Article

Design Optimization of Hyperboloid Wooden House Concerning Structural, Cost, and Daylight Performance

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Abstract: The use of parametric and multi-objective optimization (MOO) as a new way of approaching architectural design has been growing in line with current breakthroughs in computational architecture. Wood, on the other hand, is a living and unique building material that provides durability, manufacturing flexibility, and local availability. One of the structure types that provides high structural stability is the hyperboloid. However, the exploration of hyperboloid structures in building design, together with the building daylight objective, is still limitedly reported. This paper presents the application of the parametric approach and multi-objective optimization in optimizing the structure and daylight objectives of a hyperboloid two-story wooden house in Japan, made of 105 mm × 105 mm × 4000 mm Japanese timber. The method involves iterating dynamic parameters such as radius bottom, offset distance, timber members, twisting level, building height, radius-top, and roof slope to optimize the structural objective of minimizing normal force average, displacement, and cost while simultaneously maximizing building volume. Regarding daylight objectives, unit movement and glazing ratio that control the glazing strategies were explored to optimize useful daylight illumination (UDI) in summer and winter. The optimization and exploration yielded 10,098 solutions in structural analysis and 406 solutions in daylight exploration. Based on the data analysis, the proposed methodology has successfully produced the best design solution, discovering the balance between the objective trade-offs. In addition, the most influential parameter that shapes the value of design objectives has been identified. The findings of this research were expected to contribute to and enhance the performance-based design optimization, and support design decision-making process in the early design stage of a wooden house with a hyperboloid structure.

Keywords: parametric design; hyperboloid; MOO; wooden structure; daylight optimization

1. Introduction

1.1. Development in Computational Architecture

Nowadays, architecture and the built environment have been affected tremendously by the development of computational architecture [1,2]. The 21st century is a time where technology plays a key role in the design and construction fields. At the same time, architecture evolves and requires complexity in any step of its processes. “Digitalization”, or “computerization”, is used not only for presentation and other visual needs, but also for in-depth problem solving, analysis, and simulation. In the early 1970s, CAD (computer-aided design) was introduced in architecture. From “simple to complex” and from “form to code” are two terminologies that can be used to describe how the development of architecture happens when we live in today’s world. Computer development in architecture leads the design method from classical to what is called “parametric”. This new development
has changed the workflow of the static graphic primitive workflow to one that is rich in control. To accomplish the high requirements of what a design is supposed to be and to deal with the issues of performance and aspects of efficiency, applying a powerful potential that is embedded in digital systems is one of the proper actions that should be taken. The development of numerically controlled machining sparked the development of computer-aided design (CAD) systems, and now the adaptation of sensor-enabled robotic systems necessitates a rethinking of design processes and geometric representations in order to establish a stronger connection between the computational model and the material realm [3].

In structural consideration, parametric design emerged as the way design shifted from manual and classical thinking to parameter definition [4]. Aside from the ability to generate different designs based on the rules provided, parametric design can also solve various design problems that are time-consuming and cannot be handled by the architect. For example, Michael Hansmeyer, in his project “Columns”, gives an overview of the potential of computer usage in designing a fascinating column. Even though the computer cannot be parallelized with human capability, the experiment showed the extremely significant effectivity of time taken. For example, in a TED talk from 2012, he explains that nearly 16 million facets can be completed in 35 s, whereas manually arranging them takes 200 h. The phenomena of development in computerization have also led to the development of manufacturing, which is known as CAM (computer-aided manufacture). This is a tremendous leap in manufacturing processes in which the gap in architectural detail is the focus of improvement. Through this improvement, the integration between the virtual process and manufacturing can be easily controlled and adjusted. A data set that is generated during the virtual process of design can be directly transferred as the main data input in the manufacturing process. In other words, the control of the overall integrated processes of architecture is narrowed, even specific.

Multi-objective optimization (MOO) is one approach to produce best design alternatives empirically utilizing genetic algorithms (GA). The integration between MOO and building performance simulation (BPS) has been utilized to reveal the potential for observing design objectives [2,5–8]. It is used to conduct a thorough search of design alternatives in order to find high-performance solutions in terms of specified design goals. It is not only about visual and productivity, but also optimization and efficiency. Along with the rise of low energy consumption in building performance issues, the design process demands high attention for efficiency in every step and specified goals. The parametric design process allows one to perform the optimization scenario in the early design steps.

Figure 1 depicts the motivation behind this research. The parametric approach in architectural design and MOO will be used to explore if a two-story timber house can achieve an optimal design solution. Japanese timber was used as the house’s main construction concept in order to support and promote environmentally friendly and sustainable architectural design in terms of its construction material. Furthermore, the advantages of local market availability, making wood an alternative material to reduce the carbon footprint, has become a concern.

1.2. Wood in Environment and Construction

Recently, climate change has become an important issue that is calling for action from people from various disciplines. The phenomenon of global warming can only be triggered by the huge release of CO\textsubscript{2} emissions, and advancement in technology have led to a surge in the production of CO\textsubscript{2}. Most human activities that involve automation or the combustion of fossil fuels can directly contribute CO\textsubscript{2} to the environment. This phenomenon is known as the greenhouse effect, or even more broadly, global warming. Every year, about 3.3 billion tons of carbon dioxide are released into the atmosphere. This phenomenon causes the temperature at the earth’s surface to gradually become hotter and causes damage to the ozone layer.
Wood has always been a valuable resource as an easily sculptable yet long-lasting material [3]. In addition, wood is a common material for architecture. Wood’s role in the history of the built environment began since humans knew what to build. Wood is recorded as one of the oldest materials in architecture. Besides this material usually being used for its aesthetical and strength factors, it is also be used to affect human psychology [9], give a relaxing sensation and can help to maintain an optimum living environment [10].

Japan has a long history of building with wood. In Japan, wood is more than merely a building material, it is, moreover, a part of culture. In this country, the use of wood represents the honoring of life with nature. Wood differs significantly from most other building materials in that it is naturally grown. Wood has both physical and visual qualities. It is both a modern and ancient material. Wood is a vulnerable and very sensitive material that demands a strong respect for its treatment and gives a warm and a significant atmosphere due as building’s components. The use of wood also provides several advantages. It is easy to distribute and efficient in the assembly [11]. In addition, wood is a material that is available in both in global and local markets [12]. Compared to other building materials, wood has a special character in terms of design uniqueness, as it is naturally grown, fully recyclable and an extremely energy efficient building material [13,14]. According to the characteristics mentioned above, the design of wood will continue to challenge the creation of wooden designs in architecture in the future.

The use of wood in construction can reduce CO₂ in nature [15]. It can also be the trigger to raise the spirit of environmentally friendly vision in design and construction. According to the relationship with nature, wood is the only significant building material that is grown [12]. The wood that is installed on the building part will never have the same character as the other, visually and in its properties. Recently, the advantage of using wood has also been related to the potential for being earthquake resistant. Along with the development of Japanese wooden construction, Japan has tried to continue the exploration of wood in architectural practice. Japan has several types of wood that are mostly used in construction. The application of different kinds of wood always follows what the function of the part is. Function is included for structural and non-structural components.

This research focused on the use of Japanese cedar wood or Cryptomeria Japonica among the various types of wood available in the country. Cryptomeria Japonica is a fast-growing tree which, in its native habitat, can reach a height of 55 m in height and 3.7 m in diameter. The trees grow in Japan and around Southern China’s mountains, and in some areas that have high annual rainfall. Due to the fast growth, Japanese cedar can grow up to 7.6 m
in 10 years. Along with the advancement of industries and wooden construction, the use of wood as primary building material has been promoted in Japan. The advantage of using Japanese cedar is that it is very fast-growing, so the price is affordable. It is easy to obtain because its habitat, the timber factories, workshops, and retail sellers are prevalent in most of the areas of Japan. Besides that, this wood is lighter to use as a building structure compared to other kinds of wood such as Japanese cypress.

Regarding the wood modulation, the simulation uses Japanese cedar 105 mm × 105 mm × 4000 mm as the main structure of the intended house’s geometry. In Japan, particularly in Kitakyushu, the module is commonly used as a main frame for residential construction. In addition, the intention behind the use of this particular timber, besides promoting design exploration using the market’s available wooden material, is that the module of the cedar is suitable to support the concept of hyperboloid structure with the human ergonomic factor. The hyperboloid’s straight line axis could be arranged suitably according to the timber module. By proposing an irregular design approach and analysis to the utilization of common material modulation, it is expected that the finding would enrich the state of the art of timber design in Japan and, furthermore, contribute to environmental sustainability.

1.3. Hyperboloid Structure

The revolution in hyperboloid structure has been tremendously affected by the advancement in computational tools [16]. It is a doubly ruled surface and mainly known for its structural stability and is more economical in construction because of the less material required to construct the structure compared to other conventional structures, having a similar capacity to withstand load, and having greater strength. Following the logic in Figure 2, The hyperboloid surface can be formed when a hyperbola is revolved around its semi-minor axis, or more technically, the lofting of two surfaces in opposite directions that are twisted. Two identical base curves with a radius of \( r \) are drawn on two horizontal planes at a distance of \( h \) apart (Figure 2a). Then, as seen in Figure 2b, the skew line is rotated clockwise along the z-axis with the selected phase angle. Following that, with the same twist angle, the same skew line that is mirrored around the vertical axis is rotated counterclockwise (Figure 2c) [17]. The properties of a hyperboloid can also be described by the relation of one point to another. The point that spreads on two surfaces’ edges is called the foci of the hyperboloid. If the foci were connected by a straight line and then the second foci shifted following the edge of the surfaces, the line would still be straight. Groups of foci that are connected to each other can form the shape of the hyperboloid structure.

The early use of the hyperboloid principal can be seen in Antoni Gaudi’s building, Sagrada Familia, in Barcelona. Gaudi used this kind of curved surface to design the surface of the windows of his buildings. Vladimir Shukov expanded on this principle’s application in structural form. Vladimir Shukov was a Russian engineer born in 1853. His specialty was to design and build hyperboloid towers. In his career, he built more than 200 different hyperboloid towers with a height of up to 70 M. His most renowned hyperboloid tower is the Shokov Tower, also known as the Shabolovka Radio Tower. Built in the period 1920–1922, during the Russian Civil War that reached 350 m, which was 50 m taller than the Eiffel Tower.

Recently, the common application of this structure ought to utilize the minimum thickness of the concrete shell to construct a power station cooling tower. The well-known projects using this structure are the Canton Tower in Guangzhou, China, the Port Tower in Kobe, Japan, and the Aspire Tower in Dubai. For the smaller scale wooden projects, Juberg Tower Hemer, designed by Birk Heilmeyer and Frenzel Architekten, Carlos Jarpa’s Vigilante Maule is a Timber Frame Tower, Hyperboloid Boruvka wooden tower in the Czech Republic, and Tsuzumi-Mon (Wooden Gate) Kanazawa Station, Japan, were adopt the hyperboloid structure.
Figure 2. (a–c) Generation process of doubly ruled hyperboloid [17]. Reproduced with permission from Feray Maden, Geometric and Kinetic Analysis of Deployable Doubly Ruled Hyperboloids; published by MEGARON/Yıldız Technical University Faculty of Architecture E-Journal, 2017.

There are several advantages to the use of the hyperboloid structure. It is associated with aesthetics, structural integrity, and efficiency that influence modern architecture [17]. Firstly, it is very resistant to buckling due to the straight member. As hyperboloid structures are double curved, that is, simultaneously curved in opposite directions, they are very resistant to buckling. This means that it can use less material than you would otherwise need, making them very economical. Secondly, due to the aesthetic, despite it being curved in two directions, it is still formed with straight lines. Thus, the application of hyperboloid creates the paradox that the designer can get the best local buckling resistance because all the members are straight. At the same time, because the surface is double curved, the overall form would also exhibit the best resistance to buckling.

1.4. Form-Finding and Optimization in Architectural Design

Parametric design in a structural concept [18] and a series of studies that adopted MOO processes to design and optimization are reviewed in this section. The review is categorized into two categorizations related to structural analysis, particularly that use woods and hyperboloid’s structure, and daylight analysis particularly related to the relationship between daylight and glazing position and ratio.

Several studies have utilized a parametric design approach and MOO to conduct the form-finding process and structural optimization, similar to earlier in [19]. Brown et al. [20] addressed the potential of MOO in conceptual design of long span building typology. For the MOO input, the research calculated the finite element and energy consumptions to simultaneously generate building shape that not considered regular. The results showed how the MOO can produce attractive, creative, and high-performance design that can be feedback for designer. In addition, new data comparing structural factors and energy use resulting from this research provides a new insight into a specific design response to a specific climate context that shifts the best solution in unexpected ways. Yang et al. [2] proposed new computational design exploration (CDE) approach to facilitate designers in achieving a design target using the proposed re-formulation method. Taking examples of a sports building in Wuhan, China, the paper also showed the suitability of the computational platform utilized. Dzwierzynska [21] presented an algorithmic-aided method of shaping curvilinear steel bar structures for roofs, using the form-finding method in Rhinoceros. The results showed that the use of generative design could be potentially improved to produce responsive structural forms that meet both strength and aesthetic. In other research,
Dzwierzynska et al. [22] developed an original, methodological, and practical approach of designing roof shells formed by repetitive modules of Catalan surface. The study linked a geometric of the roof with their structural analysis and optimization using Rhinoceros 3D. The study concluded that the conducted simulation enabled the evaluation of various roof shell forms and the selection of the best solution. Bande et al. [23] analyzed parametric approach applied to a villa in Al Ain, United Arab Emirates (UAE), in terms of design, construction, and the energy impact. By comparing it to the full-year 2020 electricity bills, the results showed that after adding the structure made by the proposed methodology, the improvements in energy consumption (about 10%) and universal thermal climate index (UTCI) were recorded. Chi et al. [24] used parametric tools to optimize adaptive shadings in an open public space in Mexico. The environmental simulation and optimization used reduced the UTCI and resulted in an improvement of thermal comfort of 3.9, 7.4, and 3.1 °C at 8, 12, and 16 h, respectively, in the summer and 1.4, 3.5, and 2 °C at 8, 12, and 16 h, respectively, in the winter. Emami et al. [25] used a computational approach to integrate the assessment of structural and environmental performance of a perforated concrete shell structure in the context of Boston, MA, USA. The approach was intended to answer the question of how design parameters affect performance and what the tradeoff is between performance. The results showed that the perforation ratio was the most significant parameter affecting both structural and environmental performance and ≤10% to 20% was recommended for shell structures when translucent glazing is installed without shades. Danhaive et al. [18] utilized generative modeling and artificial intelligence to develop a design collaborator that allow designers to intuitively observe the design possibilities without making use of automated procedures. The results showed that the design subspace learning created in the research offered a new paradigm for performance-informed design exploration, and the results provide a navigable map to explore the design possibilities that can influence the designer in the design decision-making process.

Focusing on the hyperboloid structure, Dzwierzynska [16] utilized a genetic algorithm (GA) and MOO to optimize hyperbolic paraboloid roofs to observe the most effective structure in terms of division using Grasshopper and Karamba 3D. The results showed that MOO does not always provide a clear optimum solution, particularly when the assumed criteria are incompatible. However, it is capable of pre-estimating solutions and selecting the most advantageous ones. Khoraskani et al. [26] used Grasshopper, Karamba and SAP2000 to investigate the influence of form factors on the structural response of the structure to lateral loads, such as the ratio of width to height, the ratio of ground floor to roof diameters, the horizontal and vertical segmentation of the DiaGrid system, and others. Besides structural intention, parametric design and MOO has been utilized to find the optimum solution related to daylight. Bakmohammadi et al. [27] utilized a multi objective approach to assess the occupants’ comfort needs and energy performance of a classroom in Tehran, Iran. The research found that the proposed methodology can reduce energy consumption up to 47.92 kWh/m² and improve in occupants’ thermal and visual comfort. Konis et al. [28] demonstrated the application of a passive performative optimization framework (PPOF) to improve the daylighting and ventilation strategies in the early phase of architectural design processes. By optimizing building geometry, orientation, and fenestration configuration as parameters, the results of Konis’ research showed that the PPOF can deliver 4% and 17% in energy use intensity (EUI) while simultaneously improve daylighting between 27% and 65%, depending on the context. Naderi et al. [29] presented a MOO of a smart shading blind. The results showed that using the proposed method leads to a significant reduction in energy use (2.8% to 47.8%) and in thermal and visual discomfort (15.5–69.9% and 8.5–56.3%, respectively). Pilechiha et al. [30] presented a new MOO to analyze and optimize the energy processes of an office in Tehran, Iran. The results revealed that the maximum possible window-to-wall ratio (WWR) for the reference room, and at the same time, the results indicated that the room should be altered to meet standard criteria. Toutou et al. [31] investigated the potential of parametric design optimization to find the best parameters which lead to the optimum performance of energy consumption.
and daylighting. Using Ladybug, Honeybee, and Octopus, the proposed method with the optimum solutions of the model regarding energy consumption and daylighting was revealed. Khidmat et al. [32], developed a benchmark model to predict building energy and daylight performance of a two-story house in Orio, Kitakyushu, Japan. By iterating parameters such as glazing ratio, the overhang, and building orientation using Ladybug and Honeybee and Design explorer, the results showed that according to the context, the efficiency both in summer and winter has been recorded.

1.5. Aims and Objectives

Even though some research has been utilizing parametric design and MOO to conduct form finding to find the best solution related to design goals, the approach that is applied to hyperboloid wooden structures combining structural and daylight performance objectives is still limitedly reported. Thus, this research is aimed at exploring the potential of the implementation of the parametric design processes in the early design phase of the build of a two-story hyperboloid wooden house made of Japanese cedar to help the designer in decision making and design while considering structural and daylight optimization [25]. In addition, the intention behind the exploration is to design a structure for a two-story hyperboloid wooden house made of Japanese timber, 105 mm × 105 mm × 4000 mm, which has a structural and aesthetic function, through parametric design in the early steps of the design process, answering the following questions:

- Does the proposed approach lead to the optimization of the structural and daylight performance of the intended house?
- What is the parameter combination that produces the best design solutions in terms of structural and daylight objectives?
- What is the relationship between the geometry parameters and the structural objectives?
- What is the relationship between the opening parameters and the daylight objectives?
- What parameter is the most influential in each of the structural and daylight objectives?

To realize the research aims, the specific objectives are:

- To conduct theoretical studies about the implementation of parametric design and MOO.
- To build a parametric system based on design objectives.
- To build the parametric system of the optimization process, both structural and daylight analysis.
- To conduct an empirical analysis based on the data obtained.

The hypothesis of this research is that the proposed approaches of parametric design and MOO can lead to the optimization of the design objectives and find the most influential parameters driving the design objectives. Finally, this research aims to contribute to the field of design using wood, especially Japanese timber, and assist the designer in the decision-making process from the early stage of the design process.

2. Materials and Methods

2.1. General Insight and Project Description

This research is a design approach for a two-story hyperboloid wooden house considering the structural and daylight design objectives besides the geometry and aesthetic intention. The main target of the approach is to optimize several factors to have the best performance. The design scope starts from the conceptual design idea, progressing to the complete early-stage virtual parametric model, and ending with the data processing and analysis.

Figure 3 shows the schemes used for the entire parametric system developed in this research, which is related to structural considerations similar to the approach in [1,18,33–36] and in daylight consideration [30,37–41]. As shown in the Figure 3, the initial phase of designing a two-story wooden house began with ideation, motivation, a literature review,
and the definition of research and design objectives. Where the ideation phase is completed, the processes continue with the making of parametric definitions of geometry modeling, structural analysis, daylight analysis, data collection, and the optimization processes.

The logic of the hyperboloid structure was applied during the making process of the main geometry, the structure following the vector produced during the modeling process of the wooden bars, and the joint following the cross section between two bars with different twist directions in a hyperboloid constrain and the daylight follows the logic of the geometry panel (Section 2.4).

A set of tools was used to prepare the parametric and optimization platform. Figure 4a illustrates the main process of the modeling and Figure 4b depicts the tools used in this research. The main platform for building the parametric definition is a plugin called Grasshopper [42] working in the non-uniform rational basis spline (NURBS)-based 3D modeler called Rhinoceros [43]. For the structural analysis, the plugin called Karamba has been utilized. Simulations are conducted by using the plug-in Karamba. Karamba plugin fully works in the environment of Grasshopper. Karamba is a special plugin that is used in parametric structure analysis. Just like the Grasshopper component, the Karamba component works by using algorithms. Karamba is the plugin software for structural analysis that makes it easy to use for non-structural experts. This makes easy to combine parametrized geometric models, finite element calculations, and optimization algorithms such as Octopus or Galapagos. Karamba provides accurate analysis of spatial trusses,
frames, and shells. It is easy to use for non-experts and is tailored to the needs of architects, specifically, in the early design phase [44].

![Diagram of the entire system: (a) geometry and analysis; (b) tools used.](image)

An environmental analysis plugin called Ladybug and Honeybee [45] has been used to conduct the daylight analysis. Ladybug is a plugin software used to analyze microclimates based on the parametric platform of Grasshopper. It links the early phase design process with environmental study, allowing an effective way to evaluate the design process related to environmental consideration in a relatively less time-consuming manner. The plugin allows importing EnergyPlus Weather (EPW) data into the data analysis and visualization according to the designer’s needs. In addition, Honeybee’s tools are complementary to Ladybug in formulating calculations related to energy analysis. Ladybug and Honeybee integrated well-known simulation engines such as DAYSIM in Radiance, THERM, EnergyPlus, and OpenStudio to generate energy-related analysis and visualization. The MOO process was conducted using a plugin called Octopus [46]. In addition, in the daylight simulation optimization, the iteration was conducted using Colibri from Thornton Tomasetti (TT) Toolbox as it was also utilized in [47]. The data was analyzed and visualized using Microsoft Excel, the statistical analysis software JMP, and the Jupiter Notebook, a python-based platform run in the Anaconda launcher, after the data on the dynamic parameters and target value were collected.

The wooden house was intended to be located in Orio district, Kitakyushu, Fukuoka, Japan. Figure 5 shows the situation of the site where the wooden house is intended to be constructed. Figure 6 depicts the cluster and sequencing phase in parametric definition digital making. In the phase of main geometry, the closed brep representing Japanese wooden bars was made following the logic of hyperboloid structure. In this phase, the parameters that shape the intended hyperboloid geometry were applied (Figure 7). Besides the geometry modeling intention, the volume of the wood used, and the volume of the building affected by the geometry built in this phase were calculated to give the input for the cost analysis. After the geometry of the hyperboloid was completed, the next step was to arrange the definition for structural analysis in Karamba. In this phase, the cross sections, loads, and supports were defined to collect data on normal force average and displacement. The phase of environmental analysis modeling was conducted after the solution from the first optimization process (structural) was found and decided. In this phase, the EPW file from EnergyPlus was used. The research utilized the EPW file of Shimonoseki in Yamaguchi, Japan, as the closest available file on the map to the city of Kitakyushu [48].
2.2. Geometry Modeling

The geometry was built following the logic of a hyperboloid structure, incorporating the Japanese timber bars. Figure 7 illustrates the geometry modeling logic for the structural analysis needs. The geometry has eight dynamic parameters named radius-bottom, offset distance, timber members, twist, height, radius-top 1, radius-top 2, and the roof slope. Each parameter determines the overall shape according to each parameter’s movement and value (Figure 7a). The vector of the wooden bars was set to follow the connection between the division point in the bottom profile and the division point on the top profile (Figure 7b,c). Figure 7d illustrates the appearance of a wooden structure designed with different twisting levels and the wooden bars used.
Figure 7. Modeling logic of the hyperboloid wooden structure: (a) the set of dynamic parameters; (b) plan vector profiling; (c) illustration of random angle; (d) random examples of the structure with certain parameter combination.

Table 1 shows the parameters for units, division, and the number of movements. To avoid miscalculation and unexpected errors during the iteration processes, the geometry modeling includes multiplication and division factors that influence the movement of one parameter to another parameter. For instance, the number of timbers used was a multiplication between timber members and twist level. Radius top 1, as the value control for the ellipse profile of the roof, was influenced by the value of radius bottom, and radius top 2, was influenced by radius top 1.

Table 1. The geometry parameters.

| Parameters         | Lower Limit | Upper Limit | Interval | Units | Driven Factor | Movement |
|--------------------|-------------|-------------|----------|-------|---------------|----------|
| Radius-bottom      | 1.5         | 2.5         | 0.1      | m     |               | 11       |
| Offset distance    | −0.2        | 0           | 0.01     | m     |               | 21       |
| Timber members     | 3           | 5           | 1        | unit  | Twist         | 3        |
| Twist              | 2           | 5           | 1        | unit  |               | 4        |
| Height             | 4           | 7           | 1        | m     |               | 4        |
| Radius-top 1       | 0.1         | 0.4         | 0.01     | m     | Radius bottom | 31       |
| Roof slope         | 5           | 15          | 1        | Degree(°) |               | 11       |
research, the Karamba components that represent material properties were set manually instead of using the default material list.

Figure 8. Structural modelling workflow.

The analysis requires material properties of the used components to be able to calculate the force. In this research, the setting of wooden material properties in a component called MatProps in Karamba is presented in Table 2.

Table 2. Wooden bar properties.

| Element                  | Units     |
|--------------------------|-----------|
| Young’s modulus (E)      | 960       |
| Shear’s modulus (G)      | 450       |
| Specific weight (Gamma)  | 39.5      |
| Coefficient of thermal expansion (AlphaT) | 0.000003 |
| Yield stress (FY)        | 1.3       |
| Name                     | Japanese Timber |

2.4. Daylight Simulation Setting

The daylight simulation setting, and analysis were entirely arranged in Grasshopper targeting the UDI 300 lux–500 lux data collection. The relationship between windows and daylight utilizes the panelized division surface from the hyperboloid cylinder yielded from the optimization process 1. The glazing modelling logic is presented in Figure 9. As it can be seen in the figure, after the zone has been divided, the glazing ratio was applied following the design (Figure 9b). The consideration behind the glazing design
was both aesthetic and the basic triangulation surface, as a consequence of making the curve of the cylinder become a planar surface. Figure 9c shows the scenario of the panel division to locate the glazing as windows and the material type for the analysis. Figure 9d illustrates the visualization of daylight conditions inside the building and in relation to the site regarding the building orientation.

Figure 9. Modeling preparation for daylight analysis: (a) split brep to divide zones; (b) windows ratio setting; (c) windows application in hyperboloid structure; (d) daylight analysis and visualization.

The dynamic parameters used in this phase were the glazing units representing the location of the glazing towards the building orientation. The parameters are the movement for glazing in zone 1, or first floor, and zone 2, or second floor, and the glazing ratio. The parameter upper and lower limits of each movement and glazing ratio together with their units are presented in Table 3, and the visualization of different combinations of the parameters is illustrated in Figure 10.

Table 3. Dynamic parameters for daylight consideration.

| Parameters       | Lower Limit | Upper Limit | Interval | Unit  | Driven Factor | Movement |
|------------------|-------------|-------------|----------|-------|---------------|----------|
| Movement list top| 0           | 8           | 1        | unit  |               | 9        |
| Movement list bottom| 0           | 8           | 1        | unit  |               | 9        |
| Glazing ratio    | 5           | 9           | 1        | %     | 0.1           | 5        |

August 21 represent illuminance in the summer and 21 January represent illuminance in the winter were used as the analysis periods. The selection behind the selected date is based on the cooling design day and heating design day from the EPW stat file [49]. The weather data provided by EnergyPlus, called the EPW file, was used as a weather data input. With regard to the weather data availability, the analysis used the Shimonoseki EPW file as the closest data available surrounding Kitakyushu [48].
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| Parameters       | Lower Limit | Upper Limit | Interval | Unit | Driven Factor | Movement |
|------------------|-------------|-------------|----------|------|---------------|----------|
| Movement list    | 0           | 8           | 1        | unit | 9             |          |
| Glazing ratio    | 5           | 9           | 1        | %    | 0.1           |          |

Figure 10. Samples of the glazing movement in Zone 1 and Zone 2.

The metric used to measure the daylight was called useful daylight illuminance (UDI). UDI is defined as the annual occurrence of daylight illuminances across the work plane where the illuminances are within the range of 100 lux–2000 lux and are within a range considered “useful” by occupants [50,51]. However, this research only calculated the area with UDI ranged from 300 lux to 500 lux as it was developed and adopted in [52,53].

2.5. Multi-Objective Optimization

The optimization was based on genetic algorithms (GA) conducted using a plugin called Octopus as the MOO solver, as it was also adopted in [54–56]. This phase’s main goal is to optimize the design objective in terms of both structural factors and daylight. In structural analysis, the optimization was intended to find the targeted solution, such as a minimum or an as-close-to-zero normal force average (NFA), displacement (D), cost (C), and maximum building volume (BV). In daylight analysis, the iteration did not utilize the GA while it iterated the whole possibilities of the parameter combination. The iteration engine used was Colibri, developed by Thornton Tomasetti’s CORE Studio, TT Toolbox [57].

2.6. Sensitivity Analysis and Fitness Function Calculation

After the data generation from the first and second optimization was collected, sensitivity analysis and fitness function calculation were conducted outside the Rhino and Grasshopper platforms. The sensitivity analysis was intended to find the most influential parameter shaping the design objectives while fitness function calculation [28,30] was conducted on the Pareto front solution from optimization one and the iteration in optimization two to find the single best solution regarding the targeted value of each objective in MOO. The analysis was run by using standard least square for personality and emphasizing effect leverage.
3. Results

3.1. General Results

The simulations were carried out twice. The first was for the structural optimization and the second was for the iteration for collecting data related to daylight. Each optimization and iteration consisted of a simultaneous single simulation parameter as a genetic optimization genome to shape the optimization objectives. The structural and geometrical optimization processes took almost 24 h and yielded 10,098 individuals or design solutions, while for the daylight design exploration, the entire process took 14 h and yielded 406 individuals or design solutions.

The general result from the optimization is the datasets of the generations. The lists were filled with information about an individual’s parameters and the objective value. In Octopus, the objectives were distributed to the 3D population field according to its axis value, which in this case, were the structural and daylight objectives. The fourth and fifth axes sometimes need to be represented by color and scale.

The raw data obtained from the genetic iteration will further undergo statistical analysis for sensitivity analysis and general comparison. The Pareto front from the structural optimization was filtered using the fitness function calculation to collect the best nine design solutions for further design consideration. However, for the daylight iteration, since it was not a genetic algorithm, the fitness function was applied to the overall result due to the absence of Pareto front solutions. The details of each finding will be described in the following sub-section.

3.2. Structure Optimization Results

As previously mentioned, the structural optimization process comes up with a population field with four axes used, which are normal force average (NFA), displacement (D), cost (C), and building volume (BV). Figure 11 presents the population field populated with designed individuals. It can be seen from the left population field that the individuals or designed solutions are inclined to swarm in a particular area. During the training period, the MOO tends to pull out the individual based on the mating of the parameters and the objectives combination to the targeted area of minimum normal force average, cost, and displacement, and maximum building volume. The more generations are set, the more design solutions will be produced, and the more significant the optimization result.

Figure 11b shows the Pareto front resulted in the last generations (Generation 99 to 100). The Pareto front solutions are the collections of chosen individuals that meet the MOO criteria. A total of 177 Pareto front solutions were produced from the overall iteration to narrow the selection to the best solution balancing the four design goals. The color gradation indicates the cost of the individuals. The color red represents high cost, the color brown represents middle cost, and green represents an individual with a low cost for the timber used. Through observation in this field, the individual performs the maximum and minimum performance of each design objective that can be found. A feature called the “reinstatement solution” is used to generate the intended individuals. Up to this point, although the design target can be picked by assumption, to ensure the balance, empirical calculation and analysis are needed. Therefore, the fitness function calculation was applied.

3.3. Fitness Function

In this step, the Pareto front solution in its original order is being shorted by applying a fitness function (FF) calculation. The values and attributes that have been calculated were ranked according to the fitness function value. The nine best design solutions and their attributes, including parameters and objectives, are presented in Table 4.
In terms of parameters, the results of FF radius bottom ranged between 1.5 m and 2.5 m, which are the lower and upper limits for the radius bottom parameter setting. The offset distance seemed to randomly occur yet mostly ranged between −0.18 m and 0.2 m, except for solutions number five and eight. Timber members tend to be optimized mostly using 5 bars multiplication, which is the upper limit of the setting (Table 1). The twist, as a multiplication factor for members, occurred mostly at 2, except for individuals ranked 4, 8, and 9. The optimum solutions substantially ranged between 4 m and 4.8 m, except for solution rank 8, 5.7 m. According to the parameters set, the structural and cost objectives tend to pull the design solution to the lower limit of the setting. For the top radius one, which forms the ellipse profile of the house, the values ranged between 2.09 and 2.992, while for the top radius two, the values ranged between 2.628 and 3.624. The optimized solutions have roof slopes ranging from 5 to 8. According to the parameter setting, the number of roof slopes indicated that the lower limit height parameter occurred from the lower to the middle limit. It can be observed from Table 4 that the best solutions occurred after solutions number 7000.

Figure 12 shows the geometry of the nine best solutions based on the FF calculation. Even though the original population field in Octopus featured instant geometry feedback, up to this point, the menu has filtered into several choices, highlighting the consideration of performance-based design. As shown in Figure 12, solution rank 1 resembles solution rank 2 in appearance. In addition, the similarity in appearance also happens for solution ranks 3, 7,

![Figure 11. 3D population field as an original design distribution yielded during MOO processes: (a) History; (b) pareto front.](image)

| Radius- | Offset | Timber | Twist | Height | Radius-Top 1 | Radius-Top 2 | Roof Slope | NFA | D | C | BV | Timber Volume | Ranking | Solution Number |
|--------|--------|--------|-------|--------|--------------|--------------|------------|-----|---|---|----|---------------|---------|-----------------|
| 1.5    | −0.18  | 5      | 2     | 4      | 2.09        | 2.628        | 7          | 0.840807| 0.477199| 62,567,331,218 | 36,781,507 | 1.012753 | 1         | 9092          |
| 1.5    | −0.2   | 5      | 2     | 4      | 2.09        | 2.628        | 7          | 0.771849| 0.644391| 62,511,831,443 | 36,791,508 | 1.012752 | 2         | 7974          |
| 2.5    | −0.2   | 5      | 2     | 4      | 2.571       | 3.264        | 8          | 1.405757| 0.423516| 67,534,838,495 | 34,852,582 | 1.122756 | 3         | 7480          |
| 1.5    | −0.19  | 5      | 3     | 4.2    | 2.019       | 2.616        | 6          | 0.750567| 0.367732| 104,091,210,856 | 58,433,623 | 1.576698 | 4         | 7939          |
| 2.5    | −0.09  | 5      | 2     | 4.1    | 2.915       | 3.528        | 7          | 0.590865| 0.529607| 69,552,708,197 | 31,229,064 | 1.504852 | 5         | 10,556        |
| 2.5    | −0.19  | 4      | 2     | 4      | 2.936       | 3.14         | 5          | 1.544796| 0.420685| 57,255,335,753 | 34,714,163 | 0.974209 | 6         | 6612          |
| 2.5    | −0.19  | 5      | 2     | 4.5    | 2.915       | 3.54         | 5          | 1.396019| 0.501531| 79,055,810,126 | 35,573,888 | 1.594072 | 7         | 9415          |
| 2.5    | −0.08  | 5      | 4     | 5.7    | 2.952       | 3.624        | 5          | 1.089105| 0.634972| 189,664,817,972 | 116,958,723 | 2.922119 | 8         | 9518          |

Figure 12 shows the geometry of the nine best solutions yielded during MOO processes.
5, 6, and 7. Solution ranks 4, 8, and 9 have more timber compared to the other solutions. This was due to the larger combination of twist level and the number of timbers used.

Choosing the individual presumed to be the best involves mainly subjectivity. In this case, as seen in the figure, almost all solutions have a height of less than 5 m (Table 4). The search for the least amount of timber used to achieve the least amount of cost may have influenced the trend of less height among individuals, which is later confirmed in Figure 17c where height, along with twist and timber members, is one of the parameters with the most implications for cost. Considering enough height for a two-story house, the author picked solution rank 8, with a height of 5.7 m, to be the one that will undergo further optimization processes related to daylight. The height finding reveals unexpected results when the height was considered as a whole unity rather than as a result of the interrelationship between the heights of the first and second floors. However, this finding and consideration becomes feedback for future experiments to set the lower limit in the height parameter setting to be a reasonable value for a two-story house, and to set the interconnection between two floors.

Figure 13 shows a scatterplot illustrating the correlation between two objectives that originated in the population field in Figure 11. In this plot, the position and distribution of Pareto front solutions and the fitness function solutions have been positioned among the entire individual generations. According to the figure above, the correlation between each objective cannot be determined. The RSquare value was relatively small for all the correlations (below 0.4). The Pareto distribution seems to be evenly distributed. Considering
the weight of MOO processes, a proper logic of iteration should have pulled the individuals into the searching area (Figure 11). However, as it can be seen from the dedicated scatterplot, a proper swarm individual can only be found in Figure 13b,f, indicating that multi-objective optimization has a weighting complexity to balance the search. The lack of generation number may affect conflicting trade-offs among objectives; thus, increasing the generation number during MOO to a maximum or nearly matching with the mass multiplication of the parameters’ movement value is highly recommended for future and similar work paths.

Figure 13. Scatterplot between two objectives and the Pareto front position: (a) NFA and BV; (b) NFA and D; (c) NFA and C; (d) BV and D; (e) BV and C; (f) D and C.
3.4. Daylight Optimization Results

After one individual has chosen from the first optimization processes, a similar workflow has been applied to the second optimization related to daylight objectives. The different type of iteration between the two optimizations is that in this phase, instead of utilizing the mating of parameters through a generative algorithm, daylight objective search was utilized for design exploration from the plugin called Colibri, provided by TT Toolbox [57] as it was adopted in [58–62]. The exploration was iterated to all possible solutions from the parameter combinations that were set in the Grasshopper definition. The step is possible to be conducted when the expected number of solutions, together with the consideration of simulation time, is considered possible. Daylight optimization parameters only have a few possible design solutions (Table 3) and yielded 406 individuals representing the design solution and its attributes.

Figure 14 shows the 3D scatter plot that plots the design solution from the daylight objective iteration in optimization two. The objectives were to measure the useful daylight illumination (UDI) ranged between 300 lux and 500 lux [52,53] during designated days in summer and winter. In addition, the geometry objective, which was a glazing area to ensure the view quality to the outside, was also incorporated. According to Figure 14a, the results of the glazing ratio setting in parameters show several levels in UDI summer and winter. The glazing area objective has a strong correlation with the glazing ratio according to the color gradation. Aside from being related to the ratio (Figure 9b), the glazing area is also affected by the size of the panel produced by the exploded geometry from the optimization one when it was rotated. Figure 14b highlights the ten best individuals based on the FF calculation. The objectives were successfully located at the maximum values of UDI and glazing area, indicating that the FF calculation was performed and applied properly. To check the position of the individuals, the relationship between the two objectives in daylight optimization will be presented in a 2D scatter (Figure 15).

Table 5 lists the ten best solutions’ attributes, parameters, and objective values. In terms of parameters, the glazing movement for the top zone (second floor) ranges from 5 to 8, while for the bottom zone (first floor), it ranges from 4 to 8. The range from movement items 5 to 8 directs the windows from the Northwest to the Northeast sides of the house (Figure 9). For the bottom zone (first floor), the range of movement items from 4 to 8 has the same direction as the top zone. As a common understanding, the glazing ratio for FF pulled the individual to the upper limit of their parameter setting. The highest UDI in the summer was achieved by the solution rank 1. The highest UDI in winter was the solution rank 7,
and the highest glazing area was the solution rank 7. The optimum solution occurred after individual number 360. Interestingly, solution number 8 was the last individual from the iteration process.

Table 5. The 10 best design solutions, attributes, and objectives.

| Rank | Movement Item Top FF | Movement Item Bottom FF | Glazing Ratio FF | UDI Summer FF (m²) | UDI Winter FF (m²) | Glazing Area FF (m²) | Solution Number |
|------|-----------------------|-------------------------|------------------|--------------------|-------------------|---------------------|------------------|
| 1    | 8                     | 7                       | 9                | 159.866523         | 136.44026         | 7.9648              | 397              |
| 2    | 8                     | 5                       | 9                | 154.025604         | 138.908534        | 8.021715            | 379              |
| 3    | 8                     | 4                       | 9                | 153.782105         | 135.71133         | 8.10186             | 370              |
| 4    | 7                     | 7                       | 9                | 150.854506         | 136.910236        | 8.04021             | 396              |
| 5    | 7                     | 5                       | 9                | 145.344506         | 134.664192        | 8.177271            | 369              |
| 6    | 8                     | 6                       | 9                | 155.822131         | 126.311041        | 7.856945            | 406              |
| 7    | 7                     | 5                       | 9                | 147.017711         | 130.940005        | 7.942779            | 394              |
| 8    | 8                     | 8                       | 9                | 144.570966         | 128.956859        | 8.061792            | 387              |

To ease the observation of the individual distribution within the population fields (3D scatterplots), 2D scatterplots have been incorporated. Figure 15 depicts scatterplots...
showing comparisons between two daylight objectives from the daylight optimization processes. Firstly, the FF has been successfully locating the ten best solutions in the search area in each plot, which are maximum UDI and maximum glazing area. Secondly, there were no two objectives that were highly correlated. In terms of UDI in summer and winter, the swarm of solutions or the distribution inclined in the range of about 100 m² in summer and more than 60 m² in winter. However, regarding the relationship between glazing area and the UDI Summer, an unclear trend occurred that the iteration pulled the solutions to a positive correlation, while in Figure 15c, the tendency showed an even distribution. Thus, in the daylight objective analysis, the value of each objective cannot be determined by the value of the other objective due to the small value of correlation.

In addition to UDI performance, the various glazing positions and their effects on the UDI distribution have been visualized in Figure 16. The two visualizations of each solution rank represent the visualization of two different sky positions. The figure on the left is for summer situation, while the figure on the right depicts the UDI for a winter situation. In general, the positioning of the glazing area in zone two (second floor) mostly faces northeast directions, except for rank number 9 and rank 5 in zone one (first floor). As a result of being faced northwest, an over lit area developed, as indicated by the test point with UDI greater than 2000 lux in Figure 16 (rank 5 in zone one, and rank 9). Rank 8 in zone one has an area with over lit UDI during the winter. This was due to the direct sun vector hitting the glazing area.

Regarding the targeted UDI of 300 lux to 500 lux (blacked border), solution rank 1 visualizes the largest area with the UDI in summer, while solution rank 7 depicts the largest targeted UDI in winter. The UDI distribution in the summer mainly occupied the middle area both in zone one and zone two, while in the winter the distribution of UDI 300 lux to 500 lux mainly occupied the area above the glazing stretched to the center. It is indicated that the useful range according to [41] has the areas ranging from under the glazing area to the center of the test floor. The darkest area of the overall best ten solutions based on the FF calculation was about 200 lux, and the brightest was more than 2000 lux. In addition, almost all solutions performed UDI between 800 lux and 1200 lux (presented in the gradation color light green to yellow) except solutions four and six in zone one during the winter. According to the site orientation (Figure 5), none of the solutions from the daylight optimization had the glazing on the front view or main orientation. While most building designs tend to locate the glazing facing the front side of the site, or towards the main access to the site, the findings of this research suggest a different and opposite situation. The performance-based design applied in this research opens the discussion to more consideration related to the view to the outside.

3.5. Sensitivity Analysis Results

A sensitivity analysis was conducted to observe which parameters have the most implications for certain design objectives. The formulation and action (Section 2.6) were applied based on the overall generations that have iterated during the MOO processes. In this phase, the results of the sensitivity analysis will be divided into the following two parts: first, the sensitivity analysis of the structural analysis and optimization intention; second, the analysis for the daylight optimization intention. The results are presented in tornado plots ordered from the parameter with the largest implication to the least.
Figure 16. Best design solution related to daylight based on fitness function calculation.

The standard least squares for personality were used, with an emphasis on effect leverage. Figure 17 depicts the results of sensitivity analysis on four design objectives related to the optimization of structural and geometry goals. Figure 17a presents the influential parameter value to the normal force average (NFA). The results show that timber members, twist level, and height of the house by order are the parameters with the most implications in driving the normal force average, while radius-bottom, roof slope, and offset distance are the least influential in driving the normal force average. Figure 17b
depicts the results of sensitivity analysis between parameter to displacement (D). In terms of displacement, height, twist level, and radius bottom are the parameters that implicate the displacement the most, and the least are radius top, timber members, and the roof slope. Figure 17c parameters to cost (C), twist level, timber members, and height are the parameters that implicate cost the most. This is due to the fact that these three parameters have a direct impact on the volume of wood used and the number of joints. The parameters radius-top, bottom, and offset distance have no direct implications for the wooden volume. Figure 17d depicts the implications of the parameters to building volume (BV). The results show that building height, the number of the members, and radius bottom are the three parameters that shape building volume the most. In general, building height is one of the parameters that affects the most design goals. The twist affects NFA, C, and D, but not BV. Offset distance is the parameter that has the least implications in NFA, C, and BV, but not in D. By knowing which parameters have strong implications in driving certain design objectives, further analysis or research is encouraged to focus only on the best parameters to obtain stronger results and optimization.

**Figure 17.** Sensitivity analysis showing the significant implication of each parameter toward the objective: (a) parameters to NFA; (b) parameters to D; (c) parameters to C; (d) parameters to (BV).

Figure 18 depicts the sensitivity analysis results for the daylight optimization. Figure 18a shows that movement item bottom in zone one and the glazing ratio are the parameters that most implicate the UDI in winter, while the glazing movement in zone two (second floor) is the least parameter driving the value of the UDI distribution in winter. The situation in summer (Figure 18b) shows the opposite tendency, where glazing ratio and glazing movement on the second floor are the most influential parameters shaping the value of UDI distribution in summer. In terms of the glazing area objective, as per common sense and understanding, the glazing ratio influences the glazing area directly; thus, it becomes the most influential parameter driving the view objective, with a significant value of almost 200. In the daylight and view objective analysis, since it was not a genetic algorithm approach that was applied and the number of parameters and their value range was not as large as in the structure analysis, the number of parameters as an optimization genome was only three, thus the significant value among the parameters was not shown except in Figure 18c.
Figure 17. Sensitivity analysis showing the significant implication of each parameter toward the objective: 
(a) parameters to UDI winter; (b) parameters to UDI summer; (c) parameters to glazing area.

3.6. Parameters to Objectives

The parallel coordinate plots (Figures 19 and 20) provide an alternative to present the relationship between the design parameters and the design objectives. The range of values in each vertical axis represents the value of the design variable and the objectives. The four plots in Figure 19 represent different tendencies according to design objectives. The gradient color was set to represent the value of the objectives. Due to the use of multiple design objectives, the tendency would not conclude one absolute solution. The purple line in each plot was used to highlight only the target range of objective values, which are minimum NFA, D, and C, and maximum BV, besides the unselected value (gray-colored).

The highlighted lines in Figure 19a illustrate the tendency between the low value of the Normal Force Average (NFA) to the parameters and to the other objectives. In terms of parameters, as it can be seen in the plot, a minimum or preferable NFA is correlated with mostly minimum radius-bottom and minimum radius-top. The other parameters, such as offset distance, timber members, twist, building height, and roof slope, tend to present an even value distribution related to the minimum NFA. In terms of the relationship between low NFA value and the other objectives, the minimum NFA is also associated with the minimum value of displacement (D) and building volume (BV), yet not related to the specific value of cost (C).

In Figure 19b, the minimum value of displacement is correlated with the middle to minimum value of NFA. In the same way that Figure 19a did not show a specific tendency with C and BV, the minimum D did not show a specific tendency with C and BV. However, the inclination shows that the value seems to range from the middle to the minimum value. In terms of parameters, almost all the value ranges of parameters contribute to the minimum D except building height, where the swarm shows a tendency of the value range from middle toward minimum.

In terms of the lowest cost, the tendency Figure 19c shows that a low twist level and a lower building height are correlated. The other parameters, except twist and height, show an even distribution. Regarding the other objectives, minimum cost is correlated with the middle value of NFA, minimum D, and minimum BV.
Figure 18. Sensitivity analysis showing the significant implication of each parameter toward the objective: (a) parameters to UDI winter; (b) parameters to UDI summer; (c) parameters to glazing area.

3.6. Parameters to Objectives

The parallel coordinate plots (Figures 19 and 20) provide an alternative to present the relationship between the design parameters and the design objectives. The range of values in each vertical axis represents the value of the design variable and the objectives. The four plots in Figure 19 represent different tendencies according to design objectives. The gradient color was set to represent the value of the objectives. Due to the use of multiple design objectives, the tendency would not conclude one absolute solution. The purple line in each plot was used to highlight only the target range of objective values, which are minimum NFA, D, and C, and maximum BV, besides the unselected value (gray-colored).

Figure 19. Parallel coordinate plots for structural optimization: (a) relation to lowest NFA; (b) relation to lowest D; (c) relation to lowest C; (d) relation to highest BV.

In Figure 19d, where the colored lines highlight the targeted maximum value of BV, the tendency shows that maximum radius-bottom, height, radius-top 1, and radius-top 2 are associated with maximum BV. Related to the relationship with the other objectives, maximum BV is incorporated with the middle range of NFA and D, and the range from middle to maximum value of C.

Figure 20 depicts scatterplots showing the relationship between parameters and objectives of the data from the daylight objective’s iteration. In these plots, similar to Figure 19, the gradient color and the highlight were applied according to the targeted design objective value. Maximum UDI of 300 lux to 500 lux in summer tends to be associated with the middle to maximum glazing ratio. While there is no specific tendency related to the movement of items at the bottom and top, as well as to the other objectives. In Figure 20b, the maximum value of UDI in winter is associated with a middle to maximum value of UDI in summer, but the tendency is even in terms of parameters and glazing area. The
maximum glazing area is strongly related to the maximum glazing ratio in Figure 20c, whereas the movement items at the top and bottom have an even distribution. Besides, maximum glazing area is also associated with the range from middle to maximum area of UDI in summer and the range from middle to high area of UDI in winter.

![Parallel coordinate plots for daylight iteration](image)

Figure 20. Parallel coordinate plots for daylight iteration: (a) relation to highest UDI summer; (b) relation to highest UDI winter; (c) relation to highest glazing area.

### 4. Discussion

The results indicate that the proposed methodology that was applied in the early phase of designing a two-story wooden house, in line with the hypothesis, can identify the best design solution related to structural and daylight performance goals and answer the question of whether the proposed method could lead to the optimization and find the best
solution from the optimization and exploration processes. The best solution in structural optimization that has minimum force load, cost, and maximum building volume, balancing the trade-offs of the design objectives, was found to have a specific parameter combination, explained in Section 3.3, that has been found to be considered by the designer when deciding the hyperboloid design factors and parameters. Through this finding, the designer can be informed and focus on the factors that are significant in minimizing displacement, normal force average, and cost while maximizing building volume. Besides, as explained in Section 3.4, the proposed approach also finds the best glazing location and ratio to bring the optimal UDI of 300 lux to 500 lux for the house. Confirming that the performance-based design has been successfully conducted.

In identifying correlations, patterns, and relationships among the data obtained (objectives), the MOO produced rather unclear relationships and weak correlations. The weakness in correlation meant that the value of one objective produced in MOO could not become a significant justification factor that influenced another design objective. However, by seeing the scatterplots, it was indicated that the MOO and fitness function calculation processes had successfully located the pareto front and the based design solution to the targeted searching area (Figures 13 and 15). It then eases the designer to identify and observe the design possibilities with immediate data and geometrical feedback during the decision-making process. In terms of the relationship between parameters and the objectives, the utilization of parallel coordinate plots in Section 3.6 illustrates several tendencies and trends in the parameter value. Seeing this trend, further research can focus only on the specific range of the parameters where the lines are swarmed and dense. Besides, the parallel coordinate plots offer flexibility and interactive ways of design solution observation (purple line). Furthermore, by incorporating sensitivity analysis (Section 3.5), the most influential parameter that drives the design objectives has been successfully identified. Knowing the parameter meanings and their range will further optimize the possibilities of having more optimized design goals.

Related to the position of this research in the literature of parametric design and MOO discussion, The study provides a new insight into the performance-based design in the early phase of designing wooden structure especially in hyperboloid design [16, 26, 63], But with using more specific materials which was a Japanese lumber 105 mm × 105 mm × 4000 mm. The use of optimization method and platform in structural optimization could find the best design solution confirming research in [64–66]. Related to the daylight objective, the proposed study using a metric that developed and adopted in [41, 52] and optimized like in [30, 32, 67]. The optimization of daylight has successfully produced the best window position by iterating the glazing location and glazing ratio [30]. The combination of two disciplines of structural and daylight was in line with the ideation in [68] yet more to the application in building geometry rather than shell structure.

This research was to be applied in the early phase of architectural design. It is beyond the scope of this study to address the question of how much the proposed method in these hyperboloid cases offers in terms of efficiency. This is due to the uniqueness of its parameters, geometry, and performance. Usually, efficiency is approached by comparing the performance of the iterated model with that of the benchmark or baseline model [32, 67]. However, as the design case which raised in this study was complex, no specific constraint on the baseline model was developed. Regarding the parameters and the metrics used, this research only considered displacement and normal force average in structural consideration and the useful daylight intensity (UDI) in daylight performance consideration. Another daylight metric is finite element [69] in structural analysis, as well as Spatial Daylight Autonomy (SDA), Annual Sunlight Exposure (ASE), and Daylight Glare Probability (DGP) [70].

5. Conclusions
This study provides a new insight into designing hyperboloid wooden structures. This research aimed to explore and apply parametric design processes and multi-objective
optimization (MOO) to design a hyperboloid two-story wooden house in the Orio district, Kitakyushu, Japan, considering structural and daylight performance. The study focused on the use of 105 mm × 105 mm × 4000 mm Japanese timbers as the building’s main structure.

Based on the data yielded from the optimization and iteration processes, it can be concluded that the proposed method could bring the optimization and find the most preferable design solution that performs the targeted design goals in terms of structure and daylight. In addition, the analysis reveals the most significant parameters influencing the design objectives as well as the tendency among design objectives and between parameters towards the design objectives. Several key findings of this research are that the best design solution in terms of structural analysis was solution number 9052, having the following parameter combination: radius bottom: 1.5; offset distance: 0.18; timber members: 5; twisting level: 2; building height: 4; radius-top 1: 2.09; radius-top 2: 2.628; roof slope: 7. Regarding the daylight objective, the best solution was solution number 397, with the following parameter combination: movement item top: 8; movement item bottom: 7; glazing ratio: 9. The most influential parameter in shaping displacement and building volume was building height, while twisting level was the most influential parameter in influencing cost. This research clearly illustrates that where the intention of performance-based design in the early phase of architectural design processes has arisen, the MOO and parametric design should be fit and effective with the strategy.

Based on these findings, designers and stakeholders should consider using the parametric design approach and MOO, both of which require a set of parameters, to achieve more desirable design goals. The set of parameters can be more focused on the range of parameters where the tendency shows it is significant to a specific objective. Future research could address several limitations by incorporating additional structural and daylight metrics as data supplements. Finally, this study contributes to a better understanding of how parametric and MOO design strategies can provide an alternative approach to design strategy, thereby enhancing the existing theory and approach in computational design.

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