A Benchmark Model for Predicting Building Energy and Daylight Performance in The Early Phase of Design Utilizing Parametric Design Exploration

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Abstract. Along with the enormous impact on computational development in architecture and urban design, the way in approaching the built environment is shifting and intended to look closer to performance and evidence-based design. This development holds promise in handling complex computation to approach desired targeted design goals. However, the implementation of form-finding and design performance optimization still lacks, particularly in Japan's sub-tropical climate. This paper describes the parametric design and design exploration process's implementation through the generative algorithm platform to develop a benchmark model to predict building energy and daylight performance and find possible design solutions from the iteration process during the early phase of the design process. The variables incorporated related to the glazing ratio, the length of the overhang, and building orientation. Grasshopper, a parametric-based plugin that works in Rhinoceros, is used to arrange a parametric definition for the overall experiment. The tools used to investigate the environmental analysis and energy consumption are Ladybug and Honeybee, and the exploration process will be conducted using Design Explorer. The context will be situated in Orio district and uses the EPW file of Kitakyushu city, Fukuoka, Japan. The results of this research furthermore can potentially be a comparison for more dynamic factors.

Keywords: Parametric design, Daylight performance, Building Performance Simulation, Energy consumption, Design Explorer

1. Introduction

1.1. Research background

The tremendous impact of digitalization has implicated contemporary architecture. In terms of design, the human sense nowadays could potentially replace by artificial intelligence or machine in some respects. In architecture, the so-called parametric and generative algorithm, the design process that shifts and changes the standard design process from classical, manual form-making to the potential of automation, iteration, and form-finding [1]. The
range of research from predicting further building performance purposes [2][3] to the to the post occupancy evaluation utilizes this approaches. The benefit of utilizing it relies on the capability in handling complex formulation related to design aspects. The performance of intended architectural project both thermally and visually often has strong relation to people’s health [4] and triggering Urban Heat Island phenomena [5]. What is more, this capability often correlates to the tangible design goals to achieve designated building performance; thus, the design product’s quality could be empirically measured and validated. For example, the platform can be used to process efficiency towards energy consumption or maximize daylight performance.

On the other hand, the building sector contributes 36% of carbon emissions and 40% of energy demand. Moreover, it is predicted that in 2050, the building needs to increase by 32% and the global temperature rise by 1.5%, and cities contribute to 75% of total energy consumption, mostly caused by energy consumption during the occupancy period. Later on, this situation would trigger the heat island phenomena and bring detrimental effects on human health. Thus, the prevention in minimizing a negative impact caused by the building to the environment should be taken into account. Building performance simulation has enhanced the field of the built environment. It bridges the interest between building in the design phase to reality. Furthermore, it can help predict or calculate the environmental-related building or site performance in the early design phase, where the uncertainty about design appears with nearly accurate results. Hence, with this advancement, the intended project's detrimental impact could be mitigated since the early design phase.

Discusses the relationship between architecture and environment, besides physical and energy-related performance, materials play essential roles in defining the carbon footprint of the architectural object. Wood is considered an environmentally friendly material that has a unique characteristic compared to the other building materials. Firstly, wood grows everywhere and available mostly in every part of the globe. This availability reduces reliance and ecological footprint in production and distribution processes. Secondly, the relatively fast-growing regenerative availability ensures availability compared to the other material such as brick and or concrete that need further process before it is utilized. Thirdly, the lightness and the wood's modular shape bring this type of materials more practical and relatively easy to process, whether in the factory or on the site [6]. Japan is one of the countries with a long reputation for using wood as primary building construction, and the tradition has been inherited for generations.

1.2. Aims and objectives

The department of architecture of the University of Kitakyushu, in collaboration with Meldia research for advanced wood, has one expertise in designing and experimenting with Japanese cedar for main building construction. One of the ongoing design projects is to design a two-story wooden house made of Japanese cedar in the Orio District in Kitakyushu city. The intended will undergo a parametrical design process for both environmental and structural analysis. Thus, it needs the base case for comparison before and after attempting to seek the potential of efficiency. Thus, this research is an initial phase of designing a two-story wooden house in Kitakyushu District, Fukuoka, Japan. This research intended to develop a benchmark model as a base case for further comparison needs regarding microclimate [7] and environmental friendly aspects daylight and sun exposure, view outside, and energy consumption. The entire system was conducted in a parametric and generative algorithm platform and used the Shimonoseki EPW file [8] as metrological data input to fit the site situated in Kitakyushu city. Moreover, the objectives of this research are to develop a benchmark model for further comparison needs, to develop a parametric and MOO platform targeting low energy consumption and maximum value of view and sun exposure, to analyze the correlation of the dynamic design parameters and the targeted goals for winter and summer period.

2. Literature review and related works

2.1. Development in computational architecture

The development of digitalization has been tremendously affecting the field of design and construction. In architecture, the paradigm shifted from annual design processes to parametrical design, which allows the designer to access a considerable portion of control and come up with a variant design solution and targeted design goals automatically [9]. It processes nowadays responsible for mass customization among the architects and the people in the construction field. The automatization, the replacement of human power to computation, is believed to bring
efficiency in many aspects such as economics and energy consumption as a consequence of recent development.

Parametric design can be defined as designing with parameters. The control through parameters offers a high range of flexibility in handling complex computation that could lead to an unexpected or unpredictable solution. Furthermore, it can bring the circumstances to the greatness of freedom shape generation. The difference between classical design and generative algorithm design relies on its sequences during the initial phase of designing. Figure 1 is dedicated to comparing the classical design and parametric or generative algorithm design process. The classical design process tends to have a fixed design variable even though it can also be manually explored, yet still in the designer's visual imagination. The process started with the ideation and getting evaluated along to get better performance. When the first evaluation results do not meet the targeted design goals, further evaluation is being conducted. When the second still does not meet the expected criteria, another evaluation undergoes the design process. This continual process goes on and on until the target meets what specific performance is achieved.

In contrast, the generative algorithm processes work with top-down approaches. When the classical design puts the goals at the end of the process, the generative algorithm puts the targeted goals before the design process goes far. After the targeted goals are formulated, the next step is to determine the design parameters as dynamic design variables. The entire system is like a range of calculators with a cluster of functions or source code. Source code is meant to formulate the design variables in order to generate the preferred design solution. Thus, it challenges the idea of form-finding instead of form-making to accomplish the four criteria of the design, which are complex, intelligible, unpredictable, and desirable. The next step in the generative algorithm is the investigation of the optimized solution, so-called design exploration, the platform develop by Thornton Tomassetti through grasshopper plugin TT Toolbox which is act as generator for iterating all possible solution from the involved parameters and visualize it in designer-friendly parallel coordinate plot.

2.2. Related works
Some studies utilize a computational approach in investigating the impact of building features on the response of its microclimate. For instance, the tools such as Open Studio, Radiance, and Energy Plus worked in Grasshopper and Rhinoceros' platform to investigate the impact of the urban canyon on the microclimate in the Al Ain City, UAE. The research concluded that the North-South orientation and the larger ratios produce more comfortable space and creating wind passages could reduce UTCI by flowing the wind. Natanian, in the range of research, conducted an urban environmental analysis that has investigated the impact of urban form towards outdoor microclimate using parametric processes. The research simulated different urban typologies such as slabs, courtyards, scatters, Window to Wall ratio (WWR), glazing properties, building use, Floor Area Ratio (FAR), distance between buildings, and urban grid rotation in which the generative process produces 1920 iterations. The tools used in this research are Ladybug, Honeybee, and Colibri that were using the Mediterranean district's weather
data. The research's main finding was the mitigation of the different performance of each typology and the potential of the workflow to assist the designer during the decision-making phase [14]–[16].

In the research conducted by Zhang, two well-known engines in environmental analysis, ENVI-met and Ladybug have been compared. The research concluded that Ladybug seems more efficient for microclimatic analysis, both numerically and visually [2]. Furthermore, a prototype of a single digital workflow has been proposed to conduct regenerative performance evaluation. The set of ladybug tools such as Ladybug, Honeybee, Dragonfly, and Butterfly are used to calculate Biophilia and thermal comfort in Malaga. The research demonstrates the potential of those tools mentioned above could bring advantages in terms of visual feedback for the decision-making process [3]. The modification of the parametric platform has been proposed due to the obstacle in implementing computational microclimate analysis. It is indicated that the system is still open for custom function through custom scripting to enhance and upgrade specific needs [17].

In terms of optimization, the exploration of the impact of retrofitting measures of typical 1990s residential in Sweden has been presented using MOO. The results reveal that several optimized measures can potentially fulfil the new-build energy standard [18]. In another research, the Energy Efficient Form-Finder (EEF) that consists of Form Generation, Form Formulation Form-solution, and Form-Optimization has been introduced. The results demonstrate the reduction of annual energy demand by adopting the system proposed [19]. Moreover, the optimization impact in the use of slab and high-rise housing shapes in the correlation with energy consumption in Buenos Aires, Argentina, has been presented. The results produce a Pareto front that reflects the passive strategy's adoption in several design solutions [20].

Furthermore, the MOO has been utilized to explore the building envelope concerning energy use impact in Seattle, Washington. It was revealed that the optimum scenario with a certain percentage of Window-to-Wall (WWR) ratios [21]. Besides, the effectiveness of the energy consumption of a single room model has been used in Teheran, Iran. The design variables involved are the overhang, glazing ratio, building orientation, and material properties. The results show a decrease in cooling electricity and an increase in heating and lighting [22].

3. Research methodology

The research utilizes a set of parametric and generative algorithm [1] calculator to calculate and simulate the design object based on the targeted design objective to investigate the preferred performance and the outcome design attributes. The proposed methodology aims to search for the desired solution in a relatively large amount of data produced by the iteration process. The process could develop an unintentionally better performance design solution that generatively calculated beyond what the designer imagines. The study was implemented in a range of consecutive stages, beginning with ideation and ending with design exploration, and will be described in the following sub-section.

Figure 2 illustrates the entire system used in this research. The process started with the ideation phase, where the parameters and scenarios are decided. In this step, the standard regular box with a specific dimension has been decided, and it has been attributed by design dynamics parameters as design variables. Furthermore, the ideation
was followed up by creating a parametric definition arrangement both for the building and the environment. In this step, the design attributes that play as a dynamic design parameter are decided and inserted. After the definition for building and the site is completed, the next step is environmental analysis in ladybug and honeybee. The weather data input and analysis period were inserted in this step. After the environmental analysis was completed, the next step is making energy analysis in the honeybee. A simple calculation of heating and cooling has been established in this step. After the result obtained from a single simulation both for environmental and energy analysis, the next step was design exploration using Colibri, and the comparison between the found solution and the base case was undergoing manually in excel.

Figure 3 shows the entire parametric definition used in this research. The doted bubble indicates the cluster where the function was applied depending on each need. The first indicated cluster is for the dynamic parameters consist mostly of number sliders. The second indicated component is the EPW file of Shimonoseki that downloaded using component ladybug download EPW file. The third is the cluster of ladybug components for environmental analysis. Forth is the cluster of energy plus analysis from Honeybee and above this cluster relies on the cluster for calculating view and sun hours analysis. The last cluster that can be seen in the arrangement is the cluster of design explorer that consists of Colibri’s components.

3.1. Tools
The set of tools used in this research are the parametric based platform called Grasshopper that worked as a plugin for 3D modelling software Rhinoceros [23]. The environmental and energy analysis was conducted using plugin Ladybug and Honeybee from Ladybug tools. A ladybug is a software used to analyze microclimate based on the parametric platform in Grasshopper. It is allows importing Energy Plus Weather data or EPW [8] as a precedent in conducting an environmental analysis [24]. The plugin was built to facilitate engineers and designers and bridging the interest in conducting environmental analysis in a relatively short period. Besides, Honeybee is built to the needs of energy simulation. This plugin works in collaboration with a well-known engine such as Daysim, Therm, Radiance, Open Studio, and Energy plus. For design exploration, the plugin Colibri used to iterate all possible solutions in this phase. The design exploration was conducted using TT Toolbox from Thornton Tomasetti [13].

3.2. Geometry parametric modelling and targeted goals
The design object's geometry is the ordinary box representing a two-story house with a size of 6 meters length, 4 meters wide and 6 meters height, and it is situated to facing the south direction. The geometry was modelled in Grasshopper to embody several dynamics parameters, which are glazing ratio, overhang, and direction. Glazing ratio is a portion of the glazing towards the surface area and measured by percentage. The overhang is the length of the window's eaves measured by centimetres. The last design variable is the orientation, which is the rotation
angle shifted from the XY or North-South axis (from the top) towards clockwise and anti-clockwise direction measured by the radiant degree.

Figure 4. Geometry modelling and dynamic parameters

Figure 4 shows the position of each design variable in the geometry. Each dynamics parameter has been set to undergo several movements for iteration purposes. Glazing ratios were set to be in the south surface of the box with the portion ranging from 40% to 90% with 10% for each step means that this design variable has five steps movements. The overhang driven by number slider with a value ranging from 10 centimeters to 1 meter (100 centimeters) with 10 centimeters for each step means that this dynamic parameter has ten steps movement. The last, Orientation, has 12 steps ranging from -30 degrees to 30 degrees with 5 degrees for each step.

Overall, this system could iterate 600 iterations based on the multiplication of each parameters’ movements.

The targeted design solution is the minimum energy consumption affected by the driven parameters performs during winter and the summer period resulted from energy plus calculation in Honeybee. The minimum sun hours in the winter, maximum sun hours in summer and the maximum view percentage from the eye view cone resulted from the environmental analysis calculation in Ladybug.

3.3. Site and analysis period

Figure 5. Dry bulb temperature and horizontal infrared radiation in Shimonoseki
The weather data used in this research is the EPW file of Shimonoseki, which is the nearest database available surrounding Kitakyushu city. The time taken for the analysis period is yearly from January 1st to December 31st. Figure 5 illustrates the dry-bulb temperature and horizontal infrared radiation accumulated per-month within one year generated by Ladybug. The chart displays that August is the hottest period with an average temperature of 27.43°C and radiation of 414 kWh/m². The coldest period started from the end of December to the end of February with an average temperature of 7.9 °C and 299.48 kWh/m². Based on the graph, the hottest period begins in July to the end of September.

4. Results
In this chapter, the result and findings will be explained. The results presented are the general findings based on the exploration, the base case, and the preferred solution for winter and summer performance related to energy consumption and the view and sun hours results. The tendency between the parameters and the result and the efficiency achieved after implementing the platform will be described in the discussion section.

4.1. General findings
The result obtained from the simulation process is presented separately in the system. For the visualization need purposes, each target goal is presented in value distribution maps. However, the results are presented in the parallel coordinate plot for the iteration processes, showing the relation or the connection between the driven parameter with the targeted result. Figure 6 (top) is the parallel coordinate plot resulted from the overall parameters movements: the dynamics parameters or design variable presented in the first three-axis highlighted in black font. The rest blue highlighted axis is the results produced during the analysis process. The dotted circle is the targeted searching area of the targeted solution. The blue circle indicated the searching area for winter performance. The red circle indicates the searching area for a summer performance, and the orange is the searching area for summer and winter performance.

![Figure 6. parallel coordinate plot of the iteration’s results](image)

The system iterates 760 iterations resulted in the spread of value on the 2D visualization graph. Figure 6 (below) is the extracted specific design target from the overall simulation targeted goals. From the parallel coordinate plot, the search for the desired design solution is in the minimum value of cooling, heating axis, and in the maximum view percentage. The targeted searching for the winter is in the maximum sun hours, and the targeted searching area for the summer is in the minimum axis of sun hours.
4.2. Base case

Figure 7 is dedicated to present the results of the simulation process occurring in the base case model. The base case is the model that has no treatment, and the feature is set based on a common assumption. The parameters of the base case are deliberately designed and not the result of the form-finding process. This model was attributed with a 40 centimeters overhang, 50% glazing ratio with the 0-degree angle from the North-South axis. The design attributes and its result are highlighted in the parallel coordinate plot showing the relation between the design parameters and the results. The chart has resulted in several targeted goals, such as cooling for 34.67 kWh/m$^2$ and energy for heating 78.15 kWh/m$^2$.

![Figure 7. Base case performance](image)

Another targeted design goal stated 24% of the space with more than 250 hours of sun exposure and 99% area with more than 3% quality view of the outdoors. From the above illustration, the area exposed by the sun for less than 250 hours covers most of the area. Only a few areas are covered by the value of more than 25 hours distributed closer to the windows. The highlighted red border indicates the targeted area with a value of more than 250 hours of annual sun exposure. It can be seen from the cone of vision analysis, the bold-highlighted area indicates the area where the view quality to the outside is more than 3%, and the targeted area almost covers all the space. The picture next to the horizontal cone of vision analysis is how the base case model looks like with its glazing ratio and the overhangs.
4.3. Minimum heating (Winter)

The minimum cooling goals mean that the design attributes can be proposed for minimizing energy consumption in the winter period. For targeted design solution with minimum heating, the simulation process produces a design attributed with orientation $5^\circ$ towards an east direction or anti-clockwise, overhangs 4 centimeters, and glazing ratio 40%. The design performs energy demand for heating 74.79 kWh/m$^2$ and for cooling 22.09 kWh/m$^2$. The relation between parameters and the results is presented in the parallel coordinate plot highlighted in the bold red line. The sun hours analysis distribution map shows a small part of the space exposed to more than 900 hours. Compared to the base case, the winter period's minimum heating model has more areas covered by the sun for more than 700 hours annually. For the horizontal cone of vision, the analysis compares to the base case. More areas have a cone view of more than 3% is more than 20%. However, the overall calculation shows that the value is less than the base case counted for 91% since the glazing ratio becomes smaller compare to the base case. Similar phenomena happen for the sun hours exposure that stated a value of 18% area covers for sun hours more than 250 hours, reducing 6% from the base case.

Figure 8. Targeted design solution with minimum heating
4.4. Minimum cooling (Summer)

Figure 9. Targeted design solution with minimum cooling

The minimum cooling goals mean that the design attributes can be proposed for minimizing energy consumption in the summer period. Figure 9 presents the design solution results with minimum energy consumed for cooling in the summer. The iteration comes up with the design attributed with 50 orientation toward the east direction, 1-meter overhang, and 40% glazing ratio. Moreover, the performance related to energy consumption resulted in 28.50 kWh/m² for cooling needs and 78.77 kWh/m² for heating needs. The portion of space with more than 250 hours of sun exposure stated a value of 5%. The portion of space with more than 3% view toward the outsides stated the value of 78%. Compare to the base case. This model has fewer parts of the area exposed by the sun with a value of more than 500 hours. Similarly, the view towards the outside that has a value of more than 3% is lesser. More extended overhangs cause this implication.
4.5. Tolerable design solution (Multi-objective)

The tolerable design solution means that the low targeted performance can be proposed to be used in both summer and winter. The value is not lower than the other finding solutions, yet it demonstrates the trade-offs between the parameter and the results. The design comes up with attributes 15° orientation, 1 metre overhang and 40% glazing ratio. The cooling and heating energy consumptions are 28.62 kWh/m² and 78.24 kWh/m² while the portion of space with more than 250 hours of sun exposure stated a value of 5%. The portion of space with more than 3% view toward the outsides stated the value of 76%. The connection between parameters and the results can be seen in the highlighted line on the parallel coordinate plot. From the distribution map it shows that the sun hours that exposed more than 800 hours is minimum. Similarly, it is happening for the view to the outsides 3% for more than 20%, considering the length of the overhangs.

4.6. Maximum view and minimum sun hours

Figure 10. Tolerable design solution

Figure 11. Targeted design solution in view analysis and sun exposure
Another two target goals not related to the reduction of energy consumption are sun exposure analysis and view to the outside. Figure 11 top shows the solution with the highest value in sun exposure and view analysis. The model with the highest percentage of view more than 3% to the outside is attributed with design variable orientation 30° towards the East direction that reached 100%, overhangs 10 centimetres and 90% glazing ratio. This model performs 57.81 kWh/m² for cooling and 127.96 kWh/m² for heating. Figure 11 below shows the design solution with minimum sun hours that attributed with -10° towards the West direction, 1-meter overhangs and 40% glazing ratio. This model performs 28.55 kWh/m² for cooling and 79.21 kWh/m² for heating. The connection between the parameters and the results shown in the highlighted wire on the parallel coordinate plot for both the presented model.

5. Discussion

5.1. Parameters tendency
In the Design Explorer user interface, the designer can see the condition on each step of every provided axis, and the wires on the designated spot are highlighted when the cursor or pointer is moved and stick on it. Once the cursor sticks on a specifically targeted spot, the connection relates to that value automatically presented by the coloured wires. The selection can be by clicking or dragging to see the ranged value's connection (multiple selections).

Figure 12 shows the tendency from three design variables with the targeted goals, specifically energy used for cooling and heating. Red circled dots indicate the targeted position in the parameters, while the blue dotted bubble indicates the search area for minimum energy consumption for cooling and heating. It can be seen from the aspect of building orientation, when the searching area pointed to the minimum values in heating and cooling, the wires in the orientation axis move to the step 0 to 2, it means that minimum values in cooling and heating were driven when building facing 0° to 10° to the East direction. In overhang parameters, the search of the minimum value in energy consumption directs the wires to the length of the overhang for four means that the minimum value is found in 40 centimetres long overhangs. In terms of glazing ratio, the minimum value leads to the glazing ratio 4 means that the minimum energy consumption mostly found in glazing ratio 40%.

Figure 12. tendency between parameters
5.2. Potential efficiency compared to the base case

From the results discussed above and the tendency among parameters, there is a potential for efficiency by utilizing this system to investigate several performances in making the benchmark model of two stories wooden house in Kitakyushu city, Japan. The efficiency will be looked at by comparing the base case performance with the solutions produced from iteration processes. Figure 13 is dedicated to present the gap from the comparison phase related to energy performance. The red bars represent energy consumption for heating, the blue bars represent energy consumption for cooling, and the grey is the summary for both values. The yellow bars indicate the value gap between the base case performance and the other model performances.

![Comparison of cooling and heating from the base case](image)

**Figure 13.** Comparison and potential efficiency

From the bar chart, the efficiency calculated for a whole year period stated by the winter best performance model reached 2.58 kWh/m² in cooling and 3.36 kWh/m² in heating. Summer’s best performance model stated the efficiency of 6.17 kWh/m² for cooling but slightly exceeded in terms of energy for heating compared to the base case. For the tolerable model, it was only cooling that stated efficiency for 6.15 kWh/m². The best sun hours in the summer model stated efficiency for 6.12 kWh/m² in terms of cooling but slightly exceed the performance for heating. For the best sun hours in the winter model, both cooling and heating energy consumption stated a considerable value for about 20 kWh/m² for cooling and about 14 % kWh/m² for heating.

6. Conclusion

The parametric and generative algorithm platform to develop a two-story wooden house benchmark model has been presented. The parametric system was used to investigate the ordinary box represented a typical house with several design attributes such as building orientation, glazing ratio, and window overhang situated in Kitakyushu city, Fukuoka, Japan. The iteration process produced the geometry with the preferred performance for some of the targeted periods. The design solution shows a potential efficiency in terms of energy consumption for both winter and summer. Besides, the system also reveals the connection between dynamics parameters (design variable). In general, the research guides the design consideration related to the variables to build the house's geometry according to the targeted goals using the designated site's weather data.

The limitation of this research relies on limited materials involvement. The research only sees the relationship between geometry and orientation towards energy consumption and several views of comfort analyses. This research was not utilizing multi-objective optimization; instead, it explores all possibilities from the movement of the parameters through Design Explorer, a generative platform for iterating all possible solution that may be produced by the parametric system. For further processes, the environmental data input could be supported by on-site measurement to validate the results better. Moreover, further works are encouraged to add more design variables and involve material properties rather than default material. However, the results show the opportunity to develop efficiency by working parametrically and exploring design possibility even though with a small number of design variables.
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