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MULTI-CRITERIA EVOLUTIONARY OPTIMISATION OF BUILDING ENVELOPES DURING CONCEPTUAL STAGES OF DESIGN

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Abstract. This paper focuses on using evolutionary algorithms during conceptual stages of design process for multi-criteria optimisation of building envelopes. An experiment is carried out in optimising a panelled building envelope. The design scenario for the experiment is based on the scenario described in Shea et al. (2006) for the building envelope of the Media Centre Building in Paris. However, in their research, the optimisation process only allowed panel configuration to be optimised. In this paper, the task is to approach the optimisation of the envelope of the same building, assuming it to be in the early phases of the design process. The space of possible solutions is therefore assumed to be much wider, and as a result both external building form and internal layout of functional activities are allowed to vary. The performance intent of the experiment remains the same as that of Shea et al. (2006), which was to maximise daylight and minimise afternoon direct sun hours in the building at certain specific locations.

Keywords. Multi-criteria optimisation; building envelopes; conceptual stages of design evolutionary algorithms; parametric design.

1. Introduction

Building envelopes can be optimised for performance criteria that are often in conflict with each other and are also difficult, if not impossible, to optimise manually. Hence, there is an opportunity to explore the use of computational design and optimisation tools that facilitate the design of optimised building envelopes for multiple criteria. Previous approaches to computational building envelope optimisation include both evolutionary and numerical optimisation approaches (Bouchlaghem 2000, Gagne and Anderson 2010). The problem with most of these approaches is that they target the detail design stage when most of the design is already fixed, thereby losing on the opportunity for a more holistic exploration of design alternatives.

This research explores the use of evolutionary optimisation techniques (Holland 1975, Goldberg 1989) to optimise a building envelope during the conceptual stages of the design process for multiple conflicting performance criteria. To deal with the evaluation of multi-objective optimisation problems, Pareto ranking techniques are used (Goldberg 1989, Fonseca and Fleming 1993).

The design scenario for the experiment is based on the scenario described in Shea et al. (2006) for the building envelope of the Media Centre Building in Paris. The building consists of a 12 m × 20 m × 8 m parallelepiped shaped space, split into five internal spaces namely, gallery wall 1, gallery wall 2, meeting area, reception and office (RP1, RP2, RP3, RP4 and RP5 respectively) all with different lighting performance requirements as shown in Figure 1.

The building envelope to be optimised can be imagined as a pixel grid of panels that wrap the walls and roof of a building, where each panel can accommodate several types of panels with different lighting and cost properties (e.g. opaque, clear glass etc.).

In the design experiment by Shea et al. (2006), only the panel configuration was optimised. The external envelope geometry and the internal plan configuration were predefined and were not allowed to vary. However, during the conceptual stages of the design process, only optimising the panel configuration may not be sufficient. It may be possible to find better solutions by optimising other aspects of the design in tandem with the panel configuration. In this paper, the task is to approach the optimisation of the envelope of the same building, assuming it to be in the early phases of the design process. The space of possible solutions is therefore assumed to be much wider, and as a result both external building geometry and internal plan layout are allowed to vary.

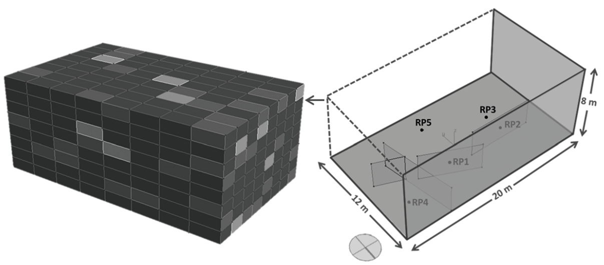


Figure 1. Paris media centre space and response point (RP1–RP5) specification.

The demonstration is divided into two experiments. In the first experiment the panel configuration and external geometry of the building are varied. In the second experiment, the panel configuration and the internal floor plan of the building are varied. The performance intent of both the experiments remains the same as that of Shea et al. (2006), which was to maximise daylight and minimise afternoon direct sun hours in the building at certain specific locations.

2. Design method

An Evolutionary system called Dexen is used to execute the optimisation process. This system is coupled to Sidefx Houdini, an advanced procedural CAD application that is used for both design development and design evaluation procedures (Janssen et al. 2011). This application includes a visual dataflow modeling (VDM) interface that allows users to create complex parametrised procedures. With the evolutionary design method, the set of parameters are referred to as the genes (which together from the genotype), the model is referred to as the phenotype, and the results from the evaluations are referred to as a set of fitness scores. The evolutionary design method requires three key procedures to be defined; namely the development procedure that generates a phenotype from a set of genes, one or more evaluation procedures that calculates fitness scores by analysing and simulation the phenotype, and a feedback procedure that performs genetic reproduction based on the fitness scores. The developmental and evaluation procedures are defined using Houdini using the VDM approach. The feedback procedure is generated automatically by Dexen based on various standardised settings. This procedure will rank groups of phenotypes using a standard Pareto ranking method, and will then create new genotypes using crossover and mutation operators.

3. Lighting analysis

For the evaluation procedures, the Radiance simulation program is used for calculating two different lighting performance criteria: lighting level and number of sun hours. Calculations are performed for certain predefined points in the model. For lighting levels, the Daylight Factor is calculated for each point. For sun hours, the total number of hours that a point receives direct irradiance from the sun of at least 120 W/sq-m is measured. (The World Meteorological Organisation refers to this as ‘sunshine duration’.)

Within Houdini VDM nodes have been created for linking Houdini to Radiance. These nodes generate the required input files from the Houdini model and then execute the radiance program.

4. Experiment A

In the first experiment, parameters related to the panel configuration and external geometry are varied.

4.1. DEVELOPMENTAL PROCEDURE

The developmental procedure for Experiment-1 involves creating the parametric model in Houdini. Though the floor plan and the internal arrangement of spaces is maintained as in Shea et al. (2006), the parameters governing the shape of the parallelepiped (the envelope) are varied along with the panel types. The three planes are divided into a total of 192 panels, each of which can be assigned a different material. For the purpose of this experiment, the materials are assumed to be the same as those described in Shea et al. (2006) i.e. opaque panels, clear glass panels, diffusing glass panels and shaded glass panels, as indicated in Table 1. In this experiment, the parameters that define the phenotype are the 192 panels and the movement of points P1, P2, P3 and P4 in the X, Y and Z direction as shown in Figure 2. The movement of points in X and Y directions controls the slope of envelope in that direction and is given a range to move towards and away from the building by 3 m. The movement of points in Z direction controls the height of the internal spaces in the building and is given a range of 4 m to 8 m. As the shape and form of the envelope changes, the size and shape of the panel change accordingly, still maintaining the same number of panels throughout the evolutionary process.

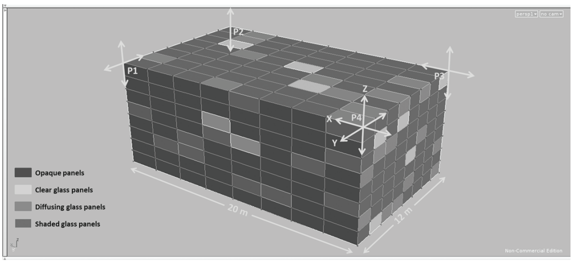


Figure 2. Points that define the geometry of the envelopes.

TABLE 1. Panel materials.

Panel material	Light transmission	Direct Sun?	U-value (W/m2k)	Cost (Euros)
00. opaque	0%	No	0.3	300
01. clear glass	75%	Yes	1.8	450
02. diffusing glass	60%	No	1.8	500
03. shaded glass	25%	No	1.6	600

4.2. EVALUATION PROCEDURE

There are in total five performance criteria for which the strength of the phenotypes will be assessed. The evaluation procedures are defined using Houdini.

The overall optimisation strategy can be defined as follows:

- Maximise daylight factor at response points (maximum of 15%)
- Achieve desired sun hours at response points
- Minimise average U-value of the panels
- Minimise overall cost of the panels
- Achieve desired height at each of the five internal spaces

The first four criteria were part of the performance criteria defined by Shea et al. (2006). The last criterion of height has been added for the purpose of this experiment. Each internal space has different height requirements, taking into consideration factors such as air-conditioning, privacy, lighting etc.

4.3. ANALYSIS OF RESULTS

The 3-D chart in Figure 3 represents 10,000 solutions, with daylight factor, cost and U-value plotted along the X, Y and Z axis respectively. Sun hours are indicated with colour coding. (On this chart, the fifth performance criterion - space height, also represented through colour coding - is not shown.) A score of 5 indicates that the solution has satisfied all the rules set for that evaluation criterion of sun hours or height. As shown in Figure 3, the solutions with the maximum score of 5 for ‘sun hours’ gradually get denser towards the origin. The Pareto front of these 10,000 solutions can be derived by filtering points in the 3D graph.

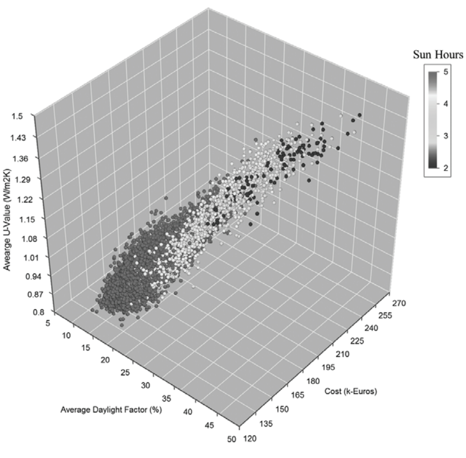


Figure 3. 3D graphs representing the 10,000 solutions for Experiment A.

The Pareto optimal solutions shown in Figure 4 represent the final outcome of this experiment. The score for ‘sun hours’ and ‘height’ criteria has reached the maximum for all the solutions in this graph. Hence it results in a 2D graph with daylight factor and U-value plotted along the X and Y axis and the third dimension of cost indicated with colour coding. For the purpose of comparison, six solutions are picked from the Pareto front and compared against each other on their performance. Table 2 compares the values of the various performance criteria of these 6 solutions. But as suggested by Caldas and Rocha (2001), these solutions must not be interpreted as optimal answers, but as diagnoses of potential problems and as suggestions for further architectural explorations.

TABLE 2. Comparison of evaluation criteria for the 6 selected solutions of Experiment A.

Name of solutions	Average daylight factor (%)	Average U-value (W/m2k)	Cost (k-Euros)	Score for height	Score for sun hours
Solution A	14.75%	0.92	129	2/5	5/5
Solution B	13.75%	0.87	132	5/5	5/5
Solution C	13.68%	0.86	152	5/5	5/5
Solution D	11.45%	0.87	157	5/5	5/5
Solution E	10.92%	0.90	158	5/5	5/5
Solution F	10.53%	0.94	172	3/5	5/5

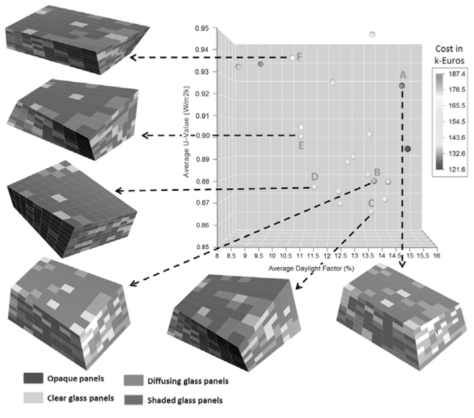


Figure 4. Experiment A – Study of Pareto optimal solutions.

5. Experiment B

In the second experiment, parameters related to the panel configuration and internal floor plan layout are varied along with the panel types.

5.1. DEVELOPMENTAL PROCEDURE

The geometry of the building is maintained as a 12 m × 20 m × 8 m (constant height) parallelepiped shaped space as in Shea et al. (2006). In this experiment, the parameters that define the phenotype are the panels and the movement and rotation of gallery walls in the floor plan as shown in Figure 5.

In this experiment, the panelled roof and the two panelled walls are divided into 1 m × 1 m panels, thereby yielding a total of 496 panels, each of which can be assigned a different material as indicated in Table 1.

The positioning of the two internal partitions defines two spaces: the space between these partitions and the solid walls is the gallery space, and the space between these partitions and the panelled walls is the office space. (The office space combines the office area, meeting area and reception area.) Paintings/artefacts may be hung either on the solid walls or the side of the partition facing the solid wall. Both partitions can move in X and Y directions within the available floor plate of 20 m × 12 m, and can be rotated to a maximum of 90 degrees. In order to avoid generating overlapping partitions, the second partition is actually positioned relative to the first partition. The 90 degree limitation to the rotation ensures that the two partitions always face the solid walls. However for a given position of the gallery walls, there are 2 methods of partitioning the internal space as shown in Figure 5. The method that results in the desired ratio of partition of office and gallery areas is chosen.

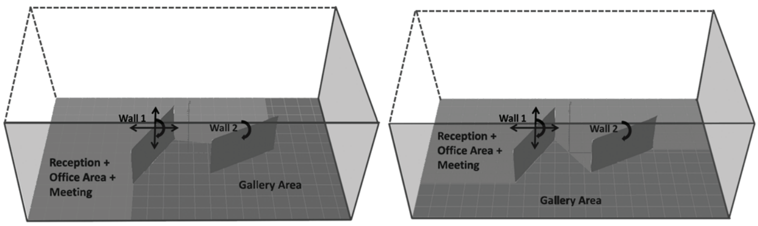


Figure 5. Movement of gallery walls and the 2 methods of area partitioning.

5.2. EVALUATION PROCEDURE

The overall optimisation strategy is the same as Experiment A except that the fifth criterion in this experiment is to achieve desired ratio of floor area between office space and gallery space. The desired ratio of partition of office and gallery areas is specified in the evaluation procedure.

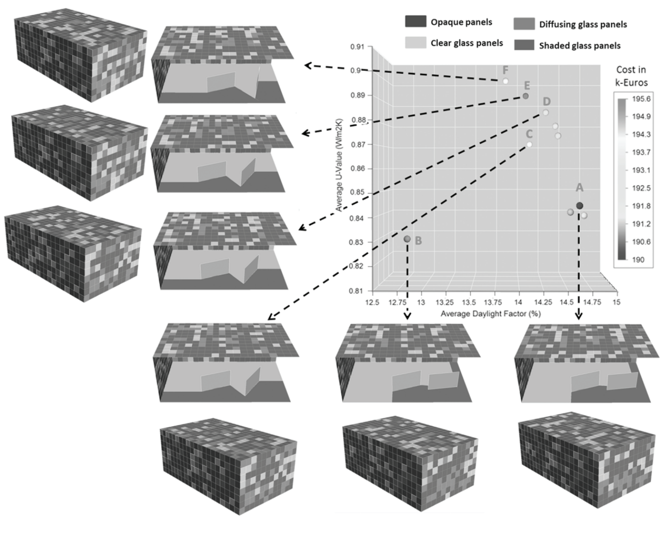
5.3. ANALYSIS OF RESULTS

The 10,000 solutions generated for this experiment are analysed in 3D graphs and a set of solutions are picked from the Pareto Front and are compared against each other on their performance. Figure 6 indicates both the internal functional space arrangement and the external panel configuration for each of the six selected solutions. Table 3 compares the values of the various performance criteria of these 6 solutions.

TABLE 3. Comparison of evaluation criteria for the 6 selected solutions of Experiment B.

Name of solutions	Average daylight factor (%)	Average U-value (W/m2k)	Cost (k-Euros)	Score for area	Score for sun hours
Solution A	14.61%	0.84	190	3/4	4/4
Solution B	12.82%	0.83	191	3/4	4/4
Solution C	14.10%	0.87	194	4/4	4/4
Solution D	14.30%	0.88	193	4/4	4/4
Solution E	14.10%	0.89	195	4/4	4/4
Solution F	13.85%	0.90	194	4/4	4/4

Figure 6. Experiment B – Study of Pareto optimal solutions.



6. Conclusions

The experiments considered both geometry and floor plan based variations to a panelled building envelope scenario presented by Shea et al. (2006). Experiment-1 evolved solutions with envelopes that opened up to daylight in certain parts and were self-shading in certain other parts of the building, thereby minimising the use of costlier panel types. (It was noted that the actual cost of constructing such a façade may be higher due to the complexity of the geometry.) Experiment-2 evolved solutions with better internal functional space efficiency for the same performance goals. The two experiments demonstrate how designers can apply evolutionary techniques to explore differing combinations of design parameters and performance criteria early in the design process during the conceptual stages. The VDM approach within Houdini allowed complex developmental and evaluation procedures to be developed without any advanced programming skills. The Dexen evolutionary system then allowed designers to setup and run advanced evolutionary design explorations.

However, searching through the design variants within the archived evolutionary data in order to make informed decisions was challenging due to both the quantity and complexity of the data. When comparing solutions with more than two performance criteria, it became difficult to visualise the strength of each solution over the other. Alternative approaches that could be explored include parallel projections, spider diagrams, and 3D and 4D graphs.

The experiments have demonstrated how designers could apply evolutionary algorithms to explore a wide range of design variants at early conceptual stages of design process. Future research will focus on developing an improved decision support system for analysing the archived evolutionary data.

References

Bouchlaghem, N.: 2000, Optimising the design of building envelopes for thermal performance, *Automation in Construction*, **10**(1), 101–112.

Caldas, L. and Rocha, R.: 2001, A generative design system applied to Siza's School of Architecture at Oporto, *in* Gero, J. et al. (eds.), *Proc. CAADRIA 2001*, Sydney, 253–264.

Deb, K. et al.: 1998, Genetic programming 1998: proceedings of the third annual conference, *IEEE Transactions on Evolutionary Computation*, **3**(2), 159–161.

Fonseca, C. M. and Fleming, P. J.: 1993, Genetic algorithms for multiobjective optimization: formulation, discussion and generalization, *Genetic Algorithms: Proceedings of the Fifth International Conference*, San Mateo, 416–423.

Gagne, J. and Anderson, M.: 2010, Multi-objective facade optimisation for daylighting design using a genetic algorithm, *Proc. 4th National Conference*, IBPSA-USA SimBuild 2010, New York.

Goldberg, D.E.: 1989, *Genetic Algorithms in Search, Optimization, and Machine Learning*, Addison Wesley, Reading.

Holland, J. H.: 1975, *Adaptation in Natural and Artificial Systems*, University of Michigan Press, Ann Arbor.

Janssen, P. H. T., Basol, C. and Chen, K. W.: 2011, Evolutionary developmental design for non-programmers, *Proc. 29th eCAADe Conference*, University of Ljubljana, 886–894.

Shea, K., Sedgwick, A. and Antonuntto, G.: 2006, Multicriteria optimization of paneled building envelopes using ant colony optimization. *Proceedings of EG-ICE*, Ascona, 627–636.

"Distributed EXecution ENvironment": 2011. Available from: <http://www. dexen.org/> (accessed 05 December 2011).