Study of the Roof Shape of a Wooden Detached House for Minimization of LCCO$_2$ Emission by Genetic Algorithm

Jieli Sui$^1$, Junzo Munemoto$^2$ and Daisuke Matsushita$^3$

$^1$Doctoral candidate, Graduate school of Engineering, Kyoto University, Japan
$^2$Professor, Graduate school of Engineering, Kyoto University, Japan
$^3$Instructor, Graduate school of Engineering, Kyoto University, Japan

Abstract
A simulation methodology has been proposed for evaluating the performance of LCCO$_2$ emission of the roof shape of a Wooden Detached House (WDH) using Genetic Algorithm (GA). Annual LCCO$_2$ emission acting as an evaluation index was studied in this paper. The geometrical shape of a roof located in Tokyo is simulated by a Béier surface. Two types of roofs are considered in this paper: the Tiled roof shape (TRS) and the Green roof shape (GRS). Two kinds of boundary condition, which are fixed corners with free boundaries and fixed boundaries, are taken into account for both TRS and GRS. Through numerical roof shape representation evaluated by GA, we conclude that: 1) A flattened TRS is more efficient in minimizing LCCO$_2$ emission; 2) Dome-shaped GRS with a larger surface area and fully covered with green lawn performs the best in LCCO$_2$ emission minimization; 3) CO$_2$ absorption by green lawn has a significant effect in minimizing total LCCO$_2$ emission from the roof of WDH, and even LCCO$_2$ emission with a value below zero may occur when green lawn is laid out on a rooftop.

Keywords: roof shape; LCCO$_2$ emission; genetic algorithm; Béier surface

1. Introduction
1.1 Background
The shape of a roof often plays an important role in the envelope system of sustainable buildings. In order to make the roof shape perform better in regards to energy consumption and indoor comfort, solar panels and green roof are used. The area of a roof, its inclination and facing direction are factors influential to the amount of materials used, heat loss, solar gain, and energy consumption for air-conditioning. These factors have a direct relationship with LCCO$_2$ emission, therefore efficient roof shape design is necessary. As in previous studies, we have investigated three kinds of Japanese traditional WDH roof shape in order to minimize their LCCO$_2$ emission by using three geometrical models (Sui, 2004). We found that for each of these roof shapes, there are different solutions for the effective minimization of LCCO$_2$ emission. In this paper, we study the performance of the curved roof regarding housing LCCO$_2$ emission reduction.

It is known that the green roof is efficient in mitigating the heat island problem, thermal load from sunlight, and reducing energy consumption for air-conditioning. The Tokyo Metropolitan Government revised the greenery standards of Natural Environment Conservation Ordinance in April 2000, to encourage the planting of 20 percent of rooftop areas (Takenaka, 2001). This inspires us to incorporate the green roof design for LCCO$_2$ minimization to be carried out in this study.

To define; if a roof is covered with tiles only, we call it "tiled roof shape" (TRS). Otherwise, whenever a part or the full area of a roof is covered with green lawn, it is called "green roof shape" (GRS).

1.2 Purpose
In this paper, roof shapes are designed by the Genetic Algorithm (GA) method. The LCCO$_2$ emission of a roof, including the performance and benefits of green lawn on roofs, is simulated. The main purpose of this study is to propose a method of finding efficient roof shapes that minimize LCCO$_2$ emission in the case of TRS and GRS respectively, and to compare TRS and GRS in order to clarify the performance of green lawn in minimizing WDH roof shape LCCO$_2$ emission. 

1.3 Past studies
Recently, researchers have been finding various effective methods for minimizing LCCO$_2$ emission in architectural design. These optimization techniques proposed materials selection and structural and shape design. Yada et al. (1999), Yada et al. (1998) and Munemoto et al. (2002) developed methods and obtained optimal building materials selection and construction methods for minimal LCCO$_2$, LCC, and LCW from a detached house. Tang, et al. (2003), Basam (2002) and Thanos (2001) studied the
relationship between house form and solar energy absorption. In the meantime, researchers suggest that sustainable design methods such as green roof are effective techniques for mitigation of the heat island phenomenon and energy consumption. Inspired by these studies, roof shape is investigated in this paper from the point of view of minimizing LCCO₂ emission and the application of the green roof.

2. Theory

The Béier surface is adopted to represent the roof shapes in this paper because this parametric surface has the following characteristics and can generate a smooth surface with a relative small number of design variables (Ohsaki et al., 2004).
1. The Béier surface does not pass through the control points except at the corners of the control point grid.
2. The surface is contained within the convex hull of the control points.
3. Any linear transformation (such as rotation or scaling) or translation of control points defines a new surface that is simply the transformation or translation of the original surface.

A Béier surface \( Q(u, w) \), where \( u \) and \( w \) varies orthogonally from 0 to 1, from one edge of the surface to the other, is formed as the cartesian product of the blending functions of two orthogonal Béier curves and defined by a set of \((n+1)(m+1)\) control points (Fig.1.) (Kaneada et al., 2001) \(Bi,j=(X(i,j),Y(i,j),Z(i,j))\). A Béier surface is formulated as:

\[
Q(u, w) = \sum_{i=0}^{n} \sum_{j=0}^{m} \begin{pmatrix} m \\ j \end{pmatrix} B_{i,j}(u) \begin{pmatrix} n \\ j \end{pmatrix} K_{m,j}(w)
\]

(1)

where \(J_{n,j}(u)\) and \(K_{m,j}(w)\) are the Bernstein polynomials of order \(n\) and \(m\) respectively, which are defined in Eqs. (2) and (3).

\[
J_{n,j}(u) = \binom{n}{j} u^j (1-u)^{n-j}
\]

(2)

\[
K_{m,j}(w) = \binom{m}{j} w^j (1-w)^{m-j}
\]

(3)

Where

\[
\binom{n}{i} = \frac{n!}{i!(n-i)!}
\]

(4)

\[
\binom{n}{i} = 0, i < 0 or i > n
\]

(5)

The derivative of \(J_{n,j}(u)\) and \(K_{m,j}(w)\) with respect to \(u\) and \(w\) are

\[
\frac{dJ_{n,j}(u)}{du} = \binom{n}{j} [j u^{j-1} (1-u)^{n-j} - u^j (1-u)^{n-j+1}]
\]

(7)

\[
\frac{dK_{m,j}(w)}{dw} = \binom{m}{j} [j w^{j-1} (1-w)^{m-j} - w^j (1-w)^{m-j+1}]
\]

(8)

and the tangent vectors of the Béier surface are

\[
T_u = \sum_{i=0}^{n} \sum_{j=0}^{m} B_{i,j}(u) \frac{dJ_{n,j}(u)}{du} K_{m,j}(w)
\]

(9)

\[
T_w = \sum_{i=0}^{n} \sum_{j=0}^{m} B_{i,j}(w) \frac{dK_{m,j}(w)}{dw} K_{n,j}(u)
\]

(10)

Area of the interested region of the surface can be calculated by

\[
S = \int_{u_1}^{u_2} \int_{w_1}^{w_2} |T_u \times T_w| du dw
\]

(13)

Assuming that, irrespective of its shape, solar energy absorption relates directly to the projection area of the roof on the perpendicular plane of sunlight, the solar energy absorbed by a roof can be calculated by the sum of solar energy absorption in each side of the roof. The following two equations are the approximate projection areas of the roof in South and North directions respectively.

\[
S_s = \frac{1}{2} \sum_{i=1}^{k} (z(u_i, w_j) - z(u_i, 0)) \Delta u \mid p = \arg \max_{z(u_i, w_j)} (9)
\]

(15)

\[
S_n = \frac{1}{2} \sum_{i=1}^{k} (z(u_i, w_j) - z(u_i, 1)) \Delta u \mid p = \arg \max_{z(u_i, w_j)} (10)
\]

(16)

These equations can be explained by looking at Fig.2. For example, the sub-regions whose central points are as shown in the dotted line in Fig.2, the projection areas of these sub-regions on the South and North can be calculated by the product of the uniform interval and the difference between the maximum elevation of these sub-regions and the boundary in the South and North of the surface respectively.

The projection areas of the surface on the East and West can similarly be obtained.
3. Method description

3.1 Outline of the model

A three-dimensional Curved Roof Surface Model (CRSM) established by Aoki (2002) is utilized to evaluate CO₂ emission of a roof (Fig.3.). We assume CRSM to be designed for a two-storied WDH, whose body shape, materials and structure (Udagawa, 1985) are fixed in Tokyo, Japan. An outline of the house is shown in Table 1. To clarify which kind of roof shape, and what the performance of green lawn on minimizing CO₂ emission are, CRSM is defined as a 4×4 grid mesh (Fig.4a). Each grid is divided into m×n intervals (Fig.4a). We assume that the coordinates in X- and Y-directions of all the nodes are fixed, while along the Z-direction the nodes are moveable. By changing the Z-coordinate of each node, we can modify the roof shape (Fig.5.). The surface material of each cell is either tile or green lawn. The number of cells covered with either of the materials depend on genes’ selection.

3.2 The LCCO₂ calculation

We select annual LCCO₂ emission per m² from the roof (Tg) as an evaluation function. Total Tg is calculated by Eq. (17):

\[
T_g = T_{g_b} - T_{g_g}
\]  
(17)

Tgb: CO₂ emission from building parts
Tgg: CO₂ absorptions by green lawn

3.2.1 The Tgb calculation method

To calculate Tgb, we consider a roof to have the following components: finish, substratum, insulation and structure. Materials and dimensions of each component are defined to be the same as a conventional WDH (Sui et al., 2003). When heat conduction in the roof occurs, heat loss will happen at the same time. It is not only because of the materials isolation, but also because of some quantity of heat detained in the roof materials. Roofs of similar materials have the same heat loss per m² of roof surface area. For simplification, the neglect of heat loss detained by materials is introduced. This means that we assume that there is no heat lost in materials in heat flow through the roof.

The calculation methods of Tgb is illustrated in Sui (2004). We give the formula as follows:

\[
T_{gb} = (T_{g1} + T_{g2} + T_{g3} + T_{g4} + T_{g5} + T_{g6})/1f + T_{g7})/Sf
\]  
(18)

where,

Tg1: CO₂ emission from building
Tg2: CO₂ emission from materials production
Tg3: CO₂ emission from the framework construction
Tg4: CO₂ emission from recycling and scraping
Tg5: CO₂ emission from transporting materials
Tg6: CO₂ emission from transporting waste
Tg7: CO₂ emission from operation
Tgb: CO₂ emission from building parts
1f: Years of effective usage of the body
Sf: Gross floor area

Table 1. Outline of Detached House

| Location     | North-south |
|--------------|-------------|
| Direction    | Timber frame, two-storied |
| Floor        | 2.7m |
| Gross floor area | 128m² |
| Ratio of windows-floor | 0.158 |
| Area Ratio of 2nd floor to 1st floor | 1 |
| Ratio of south-east side length | 1 |
| Life span    | 24 years |

While calculating Tg7 (CO₂ emission from operation), meteorological data of Tokyo in four typical days are utilized to calculate solar energy absorption by roof shape (Table 2.) (Takeda et al., 2004). Direct radiation of the sun is considered in this paper. Furthermore, we assume that the weather on a given day is clear, irradiation time is from 8 am to 4 pm every day. The suns altitude and azimuth angles affect solar energy absorption and we take this into account (Fig.6). The following are the equations utilized to calculate the average height (Hs), zenithal angle (A), hour angle (τ) of the sun:
\[
\sin H_s = \sin \phi \sin \delta + \cos \phi \cos \delta \cos \tau, \quad (19) \\
\sin A_i = \cos \phi \sin \tau, \quad \sec H_s, \quad (20) \\
\cos A_i = (\sin H_s \sin \phi - \sin \delta) \sec H_s, \quad \sec \phi, \quad (21) \\
\]

where,

- \( H_s \): Height of the sun in space of time \( i \)
- \( A_i \): Zenithal angle of time \( i \)
- \( \phi \): Latitude [deg]
- \( \delta \): Longitude [deg]
- \( \tau \): Hour angle of time \( i \)

### 3.2.2 The \( T_{gg} \) calculation method

We assume that green lawn covering the roof is sedums, with plant grown throughout the four seasons. The thickness of sedums is less than 30cm (Fig.7.) and water in the artificial soil is sufficiently supplied throughout. It consists of 6 layers: (1) sedums, (2) artificial soil, (3) planting mat, (4) retention and drainage board, (5) waterproofing, and (6) insulation. The technical details are shown in Table 3.

We calculate \( T_{gg} \) by Eq. (22):

\[
T_{gg} = \sum n T_{gc} \quad (22) \\
T_{gc} = V_{gc} \times S_{gc} \times \theta_{gc} \times h \quad (23)
\]

where,

- \( T_{gc} \): Total CO\(_2\) absorption by the green lawn
- \( T_{gc} \): Numbers of roof green cells
- \( V_{gc} \): Velocity of photosynthesis
- \( S_{gc} \): Area of a roof green cell
- \( \theta_{gc} \): Included angle between a normal cell \( i \) and sunlight
- \( h \): Irradiation time

Thermal conductivity (R) of a roof is an important factor, which has an influence on CO\(_2\) emission from air conditioning. R-value in this paper differs depending on the type and the covered area of different materials on the roof. If the roof is fully covered with tile or green lawn, R-value can be calculated easily. The calculation methods are the same as those used by Yada (1999). If the roof is covered with tile and green lawn at the same time, we calculated the R-value by the following equation.

\[
R = (S_{rt} / S_{rg}) \times R_r + (S_{rg} / S_{rt}) \times R_g \quad (24)
\]

where,

- \( S_{rt} \): Area of the tiled roof
- \( S_{rg} \): Area of the green lawn roof
- \( R_r \): Ratio of thermal conductivity of the tiled roof
- \( R_g \): Ratio of thermal conductivity of the green roof

### 4. GA Simulation

Based on the assumptions made above, we apply the evaluation computation with Genetic Algorithms (GA) for optimization to find optimal roof shape with minimum LCCO\(_2\) emission. We encode the Z-coordinates of nodes and material of cells as genes, the string is shown in Fig.8. Forty one genes are applied by the GA program. We assume that the domains of the Z-coordinates of nodes are from 0m to 3m, and each gene has four levels. The genes of

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**Table 2. Meteorological Data of Tokyo**

| Seasonal data | Winter Solstice | Summer Solstice | Autumn Equinox | Spring Equinox | Average |
|---------------|----------------|----------------|---------------|---------------|---------|
| Atmosphere transparency | 0.8 | 0.63 | 0.68 | 0.74 | 0.71 |
| Direct irradiation on normal plane (Mj/m\(^2\).D) | 11.8 | 6.7 | 7.1 | 11.7 | 9.3 |

**Table 3. Information of Green Lawn**

| Layers of the green lawn | Thickness: \( d \) (m) | Thermal conductivity: \( \lambda \) (w/mk) | Thermal coefficient \( R = \lambda / d \) (m\(^2\)k/w) |
|--------------------------|------------------------|------------------------|------------------------|
| Sedums                   | -                      | -                      | 0.04                   |
| Artificial Soil          | 0.3                    | 1.16                   | 0.25                   |
| Planting mat             | 0.001                  | 0.3                    | 0.003                  |
| Retention and drainage board | 0.1              | 0.3                    | 0.333                  |
| Insulation sheet         | 0.006                  | 0.19                   | 0.032                  |
| Waterproofing sheet      | 0.008                  | 0.19                   | 0.042                  |
| Total                    | 0.415                  | 2.14                   | 0.7                    |

---
the cells materials have two alleles, namely, 0 and 1. If 0 is selected, it means that the cell material is tile, otherwise it is green lawn. Different roof shapes and different covering materials vary LCCO₂ emission from the roof. Relying on the analysis program of the optimization iteration process (Fig.9.), we can find optimal roof shapes with minimized LCCO₂ emission. The initial conditions of GA operations are:

- Total Trials = 40,000
- Population Size = 200
- Crossover Rate = 0.6
- Mutation Rate = 0.001

The method of crossover utilized in this paper is the same as that proposed in Genesis Version 5.0 (John, 1990).

The results obtained from the analysis program will be translated and plotted in MATLAB Version 6.0 (The Math Works).

We execute two simulation steps in the optimization process: In step one, we have an evaluation on TRS. The purpose of this step is to make clear which kind of TRS is effective in minimizing LCCO₂ emission. In step two, materials of cells are selected by genes: tile or green lawn. This is to clarify which kind of roof shape and which material is efficient in reducing LCCO₂ emission. We then make a comparison between TRS and GRS based on the same assumptions. We made the comparisons in two settings: one is to fix the four corners of the roof, and the other to fix the nodes on the boundaries.

5. Results and Discussions
5.1 Results of step one
We fix the four corners of the roof and apply the GA program for 4×10⁴ times to search for the optimal solution of TRS. Fig.10. is Best-so-far fitness vs. genes of TRS evaluations, the values of CO₂ emission are stable after generation 474. Fig.11. shows the transition of optimum individual generations. We found that TRS becomes a flat-roofed as the genes changed. Finally, we obtained a perfectly flattened roof: Solution One (Fig.12.). The result can be explained thus: With TRS, the roof area is the dominant factor influencing the LCCO₂ emission; the smaller roof area can not only decrease the amount of materials used, but also mitigate loads from sunshine and heat loss. The minimum value of LCCO₂ emission in all roof shapes of TRS is 3.74 (kg-c/m²·y). Since we obtain a flat roof shape when 4 vertices are fixed, there is no need to check cases when nodes on the boundary of the roof are fixed.

5.2 Results of step two
At the initial stage of step two, we fixed 4 corners of the roof and let the genes modify the roof shape and select materials for each cell to search for the optimal solution for minimized LCCO₂ emission. We applied the GA program for 1×10⁴ times, and found that from generation 78, value of CO₂ emission becomes constant. Therefore, we assume it is the optimal solution. Fig.13. shows the Best-so-far fitness vs. genes of GRS evaluations. We found that as generations varied, GRS are selected. Moreover, the values of LCCO₂ emission become lower and lower and even negative, while on the contrary, areas of the roof become larger and larger, and the Z-coordinates of all nodes (except for the 4 fixed nodes) become the highest levels. Finally, the roof shape became a perfect arch in the E-W direction and was fully covered with green lawn: Solution Two (Figs.14., 15.). The value of LCCO₂ emission is -6.18 (kg-c/m²·y). We show the transition of optimum individual generations in Fig. 16.
Fig. 17. shows the average irradiation time in four azimuths in Tokyo. The irradiance time of the South is the biggest, and the total irradiation time of the South and North are bigger than that of the East and West at all times. Since solar absorption has much impact on air-conditioning running loads, if loads from solar radiation are always larger in the summer than winter. This means that solar irradiation should be avoided, especially in the directions which have longer irradiation times. Namely, we should decrease roof area on the South and North. This is the reason why optimal roof shape in 4 fixed nodes cases is an arch in the W-E direction. In this case, the roof area in the W-E is maximized, which minimizes the area in the South and North become minimization in the meantime, leading to a lower load from air conditioning.

Also, we found that from generation 20 the roof cells are fully covered with green lawn, resulting in the green lawn area becoming bigger and bigger. This means that it is not the roof area that is the dominating factor which influences LCCO₂ emission, but the green lawn. Even when the roof area becomes larger and larger, causing the Tₐ to increase, the Tₛ still decreases. The reasonable explanation is that Tₐ is a dominating factor. Moreover, the larger the roof area is, the larger the Tₛ is. This could explain why the Z-coordinates of all nodes reached the maximum levels.

At about 5×10⁴ times of operation, we obtained the optimal roof shape when roof boundaries were fixed. It is a perfect dome: Solution Three (Fig. 18.). The transition of the optimum individual of generations is shown in Fig. 19. Value of LCCO₂ emission is -1.08 (kg·c/m²·y). The same reason is applicable to explain the results when 4 corners were fixed.

6. Conclusions

This paper has developed a method to find the optimal roof shape for minimum LCCO₂ emission. Based on analyses above, it could be concluded that:

(1) If the roof is TRS, the roof area is the main factor to decide LCCO₂ emission from the roof shape. The flat roof is more efficient in reducing LCCO₂ emission than other tiled roofs.
(2) If the roof is GRS, when its four conners were fixed, an E-W arch resulted to minimize LCCO$_2$ emission. When the bounderies of the roof shape are fixed, a perfect dome is the optimal solution.

(3) The performance of green lawn on CO$_2$ absorption was tested. The roof with green lawn is more efficient in reducing LCCO$_2$ emission than the tiled roof. The LCCO$_2$ value of the most efficient GRS (Solution Two) is 10 (kg-c/m$^2$.y) less than that (Solution One) of TRS.

7. Future study

We have studied the relationships between roof shapes and LCCO$_2$ emission considering green lawn, and have found the efficient roof shapes reduce LCCO$_2$ emission. By applying a CRSM, we obtained our results based on the assumption that the coners and boundaries of roof shape are fixed respectively. In later studies, we should consider also other shapes and the performance of elements such as wall shape, window shape, etc. on LCCO$_2$ emission. Furthermore, as this paper is the initial step in our research, some bold simplifications have been assumed in the setting of boundary conditions when calculating LCCO$_2$ emission, such as heat flow through the roof that critically influences the air conditioning load of buildings. More complex cases should be studied in the future as well.

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Fig.19. Transition of Optimum Individual of Generations

Generation 2
Generation 5
Generation 14
Generation 32