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Research paper

PERFORMANCE-BASED DESIGN IN ARCHITECTURAL EDUCATION: CLIMATE-RESPONSIVE URBAN DESIGN THROUGH ENVIRONMENTAL SIMULATION

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Abstract

The increasing frequency of extreme heat events in urban environments requires architects and urban designers to develop new competencies for creating climate-responsive cities. In this context, performance-based design (PBD) approaches, supported by environmental simulation and optimization tools, have become an essential component of contemporary architectural education and practice. This paper presents an educational framework implemented within a Master's level architectural course, where students are trained to integrate environmental performance analysis into the early stages of the design process. The course introduces parametric and simulation tools such as Rhinoceros, Grasshopper, Ladybug and Galapagos, Ecotect and City Engine enabling students to evaluate and optimize urban design proposals based on measurable environmental criteria.

Students independently address urban climate-related design challenges and develop parametric models to investigate potential improvements in insolation and outdoor thermal comfort. The projects presented in this study include the optimization of tree placement to reduce insolation in children's playgrounds and the modification of building heights and massing configurations to improve thermal conditions in courtyard spaces while maintaining comparable floor area ratios. Also, outdoor thermal comfort is evaluated under the canopy whose geometry was optimized.

The results demonstrate that integrating PBD methodologies into architectural education enhances students' understanding of the relationship between urban form, vegetation and environmental conditions. Furthermore, the use of simulation and optimization tools supports informed decision-making in the earliest design stages, enabling future architects to identify and mitigate potential environmental problems before implementation. Such educational approaches contribute to the development of professional competencies necessary for designing sustainable, climate-adaptive, and resilient urban environments.

Key words: *Performance-based design, Climate-responsive urban design, Urban design education, Environmental simulations, Parametric modelling.*

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1. INTRODUCTION

Climate change and rapid urbanization have increased environmental challenges in cities, including urban overheating and reduced outdoor thermal comfort [1,2,3]. These issues have highlighted the importance of climate-responsive approaches in urban design. Architects are expected not only to develop spatial solutions but also to understand how their design decisions affect environmental conditions during the design process.

Recent developments in digital design and environmental simulation tools have created new opportunities for integrating environmental performance assessment into architectural practice. Performance-based design (PBD) enables designers to evaluate and compare design alternatives using measurable environmental indicators, supporting more informed design decisions. Tools such as Rhinoceros (3D modelling software) [4], Grasshopper (Rhinoceros plug in, visual programming software) [5], Ladybug (Grasshopper plug in, software for environmental analysis) [6], Ecotect (software for environmental analysis) [7], City Engine (software for procedural modelling of urban areas) [8] and optimization algorithms [9] allow designers to investigate the influence of urban form, vegetation and insolation on outdoor environmental conditions [10,11]. These tools are particularly valuable during the early design stages, when decisions can have a significant impact on the future performance of urban spaces.

As environmental performance becomes a more important part of design practice, architectural education must prepare students with the knowledge and skills needed to apply these methods. The integration of environmental simulation and optimization techniques into course can help students better understand the relationship between design decisions and environmental performance while encouraging a more analytical design approach [12,13,14].

This paper presents an educational framework implemented within a Master's level architectural design course focused on climate-responsive urban design. Using Rhinoceros, Grasshopper, Ladybug and Galapagos, students explore and optimize urban design solutions addressing issues such as insolation and outdoor thermal comfort through vegetation and built form modifications. The paper describes the course methodology and presents representative student projects that demonstrate how environmental simulation and optimization tools can be effectively integrated into architectural education to support sustainable urban design and improve environmental performance in urban spaces.

The findings suggest that integrating performance-based design methods into architectural education can help students better understand the environmental impact of design decisions and develop skills needed to address contemporary challenges in the built environment.

2. COURSE METHODOLOGY

The presented framework was developed within a Master's level architectural course focused on climate-responsive urban design and environmental performance assessment. The primary objective of the course is to introduce students to PBD methodologies and enable them to integrate environmental analysis and optimization into the early stages of the design process.

The course combines theoretical lectures with practical workshops. Students are introduced to parametric modeling and environmental simulation tools, including Rhinoceros, Grasshopper, City Engine, Ladybug, Ecotect and Galapagos. These digital tools allow students to evaluate the environmental performance of urban spaces and test alternative design solutions based on measurable criteria.

At the beginning of the semester, students select a specific urban environmental problem related to urban ground insolation and outdoor thermal comfort. The selected urban design is modeled using Rhinoceros, Grasshopper and City Engine, while environmental simulations are conducted using Ladybug and Ecotect.

Depending on the project objectives, students define performance indicators and optimization criteria that serve as the basis for the design process.

A typical workflow consists of the following stages:

1. Identification of an environmental problem within an urban context.
2. Development of a parametric digital model.
3. Definition of design variables.
4. Environmental simulation and performance evaluation.
5. Optimization.
6. Comparison and assessment of alternative design solutions.

The use of Galapagos enables students to explore multiple design iterations and identify solutions that best satisfy predefined performance objectives. Through this process, students gain practical experience in decision-making and develop an understanding of the relationship between urban form, vegetation, and environmental performance.

3. REPRESENTATIVE STUDENT PROJECTS

The projects cover different topics and address environmental challenges in contemporary urban contexts. However, all projects follow the same methodology based on simulation, performance evaluation and optimization.

3.1 Optimization of tree placement to mitigate insolation in playgrounds

This type of project focuses on reducing insolation in children's playgrounds during the summer period. High levels of insolation often limit the usability of these outdoor spaces and increase thermal stress for users.

Students explore how the arrangement of existing trees can be optimized to mitigate insolation. 3D models were created in Rhinoceros and referenced within Grasshopper. Tree and playground locations are defined as variable parameters, while optimization is carried out using the Galapagos algorithm in combination with randomly generated points and the Populate 2D component. Solar radiation analysis is performed using Ladybug to evaluate the effectiveness of different configurations.

The optimization process identifies tree layouts that minimize insolation, resulting in a 24.4% reduction (from 469.02h to 354.35h) in solar exposure within the defined analysis period (from 21 June to 21 September, from 11:00 to 18:00), while respecting spatial constraints within the site. Convergence was achieved through repeated simulation cycles until no further improvement in the fitness function was observed. Through this exercise, students learn how vegetation can be strategically integrated into urban design to improve outdoor microclimatic conditions. The workflow of this project is presented in *Figure 1*.

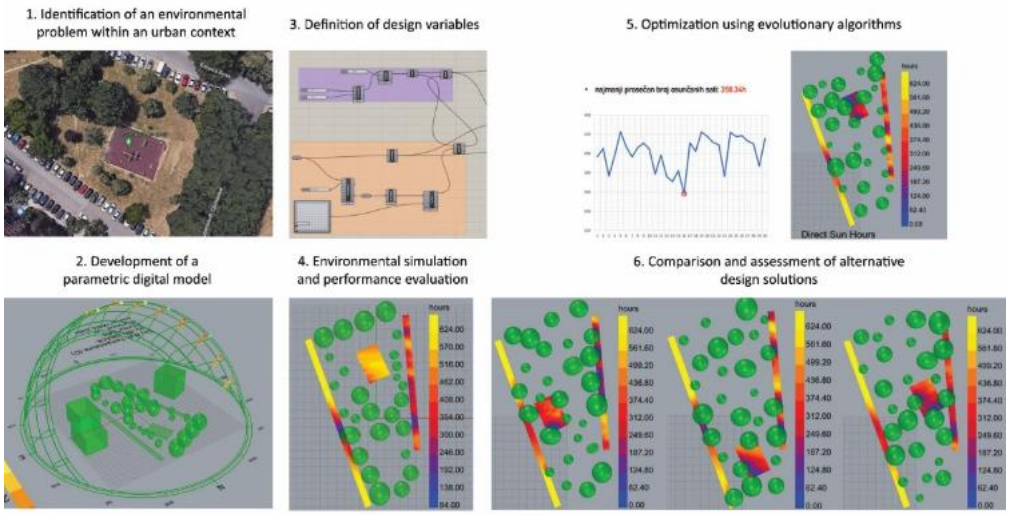


Figure 1. Workflow for optimization of tree placement for mitigating insolation in playground. Project by student Milica Simovski.

3.2 Manual optimization of building heights for mitigating insolation

The second project investigates the influence of building morphology on insolation within urban blocks. Students develop parametric models in which building heights can vary while maintaining approximately the same gross floor area. This constraint ensures that environmental improvements are evaluated without significantly affecting development capacity. 3D models are generated in City Engine while the insolation simulations are performed in Ecotect. Optimization process is manual / semi-automated iterative parameter search with attribute-driven variation in City Engine, involving the generation and evaluation of approximately 50 different 3D urban design configurations.

Through iterative insolation simulations, students explore how modifications in building massing influence shading patterns. The results demonstrate that relatively

small changes in building heights and spatial configuration can significantly improve microclimatic conditions within urban courtyards and pedestrian areas , resulting in a reduction of insolation from 1236.51 kWh/m² (existing urban design) to 1134.62 kWh/m² (improved urban design), which corresponds to an approximate 8.2% decrease.

These projects encourage students to understand the complex relationship between urban density and solar access. The workflow of this project is presented in *Figure 2*.

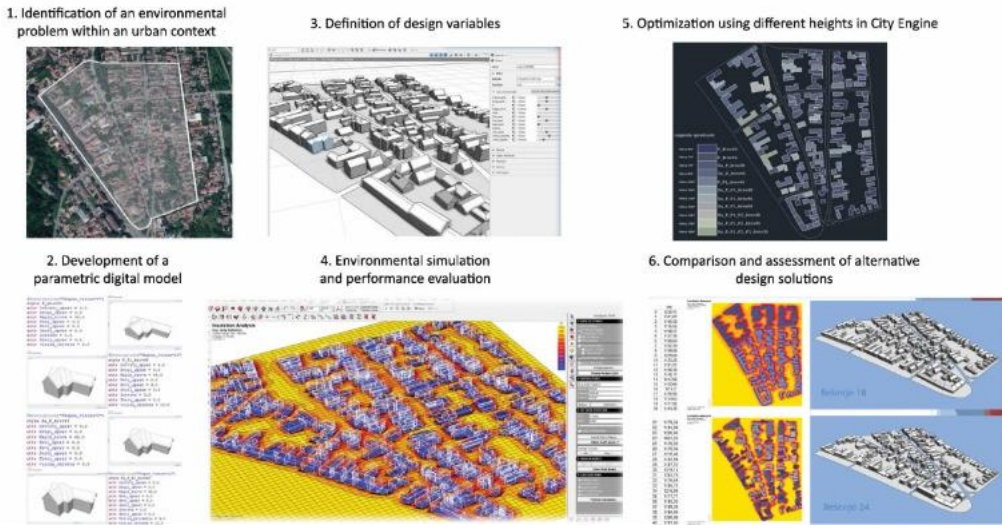


Figure 2. Workflow for the manual optimization of building heights for mitigating insolation. Project by student Marija Esapović.

3.3 Optimization of canopy design to improve outdoor thermal comfort

A third project focuses on architectural shading devices as a means of improving outdoor thermal comfort in public spaces. Students investigate the parametric design of canopies and their environmental performance.

Parametric models created in Rhinoceros and referenced within Grasshopper are used to modify key geometric parameters of the canopy, such as roof opening size, arched opening size, number of side openings, and side opening size. The environmental performance of outdoor thermal comfort is evaluated within Ladybug using the Universal Thermal Climate Index (UTCI), while optimization tool Galapagos is used to identify configurations that maximize shaded areas and improve thermal comfort conditions below the structure. The optimization process was carried out iteratively until no further improvement in the fitness function was observed.

The results show a clear improvement in outdoor thermal comfort, with the average value for all analyzed points decreasing from 28.57°C (existing condition) to 23.95°C (optimized solution), corresponding to an approximate 16.2% reduction in average thermal stress conditions.

This project demonstrates how architectural elements, when designed through PBD parametric workflows, can function as active environmental modifiers in urban outdoor spaces. The workflow of this project is presented in *Figure 3*.

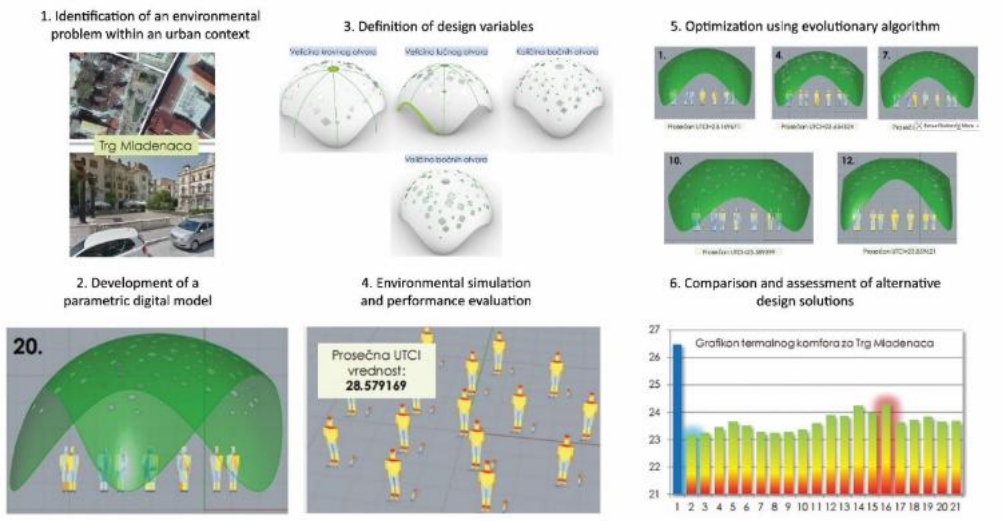


Figure 3. Workflow for the optimization of canopy design to improve outdoor thermal comfort. Project by students Natalija Manja, Aleksandra Gatarić and Aleksandar Lesmajster

4. RESULTS AND EDUCATIONAL OUTCOMES

The implementation of PBD methodologies within the Master's level course has indicated several educational outcomes based on student project work and course observations:

- By applying simulation workflows, students demonstrated engagement with the relationship between design decisions and environmental performance.
- The project approach enabled students to explore a wide range of climate-responsive design strategies while operating within realistic spatial and functional constraints.
- The projects indicate students' ability to apply simulation-based methods in addressing urban design problems.
- The use of evolutionary optimization tools encouraged students to explore the complexity of urban design problems. Rather than searching for a single predefined solution, students explored multiple design iterations and examined trade-offs between environmental performance and spatial constraints.

The results suggest that relatively modest modifications in urban form and vegetation distribution can produce noticeable improvements in key environmental indicators.

The variety of student projects (*Table 1*) also highlights the flexibility of the proposed educational framework. Although projects addressed different scales and topics from urban vegetation and microclimate improvement to building massing and shading performance the same performance-based methodology proved transferable across various design contexts.

Table 1. Integrated workflow for parametric modelling, simulation and optimization for different student projects.

Case study	Design variables	3D modelling tool	Optimization approach	Simulation tool	Outcome
Tree layout	Tree position	Rhinoceros 3D, Grasshopper	Automatic (Galapagos)	Ladybug	Reduced playground insolation by 24.4%
Buildings height	Height variation	City Engine	Manual iterative variation (City Engine)	Ecotect	Reduced courtyard insolation by 8.2%
Canopy design	Geometry parameters	Rhinoceros 3D, Grasshopper	Automatic (Galapagos)	Ladybug	Reduced UTCI by 16.2%

5. CONCLUSION

The presented educational framework highlights the potential of integrating PBD methodologies into architectural education. By combining parametric and procedural modeling, environmental simulation, and evolutionary optimization, students develop design solutions based on measurable environmental criteria rather than intuition alone.

The use of tools such as Rhinoceros, Grasshopper, City Engine, Ladybug, Ecotect and Galapagos are used to explore the relationships between urban form, vegetation, insolation, and outdoor thermal comfort. Through projects, students work through iterative design processes and evaluate alternative solutions during early design stages.

The presented student projects illustrate how environmental simulation can support the development of climate-responsive urban design strategies, including the optimization of tree placement, building morphology and shading configurations. These exercises provide a structured environment for exploring the environmental consequences of design decisions within a performance-based workflow.

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