SHORT TERM SCIENTIFIC MISSION (STSM) SCIENTIFIC REPORT

This report is submitted for approval by the STSM applicant to the STSM coordinator

Action number: CA 15140
STSM title: Towards increased application of optimization tools for assisting the architectural design process

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PURPOSE OF THE STSM:

(max.200 words)
The construction industry is pointed out as 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 thus held responsible for nearly 40% of the global 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 their performance evaluation 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.
Hence, the objective of the research is to conduct a review on state-of-the-art literature and available tools for optimization of the architectural design on different scales, such as urban and building level. Evolutionary optimization algorithms such as genetic algorithms (GAs) will be also 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 will be made on current achievements in the architectural design theory and the architectural design practice regarding application of optimizations tools and research on case-studies and built examples that have utilized optimization driven design process. Also, the coupling of optimization tools and building performance assessment software will be investigated.
One of the aims of the STSM is to show that the optimization tools can greatly assist the architectural design process, make it more efficient and effective in relation to design quality. It will also stress 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

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the design can reduce the energy consumption of buildings. As the design process is iterative it needs a tool to produce many design proposals which could be effectively evaluated.
In this regard, one of the aims is to develop an optimization algorithm that will generate an optimal façade shape for a given fitness function, such as optimal use of solar radiation for passive heating of the building, thus decreasing the energy consumption of the building and improving its overall sustainability. The algorithm will be tested on a case study of a building and comparison will be made between the conventional façade and the optimized façade shape in regard to the fitness function and the energy performance.

DESCRIPTION OF WORK CARRIED OUT DURING THE STSMS

(max.500 words)
During the STSM research, more than 43 research papers in the domain of application of optimization in architectural design and optimization tools assisting the architectural design process have been examined. The nature of the architectural design was investigated, and it is noted that it is commonly a multicriteria problem, demanding optimal solution amongst conflicting criteria and building demands. Different types of optimization methods have been investigated, such as [1]: enumerative, calculus-based, and random, however, they serve for monocriteria problems of optimization.
The parametric simulation method has been analysed and certain drawbacks have been noted. In the recent years in order to obtain an optimal solution or a near optimum solution, several global optimization algorithms have been developed, such as: evolutionary algorithms, derivative-free search methods, and hybrid algorithms. 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 [3].
Its been noted that the Genetic Algorithms (GAs), from the group of evolutionary algorithms, are the ones being most often applied in the architectural design and research, especially used a lot in building performance optimization [2]. Further, it is noted using Non-dominated Sorting Genetic Algorithm II (NSGA-II) combined with Artificial Neural Network (ANN), are an effective method to apply on the problem of multi-objective optimization in 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. It is noted that 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.
Certain building energy optmization tools are compared, 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. However, they 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).
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.). 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 [5].
The application of optimization algorithms in the architectural practice was investigated in the work of several renowned architects, such as: Zaha Hadid, Arup etc. The optimization is utilized on different

scales, such as: urban, building (different aspects) and detail scale of the building.
Further, several methodologies for sustainability assessment and regenerative building certification are 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.
Hence, it is concluded that it is necessary to develop an optimization algorithm that would enable the reduction of energy demand during the building's design.

DESCRIPTION OF THE MAIN RESULTS OBTAINED

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 more and more utilized. The research of the potential for application of the optimization tools in architecture is quite broad.
Analysis was made for tools that assist the architects in different domains, such as: achieving LEED building certification criteria [7], optimization of the construction; HVAC system sizing 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 of 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.
Authors [4] 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. The building energy optimization design parameters, are related to the architectural elements such as building form, window size, material types, ventilation, daylight etc.
During the STSM research an algorithm was developed in order to find near optimal design of a façade and to evaluate its energy performance. The goal of the defined algorithm is to enable designers to have a more sustainable driven design process. The algorithm is set in Grasshopper, and the model is drawn in Rhinoceros. The optimization in the algorithm is run by the plugin Galapagos.
The algorithm is tested on a model of an existing building, situated in Skopje, R. of Macedonia. It is a two-story building with a height of 10 m, positioned between neighboring buildings and the only exposed façade is the south-east one. The energy consumption due to lighting, heating and internal loads are modeled and calculated in Ecotect which is connected initiated by the algorithm using the plugin Geco.
The south-east facade surface is drafted in Rhinoceros replacing the existing façade, and which is further parameterized using points to describe the surface in Grasshopper. For each of the points a value from 0 m to 1.5 m is assigned, describing the allowed extension of the façade towards the street, according to the Construction Law. An increment of 0.1 m to is assigned to each of the points, allowing flexibility of their position and being able to move perpendicularly to the façade surface.
Such defined points of the buildings` façade are set the genes that form the gene pool. The objective of the optimization problem is to find the most optimal position of each of the points in order to produce surfaces that have maximum exposure to the sun's solar radiation and to support the passive design features of the building. The fitness value is defined as a maximum solar insolation. The Grasshopper model of the façade is connected to Ecotect using the Geco plugin in order to retrieve data on solar radiation for the given climatic context.
The facades' surface is subdivided with an array of 6 smaller surfaces. Within the algorithm it is defined that the surfaces that receive the highest solar energy would have largest windows and the opposite applies for the surfaces that receive the lowest solar energy. A restriction parameter was set to the glazing, limiting the total area of the windows surface not to exceed 30% which is recommended to avoid overheating in the interior space.
Due to the inherent randomness of GA, the program run three times for approximately 9 hours. The energy demand analysis of the reference model and the model with optimized façade shows that it has a decrease on the energy demand by 42%.
The case studies demonstrated that the surface optimization can substantially improve the energy performance of the buildings and should be more included during the architectural design.

FUTURE COLLABORATIONS (if applicable)

Considering the Hosts strong experience in energy performance simulation and optimization tools it has been discussed to further collect information about optimization techniques and tools. Also, the possibilities for their integration into the architectural design would be of further research interest as it is much needed in the architectural design practice. Moreover, new ideas will be deepend to examine areas of the architectural design process which can be support by the development of new optimization tools.
In that regard, it is essential to have suitable tools available at the conceptual design stage that can assist designers in finding better design alternatives efficiently. The current stage of this study, however, focuses on optimizing only the building envelope. Future work should be focused on inclusion of multiple parameters that can be optimized. The scope should be expanded to cover day lighting aspects, mechanical systems, other passive solar design strategies and economic optimization.