High-rise Building Optimization

A Design Studio Curriculum

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The paper presents an educational method used in teaching design of high-rise buildings in the city center. The author outlines the processes developed by students, the tools they used and the final results of design studio project and the supporting seminar, focused on exploring information processes in design. For the purpose of the design studio the students developed their own generative strategies that allowed incorporating optimization procedures into the design process. Within the framework of the seminar classes students developed individual optimization tools with the use of genetic algorithms in order to explore the search space and select the best possible architectural solutions for the specified criteria. The students used the above-mentioned tools mostly during the building's form-finding design stage or attempted to optimize just the building structure.

Keywords: Genetic algorithm, High-rise building, Skyscraper, Environmental analysis, Office building

INTRODUCTION

In recent years we have been experiencing a rapid development in the field of digital design tools. CAD software packages are being extended by geometric and numerical constraint solvers, which thus allow architects not only to formalize they design rules but also to incorporate computational optimization methods in the design practice. Computer aided design systems enable designers to explore design concepts and inform about its performance. Recent research initiatives (Xie et al. 2005; Kilian 2006; Hough et al. 2007; Aish et al. 2012) have shown that design process is shifting from pure form driven approaches towards the generation of form based on performance strategies of design. The computational optimization methods used by architects to design tall buildings have been recently well developed in terms of the building's structural performance (Almusharaf and Elnimeiri 2010) as well as for environmental performance (Dritsas et al. 2006; Castorina 2012).

A growing number of generative and analytical tools used in the architectural design process together with the development of new design methodologies result in the popularization of computation in architectural design. This requires both testing of such methodologies under various conditions and educating with regards to their usefulness.

Computer-aided design comparing to analog
process of designing is more a knowledge-based profession than one based on intuition. The integration of computer related subjects into design studio is a crucial response to the ongoing change in design methods. Combining design courses with algorithmic design tools allows students to create digital models of their buildings, which are informed by quantitative factors (Martens et al. 2001). The inclusion of new design technologies in architectural curricula promotes creative design thinking when is used as a conceptual tool and not just as a tool for creating project presentations (Duarte et al. 2010). When one compares the case study conducted in Technical University of Lisbon, School of Engineering in Portugal, whose curriculum is based on a combination of design courses with computer education, with the one from School of Civil Engineering, Architecture and Urban Design of Campinas State University in Brazil, where students are taught separate digital skills with less connection to design studios, it is apparent that the former is more effective in terms of equipping students with usable expertise of contemporary design methods.

During 3rd semester of Architecture for Society of Knowledge Master's program at Warsaw University of Technology design studio classes are being closely integrated with computer related subjects. Design Studio 3 (DS3) tutored by Dariusz Hyc and Krystian Kwieciński is supported by Technic Integration seminar and lectures tutored by Agata Pasternak and became a test field for verifying how such methodologies could be employed in solving complex architectural design problem under specific local conditions. The goal was to investigate the potential of incorporating computational optimization methods in advancing designs and to verify how the simulation of real architectural practice conditions might constrain or strengthen the design process and influence final outcomes. During DS3 students were developing design projects of high-rise office building located in the centre of Warsaw in accordance with Polish building regulations.

**METHODOLOGY**

Design Studio 3 was divided into two parts. In the first part students were introduced to the practical knowledge related to the design of high-rise office buildings in the city centre, in context of Polish building regulations. The students were also provided with information about architectural constraints which are influencing the design of this type of buildings. These included urban regulations, environmental impact on the surrounding, optimal working conditions, fire safety regulations, evacuation, technical installations, facade systems, functional programs and current tenancy strategies.

Provided information was accompanied by examples of design solutions for particular building elements like the core or facades of the building, most common structural systems, vertical communication and types of office space layouts. Architectural knowledge was juxtaposed with the knowledge coming from other fields of expertise. The invited property consultant from PWC shared his expert’s knowledge about Polish real estate market and how architectural design influences the market value of office buildings, especially high-rise office buildings. Students were informed about factors influencing the construction costs of tall building, how it is affected by the building’s height, what the lessee’s business profiles in Central Business District are or what factors influence the profitability of the project.

A sustainability engineer from BuroHappold introduced students to the aspects of sustainable strategies for designing a high-rise office building, existing technical solutions for installation systems, certification of office buildings and how they alter the design process.

In the first part of the studio groups of students were supposed to prepare design sketches of the main building elements of a high-rise office building for a chosen location in Warsaw. The goal of this task was to test in practical terms the provided knowledge and discover main constraints of the given task. At this stage the maximum building volume was also analyzed in order to fulfill the Polish insolation reg-
Due to the complexity of this task the optimization procedure was performed by dedicated PRC Analysis software developed by Jacek Markusiewicz (2014). This resulted in a 3d form which was further developed by groups of students in order to design rational communication schema, functional layout, ground floor plan and repetitive floor layout. The invited guests evaluated the design proposals during mid-term project reviews.

In the second part of the course, the students worked individually on their design proposal. The conceptual designs, developed in stage one, formed a starting base for individual work. During this stage, students have used the optimization procedures developed at the Techniques Integration seminar to inform their design concepts.

The design studio follows the curriculum of CAD-Plus Studio: integrating knowledge about performance into the design process, where students are encouraged to use simulation and analysis tools to enhance the process of creating the building form (Gross and Do1999). As specified by Gross and Do, such a studio relies on auxiliary courses and lectures by invited guests to provide knowledge to students in areas such as structural design, environmental analysis or acoustics. The DS3 course was supported by a series of consultations with the aforementioned experts as well as the lectures delivered within the Techniques Integration module, which dealt with theory of architectural optimization, technical aspects of genetic algorithms and topics related to environmental and structural analysis. Some of the lectures were supplemented by software tutorials.

During the Techniques Integration seminar students worked on a detailed aspect of their building, such as a fragment of the building skin or its structure. In practice, Galapagos plugin for Grasshopper was used to create and control genetic algorithms. In the design, factors such as: construction, insolation and visibility were taken into account. Grasshopper, as an open source software, has many extensions, such as Kangaroo, Geco or DIVA, that allow, among other, environmental and structural analysis.

BUILDING VOLUME OPTIMISATION IN RELATION TO INSOLATION CONDITIONS

The Polish building regulations pertaining to the minimal insolation conditions that every living space has to fulfill are very restrictive and at the same time difficult to analyze due to the lack of flexible methods of estimating whether an analyzed space meets the requirements. A commonly used method in this respect is the shadow analysis, which is not flexible enough to facilitate a dynamic approach to design, as it requires time consuming calculations to be repeated after each change in the designed shape of the building.

PRC Analysis is a computer program developed by Jacek Markusiewicz, which was utilized in the first part of Design Studio course (Fig. 1). The software was used to analyze the existing insolation conditions of living spaces in the neighborhood of the design localization and how they might be affected due to new development. Shadow analysis performed by the software are calculated, using ray tracing method, the insolation in specified windows based on the exact position of the sun for the chosen location. From each of analyzed windows and for each position of the sun in the analyzed time interval a vector is calculated in the direction opposite to the direction of the sun rays. The rays are utilized to determine whether they encounter an obstacle blocking them. The program automatically calculates the insolation of all the windows in the selected time span based

![PRC Analysis screenshot](source: jacek-markusiewicz.com)
on the imported 3d models of designed building, surrounding buildings and windows that need to be analyzed. The calculation of the insolation time for each window involves simulating of the sun path for the given day in a chosen location. Additionally the software can also optimize the building volume in order to meet the required insolation regulations for each of the analyzed windows. The building volume is being cropped so that it meets the minimum requirements of the sun insolation on a given day. This optimization strategy was used during the Design Studio in order to establish the maximum building volume that would fulfill the required insulation regulations. The resulted 3d form reduces negative impact of the development on the surroundings by minimizing the time when windows of existing living spaces are being shaded. This form constrained individual design solutions developed in the second part of the Design Studio by setting a maximum building volume which could not be exceeded (Fig. 2).

OPTIMIZATION PROCEDURES
Genetic algorithms (GA) are a subcategory of evolutionary algorithms inspired by natural processes. The GA follows the process of natural evolution by using mutation and recombination of genes to create a population of objects that are transferred from generation to generation (Holland 1975). Objects whose fitness value is the lowest are not selected for breeding and therefore are not involved in the process of creating new individuals. GAs are often used to solve architectural optimization problems, because they allow multi-criteria optimization and they allow analysis of various data types (Goldberg 1989).

In a GA, a population of candidate solutions to an optimization problem is evolving toward better solutions. The notions of the genotype, the phenotype, the fitness function as well as such concepts as crossover and mutation are essential for optimization processes. In science, the genotype of an organism stands for the inherited instructions within its genetic code. In computing, genotypes are parameters that code the appearance or behavior of phenotypes in genetic and evolutionary algorithms.

When using GAs the optimized object is created or literally "grown" in a manner analogous to natural selection. The first step of this process is the creation of the group of individuals that form the starting population. The individuals are generated according to the programmed algorithm using random values of parameters from the provided ranges. All the dependencies between the object's elements are controlled by a genotype, which has the form of a numeric code. The parameters encoded in the genotype are each time translated into a physical form, called the phenotype. Each phenotype is then examined the extent to which it meets the predetermined conditions, such as structural strength, interior insulation or the building production time and cost. Subsequently every individual is evaluated and assigned a relevance factor, called the fitness value, which corresponds to the fulfillment of the target function. Individuals who belong to the population that have the highest fitness value will be attributed the proportionally high rate of probability of being selected for breeding. Those individuals are called "parents" for the new individual - the "offspring". The parental genotypes of pairs of individuals are crossed; fragments of genetic codes are combined, which leads to the formation of new probably fitter object. The higher the value of the fitness function the individuals have, the more often they are selected for repro-

Figure 2
Maximum building volume; the result of PRC Analysis software.
duction. In the final effect the entire process leads to homogenization of the population, in which, despite the use of mutation, individuals do not undergo further modifications.

Two main trends are present in students projects, which are the result of the described design studio and the supplementary seminar. The first group of solutions are the projects that use optimization as a form finding procedure, among which are projects generating the building form or shaping the building external skin. The second group of solutions are optimization procedures that deal with particular, isolated building element, such as structure or shading system. In subsequent paragraphs we present four student projects, two from each category, and describe in details the optimization strategy and the resulting building form.

CASE STUDIES
The Rondo ONZ area is becoming a very important financial zone in Warsaw (Fig. 3). It is located close to the city center with access to a well-developed public transport network, which was recently upgraded with a second metro line. The district provides many workplaces, but is not sufficiently equipped with gastronomic infrastructure.

The square between the designed buildings may potentially attract workers from other high rise buildings located in the surrounding. The main issue of that space is the lack of sunlight. It is surrounded from three sides by tall buildings and only the northern side is open. Two described below projects are providing solutions for that problem. The other two relate to the aspects of structural optimization.

Project 1, Maciej Sutula:
The project by Maciej Sutula uses optimization procedure to increase the insolation of the square by shaping the facade of the building. The west-facing facade is divided into panels of two-storey height, which are rotated around their vertical and horizontal axes to reflect the sun coming from specific direction (Fig. 4).

The façade is divided into five types of panels, each of which reflects light in a given period of the year, when additional light on the square is needed, e.g. in December between 12.00 and 3 pm (Fig. 5). The panels are randomly distributed on the facade so that they don’t produce a concentrated glare.

At the beginning, the volumes of the two buildings and the square are modeled. The western fa-
Facade of the taller building is divided into panels. Each panel is 7.20 m tall and 2.70 m wide. Sun vectors for specific time of the year are generated using the Autodesk Ecotect software. For each vector a plane perpendicular to it is drawn. On the facade 1/5 of all panels are randomly selected.

From each centroid of the panel the closest point to the selected sun positions are found and lines connecting them are drawn. Then with the help of geometric transformation (mirror) lines representing the reflections of 'light rays' are drawn. Intersections between 'light rays' and the surface of the square are found and counted. The number of 'heats' represents the fitness value of the genetic algorithm. The rotation of panels in two axes are the genes, which need to find its optimal values in order to reflect from different parts of facade as much light onto a relatively small surface. The same procedure is conducted for all 5 types of panels designed so that they suit particular time of the year (Fig. 6).

**Project 2, Katarzyna Gorowska:**
The designed office building is divided into two parts in order to achieve maximum natural light inside the building and maximize the area of office spaces (Fig. 7). Shading analyses were carried out in order to check the availability of natural light in offices and direct light in the park behind the building. The preliminary analyzes demonstrated the square is almost completely shaded by the proposed investment.

It is preferred to maximize the park illumination during lunch hours. The optimization goal is to lit the park during spring-summer period from 9 am to 3 pm and maintain the greatest rentable floor area. The building’s initial form is slightly sculpted to fulfill that goal. The southwest edge of the building is controlled by five coordinating points, three of which can move in X and Y-axes (Fig. 8). The offset of the control points is the genotype of this form.
The described multi-criteria procedure aimed at finding such an arrangement to curve’s control points to reduce the usable area of the building to a minimal extent and ensure maximum illumination of the park. The final values of the parameters allowed for a significant improvement of insolation conditions in the park (Fig. 9).

The final building facade is constructed from prefabricated concrete-glass cubical units that are being shifted in accordance with the building form curves resulting from the conducted optimization procedure (Fig. 10). The small modules of 2.7 meters width and of 3.6 meters height are grouped by three, forming structural modules with dimensions of 7.1 by 3.6 meters. This modular facade subdivision system is structurally and functionally efficient and results in visually attractive visual building form.

**Project 3, Maciej Kurkowski:**

The project by Maciej Kurkowski attempts to optimize the structure of the building load bearing façade at the early stage of the architectural concept. Preliminary aesthetic decisions of façade geometric subdivision have been analyzed in order to diversify the thicknesses of the structural elements depending on the deformation of the structure under the applied forces (Fig. 11). To perform the task the author used the plugin Kangaroo for Grasshopper, which enables the modeling of a spring-particle system.

All elements of the facade have been converted to springs for analysis of deformation of the structure. After applying the loads the maximum deformation lengths of individual elements were measured and, depending on the value, each of the elements obtained the proper thickness (Fig. 12).
Project 4, Jacek Sochacki:

As in the previous project, Jacek Sochacki uses the spring-particle system to modify the initial project design so as to achieve the most optimal arrangement of load bearing facade structural elements.

The initial form of the building was derived from points that were written into the geometry of the building that was designed by the group. The polygon that shaped the building layout is divided into segments of equal length on each side. A column is placed at every subdivision point of the polygon (Fig. 13). The genes control the distances between the columns. The optimization goal is to alter the initial shape at a minimal level and create a state in which all the distances between the columns on each side of the polygon will be the same. As a result of the optimization procedure the building's load-bearing columns are spaced at a distance of 405 cm.

The lobby, retail spaces, business center and a restaurant occupy the first two floors of the building. At this level the optimized structure is subjected to some spatial modifications in order to highlight the different functions located at these floors. Offices occupy all the upper floors and the structure of the building becomes stricter and from there all the structural elements are uniformly arranged, according to the optimization procedure (Fig. 14).

CONCLUSIONS

The effects of the course are the projects of high-rise office buildings, during the design of which students have used optimization procedures based on genetic algorithms. One of the key issues when creating such procedures is thorough understanding of the components of the genetic algorithm so as to properly set the relationships between the various parameters and construct a fitness function. The more optimization criteria we try to take into account at a time the harder the task becomes. Then the most important is to bring all the values representing the individual fitness functions in the forms of mathematical expressions to values in a range of 0-1. This allows controlling the importance of specific objectives of the multi-criteria optimization by giving them validity parameters.
Among the described projects, one utilized a multi-criteria optimization. Two conflicting goals were established as equally important, with the validity parameter equal to 1 for both objectives. We believe that it would be worth comparing the effects of the same multi-criteria optimization procedure with just different assignment of validity parameters for particular objectives.

The premise of the project was to introduce students to the actual realities of designing high-rise office buildings in the context of local building regulations and restrictions arising from the specific location of the investment. Thanks to the consultations with the specialists and the series of lectures, the students were given basic knowledge to properly establish the relationships between all the elements of such a project. Thanks to the work in groups at the initial design stage of the project they supported each other in design making, which was a simulation of work on such a complex project in reality.

High-rise buildings are usually subject to numerous optimizations. This is due to, among other things, the high price of land in central locations in the city, where such buildings are localized. What are in these cases important are structural, lighting and environmental optimizations. The ideal scenario is when many aspects of the design and optimization goals can be combined into one efficient system that takes into account all the important factors affecting the project. Such a design process, especially for an experienced designer, is limited in terms of the possibility of creating a multifaceted design process with incorporated optimization procedures, due to the difficulty of such a procedure and the lack of time. The students preferred to create dedicated tools for solving certain design problems and explore the search space in order to objectively motivate their design decisions rather than optimize the whole building.

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