

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

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# 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

<i>ADO</i>	Architectural Design Optimization.
$x, y$	in Equation (1). Set of parameters in the parametric catenary equation.
$\alpha$	in Equation (1). Control parameter for shape and inclination of the curve.
$t$	in Equation (1). Set of curve control point.
<i>NURBS</i>	Non-Uniform Rational Basis Spline.
<i>AEC</i>	Architecture, Engineering and Construction.
<i>CAD</i>	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.
<i>PSO</i>	Particle Swarm Optimization.
<i>GAs</i>	Genetic Algorithms.
<i>SPEA – 2</i>	Improved Strength Pareto Evolutionary Algorithm.
<i>KPIs</i>	Key Performance Indicators.

## 1 1 Introduction

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

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

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

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

This is an example created from parts of other articles, it is not designed to be read for sense.

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

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

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

## 63 **2 Parametric Design in AEC Industry**

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

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

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

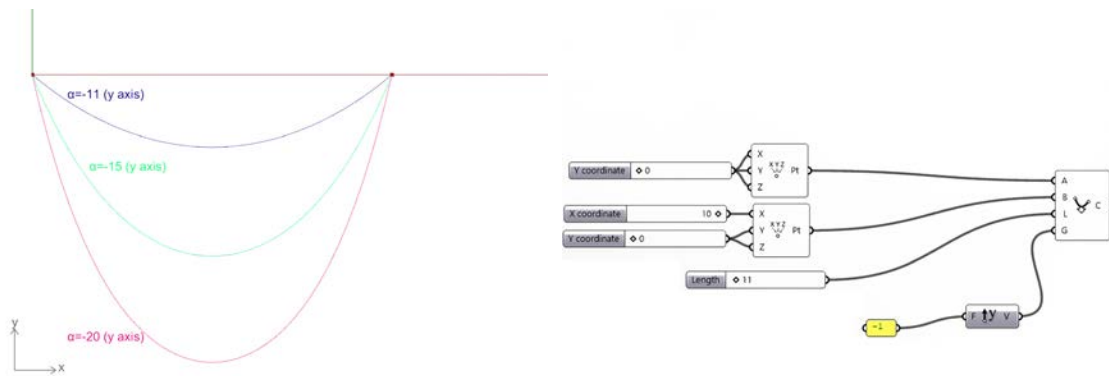
85 The term "parametric" originates from mathematics (parametric Equation) and refers to the use  
86 of specific parameters or variables that can be edited to manipulate or alter the result of an

87 equation or system. For instance, an example of a parametric equation is the formula that defines  
88 a catenary:

89  $x(a, t) = t$  1.

90  $y(a, t) = a \cosh \frac{t}{a}$  2.

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



96 **Figure 1. Parametric development of a generic catenary with  $\alpha$  variable and fixed anchor**  
97 **points.**  
98

99 The bond between the mathematical parameterization - as in Eq.1 - and the architectural one  
100 concerning composition is similar: many parameters (as design variables) create an architectural  
101 organism as a response. On the other hand, parametrization in architecture is a process based  
102 on algorithmic thinking (a finite sequence of defined instructions) that empowers the articulation  
103 of parameters and norms. Tether defines and encodes the relationship between design intent and  
104 design response (Wassim, 2013). In *Elements of Parametric Design*, Woodbury describes  
105 Parametric modelling (also known as constraint modelling) as a process that introduces  
106 remarkable changes in the whole method of architectural planning. The traditional digital design  
107 tools, such as Computer-Aided Design systems, create the flow in which the designer "adds and  
108 erases" (Woodbury, 2010) objects. However, with parametric modelling tools, it is possible to  
109 retrieve different solutions by varying the parameters for a single model. Indeed, parametric

110 design requires a complex act of thinking since it does not lead to a single design solution (as the  
111 conventional design), but it usually leads to a set of feasible design solutions.  
112 With the rapid technological development, Computer-Aided Design has been enriched with  
113 parametric design techniques and tools. Nowadays, more professional figures involved in the  
114 AEC industry use visual programming and scripting tools to produce their designs. Moreover,  
115 from a single concept, the generative modelling can cause the exploration of all the possible  
116 combinations among the design variables; this evaluation would have been impossible to be  
117 carried out in a short time by manual operations.

### 118 **2.1 Computational tools for Parametric Modelling**

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

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

124

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

- 127 - Solidworks

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

- 131 - Revit

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

135

136 In the Revit model, every drawing sheet, 2D and 3D view, and schedule is a presentation of  
137 information from the same virtual building model. Revit collects information about the building  
138 project and coordinates this information across all other representations of the project. The Revit

139 parametric change engine automatically coordinates changes made anywhere—in model views,  
140 drawing sheets, schedules, sections, and plans (Autodesk, 2021).

141 - CATIA

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

145 - FreeCAD

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

149 - Grasshopper in Rhinoceros 3D

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

155 - Inventor

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

160 - SAP2000

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

165 - SCADA Pro

166 SCADA Pro (Structural Computer-Aided Design & Analysis) is an integrated software application  
167 for static and dynamic analysis and design of reinforced concrete, steel, timber, and masonry  
168 structures, according to Eurocodes and the respective National Annexes for most European

169 countries (ACE - Hellas S.A., 2021). Different add-ons have been integrated into the platform to  
170 analyse structure considering a wide range of materials, allowing importing any project in  
171 ScadaPro from different formats.

## 172 **2.2 Survey for the Architectural Design Optimization**

173

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

180 As a well-known technique, the optimization techniques originated to find the minimum or  
181 maximum value of a function, given certain parameters, so-called design variables (Vanderplaats,  
182 1984).

183 The first analytic definition of structural optimization began with the early works of Maxwell in  
184 1869, followed by Mitchell in 1904. The initial development of optimization techniques was  
185 developed in the aircraft and space industry due to minimum weight requirements in the  
186 engineering design (Tushaj & Lako, 2017). Between the 1940s and early 1950s, considerable  
187 analytical work was done on optimizing components in resented in works such as Shanley's  
188 Weight-Strength Analysis of Aircraft Structures. Subsequently, the progress of linear  
189 programming techniques by Dantzig, together with the application of digital computers, led to  
190 working out mathematical programming techniques for the plastic design of beams and framed  
191 structures as described by Heyman around 1951.

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

$$194 \quad \{p_i\}_{i=1,\dots,N} \quad 2.$$

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

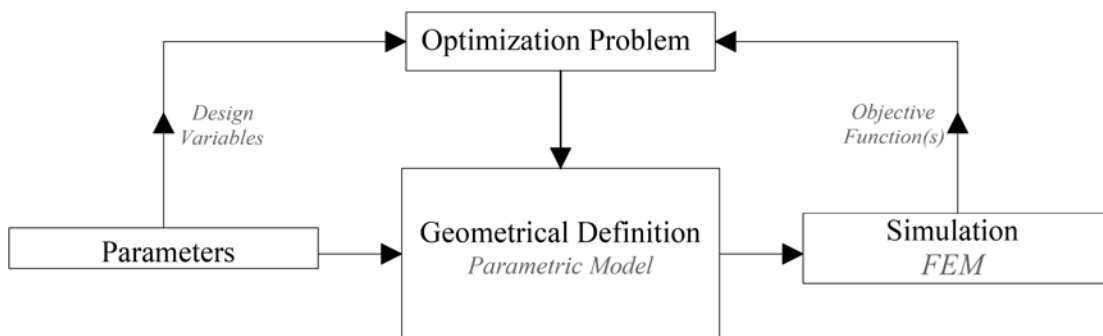
$$197 \quad \min_{\{p_i\} \in P_{ad}} J_1, J_2, \dots, J_m(P_1, \dots, P_m) \quad 3.$$

198 where  $P_{ad}$  is a set of admissible parameters and  $J_1, J_2, J_m$  represents respectively the possible  
 199 objective to be minimized in a MOOPs.  
 200 Depending on the formulated problem and its purpose, the optimization may be subjected to  
 201 equality (Eq. (4)) or inequality (Eq. (5)), called *constraint functions*, on which the feasibility of the  
 202 optimization results will depend as follows:

203  $h(p_2, \dots, p_m) = x^u$  4.  
 204  $g(p_2, \dots, p_m) \leq x^u$  5.  
 205

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

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



211  
 212 **Figure 2. General Workflow of Architectural Parametric Design Optimization Method.**  
 213

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

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

- 219 - Size/Parametric Optimization,
- 220 - Shape Optimization,
- 221 - Topology Optimization.

222 To summarize, size optimization deals with the optimal configuration regarding the size of specific  
 223 structural elements (such as trusses elements) to minimize (or maximize) the response of the

224 objective function depending on the settled problem. On the other hand, shape optimization  
225 focuses on the optimal geometric configuration based on the fixed domain. Finally, topology  
226 optimization minimizes the number, shape, and position of the elements for continuum systems.  
227 Different definitions for optimization problems can be found in literature, and their meaning  
228 depends on the application and its purpose. This diversity results from many objective functions  
229 to be applied in optimization problems, different data (variables discrete or continuous), and the  
230 constraints that must be imposed (Boyd & Vandenberghe, 2004). Due to many mutable  
231 parameters and the variety for which the optimization processes can be applied, there are no  
232 constant rules in the optimization theory and application.

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

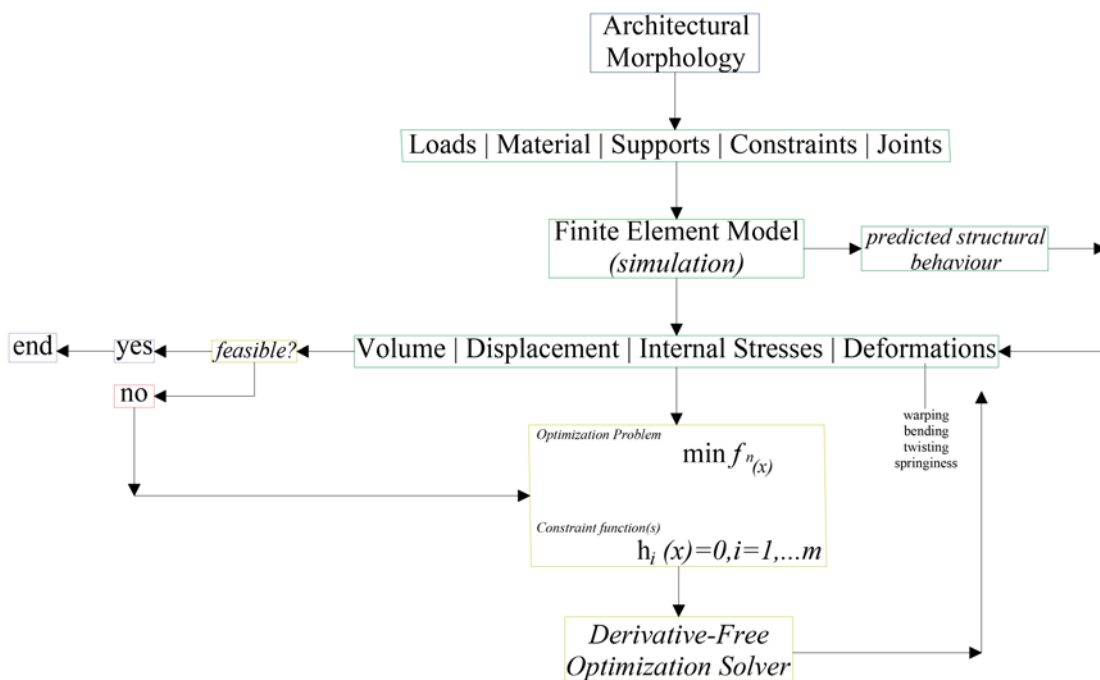
238 The analysis and optimization process across architectural and structural objects  
239 parameterization had further been supported by directly connecting Finite Element Analysis (FEA)  
240 tools. With the produced models (with FEM) is possible to obtain physical information (such as  
241 stresses,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

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

244 The interest in optimizing the shape (or geometry) and the topology has exponentially increased  
245 in the last decade due to the newest technologies in computational power given by the developed  
246 tools specifically for the AEC industry and the demand for complex designs/applications to real-  
247 world structures. Many tools nowadays are available to support the choices of architects,  
248 designers, and engineers for the most performing solutions. The selection of the best criteria  
249 depends on the formulated problems that in architecture are correlated with factors such as the  
250 reduction of the self-weight of the structure (i.e., the costs and environmental benefit), of the  
251 general structural performance, the consumptions (linked to the sunlight exposition). These  
252 factors must be described as correlated operations used in the design and paralleled inclusion of

253 performance of numerical calculations to present complexities in form of function and, finally, be  
254 expressed in computable formulas (Melchiorre, Bertetto, & Marano, 2021).

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



259  
260 **Figure 3. Optimization Workflow integrating FEA and derivative-free optimization tool.**  
261

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

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

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

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

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

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

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

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

### 305 **2.3 Structural Design Optimization**

306

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

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

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

318 Different variations and applications for structural optimization can be found in literature and real  
319 projects, and it is different for each problem, generically expressed in Equation 2; anyhow, the  
320 variations of structural optimization can be classified considering not only the type of optimization  
321 (Shape, size, Topology, §2.1) but also considering the i) analysis pattern (i.e., linear static,  
322 nonlinear, Multiphysics, eigenvalues, flexible multibody, time-transient), the ii) application  
323 domains (Civil engineering, mechanical, naval architecture, etc.) and the iii) research focuses

324 (geometry parameterization, optimization algorithms, approximation methods such surrogate  
325 models, etc.) (Saitou, Izui, Nishiwaki, & Papalambros, 2005).

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

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

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

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

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

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

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

377 Solving real-world structural optimization problems means achieving coaction between the  
378 accurate and computationally - efficient numerical model of the physical problem and applying

379 the most suitable optimization algorithms to improve the design while handling the system  
380 uncertainties.

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

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

### 395 **3 Parametric Process for Optimized Models – Practice in the AEC industry**

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

403 ***Smakkelaarspark, Utrecht, Netherlands, ARUP Group***

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

407 The area next to Utrecht's central railway station has been the subject of study and urban  
408 redevelopment through the transformation of a lot subject to the abandonment of approximately  
409 20,000m<sup>2</sup> into an area used as a residential complex and green accommodation. The site's  
410 redevelopment was requested by a leading consortium including Lingotto, Studioninedots, ZUS,  
411 VKZ and Arup, which were collaborated to carry out a project with a high-tech brand able to  
412 provide a sustainable solution. The parametric model was implemented to design  
413 Smakkelaarspark following different steps. Among the requirements was a maximized park  
414 area, defining a healthy environment with sustainable residential units. From the Parametric  
415 models linked to MOOPs, an optimized model was retrieved.

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

- 419 i) Sun in the park
- 420 ii) Low noise in the park and the apartments
- 421 iii) View on the park
- 422 iv) Multi-sided apartments
- 423 v) Sun on the façade
- 424 vi) South facades and PV roof areas

425 The six KPIs established as the value of constraints in MOOPs which contributed to complex's  
426 design and also protecting the entire area - including the park - from the noise generated by the  
427 urban surroundings and at the same time optimizing the hours of sun exposure of the site while  
428 maximizing the views of the city for the apartments. In addition, solar exposure was studied to

429 offer the best internal lighting to the apartment and determine the positioning of the photovoltaic  
430 panels on roofs and facades, generating 50% of the total expected consumption (ARUP, 2019).

431 ***The Great Canopy, Hong Kong, Foster + Partners***

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

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

439 The project's development was possible thanks to the computational techniques linked to the  
440 3D Computer-Aided Design model of the structure in which the characteristic of the environment  
441 has been simulated (Peters, The West Kowloon Masterplan, Second Stage Competition Hong  
442 Kong, China, 2003-2004 - Foster + Partners, 2005). The whole system was entirely parametric,  
443 allowed the control of all the design variables simultaneously and produced a complex surface  
444 easy to manipulate with high precision.

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

452 ***Alif, mobility pavilion in Dubai, Foster + Partners***

453 It is a project of Foster + partners', one of Expo 2020 Dubai's three signature pavilions. This  
454 structure merges the digital and the physical world to inspire visitors of expo 2020 Dubai to

455 envision the future they want. The building has a characteristic trefoil shape with three large petals  
456 projecting outward from the base of the building. The designer's referenced wind tunnel images  
457 and aeronautical elements to capture the idea of movement in the external envelope of the  
458 building; the horizontal bands flow around the building, widening to allow light inside and lifting to  
459 create the entrance canopies. The pavilion transforms from day to night, picking up the colours  
460 and light of the Expo.

461

462 ***livMatS Pavilion, ICD/ITKE University of Stuttgart***

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

470 ***Mayfair, Melbourne tower, Zaha Hadid Architects***

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

482 ***3D print pavilion in Saudi Arabia, Precht and Mamou-Mani Architects***

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

490 **4 Conclusions**

491 This paper has proposed potential directions for the use of parametric and optimization  
492 applicable tools. Optimization tools for architects/engineers are promising for evolving  
493 aesthetically pleasant elements, contributing to multi-objective optimization (MOOPs). It is a  
494 reference study that presents the power of algorithmic design in architectural optimization.  
495 From the presented brief review concerning the performance-based design integrated with  
496 parametric modelling, simulation, and architectural optimization, it emerged that unprecedented  
497 new solutions and workflows had been implemented in the AEC industry, focused on the  
498 generated architectural shapes and the computational speed. Furthermore, the recently carried  
499 out studies and the progress in computing power drove a more straightforward resolution of  
500 problems concerning the form and sustainability of a project.

501 After the analysis of case studies in the world's architecture, multiple advantages of ADO have  
502 been recorded: i) material savings (low-waste constructions), ii) cost reductions, iii) low energy  
503 consumption.

504 The techniques described in the present contribution can be explained as a result of the  
505 demands of society concerning the ethical use of limited resources employed in architecture (in  
506 terms of material and energy consumption). Therefore, using such tools to control material and  
507 energy waste must be the least requirement for future constructions.

508 If, on the one hand, the new features of parametric software are characterized by the ease of  
509 use which is leading to architectural projects that safeguard the environment and the creation of

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

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

521

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