

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

Evangelia Frangedaki¹, Laura Sardone², Nikos D. Lagaros³

1. Department III, Architectural Language, Communication and Design, School of Architecture, National Technical University of Athens, Heroon Polytechneiou 9, 157 80 Zografou, Greece; efrangedaki@arch.ntua.gr

ORCID number

2. Department of Civil Engineering Sciences and Architecture (UR3) - DICAR, Politecnico di Bari, Via E. Orabona, 4, 70126 Bari (BA), Italy; laura.sardone@poliba.it

ORCID number

3. Institute of Structural Analysis and Antiseismic Research, School of Civil Engineering, National Technical University of Athens, Heroon Polytechneiou 9, 157 80 Zografou, Greece; nlagaros@central.ntua.gr

ORCID number

Full contact details of corresponding author.

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.
α	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).

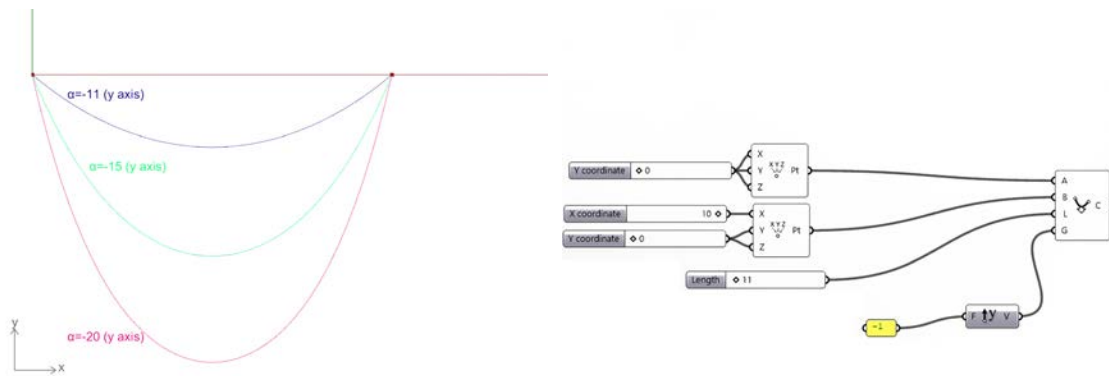
85 The term "parametric" originates from mathematics (parametric Equation) and refers to the use
86 of specific parameters or variables that can be edited to manipulate or alter the result of an

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 the
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 α 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:

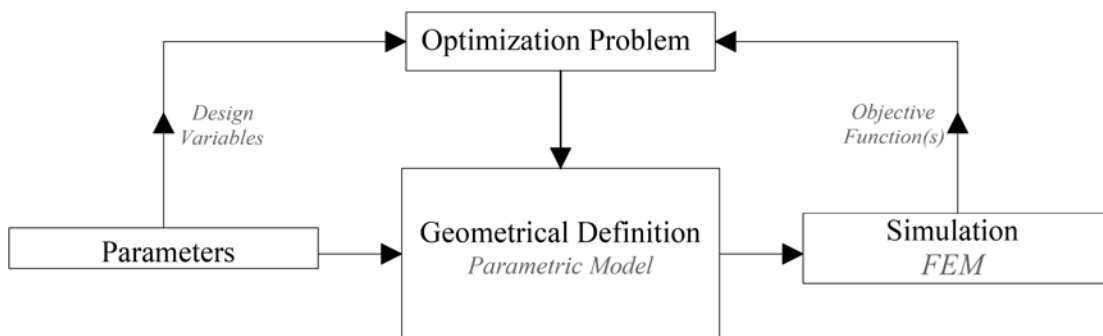
$$197 \quad \min_{\{p_i\} \in P_{ad}} J_1, J_2, \dots, J_m(P_1, \dots, P_m) \quad 3.$$

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.

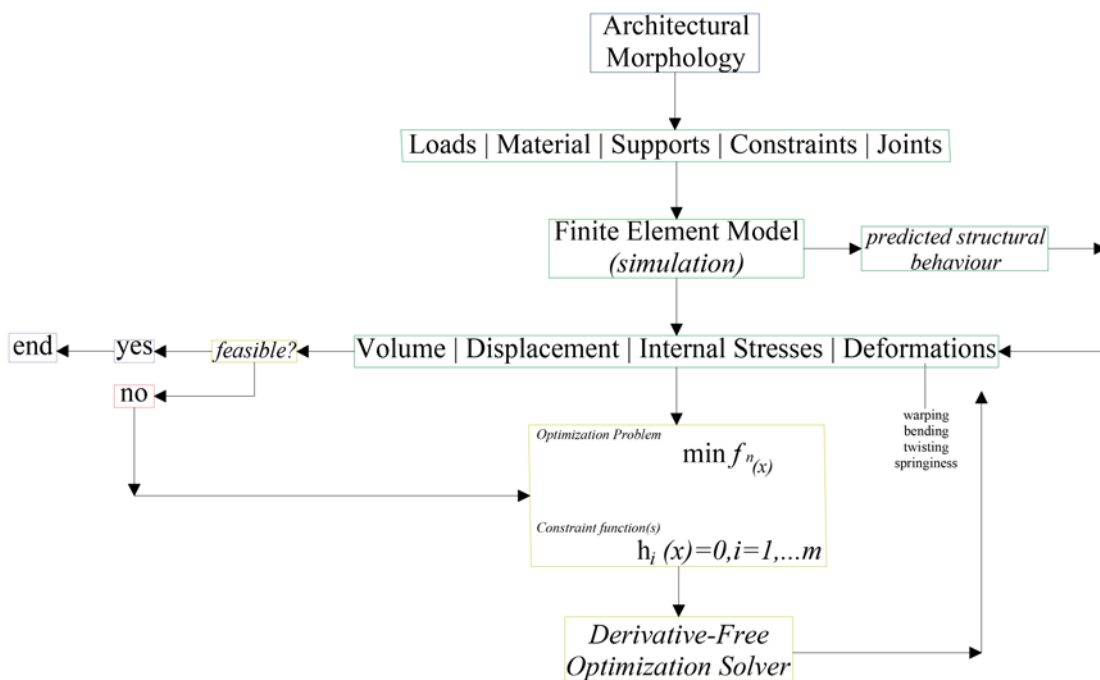
238 The analysis and optimization process across architectural and structural objects
239 parameterization had further been supported by directly connecting Finite Element Analysis (FEA)
240 tools. With the produced models (with FEM) is possible to obtain physical information (such as
241 stresses, mass 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 20,000m² 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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