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Optimisation of Low Exergy Architectural Design in the Tropics

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***Abstract**: This paper describes the process of designing and optimising low exergy architectural design in the tropical climate. The low exergy strategy used includes the separation of sensible and latent cooling and the use of Building Integrated Photovoltaics (BIPV) for the generation of electricity. Low exergy emission cooling systems such as radiant cooling panels and decentralised ventilation units are used. The radiant panels are responsible for the sensible heat gain, while the latent heat gain is handled by the decentralised ventilation units. The use of radiant panels has its limitation; if the sensible heat gain exceeds a certain limit the use of radiant panels might not be feasible. Thus, a certain quality of building envelope is required. These constraints amount to an architectural design issue where dependencies and interaction between the envelope design and building systems are considered. The paper proposes an iterative design process that involves the use of parametric modeling, simulation programs and optimisation techniques to help the architect to implement and explore possible design options. A case study is described to illustrate the process; the BubbleZERO laboratory facade design. The result of the design process will present to the architect a series of different designs that satisfy the chosen criteria. This will greatly aid the architect in making design decision during the design process.*

Keywords: Low exergy design, Parametric modeling, Performance driven design, Evolutionary algorithm in architecture design

1. INTRODUCTION

The current building stock account for a significant amount of global CO_2 emissions (Rogner, Zhou et al. 2007). It is important for the building sector to reduce the CO_2 emissions to minimise global warming. One of the major contributing components is the burning of fossil fuels to power the operations of the building systems. Thus, it is essential to reduce the energy consumption of building systems which is mainly caused by the heating ventilation and air conditioning (HVAC) system in order to reduce the CO_2 emissions, and substitute fossil energy source with renewables. The conventional low energy architecture design strategies try to achieve this objective by focusing on the use of passive systems. Low exergy design strategies take a more holistic approach by incorporating both the passive and active systems.

In thermodynamics, exergy is defined as the maximum work that can be obtained from an energy flow. It describes both the quality and quantity of an energy source. Exergy analysis is commonly used in the optimisation of power station to maximise the production of exergy. In recent years exergy analysis has been adapted for the analysis of energy consumption in buildings (Shukuya and Hammache 2002; Schmidt 2004). In the building case, the aim is to reduce the amount of exergy input to sustain a comfortable indoor environment for the users (Meggers and Leibundgut 2009). The exergy content of a heat flux moving out of an indoor environment of temperature and outdoor reference temperature:

$$Ex = Q(1 - (\frac{T_o}{T_i})) \qquad (1)$$

Where Ex is the exergy content of the heat flux and Q is the heat flux in Joules (J), T_o is the outdoor reference temperature and T_i is the indoor temperature in Kelvin (K). If Ti < To , Q refers to the heat rejected from the room and will be negative and (1-(To/Ti)) will be negative resulting in a positive exergy value (Jansen and Woudstra 2010). For a room of temperature 25°C and an outdoor reference temperature of 32°C the exergetic content needed to reject the heat is about 3%. The exergetic content of electricity is almost 100%. An exergy approach would be to reduce the use of high exergy energy source and substitute it with an energy source of appropriate exergetic content. The Building Systems Group at the ETH Zurich have extended the exergy approach and implemented exergy strategies in building projects. They integrated an array of low exergy systems to reduce the energy consumption. The key components of low exergy systems in temperate climates consist of heat pumps with ground boreholes, decentralised air supply units, P/V hybrid panels and radiant panels (Meggers, Ritter et al. 2011). An attempt to transfer the technology from the temperate climate in Zurich to the tropical climate in Singapore is carried out through the BubbleZERO research laboratory (Meggers, Bruelisauer et al. 2012).

2. LOW EXERGY DESIGN STRATEGIES IN THE TROPICS

The low exergy strategy tested in the bubbleZERO laboratory focuses on the separation of the latent and sensible cooling. Latent cooling is the dehumidification of air supply and it is an exergy intensive process compared to sensible cooling, thus it would be beneficial by separating the two processes. The sensible cooling process is the removal of heat generated from occupancy load, plug load and solar heat gain load. Through initial calculation there is a potential of up to 20% reduction in energy consumption. This is done with the use of the heat pump, radiant panels and decentralised ventilation technologies.

2.1 Heat pump (Chiller)

The heat pump moves heat from a cooler to hotter region. The efficiency of a heat pump is limited by the Carnot value of Coefficient of Performance (COP):

$$COP_{real} = g \times \frac{T_{hot}}{(T_{hot} - T_{cold})} \qquad (2)$$

Where g is the Carnot factor, it is usually around 0.5. T_{hot} is the temperature of the hotter region and T_{cold} is the temperature of the colder region in (K). By reducing the temperature difference between the indoor space and the reference environment one can increase the COP of the heat pump. This will in turn reduce the energy consumption for cooling down the space according to equation 3.

$$Heat_{remove}\ (\mathrm{Q}) = COP_{real} \times Ex_{in} \qquad (3)$$

Where Ex_{in} is the exergy needed to remove the heat in the space in (J), it is usually supplied in the form of electricity.

2.2 Separation of latent and sensible cooling

The latent or the dehumidification load is dependent on the occupancy of the indoor space. The higher the occupancy the more fresh and dehumidified air that is needed for the occupants. This is provided through the use of decentralised ventilation units. For dehumidification, the heat pump will need to produce chilled water of around 8°C. The sensible load in the room is removed by the radiant panels. The required water temperature for cooling is about 18°C. However, there are some constraints associated with the use of radiant panels. The cooling capacity is dependent on the availability of cooling surface and the temperature of the supplied water. Thus, if the heat gain is too high and there is insufficient cooling surface the radiant panels are not powerful enough to remove the sensible heat load. This relationship is illustrated in equation 4. The architectural implications of these system parameters are outlined in Table 1.

$$Cooling\ surface\ needed\ (m^2) = \frac{Heat\ Gain\ (Watts)}{Heat\ Removal\ Rate\ (Watts/m^2)} \qquad (4)$$

Table 1 The architectural implication of using radiant panels

System Parameters	Architectural Implications
Heat Gain	Improve the passive system of the building mainly the envelope quality, window wall ratio, shading etc.
Heat Removal Rate	Decrease the supply temperature of the water to the radiant panels and increase the heat removal rate. There are limit to how low the temperature can go due to human comfort and condensation issue.
Cooling Surface Needed	Factor in the availability of cooling surface needed for the cooling into the design of the building. This could be a unique architectural feature that arises from the system consideration.

The conventional cooling process of not separating the two processes will requires 8°C chilled water for the system, resulting in a lower COP of the heat pump due to the high temperature difference according to equation 3. While the separation of latent and sensible cooling significantly reduces the temperature difference for the sensible cooling it will result in a better performance for the overall system.

3. BUBBLEZERO FAÇADE DESIGN PROCESS

The BubbleZERO is a research laboratory for test bedding new low exergy systems in the tropics. The low exergy systems include the heat pump, 18m^2 of radiant panels and decentralised ventilation units. The façades (highlighted in red in **Figure 1**) on both end are modular and are interchangeable. A new set of façade is planned for the next phase of the research. The white colour pneumatic bubble skin is constantly reflecting heat while the constant flow of air in the bubble skin acts as high performance insulation for the interior. Capillary tubes run along the interior walls of the bubble skin to regulate the surface temperature, so we could simulate BubbleZERO as a space in a larger building. This case study presents the preliminary design of the BubbleZERO façade. The bubble skin is not altered in the experiment.

The exergy approach increases the efficiency of the building system through the manipulation of temperature differences and result in the reduction of the energy consumption. At the same time, it also looks at the supply side of the equation for clean energy sources to substitute the use of fossil fuels. With the abundance of sun light in the tropics, the application of Building Integrated PhotoVoltaics (BIPV) resembles a potential exergy source. This is demonstrated in the design process of the new façade of the BubbleZERO laboratory where BIPV are integrated into the façade design. The façade will also affect the daylighting for the interior space. For example, if longer shades are added it will reduce the heat gain but at the same time reduce the interior daylighting. Thus, the design requires the architect to not just look at the energy aspect but also many other issues such as daylighting and costing in the project.

The pilot study of the BubbleZERO is a reference for the future façade design. The project has many existing limitations such as the orientation, window size and glazing materials M-glass which was kept constant for the experiment. But it is a simple and clear example to test out the exergy strategy and the design method proposed.

Figure 1 BubbleZERO laboratory

4. DESIGN METHOD

An iterative design method is used to explore and optimise possible low exergy design options. The design method uses parametric modeling for generating design variants, evaluation methods for assessing the performance of the design variants and lastly the use of optimisation technique to optimise the design. The low exergy strategy described in section 2 will act as the basis for the design method.

Parametric modeling in architecture is the description of a design project using a series of parameters. These parameters could be materials, geometrical, spatial configuration or even building systems properties. The parameters are constrained or relational to each other. The parametric model is capable of generating design variants by altering the parameters. This parametric model is referred to as the design schema (Janssen 2004). The design schema captures the design intention of the architect and it is also influenced by the low exergy strategy proposed. Recent development in Computer Aided Design (CAD) tools have made parametric 3d modeling accessible to architects. Programs such as Rhinoceros Grasshopper, Generative Components and Houdini 3d have made constructing parametric models manageable.

The evaluation methods can vary from complex simulations to just a simple cost factor calculation of the design project. The generated design variants will be evaluated and an optimisation technique will be employed to optimise the design variants based on feedback from the evaluations. In the design process, the architect will try out different schema to test different design ideas and previous design schemas will serve as feedback for the next schemas.

3.1 Evaluation methods

In this case study four evaluation methods were used. The Envelope Thermal Transfer Value (ETTV) (Chua and Chou 2010) was used for calculating the solar heat gain. The rest of the internal load was estimated and added onto the solar heat gain. Substituting the internal load into the radiant panel equation, one could obtain the surface area needed for the cooling. A $50W/m^2$ heat removal rate is assumed, this is the heat removal rate in which 18°C chilled water can provide. Therefore, if a design variant has enough surface area to provide the necessary cooling it will separate the sensible and latent cooling and have a higher COP and reduce the energy consumption. On the other hand if a design variant does not have enough surface area for cooling, it will not be able to separate its latent and sensible cooling and it will have a lower COP and therefore have higher energy consumption. In this case, the cooling surface area available in the BubbleZERO is $18m^2$ as there are already radiant panels installed. The energy consumption is measure in Watts (W).

For lighting simulation Radiance (Ward 1994) was used for both the evaluation of solar irradiation falling on the façade for calculating energy generation from BIPV and also the daylighting evaluation. The Radiance simulation calculates the amount of solar irradiation falling on potential surfaces on the façade in a year, which surfaces are the potential surfaces are determined by the design schema. BIPV of 15% efficiency was assumed to be used. It is expected that 15% of the total solar irradiation will be converted to electricity. The electricity produced is measured in (Kwh/annual).

For the daylighting evaluation an interior grid was created where each point on the grid is measuring the daylighting in lux. 300 lux is the level of daylighting required for doing task of general purposes such as reading and writing. Thus, the evaluation method expresses the number of points that is receiving 300lux over the total number of points as a ratio and expresses it as a percentage.

The last evaluation method is a simple cost calculation of the materials used for the façade. There are in total four different materials used for the façade. The better performance material will cost more compared to the lower performing material. A cost factor is assigned to each material (Table 2). The cost is the multiplication of the cost factor by the area of the material used and eventually the sum of all the individual material cost.

Table 2 Material and cost factor

Material	U Value	Cost Factor
(3mm steel cladding/20mm expanded polystyrene/3mm steel cladding/20mm wood chipboard)	1.145	1.5
(3mm steel cladding/20mm polyurethane foam/3mm steel cladding/20mm wood chipboard)	0.881	2
(3mm steel cladding/10mm expanded polystyrene/3mm steel cladding/10mm wood chipboard)	1.9	1
(3mm steel cladding/10mm polyurethane foam/3mm steel cladding/10mm wood chipboard)	1.54	1.3

3.2 Evolutionary algorithm (EA)

The optimsation algorithm used is the EA. EA is an optimisation algorithm inspired by biological evolution, in which mechanism such as crossover, mutation and selection are used to generate fitter individuals. A fitness function is used to determine whether an individual is performing well. In the context of an architecture design, an individual will be a design variant generated from a design schema and the fitness functions would be the evaluation methods. At each cycle of the EA:

1. A population of 100 design variants are randomly generated by assigning parameter values to the design schema
2. Each design variant is evaluated and assigned scores for the evaluation methods. Each evaluation method is to be either minimise or maximise. The energy consumption and cost factor are to be minimise, while the energy production from BIPV and daylighting is to be maximized.
3. A sub-population of 50 design variants are randomly selected from the main population and pareto ranked according to their scores.
4. 25 design variants at the bottom of the ranking will be “killed” and 25 new design variants will be “reproduced” from the better performing design variants. The reproduction process is done through crossover techniques and the mutation rate is 0.01

5. The cycle is repeated from step 2 with the newly produced design variants. As a result better performing design variants are generated with each generation.
6. The EA cycle stops as specified by the users.

Lastly, a scientific workflow system is used to link the environmental simulation, CAD and optimisation algorithm programs together. It is a design environment which enables the architect to manipulate and manage the design process (Chen, Janssen et al. 2012).

5. PILOT STUDY

4.1 Design schema 1

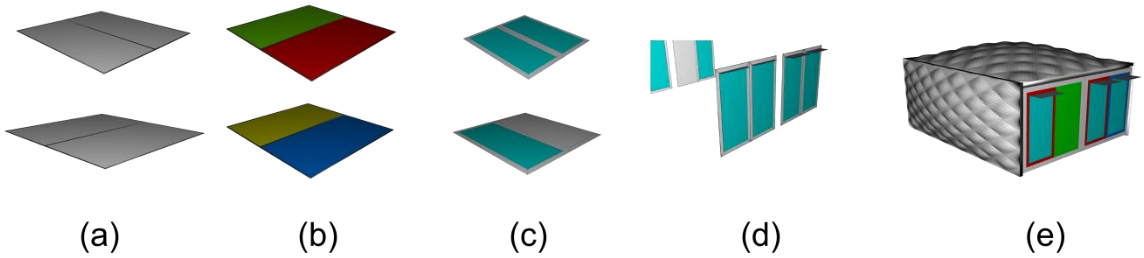

Figure 2 Design schema 1

Design schema 1 (**Figure 2**) is described as follows:

a) A façade is divided into two panels, they can be divided either horizontally or vertically.
b) Each panel is assigned one of the four materials, each colour represent a different material.
c) One or both of the panel can be chosen to be the window. The material of the glass is the M-glass which is given to the BubbleZERO project.
d) Each window can have a shade of maximum 1 meter or without any shade.
e) This façade will be applied to one of the four façade of the bubbleZERO. This is repeated 4 times to generate façades for the four sides. The facade with the door is an exception, where the placement of the door needs to be considered. The schema has 18 parameters in total.

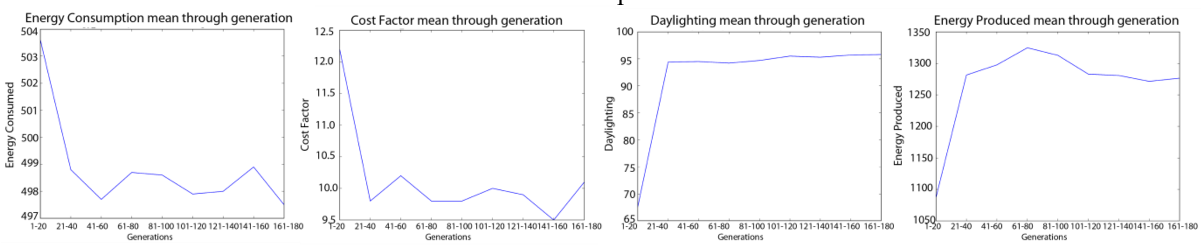

Figure 3 Means of the four evaluations throughout the optimisiation of schema 1

As one can see the optimisation got stagnant after the 20th generation. This is mainly due to the limitation of the parametric model. The parameters are too constraint resulting in a quick convergence of the result. A filtering process was done to look at the better performing design variants. A quick look at the design variants produced showed designs of low variability. However, the designs did perform well in terms of daylighting, energy consumption and cost. Thus, these results would serve as a benchmark for the later schemas for comparison.

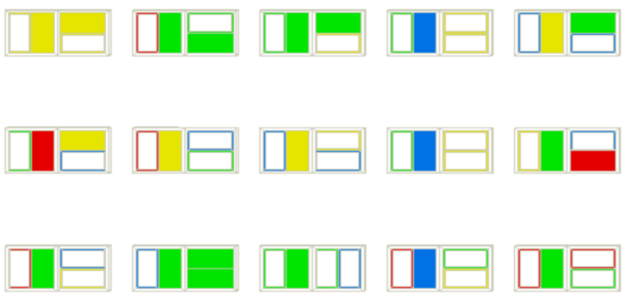

Figure 4 Schema 1 design variants facades

4.2 Design schema 2

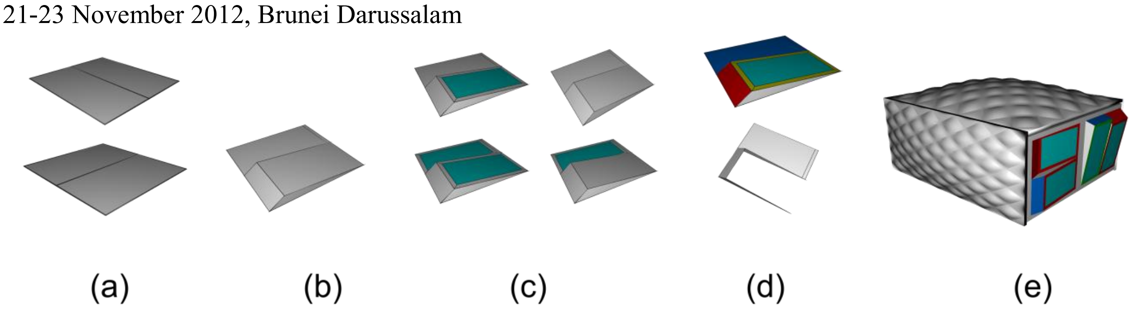

Figure 5 Design schema 2

Design schema 2 (**Figure 5**) is described as follows:

a) A façade is divided into two panels, they can be divided either horizontally or vertically.
b) The 2 panels are divided into 2 smaller panels, resulting in 4 panels in total. The division lines are allowed to move along the panels and outwards and inwards.
c) The m-glass window can be on either side of the panels, on both side, or on neither of the panels.
d) Each panel will be assigned a material and it is represented by a colour. Panels that are not windows are potential solar panels.
e) This façade will be applied to one of the four façade of the bubbleZERO. This is repeated four times to generate façade for the four sides. The facade with the door is an exception, where the placement of the door needs to be considered. The schema has 47 parameters in total.

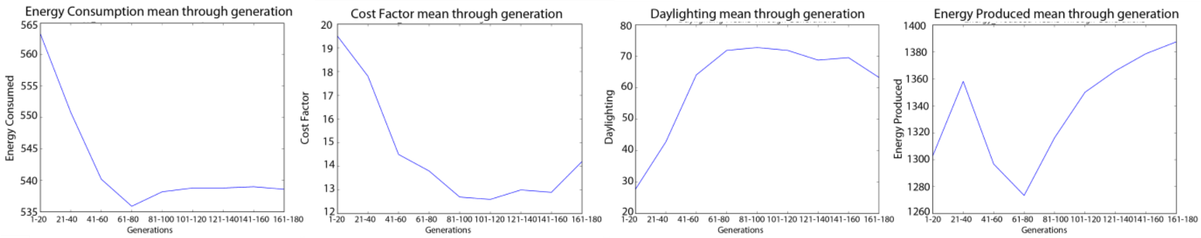

Figure 6 Means of the four evaluations throughout the optimisiation of schema 2

Design schema 2 is an attempt to integrate the shading in design schema 1 by tilting the façade to shade itself from the sun. Design schema 2 tries to achieve a similar performance with design schema 1 by having a combination of different tilting angle, materials and the low exergy systems. The design variants produced are of higher variability compared to design schema 1. However, it does not perform as well as schema 1. Despite, more appealing architecturally the tilting of the façade decreases the performance of the daylighting and the lack of shading has significant effect on the energy consumption. This also affects the costing evaluation where better insulation is required in order to use low exergy systems.

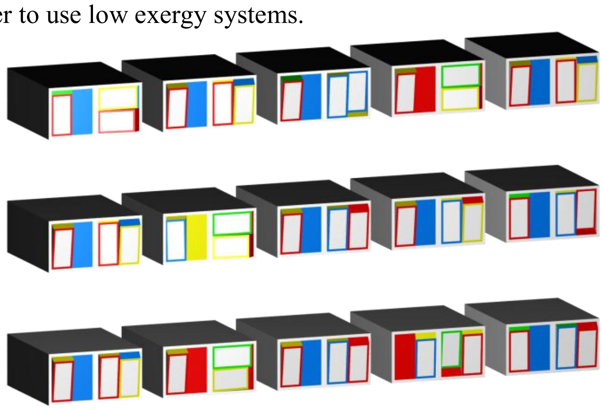

Figure 7 Schema 2 design variants

4.3 Design schema 3

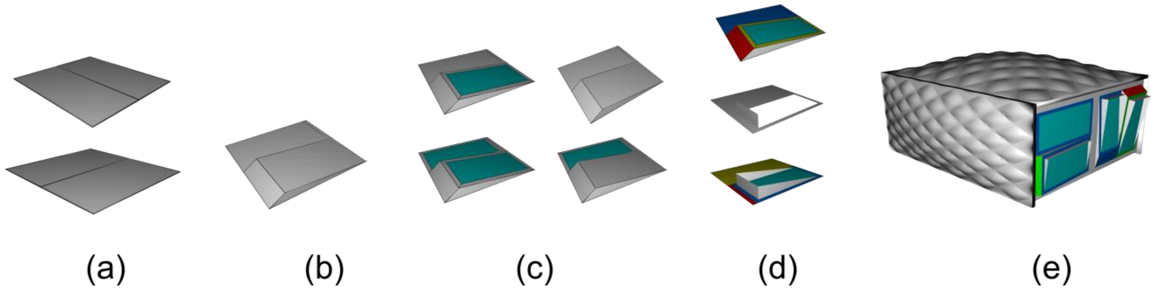

Figure 8 Design schema 3

Design schema 3 (**Figure 8**) is described as follows:
The design schema 3 is an improvement of design schema 2. The tilting of the façade was not sufficient in solely providing shades from the sun. A new parameter of shades for the windows was added to the schema. (a) – (c) are the same as design schema 2.

d) Each panel will be assigned a material and it is represented by a colour. Panels that are not windows are potential solar panels. Windows can have shading devices with a horizontal extension between 0m and 0.4m. At the same time the shading devices also provide the area for potential solar energy generations.
e) This façade will be applied to one of the four façade of the bubbleZERO. This is repeated four times to generate façade for the four sides. The facade with the door is an exception, where the placement of the door needs to be considered. The schema has 60 parameters in total.

Design schema 3 attempts to combine the benefit of the previous two schemas by introducing a form of shading element to complement design schema 2. It is assumed that both shading and tilting decrease the energy consumption. The extra shading surfaces will provide more surfaces for potential installation of solar panels. **Figure 9** describes the optimisation process through the means of each evaluation method. The introduction of the shades manage to improve the generation of energy as there are more horizontal surfaces for receiving solar irradiation. The performance of the daylighting is better as there is more space for negotiation with the extra mechanism of the shading. Lastly, the cost factor also performs better as shading is a cheap solution compared to using better insulation. However, the energy consumption is of similar performance to schema 2.

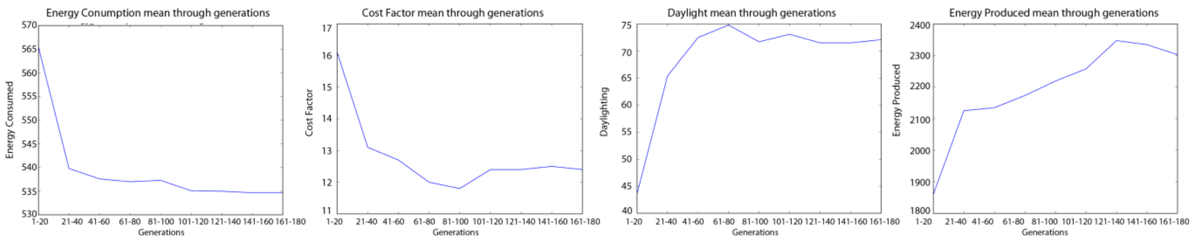

Figure 9 Means of the four evaluations throughout the optimisiation of schema 3

Figure 10 shows a series of the parallel plots that gives a more detailed description of the EA process. Each plot shows the design variants generated in 20 generations. One can see as the EA proceeds the design variants perform better, it is interesting to note within around 20 generations all design variants that was not able to employ low exergy systems were eliminated. One can observe from generation 121 to 180, there is a split at the energy generation axis. The split is due to the use of shade or just having well insulated materials, as these two mechanisms produces similar results for the rest of the three evaluation methods. However, from generations 161-180 the EA is slowly moving towards well-balanced solutions of shades and appropriately insulated materials.

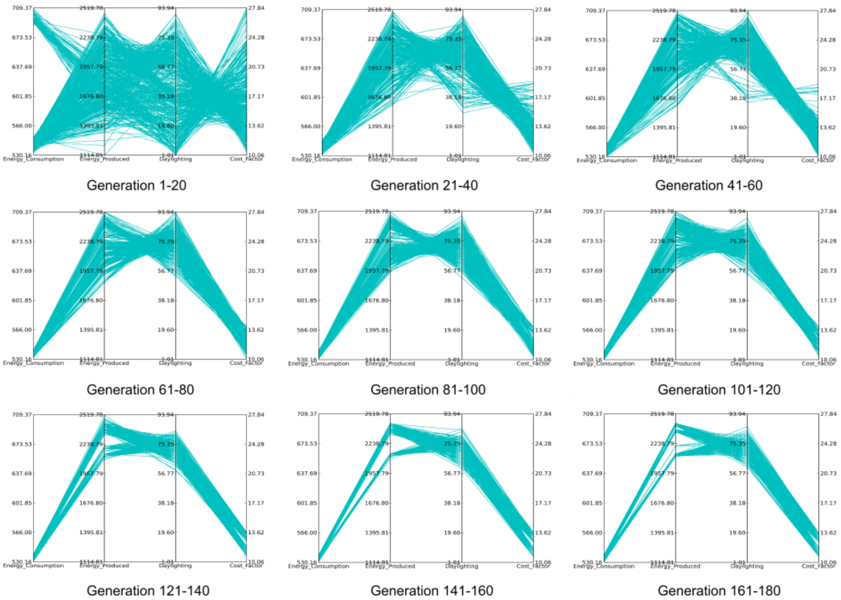

Figure 10 Parallel plot of the evolution process

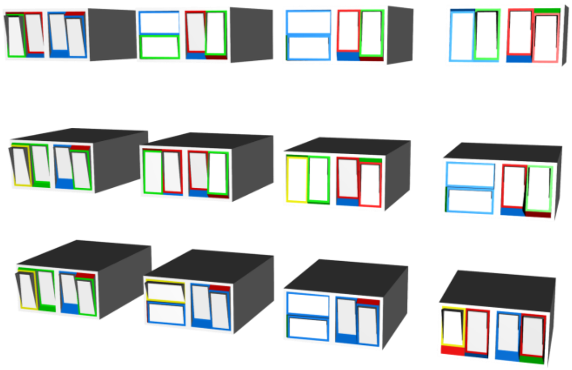

Figure 11 Design variants of design schema 3

A simple filtering process was used to choose among the 4000 design variants. The designer wants to get the best performing solution of the evaluation methods. A filter was carried out with the following ranges. Energy consumption between 538W and 500W, energy produced between 2500kwh/a and 2000kwh/a, daylighting between 100% to 80% and cost factor between 11 and 8. The filter eliminated most of the design variants and 15 design variants were left. The architect can further examine the 15 design variants and continue to develop a more detailed design scheme for later stage of design.

5. CONCLUSION

The integrated design process shown is capable to aid the architect in his explorations of possible design options. It is possible to satisfy the performance criteria by maintaining design quality and architectural intention. By incorporating both active and passive systems, it is possible to generate designs of certain variability but at the same time of similar performances. This will expose the architect to more design possibilities instead of the usual more restrictive perspective of just manipulating the passive systems.

The optimisation technique EA requires the generation of thousands of design variants. This is suitable for big scale design projects with more parameters where there is a significant variability between the design variants generated. However, for a small scale design project the thousands of design variants generated have little variability. Thus the research will look at other possible optimisation techniques; one example is Micro Genetic Algorithm. It generates five to ten design variants in a generation for optimisation, the number of design variants is more manageable for design project of a smaller scale.

The low exergy approach provides a more holistic perspective to achieve sustainable buildings while the parametric modeling, evaluation method and optimisation technique is actively engaged in an integrated design process. It provides feedback for the architect on the chosen design schema, by examining and analysing the results the architect can extrapolate the potential of a design concept and improve it in the next design schema. Further investigations include looking at different low exergy strategies applicable in the tropics and extracting its architectural implications. These will be formalised to refine the design process to facilitate the design of low exergy architecture in the tropics. The pilot study shows the feasibility of the design method. The research will look at case studies of bigger scale and flexibility to test out the design method.

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