Optimisation-driven design in the architectural, engineering and construction industry

Optimization Driven Design in Architectural, Engineering and Construction Industry: an overview

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Abstract (150 – 200 words)

In the present study, design optimization from the perspective of architectural design is explored. Even if optimization is usually recognized as a tool based on "hard" mathematical tools (and so quite far from architectural design), evolution in efficiency and usability increases the appeal to be used as a valuable way to improve and simplify the architectural design.

This work presents and compares different strategies for different parameterizing variables involved in the definition of each architectural synthesis, which can be carried to the main goal, the Architectural Design Optimization (ADO). This study also reviews applications for parametrized architectural design and provides an overview on criteria that conclude the optimal between different solutions. A specific description is developed on the main classes of structures design such as size, geometry, topology and how they could be adopted by the Architectural, Engineering and Construction (AEC) industry. Subsequently, an overview of available optimization tools for the best solution of potential architectural designs is presented. Recent paradigms from the built environment based on mathematical tests and simulation problems are presented, and the parametric process followed produced optimized models in the architectural realm. Finally, variant design approaches are analyzed where an optimization process is used in a more efficient way from the beginning of a project, at the conceptual design stage.

Finally, this work focuses on the use of numerical optimization techniques to design material-efficient or cost-effective structures, which has great potential for the construction industry

Keywords chosen from ICE Publishing list

Buildings, structures & design; Design methods & aids; Sustainable development.

List of notations

ADO	Architectural Design Optimization.
x, y	in Equation (1). Set of parameters in the parametric catenary equation.
α	in Equation (1). Control parameter for shape and inclination of the curve.
t	in Equation (1). Set of curve control point.
NURBS	Non-Uniform Rational Basis Spline.
AEC	Architecture, Engineering and Construction.
CAD	Computer-Aided Design.
x	in Equation (2). Set of represents the design variable vector in Optimization Problem.
n	in Equation (2). Number of parameters in Optimization Problem.
x^l	in Equation (3). Vector of lower bounds in Optimization Problem.
x^u	in Equation (3). Vector of upper bounds in Optimization Problem.
$h_i(x)$	in Equation (4). equality constraint function.
$g_j(x)$	in Equation (4). inequality constraint function.
PSO	Particle Swarm Optimization.
GAs	Genetic Algorithms.
SPEA – 2	Improved Strength Pareto Evolutionary Algorithm.
KPIs	Key Performance Indicators.

1 Introduction

We argue that the implementation of parametric design from the early stage of design just after cognitive research of the project can direct to a project with attribution of optimized characteristics. This change in traditional tasks can easier be implemented through the evolution of software and computational systems where no deep knowledge of mathematical computation is needed. Another realization is that parametric design requires an extra effort to create the first associative best-designed models or projects.

In the current design process in the Architectural, Engineering and Construction (AEC) industry, the "optimal design" is a choice among a minimal set of design alternatives ordered by the designer's experience and intuition. Thus, the optimization process refers to an integrated and comprehensive collection of various quantifiable performances of buildings.

Modern design requires to account for a significant number of criteria deriving from multiple disciplines. Optimization methods help study, aid, and resolve structural problems such as optimal form, floor plan layout design, energy consumption, sustainable orientation, sunlight, and costs (Gassar, Koo, Kim, & Cha, 2021). Furthermore, several problem formulations provide a constrained optimization process in which the minimization of total weight and economic cost is considered (Cucuzza, Rosso, & Marano, 2021).

A design contains different feasible standards and dimensions for a set of objectives that must satisfy all design requirements maximizing the quality of the output of the architectural and structural plan. The main problem in the architectural composition is due to its multidisciplinary nature, which complicates enhancing the way a problem is solved. In fact, from the very first design phase exists many parameters to be investigated, such as architectural syntax (i.e., language), traditions of the specific site for each project, physics, and last but not least, the importance of the material chosen for the architectural form. This means that studying an architectural layout involves enough and complex effort in addition to standard engineering problems. Furthermore, objectives such as the minimization of costs (and volume), the possessed structural performance, and the architectural morphology are also linked to the aesthetic and usability of the layouts, which are, by definition, difficult to be described in a strictly mathematical way.

The attempts to define an automated design process started over 50 years ago from Luigi Moretti, who has formulated the parametric design. The absolute necessity of harmony in architecture was a significant concept of the Roman architect's, and after his research, the concept is translated into a question that parametric architecture tries to respond to. This architectural research's starting point is based on the relationship between shape and structure, meaning the latter as the "created ordinance" of relations conceived in mathematical terms that link the individual parts (De Marco, 2015). In the last decade, the demands of complex and performative systems in the AEC industry led to a growing demand for the rapid development of software systems capable of reflecting efficiency queries. The demand often refers to integrated methods that aim to automate the search for the best solutions in architectural shapes and internal layout, giving designers more options for final decision-making. This can be possible through generative design, which can "collect a set of attributes (or parameters) in a model, to be evaluated and produce the final configuration of the architectural and structural shape after applying optimization techniques.

Multiple requirements can determine the need of optimizing an architecture. Nowadays, the Construction industry is still considered a sector with the highest level of emissions and waste. However, due to social evolution and the increasing comfort demands, increased energy use became a standard in everyday life. Moreover, according to recently conducted surveys (Lagaros N. D., The environmental and economic impact of structural optimization, 2018), in Europe, more than 40% of total material use, such as steel and concrete, is attributed to the building industry. Additionally, the efficiency of new construction buildings is wretched: 40% of overall energy usages is for lighting, cooling, and heating while producing 39% of the global greenhouse gas emissions (Gassar, Koo, Kim, & Cha, 2021). Therefore, searching for an efficient strategy to design optimized architecture from several points of view, such as low-energy consumption and low-waste material, becomes a necessity if not a mandatory act. The need for complicated and environmentally friendly structures coincides with several optimization techniques and methods that enhance architectural and structural response, performance. The factors, i.e. parameters, can influence and control the entire system through trade-offing design variables to produce different configurations and performances in optimization processes.

Based on this survey, taxonomy has been created, which is used to classify the existing research connected to Parametric Optimization techniques. Furthermore, this review's systematic analysis of this literature research aims to give the research community an agenda for future developments in the architectural optimization field.

2 Parametric Design in AEC Industry

For decades, buildings have been designed with nothing more than a pen and a piece of paper, and every variation on the design has been time-consuming. Parametric design is a fast-growing procedure of CAD that gives architects and designers the ability to specify the critical parameters of a generic architectural and structural model and implement changes interactively. In the digital era, many different designs can be executed with care and exactness in every detail with instant feedback on their performance. The complexity of the topical architectural design gives the main issue: the number of variables is difficult to evaluate if we consider the aesthetic requirement for the shape of the architectural project, which is provided by commission based on the non-objective choices in most cases. When the design variable can be easily identified, they cannot be expressed mathematically in most cases. Moreover, when the problem and its variables are formulated, the mathematical optimization problem functions need to be computable. This means that if mathematical formulas are available for each variable and constraints, they are retrieved in the form of the solution of a system of partial differential equations; an existing mathematical optimization software typically does not allow systems of equations to be expressed as part of the problem formulation (Wortmann & Nannicini, 2017).

The problem can be overcome through derivative-free optimization, which lately represents the most used technique in ADO (Architectural Design Optimization), using Finite Element Models.

With the implementation of new tools concerning parametric design, a new way to connect architectural needs and structural performance arose. Many parameters can be added in the optimization problems considering geometrical and performative constraints without developing the analytical form of the problem (with a single or multiple goals to achieve).

The term "parametric "originates from mathematics (parametric Equation) and refers to the use of specific parameters or variables that can be edited to manipulate or alter the result of an equation or system. For instance, an example of a parametric equation is the formula that defines a catenary:

$$x(a,t) = t \qquad 1.$$

$$y(a,t) = \alpha \cos h \frac{(t)}{a} \qquad 2.$$

The above expressions meet the criteria of the parametric Equation in which the variables *x* and *y* express the set of quantities as the first two parameters. The parameter *α* controls the shape of the catenary curve and its inclination (Figure 1) and also parameter *t* to determine the curve's control point (as in NURBS). This technical mathematical definition originates the term parametric: a set of quantities expressed as an explicit function of several parameters (David, 2013).

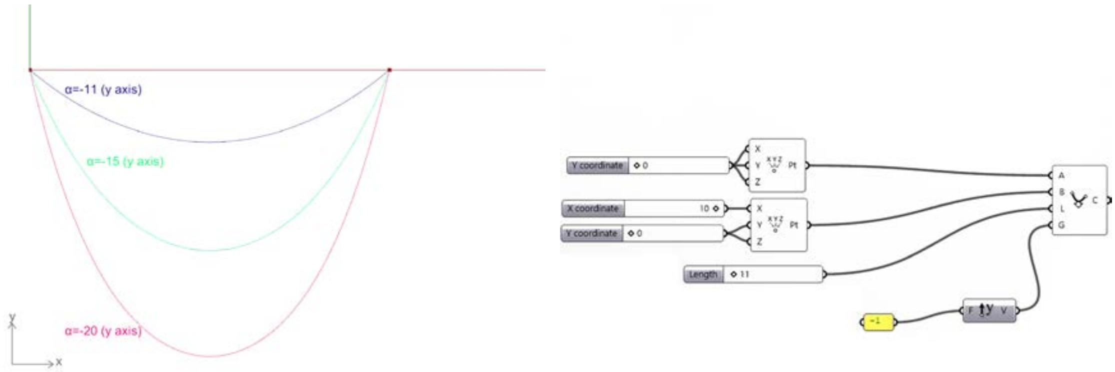

Figure 1. Parametric development of a generic catenary with α variable and fixed anchor points.

The bond between the mathematical parameterization - as in Eq.1 - and the architectural one concerning composition is similar: many parameters (as design variables) create an architectural organism as a response. On the other hand, parametrization in architecture is a process based on algorithmic thinking (a finite sequence of defined instructions) that empowers the articulation of parameters and norms. Tether defines and encodes the relationship between design intent and design response (Wassim, 2013).In *Elements of Parametric Design*, Woodbury describes Parametric modelling (also known as constraint modelling) as a process that introduces remarkable changes in the whole method of architectural planning. The traditional digital design tools, such as Computer-Aided Design systems, create the flow in which the designer "*adds and erases*" (Woodbury, 2010) objects. However, with parametric modelling tools, it is possible to retrieve different solutions by variating the parameters for a single model. Indeed, parametric design requires a complex act of thinking since it does not lead to a single design solution (as the conventional design), but it usually leads to a set of feasible design solutions.

With the rapid technological development, Computer-Aided Design has been enriched with parametric design techniques and tools. Nowadays, more professional figures involved in the AEC industry use visual programming and scripting tools to produce their designs. Moreover, from a single concept, the generative modelling can cause the exploration of all the possible combinations among the design variables; this evaluation would have been impossible to be carried out in a short time by manual operations.

2.1 Computational tools for Parametric Modelling

The essential differences between the additive process (typically used in CAD systems) and the generative modelling are:

- Real-time shape redevelopment while changing the design variable.
- Easy development of complex geometry.
- Reusable scripting for the development of a new object.

The software industry provided many digital tools on the market, combining CAD and parametric modelling. Some of these are:

- Solidworks

Solidworks is a software program to work on mechanical elements. This Parametric software assists the designer in creating efficient models, working on mechanical initiatives and advanced product designs.

- Revit

Revit is a design and documentation platform that supports the design, drawings, and schedules required for building information modeling (BIM). BIM delivers information about project design, scope, quantities, and phases when you need it.

In the Revit model, every drawing sheet, 2D and 3D view, and schedule is a presentation of information from the same virtual building model. Revit collects information about the building project and coordinates this information across all other representations of the project. The Revit parametric change engine automatically coordinates changes made anywhere—in model views, drawing sheets, schedules, sections, and plans (Autodesk, 2021).

- CATIA

Developed by Dassault Systèmes®.CATIA is a software program for designers, engineers, systems engineers, and construction professionals. This program is addressed to professionals as a complete software program with instruments for parametric modelling.

- FreeCAD

AS it is an open-source Parametric 3D software, FreeCAD gives the possibility to inexperienced users because of its intuitive interface. It finds wide use in architectural development and mechanical elements.

- Grasshopper in Rhinoceros 3D

Grasshopper is a cutting-edge parametric modelling tool that works with Rhinoceros (a CAD software) to create great precision and detail shapes, providing a powerful and efficient new way of designing architecture including the structural definitions thanks to the multiple add-ons developed to retrieve FEM. Grasshopper has a host of plug-ins and is included within Rhinoceros software.

- Inventor

It is a 3D program by Autodesk. This product is helpful for 3D mechanical design, simulation, visualization, and documentation of a project. Inventor can aid in simulations and visualizations for different purposes being a dimension driven CAD application used in engineering and architectural designs, visualization simulation, and documentation. .

- SAP2000

SAP2000 is general-purpose civil-engineering software developed to analyze and design several structural systems. Using SAP2000 allows the modelling, analysis and design of advanced complex systems through an intuitive object-based modelling environment that simplifies and streamlines the engineering process (Habibullah, 2021).

- SCADA Pro

SCADA Pro (Structural Computer-Aided Design & Analysis) is an integrated software application for static and dynamic analysis and design of reinforced concrete, steel, timber, and masonry structures, according to Eurocodes and the respective National Annexes for most European countries (ACE - Hellas S.A., 2021). Different add-ons have been integrated into the platform to analyse structure considering a wide range of materials, allowing importing any project in ScadaPro from different formats.

2.2 Survey for the Architectural Design Optimization

The optimization process of design outcomes an optimal solution or a pool of optimized design alternatives which meet the objective functions set; also, the optimization process in ADO can be seen as a supportive tool for decision making. Moreover, due to the possibility of obtaining different solutions from a single processed object, each solution/decision can be considered feasible from the structural point of view concerning (also) the geometrical and shape query bound by the provisions and the designers.

As a well-known technique, the optimization techniques originated to find the minimum or maximum value of a function, given certain parameters, so-called design variables (Vanderplaats, 1984).

The first analytic definition of structural optimization began with the early works of Maxwell in 1869, followed by Mitchell in 1904. The initial development of optimization techniques was developed in the aircraft and space industry due to minimum weight requirements in the engineering design (Tushaj & Lako, 2017). Between the 1940s and early 1950s, considerable analytical work was done on optimizing components in resented in works such as Shanley's Weight-Strength Analysis of Aircraft Structures. Subsequently, the progress of linear programming techniques by Dantzig, together with the application of digital computers, led to working out mathematical programming techniques for the plastic design of beams and framed structures as described by Heyman around 1951.

A general architectural (or structural) objects and systems are described by means of a set of physical parameters (Dapogny, Frey, Omnès, & Privat, 2018):

$$\{p_i\}_{i=1,\cdots,N} \qquad 2.$$

In Equation (2) are defined the design variables subjected to further possible changes (trade-off) in the optimization phase, described by the following equation:

$$\min_{\{p_i\}\in P_{ad}} \mathrm{J}_1, \mathrm{J}_2, \ldots \mathrm{J}_m(P_1, \ldots, P_m) \qquad 3.$$

where P_{ad} is a set of admissible parameters and J_1, J_2, J_m represents respectively the possible objective to be minimized in a MOOPs.

Depending on the formulated problem and its purpose, the optimization may be subjected to equality (Eq. (4)) or inequality (Eq. (5)), called *constraint functions*, on which the feasibility of the optimization results will depend as follows:

$$h(p_{2,\dots}p_m) = x^u \qquad 4.$$

$$g(p_{2,\dots}p_m) \leq x^u \qquad 5.$$

In cases of constrained optimization, the process of optimizing an objective function is done concerning the variables in the presence of constraints on those variables.

The approach to the Optimization process in ADO using parametric modelling can be summarized in different phases in which each step is strictly connected with the others in a row, as a direct consequence of changing the design variable (trade-off) (Figure2).

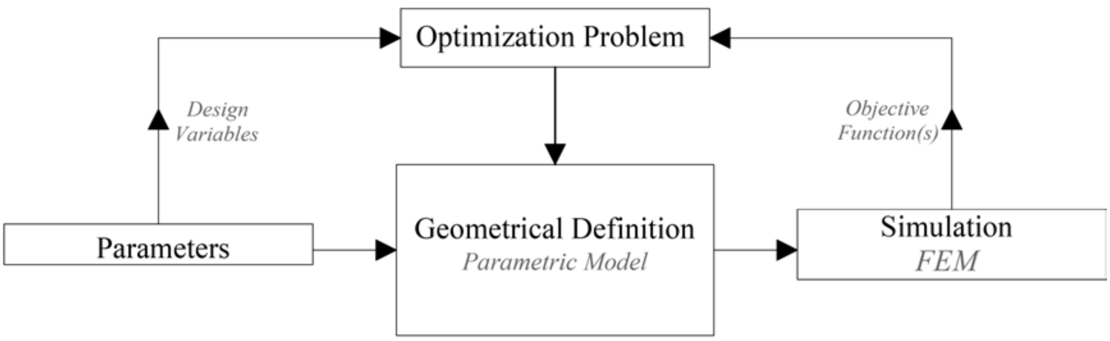

Figure 2. General Workflow of Archiectural Parametric Design Optimization Method.

The parametric definition of a generic architectural object is a mandatory step to define a final optimization problem according to the design variables and starting design intention. Then, each optimization problem can be solved with the appropriate algorithm.

The structural optimization problems are defined and divided into three different categories as follow (Christensen & Klarbring, 2009) (Kirsch, 1993):

- Size/Parametric Optimization,
- Shape Optimization,
- Topology Optimization.

To summarize, size optimization deals with the optimal configuration regarding the size of specific structural elements (such as trusses elements) to minimize (or maximize) the response of the objective function depending on the settled problem. On the other hand, shape optimization focuses on the optimal geometric configuration based on the fixed domain. Finally, topology optimization minimizes the number, shape, and position of the elements for continuum systems.

Different definitions for optimization problems can be found in literature, and their meaning depends on the application and its purpose. This diversity results from many objective functions to be applied in optimization problems, different data (variables discrete or continuous), and the constraints that must be imposed (Boyd & Vandenberghe, 2004). Due to many mutable parameters and the variety for which the optimization processes can be applied, there are no constant rules in the optimization theory and application.

The association between architectural design and optimization problems has burst thanks to the development of tools able to convey the architectural design principles in logical frameworks, giving as a starting point a vital instrument to translate a mathematically set of imposed ideas. The software created for generative architecture enables designers to foretype links between ideas, practical design applications, and optimization.

The analysis and optimization process across architectural and structural objects parameterization had further been supported by directly connecting Finite Element Analysis (FEA) tools. With the produced models (with FEM) is possible to obtain physical information (such as stresses, mass or volume, displacements) of any object described by frame elements or shells.

The simulation models are developed based on a dataset of detailed information for each component to optimize the performance of architectures.

The interest in optimizing the shape (or geometry) and the topology has exponentially increased in the last decade due to the newest technologies in computational power given by the developed tools specifically for the AEC industry and the demand for complex designs/applications to real-world structures. Many tools nowadays are available to support the choices of architects, designers, and engineers for the most performing solutions. The selection of the best criteria depends on the formulated problems that in architecture are correlated with factors such as the reduction of the self-weight of the structure (i.e., the costs and environmental benefit), of the general structural performance, the consumptions (linked to the sunlight exposition). These factors must be described as correlated operations used in the design and paralleled inclusion of performance of numerical calculations to present complexities in form of function and, finally, be expressed in computable formulas (Melchiorre, Bertetto, & Marano, 2021).

In order to simplify all the operations of black-box (derivative-free), optimization tools have been implemented for ADO (Figure 3). More specifically, with the exploit of Parametric design methods linked to the numerical simulations as part of design development in architectural design, the applications of black–box optimizations tools have become increasingly used.

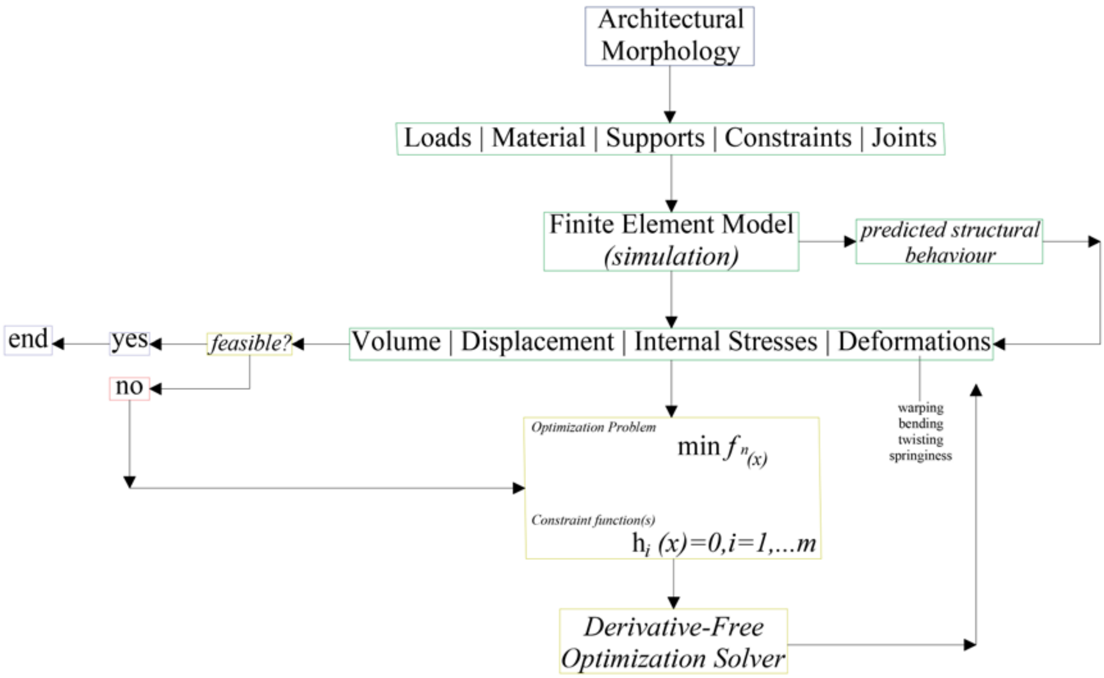

Figure 3. Optimization Workflow integrating FEA and derivative-free optimization tool.

The derivative-free optimization field (or black-box) solves optimization problems by setting only the objective functions (single or multi-objective) and constraints. At the same time, the analytical development of the solver (algorithm) remains unknown (Wortmann & Nannicini, 2017). On the other hand, the black–box optimization tools have caught on ADO, and black boxes are often governed by solvers using EAs-based optimization strategies. This is the case with solvers implemented for one of the most popular platforms for parametric design definition. i.e., the

Grasshopper canvas in Rhinoceros 3D (mentioned above in §2). Among these, we find different tools based on the metaheuristics:

- Galapagos. Released in 2010, now considered obsolete, it was one of the first add–on based on GAs for Grasshopper Rhino. The tool can optimize an object (mostly the shape) to achieve a single goal defined by the user. Galapagos needs a series of genes (design variables) and a defined objective function called fitness value. The fitness function is a function that takes a candidate solution to the problem as input and produces as output how "fit" our how "good" the solution is concerning the problem formulated.

- Octopus. Octopus was created for Multi-Objective Evolutionary Optimization allowing the search for many goals simultaneously. It produces a range of optimized trade-off solutions between the extremes of each goal introducing the Pareto-Principle for Multiple and Single Goals. The solver is based on SPEA-2 and HypE algorithm from ETH Zurich (Zitzler, Laumanns, & Thiele, 2001).

- Goat. It is an optimization add-on component for Rhino's Grasshopper developed by Simon Flöry, Heinz Schmiedhofer, and Martin Reis. It perfectly complements Galapagos, David Rutten's evolutionary solver. The component pursues a mathematically rigorous approach delivering fast and deterministic results relying on gradient-free optimization algorithms. Goat is a drop-in replacement for Galapagos. It is based on David Rutten's Galapagos GUI and interfaces NLopt, a collection of mathematical optimization libraries (Flöry, Schmiedhofer, & Reis , 2016).

- Optimus. It is a new metaheuristic optimization plug-in for Grasshopper. The first version implements the Self-Adaptive Differential Evolution with Ensemble of Mutation Strategies (jEDE). While the self-adaptive approach updates crossover and mutation rates, the ensemble of mutation strategies uses three operators to find the optimal result. The primary purpose is to support the Performative Computational Architecture framework during the design decisions in the conceptual phase (çubukçuoğlu, Ekici, Tasgetiren, & Sevil, 2019).

- Silvereye. Silvereye is also an add-on component for Grasshopper. It has been created for single-objective searches in complex optimization problems. The add-on is based on PSO (Particle Swarm Optimization) Algorithm, inspired by a biological system based on the social behaviours of flocking birds and schooling fish (act as a single organism). The particles interact and learn from the others to find the optimal configuration (Cichocka, Migalska, Browne, & Rodriguez, 2017).

The above most used tools represent just a small part of all the tools released for the AEC industry, and the list is proliferating with the implementations of add-ons capable of achieving performing solutions in less time.

2.3 Structural Design Optimization

The design optimization process gives optimal outcomes (solutions) or a pool of optimized design alternatives that meet the objective functions set in the problem. The process of finding the best solutions and techniques in structural design optimization has been searched for more than 100 years (Maxwell, 1890) (Michell, 1904).

Structural analysis, in general, aims to predict the response of a structural object considered external loads and stresses. In the AEC industry settings, the structural studies are typically conducted by FEA on objects generated thanks to the Computer-Aided Design Software.

As seen in the previous sections, the applications of computational methods integrated optimization components to FEM software through new developments. Furthermore, the integration of the Optimization add-on allows engineers and designers to develop and solve structural optimization problems based on the needs set in each specific project to be evaluated.

Different variations and applications for structural optimization can be found in literature and real projects, and it is different for each problem, generically expressed in Equation 2; anyhow, the variations of structural optimization can be classified considering not only the type of optimization (Shape, size, Topology, §2.1) but also considering the i) analysis pattern (i.e., linear static, nonlinear, Multiphysics, eigenvalues, flexible multibody, time-transient), the ii) application domains (Civil engineering, mechanical, naval architecture, etc.) and the iii) research focuses (geometry parameterization, optimization algorithms, approximation methods such surrogate models, etc.) (Saitou, Izui, Nishiwaki, & Papalambros, 2005).

Optimization in engineering aims to achieve a design relative to a set of prioritized criteria or constraints. Dealing with constrained optimization problem is nowadays an active research field, and recent studies even adopt machine learning and artificial intelligence techniques to improve the metaheuristic optimum research (Rosso, Cucuzza, Di Trapani, & Marano, 2021). In more detail, design, construction, and maintenance of any engineering system, engineers need to take several technological and managerial decisions at many stages (Lagaros N. D., 2018). The contemporary optimization computational tools can support the processing at the very early conceptual phase of the project. The collection and management of data are already used in design tools to optimize space, minimize environmental damage, and reduce energy use.

Considering real-world structural systems, to obtain optimized design with high accuracy, the procedure must lean on numerical simulation consulting physical characteristics of the system itself (i.e., self-weigh, morphology, numbers of elements and its shape and size) and the problem related to the manufacturing and the predicted performance subjected to specific external conditions.

The tools developed to solve problems in structural optimization should supply several goals: the accuracy of numerical simulations and response for structural systems (displacements/stresses under a set of loading conditions), the design procedure for performing the constraints checks imposed by the design codes or engineers and provide efficient optimization algorithm for achieving optimized designs able to satisfy financial and design requirements (also linked to the manufacturability).

Based on this statement, a specific platform – Optimization Computing Platform - have been implemented to meet the morphological, physical, and structural needs (Lagaros N. D., A general purpose real-world structural design optimization, 2014). The OCP, based on metaheuristic techniques, incremental dynamic analyses and parallel computing required, has been created to assess the structural performance and solve optimization problems while supporting deterministic and probabilistic formulations.

The objective functions supported by OCP comprehend material cost, life cycle cost, the ratio of torsion, stiffness eccentricity, strength eccentricity, BST (Chopra), overstrength variance, ductility demands, drift variance, eigenfrequencies, base reactions (Fx, Fy, Fz, Mx, My, Mz), buckling factor, solid stress, displacements allowing the setting of multiple objective functions through the weight coefficient for each one objective. OCP also supports various design variables concerning the main features of the structural object and its material (Cross-sections of beams and columns, material type, set of the slab and shear walls); moreover, the platform supports probabilistic and determinist formulations. Three design formulations which are considering the probabilistic system response is supported: reliability-based design optimization (RBO), robust design optimization (RDO), and the combined formulation denoted as reliability-based robust design optimization (RRDO). OCP is integrated with the optimizer component provided with the eight metaheuristic optimization algorithms (MOA – i) GA's, ii) Evolution Strategies, iii) PSO, iv) Differential Evolution, v) Harmony Search, vi) Covariance Matrix Adaptation, vii) Elitist CMA and viii) Ant Colony Optimization); additionally, the component provides the use of the Cascade Optimization.

In addition to the optimization component - just mentioned - a feature that allows structural analysis has been implemented: OCP supports all the analysis procedures that are suggested by the design codes (as in SAP2000) while adding as a separate module the development of the Incremental Dynamic Analysis (IDA) (Vamvatsikos & Cornell, 2001) and the Multi-component Incremental Dynamic Analysis (MIDA) (Lagaros N. , 2009).

In OCP, implementing a PBD (Performance-Based Design) allows designing structural objects and systems according to the imposed appropriate level of seismic and wind hazard corresponding to a structural performance level. The Performance-Based Design (PBD) is a different approach that ensures site selection and development of the design stages, including construction and maintenance stages, to predict structural performance over its life.

Solving real-world structural optimization problems means achieving coaction between the accurate and computationally - efficient numerical model of the physical problem and applying the most suitable optimization algorithms to improve the design while handling the system uncertainties.

Soon, according to machine learning evolution, software applications will give the ability to synthesize vast amounts of architectural knowledge in seconds. However, architects' knowledge acquired through the education and experience needed to design buildings will be poor to compete for computational procedures.

The next step in a software design application is to produce a user-friendly tool for architects/designers to give the benefits of parametric design without any coding knowledge (such as Grasshopper is needed). Designers in collaboration with software engineers have already developed parametric design tools, which uses data inputted into it related to the size of the building and local planning regulations to create an optimum internal plan either in two or three dimensions. Software such as Finch adds decisions in early-stage planning through adaptive design (McSweeney, 2020). The design tools have already been implemented in videogames such as "The Sims", which include a series of life simulations (Arts, 2021). These design tools include algorithms that continuously determine crucial details that typically would have taken hours of manual effort.

3 Parametric Process for Optimized Models – Practice in the AEC industry

Although various research groups in the academic environment have studied only recently computational design, the power of computing architecture has quickly gained a foothold for creating architecture. As a result, major architectural firms have adopted this design process. The benefits given by ADO and parametric design can be seen in several contemporary works. In the following examples are mentioned examples of real - works conducted by architectural firms (such as Arup, Foster + Partners, Zaha Hadid Architects) based on parametric design to achieve a holistic design approach in the architectural and structural field.

Smakkelaarspark, Utrecht, Netherlands, ARUP Group

The ARUP Group used parametric design and optimizations as a final solution in the Project of Smakkelaarspark (Utrecht, Netherlands) to face the requirements of high performing structure with particular attention to energy consumptions and environment,

The area next to Utrecht's central railway station has been the subject of study and urban redevelopment through the transformation of a lot subject to the abandonment of approximately 20,000m2 into an area used as a residential complex and green accommodation. The site's redevelopment was requested by a leading consortium including Lingotto, Studioninedots, ZUS, VKZ and Arup, which were collaborated to carry out a project with a high-tech brand able to provide a sustainable solution. The parametric model was implemented to design Smakkelaarspark following different steps. Among the requirements was a maximized park area, defining a healthy environment with sustainable residential units. From the Parametric models linked to MOOPs, an optimized model was retrieved.

In the project, six KPIs (Key Performance Indicators) were used. The KPIs are established measures to evaluate the performance of the architectural design. For the Smakkelaarspark the KPIs were consisted of (Titulaer, Christodoulou, & Vola, 2019):

i) Sun in the park

ii) Low noise in the park and the apartments

iii) View on the park

iv) Multi-sided apartments

v) Sun on the façade

vi) South facades and PV roof areas

The six KPIs established as the value of constraints in MOOPs which contributed to complex's design and also protecting the entire area - including the park - from the noise generated by the urban surroundings and at the same time optimizing the hours of sun exposure of the site while maximizing the views of the city for the apartments. In addition, solar exposure was studied to offer the best internal lighting to the apartment and determine the positioning of the photovoltaic panels on roofs and facades, generating 50% of the total expected consumption (ARUP, 2019).

The Great Canopy, Hong Kong, Foster + Partners

Foster + Partners used scripting techniques to obtain a complex model as a proposal for their Great Canopy Project at the West Kowloon Cultural District in Hong Kong (2004).

The Masterplan of the cultural district of West Kowloon included a vast project for residential towers located on a park with several historical-cultural buildings, including museums, theatres, arenas and outdoor amphitheatres. The Project of the Great Canopy represents the park's roof: a 1500 m2 roof that acts as an environmental modulator to protect the area from the external environmental agents and modify the microclimate.

The project's development was possible thanks to the computational techniques linked to the 3D Computer-Aided Design model of the structure in which the characteristic of the environment has been simulated (Peters, The West Kowloon Masterplan, Second Stage Competition Hong Kong, China, 2003-2004 - Foster + Partners, 2005). The whole system was entirely parametric, allowed the control of all the design variables simultaneously and produced a complex surface easy to manipulate with high precision.

The project that resulted from the computation techniques contained many components which have been physically fabricated through digital fabrication. Therefore, the canopy could be printed with all its components from the information retrieved by the generative scripts. Due to the massive size of the architectural object, the structure was divided into seven parts: glazing components were laser cut from digital files and assembled by the in-house model shop and combined with a model of the rest of the scheme (Peters & Whitehead, Geometry, Form and Complexity, 2008) (Peters & Whitehead, Geometry, Form and Complexity, 2008).

Alif, mobility pavilion in Dubai, Foster + Partners

It is a project of Foster + partners', one of Expo 2020 Dubai's three signature pavilions. This structure merges the digital and the physical world to inspire visitors of expo 2020 Dubai to envision the future they want. The building has a characteristic trefoil shape with three large petals projecting outward from the base of the building. The designer's referenced wind tunnel images and aeronautical elements to capture the idea of movement in the external envelope of the building; the horizontal bands flow around the building, widening to allow light inside and lifting to create the entrance canopies. The pavilion transforms from day to night, picking up the colours and light of the Expo.

livMatS Pavilion, ICD/ITKE University of Stuttgart

It is a novel co-design process that accounts for geometrical, material, structural, productional, environmental, and aesthetic requirements and advanced robotic fabrication techniques applied to natural materials. ICD/ITKE University of Stuttgart has designed this project. It has been bio-Inspired structure, robotically woven. The material of the pavilion is an efficient alternative to conventional construction and steps towards architectural sustainability. The structure affiliates as the first load-bearing construction entirely wound of robotically woven flax fibre. It is about a generated unique architectural form with high ecological value.

Mayfair, Melbourne tower, Zaha Hadid Architects

It is a 64-metre apartment block that will feature facades covered in angular balconies. The project was conceived in collaboration with Zaha Hadid Architects with local architect Elenberg Fraser. The facade's composition has evolved from a system of simple wave formations that is further developed to generate variables of the same design language. The parameterization allowed the designers to reduce the number of different facade panels required for the tower and, as a result, led to a reduction in its cost. The use of algorithms to identify these variables allowed the facade to adapt to the wide variety of apartment layouts and adapt to the irregular location. The parametric design allowed an optimizing algorithm to identify shape similarities within the facade to a tolerable degree and minimize the number of different facade panels required. The result of this process drove to create a sculpted facade that would have otherwise been prohibitive in terms of cost (Mairs, 2017)

3D print pavilion in Saudi Arabia, Precht and Mamou-Mani Architects

The pavilion Sandwaves in Diryah is a 3D printed structure from sand and furan resin as street furniture at Diryah Season (a sports and entertainment event in the Al-Turaif District). Parametric design tools were used to generate the optimum shape and thickness of each piece. Among different parameters was the use of local material, abundant in the area and responding to local building traditions. The final design is sand waves comprised of 58 individual 3D-printed elements combined to form the continuous ribbon, making narrow alleys and wide plazas (Crook, 2020).

4 Conclusions

This paper has proposed potential directions for the use of parametric and optimization applicable tools. Optimization tools for architects/engineers are promising for evolving aesthetically pleasant elements, contributing to multi-objective optimization (MOOPs). It is a reference study that presents the power of algorithmic design in architectural optimization.
From the presented brief review concerning the performance-based design integrated with parametric modelling, simulation, and architectural optimization, it emerged that unprecedented new solutions and workflows had been implemented in the AEC industry, focused on the generated architectural shapes and the computational speed. Furthermore, the recently carried out studies and the progress in computing power drove a more straightforward resolution of problems concerning the form and sustainability of a project.
After the analysis of case studies in the world's architecture, multiple advantages of ADO have been recorded: i) material savings (low-waste constructions), ii) cost reductions, iii) low energy consumption.
The techniques described in the present contribution can be explained as a result of the demands of society concerning the ethical use of limited resources employed in architecture (in terms of material and energy consumption). Therefore, using such tools to control material and energy waste must be the least requirement for future constructions.
If, on the one hand, the new features of parametric software are characterized by the ease of use which is leading to architectural projects that safeguard the environment and the creation of

stunning building's solutions, on the other, it must be recognized that many optimization processes used for architectural development cannot be considered as the primary tools to design. This is because many architectural aspects cannot be translated into scientific values. The risk - using only algorithmic methodologies - is to lose the balance between the needs (intended as reasons why architecture is created, combined with the requirements of comfort from a human point of view), morphology, structure, and the site of which a generic architecture is belonging.

As a result of this study, it must be said that this new way of doing architecture influenced the architectural lexicon irreversibly. Nevertheless, to create a quality architectural design, the designer must have a deep knowledge of using the tools appropriately to preserve the design intentions dictated by the main idea rather than by the software's suggestion.

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