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A Hybrid Approach of Dynamic Programming and Genetic Algorithm for Multi-criteria Optimization on Sustainable Architecture design

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ABSTRACT

This paper proposes a method to find heuristic solutions in early decision stages for sustainable building design. This method integrates dynamic programming and genetic algorithm into the design workflow, by separating design criteria into three decision stages to reduce the complexity. In each stage, the designer setups parameters related to sub-criteria and objective functions to optimize by Genetic Algorithm. Dynamic programming is used to guide the search and combine solutions for all stages. An actual project is used to test and demonstrate the proposed method. For implementation, we develop a parametric design system with Rhino, Grasshopper and HLGA to provide a graphical design environment, in which heuristic solutions for each decision stage are found and combined.

Keywords: dynamic programming, genetic algorithm, sustainable architecture design.

1. INTRODUCTION

Sustainable building design is a growing global issue. One of its most important goals is energy efficiency over the entire life cycle of buildings. Design decisions for sustainable buildings are often concerned with a large set of decision variables and multiple criteria so complex that can hardly be resolved at once. Genetic Algorithms have been demonstrated to solve multi-objective optimization problems [7] and consistently get close to the best. Bouazara and Richard studied three types of suspension system (active suspension, semi-active suspension and passive suspension) for an eight-degree of freedom vibration control of a 3-D vehicle model [3]. In this research, Bouazara combined all criteria into one objective function for a single-objective optimization. For this requirement, he used weighting coefficients to adjust different criteria in the single-optimization design process. This weighting methodology optimization is so called Hajela-Lin Genetic Algorithm. The evident research showed the optimization of application using Genetic Algorithm to find optimum. However, GA requires tens of thousands of simulations to converge to the global optimal [8], yet multi-criteria GA will take more.

And it is widely acclaimed that the most important design decisions concerning building sustainability have to be made in the early design stages by the architect or building designer [15]. In this stage, an architect also has to consider other aspects, such as regulations, views, construction cost, and so on. Therefore, an architect has to comprise all diverse decisions to find the possible optimal solution. However, most of the researches for sustainable architecture design only concerns closely related issues. Chen Kain Wee proposed a design method for multi-criteria optimization of low energy architecture by using GA in the early design stage [5]. His research focuses on the exploration of holistic low exergy design on passive and active system with only energy related issue. In this paper, we propose that those diverse criteria could be separately optimized by GA and re-structured in several stages by dynamic programming workflow formulation.

2. THE HYBRID APPROACH

The re-structured method is a hybrid approach of Dynamic Programming and Genetic Algorithm for multi-objective optimization on sustainable architecture design. Based on the main concept of dynamic programming [13], this hybrid approach breaks down multiple criteria into subsets for some decision stages, and uses HLGA to evaluate and optimize design decisions based on sub-criteria. Then combining the solutions of sub-criteria reach overall possible optimal solutions. The relationship between

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sub-criteria could be defined by the formulation of design workflow at an architecture project in early design stages. This hybrid design approach is divided by two structures: one is the design workflow and another is sub-criteria stages.

2.1. The Structure of Decision Workflow

In an architectural design project, designers break down the process into stages, in which the design problem is divided into sub problems consisting with subsets of design variables and criteria according to the decision workflow. Each subset of design variables is resolved in their corresponding design stage. Let $\boldsymbol{n}$ be the number of decision stages. Within each stage we should consider all possible states of the sub problem. An input state describes the state of the system before the operation of the stage, and an output state describes the state of the system after that stage. Therefore, the output state provides all the information about design variables that is necessary for the next stage. The value of this variable provides the information as a *state variable*, and denotes the output states from stage n by $\boldsymbol{X_n}$. At each stage, the added structural component should be defined with some design decisions and its relationship to the partial decision before it was added, whose total cost should be minimize for the set of components considered so far. The variables we can control as design decision are known as *decision variables*, and the decision variables at stage n are denoted by $\boldsymbol{D_n}$. The additional cost of stage n is known as a stage return and it is denoted by $\boldsymbol{R_n}$. In summary, the dynamic programming terminology has the following variables at stage n:

1. n is the current stage.
2. Input states, X_{n-1} (No input state, when this is the first stage).
3. Output states, *Xn*.
4. Decisions, *Dn*.
5. Stage returns, *Rn (Xn, Dn)*

The optimal return at stage n will be given by

$$f_n(X_n) = opt(R_n(X_n, D_n) + f_{n-1}(X_{n-1})) \tag{2.1}$$

When we adopt HLGA into Dynamic programming, its terminology changes as described in next section.

2.2. The Sub-criteria Stage Structure

In each stage, the sub-criteria could be reduced to one or two. The designer setup parameters only related to sub-criteria and object functions to optimize by HLGA. Hajela-Lin Genetic Algorithm makes use of weighted-sum aggregation of multi-objective function to search for a set of optimal solution [16]. Each objective is a weight $\boldsymbol{wj} = [0,1]$ for the jth objective such that $\Sigma wj = 1$, and the scalar fitness value for an individual i is calculated by summing up the scaled weighted objective values as given below:

$$\mathrm{Fit(i)} = w_j.{*}\mathrm{Fj(i)/Fj} \tag{2.2}$$

where F_j is a scaling parameter for the j the objective, which needs to be chosen properly for each objective F_j in order to cater for the difference in magnitudes for various objective function.

In each stage, the front stage's states are the input condition of the back stage. That is, the search space of current stage will be limited by the front stage. In fact, this is our strategy to reduce all multi-criteria into sub-criteria, that is, following the sequence of stages, the sub-criteria will integrate all multi-criteria at final stage. In summary, this hybrid approach could be defined as follows:

1. n is the current stage.
2. Input states, X_{n-1} (No input state, when this is the first stage).
3. Output states, X_n as possible optimal Set generated by GA in objective function F_j.
4. Decisions, D_n as scaled weighted $F_n(X) = w_j * F\ n_j(X)$, a weight $w_j = [0,1]$ for the jth objective function F_{nj} such that $\Sigma w_j = 1$.
5. Stage returns, R_n (X_n, D_n).
6. The optimized result in each stage will be given by:

$$\begin{aligned} f'(X_n) &= (R_n(X_n, D_n), F_{n-1}(X_{n-1})) \\ &= (F_n(X_n), F_{n-1}(X_{n-1})) \\ &= opt(w'_{j'} * F_{nj}(X_n) + w'_{j-1} * F_{nj-1}(X_{n-1})), \\ &\quad \text{where} \quad \Sigma w'_j = 1 \end{aligned} \tag{2.3}$$

3. DEMONSTRATION

An actual project is used to study the proposed approach. It is the design of a public apartment in a subtropical region, Taipei Taiwan (as indicated in Fig. 1), for which the environmental impact, sustainability and construction cost efficiency have been set as the objectives in the planning phase. The site of the project is in a special condition that this new building might affect the nice view towards open spaces of some neighboring apartments; and in the meantime, the architect would also seek for the best possible view for the apartment units of this new building. The government hopes that this public apartment should meet both the low-energy consumption and low construction cost criteria.

There are several design features can affect the energy efficiency of building. In public works, Wang et al. [18] presented a multi-objective optimization using economical and environmental performance to select the orientation, the wall type, window type and roof type. Ouardghi and Krarti [12] have examined

Fig. 1: The drawing on the left is the site location and surrounding land use. The picture on the right shows the current status of the project site.

optimization of the office building form as function of building envelope features including wall and roof construction, window-to-wall ratio, and glazing solar heat gain coefficient. The optimization method uses Genetic Algorithm, and optimizations were performed for energy cost, as well as for combined construction and energy costs. Caldas and Norford [4] developed a design methodology for optimal control of chiller systems that minimized annual energy use, at same time, exploring the tradeoffs between heating, cooling and lighting. In this research, the optimization considered selected features of building envelope including window type, window area, and, wall type.

The most important goal for sustainable architecture design over environmental concern is energy efficiency as mentioned in the introduction paragraph. The energy associated with buildings includes the operational energy and the construction energy. The construction energy is known as the embodied energy [14]. However, for the consideration of the construction cost from the government, this issue will be not discussed in this project. The operational energy is the energy used to heat, cool, ventilate and light the building, provide hot water, and run appliances and equipment. Minimizing energy needs on these sustainable strategies is the target for this project.

Through a series of discussion with the design team, the design workflow of the project was studied and adopted as a three-stage decision process as well as the decision criteria in each stage. At the front stage, the shape and orientation of the building mass are decisions to be made, with the objectives based on the view criteria of the neighboring and own apartment units. In the middle stage, the window wall ratio (WWR) and the energy-related issues are to be decided based on the very likely conflicting criteria of building energy consumption and opening for natural lighting. The higher WWR increases natural light and decreases the demand for artificial lighting. It also increases the energy consumption for the incoming solar radiation through opening. To minimize the energy consumption, the materials and construction types of walls, floors and roofs, windows and cooling systems will be considered. This site is located in the subtropical zone and only cooling systems will be used. As for the back stage, construction materials are the decision variables to find a balance between construction cost and energy consumption.

3.1. Reference Building

In this research, we choose the Building American Research Benchmark model for the reference building [9]. The benchmark model specifies all related features for residential buildings, including the characteristics of envelope, HVAC system, schedules and internal loads. The specifications of this benchmark vary by climate zone. In order to mapping climate zone for our site, Taipei Taiwan, we select the climate zone as 2 defined in ASHRAE Standard 90.1-2007 [1] by an energy research report for Asia area [10]. The shape of this model is defined as square (as Fig. 2 (a)) which should be the best performance shape and the

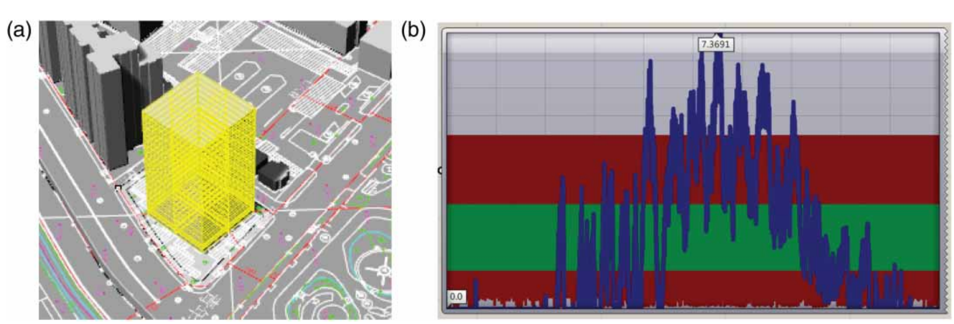

Fig. 2: (a): The shape of benchmark. 2(b): The result of energy simulation: It shows low cooling load (blue area) but high lighting load (red area).

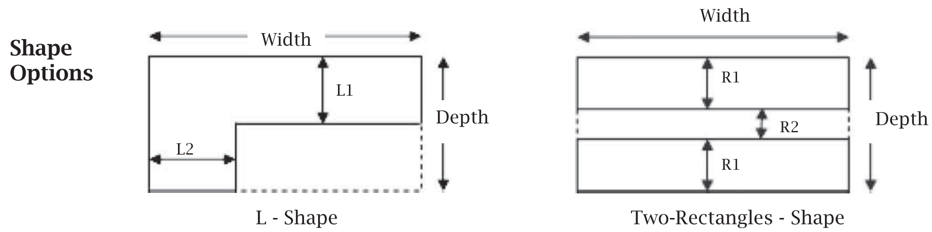

Fig. 3: Option for building shape.

result of energy simulation is the standard base (as Fig. 2 (b)) to compare.

3.2. Parameters of the Optimization-simulation

For the work presented in the paper, the Genetic Algorithm is used for the optimization-simulation, while a detail whole building simulation program, DIVA 2.0 is used for lighting, energy and cost analysis. All criteria as parameters for Genetic Algorithm for this project are presented below.

3.2.1. Shape and orientation-related parameters

Various building shapes are investigated in the optimization process. To meet the two best view criteria, the designer selected L-Shape and two parallel rectangles as in Fig. 3. Parameters for shape as width and depth define the boundary limit of each shape and other two parameters are shape-specific. Other parameters are the direction of orientation and the square measure of the shape reaching the maximum of building coverage rate.

3.2.2. Lighting and Energy-related parameters

There are reports stated that daylight-illumination methodologies had the potential for significant energy savings in building. Bodart and De Herde estimated that the appropriate daylight design could reduce artificial lighting power costs from 50 to 80%. However, operating the air conditioning system to compensate for the heat produced by the lighting shows a significant proportion of the total building cooling load during summer months [2]. The research on the both thermal and lighting issues found that optimum WWR resulted in significant energy saving (more than 50%) for heating, cooling and lighting [11]. The WWR parameter on each face of facade has different value owing to the solar radiation by considering the effect of the local climate. This parameter applies on cell unit for each tenant in two types of shape (Fig. 4).

According to the energy research by Caldas and Norford [4], the parameters for optimization-simulation could be categorized in several aspects, including building shape, glazing type, glazing area, and wall construction. In our research, we add roof construction and infiltration for considering the factor of subtropical climate protecting the heat conduction from roof by solar radiation and add natural ventilation for cooling by considering infiltration design flow rate when HVAC does not operate and/or driven by wind and forced air for times when HVAC system operates. We adopt DIVA 2.0 for lighting and energy simulation, which allows the modeling of single-zone thermal models using EnergyPlus and lighting using DAYSIM. Tab. 1 shows the energy related parameters except building shape and orientation.

3.3. Constraints on the Dataset of Parameters

Constraints stipulate the conditions that need to be satisfied by the dataset of parameters in different stages. According to the features of involved parameters, constraints can be categorized into box constraints and selection constraints. These constraints are described below.

3.3.1. Constraints on the Dimension and the orientation Angle of shape

The width and depth of two shape options all limit by the dimension of the building lot offset by 3 meters

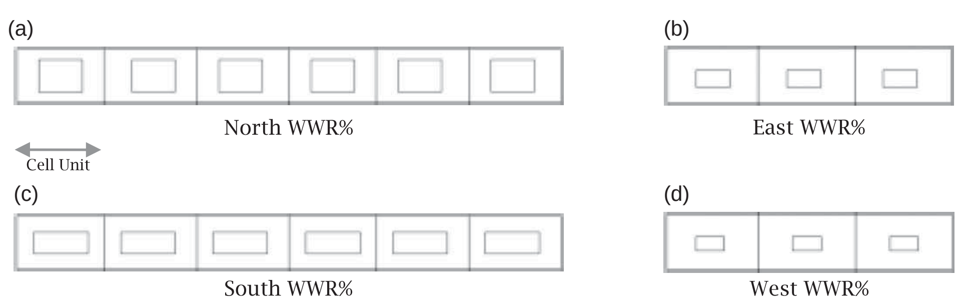

Fig. 4: Layout concept of cell unit with different WWR on each face of facade.

Glazing type	Wall construction	Floor mass	Roof insulation	Air-conditioner COP
Double Low-E Tint 6 mm/13 mm Air	15 cm Concrete + 2″ PS (insulation)	15 cm Concrete + 1″ PS (insulation)	15 cm Concrete + 4″ PS (insulation)	5
Laminated glass w. standard SHGC	15 cm Concrete + 1″ PS (insulation)	15 cm Concrete (no insulation)	15 cm Concrete + 2″ PS (insulation)	4
Single clear 6 mm	15 cm Concrete (no insulation)		15 cm Concrete (no insulation)	3

Tab. 1: Energy related Parameters.

from the building line. However, to satisfy the maximum of floor area ratio, once the depth of shape is decided then the width of shape will be stipulated by the maximum floor area calculated by floor area ratio. In this site, owing to the requirement of the minimum depth of the room, the depth of shape will be decided firstly and the box constraint corresponding to that parameter is 1200 cm ≦the depth of shape ≦ 2900 cm. Therefore, the width of the shape will be as equation (3.1).

$$\text{width of shape} = \frac{\begin{array}{c}\text{the area of building lot offset}\\ \text{by 3 meters} * \text{floor area ratio}\end{array}}{\text{the depth of shape}}. \tag{3.1}$$

The orientation angle at the center of shape will be limited by the rotated shape which should be bounded inside the building lot.

3.3.2. *Constraints on WWR and Energy-related dataset of parameters*

The minimum WWR in each cell unit is stipulated by the Taiwanese building technical regulations. In summary, the box constraint for this parameter is 0.3 ≦ WWR ≦ 0.9. In the building energy simulation part of DIV 2.0, the weather data is specified by the annual local weather data collected from the Taiwan Central Weather Bureau and the simulation period is one year. The dataset of energy related parameters list in table 1 are selection constraints by the Construction Cost Data of Taiwan [7] and also limited by ASHRAE Standard 90.1-2007 [1].

3.4. Optimization Procedure

In each stage, criteria are optimized by Hajela-Lin Genetic Algorithm (HLGA) as described in section 2.2. This optimization procedure combines the Grasshopper Genetic Algorithm tool - Galapagos and scaled sum of weighted objective functions. The flowchart diagram for this HLGA is shown as Fig. 5.

For the case study, Genetic Algorithm (Galapagos) is used as follows:

1. A population of 100 is randomly generated by assigning random parameter values from the constraint dataset of parameter model.

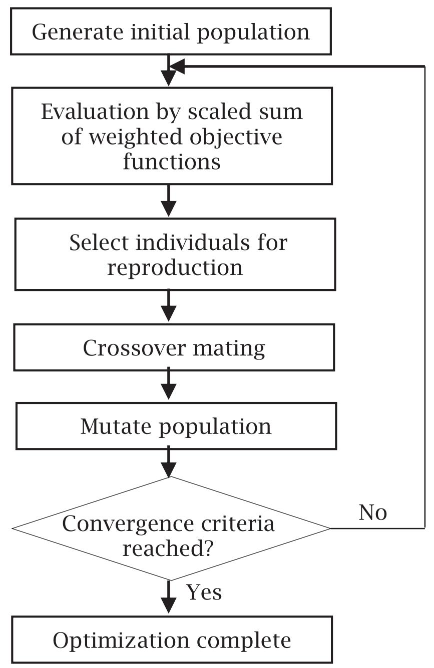

Fig. 5: Flowchart diagram for HLGA.

2. Each population is evaluated by maximum of the scaled sum of weighted objective functions.
3. A sub population of 75 is generated from the combining of the best 5 design alternatives from last generation. Remaining population of 25 is generated by random crossover and mutation .
4. The cycle repeats from step2, and stops after the population converges.

3.5. Evaluation of the Optimization-simulation

The criteria of Genetic Algorithm at different stages have different objective functions for finding the possible optimal solutions. They are summarized by our hybrid method to find the overall possible optimization. The different objective functions at each stage are defined as below:

3.5.1. *Maximum area of visual view*

At the first stage, based on the shape and orientation parameters of the new building, the objective function for best possible view for both neighborhood and this new building is defined as equation 3.1 and

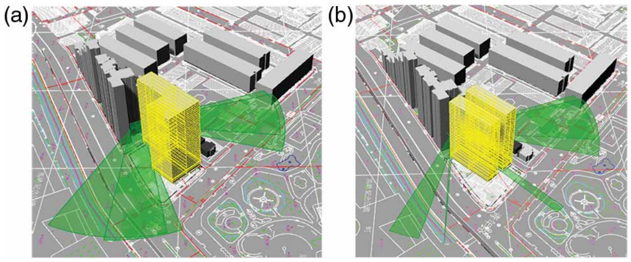

Fig. 6: Green area shows: (a) Visual view of neighborhood of L-Shape. (b) Visual view of neighborhood of Two-Rectangles Shape.

shown as Fig. 6.

$$F_{11} = \text{Max Visual View Area}_{\text{ neighborhood}}$$

$$F_{12} = \text{Max Visual View Area}_{\text{ new building}}$$

The first stage return function is defined in equation (3.1).

$$F_1 = 0.5F_{11} + 0.5F_{12}, \text{ where } w_j = 0.5 \forall j \in \{1, 2\} \quad (3.2)$$

3.5.2. *Maximum daylight and Minimum Energy cost*

At the second stage, two conflicting criteria of maximum daylight-illumination and minimum energy cost should be conformed at same time. According to Taiwan Building Technical Regulations, the minimum requirement of illumination is 300 Lux, therefore, the floor area receiving over it would be calculated by DIVA/DAYSIM lighting simulation. The objective function for lighting is described as below and shows as Fig. 7:

$$F_{21} = \text{Max}\frac{\text{Area}_{\text{ lux}>300}}{\text{Area}_{\text{ floor}}} \quad (3.3)$$

Daniel [17] and Ouarghi [12] use the relative compactness (RC) to evaluate the energy cost basing on benchmark building. Relative compactness is defined in equation (3.3)

$$RC = \frac{(V_{As})_{\text{ building}}}{(V_{As})_{\text{ reference}}} \quad (3.4)$$

where; RC = relative compactness; V = volume of building; As = surface area of building

Since the floor area and height of all the buildings are the same, then equation (3.3) could be reduce to equation (3.4)

$$RC = \frac{(A_S)_{\text{ building}}}{(A_S)_{\text{ reference}}} \quad (3.5)$$

The object function for energy cost is defined in equation (3.5):

$$\frac{\text{Total Energy cost}_{\text{ building}}/(A_S)_{\text{ building}}}{\text{Total Energy cost}_{\text{ reference}}/(A_S)_{\text{ reference}}}$$

$$\Rightarrow \frac{\text{Total Energy cost}_{\text{ building}}}{\text{Total Energy cost}_{\text{ reference}}} * \frac{1}{RC}$$

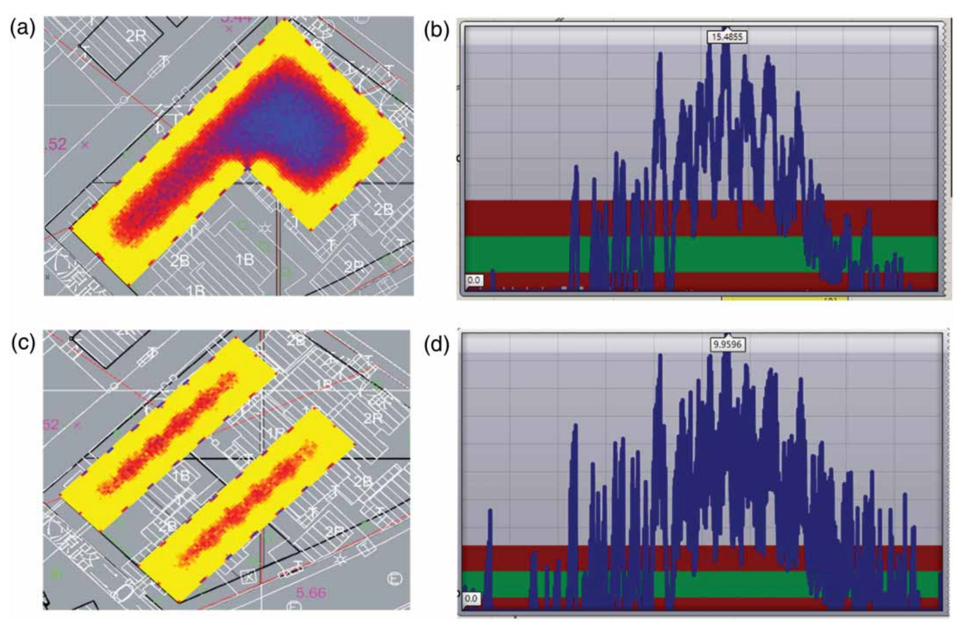

Fig. 7: (a) Lighting simulation result of L-Shape (b) Total energy consumption simulation result of L-Shape (c) Lighting simulation result of Two-Rectangles Shape (d) Total energy consumption simulation result of Two-Rectangles Shape.

Materials	Cost $/m^2$	Materials	Cost $/m^2$	Air-conditioner COP $/piece	Cost $/piece
Double Low-E Tint 6 mm/13 mm Air	4200	4″ Polystyrene (PS)	330	5.0	30,000
Laminated glass w. standard SHGC	1100	2″ Polystyrene (PS)	660	4.0	20,000
Single clear 6 mm	400	1″ Polystyrene (PS)	1320	3.0	15,000

Tab. 2: List of material and equipment cost.

$$F_{22} = \text{Max}\frac{\text{Total Energy cost}_{\text{building}}}{\text{Total Energy cost}_{\text{reference}}} * \text{RC} \qquad (3.6)$$

The second stage return function is defined in equation (3.6).

$$F_2 = 0.5F_{21} + 0.5F_{22}, \quad \text{where} \quad w_j = 0.5 \forall j \in \{1, 2\} \qquad (3.7)$$

Total energy cost is simulated by DIVA/Energyplus with construction material options and benchmark building settings as shown in Fig. 7.

3.5.3. Minimum construction cost

Seeking the minimum energy cost is most likely increasing construction cost, since construction and equipment cost should be compensated from saving from reduced energy consumption. At back stage, finding a minimum cost function to balance these conflicting criteria is to couple an optimization function by object functions. One object function is the construction cost listing in Tab. 2 obtained from construction cost data [6] and cooling equipment cost data shown in Tab. 2. Second object function is the accumulative annual electric cost for 5- year rent contact. The coupled optimization function is shown below:

$$F_{31} = \text{Min construction cost}$$

$$F_{32} = \text{Min Electric cost}$$

The back stage return function is defined in equation (3.7).

$$F_3 = 0.5F_{31} + 0.5F_{32}, \text{ where } w_j = 0.5 \forall j \in \{1, 2\} \qquad (3.8)$$

4. RESULT AND DISSCUSION

4.1. Optimal Shape – The Front Stage

The GA ran for 49 generations for L-Shape and ran for 79 generations for Two-Rectangles-Shape. The optimal L-shape is not L-Shape anymore; the simulation result is a rectangle as Fig. 8 (a). The result also shows that the shape for the best view of both the neighborhood and new building is aside the boundary and no orientation to maximize the range of visual view for residents. However, the optimal simulation of Two-Rectangles shapes didn't converge and the

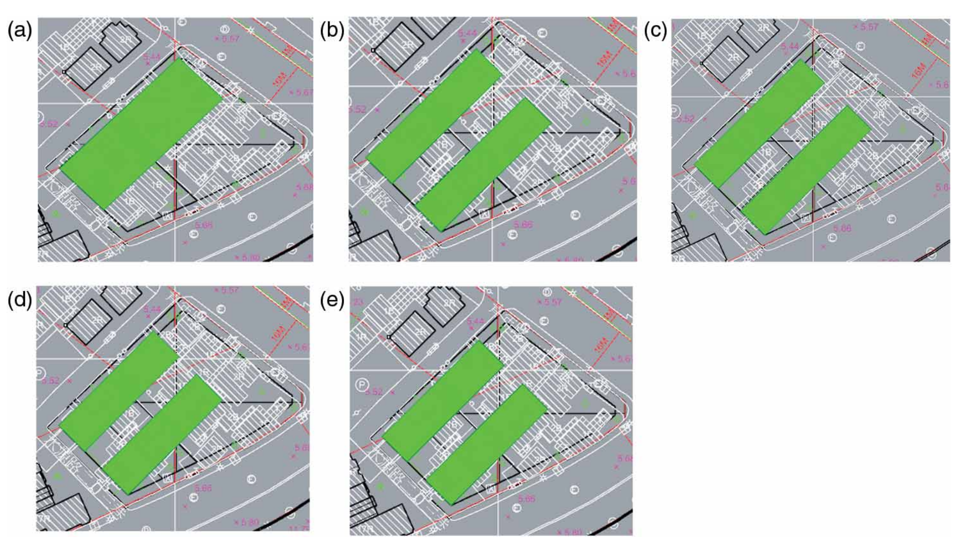

Fig. 8: Shapes for (a) optimal L-Shape and Two-Rectangles Shape for (b) gen. No.79 & 75 (c) gen. No.78 (d) gen. No.77 (e) gen. No.76.

Generation No.	Width	Depth	R1	R2
79	45	30	21	9
78	44	30	20.5	9.5
77	43	30	22.5	7.5
76	42	30	22	8
75	45	30	21	9

Tab. 3: List of .parameter value for Two-Rectangles Shape in the last 5 generations of GA-simulation.

diverse depths of rectangle were shown as Tab. 3 and Fig. 8(b) ∼ (e). The designer decided to use generation no.79 & 75 for the consideration of housing usage. Normally, GA (Galapagos) will converge in 20 generation. The one reason why Galapagos did not converge is that GA may have a tendency to converge towards local optima, when there are two similar local optimums found then it will hard to converge. This defect could be solved by increasing the mutation rate.

4.2. Optimal WWR and Energy Consumption – The Middle Stage

For shape types, there are optimal solutions found by GA simulation in 45 generations as Tab. 4. And the related lighting and energy consumption simulation are shown as Fig. 9.

According to the two simulation results for L-Shape, the bigger WWR value (L-Shape 2) needs better performance air-conditioner and could get less energy consumption than the smaller one. The Two-Rectangle Shape has bigger RC value then it gets higher energy cost ratio than L-Shape.

4.3. Optimal construction cost and energy consumption – the back stage

At back stage, the capital cost including construction cost and equipment cost will be optimized in minimum and balance with electric cost shown as Tab. 5. The GA ran for 39 generations at this stage.

The overall performance for alternative L-Shape shows that L-Shape 2 has better performance than L-Shape 1. L-Shape 2 has bigger opening than

Shape type	North WWR %	South WWR %	East WWR %	West WWR %	Air-conditioner COP	RC	Total energy cost ratio
L-Shape 1	40	20	30	60	4	1.1	1.137
L-Shape 2	60	50	50	60	5	1.1	1.05
Two-Rectangle-Shape	40	30	50	50	4	1.24	1.89

Tab. 4: alternative parameter values for L-Shape.

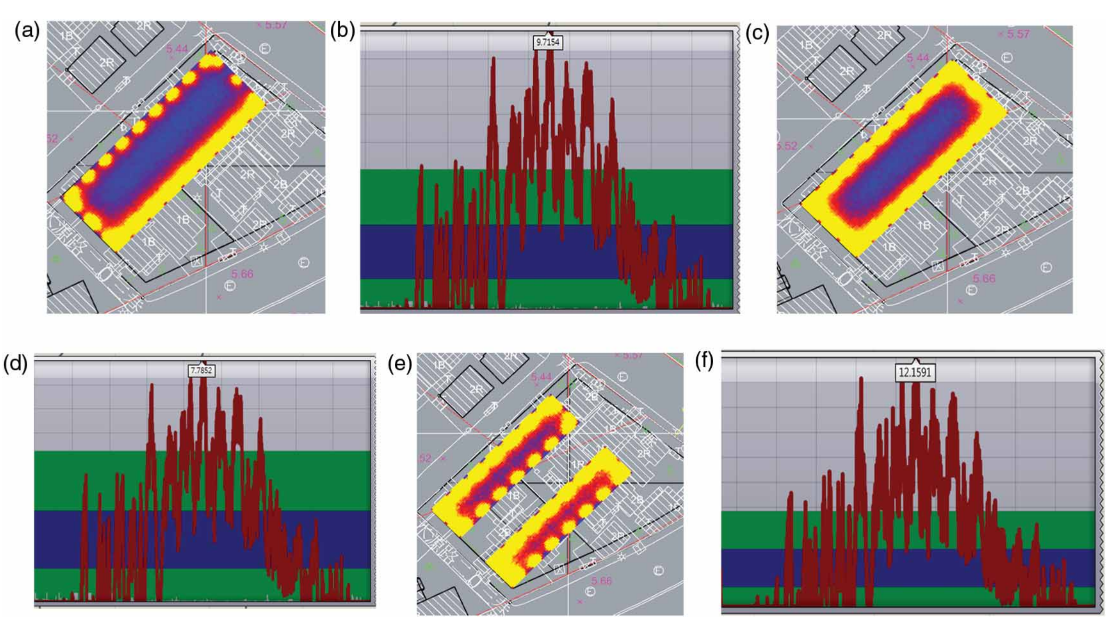

Fig. 9: (a) Lighting simulation result of L-Shape 1 (b) Total energy consumption simulation result of L-Shape 1 (c) Lighting simulation result of L-Shape 2 (d) Total energy consumption simulation result of L-Shape 2 (e) Lighting simulation result of Two-Rectangle-Shape (f) Total energy consumption simulation result of Two-Rectangle-Shape.

Shape.	Window	Wall	Floor	Air-conditioner cost	Capital cost /nt	Electric cost /nt
L-Shape 1	Double Low-E Tint 6 mm/13 mm Air	15 cm Concrete +1″ PS (insulation)	15 cm Concrete +1″ PS (insulation)	20,000	311,931,000	4,703,450
L-Shape 2	Double Low-E Tint 6 mm/13 mm Air	15 cm Concrete +1″ PS (insulation)	15 cm Concrete +1″ PS (insulation)	30,000	294,213,000	4,378,900
Two-Rectangle-Shape	Laminated glass w. standard SHGC	15 cm Concrete +1″ PS (insulation)	15 cm Concrete +1″ PS (insulation)	20,000	174,256,000	4,852,000

Tab. 5: List of cost for all shapes.

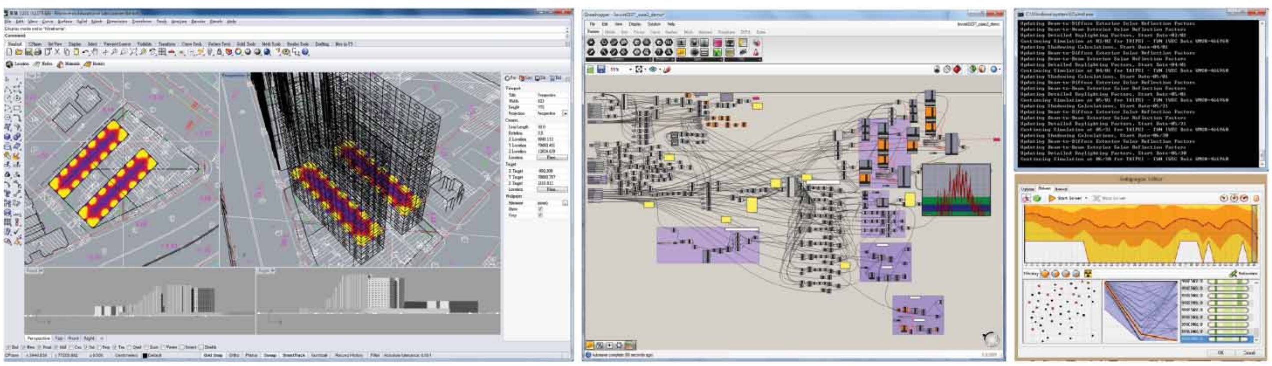

Fig. 10: The integrated system.

L-Shape 1, that is because it has better performance air-conditioner then it gets lower capital cost, energy cost and electric cost. Two-Rectangle Shape compares to L-Shape has smaller opening and cheaper window material then it gets much lower capital cost but only 10% higher electric cost.

In summary, the final list of optimal solutions provides the designer the critical information of performance simulation and analysis for different criteria in the parameterized design workflow. This visually informational workplace could reduce the overall complex problem to just only some optimal solutions. The integrated system is shown as Fig. 10.

5. CONCLUSION

This integrated computer-aided design system, not only provided the visual linkage between architecture model and the simulation result, which helps the designer to realize his design strategies, but also results with some heuristic proposals with critical information. However, this hybrid-integrated system takes an architect more efforts to understand some issues specific to the sustainability aspects. Therefore, this system provides a platform, upon which architects and sustainability expert may efficiently work together. The future work will focus on finding possible heuristic solutions instead of weighting-factor GA, we shall use pareto-optimal GA, which is a popular algorithm for multi-criteria optimization. Using weighting factor GA for two conflict criteria, it generates simple and easy readable optimized results, however, it has the bias factor owing to the value of weighting factors. Although, pareto-optimal GA could generate a set of pareto-optimal solutions without bias factor, it adds the difficulties for the designers to understand. Therefore, our future work also wants to overcome this problem.

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