1.

CDO:

Computational design + optimization in building practice

Chris Luebkeman Kristina Shea

Introduction

Computers continue to change the world of engineering and design, increasing the complexity of what can be designed and built as well as enhancing our imaginations and understanding. In today's competitive global market, exploring and exploiting new ways to use computing is key to creating and fabricating innovative designs that expand the perceived boundaries of possibilities.

Imagine a team working on a large-scale building project with complex geometry. Many design parameters can be varied, and their impact on balancing different design performances is not always predictable. Using a new approach to design, the team creates an optimization model that computationally encodes client, architectural, engineering, fabrication, and construction-related parameters and desired performances. Making use of the considerable computer power across the Arup network, a computational optimization process rapidly generates, evaluates, and mediates among thousands of design variations. The result is a set or 'point cloud' of optimized designs from which good designs can be selected based on preferences among performances, or viewpoints on the design.

Navigating the performance space promotes lateral thinking among designers and illustrates the relation between design variations and complex performance trade-offs. The optimization model can then be adjusted and the process rerun with little extra effort to study impacts of parameter changes. Such studies can help designers to determine the best trade-off among performance and cost regions for the design as well as aiding multidisciplinary negotiations. This new design process enables improved design quality in less time with reduced cost, and can make new levels of complexity and new aesthetics possible.

To move towards this future design process scenario, Arup is incubating expertise in computational design + optimization (CDO) within its Foresight, Innovation and Incubation (FII) group in London. CDO is about formalizing aspects of design tasks as computational models so that iterative computation, both interactive and automated, can be used to find feasible and performance-driven design alternatives that would be difficult to arrive at using conventional computing and design processes alone. CDO builds on and incorporates other emerging design computing technologies, including algorithmic design, 3-D parametric and associative geometry, performance-based design, integrated design tools, and design automation.

The primary focus of the CDO incubation period over the past three years has been to ask: with clients demanding high-quality engineering solutions for more and more complex projects, can CDO provide competitive edge in meeting and exceeding increasing demands? The current focus is on engineering design tasks within building projects.

Motivation for CDO

In industries like automotive, aerospace, and boating, CDO is an essential component of the design process in performance-critical applications. It has led to lighter, stronger, stiffer, and often cheaper automotive bodies, aeroplane wings, and ship keels. In building and infrastructure projects, however, it is only applied in small pockets and mostly for detail design tasks, eg automating the sizing of steel and concrete members for tall buildings, which have enabled both cost and design time savings.

To explore current Arup experience in CDO and future benefits, a half-day 'Arup Explores' event was held in March 2004 involving 53 delegates across four international sites and several sectors. One general conclusion related to building projects was that applying CDO early in design opens up the potential to influence performance-driven changes in building form.

Drivers for increasing expertise in CDO include gaining marketing edge due to increased competition, desire for improved quality, shorter design time and cost, increased complexity (eg geometric) of projects, and to foster improved collaboration among multidisciplinary design teams. In addition to drivers, it is timely to expand expertise and the scope for CDO now since it is enabled by increased computing power in both hardware and software capabilities, and increased computer fluency of young designers.

2. Rendering of the proposed Bishopsgate Tower for DIFA in its City of London setting.

Bridging the gap between research and practice

The CDO field is vast, and comprises research in mathematics, operations research, architecture, aerospace, mechanical engineering, and civil engineering. However, a large gap still exists between research and practice in CDO, especially within the building industry.

The reasons for this relate to methods, tools, and people. First, optimization methods are often only tested on small-scale benchmark tasks and do not often include practical design considerations and constraints, some of which can be difficult to model and are project-specific. Potential optimization tasks that could benefit from CDO generally have anything from five to 25 000 variables, from one to millions of design constraints, and from one to as many independent design performance objectives as can be incorporated.

There is also often a mismatch between the areas where CDO can benefit projects most, ie in early design stages, and where it is straightforward to formulate computational optimization models, ie in detail design stages.

Further, current commercial software for CDO, which most often is developed for the automotive and aerospace industries, does not often match the needs of the building industry (eg taking into account country-specific design codes), requiring in-house customization and development of new tools. This is true apart from some building industry-specific software for structural member section sizing, and application of other software to individual building components that strongly resemble mechanical components.

The final reason relates to people, since CDO requires them to think and work differently. Making step changes in design processes is generally difficult. CDO requires new ways to model design tasks in terms of quantifiable design variables, constraints, and performance objectives, as well as giving up direct control of some design variables to a computational process that will determine their best values based on an optimization model formulated by the design team. CDO has been used most extensively so far on projects whose complexity has driven the need to adopt new computational processes. For example, on the Aquatics Centre project for the 2008 Beijing Olympics, without a new automated approach to selecting section sizes and checking them to design codes for all 25 000 steel sections, it would not have been possible for the team to find a working solution, and one that was near the targeted roof weight.

Work within Arup's FII group is addressing these challenges to help bridge the gap between research and practice. Application to live projects is the priority, to raise understanding of how CDO can best be integrated within design processes to improve and extend service to clients. Arup is now using CDO on projects in London, the Solihull Campus, Manchester, Hong Kong, Detroit, Los Angeles, and Sydney.

A good design optimization task is one where there are design variables to work with and the designer needs to better understand the influences of their changes on one or more performances, to both meet design constraints and improve performances. The number of design variables and trade-offs among performances should be meaningful enough to justify the effort involved in creating an optimization model, finding or developing an integrated CDO tool, and carrying out optimization studies. This justification can be through sheer number of design variables, or potential gains in performance, or limited knowledge of how design variables and performances, especially multi-disciplinary performances, interact.

Through direct project work and many discussions about beneficial CDO applications on Arup building projects, three areas with high potential are emerging: structures, façades and building physics applications.

3. Complex canopy entrance to the Bishopsgate Tower.

Generating optimal structures

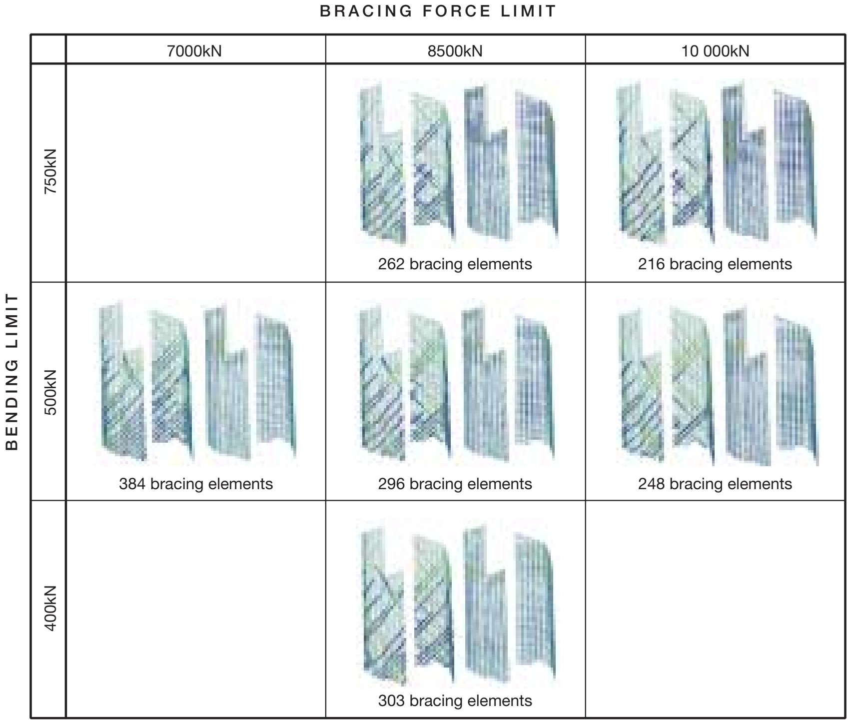
With regard to structures, CDO has been used to generate efficient and aesthetically-pleasing bracing systems for the proposed Bishopsgate Tower in London for Deutsche Immobilien-Fonds AG (DIFA), in collaboration with Arup's Building London Group 4 and working with architects Kohn Pedersen Fox Associates (International) PA (KPF) (Fig 2 & 3).

This curved tower, some 307m tall, required a lightly braced, randomized layout for the steel tubular stability system - 'spirals' of fixed inclination wrapping around the irregular building envelope, emanating from column bases and terminating at varying heights up the building. A variable density bracing pattern was desired with more bracing elements at the bottom of the tower transitioning to fewer at the top.

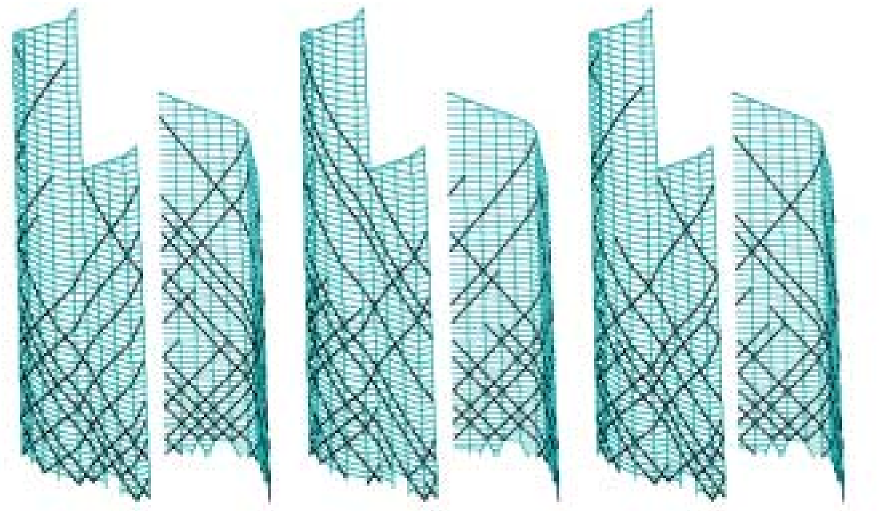
The optimization model for this task encoded 3x10^{48} possible designs, a large number of design variants compared to what can be considered by hand. The objective was to minimize the number of bracing elements while meeting structural limits on maximum axial force in them, and maximum bending moment in the horizontal beams of the perimeter framework (Fig 4).

A new CDO tool was developed initially to automate the manual, collaborative process carried out by the architects and engineers for generating, analyzing, and understanding design alternatives. The search method employed is a variation of pattern search, originally proposed in 1961[1], that evolves efficient bracing patterns through iterative element removal and addition from fully-braced and random starting patterns. This approach would not be possible using traditional numerical, or gradient-based, optimization methods. The 'intelligent' search method, compared with basic automated iterative analysis and removal of under-utilized elements, gave improved designs in terms of reducing the number of required bracing elements for similar structural performance. It also needed substantially less computing time - three hours compared to 14 hours for basic design automation.

Adding a random component to the search procedure and stochastic variation of the starting pattern enable a wide range of design alternatives to be generated from the same process, all with similar structural performance. This benefits a team looking to select designs based on aesthetics, which are difficult to model explicitly within the CDO method itself. Parametric studies were carried out to explore the influence of structural limits on the minimum number of bracing elements in the system, allowing the team to make a more informed decision about which design performance region provided the best trade-off between the bracing pattern and structural limits (Fig 4).



4. Parametric design study of bracing patterns for the Bishopsgate Tower.



271 elements (684kNm, 8398kN)

251 elements (744kNm, 8489kN)

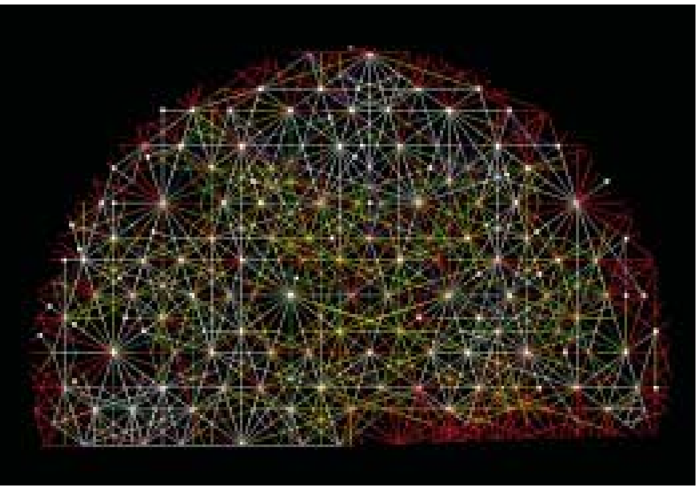
251 elements (726kNm, 8475kN)

5. Planning application schemes for the bracing system of the Bishopsgate Tower.

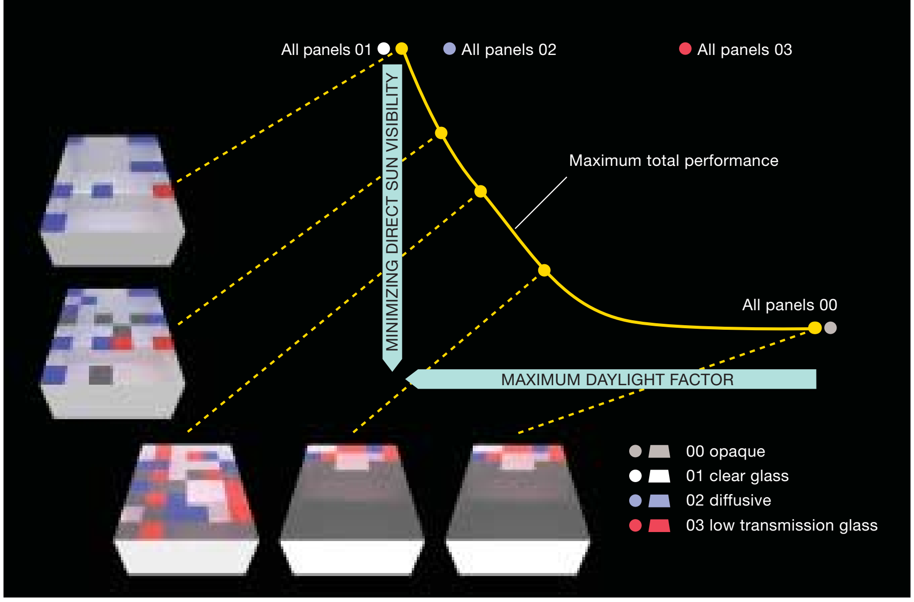
The results of this study were presented to the architects who were enthusiastic and interested in both the bracing schemes generated and the novel design optimization process. Final bracing schemes for the planning application were submitted to the Corporation of London in June 2005 (Fig 5).

The final bracing pattern generated was modified slightly for the planning application, so as to improve the reading at the entrance to the building only. CDO tools may be used again as the design develops, both to investigate the possibility of refining the bracing pattern further and to incorporate, within the same process, parallel studies into the effects of varying individual steel member sizes on the overall efficiency of the building structure. This successful application of an established search method, tailored and extended, provides a valuable case study in applying structural optimization effectively, beyond section sizes alone, on a live building project[2].

Other CDO projects in the area of structures include development of a Rhino CDO toolkit and an application to a steel spaceframe stadium roof. Both involve developing automatic links between CAD tools and GSA, also called integrated design tools. The first project links Rhino and GSA to evolve novel frame structures, whilst the second links a parametric model in CATIA with GSA to optimize section sizes for the steel spaceframe roof according to design codes. Integration of CAD tools and GSA enables automatic creation of GSA models from CAD geometry and structural attributes attached to geometry as well as the potential for gaining fast structural feedback within a CAD environment.



6. Generating an intriguing network of acrylic tubes for a proposed installation by combining a spatial tiling with evolutionary structural optimization (ESO). Colours indicate the iterations of the structural erosion process.



7. Exploring the tradeoff between daylight factor and sun hours for a simple two-room scenario.

The Rhino CDO toolkit was motivated by an installation comprising a unique network of acrylic tubes. The approach taken combines spatial tilings, which are 3-D space-filling algorithms, with performance-driven structural erosion methods, in this case evolutionary structural optimization[3]. Since spatial tilings are not often efficient structures, the aim is to find optimal networks of members within a given spatial tiling driven by the force or utilization in each member, while checking constraints such as strength, buckling, and displacement. The scale of the erosion takes starting designs consisting of thousands of members and erodes them down into a network of the most highly utilized of 500-800 members and support locations (Fig 6).

Panelizing curvy surfaces

Another promising area for CDO addresses the task of panelizing and rationalizing curvy surfaces. Typically panelization of so-called ‘freeform’ surfaces with flat or limited warp panels, triangular or rectangular, requires all the panels to be of unique dimensions. While it is possible to manufacture using state-of-the-art CAD/CAM capabilities, the fabrication and construction costs can be significant.

CDO can be used to inform and negotiate building form rationalization to navigate the spectrum between extreme free-form surfaces and over-rationalization. A proof-of-concept investigation was carried out using a sample curvy surface for two scenarios:

1) panel joints allowed anywhere on the surface assuming that the outer surface is disconnected from the floor plates, and
2) panel joints required to remain at floor plate heights.

The design objectives include matching the original surface within a chosen tolerance, using only flat panels and achieving some repetition in panel geometry. A purpose-built CDO tool was developed as a Rhino plug-in to operate on any defined surface in Rhino, given initial panelization defined as a mesh. The tool uses the stochastic optimization method of simulated annealing[4] to carry out tens of thousands of iterations in about 15 minutes, trying to improve geometric uniformity among the panels while maintaining defined geometric constraints. CDO was successful in reducing the number of unique panels for the two scenarios described by 10% and 18% respectively. Relaxing the tolerance on surface fit can then be used to guide surface rationalization. As architects’ desire for curvy building forms continues to grow, CDO can enable more cost-effective panelization solutions that preserve design intent.

Building envelope optimization

CDO also links with Arup’s increasing interest and expertise in designing with building physics. The goal here is to develop new CDO tools that facilitate the design of optimized building envelopes in response to lighting and energy criteria (Fig 7).

As a starting example, CDO has been used to generate optimized design alternatives for a scenario involving a media centre in Paris that includes a gallery space, meeting room, reception area, and director's office, all with different lighting requirements. The façade comprises 496 panels (design variables) chosen from four types (opaque, clear, diffused, shaded) that combine to produce 4.2×10^{298} possible designs (Fig 9). The internal walls do not reach the ceiling, allowing light to pass between the spaces. Design performance is assessed by evaluating five response points in the space for daylight factor and sun hours, two points for view, and the entire space for cost and thermal performance, thus defining 15 independent performance objectives in total. Optimization is carried out using a multi-objective 'ant colony' optimization method[5]. The result of one optimization process consists of a set or point cloud of 'Pareto optimal' designs (ie where no improvement in one performance is possible without damage to another performance[6]) that can be browsed using a graphical interface developed for this project. There are no predefined weightings among performance objectives and all designs in the optimal set are 'optimal' with respect to a certain viewpoint.

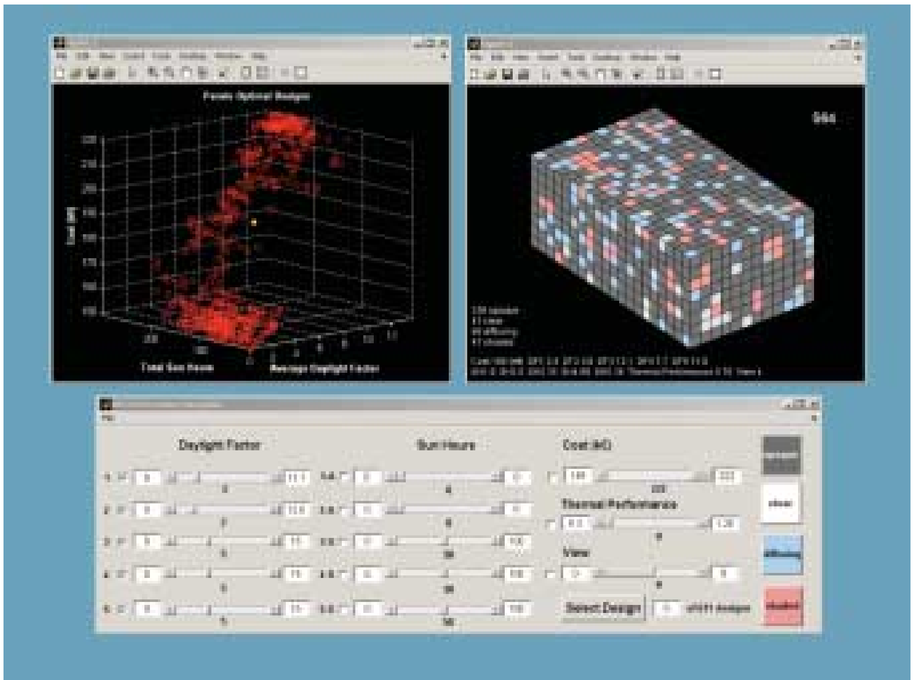
By setting preferences among performances, designers can tune the design to best meet and balance their combined goals (Figs 7 & 8). Many extensions to this work now exist, including expanding energy and cost models as well as aesthetic models. Greater benefits will be achieved by allowing the building envelope to change form in addition to changing the envelope panel layout.

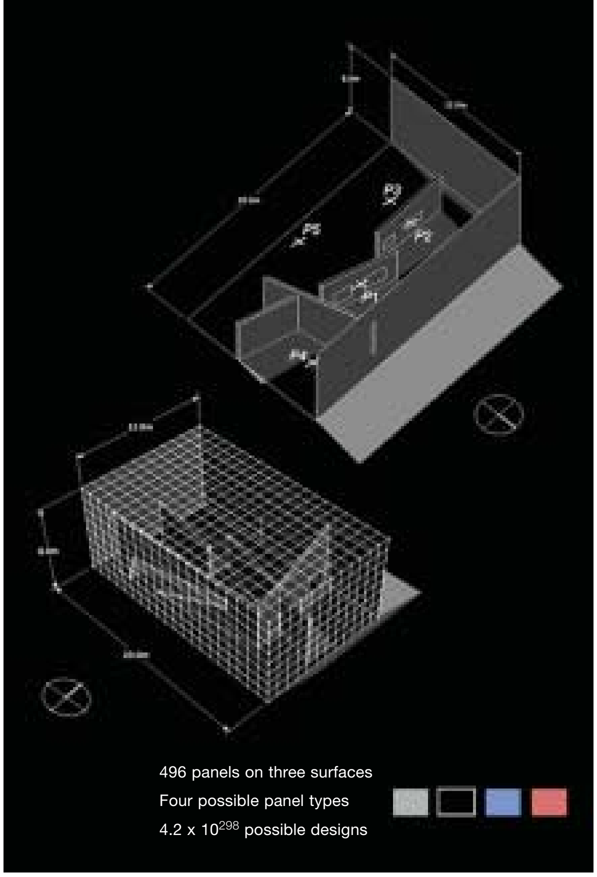
CDO futures

Extending expertise in CDO involves successfully combining modelling, methods, tools, and people. Recent progress in applying CDO in practice has extended the state-of-the-art of use in Arup as well as contributions to academia. Benefits starting to be realized include extending what designers can currently do, enhancing design understanding, and improving design quality, time, and cost. Design time savings are often realized through the design automation component of CDO.

Successful applications require designers who are willing to think outside the box in terms of both the design variants they are willing to consider and embracing new design processes that take advantage of emerging computational methods and tools. The next opportunities for CDO at Arup, which will increase the potential benefits, include incorporating multidisciplinary viewpoints within CDO models and widening the scope to optimizing building form through collaboration with like-minded architects, and perhaps clients, to apply CDO at earlier design stages.

8. Tuning the building envelope to balance a mixture of design performance goals.





9. Scenario for optimizing a panelized façade for a multi-purpose room within a media centre.

Dr Chris Luebkeman is Director of Arup's Foresight, Innovation and Incubation (FII) Group.

Dr Kristina Shea is a senior engineer in FII.

Projects

Bishopsgate Tower: with Arup's BEL4 group (Damian Eley, Chris Neighbour) with Cambridge University Engineering Design Centre (Rob Baldock)

Building envelope optimization: with Arup's BEL5 group (Andy Sedgwick, Jeff Shaw, Arfon Davies, Giulio Antonutto-Foi) with Gianni Botsford Architects (Gianni Botsford)

Rhino CDO toolkit: with Arup's Advanced Geometry Unit (Cecil Balmond, Daniel Bosia, Tristan Simmonds)

Illustrations: 1 Stefan Klein/iStockphoto; 2, 3 Images by Cityscape Digital Ltd (architects: KPF); 4-9 Arup/Cambridge University Engineering Design Centre

References

(1) HOOKE, R *and* JEEVES, TA. Direct search solution of numerical and statistical problems. *Journal of the Association for Computing Machinery*, 8, pp212-229, 1961.

(2) BALDOCK, R, *et al*. Evolving optimized braced steel frameworks for tall buildings using modified pattern search. International conference on computing in civil engineering, American Society of Civil Engineers, Cancun, Mexico, 2005.

(3) XIE, YM, *et al*. Evolutionary structural optimization. In 'Recent advances in optimal structural design', edited by SA Burns. American Society of Civil Engineers, 2002.

(4) KIRKPATRICK, S, *et al*. Optimization by simulated annealing. *Science*, *220*(4598), pp671-679, 1983.

(5) DORIGO, M, *et al*. Ant algorithms for discrete optimization. *Artificial Life*, 5:2, pp137-172, 1999.

(6) PARETO, V. *Cours d'economic politique*. Lausanne, Rouge, 1896.