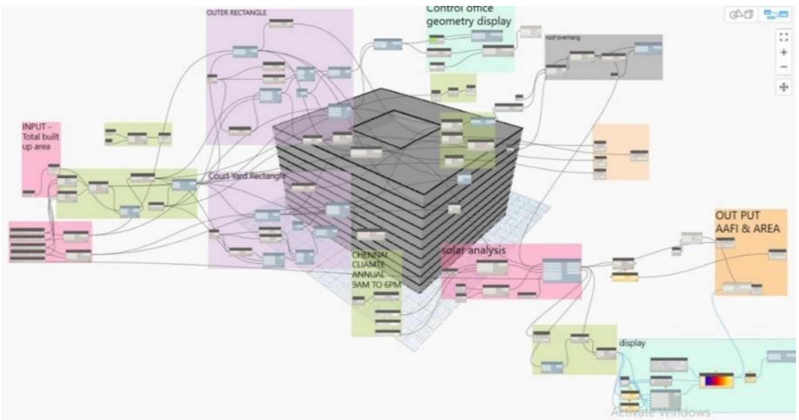


Fig. 12 - Dynamo geometry script for output results for solar insolation and façade area in the rectangular court form typology

4.3.2 Form Rule 2

For low solar insolation for orientation by adding the solar analysis node for Dynamo and model rotated to get AAIFA in W/m^2 and orientation angle in Project refinery for each type. The solar analysis node in Dynamo gives the annual average solar insolation for the Chennai location from 9 am to 6 pm. The data is compiled for all the 13 typologies of AAIFA in W/m^2 derived from the formula below. The results of AAIFA for all the types are ranked as in rule 2 of Table 2.

$$\text{Solar insolation per floor area (AAIFA) in Wh/m}^2 = \frac{\text{AA Insolation of the Façade Wh/m}^2 \times \text{Facade Area m}^2}{\text{Total office floor area in m}^2}$$

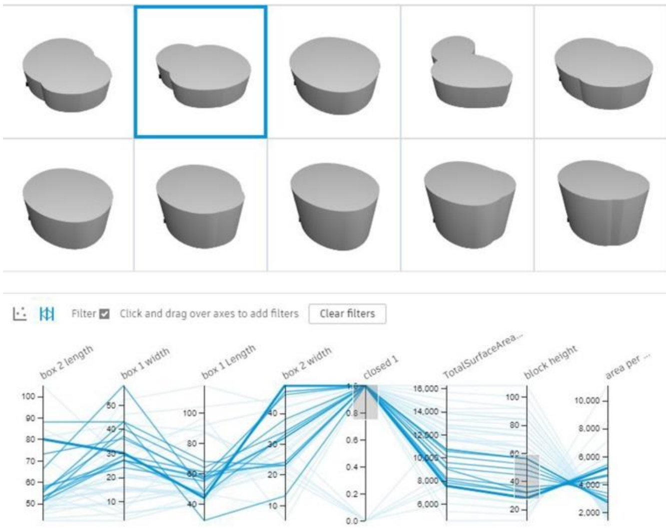


Fig. 13 - Image of project refinery output results for a closed spline Union form typology

4.3.3 Form Rule 3

Criteria 2 for low-impact design strategies where a cube is created with the same surface area of the design case. This base case cube and the design case are analyzed for peak summer solar insolation (i.e., April 1st to June 31st). Create the massing model in Revit for all the types and solar insolation analysis in Insight. The results of the 13 typologies are ranked better than the base case Griha cube as in rule 3 of table 2.

4.3.4 Form Rule 4

The 13 models are created in E-Quest for energy performance as schematic development wizards to get the EPI in kWh/m^2/year. Each model has core areas, office spaces, and envelope material as per the existing building in the case site and assumption as in section 4.2.4. Here, the 13 typologies are ranked from low to high for EUI as in rule 4 of table 2 and Chart 1. Griha v19 threshold of 121.5kWh/m^2/year for the hot and humid climatic region for 6 days a week.

Chart 1 - EPI and SDA % for all the forms with the thresold for green building regulations

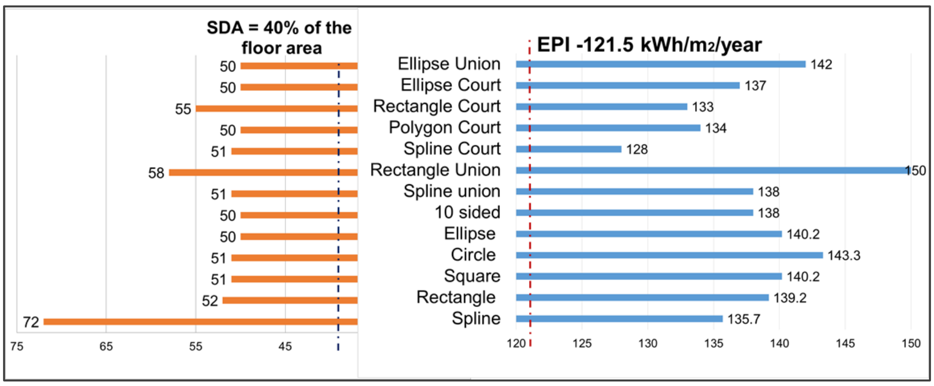
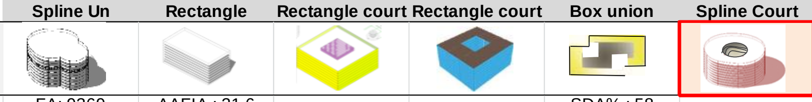
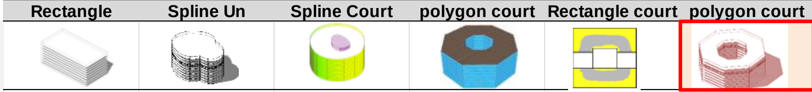
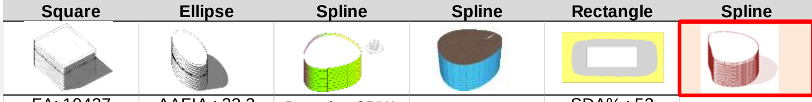
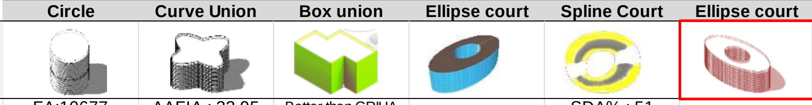
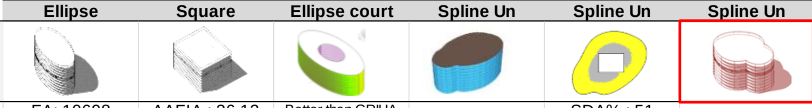
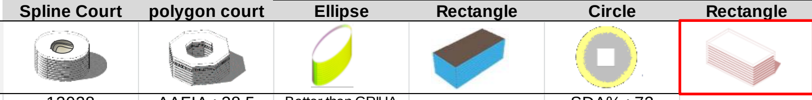
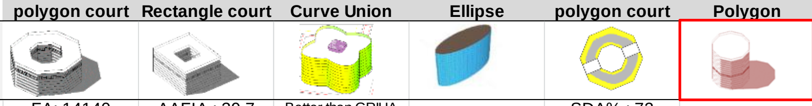
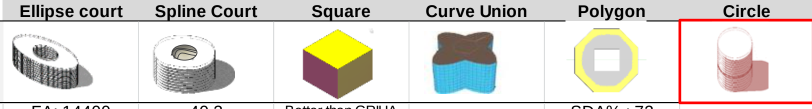
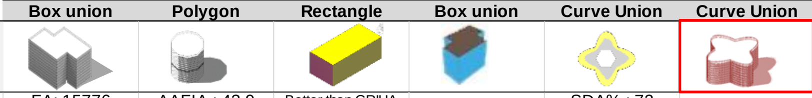


Table 2 - Table of performance ranking for form – finding by SG rules 1 to 6 for the case sample site.

Rank	RULE I	RULE 2	RULE 3	RULE 4	RULE 5	RULE6	Rank
	Spline	Spline	polygon court	Spline Court	Spline	Rectangle court	
1							1
	FA : 8490 Floors : G+9	AAFIA : 27.08 orinetation : 0 ° N	Better than GRIHA cube: -7%	EPI :128	SDA% : 72 ASE% : 18	PHGE :47.9	
	Spline Un	Rectangle	Rectangle court	Rectangle court	Box union	Spline Court	
2							2
	FA: 9369 Floors : G+8	AAFIA : 31.6 0 ° N	Better than GRIHA cube: -6%	EPI :133	SDA% : 58 ASE% : 17	PHGE : 76.2	
	Rectangle	Spline Un	Spline Court	polygon court	Rectangle court	polygon court	
3							3
	FA:10188 G+8	AAFIA : 32.24 0 ° N	Better than GRIHA cube : + 7%	EPI :134	SDA% : 55 ASE% : 15	PHGE : 80.4	
	Square	Ellipse	Spline	Spline	Rectangle	Spline	
4							4
	FA: 10437 G+9	AAFIA : 33.2 0 ° N	Better than GRIHA cube: +8%	EPI :135.7	SDA% : 52 ASE% : 16	PHGE : 86.2	
	Circle	Curve Union	Box union	Ellipse court	Spline Court	Ellipse court	
5							
	FA:10677 Floors: G+14	AAFIA : 33.95 0 ° N	Better than GRIHA cube: +10.3%	EPI : 137	SDA% : 51 ASE% : 9	PHGE : 90.24	
	Ellipse	Square	Ellipse court	Spline Un	Spline Un	Spline Un	
6							
	FA: 10698 G+10	AAFIA : 36.12 350 ° N	Better than GRIHA cube: +11%	EPI : 138	SDA% : 51 ASE% : 9	PHGE : 93.4	
	Polygon	Box union	Polygon	Polygon	Square	Ellipse	
7							
	FA: 10932 G+14	36.15 0 ° N	Better than GRIHA cube: +12.3%	EPI :138	SDA% : 51 ASE% : 9	PHGE : 96.7	
	Spline Court	polygon court	Ellipse	Rectangle	Circle	Rectangle	
8							
	12028 G+9	AAFIA : 38.5 0 ° N	Better than GRIHA cube: +13.1%	EPI :139.2	SDA% : 72 ASE% : 18	PHGE : 101	
	Curve Union	Ellipse court	Circle	Square	Ellipse court	Square	
9							
	FA: 12886 G+9	AAFIA : 38.5 10 ° N	Better than GRIHA cube: +13.3%	EPI :140.2	SDA% : 72 ASE% : 18	PHGE :102	
	polygon court	Rectangle court	Curve Union	Ellipse	polygon court	Polygon	
10							
	FA: 14140 G+8	AAFIA : 39.7 338 ° N	Better than GRIHA cube: +13.8%	EPI :140.8	SDA% : 72 ASE% : 18	PHGE : 103.4	
	Ellipse court	Spline Court	Square	Curve Union	Polygon	Circle	
11							
	FA: 14400 G+8	40.3 15 ° N	Better than GRIHA cube: +13.8%	EPI :142	SDA% : 72 ASE% : 18	PHGE : 104.8	
	Rectangle court	Circle	Spline Un	Circle	Ellipse	Box union	
12							
	FA: 15040 G+9	AAFIA : 42.11 0 ° N	Better than GRIHA cube: +14.1%	EPI :143.3	SDA% : 72 ASE% : 18	PHGE : 108.4	
	Box union	Polygon	Rectangle	Box union	Curve Union	Curve Union	
13							
	FA: 15776 G+8	AAFIA : 43.9 0 ° N	Better than GRIHA cube: +14.4%	EPI :150	SDA% : 72 ASE% : 18	PHGE : 110	

4.3.5 Form Rule 5

The annual daylighting analysis as per LEED v4.1 method. The Revit massing model is created as a Lightweight BIM model with the walls, floors, core areas, office spaces, roof, and curtain system of 6mm single glazing in an aluminium frame system per the existing case sample building. SDA % and ASE % as per section 4.2.3 The results for SDA% are ranked from high to low as in rule 5 of table 2 and chart 1 with LEED v4.1 threshold line for SDA at 40% of the office floor area.

4.3.6 Form Rule 6

The performance criteria for peak heat gain by façade. Each model results from E-Quest, the PHGE is calculated per section 4.1.3 d. The results are ranked from low to high, as in Table 6 of table 2.

4.4 Observations of Form-Finding

1. In Rule 1, the point/block forms have a lower façade area than the other typologies, with a court form with maximum façade area.
2. In Rule 1, more no floors with more façade area. The cylindrical form would have the lowest façade area for the same floor. However, less radius of the circle inscribed within the site result in 15 floors, with more façade area.
3. In Rule 2, The orientation for most of the forms is best at 0 °N except for squares at 350 °N, rectangular at 10 °N, and rectangular courts at 338°N.
4. In Rule 2, the spline and spline union form with the lowest AAIFA, followed by form types with the longer side facing north orientation.
5. Rule 3, the Griha cube to compare with the design case, the court forms with more façade area and low insolation are the best-ranked forms.
6. In Rule 4, the spline, rectangular, polygon, and spline court are the four lowest EPI.
7. In Rule 4, the core area for block and union forms will be located in the center, with mechanical ventilation having more EPI than the court forms.
8. In Rule 5, the curved typology of formsforms performed better in SDA% and ASE. % results than the straight typology of forms.
9. In Rule 5, all forms' daylighting performance passed the LEED v4.1 threshold of 40% of the office floor area, as in chart 1. Among the top 4 ranked forms selected, the spline is the only block form type with low EPI and good daylighting performances.
10. In Rule 6, The spline and Rectangular courts have lower peak heat gain factors than the other forms but are above the Griha V19 threshold of 35 W/m^2 for a hot and humid climate zone.

By the SG process of applying the above 6 rules, the 13 types of forms are ranked and selected—the best 2 as in table 2. The rectangular and spline court forms are selected for the next stage of the façade plane-finding SG process.

4.5 Façade Plane – Finding SG Rules

The façade plane-finding is a crucial factor for energy efficiency as the layout of the façade plane determines the efficiency of the façade. The major cost difference for the curtain wall glazing is the size of panels, type of glass, and customization of glazing panels. The rectangular court form is selected for the façade plane-finding SG process as it would have fewer custom panels with straight glazed planes than the spline court form. The SG for the façade plane-finding process by applying 5 rules, the flow chart as in fig14. At first, many types of extrusion in the Z-plane for an atypical/untypical floor plan. The second step is the XY-plane corner transpose, the third step for the roof overhang, and the 4^{th} rule for plane deviation of each orientation of the façade planes. The final step is for zero or minimum custom panels. The SG rule from 1 to 4 in Dynamo with solar analysis node to get the output criteria of low AAIFA in PR.

4.5.1 Plane-Finding Rule 1

The rectangular court form with the option of perpendicular extrusion in the Z-plane to create atypical or untypical floor plans. The 5 options in Fig 14 such as,

- Option 1: sloped/stepped - each floor outward.
- Option 2: sloped/stepped - each floor inward.
- Option 3: top face rotated in the XY plane.
- Option 4: Top face moved in XY plane.
- Option 5: Random shuffle the floor plate in XY plane.

The above 5 options are a few ways to create an atypical/untypical floor plan. The plane's normal rectangular court massing is manipulated in Dynamo by scaling, rotating, or moving the top face with a variable number range within the permissible limits as the input. Option 1 and 2 by scaling the top face, reducing the slope inward, and enlarging the slope outward. The top face is moved in option 3 and rotated for option 4. For option 5, by creating a circle in the center of the plane's normal form, dividing the circle with equal points per the total number of floors, and assigning the center of each floor to these points. The random Dynamo node is the input to move each floor randomly along the points in the circle. The process in PR is shown in fig 15. In all the options, the center courtyard position is fixed. With the variable input for each option, the PR selects the best option with low AAIFA for the next stage.

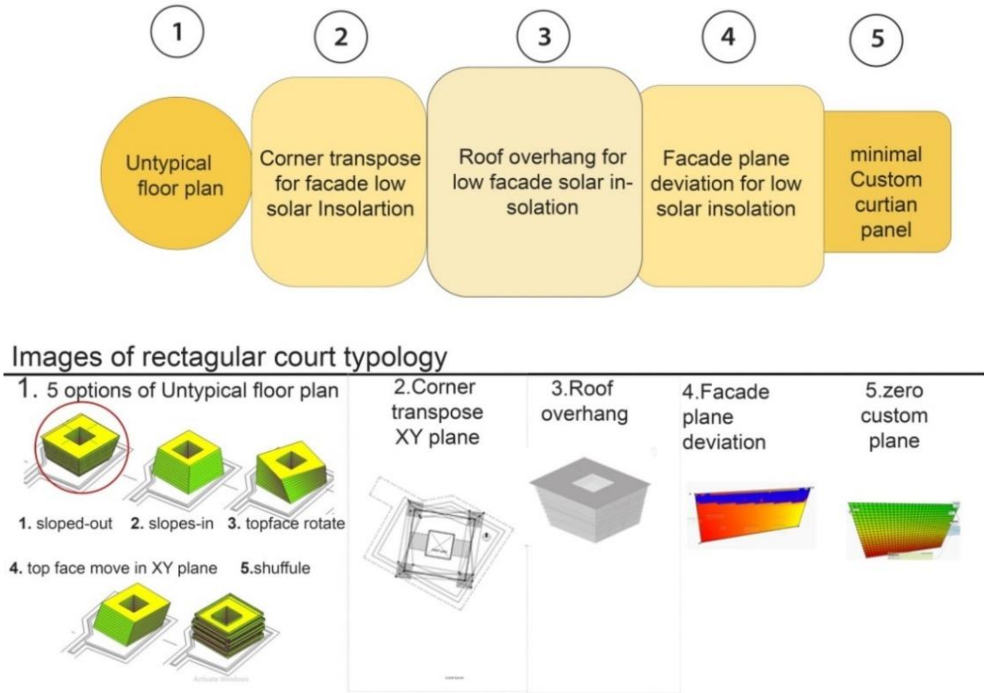


Fig. 14 - Shape grammar process and rules for façade plane- finding

4.5.2 Plane Finding Rule 2

The forms of exterior corners 4 points of the bottom plane are moved or transposed within the site setback as shown in FIG 16 for a grid of 2 x 2 m, by creating the geometry transpose in Dynamo and refined for low AAI per FA in PR. This process deforms the regular rectangular shape into an irregular polygon by optimization of the XY plane plan for low thermal radiation on the total façade plane.

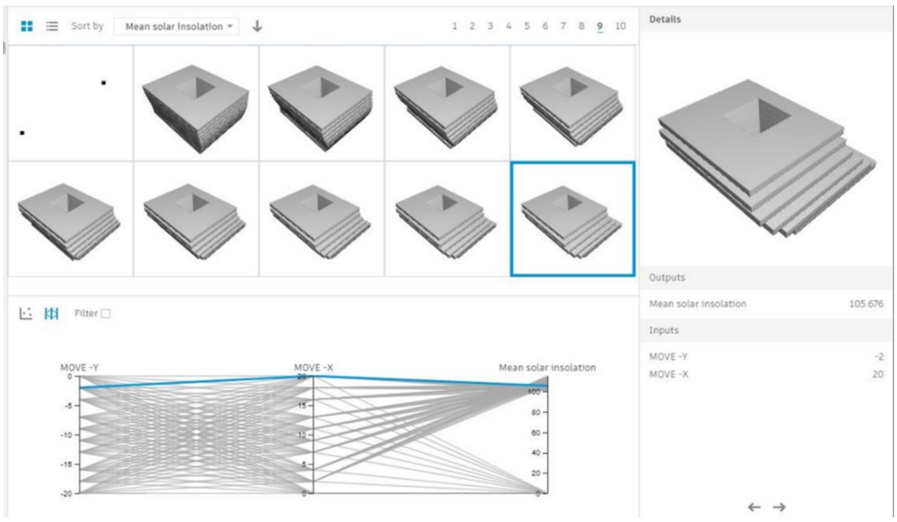


Fig 15 - Project refinary for option 5 for Random shuffle the floor plate in XY plane

4.5.3 Plane Finding Rule 3

A roof overhang is added so that limits within the permissible coverage and setbacks by adding an overhang geometry in Dynamo with variable inputs in 0.5m intervals by offsetting the roof profile in each orientation. The PR selects the offset distance with low solar insolation on the façade area with an overhang as the shading element for each orientation. The result of 1m overhangs in the east, 2 m overhang in the south and west, and 0.5m overhang in the north façades were assigned.

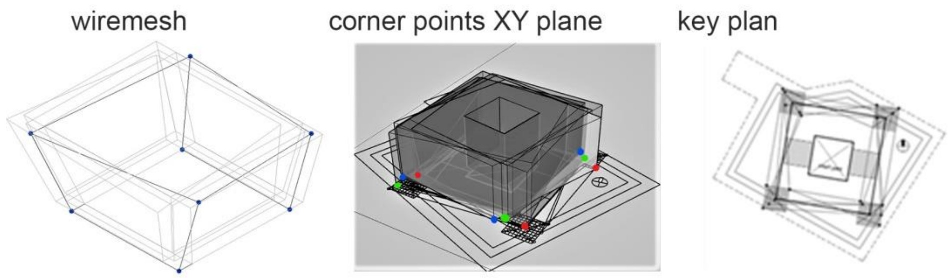
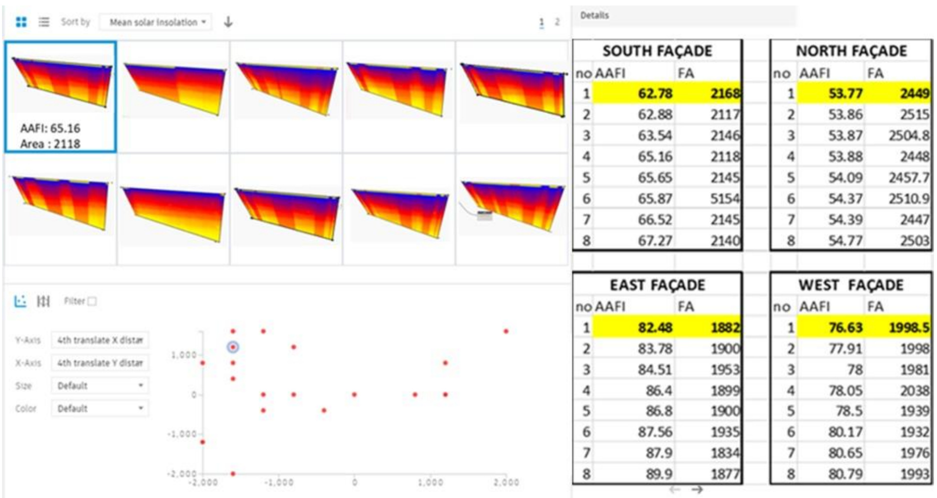


Fig 16 - Rule 3, the exterior corner transpose 3d views for rectangular court form



SOUTH FAÇADE		
no	AAFI	FA
1	62.78	2168
2	62.88	2117
3	63.54	2146
4	65.16	2118
5	65.65	2145
6	65.87	5154
7	66.52	2145
8	67.27	2140

NORTH FAÇADE		
no	AAFI	FA
1	53.77	2449
2	53.86	2515
3	53.87	2504.8
4	53.88	2448
5	54.09	2457.7
6	54.37	2510.9
7	54.39	2447
8	54.77	2503

EAST FAÇADE		
no	AAFI	FA
1	82.48	1882
2	83.78	1900
3	84.51	1953
4	86.4	1899
5	86.8	1900
6	87.56	1935
7	87.9	1834
8	89.9	1877

WEST FAÇADE		
no	AAFI	FA
1	76.63	1998.5
2	77.91	1998
3	78	1981
4	78.05	2038
5	78.5	1939
6	80.17	1932
7	80.65	1976
8	80.79	1993

Fig 17 - Rule 4, solar insolation by façade corner transpose in project refinery and the data chart for all the planes

4.5.4 Plane Finding Rule 4

Each glazing plane's corner point is moved in the XY plane and analyzed for solar insolation with the overhang as the shading element. The selected plane's 4 corner points are moved in a grid of 1m x 1m in the XY plane by creating the geometry in Dynamo with a number variable for point transpose so that the plane is twisted and refined in the Project refinery for low solar insolation for each orientation as in Fig17.

4.5.5 Plane Finding Rule 5

In this last stage of generative optimization, minimize or zero custom panels of glazing as it is an economical design. The plane deviation of the façade plane depends on the panels' size and the deviation between the corner points of a curtain plane. The dynamo scrip is created for the output of panel size and maximum deviation in mm. It was then refined in the Project refinery for maximum panel size with minimum plane deviation, as 4mm of minimum deviation does not require the custom panel [40]. The panel size is 1750 x 2080 mm, and the deviation is 1.45mm for the south façade, as in FIG18. This process is repeated for all the orientations and filtered for the final façade plane.

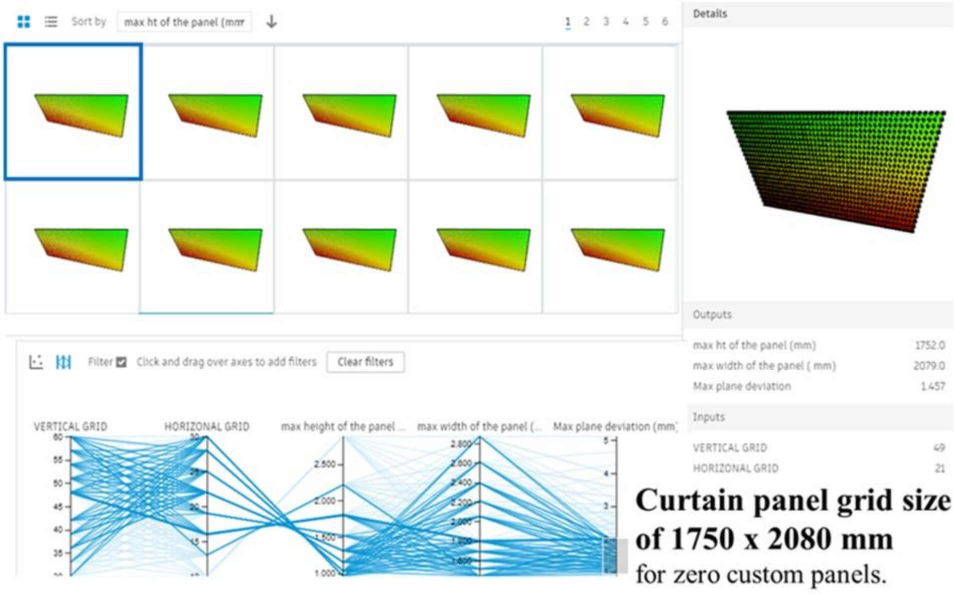


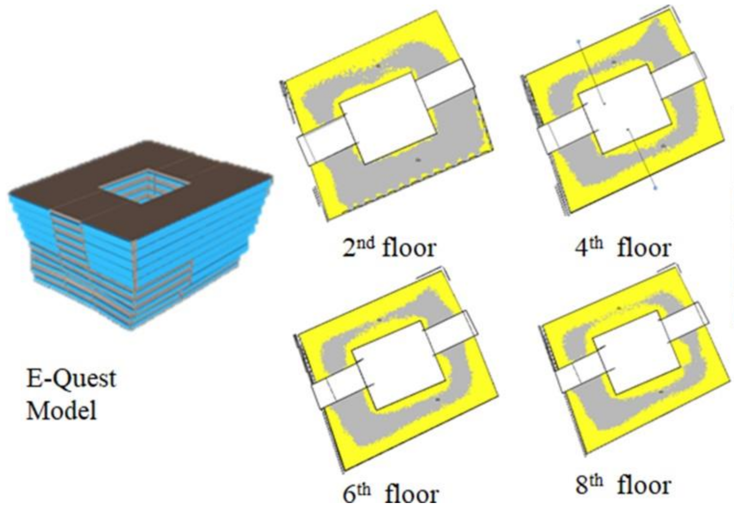
Fig. 18 - Rule 5, plane deviation and maximum panel size for < 2mm deviation in the south glazing façade plane

4.6 Observations

1. In Rule 1, among the 5 options in plane-finding rule 1, the sloped/stepped outward has the lowest AAI/FA.
2. option 5 of rule 1, the random shuffle has the lowest AAI/FA but is not selected as its cantilever will add to the permissible built-up area and increase construction cost due to multiple floor cantilevers.
3. In rule 2, to avoid the twist or skew of the façade plane, the exterior corner transpose is done only for the bottom face and not applied to the top face or the courtyard facade planes.
4. By rule 2, the facade profile has a longer north and east façade than the south, and west facades, making it an irregular 4-sided polygon.
5. By rule 3, adding roof overhang, the thermal radiation on the façade is lower as its shading for the top area of the façade in each orientation.
6. By rule 4, plane deviation of the façade can reduce the thermal radiation by > 5 % for all the orientations, as in fig 17.
7. By rule 5, the Plane deviation for optimizing the glazing panel design to get the optimum size for less or zero customized panels, as in fig 18
8. The final form's daylighting results are low on lower floors as the WWR is 40% compensated on the upper floors as in fig 19.
9. The EPI and annual daylighting performance are lower than the benchmark, but the PHGE results are more than the 35 W/m^2 as the glazing is single reflective glass with an SHGC of 0.39.

4.7 SG Generated Form

The finalized form is imported back to Revit to create the BIM model with floors, roof, curtain walls, core areas, and other building components similar to the case sample existing building design. The WWR % revision of the façade plane as per case sample building, with WWR 40% in the lower level, courtyard & core area. This model is checked for annual daylighting as in section 4.2.3. for alternative floors as per the LEED v4.1 method (fig16). For energy simulation, the model is created in E-Quest, With the HVAC zone, core areas, and building envelope elements per the existing building design in the detail design wizard. Energy simulation as per section 4.2.4 for EPI, PGHE results as in fig19.



	design	benchmark
SDA %	52	>50
ASE %	18	<20
PHGE W/m²	38	35
EPI - kWh/m²/year	115.4	121.5

Fig. 19 - SG finalized form final results energy model, SDA floor plans and table of results

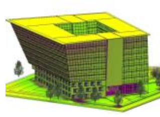
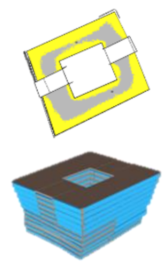
5. Evaluate: SG Result with the Existing Case Sample Building.

The existing building in the selected case sample site is *Raheja Towers* have a total built-up area of 38,653 m^2 in a cruciform shape with a DOF of 23 m with the core in the center, as in table 3. The more extended wing of the cross faces north. Its HVAC equipment is less than 5 years old with an EPI of 207 kWh/m^2. Using field survey data of the context, geometry, and building materials, a base case model was created in Revit BIM for annual daylight analysis such as SDA% and ASE%. The BIM model is created for energy analysis in E-Quest to get annual, monthly, daily, and hourly results.

Evaluation of the SG resultant form with the same no of floors, area per floor, glazing type, and WWR % have better performances than the existing building simulation results, as shown in Table 3. Comparing the simulation results of both the forms in the same context and simulation tools revealed that the SG resultant form has more than 8% façade area and 1/3 lower ratio of glazing area to office area than the existing building. With low glazing area in the office spaces, better SDA %, more than 40% low solar insolation, and more than 40 % low EPI and PHEG than the existing building.

Evaluating the existing building design developed with form-making methods has proved to be an inefficient forming process characterized by coincidence and no logic. The PBSG result by form-finding using today's simulation tools at the early design is efficient, with design's driven performance criteria at each stage of the process.



SG form for case sample site	Description	existing building in case saemple site
10	No of floor	10
4	Floor to floor height	3.05
3754	area per floor	3890
20	% of core area to floor area	29.04
75%	WWR %	72%
16%	% of Glazing area to Office area	26%
5.2	Glazing U factor	5.2
16161	façade area	14883
0.39	SHGC	0.39
39.7	AAFI/ m2	72
52	SDA %	48
16	ASE %	12
112.5	EPI	195
38.02	PHGE IN W/m2	69.04

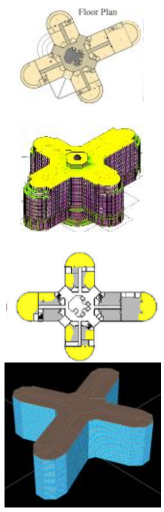


Fig. 20 - Comparison of SG resultant irregular rectangular court form with existing building design on the case sample site

6. Results and Discussion

1. As the form-finding generative design method is not artistic or intuitive design process could result in irregular / awkward-looking buildings.
2. Among the forms, the court form is the most suited for this climatic context, with better daylighting and natural ventilation for the core/utility spaces.
3. The SG rules are an effortless yet more accurate way of filtering for green building benchmarks in the early design stage with basic building data.
4. The SG form-finding method can be applied to any scale, type, or use of generative form-finding for energy efficiency.
5. The SG method for plane-finding mostly applies to medium to large-scale sites with enough setbacks to modulate and manipulate the facade planes.
6. The spline court results are lower than the rectangular court form for EPI results in stage 1 which will be more than the conventional cost.
7. The SG resultant form, the irregular rectangular court, is 42% more energy-efficient than the existing design using the same envelope materials and HVAC equipment and at the same or little extra cost.
8. Little extra cost as the form slopes outward with 0.9m cantilevers from the 3rd floor to the top floor.
9. The final result for Peak heat gain from the envelope is more than the GRIHAv19 threshold of 35 W/m^2 as it is only single reflective glazing with SHGC of 0.39. The threshold could be achieved by changing the glazing type to well-insulated glazing or adding shading devices.
10. When the WWR % is less than 40, it is energy efficient as per green building regulations (ECBC, 2017), but fully glazed (WWR>70%) needs advanced design strategies with simulation methods for performance criteria.
11. This generative optimization process for sustainable design methods allows us to view unlimited options and filter for mathematical objectives such as site limitations, development control rules, and green building regulations.
12. This method of generative design in Dynamo and Project refinery is only in the nascent stage; later, we should be able to combine solar, daylighting, and energy analysis in one single package or script.

7. Conclusion

The growing magnitude of FGM in India needs an innovative form-finding design method to achieve energy efficiency in hot and humid climates. This paper proposes a shape grammar generative-based methodology to assist designers with a performance-driven design process. PBSG method at the conceptual design phase was applied on a case sample site and compared with the existing building design. Through multiple generative SG rules for an irregular rectangular court, the FGM office building is >40% energy-efficient compared to the existing building design in the same context. The form-finding method at the early design stage with generative simulation tools are energy-efficient compared to form-making tradition form design methods for the FGM office building in this context.

When the form is defined in the early design stages, energy performance information for the façade design is normally non-existent due to modeling for energy simulation being time-consuming, expensive, and frequently overlooked at this phase. With this method, it was possible to generate multiple options with easy and simple simulation packages at the early design stage. The approach to form-finding as an innovative design method using today's simulation tools is the novelty of this research.

Furthermore, the method is not fully automated, with the designer's interactions to set performance criteria at every stage of the PBSG generation. The PBSG proved flexible enough to incorporate constraints that allow the user to manipulate certain architectural design intentions. The SG rules are based on a project framework that can be customized to any context for the required performance criteria set by the designer. The outcome of this study provides a framework for a generative design process using SG in the early design stages and suggests selection based on performance criteria.

The concern related to generative design tools is that they are highly computationally demanding, and studies usually take up to several hours to generate the results. This research for PBSG generative design predominantly for low façade solar insolation can be applied only to hot climates with fully air-conditioned spaces, FGM office buildings, and construction cost & technique in developing nations.

The departures from the intuitive design proposed by the algorithm suggest that this generative system may be a useful tool in exploring multiple paths during the design process. This method of generative design in Dynamo and Project refinery is only in the nascent stage; later, we should be able to combine solar, daylighting, and energy analysis in one single package. We hope that this research has the potential to improve the design and performance at multiple scales of future buildings, neighbourhood, and cities towards a more sustainable world. Future research must explore how implementing these tools in the early phase can evaluate performance at post-occupancy.

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