OPTIMIZATION TOOLS FOR ASSISTING THE ARCHITECTURAL DESIGN PROCESS

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Abstract- The majority of the buildings are designed in an unsustainable manner and are responsible for a large part of the waste creation and resource consumption. The sustainable design means holisticaly integrating multitude of design aspects, previously not considered in the conventional building design, and which include the environmental, social and economic domain. The multifaceted nature of the sustainable design often brings need for resolving conflicting building demands, leading to the neccessity of their trade-off and interdependent balancing. The conventional design process is not able to cope with such complexity and therefore an iterative, parametrized design process is needed that utilizes optimization tools and algorithms in order to find near-optimal solutions within a short timeframe. This research is oriented towards investigation of the existing optimization tools and their application in the architectural design process. It is investigated in which building design aspects the optimization procedure is most commonly used and which tools are used. The research shows that the optimization tools can greatly assist the architectural design process, make it more efficient and effective in improving the buildings` design sustainability. It is noted that the optimization tools can greatly alleviate the decision making process during the buildings` design and make it a more informed process. Additionally, the findings show that the optimization is a complex process demanding knowledge and skills among architects that exceed the architectural domain. The authors would like to acknowledge the support of the CA15140-Improving Applicability of Nature-Inspired Optimisation by Joining Theory and Practice (ImAppNIO) Cost Action for its excellent research and networking possibilities.

Keywords- Optimization, Building Simulation Performance, Energy performance, Sustainability.

I. INTRODUCTION

The construction industry is pointed outas one of the most intensive industries with a share of 50% in resource consumption, 40% energy consumption and 50% waste creation [1]. The largest part of the existing buildings are designed in an unsustainable manner and contribute to nearly 40% of the energy consumption and approximately 36% of the total carbon dioxide emissions [2]. The relatively novel concept of sustainability demands meeting the basic needs of all people and extending the opportunities for environmental, economic and social advancement. Therefore, the delivery of sustainable buildings is of great importance for the future sustainable development of humanity.

The design of buildings and the evaluation of their performance is a complex process which includes multitude of different design criteria, both qualitative and quantitative. With the implementation of the concept of sustainability in the buildings` design, the number of design criteria rises, which increases the complexity of the design. The architectural design process is an iterative one, where the optimization problem is inherent to the design practice, meaning that different design solutions have to be compared to achieve one or more objectives. Starting from an urban level planning, to building level design and on a detail level scale there is a need for optimization of the design solutions. The buildings` form finding is based on a search of an optimum performance between different, often conflicting criteria, such as: energy performance, daylight quality, costs, life-cycle performance etc.

With the development of the computing power, the Building Performance Simulation (BPS) and its supporting tools have a significant role in the architectural design process. The possibilities for quantitative measurement and evaluation of the design performance, its characteristics and drawbacks, enable data-based informed-decision making process that can improve the buildings design. Additionaly, the parametric modeling contributes towards a faster and automated delivery of architectural design proposals.

Hence, the objective of the research is to conduct a review on the state-of-the-art literature and available tools for optimization of the architectural design. Evolutionary optimization algorithms such as genetic algorithms (GAs) are examined, which are search methods for optimization based on analogies with natural genetics recombination and natural selection, firstly developed by Holland [3] and Goldberg [4]. A review is made on current achievements in the architectural design theory and the architectural design practice regarding application of optimization tools on different design scales, starting from a city scale, building scale and detail level scale. Also, the coupling of optimization tools and building performance assessment software is be investigated.

II. LITERATURE REVIEW

A. Optimzation methods

The optimization utilizes mathematical quantitative measures to get the best course of action possible for a decision problem [5]. Researchers in order to investigate a large number of design alternatives for

finding efficient design with a positive environmental impact and to explore multiple design scenarios have applied used two general approaches: parametric optimization and evolutionary optimization. Parametric optimization studies are rarely used in architecture because of their long computational time, while the evolutionary optimization methods reduce the number of simulations required for exploring a large design space.

Different types of optimization methods have been investigated, such as [4]: enumerative, calculus-based, and random, however, they serve for monocriteria problems of optimization.

Evolutionary optimization methods are investigated, which are based on a population approach where more than one solution participates in an iteration process and a new population of solutions evolves with each iteration [6]. The evolutionary computation has significantly evolved and a multitude of search algorithms and their variants are developed and new bio-inspired optimization paradigms emerge [7].

The model-based optimization is noted as an innovative, machine learning-related optimization strategy, appropriate for time consuming building performance simulations [8]. Moreover, those methods have been proven to find good results by means of a relatively small number of simulations [9]. Considering that BPS takes longe time, authors [8] state that it is impractical to utilize population-based metaheuristics such as genetic algorithms (GAs).

Therefore, global black-box (or derivative-free) methods are proposed [8], which are not based on mathematical formulations of optimization problems and unlike methods based on local optimization, are not centered on a local optima but have a holistic approach of the design space.Such global black-box methods are organized in three categories, such as: direct search, model-based methods and metaheuristics.The characteristic of the drect search methods is that they evaluate a deterministic sequence of solutions without approximation of the design space. The model-based methods approximate the design space as a whole by constructing surrogate models of the implicit mathematical formulations of simulation-based problems. Such methods work on the principles of constructing surrogate models by utilizingstatistical (Polynomial Regression and Kriging) and machine learning-related techniques (Radial Basis Functions, Neural Networks and Support Vector Machines).

The last type of black-box methods, the metaheuristics is a stochastic method based on swarm intelligence and demands a broad parameter setup, whilst due to the poor proof of convergence [10] are dubbed as "methods of last resort" [11]. Despite this notion, they are widely used in the architectural practice, especially the evolutionary optimization algorithms.

The evolutionary optimizationis inspired by the Darwinian evolution theory and is used to automate the process of searching for an optimal solution[12]. The most widely used evolutionary optimization algorithms are the genetic algorithms (GAs) which are search methods for optimization based on analogies with natural genetics recombination and natural selection. These algorithms were firstly developed by Holland [3] and Goldberg [4]. The algorithms consist of a set of variables called genes which make a gene pool, then the evaluation is made and basic genetic operators are applied (reproduction, crossover and mutation) [13], [14]. The artificial evolution explores vast regions of the search space based on a selection principle of “survival of the fittest”. Evolutionary computing works by giving each variable, called a gene, an assigned fitness value. The solver iterates and solutions are generated until the objective function converges to a specific optimum value set [15]. Commonly, the algorithm terminates when either a maximum number of generations has been produced, or a satisfactory performance has been reached for the population.Their application has proven that evolutionary algorithms are effective on many hard optimization problems [16].

Additionally, Sudholt [17], states that the inclusion of local search techniques into the random search process of evolutionary algorithms is gaining in popularity. Such hybrid algorithms are also known as memetic (evolutionary) algorithms (MAs), evolutionary local search, genetic local search, global-local search hybrids, large-step Markov chains, and others.

B. Optimization tools as a support for the architectural design process

Several types of tools assisting the optimization process for architectural design have been examined. They have been categorized in the following groups, such as: Custom programmed algorithms; General optimization packages and Special optimization tools for building design. The custom programmed algorithms require advanced programming skills and are difficult to implement in the architectural practice, while the general optimization packages, which up to certain extent have been used are: modeFRONTIER, MatLab and GenOpt. The GenOpt is a generic optimization program for the minimization of cost function that is evaluated by an external simulation program and has been quite extensively been used in the architectural practice. Additionaly, it enables coupling with any BPS tool, such as: EnergyPlus, TRNSYS, Dymola, IDA-ICE and DOE-2 and Radiance.

Authors [18], compare building energy optmization tools such as: BEopt 2.3.0.2, jEPlus+EA1.51, MOBO0.3b, DesignBuilder V4.2, Opt-E-Plus, GENE_ARCH, MultiOpt2, regarding criteria such as: data completeness, interoperability, optimization parameteres and postprocessing capability. They

conclude that none of them stands out compared to the others and do not support fully the architectural design process.

More tools are developed as adhering GA`s with a BPS, among which are: ParaGen which combines parametric modeling, performance simulation software and a GA to explore design alternatives; MultiOpt which utilizes the NSGA-II coupled to TRNSYS, BuildOpt is a BPS used for building design optimization.

Among the most popular platforms used in the architectural design and research are:McNeel's Rhinoceros (Rhino) and Grasshopper (GH) for parametric modelling, which belongs to the category of simple genetic algorithms (GAs). However, both of them have been identified as most widely used in the architecture discipline.The Grasshopper includes various plug-ins for: BPS (Ladybug and Honeybee); for daylight and energy simulation, structural analysis with finite element calculations plugins (Karamba, Octopus etc.); solar radiation (DIVA); optimization (Galapagos, Opossum, Goat etc.). Galapagos is the most commonly known evolutionary solver with a wide support community. The plug in Opossum uses advanced machine learning techniques to find optmial solutions with a small number of function evaluations. The Goat plugin, is described as a complementary to Galapagos. It is based on gradient-free optimization algorithms and mathematical rigorous approach delivering fast and deterministic results, thus providing same results in each run. Additionally, it is noted that researchers frequently couple BPS tools, with EnergyPlus and with optimization tools (BeOpt, GenOpt, jEPlus software, which is parametric tool and others.). Additionaly, RBFOpt is a model based optimization tool driving the Grasshopper plugin Opossum.

C. Utilizing optimization tools in the architectural design

The research of the potential for application of the optimization tools in architecture is quite broad. Certain authors investigate the coupling of Building Performance Simulation tools (BPS) with Computational Fluid Dynamic (CFD) software and their potential to support environmental control while optimizing architectural forms [27]. The optimization of buildings is introduced for improving indoor thermal comfort while reducing building energy demand by coupling Non-dominated Sorting Genetic Algorithm II (NSGA-II) coupled with the Artificial Neural Network (ANN) [28]Many researchers have used optimization methodologies for improving specific sustainability aspects of the buildings. It is used for assisting the design process in finding optimal architectural floorplan layout, utilizing the efficiency of gradient-based algorithms and evolutionary algorithms for making discrete decisions and conduct global search [19].

The spatial configuration in buildings is related to finding feasible locations and dimensions for a set of interrelated objects that meet all design requirements and maximize design quality in terms of design preferences [19]. The spatial configuration design concerns different scales of the architectural design, such as the urban scale level and its spatial configuration and context as well as the building scale and its programatic content and size. Therefore, the spatial layout issue is relevant to all physical constructs and introduction of optimization in such a form-finding proces is necessary.

Mainly, two approaches have been noted for spatial allocation [19]. The first one defines the available space as a set of grid squares and utilizes an algorithm for allocating a square to a particular room or activity. In the second approach the building layout design space is decomposed and represented in two parts: topology and geometry, where topology refers to logical relationships and constraints for the geometric design space between layout components, while geometry refers to the position and size of each component in the layout.

Other authors investigate three major types of black-box optimization: metaheuristics, direct search, and model-based methods, showing that metaheuristics are greatly outperformed whenever evaluating tens of thousands of design candidates is not an option, and suggest direct search and model-based methods as viable and more efficient alternatives [8].

Al-Homoud in [5] optimizes the heating and cooling energy, while Wetter in [20] optimizes the lighting energy consumption. Improving energy performance has been researched by Hauglustine et al. in [21]where they propose optimization for increasing energy as well as cost performances of the object by using a genetic algorithm. Researchers have also used genetic algorithms in optimization of time-costs relationship [22]. Other researchers have focused on technological optimization such as Flager et al. in [23]. They propose a method for optimization whose scope is limited to the building envelope and mechanical systems where the variables taken into account are limited to building orientation, glazing percentage and glazing type. This method provides systematic evaluation of a predefined range of design alternatives in terms of Life-Cycle Costing (LCC) and carbon footprint.

Wang et al. [24] discusses that if the operation energy is the only optimization criteria, the analyzed building would have over dimensioned insulation. To overcome this problem an inclusion of multiple aspects of the building in the genetic optimization algorithm has been made by many researchers. Marzouk et al.in [25] perform optimization of project objectives, taking into consideration the interaction amongst involved resources. They suggest that the total duration and costs can be estimated and optimized.

In general there is a great interest in the building research community and according to Nguyen et al.

in [26] the future research on optimization should be oriented towards improving the efficiency of search techniques and approximation methods for large scale building operating performance and reducing time and effort.Authors [18], categorize the optimization parameters into two parts, such as: optimization engine functional parameters and optimization design parameters. The optimization engine functional parameters means defining and selecting an algorithm and its characteristics.

Further, several methodologies for sustainability assessment and regenerative building certificationare analysed, such as: LEED, BREEAM, DGNB, OpenHouse etc., from which different indicators are examined. From the comparison it is noted that the Energy category has the largest share in the overall assessment. Also it is noted that the buildings' envelope and especially the facade is one of the main contributors to the buildings' energy consumption and environmental and economic impact. Henceforth, the building energy design parameters, are related to the architectural elements such as building form, window size, material types, ventilation, daylight etc., which are all aspects that have been investigated in some part from an optimisation standpoint.

Analysis was made for tools that assist: achieving LEED building certification criteria [29]. optimization of the fabric construction, HVAC system size and the control strategy; minimize annual energy use; optimize the design buildings; optimization of urban building efficiency potential; optimize the ceiling and daylight uniformity; multi-criteria optimization of building refurbishment; optimize the form of the building; building envelope optimization; thermal insulation and the thermal inertia optimization; optimization on solar energy utilization; optimal architectural design layout by minimizing accessways, hallway, lighting, heating and cooling cost; optimization of prefabricated structures regarding environmental impact, cost structural safety issues; optimisation of building form, envelope and cooling system for improved building energy performance etc.

III. RESULTS AND DISCUSSION

The review of the state-of-the art literature, showed several significant insights. It was evident that optimization techniqes are gaining in relevance in the architectural design domain and their potential is getting increasingly utilized.

A. Application of optmization in the practice

Due to their potential, the parametric, BPS and optimization tools are being extensively utilized in leading architectural and engineering practices.

The parametric control is often achieved in Building Information Modeling (BIM) tools, such as: Revit, ArchiCad etc.

The optimization is utilized in the urbanistic and architectural design, i.e. on several design scales, starting from the city-level, building-level and even on detail level.

A study on the increase of skyscrapers in a city has recognized a pattern "of certain self-organized biological systems" and by using genetic evolutionary algorithms a tool was developed to predict the urban growth on a case-study of Tokyo[30], Fig. 1.

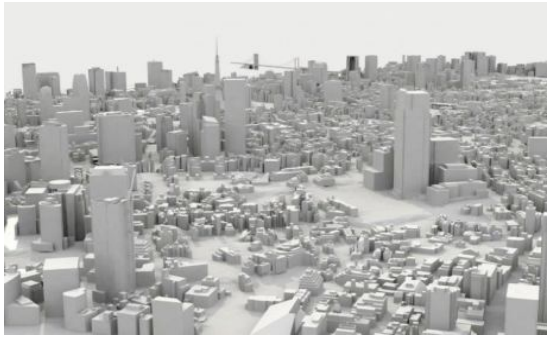


Fig. 1 Optimization on a city level [30]

The application of optimization is most common on the building level design, regarding different design aspects as mentioned in this paper earlier.

Multitude of architectural and engineering offices are amongst the leaders of the new developments and applications of optimization technicques. Some of them are using pre-existing tools and algorithms, while others develop their own custom software platforms, tools and unique algorithms that adress unique design problem, Fig 2.

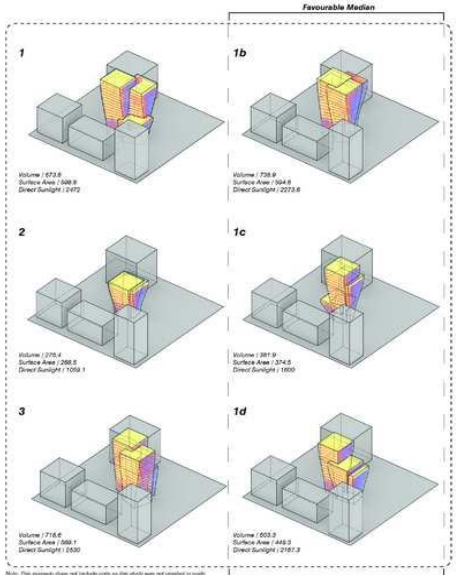


Fig. 2 Optimization on a building level[31]

Zaha Hadid architects have developed structure for a dining pavilion that combines computational design, lightweight engineering, and precision fabrication. By using the Altair OptiStructtopology optimization algorithm the structural system and skin of the pavilion are optimized regardingefficient material use, achieving light and stable design[32], Fig 3.

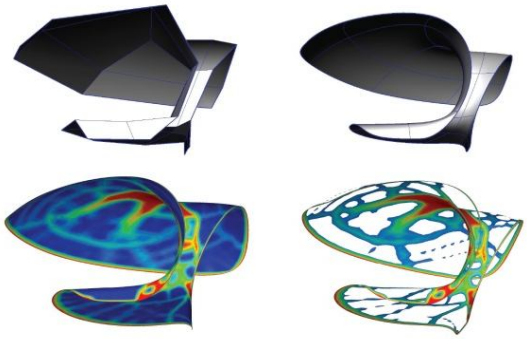
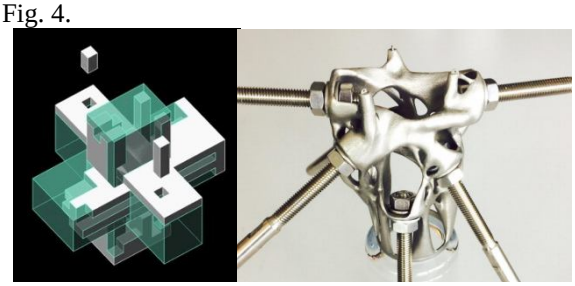


Fig. 3 Optimization on a structural level [32]

In a more recent utilization of optimization, there is development of genetic algorithms that adress the detail scale level of the architectural design process.
A research [33] shows an algorithm that is able to generate multitude unique design options of structural elements forming a japanese inspiredstyle of a joint, Fig. 4.



a. Janapese joint [33] b. Metalworks joint [34]
Fig. 4 Optimization on a detail level

Leading architectural and engineering offices use digital manufacturing process in order to produce freeform architecture in a process called Additive Manufacturing (AM) or 3D printing, Fig. 4.

CONCLUSIONS

The research shows that the optimization tools can greatly assist the architectural design process, make it more efficient and effective in relation to design quality. It stresses the notion that the optimization tools can alleviate the decision making process during the buildings` design and make it a more informed process. Further, on a building level, the facade is noted as one of the main contributors to the buildings' energy consumption and environmental and economic impact and optimizing the facades` design can reduce the energy consumption of buildings. As the design process is iterative it needs a holistic optimization tool for the delivery of several design proposals which could be effectively evaluated. Moreover, the optimization is a complex process demanding knowledge and skills among architects that exceed the architectural domain.
The coupling of parametric design, building performance simulations and optimization algorithms in a form of a user friendly tool would be a strong support for the architects in the prompt delivery and assessment of high quality sustainable architectural design solutions.

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