OPTIMIZACIJA ZA ODRŽIVOSTI OBJEKATA

OPTIMIZATION FOR SUSTAINABILITY OF BUILDINGS`

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U toku projektovajna objakata, njihova struktura se najpre dizajnira, evaluira po sto niz iterativan process se predlaga novo projektno resenje, sto prestavlja konvencionalan i neefktivan pristup. Uzimajuci u obzir da rane projektne odluke uticu na 70% od performanse projekta i njegovu odrlizvost, nosiva strukura objekta e od velikog znacaja za optmilani performansi i odrzlivosti objekta. Zbog toga, sa cilja da se unapredi proektni proces, potrebna je optimizaciska alatka za efikasna izrada optmilana proektna resenja koja ce biti dalje evaluirana. U istrazivanja, a i u arhitektonskoj praksi, nekoliko metoda za strukturna optimizacija su razvijeni, a del od njih so istrazeni i prezentovani u ovaj rad. Optimizaciske alatke su istrazeni sa stanovista njihova upotreblivoska i aplikaciju za optimizacij razlicite gradezne elemene i strukturne sustem. Analiza na relevantni naucni dostignuca ukazuce da tezina strukturne elemente moze biti optimizovana za 10-15%, direktno uticajuci na odrzlivosti objekta i namaljenje njegov uticaj vrz zivotnoj sredini. Rezultati pokazuju veliki potencijal optimizacione alatke i identifikuje moguvnosti za njihova sira aplikacija u arhitektonskoj praksi, osobito u toku projektna faza i zadaju nasoke za njihov dalji razvoj.

Ključne reči: *optimizacija; alati za optimizaciju; parametarsko projektovanje; strukturalni system; održivost*

During the buildings`design process, the buildings` structure is at first drafted, then evaluated, after which a new design is proposed in an iterative process which is inneffective when conducted in a conventional manner. Considering that the early design decisions influence 70% of the designs` outcome and its sustainability, the buildings` primary load-bearing structure is of utmost importance in terms of its optimal performance and buildings` sustainability. Therefore, in order to facilitate the design process an optimization tool is needed that can deliver optimal design solutions which can be further evaluated. In the research community as well as in the architectural practice, several methods for structural optimization have been developed, and part of them are investigated and presented in this paper. Also, optimization tools are examined from a point of view of usability and their application on optimizing various building structural elements and structural systems. The analysis of the state of the art literature shows that the buildings` structural members` weight can be optimized by 10-15%, thus directly improving the buildings` sustainability and alleviating the impact onto the environment. The findings show the large potential of the optimization tools and identifies possibilities for their much broader application in the architectural design practice, especially during the design phase and points out directions for their future development.

Key words: *optimization, optimization tools; parametric design; structural system; sustainability*

1 Introduction

The most widely adopted architectural design process of buildings is where a certain design is drafted, then evaluated and afterwards a new design is being made, drawn from the past experiences to make the problem more tractable [1]. However, the design process is an iterative one and it needs a tool to produce several design proposals which could be effectively evaluated and choosing an optimal one. Several authors stress that early design decisions influence 70% of the later decisions and it has been concluded that implementing optimal design for a given building can reduce its environmental impact by 30-40% with no extra costs [2].

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In that regard, the buildings` primary structure is of utmost importance. Its design, cost-effectiveness and functionality needs to be incorporated in the early design phase of the building in order to prevent project drawbacks, because any changes made during late design stages are shown to have considerable environmental and economic cost ramifications. This is especially important in the design of high-rise buildings. Their optimization is usualy organized in three levels, such as: the buildings` shape (wind tunnel tests and CFD), optimization of the buildings` structural system and design and sizing of the structures` members.

Due to the necessity for structural optimization, several methods have been developed, such as: discrete topology optimization, evolutionary algorithms, continuum-based optimization methods, generative design etc. While generative design is a fairly recent term, the idea of topology optimization has been around for decades and it is described as a "methodology to derive an optimal material distribution for a design under given usage conditions". Despite the availability of design tools currently used in science and the existence of powerful computational technologies and optimization techniques, they have been scarcely applied in design projects due to the lack of expertise in the architectural community.

The objective of this research is to investigate current optimization methods and tools, to examine how the optimization is applied in the architectural practice and to promote its increased application. State-of-the-art case studies of buildings` structures optimization are examined both in theory and in practice. Further, a review on available tools for structural optimization of the buildings` design is performed. The focus of the research is to contribute towards a broader integration of the optimization tools during the architectural design process, especially the integration of optimization plugins within the CAD/BIM environment.

Considering that the buildings` structure significantly influences the environment, during the STSM the coupling of structural optimization tools with environmental optimization tools for buildings will be also analyzed.

2 Optimization methodologies

In the structural design of architectural buildings, different optimization methods have been used, such as: size optimization, shape optimization, genetic algorithms, topology optimization and others.Size optimization is frequently utilized in the findings of optimal cross-sectional area of beam elements in a frame system. It is also used for the calculation of the optimal thickness of plate elements at the same time satisfying predefined design criteria. In this method, the shape or connectivity of members may not change [3].

The shape optimization is a technique that considers the shape of the initial material layout within a given design domain and it morphs the shape boundaries to obtain an optimal design solution. This method of optimization can reshape the material which is within the given optimization domain and at the same time it retains its topological properties such as number of holes [4].

In the industry, several optimization tools are used which are based on genetic algorithms. They are based on the principles of nature and natural selection and are used for the identification of optimal design solutions for a given set of criteria and within a certain design domain. It is noted that this technique can be applied on a broad range of design problems (such as size and shape optimization) however, it does not require the use of potentially complicated derivatives, but it requires more function evaluations and is not necessarily convergent, even to local minima [5,6].

For the overcoming of the fore mentioned limitations on the previous optimization methods, the topology optimization is developed. Due to their large potential, the topology optimization applications in the construction sector have been studied in the recent years. Topology optimization is a mathematical method that starts in a design domain and searches for the optimal material distribution inside that domain in order to improve a specific objective (design criteria) in the structure for a given set of loads and boundary conditions.

Additionally, the topology optimization objective can be formulated in several ways. Topology optimization is often based as a mathematical gradient design tool which determines the location in a design domain to calculate the required material based on the loads and boundary conditions for a specific objective, which can be: structural member deflection, compliance etc. Hence, the optimal solutions can be of different shapes, sizes or means of connectivity [7]. In the topology optimization, the finite element method (FEM) is applied by splitting a design domain into several small pieces, known as finite elements.

Topology optimization can be used as a means to minimize the material consumption in a structure, while at the same time providing a tool to generate design alternatives of benefit to both engineers and architects, due to the inherent characteristics of the architectural design proces in which the architects cooperate intermittently with the structural engineers, [7], especially during the early design phase. Topology optimisation is used to minimise the strain energy (when considered as the objective function) in a FEM model by varying element densities and is used to vary the simulations of a co-evolutionary design process (which are interpreted as asymmetric subspace optimisation [8].

Regarding the numerical schemes for topology optimization, a major advancement was achieved with the introduction of a technique for the least-weight layout of trusses [9]. This advancement was further developed by different authors [10,11] for application in discrete structures, where it was focused on the optimal layout geometry of discretized cantilever beams and trusses with finite numbers of joints and members. Authors have introduced the homogenization method used for the topological optimization of continuum structures. Its further advancement established the Solid Isotropic Material with Penalization (SIMP) model with its evolutionary techniques such as Evolutionary Structural Optimization (ESO), level-set methods, methods based on topological derivative and phase-field methods [12,13]. It can be noted that the SIMP method is frequently used and shows potential for new research techniques with the introduction of the 99-line code for Matlab. In that regard authors [7] propose optimization method for the generation of alternative designs where the engineering is integrated with the architecture, where the method is based on a SIMP coupling it with a Matlab code.

By selectively distributing structural members in a building, the efficiency of the design can be optimized, resulting often in non-intuitive forms. From the application of structural optimization it can be noted that it is most frequently used for the design of the structural members of high-rise buildings.

The application of topology optimization is of high importance, it is dependent on a close collaboration between the architects and engineers, and offers an alternative approach to generate new, integrated design ideas by means of a tailored structural topology optimization framework, which can potentially be of benefit to both the architectural and structural engineering communities.

Further, the buildings` spatial design is largely determined by the design space of the problem, and often the buildings` designs can be constrained by how they are represented (ex. can be restricted to orthogonal shapes due to the lack of representation in curves in a building design). Hence, the optimization efficiency and success is dependent on the design. In that view, the most commonly used representations are the supercube representation and the movable and sizeable representation, based on the super-structured and the super-structure free approaches respectively.

The literature review showed that there are couple of optimization methods that handle super-structure free representations, such as simulated annealing, evolutionary algorithms, and heuristic local searches. The simulated annealing is applied often in the design of processes, while for the buildings` structural design the super-structure free approach is applied [14].

Authors propose optimization with an objective for minimizing compliance, which is equivalent to increasing the overall stiffness of the structure [15]. Other researchers propose toolbox based on evolutionary algorithms for structural design optimization (with the objective to minimise the strain energy of a building spatial design) and thermal building design optimization (with the objective to minimise the heating and cooling energy required) [16].

It is noted [16] that with the development of multi-disciplinary design modification based on simulations of co-evolutionary design processes, the design space can be cyclically both explored in-depth (via the super-structure) and globally (via the super-structure free representation) [17].

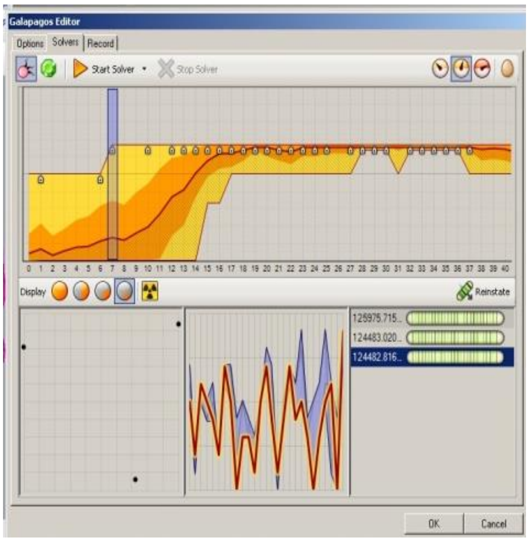

Figure 1 Galapagos optimization of the model [16]

Additionally, the multidisciplinary design optimization (MDO) focuses on the use of optimization for the design of systems that involve a number of disciplines or subsystems [8], for which different classifications are found in the literature. The parametric mixed-integer non-linear programming (MINLP) optimization approach was used for optimal design of single-story industrial steel building structures, where the objective function is the structure's mass. GAMS programing language is used for the MINLP optimization of the minimal possible structure mass, the optimal topology and the optimal standard cross-sections of each structural member.

Multiobjective optimization using simulated annealing is proposed taking in consideration cost minimization, constructability, minimization of the environmental impacts and maximization of structural safety. Optimization is used for an automatic grouping of: beam cross-section dimensions, planes, trusses frames, fiber-reinforced concrete beams, etc. Hybrid method is proposed, which combines simulated annealing and the firefly algorithm for the optimization of I beams [18]. Researchers propose multicriteria optimization of the shape and structure of energy-saving buildings, as well as optimization of heat sources [19], thus optimizing: internal partitions the shape of building and the heat sources.

Authors propose a multi-objective optimal genetic algorithm (MOGA) developed in MATLAB, for the optimization of the parameters of the base isolation system in high-rise building structures, [20] and in order to simultaneously minimize the objective functions (the displacement response of the building's top story and that of the base isolators relative to the ground), a fast and elitist non-dominated sorting genetic algorithm (NSGA-II) approach is used to find a set of Pareto-optimal solutions.

The heuristic methods involve different algorithms such as: simulated annealing, genetic algorithms, ant and bee colony algorithms, harmony search, and particle swarm optimization. From the literature review it can be concluded that the genetic algorithms and simulated annealing are the most widely applied both in theory and practice. The comparison of methods shows that simulated annealing had a slight advantage compared to the other simulations methods, being more efficient in the search for an optimal solution.

Researchers propose a method for a parametric modeling and evolutionary optimization for cost-optimal and low-carbon design of high-rise reinforced concrete buildings and shows that the carbon emissions and material cost can be both reduced by 18–24% after performing an optimization [16, 21]. The building structural efficiency varies with the changes in both the structural topology and the distribution of member sizes in order to identify the optimal size of structural members, and which need to be addressed simultaneously for achieving an optimal design. Such a hybrid method is based on a topology arrangement of structural members using the evolutionary GA, and then an optimal dimensions of the individual members is achieved by using the optimality criteria (OC) method. Authors [22] propose Integrated Structural–Architectural Design for Interactive Planning by establishing interactive architectural modelling framework as well as a constrained optimization module, however, the lateral forces are not considered. Discrete Evolution Strategies optimization algorithm is employed to minimize the total cost of materials in structural optimization of earthquake-resistant buildings with steel or composite columns.

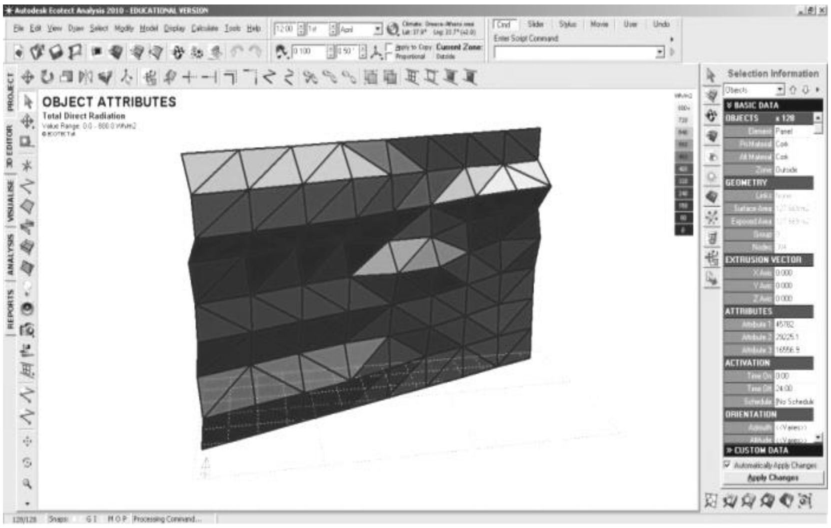

Figure 2 Facade surface optimized for utilizing solar radiation benefits [16]

3 Optimization tools

There are many algorithms in the literature for solving multi-objective algorithms [23], where for the GA, most common is Non-dominated Sorting Genetic Algorithm (NSGA), while other popular algorithms are: Multi-Objective Particle Swarm Optimization (MOPSO), Multi-objective Ant Colony Optimization, Multi-Objective Differential Evolution, Multi-objective Evolution Strategy, which are proved to be effective in finding non-dominated solutions for multi-objective problems. In the architectural practice and research, the Rhino/Grasshopper environment enables the use of various optimization plugins, such as: Optimus (metaheuristic optimization, Galapagos (genetic algorithm), SilverEye (particle swarm optimization), Opossum (single-objective algorithms - model-based RBFOpt and evolutionary CMA-ES), Millipede (topology optimization), tOpos (3D Topology Optimisation), TopOpt (Topology Optimisation), Goat (gradient-free optimization algorithm), Dodo (collection of tools for machine learning, optimization, while regarding AI it features neural networks, gradient descent, stochastic gradient descent and swarm optimization, Discover (optimization tool), Design Space Exploration (DSE) (gradient-based optimization enabling multi-objective optimization), Ameba (topology optimization), Octopus (multi-objective, genetic algorithm) etc. Also, there are certain studies on coupling structural optimization with sustainability performance, which can be assisted with tools such as: LadyBug, HoneyBee etc., which operate in the Grasshopper environment. It can be concluded that their implementation during the structural design phase is very rare due to the complexity of the tools and lack of knowledge among engineers.

4 Conclusions

From the research it is concluded that the application of topology optimization can bring architects and engineers to collaborate more closely and can improve the buildings` sustainability. It can contribute to the reconciliation of the conflicting paradigms in architecture, such as “the form follows the function” and “the function follows the form”, as they will be integrated. Hence, the optmization methods and tools can strongly support the delivery of a sustainable and optimal design solution for the buildings` structural systems by decreasing the material being used for the construction of structural members by 30-40% [2]. The drawback is that this technology is not adapted to the architects workflow process and it is not well integrated in the CAD environment. However, there are significant advances with the connection of BIM and parametric/optimization tools, such as ArchiCad and Rhinoceros/Grasshopper. Additionally, it can be concluded that for the optimization of high-rise buildings, the most common objective function is the stiffness/deflection under lateral loads. In the structural members of the system, the objective functions can be the minimization of: displacement, deflection, von Mieses stress, strain energy, stress deviation, load buckling factor, as well as material use, costs etc.

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