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Reiterative Energy Simulation Workflow towards Parametric Sustainable Industry Design in Developing Countries

Fahmida Chowdhury [a]****, Syed Monirul Islam*** [b]***, Masud Ur Rashid*** [c]

[a] *Department of Architecture, Military Institute of Science & Technology, Dhaka, Bangladesh. arch.2mist1625@gmail.com*
[b] *Associate Professor, Department of Architecture, Military Institute of Science & Technology, Dhaka, Bangladesh . monirul1971@gmail.com*
[c] *Associate Professor, Department of Architecture, Southeast University, Dhaka, Bangladesh. masudurrashid@yahoo.com*

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ABSTRACT

As being one of the fastest-growing businesses in Bangladesh, the industry is steadily expanding its job opportunities. The local rules & regulations for an Industrial building design control the design metrics such as building length, width, height, courtyard dimensions, etc. Although these metrics have an unequivocal relationship with visual comfort and energy performances, limited studies are informed to compare the parametric iteration approach with those stipulated in the regulations. In the climatic setting of Bangladesh, this project intends to give an environmental performance-based design process rather than solely focusing on regulation-based designs. The proposed framework utilizes parametric modeling and iterative energy simulations to evaluate abundant design possibilities instantaneously. It is hypothesized that this process can generate optimal design options and suggest the ranges of design metrics for contributing to the local rules and regulations. In the first step of the workflow, a hypothetical industry building was permanently modeled. The second step was to define the design variables for the simulation process. Finally, the parametric design options were iterated to measure Useful Daylight Illuminance (UDI), Energy Use Intensity (EUI), Percentage of People Dissatisfied (PPD), and Envelop cost (EC). The research explains simulation iterations, complexities in the application, and constraints to handle regulation variables. The suggested process is expected to be applied by regulatory body planners and architects to define design parameters based on energy performances that might enhance occupant health.

Introduction

Nomenclature

A ISM – Iterative Simulation Modeling
B EC – Envelop Cost
C PPD – Percentage of People Dissatisfied
D UDI – Useful Daylight Index
E EUI – Energy Use Intensity
F HVAC – Heating Ventilation and Air Conditioning

One of UN's primary goals for sustainable development is making cities and other developments sustainable (UN, 2015). While sustainable development necessitates preserving natural resources and their prudent usage, the design and maintenance of an industry need to be resource-efficient and environmentally conscious. Industry buildings constructed sustainably tend to reduce their environmental impact by maximizing energy and resource usage. The heat & other substance generation and high energy consumption in the built environment, especially in this specific building, affect the environment and the workers physically & mentally (Ortiz et al., 2017). As a result of industrialization, the World Bank Group (WBG) created several international legislation, health, and safety requirements to avoid environmental consequences when constructing industrial

* *Corresponding author: Fahmida Chowdhury, Department of Architecture, Military Institute of Science & Technology, Dhaka, Bangladesh.*
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and other projects (WBG,2008).

Despite the fact that industries have a greater influence on economic growth in Bangladesh (Salam et al., 2020), the Government of Bangladesh (GOB) relies nearly exclusively on fossil fuels (99.1%) to supply the energy demands of the industries (Maps of India, 2018). This inadequate use of resources puts a tremendous strain on the country's overall energy consumption every year. In practice, the factory or Industry designs are mainly based on the production scale and national building regulations. Centralized building regulation authorities generally determine thumb rules based on property dimensions, locations, and floor area ratios. However, these regulations merely focus on the environmental impact the industries may have due to inappropriate building configurations. Workers' health, working environment, correct light intensity, and thermal comfort are ranked lower on the priority list, although these elements directly influence production efficiency and yearly energy consumption. Therefore, the early-stage design of industries is often focused on production capacity considering mechanical aids to support the environmental issues such as daylighting, ventilation, heating, cooling, etc. Working in a closed indoor environment with hundreds to thousands of people is unbearable in the warm-humid climatic conditions of Bangladesh. As a result, the built environment of these industries frequently uses more energy and provides worse indoor health conditions (Joarder and Iqbal, 2015).

The percentage of Dissatisfied (PPD) and Energy Use Intensity (EUI) is so high, and there is less probability of Useful Daylight Intensity (UDI) is a significant environmental consequence typically evident in current industry designs. The PPD index estimates the number of people in a place who would be displeased with the thermal conditions (Fanger, 1970). On the other hand, the percentage of useful hours to total yearly occupied hours is used to calculate UDI. The EUI is the total amount of the annual heating, cooling, equipment, and lighting loads (Aman et al., 2021). According to current research studies, environmental challenges such as PPD, EUI, and UDI must be addressed while meeting local rules during early-stage industry design (Obidul et al., 2020). In this context, rather than solely relying on regulation-based designs, this study aims to provide an environmental performance-based design method. The paper attempts to introduce an envelope design workflow that can be adapted by architects, designers, engineers, and other researchers.

A computer-aided Iterative Energy Modeling (ISM) prototype was introduced in the workflow to quantify daylighting and energy performance. The prototype employs parametric modeling and energy simulations to examine several design options instantaneously. Policymakers utilize locally available materials and construct the factories in conventional methods, with little consideration for the environment or ecology. As a result, reorganizing factories using various sustainable methods is a much-needed reform to improve these living conditions. Therefore, the workflow was implemented for a case study to investigate energy consumption. This study assumes that architects and designers will use the proposed structure in the early design stage to help develop the traditional factory design framework. This approach is anticipated to provide optimal design solutions and offer metric design ranges for responding to local rules and regulations.

1. Aim and Objectives

To achieve sustainable industries and workers friendly environment, a climate-based design method is essential. This study aims to achieve a design method and contribute.

Specific objectives of this study are:

- To develop an iterative energy simulation workflow for the design of industrial factories.
- To recommend the best architecture variables for the best daylighting and energy efficiency trade-offs.
- To provide an approach that uses parametric modeling and iterative energy simulations to quickly assess a wide range of design options.

1.1. Literature Review

The energy use intensity (EUI) of a building's design or activities is a measure of its energy efficiency. Useful daylight illuminance (UDI) is a daylight availability metric that measures the percentage of occupied time when daylight meets a specific range of illuminances at a particular place in a location. Envelop Cost (EC) can be found by the glazing and wall ratio which is WWR. Percentage of People Dissatisfied (PPD) is calculated to ensure a comfortable indoor environment for the workers. All of these should work together to ensure a sustainable industry design.

2. Industrial building geometry iteration and result generation framework

2.1. Methodology

The factory model geometry iteration and result generation analyze the dimensions and its independent variables of an Industrial factory. Figure 1 shows as follows: First, in step 1, a hypothetical industry building was parametrically modeled depending on the production scale based on generalized industry rules and regulations. Step 2 was to define the flexibility of the variables within specific ranges for the simulation process. Step 3, The parametric design options were iterated to measure Energy Use Intensity (EUI), Useful Daylight Illuminance (UDI), Percentage of People Dissatisfied (PPD), and Envelope cost (EC).

2.2. Prototype Development

Figure 2 Shows the software prototype for simulation iteration and energy calculation process. First, the hypothetical industry building was applied as an input in the Rhinoceros-Grasshopper platform. Ladybug tools, Colibri, OpenStudio, Radiance, and Daysim, were used to run parametric simulation modeling and simulations. OpenStudio is a cross-platform, collection of software tools to support whole building energy modeling using EnergyPlus and advanced daylight analysis using Radiance. Daysim calculates a series of climate-based daylight metrics useful daylight illuminance (UDI). Finally, the software 'Thread' is used to create a visualization of results with the data collected from the analysis.

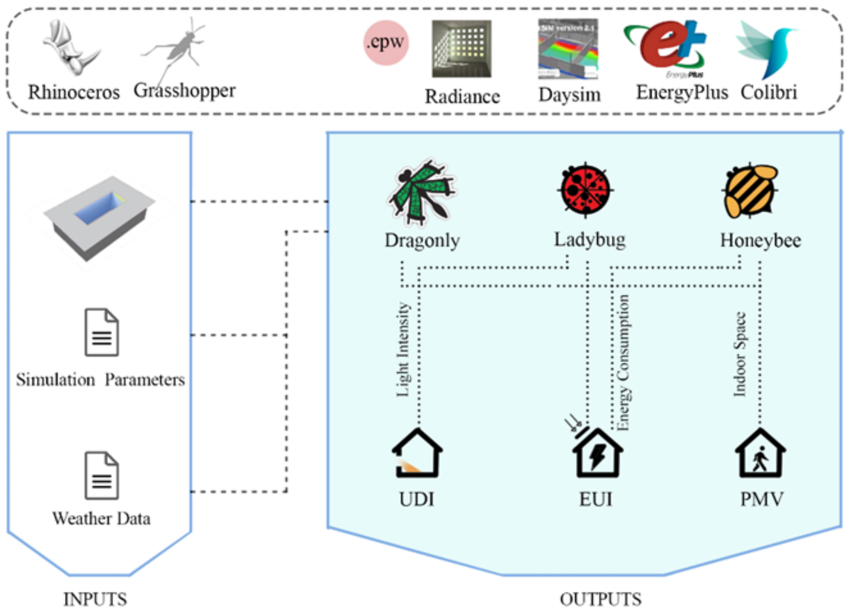

Figure 01- Schematic analytical workflow of inputs and outputs (Source: Authors)

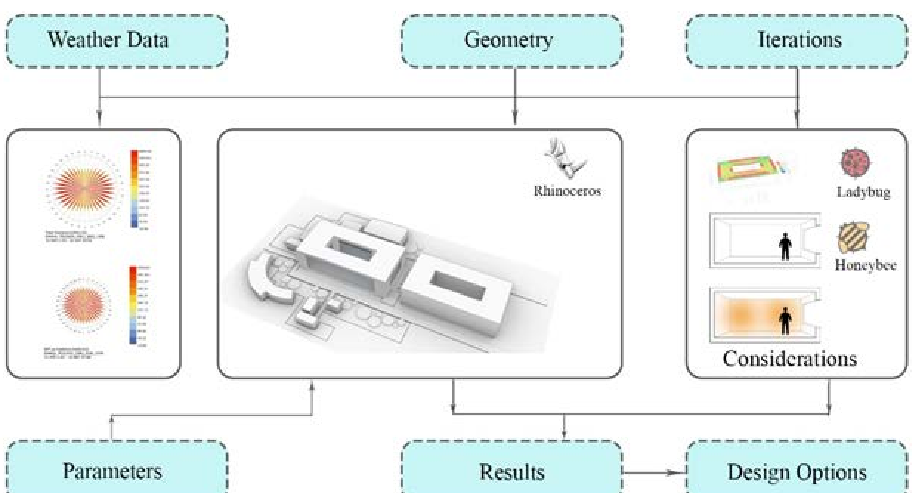

Figure 02- Calculation workflow diagram with details (Source: Authors)

3. Implementation

3.1 Factory Building Geometry Development

Approach was followed in three types different type of geometry to format the building prototype: (a) With generalized standards, rules, and regulations incorporation with traditional design practice. (b) Depending on the scale of the production and schedule. (c) Composite modeling where the building performance is also incorporated.

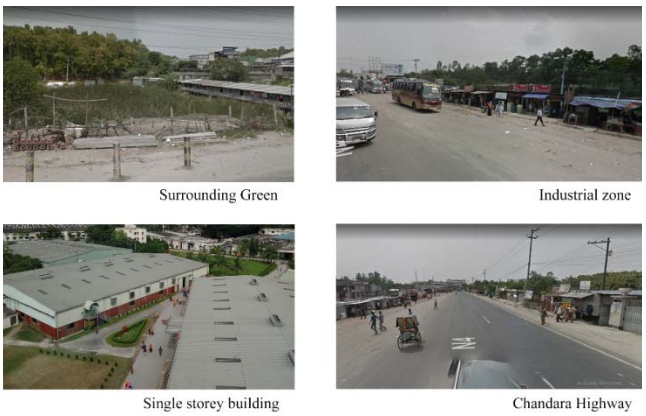

Figure 03- Shows the current state of the case field (Source: Authors)

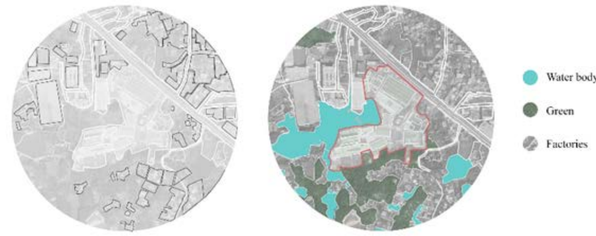

Figure 04- Land use of surroundings (Source:Authors)

The hypothetical model is guided by the standards of Industrial buildings and the rules and regulations provided by the policymaker. Site surroundings were considered. Also, depending on the need of production scale and the company requirements, a basic geometrical shape was formed. To provide a better ventilation system a courtyard was introduced. The floor height with the windows, shades, and multiple stories are designed to maintain the standards.

Table 01- Detailed information of the case area (Source: google earth pro)

Sl. No.	Information	Case area
01	Location	Shafipur
02	Altitude	24.0339018571502
03	Minimum Temperature	14.3°C
04	Maximum Temperature	33.3°C
05	Relative Humidity	highest 86%, lowest 73%
06	Common construction materials	In general the standard material used for constructing industrial factories is red brick, concrete, Steel, Iron, glass, etc. The walls are generally made of bricks and concrete. The roof or shading device materials are concrete or CGI sheets. For flooring, tiles and mozaic are popular choice.

3.2 Building Geometry Development

The standard Industrial factory building dimensions and variables were sourced from Industrial guidelines and standards. The length and width of the factory building were considered following local regulations and footwear factory production layout dimensions, the courtyard length and width were considered following National Building Code standards. A local study survey shows that a single line machine layout requires 1.8m along with a 1.2m emergency walkway and it's a major part when considering the dimensions of a production line as well as the production scale. It is obvious that the basic dimensions of the building will come from the production space and layout but here we have worked on the flexibility in building dimention to achieve our goal. The hybrid perametric model was designed in Rhino-Grasshopper platform considering the design variables. The variables were (WWR) window to wall ratio on East, West, North, South façade, courtyard Length & width, window hight, window sill hight, Orientation and shading depth. The range of these variables was implemented considering building regulations. The average value of each variable's range was considered for the hypothetical building model dimensions.

The main objective of this study was to propose a sustainable and worker-friendly Industrial factory design to provide maximum useful daylight and minimize the energy consupmtion. To achieve these, Window-Wall Ratio, Shading was inputted as the independent variables. These two variables have a major impact on energy usage and daylighting (Aman, 2017). Daylight access, indoor temperature and the impact of solar radiation in the interior are dependent on WWR. The ratio can be estimated by dividing the total glazing area by external façade area. (ConstruPM, 2020). For example, if the building facade wall area is 100 sqm, and the glazed opening area is 40 sqm, the ratio WWR will be 0.40. Here, we considered the WWR range 0.35- 0.80 for North and south facades and 0.30- 0.60 for east and west facades, Shading depth 0.50m to 1.00m, the length and width of the factory building 100m to 110m and 55m to 65m, the courtyard length and width 50m to 60m. and 19m to 24m were considered for the iteration process. Useful Daylight Index (UDI) and Energy Use Intensity (EUI) metrics are outcome variables. UDI was calculated through the ratio between the number of useful hours to the total annually occupied hours (Nabil & Mardaljevic, 2005). The total calculation of lighting, cooling, annual heating, equipment and loads, and the energy unit is in KWh/m2 are consedered in the EUI. Multiple outcome goals were considered in this analysis-Useful Daylight Illuminance (UDI) and Energy Use Intensity (EUI)- to gain insights into the best potential alternatives and assess the effect of design variables on the solutions.

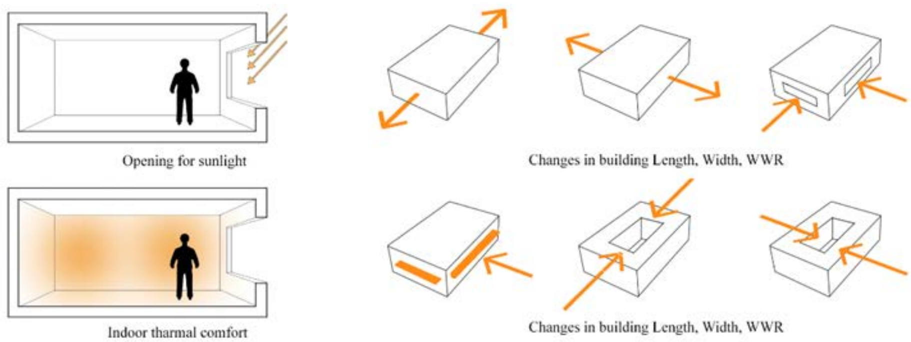

Figure 05- Building model (Source: Authors)

4. Simulation Analysis

The previous step helped in selecting the proper metrics for the building length & width, Courtyard length & width, shading device, WWR of the facades to amass relevant attributes in preparation for a subsequent procedure. The hypothetical model was fed into the simulation phase in the third stage. Creating stimuli for daylighting and energy analysis, running the simulation, and transmitting iterated simulated results are the three major simulation stages. The Grasshopper meaning script that performs such tasks is shown in Figure 6.

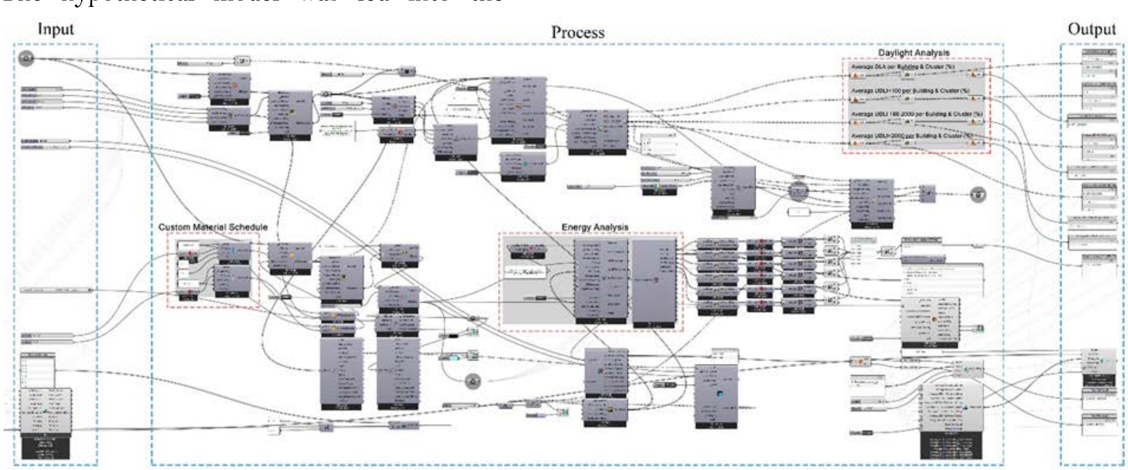

Figure 06- Iterative simulation modeling using the Grasshopper definition script (Source: Obidul et al, 2020)

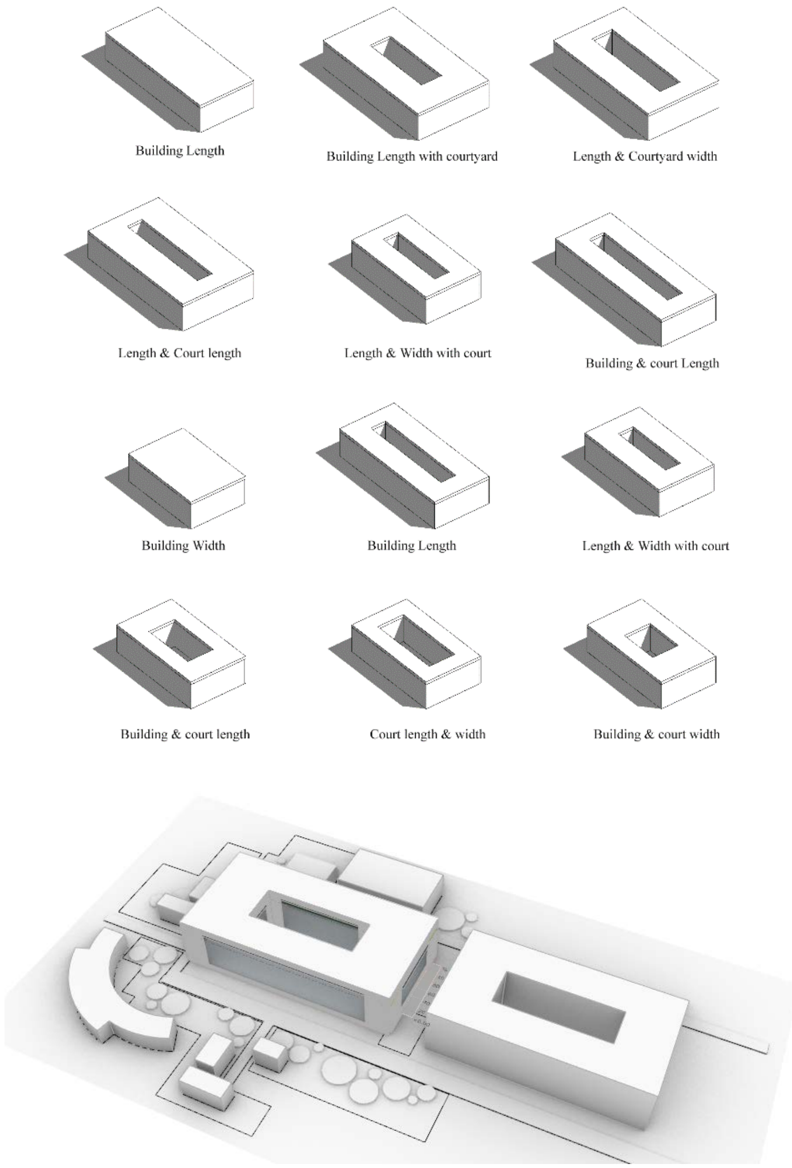

Figure 07- Factory building model context input (Source: Authors)

Through the Grasshopper plugins Ladybug and Honeybee, the parametric geometries were linked to Radiance (Lartigue et al., 2018) and Daysim (Bourgeois et al., 2020) for annual daylight study (Pak et al., 2013). Daylight sensors were mounted 0.75 meters above the floor of each zone for the study. The containers were allocated to various zones for transferring into the energy study. Honeybee creates a construction blueprint for a particular design and internal loads for the interior are based on a collection of energy schedules captured in the first phase. Furthermore, the honeybee platform offers custom and pre-configured materials, which aid in the creation of unique materials required for the study. Figure 9 depicts the visualization of simulation analysis for the Container Cluster System.

The outer envelopes of factory buildings, which are usually made of brick or concrete, were a major source of concern. Custom material properties in Honeybee called for the assignment of thermal insulation material to the interior walls. Glass material was allocated to the glazed areas, while radiance opaque material with reflectance was assigned to the interior walls, floors, and ceilings of the building. Another essential piece of data that must be passed to the energy simulation phase is weather data.

Local weather data for Chattogram (EnergyPlus, 2020) was imported into Ladybug in: epw format for connecting to both daylight and energy analysis engines in this study.

4.1 Automated Iteration Process

The energy models were then linked to another TT Toolbox plugin, Colibri, in the final stage. (Tomasetti, 2018). Colibri employs Iterator and Aggregator nodes to manipulate a predetermined set of predictor parameter values and save simulation results and visualizations for post-analysis. As parametric input variables for iterations, WWR for north, west, south, and east, shading depth, building length and width, and courtyard length and width are used. The parameter sets and values for the simulation iterations are shown in Table 1.

Despite the fact that a large number of iterations could be used to obtain more accurate results, due to the time and resource limitations, only a small number of parameters and values were tested. The data for the hypothetical model used to forecast energy patterns were analyzed for this paper. (The R Foundation, 2020) and CORE Studio developed Thread cloud systems (Tomasetti, 2018). For this review, a total of 2048 simulations were run. The simulation took about 3 minutes per iteration on an ASUS ROG FX553VD computer.

Table 02- Iterative simulation parameter sets (Source: Authors)

Sl. No.	Parameter Inputs	Values	Number of Iterations
P1	WWR- North	0.30, 0.70	2
P2	WWR- West	0.30, 0.55, 0.70, 0.80	4
P3	WWR- South	0.30, 0.55, 0.70, 0.80	4
P4	WWR- East	0.30, 0.50	2
P5	Shading Depth	0.50m, 1.00m	2
P6	Courtyard Length	50m-60m	2
P7	Courtyard Width	19m-24m	2
P8	Building Length	100m-110m	2
P9	Building width	55m-65m	2
Total Iterations			2 x 2 x 3 x 2 x 2 x 2 x 2 = 2048

5. Results and Discussion

This part demonstrates the design iteration analysis process. Here, the Colibri plugin is responsible for the multiple object iteration process. Scatterplot was generated with the data from the iteration generated by Colibri where every dot can be a design option. To analyze data in detail Parellel Coordinates graph was used which was exported through the TT Toolbox plugin in Gasshopper.

The data for the hypothetical model used to forecast energy patterns were analyzed for this paper to find out the best fitting dimensions for building and the impacts of the input variables. To exhibit the iterated 2048 design options, Figure:10 provided several graphs. Based on data from iterations, 2048 design options the Scatterpilot and Parallel Coordinates were established. The analysis becomes more complicated when the variables are more. Here, nine independent variables were used, so the interpretation of the result was challenging with the scatterplot or parallel diagram. So the Thread was used to find out the required results (best & worst). The efficiency indices of the daylighting measure matric UDI 100-2000 were compared to the energy measure matric EUI using a scatterplot. The visual position of each design alternative, depicted as a colored dot, can be used to illustrate success in this plot. Since these variables are inversely proportional, the easiest way to find the dot that consumes the most UDI and the least EUI for optimized design choices is to find the most UDI dot and the least EUI. The red dot in the upper left corner represented the most feasible design choice, while the blue dot in the lower-left corner represented the least viable design option. The predictor variables, building and courtyard dimensions, can be found using the parallel coordinate graph and comparative map. The parallel coordinate diagram and comparative chart revealed that five predictor variables, including windows of all orientations and shading depth, were the most important in varying daylighting and energy efficiency.

Figure 08- Iterated Daylight modeling visualizations for hypothetical model (Source: Authors)

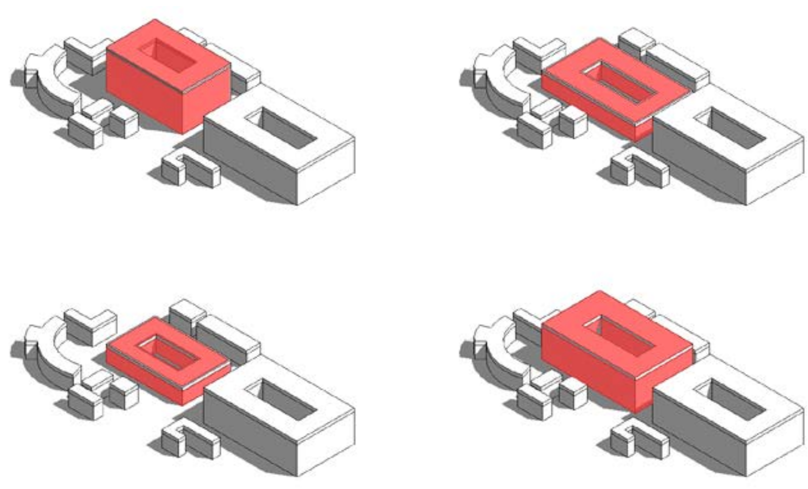

Figure 09- Representations of posibilitie in dimensions (Source: Authors)

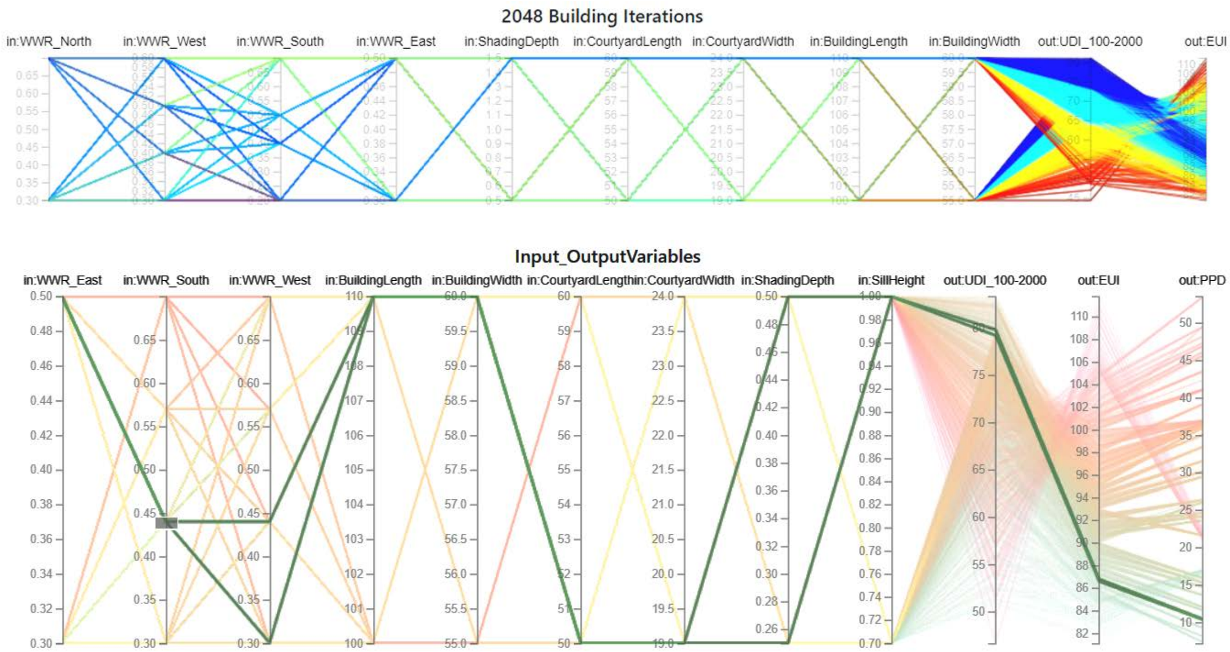

Figure 10- Iterated results visualizations (Source: https://thread.thorntontomasetti.com)

A statistical test from the results revealed that the window to wall ratio on the south and east façades had a substantial impact on the percentage of usable daylighting and energy efficiency. The visualizations of the results showed the difference in daylight between the spaces based on their position, Figure 8. WWR, on the other hand, showed no improvements in the north and west. Perhaps the percentage of useful daylighting differed significantly depending on the shading depth, with such an overall significant impact.

Table 03- Iterated result comparisons (Source: https://thread.thorntontomasetti.com)

In.Serial	447	511
in.WWR_North	0.7	0.7
in.WWR_West	0.6	0.6
in.WWR_South	0.7	0.7
in.WWR_East	0.5	0.5
in.ShadingDepth	0.5	1.5
in.CourtyardLength	60	60
in.CourtyardWidth	24	24
in.BuildingLength	100	100

in.BuildingWidth	55	55
out:UDI_100-2000	44.439153	44.439153
out:EUI	111.353011	110.576906
out:TotalCost	417393.2188	417393.2188

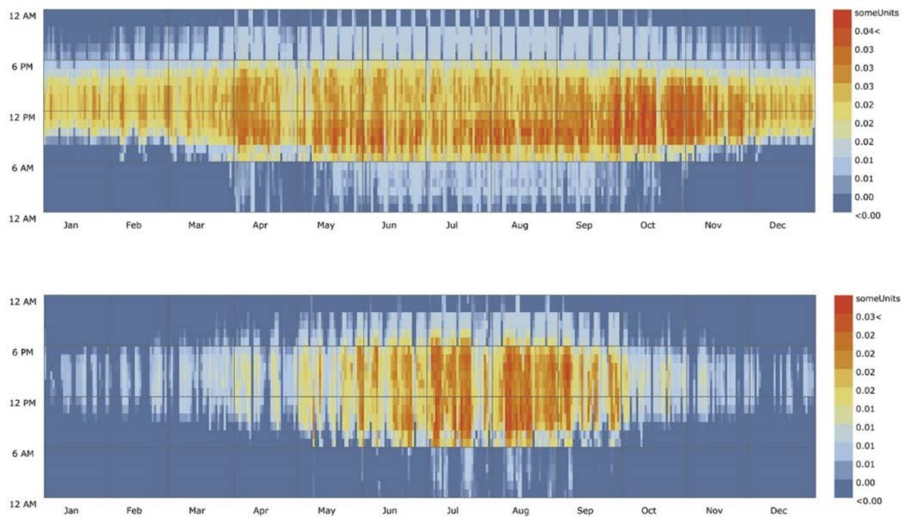

Figure 11- Representing the Needed EnergyLoad for Cooling between average Bangladeshi factory and modeled factory (Source: https://thread.thorntontomasetti.com)

The aim of this study was to suggest a computer-aided prototyping approach that would be able to calculate the most appropriate options. Furthermore, the method should be able to figure out the design variables and determine that are the most feasible choices for increasing daylighting and energy efficiency. To evaluate, prototyping provided the right to monitor several parameter values for factory building modules within a minimum and maximum range. A literature review revealed that few studies concentrated on daylighting optimization, specifically, despite the fact that there are many iterative energy efficiency studies on traditional buildings.

This study aims to contribute to closing the gap by establishing an iterative energy modeling methodology for the best suitable alternatives. Rather than focusing primarily on regulation-based designs, this project aims to provide an environmental performance-based design methodology. The proposed approach uses parametric modeling and iterative energy simulations to quickly assess a wide range of design options. This technique can produce the best design solutions and suggest design metrics for contributing to local laws and regulations. Regulatory body planners and architects are anticipated to use the proposed methodology.

Scope and Limitations of the study

The scope of this study includes site surrounding research, climatic studies, production scale, study of the expected users, material exploration study, actual site condition study, and user needs analysis for determining the parameters. Construction data, land-use trends, and comprehensive interior design are not included in the scope of this article.

The limitations with this paper are primarily technical in nature and are dictated by the study's scope. If the limitation is discussed in the future, this research would be even more valuable.

- To simulate 2048 design options, this methodology took about 119 hours. The main problem with the research tools was the convergence of various simulation engines on a single board, which made the method more complex and time-consuming. To minimize computation time, a machine learning algorithm, such as the Generative Adversarial Network approach, can be used. (Duering et al., 2020).

- Multi-objective equilibrium potential can be used to take advantage of the genetic algorithm it employs, which modifies the population of outcomes using values found in nature.
- \- To make the design optimization process easier, ANOVA statistical test was needed (Fang & Cho, 2019). To investigate the relationship between both the input variables and output variables, several analytical models were tested. However, sensitivity analysis is essential to identify key design variables that influence performance indices.

Conclusion

This research paper addresses the importance of environmental performance-based industrial building design and design workflow in Bangladesh and similar context. Promoting environment and climate based design method and establishes a framework through which it can be achieved. Several physical surveys in Dhaka, Bangladesh, took place in this research to study the pattern those are followed by the industrial desingers in Bangladesh. The researchers developed a conceptual prototype of a model based on production, scale, and layout. Several shortcomings in the framework were observed during this application. The study's methods included architectural design of a standardized factory building for industry, simulation of energy efficiency for a baseline vs. conventional model, and simulation data analysis to propose the structure. More design variables, along with insulation thickness and glazing form, must be considered, for example. In addition, design goals like thermal comfort, ventilation, and outdoor courtyard comfort will help to improve the design. A few criteria, such as detailed technical infrastructure aspects of the industry, user reaction, detailed floor plans, and so on, were deemed out of scope for this research. Its goal is to raise awareness among engineers, architects, and policymakers about the rising need for sustainability and the potential for energy savings. In the conventional design approach, however, getting the best measurements and solutions is challenging. This research began by looking at industrial design as a generalized method. It concludes by proposing a novel paradigm that, with further analysis, can become an essential part of this field of study and opens up a new avenue for researchers to consider environmental, worker, and sustainable issues.

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