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A systematic framework for evolutionary multi-objective optimization to complex building design problems at the early design stage

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Abstract. As in biology, multi-objective evolutionary algorithms cross-reference various design parameters in the search to maximize or minimize one or more specific objectives, thus finding the best solution for the specified purposes. In addition, it is possible to perform the appendment of many variables simultaneously and make numerous real-time simulations. This paper proposes a systematic framework for evolutionary multi-objective optimization to complex building design problems at the early stage. The framework is demonstrated by optimizing the courtyard geometry as a case study. The methods include generating courtyard geometry (i.e., height/width ratios and orientations) as design variables according to solar geometry. Simulations are explored, providing recommendations to maximize solar access in winter and filled shade during summer. The outcomes are a framework resumed systematically to address the contrasting objectives of the given building problems. The framework's application can adapt to each case's architectural, environmental, and technical criteria.

1 Introduction

The early building design produces rapid and iterative feedback for making the final and appropriate responsive decisions before applying them. However, it is still challenging to understand the implication of sustainable criteria for different aspects of building design, which often contrast with each other. The multi-objective evolutionary algorithms are an innovative and creative process for solving these conflicting requirements.

Evolutionary algorithms are typically used to provide near-optimal solutions to problems that cannot be solved efficiently using other techniques. Various evolutionary computation algorithms, such as evolutionary programming [1], evolutionary strategies [2], and genetic algorithms [3], have been proposed and studied. They are all based on a natural selection and adaptation process that mimics biological evolution (Darwin), including inheritance, crossover or combination, and mutation. However, genetic algorithms (GAs) are the most predominant class for optimizing complex problems in various domains, principally in optimizing the building's performance, due to their elitist classification that accelerates the convergence of the solution [4;5;6].

On the other hand, multi-objective optimization is the use of two conflicting objective functions that will generate a Pareto curve. The best solution will be the one closest to the utopia point in the search for minimization or maximization of the selected objective functions.

The aim of this paper is to propose a systematic multi-objective optimization framework for complex building design at the early design stages. The framework is demonstrated by optimizing the courtyard geometry as a case study using the Strength Pareto Evolutionary Algorithm 2 (SPEA2) genetic algorithm as a calculation engine.

2 Problem Formulating of Courtyard Geometry in terms of solar control

The geometry of the courtyard directly affects the amount of incoming radiation [7]. It is expressed by the sunlight and shading areas resulting from the interaction between the courtyard geometry parameters and the sun's position in the sky (i.e. azimuth and sun elevation angles). It has a crucial effect on the thermal behaviour of the courtyard and the internal spaces next to it. Shading decreases the convective heat transmission from sunlight and inner and ground surfaces, while solar access increases it.

In semi-arid regions with hot summers and cold winters, achieving trade-offs between winter sun and summer shade areas for courtyard design is challenging. It requires a careful balance of courtyard geometry to achieve conflicting objectives, constrained by various variables that vary according to summer and winter needs.

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3 Methods

This paper utilizes a case study of a courtyard design in a semi-arid region of Algeria to demonstrate how we can design an optimal courtyard geometry in terms of solar control. An evolutionary algorithms approach via Octopus plugin for GrasshopperRhinoceros software was used to optimize. Rhinoceros is a 3D computer graphics and computer-aided design application software that utilizes the Non-Uniform Rational B-Splines mathematical model. Grasshopper is a visual programming language and environment within the Rhinoceros 3D computer-aided design application. Octopus is a Grasshopper module developed initially for evolutionary multi-objective optimization.

Two objectives were optimized in the process, i.e., maximize solar access in winter and maximize shade in summer. The combinations of courtyard H/W ratios and orientations that maintain adequate solar access during the cold period while maintaining shading during the hot period were chosen as design variables. The study is divided into three main steps, including (1) modelling the courtyard with design variables, (2) solar access shade simulation performance, and (3) multi-objective optimization and verification of the optimal solution. The results for each step are described in the following section.

4 Experimentation and Results

We present an application example on courtyards in Constantine City (36°17' latitude), Algeria. Eleven typical courtyards were generated and simulated based on a Grasshopper-based automated geometric generation and simulation system using the Ladybug plugin to predict full sunlight and shading areas.

4.1 Modelling design variables of courtyards

We generated an algorithm on Rhinoceros/Grasshopper for modelling the courtyard parametrically with a set of parameters such as the different dimensions of length, width, height, H/W ratio and orientation (Figure1).

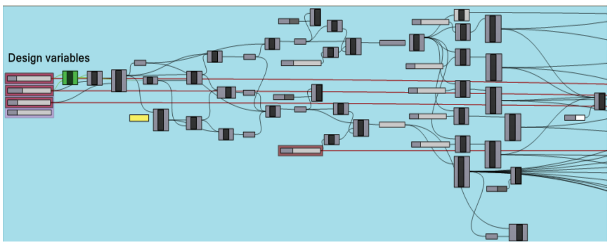

Fig. 1. Courtyard geometry components

4.2 Simulation performance of solar access and shade

The simulation performance of the courtyard was carried out using various components of the Ladybug plugin in Grasshopper to implement the algorithmic definition and simulate the performance of the courtyard in terms of solar access and shade in courtyard surfaces over a day. These components consist of import EPW, Sun Path, Sunlight Hours Analysis and some mathematical operators. Each component has inputs and outputs.

- The import EPW component imports the weather data into Grasshopper from a .epw file. The requisite input is the .epw file path, latitude, and location, while the climatic parameters are the output.
- The sun path component creates a 3D sun path in the Rhinoceros interface and uses sun vectors to analyze sunlight hours or shading design. The requisite input is _location outputted from the "LB Import EPW" component.
- The sun hours analysis component calculates the sum of direct sun hours the geometry receives using the sun vectors from the "LB SunPath" component. The requisite inputs include Geometry for which the sunshine hours were analyzed. The "_context geometry" entry is also obligatory to block sunlight from the _test geometry. The "Sun Vectors" input of "LB SunPath" resolute the number of hours of direct sunlight the test _geometry received. "Grid size" is a number in Rhino model units representing the average size of the grid cells for the analysis of sunshine hours on the test _geometry.
- The _disFromBase is a number in Rhino model units representing the offset distance of the test point grid from the input test _geometry to ensure that the sunlight hours analysis is performed for the right side of the test _geometry. The main outputs used for this simulation are: "sunlightHoursResult," which represents the total number of _sunVectors connected to direct sunlight received by each test point of the input test _geometry, and "sunlightHoursMesh," which signifies a coloured mesh of the test _geometry representing the hours of direct sunlight received by this input _geometry.

The simulation results of all these steps demonstrate and validate the contribution of courtyard surfaces in solar access and shade (Figure 2). The algorithmic definition in detail is shown in (Figure 3) and (Figure 4).

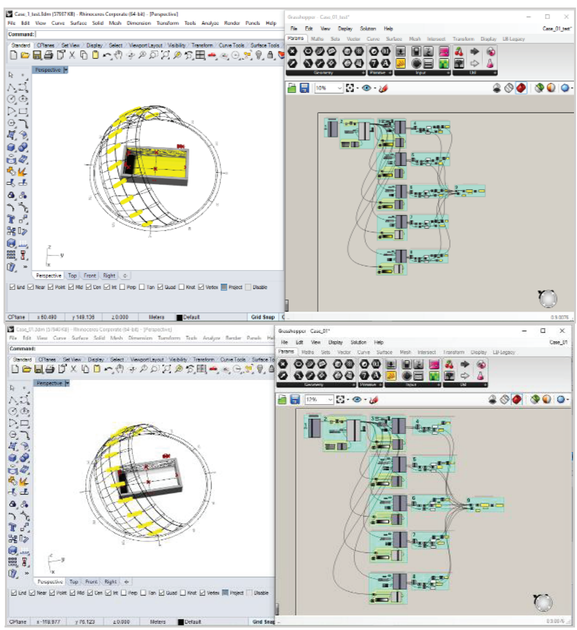

Fig. 2. Example of solar access and shade simulation

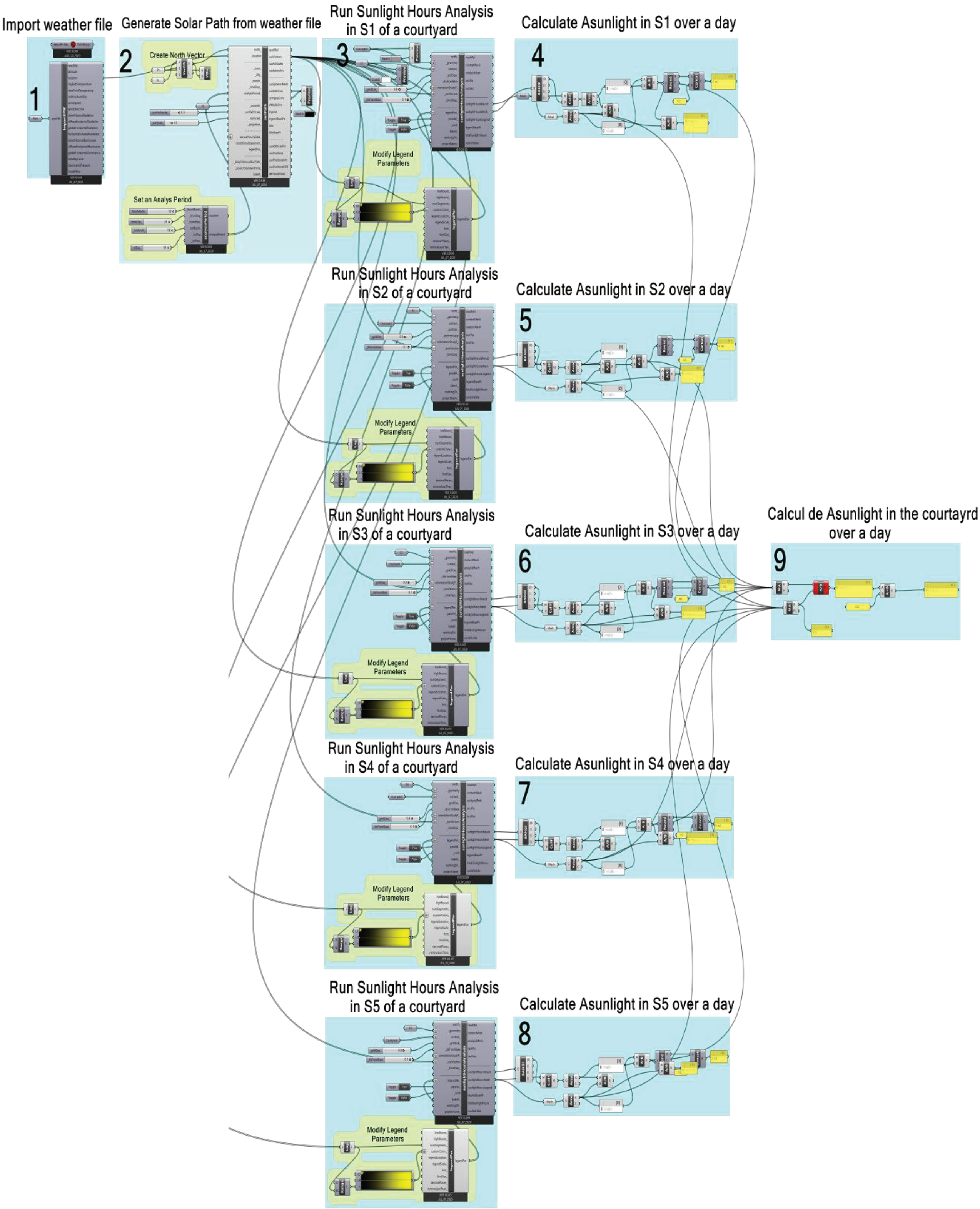

Fig. 3. Algorithmic definition for calculating the percentage of Asunlight over a day

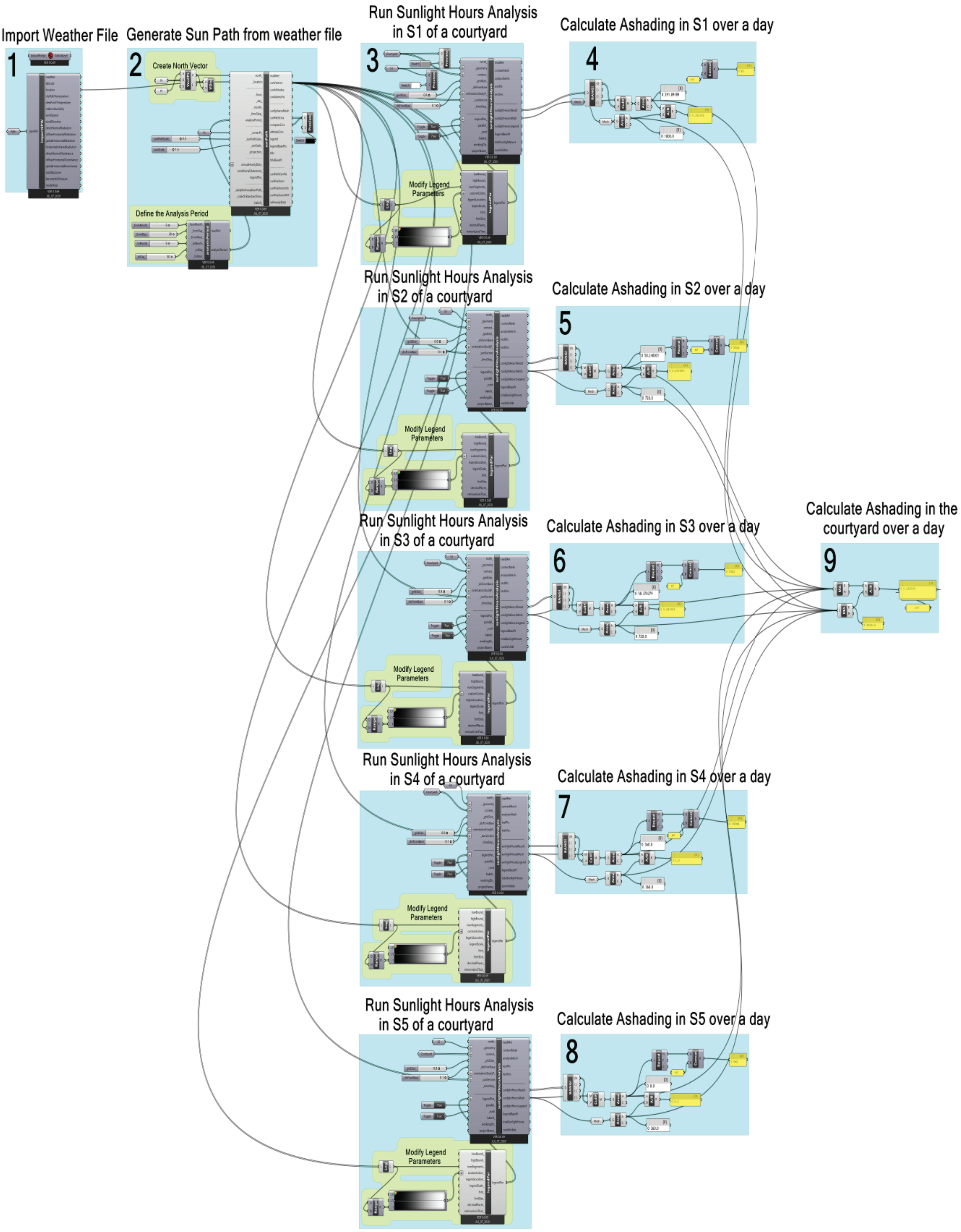

Fig. 4. Algorithmic definition for calculating the percentage of Ashading over a day

4.3 Multi-objective optimization

This step optimizes the courtyard geometry to achieve two objective functions: maximize solar access and maximize shade within the yard during the year. Several optimization parameters were selected and combined in a multi-objective optimization tool (Octopus) using the Pareto optimality theory with an evolutionary algorithm (Figure 5).

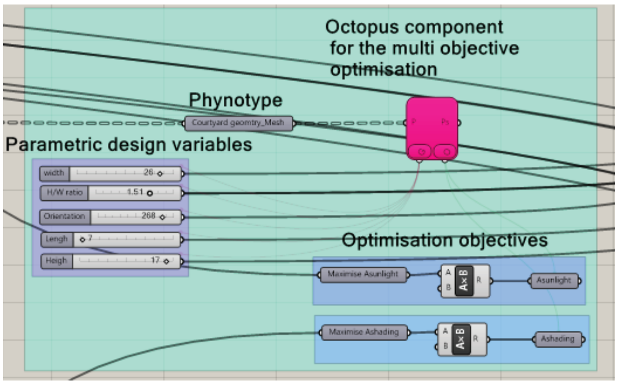

Fig. 5. Courtyard geometry components

As shown in Figure 4, the H/W ratio and the orientation were set as design variables. Maximizing solar access during the winter and maximizing shading during summer were defined as objective functions. The phenotype represents the geometry of the courtyard used in the optimization process.

After running the simulation, several solutions for different H/W ratios and orientations variables were explored to achieve the objective function (sunlight and shading requirements). They are scattered through a three-dimensional graphic that presents the various configuration of the courtyard where all possible best trades between the two objectives could occur.

5 Discussion and Conclusion

The paper presents a systematic framework of multi-objective optimization based on genetic algorithms to achieve different or contrasting objectives for given problems. The framework is demonstrated by optimizing the courtyard geometry as a case study.

The methods included generating courtyard geometry (i.e., height/width ratios and orientations) as design variables according to solar geometry. While two contradictive objectives were optimized in the process, i.e., maximize solar access in winter and maximize shade in summer.

The outcome provided a systematic framework for evolutionary multi-objective optimization to balance the various, sometimes conflicting, environmental building performance goals in the following steps:

(1) Identifying fundamental objectives and design variables and constraints.

(2) Setting performance constraints based on environmental and building contexts.

(3) Formulating fitness functions based on design variables and other problem parameters,

(4) Selecting algorithms optimization process

(5) Running the simulations to find the appropriate performance (optimal) and constraint satisfaction solutions

(6) Finally, creating a performing design based on the decision variables for which the objective function reaches its optimal value.

Based on the developed framework, designers can get valuable information to make more effective and accurate decisions during the design process. Since several alternatives derived from the multi-objective optimization features are presented, designers can choose the appropriate one according to the requirements of any specific design project. They can also use this method during the early stages of their decision-making by applying the mentioned tools, increasing the opportunities for solving complex problems.

Moreover, this approach could be appropriate to address the urgency of adaptation and resilience to climate change by identifying a series of suitable solutions by exploring possible combinations within a reasonable time [8]. In particular, the complexity and extent of the implementation of climate change adaptation depend on the cooperation of diverse stakeholders with different perspectives, expectations, and interests in line with the policy implementation characteristics in each country [9], which often contrast with each other.

In summary, applying the developed framework can adapt to each case's architectural, environmental, and technical criteria. It would determine the construction of more energy-efficient, low-emission, cost-effective, and comfortable buildings as well as enhance Climate change resilience generally. This would be fundamental to promoting sustainable development in its double meaning; a better life for us and a (better) life for future generations.

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