# COMPUTATIONAL DECISION SUPPORT for AN AIRPORT COMPLEX ROOF DESIGN

A case study of evolutionary optimization for daylight provision and overheating prevention

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## ABSTRACT

This study focuses on generating geometric design alternatives for an airport roof structure with an evolutionary design method based on optimizing solar heat gain and daylight levels. The method incorporates a parametric 3D model of the building, a multi objective genetic algorithm that was linked with the model to iteratively test for various geometric solutions, a custom module that was developed to simulate solar conditions, and external energy simulation environments that was used to validate the outcomes. The integral outcome was achieved through an iterative workflow of many software tools, and the study is significant in dealing with several space typologies at the same time, taking real-life constraints such as applicability, ease of operation, construction loads into consideration, and satisfying design and aesthetic requirements of the architectural design team.

#### **KEYWORDS**

Evolutionary algorithms, daylight and energy performance, multi-objective optimization

#### **1 INTRODUCTION AND MOTIVATION**

This paper presents a case study in which geometric design alternatives for an airport roof structure were generated with an evolutionary design method based on optimizing solar heat gain and daylight levels. Our method incorporates a parametric 3D model of the building, a multi objective genetic algorithm that was linked with the model to iteratively test for various geometric solutions, a custom module that was developed to simulate solar conditions, and external energy simulation environments that was used to validate the outcomes.

While simulation methods for energy performance mostly allow for the testing of specific design scenarios, evolutionary methods iteratively generate and test several scenarios, presenting a range of optimal solutions to the designer. The benefits of the use of evolutionary algorithms for multi-objective optimisation in architectural design have been extensively studied [1–4], and several case studies that utilize such approaches can be found in literature [5–9].

Similar to the study presented in this paper, a number of these studies are concerned with geometric optimisation of roof structures [1, 2, 6]. As design objectives, many consider reduction of energy consumption while attaining sufficient natural daylight for illumination, and their methods incorporate trade-off decisions between these generally conflicting objectives [1, 2, 4–6, 8]. While it is a common approach to link a parametric model, a simulation engine and a genetic algorithm within the workflows of similar studies [1–3, 9], our presented method integrates a custom module that simulates solar rays for critical hours to test seasonal extreme conditions and a genetic solver already available as a plugin for the parametric modeling environment utilized. Among the few studies that take into consideration the spatial functional requirements of the buildings as cases presented [1, 6] (sports building), [3, 7, 9] (office building or spaces), our study is uniqe in that it considers specific daylight and solar radiation conditions required for spaces of varying functions within the airport complex (offices, cafes, indoor landscape elements, walkways, parking lots).

Along with these uniqe aspects, the work introduced here is a real-world study carried out for a building under construction in Cukurova, Turkey. We propose a replicable workflow for design problems where geometric alternatives are to be explored for optimisation of daylight and solar gains using parametric modelling and evolutionary algorithms.

### 2 THE CASE STUDY

This study was commissioned by the architectural design team of an airport project, to support the design decision process for the roof shell.

The airport was designed in a coastal, hot-summer Mediterranean climate. The complex consists of two independent buildings: The main one is the terminal building that accomodates terminals, a hotel and a carpark, with a footprint of 150.000 sqm (Fig.01). The second is a single storey building with a footprint of 20.000 sqm that houses CIP and VIP lounges (Fig.s 03 and 04). The building is under construction at the time of the submission of this paper.

In both buildings, the roof was designed to be supported by a concrete shell that spans over separate building blocks. The semi-open spaces between the two blocks required openings above to allow sufficient daylight in; and these openings posing the issue of overheating risk was the nexus of the environmental dilemmas our team faced.

The roof had already been designed by the architecture team as a grid shell, within which regions had been determined to be opened by the use of four different concrete modules, designed with varying perforation levels (Fig. 04).



Fig.01 3D visualization showing the two buildings (from design team's website)



Fig.02 Schematic plan of the main building



Fig.03 Schematic plan of the secondary building



Fig. 04 Modules and their opening ratios

The objectives of our study were to;

 Minimize energy consumption of active cooling particularly during hot seasons,
Provide sufficient natural daylight for interior and transitional spaces while preventing over-illumination and sun patches,

3. Take into consideration additional environmental stimuli such as rain and wind, particularly in the car park area,

4. Achieve these by primarily using the modular roof elements that were approved by the design team and were to be easily manufactured.

When the climate data was analysed, it was clear that preventing overheating was the main objective as direct solar radiation amounts were quite high. Based on global illumination and diffuse radiation levels, providing adequate amount of daylight did not seem to be a predominant problem. For these reasons, the optimisation process was based on a model of solar rays, in order to simulate direct sunlight, ergo solar radiation. While the quantity of natural daylight was usually not an issue, the quality needed to be controlled, therefore the daylight performance of generated roof geometries were simulated.

## **3 METHODOLOGICAL PROCEDURES**

Preliminary studies determined that three different evaluation methods were required for different areas of the building:

- 1. The main building's roof, the part that covers the terminal and hotel areas,
- 2. The main building's roof, the part that covers parking lots, and
- 3. The secondary building's (CIP/VIP building) roof (Fig. 05).

At the previous stages of design it was already decided by the design team that the shell structure was to be constructed with a 16m x 16m grid. Perforations deployed to optimize sunlight were to be configured through an arrangement of modules of this size, already designed by the architecture team.

In the CIP area, as the spaces underneath the shell is much smaller, the resolution of 16m x 16m was not sufficient. In this part of the roof structure, to provide an optimized solution, we proposed to use different opening ratios within a single module.

While the required perforation percentages for each area were determined by an initial basecase simulation run without any roof structure at all, the distribution of openings to provide the necessary perforation levels were calculated by the genetic algorithm.

The genoms provided to the GA for each of the three parts of the building studied were different due to the varying requirements. In the main building's terminal and hotel areas, the four different module options (0, 1, 2, 3) for each 16m by 16m grid cell constituted our discreet variables. For the parking area, an angle of extrusion for all the shading surfaces that changed at intervals of 5 degrees between 0 and 360 degrees (0, 5, 10,...355) were our discrete variables. For the CIP area, the perforated (1) and non-perforated (0) grid cell for each of the 100 cells in each 10m by 10m module were our discrete variables. A grading system that took into account all the spatial requirements was developed, which was then fed into the algorithm as the fitness formula. This grading system is to be further explained in the next sub-sections.



**Fig. 05** Schematic plans showing 3 different areas of study

# 3.1 ROOF OVER THE TERMINALS AND THE HOTEL

The complex has two separate roof surfaces that light needs to penetrate through; the larger main roof and the roofs of the blocks underneath. This requires a strategic positioning of the openings in the upper roof to selectively let the light in, also considering the greatly varying incident angles of wanted/unwanted sunrays (Fig. 06).

Base-case solar radiation simulations (without any roof at all) were run for each level, both for summer and winter conditions in order to understand how the masses of each block affect each other and the open spaces in between. These simulation results showed how much sunlight the areas could receive. Another investigation was mapping the differentiating spatial typologies (offices, hotel, terminal, cafes, etc.); which showed how much sunlight the areas needed to receive. Overlapping these, the areas and their corresponding roof parts were divided into different zones, and each zone was assigned a percentage of perforation that would transform the available sunlight into what was required.

A grading between -2 to 2 allowed for defining the most and least desirable times for direct sunlight to be received by each zone based on functions of spaces (Table. 01). The genetic algorithm was run on one zone at a time. Within given tolerances the algorithm produced many different results, each approaching the goal with slight variations.

#### Table 01. The grading system

		Bonus/penalty factors for spaces based on time and day						Weights factors for genetic algorithm	
		Hotel Facade	Terminal Facade	Office Facade	Cafe/Lounge Facade	Active greenery	Ground	Bonus/pena Ity factors	Perforation requirement (%)
June 21 <sup>st</sup>	09:00	1	-1	-2	-2	1	0	50%	50%
	12:00	-1	-1	-2	-2	-1	0		
	15:00	-1	-1	-2	-1	0.5	0		
	18:00	0	0.5	-2	0.5	1	0.5		
December 21 <sup>st</sup>	09:00	1	1	-1	1	2	2		
	12:00	0	1	-1	1	2	2		
	15:00	1	1	0	1	2	2		
	18:00		-	-	-	-	-		

In the algorithm we utilized for this part of the roof:

1. Our discrete variables were the four types of concrete modules (0,1,2,3),

2. Each case consisting of a configuration of varying modules within one zone was an individual,

3. The fitness criteria were formulated, based on the grading system (Table 1) providing negative and positive coefficients for the amount of desired and unwanted light rays, and total percentage of perforations in each case.

4. Octopus genetic solver [10, 11] was used with in the Grasshopper [12] visual programming environment in Rhinoceros3d [13] software. Octopus was chosen as it allows for the multi dimesional visualisation and analysis of results, each

dimension representing independent objective functions. The solutions are represented as points on this 3d graph, the position of each result demonstrating its proximity to satisfying each of the criteria (Fig. 10). The three fitness criteria corresponding to the 3 dimensions of the results graph in our study are as follows:

$$DP - \frac{\sum_{i=0}^{n} p_i}{n} \tag{1}$$

Where DP = desired perforation percentage per area

n=number of 16x16m cells populated with modules for the main terminals and the hotel

p= perforation percentage of each cell

$$-1 * \sum_{i=0}^{n} c * r_i \tag{2}$$

n= the number of regions per different time frames with different coefficients in the grading system

c= the coefficients determined by the grading system

r= number of solar rays that fall onto each region with different coefficients assigned to them in the grading system. Only, the rays falling onto the landscape elements are excluded here since they are taken into account seperately in a third fitness function.

The octopus genetic solver always tries to minimize the results, therefore this equation is multiplied by -1.

$$-1 * \sum r$$
 (3)

Where r = solar rays that fall onto the landscape elements.

1. The genetic solver was expected to pick successful patterns leading it to establish a set of pareto-optimized solutions. A brute force calculation of running all possibilities was impossible due the large number of possibilities. There are 50 openings only in Zone 10. 5 module option in all 50 openings would lead to a solution space of 550 (1.2089258196146292e+24) options.

2. In the genetic solver the greenery has been solved as an independent dimension. Altough it was preferable to get direct light on the interior landscape elements it was not vital for the performance of the building, keeping in mind that the landscape design was not completed during the study. When indoor landscape elemens were included in the overall grading system, it was observed that the genetic algorhytm achieved numeric success by only focusing on providing light on the landscape elements.



21 ARA 9:00

21 ARA 12:00







Fig. 06 Reflection of sunrays on the roof on different times & placing the openings strategically











Fig. 07 A sample from base-case simulations





Fig. 09 Genetic Algorithm Pareto-Optimized Solutions

Average Perforation Percentage

The evolutionary optimisation was run with a population size of 30 and 50 generations for each zone. The final selection of generated geometry was done manually. Octopus was choosen mainly due to its ability to remember previous iterations and its ability to navigate through multi dimensional results visually. Fig. 09 shows the relation between opening levels and numeric success of the grading system.

Best generated roof design proposals were tested in Ecotect [14] and Radiance [15] softwares, and compared with basecase runs on each level of the building for validation (Fig. 10).

# 3.2 ROOF OVER THE PARKING LOT

The parking lots being unconditioned areas without any envelope changed the performative priorities of the roof drastically due to any openings in the roof making it prone to rainwater directly. Additionally, achieving sufficient daylight levels throughout the year became more substantial than the risk of overheating. A new methodology was developed in order to evolve light wells with closed surfaces in the water-flow directions while letting maximum winter light in and preventing over-illumination and heteregonuous sun patches on the ground in summer (Fig. 11).

The idea of light wells had already been conceptually concieved when this study started. The expected performance criteria from the wells were: (1) to prevent direct rainfall, (2) while doing so, to satisfy the natural daylight requirements. In order to prevent rainfall, a slanted geometry was in question, therefore the geometrical limits to the wells were due to constructability rather than aesthectic. Due to the tricky process of removal of molds from a slanted well, the angle and height limits were set. These limits have been transfered to Grasshopper environment as the upper and lower bounds of number sliders. The results were validated through Radiance for daylight levels and distribution at the end of each iteration.

The study not only focused on the geometry of a single well, but also included how the wells were to be arrayed on the roof. At this stage of the study, the civil engineering team had to calculate the additional loads the proposed wells were causing, and this was one of the parameters our team had to take into account. In the algorithm:







Fig. 10 Control simulations for solar radiation



Fig. 11 One of the generated light wells and corresponding daylight simulations

 The light wells are slanted extrusions of a given base opening and an independently slanted cutting plane to be aplied on the extrusion.

 The optimization was run in a separate shoe box test, in order to see if the resulting daylight levels and distribution were within comfort band.
The fitness criterion used for the parking area optimization are as follows:

$$-1 * \sum_{i=0}^{n} c * r_i$$
 (4)

n= the number of regions per different time frames with different coefficients in the grading system

c= the coefficients determined by the grading system

r= number of solar rays that fall onto the ground with different coefficients assigned to them for each time frame in the grading system.

# 3.3 ROOF OF THE SECONDARY BUILDING

Due to the secondary building consisting of smaller blocks and in-between areas under the roof, a higher resolution study for the perforations was needed and the optimization was done by a perforation grid of  $1m \times 1m$  (Fig. 12).

The fitness criteria for the CIP area consists of the same formulation (1), (2) and (3); with a modification in formula (1) as follows:

$$DP - \frac{\sum_{i=0}^{n} p_i}{n}$$

Where DP = desired perforation percentage per area n=number of 10x10m cells populated with varying modules for the CIP p= perforation percentage of each cell

# **4 RESULTS AND OBSERVATIONS**

The decision making process in the study was intricate, iterative and multi-faceted. The integral outcome was achieved through an iterative workflow of many software tools, with an effort to prevent getting lost in translation regarding both the communication with the design team; and also in the use of many digital mediums.

Several studies have utilized evolutionary optimisation in the design of building envelope structures [1–3, 7–9], however the case we present is unique due to specific requirements and approaches utilized in the solution of the optimisation problem. Multiple different climatic conditions for multiple space typologies were considered including cafes, lounges, terminal areas, offices, a hotel, car parking and areas of indoor landscape; scattered in a complex 3D mass. To formulate these requirements into fitness criteria, a grading system was developed for each space typology adapted from CIBSE Guides for thermal and lighting requirements in different types of spaces [16–18]. Rather then linking a climatic simulator to the genetic solver, the solar rays that were simulated for eight specific hours in the duration of a year were utilized for efficiency of time and computing power. The project was a real-world case, therefore the study was carried out in coordination with a design team and required consideration of additional aspects usually disregarded in academic studies. These included aesthetic choices by the design architect, applicability, production cost, and ease of operation. Additionally, our workflow incorporated a final stage where we re-simulated performances of a number of manually selected geometries amongst the pareto-optimal solutions and made informed decisions to chose the most appropriate for the rest of the design. Finally, while it is common for architects to collaborate with several engineers in similar studies, it is rare to incorporate landscape architects. The optimisation parameters included the placement of active greenery as it was important to the designers to have live trees and foliage under the roof. For these reasons, the project is significant within applications of multi objective genetic algorithms in design optimisation, and is known to be first of its kind in Turkey.







(1)

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