

A DESIGN METHOD FOR MULTICRITERIA OPTIMISATION OF LOW EXERGY ARCHITECTURE

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Abstract. This paper proposes a design method for the exploration of holistic low exergy design strategies which factor in limitations and constraints of both passive and active systems. A design method that consists of a two loop structure is proposed. The inner loop consists of an automated workflow that includes three main components: a developmental procedure for generating design variants; evaluation procedures for evaluating design variants; and an optimisation procedure for optimising populations of design variants. The outer loop consists of a manual workflow that has two main components: a schema formulation process for defining the inputs to the automated workflow and a data analysis process for analysing the data produced by the automated workflow. A case study is presented that demonstrates the proposed method.

Keywords. Low exergy design; parametric design; evolutionary design; integrated design process; performance driven design.

1. Introduction

The growing concern over environmental issues such as global warming has increase the importance of energy efficient building. The current approach in architecture design mainly concentrates on optimising passive systems. However, by just focusing on passive systems it limits the potential to achieve high performance

low energy design (Ritter and Meggers, 2010). Thus a more holistic approach needs to be adopted that includes both the passive and active systems.

The concept of exergy describes both the quality and quantity of an energy source. In the tropics, the exergy of “cold” is applied in the cooling of buildings (Jansen and Woudstra, 2010). This requires the architect to look into temperatures in a design scenario to assess the appropriate exergy needed. One of the low exergy strategies appropriate for the tropics is the separation of sensible and latent cooling. However, there are limitations and constraints for implementing this strategy; the sensible heat load needs to be within the cooling capacity of the high temperature cooling systems used and systems like radiant panels will require sufficient surface area for the cooling down the space. (Chen et al., 2012b).

Thus, it is important to start considering such limitations and constraints in the early architectural design stage when alteration can still be easily made.

This paper proposes a design method for architects to explore low exergy design in the early design stage. The proposed design method combines integrated optimisation system such as GENE_ARCH (Caldas, 2006), ParaGen (Turrin et al., 2011) and DEXEN (Janssen et al., 2011) with low exergy design evaluation tools such as the DPV (Schlueter and Thesseling, 2008).

2. Integrated Design Method

The design method has a two loop structure consisting of an inner loop and the outer loop. The inner loop is an automated loop consisting of three procedures: developmental, evaluation and optimisation procedures. The outer loop is a semi-automated loop with two main components the schema formulation process and the data analysis process. The outer loop enables the architect to interact with the inner loop. The method is as follows:

1. Low exergy approach – Specific strategies appropriate to the tropical climate are selected. These strategies will affect how a design is formulated, developed, evaluated and optimised. The design project will also have an influence on the possible low exergy strategies that can be employed.
2. Outer loop
 - 2.1. Schema formulation process – Architects develop design base on the usual requirements of a project and with influence from low exergy strategies. The design will be parameterised into a design schema. A design schema encapsulates the design intention of the architect. It includes the generative concept for the developmental procedure and the evaluative concept behind the evaluation procedures.
 - 2.2. Data analysis process – Architects visualise the performance of the design variants generated from the inner loop.

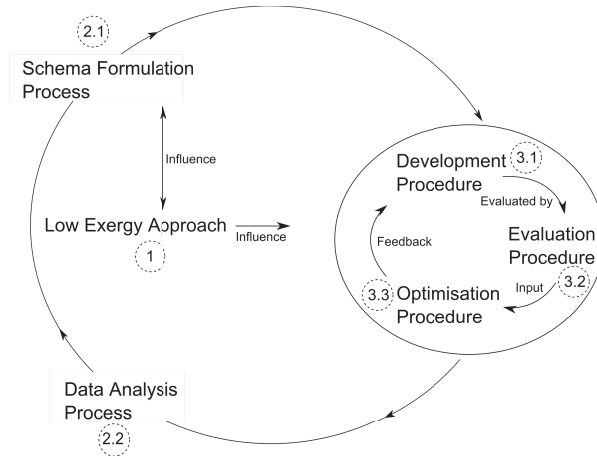


Figure 1. Integrated design method.

3. Inner loop

- 3.1. Developmental procedure – Models of design variants are generated using the parametric model.
- 3.2. Evaluation procedure – Models of design variants are evaluated according to various performance criteria specific to the design project.
- 3.3. Optimisation procedure – An optimisation algorithm is used in order to generate better design variants.

The two loop structure ensures there is an active exchange of information between the design method and the architect. This allows the designer to escape the limits of search space imposed by a specific design schema. Information generated from the inner loop feedback into the outer loop and it will help the architect to redesign his schema. This results in a two loop iterative design process.

An architect will start a design with the schema formulation process, while in parallel considering appropriate low exergy strategies. The selected low exergy strategies will directly affect the schema and the development, evaluation and the optimisation procedures. The schema is then input into the inner loop, where design variants are optimised through an iterative process. Selected design variants are then output to the data analysis process. Based on this data analysis, the architect will gain insights on how the design schema can be improved. Once the schema has been redesigned, the inner loop can be repeated.

Each procedure is manifested into a series of workflow by using scientific workflow management tool. This facilitates the implementation of the design

method in a design scenario (Chen et al., 2012a). In the following, the design schema and the proposed method are described in detail.

3. Demonstration

A case study is presented that demonstrates the proposed method. The design schema is loosely based on the Bumps Beijing project (ArchDaily, 2009) (Figure 2). The design consists of a set of prefabricated rectangular modules stack on top of each other in a grid formation. Each module, measuring 8x24x6 metres, is two floors high. The modules are offset from one another, thereby generating overhangs and insets. For the demonstration, the design is placed in the Singapore climate.

Each module is treated as a separate zone. An exemplary low exergy strategy, the separation of latent and sensible cooling and the decentralisation of the cooling systems is used. These strategies allow each zone to have control over its own cooling system. Depending on the position, window wall ratio (WWR) and orientation of the zone, its cooling load will differ. In each zone the supply temperature for the radiant panels can be varied to meet the cooling load. The needed cooling rate is dependent on equation 1 (ASHRAE, 2008).

$$\text{Cooling rate (W/m}^2\text{)} = \text{Cooling load (Watts)}/\text{Cooling surface area (m}^2\text{)} \quad (1)$$

Based on the size of the module, the amount of available cooling surface area is assumed to be constant at 307m². The supply temperature is related to the cooling rate, where 18°C provide about 50W/m² of cooling (ASHRAE, 2008). The Coefficient of Performance (COP) of the chiller could be optimise for the specific cooling load of each zone and thus reduce the overall energy consumption of the project according to equation 2.

$$\text{COP}_{\text{real}} = g \times (\text{T}_{\text{hot}}/(\text{T}_{\text{hot}} - \text{T}_{\text{cold}})) \quad (2)$$

where g is the carnot factor, T_{hot} and T_{cold} is the reference rejection and supply temperature respectively.

3.1. DEVELOPMENT PROCEDURE

The parametric model is constructed using SideFX Houdini 3D as follows:

- a. The schema is an abstraction of the Bumps Beijing project.
- b. The 8m x 24m x 6m module

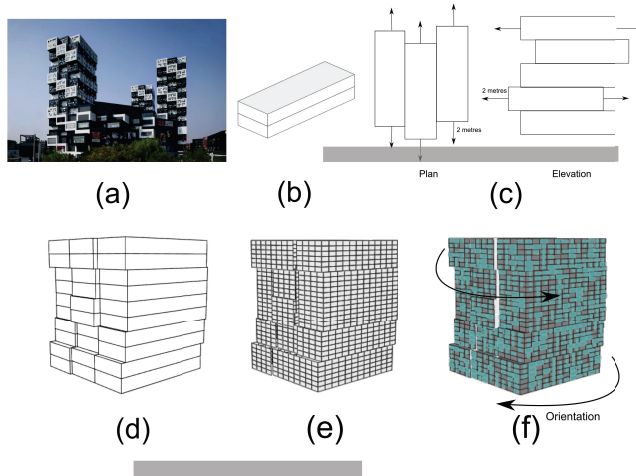


Figure 2. Design schema.

- c. The positions of modules are place as shown. On the plan view they could slide along each other with a maximum limitation of two metre.
- d. The modules are stacked to create the overall 3d massing.
- e. A grid of 2m x 1.5m is overlaid of the façade
- f. Each 2mx1.5m grid is assigned a window parameter. It has four window options and one no window option. Each window option has different dimensions and as a result will affect the WWR thus affecting the daylighting and cooling energy consumption of the building. Each window is also assigned a material parameter with a cost factor; the better insulated materials are assigned a higher cost. Finally, the building is orientated in a particular direction.

3.2. EVALUATION PROCEDURES

There are four evaluation procedures; cooling energy consumption, cost factor, daylighting and solar potential.

- Cooling energy consumption – The procedure first checks if the cooling load of each module is within the radiant cooling capacity. If the cooling load of the module is within the radiant cooling capacity, then a radiant cooling system is used. Otherwise, a conventional cooling system is used. The cooling energy consumption of the building is then calculated. The cooling energy consumption is to be minimised in the optimisation procedure.
- Cost factor – The cost factor of the building is calculated according to the different materials and the cooling systems used. The implementation cost of the low exergy

strategy is two times higher than the conventional cooling method. The cost factor is to be minimised in the optimisation procedure.

- Daylighting – The floor area receiving more than 300 lux of natural daylight is calculated using Radiance lighting simulation. The simulation is conducted using an overcast sky model, which is assumed to be the worst case scenario. The daylighting is to be maximised in the optimisation procedure.
- Solar potential – The maximum possible amount of energy generated from photovoltaics (PV) is calculated assuming the external façade is cladded with PV panels. The efficiency of the PV panels is assumed to be 15%. The solar irradiation is calculated with Radiance. The solar potential is to be maximised in the optimisation procedure.

3.3. OPTIMISATION PROCEDURE

The aim of the optimisation is to find a series of solutions that balance the trade-offs between multiple conflicting performance criteria. For example, to minimise the cooling energy consumption better quality materials can be used, however this will increase the cost factor. In order to maximise the solar potential, it is best to orientate the building towards the sun, but this will increase the cooling energy consumption. In order to reduce the cooling energy consumption, the WWR can be kept low, but this will reduce the daylighting in the interior. A design decision that is good for one criterion will result in a bad performance on another criterion.

As optimising one criterion will lead to the degradation of another, an evolutionary multi criteria optimisation is performed. The Evolutionary Algorithm (EA) can be used to effectively explore populations of design variants based on a specific design schema (Janssen, 2004). In order to compare design variants with multiple performance criteria, multi criteria EA typically uses Pareto ranking. This technique ranks design variants according to the concept of dominance. If design variant x performs better than design variant y in one criterion but perform as good in the other criteria, it is said that design variant y is dominated by design variant x. For the case study, an EA was used as follows:

1. A population of 100 design variants are randomly generated by assigning random parameter values to the parametric model.
2. Each design variant is evaluated and assigned a score for each evaluation criteria.
3. A sub-population of 60 design variants is randomly selected and pareto ranked according to their scores.
4. The 30 lowest ranking design variants are “killed” and 30 highest ranked design variants are reproduced, thereby generating 30 new design variants. For reproduction, standard crossover and mutation operators are used, with a mutation probability of 0.01.

5. The cycle repeats itself from step 2. After each generation the design variants will gradually become “fitter”.
6. The EA cycle was stopped after 164 generations.

4. Results

The EA ran for 164 generations and a total of 5000 design variants were generated. Figure 3 gives an overview of the optimisation process and Figure 4 shows the parallel coordinate plots of the evolution process. Figure 4(b) shows the design variants on the Pareto front. This Pareto front is made up of all design variants that are non-dominated by other design variants.

Figure 5 shows design variants of high performance. Figure 5(a) shows the designs that use low exergy systems while Figure 5(b) shows the design that use the conventional cooling systems. Interestingly, all the design variants in Figure 5(a) and (b) have the same orientation facing northwest. The geometry of the design variants are similar and are optimised to maximise both daylight and solar potential. Lastly, the WWR ranges from 0.26 to 0.28.

Figure 6 shows two design variants, with the top one being a low exergy design and the bottom one being a design using conventional systems. One can see the

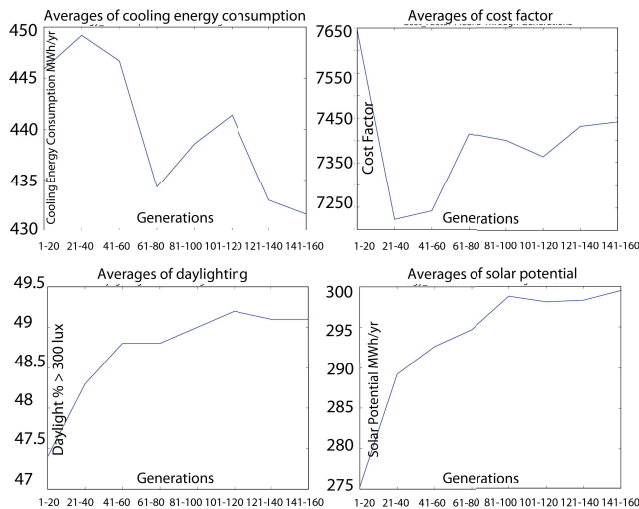


Figure 3. Averages of evaluations in interval of 20 generations.

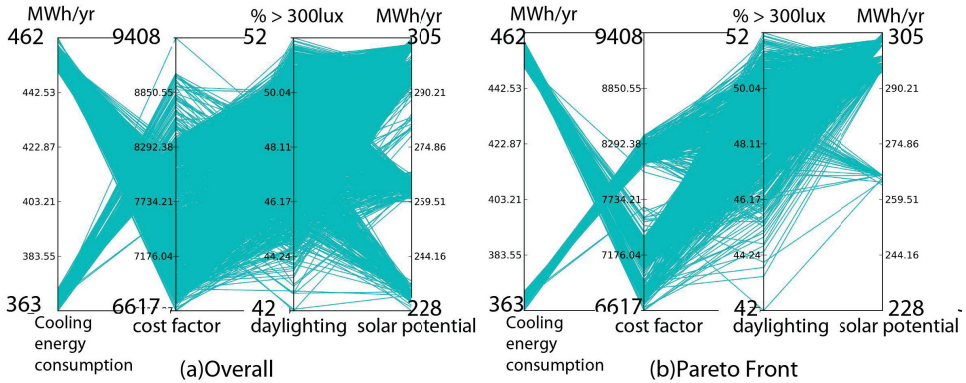


Figure 4. Parallel coordinate plots of (a) 5000 design variants, (b) Pareto front.

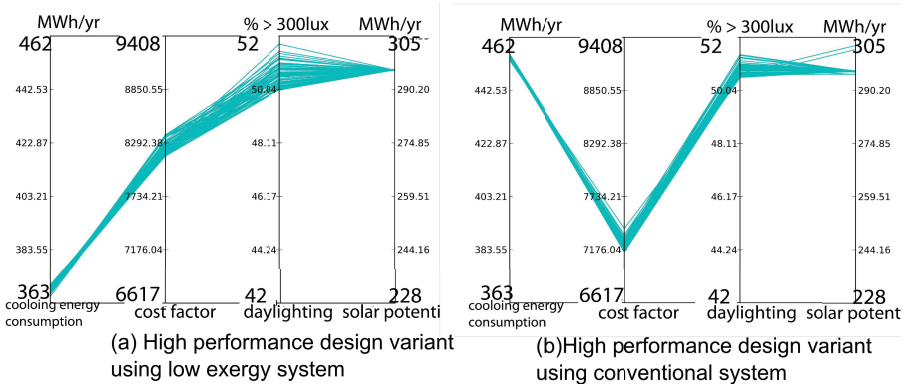


Figure 5. (a) high performance design variants using low exergy systems (b) high performance design variants using conventional systems.

similarity of the two designs in terms of the geometry, orientation and WWR. Design variant 1611 has more windows using triple low-E glass while design variant 1386 has more windows using double glaze low-E glass. For the additional material cost factor of 1177 the building could have so much more cooling energy consumption savings.

Through, the optimisation process the architect will be able to explore the alternative trade-offs between conflicting performances criteria and make more informed design decision.

This information can then be fed back to the outer loop for the next round of optimisation. For example, with information of the best orientation and WWR one

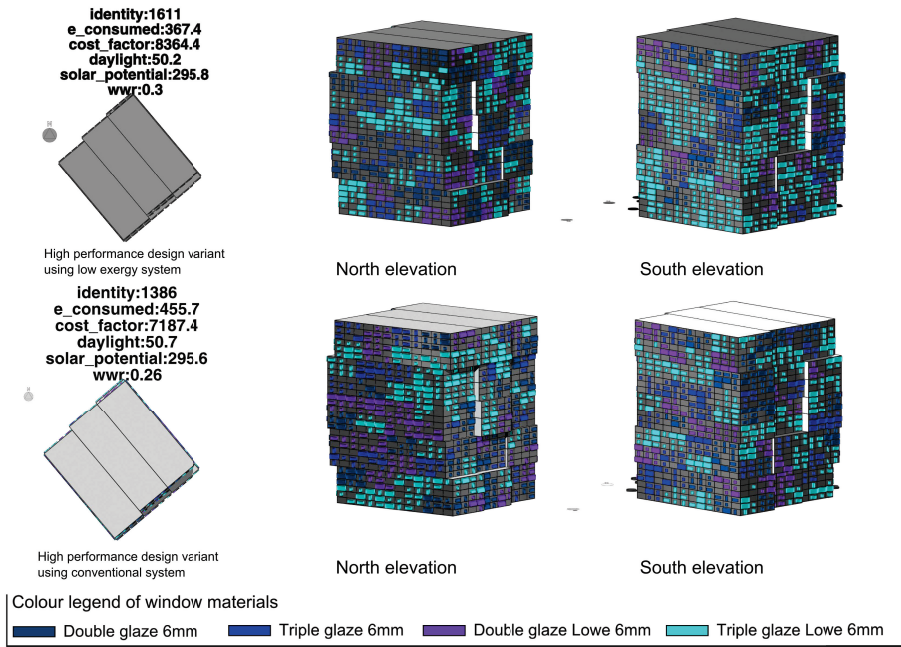


Figure 6. Top: design variant using low exergy system Bottom: design variant using conventional systems.

could narrow down the schema by removing the orientation parameter and constraining the WWR. The next round of optimisation could then focus on the exploration of improved façade design.

5. Conclusion

The optimisation process highlighted key strategies that could be used with regards to the geometry and orientation of the building. All the best performing design variants face northwest and have a similar geometry. The WWR of 0.26 to 0.28 gives a good daylighted interior while at the same time maintain the cooling load with a certain level of envelope quality.

Through analysing and generalising the results of the optimisation run, the architect can discover design strategies that consistently result in good performance. In this way, the computer becomes an active participant in the design process. This is only possible with a well-integrated design method. Further investigations will look at niching of the genetic algorithm data to give a more diverse population in the result and thus give the architect more design options.

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