Advanced Applications in Computational Design

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Abstract This chapter describes several real-world international case studies of parametric design, covering building and infrastructure design. It describes a range of different approaches, techniques and programmes used by experienced practitioners. The case studies explore the individual project requirements and constraints, the solution heuristics, implementation, lessons learned and project legacy. The projects include residential buildings, stadia, botanical garden domes, sculptural and recreational structures.

Keywords Computational design · Parametric design · Algorithmic design · Interoperability · Digital workflows · Optimisation · Case studies

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1 Computational Design

Computational design has become a dominant design methodology in civil and structural engineering and architectural design in recent years. This chapter will present a series of case studies covering a wide range of projects and design approaches, from sculptures to leisure structures, hothouses to stadia and from initial development massing to fabrication and construction, accounting for factors from solar gain to structural efficiency. Situations where computation design is useful include:

- Complex geometry—the shape of each floor might need to vary or the roof bridging the gap between a series of buildings might arch to minimise weight
- Large projects—to define a structural component once might be easy but to define a thousand requires automation
- Design changes—design is an iterative process. Clients add to their requirements, Architects refine their design, consultants' detailed designs reveal flaws in the scheme, site investigations reveal new problems and restrictions, and so on.
- Design optioneering and optimisation—rules of thumb and the difficulty in producing manual designs can lead to massive over-specification of buildings. The construction industry is a major contributor to environmental damage and greenhouse gas emissions, from material extraction and refinement to demolition waste production. The challenge for the industry is to design buildings that use zero carbon over their lifetime [1–4].

Computational design's ability to explore multiple options and optimise against conflicting project requirements is a key tool to achieving these goals.

As stated in the previous chapter, there are essentially three categories of computational design: parametric, generative and algorithmic. Like many taxonomies, the boundaries between them are fuzzy, but the differences between each can be explored via some examples.

1.1 Parametric Design

Parametric design is, as the name suggests, a design that is automated and driven by parameters. Like many engineering design tools, it originated in aeronautical

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design, automating the geometric definition of wing and body aerodynamic shapes using complex formulas. Parametric design allows the architect or engineer to define a series of dimensions and formulas for their design, where changing one value cascades through the project, updating the geometry and other aspects.

Possibly, the most significant early use of parametric design in architecture is Frank Gehry's Guggenheim museum in Bilbao [5]. Commissioned in 1991 and opened in 1997, its titanium-clad, boat-shaped design was made possible using *CATIA*, a computer-aided design (CAD) programme created by Dassault Systèmes [6].

In the 1990s, parametric design was rare and exclusive due to the high costs of its software; today, it is a regular part of architectural and structural engineering workflows. A typical workflow might start with a Rhino [7] scheme design model being controlled using a Grasshopper [8] visual script. This will create geometry that might represent a building envelope, structural frame, or other aspect of the project. For example:

- The rise of an arched roof might be set as a percentage of the span.
- The numbers of arched ribs can be determined by the building extents and maximum spacing rules.
- Within the truss, the spacing of the diagonals and other members might be driven by the depth and other rules.
- The magnitude of the wind and snow loads might be a function of the arch size and slope.
- Finally, the section sizes of the truss members might be determined by their loads, including self-weight, effective lengths derived from the geometry and governed by the appropriate design code.

With parametric design, each parameter is under the control of the engineer or architect, and each combination of parameters leads to a single answer. Manipulation of these parameters allows the designer the scope and flexibility to explore the different design options.

1.2 Generative Design

Generative design can be thought of as automated parametric design, allowing the designer to programmatically explore the design space (the range of possible design solutions) searching for the best answer when the effects of the design parameters are too complex or nonlinear for parametric design. The generative design might explore the building shape, topology, size [9] or other parameters to maximise performance or minimise cost (financial, energy, environmental impact, etc.). It might optimise the overall form of the building or the ideal shape of a structural section. It might also explore the topological options, such as construction methods and materials used, numbers of elements and span directions. And it might fine-tune the results to reduce the material used in a design.

Generative design includes:

- Hill-Climb or Gradient Methods—adjust a parameter step-by-step until either a solution is found or there is no improvement in the design.
- Simulated Annealing—an improvement on a hill-climb method and inspired by the way that metal properties change as they cool. A 'heat' parameter governs the step size, which is increased if a better answer is found and reduced if not. This means that the design space is initially quickly explored, before focussing in on the solution.
- Genetic Algorithm—inspired by evolution in nature, multiple possible designs are generated where the various parameters are chosen randomly. Each is then assessed for 'fitness'—how well they meet the design brief—with the best examples then being cross-bred to produce the next generation of design solutions. The crossbreeding takes some parameter settings from one solution and the rest from the other to create new designs that improve generation by generation.

There are many more generative design options, such as particle swarms and ant colony optimisations, several of which use stochastic methods to explore the design space.

1.3 Algorithmic Design

Algorithmic designs use a combination of parametric and generative methods, such as embedding optimisation routines or libraries into parametric scripts.

1.4 Digital Workflows

To maximise the efficiency of computational design, the output of one parametric process might be used to provide the parameters of the next stage of the design. For example, the parametric definition of a building structural geometry might occur in the initial programme before being exported into another programme that is dedicated to analysis and design. In the case of a structural frame, this could be to a finite element analysis (FEA) programme such as Oasys GSA [10]. Both the scheme geometry and structural member might then be read into building information model (BIM), such as Autodesk Revit [11], for detailing, coordination and documentation. Further scripts (Revit, for example, uses the dynamo visual programming language [12]) might be used to define aspects of the subsequent model, such as predicted pile lengths to the bedrock surface, staircases to meet building regulations, or HVAC plant to meet heating and cooling requirements. This model might then be exported to fabricators for detailed design and manufacture of the steelwork including connections, or the HVAC plant and ducting, prior to construction.

2 Case Studies

2.1 Transport for London Mass Land Viability Study

Ramboll was approached by Transport for London's (TfL) Commercial Development Housing Strategy Team, who wanted help with examining the development potential of land associated with transport infrastructure in London. The full portfolio of land totalled over 2200 separate sites across London with a combined area of 16.26 million m^2. Each of these sites needed to be assessed for its development potential, considering the number of residential units which could be built, the expected return on investment and any key risks on the site. The sheer quantity of sites to be considered meant that it would not be feasible to conduct such a study manually, and therefore, an automated approach was developed utilising Ramboll's SiteSolve tool [13].

SiteSolve is a generative platform for early stage massing and building design developed internally by Ramboll's computational design team [14]. The software allows the user to input site-specific constraints and preferences, generating and optimising viable building configurations within those constraints. The software allows for over 60 different types of constraint parameter to be specified and can output automated analysis data on over 50 evaluation metrics including key areas, unit numbers and embodied carbon estimations. The generation procedure embeds Ramboll specialist's knowledge to allow the creation of building forms with realistic consideration of structural, mechanical, fire and vertical transport requirements.

The SiteSolve software has been developed over three years from initial Grasshopper prototypes to a fully fledged standalone design tool. This independence from third-party software allowed the tool to be easily expanded and customised to meet the needs of this project. Typically, the software is used via a graphical interface (Fig. 1) to look at sites individually. However, to facilitate the large number of sites, a new 'headless' version was created to automatically batch-process all the different site data at once.

SiteSolve acted as the generative core of the project, but the full scope of the study required a multidisciplinary process shown in Fig. 2 which incorporated inputs from many different parties working in unison [15].

Transport for London provided some of the site data as well as an agreed set of base assumptions to be used across the land portfolio. Urban intelligence [16] provided further insight on the available land and was responsible for processing and filtering the key input information including site boundaries and height limits which was then processed by SiteSolve. Unit values were calculated using date provided by Hometrack, whilst Hatch Regeneris provided an estimation of value uplifts over a 30-year period. The closest integration was with Turner & Townsend, who provided a custom costing application programming interface (API) which SiteSolve could directly access to feed in quantities and abnormalities and receive back estimated costs interactively. This multi-party workflow enabled each site to be optimised based on overall expected return. Throughout the project, regular

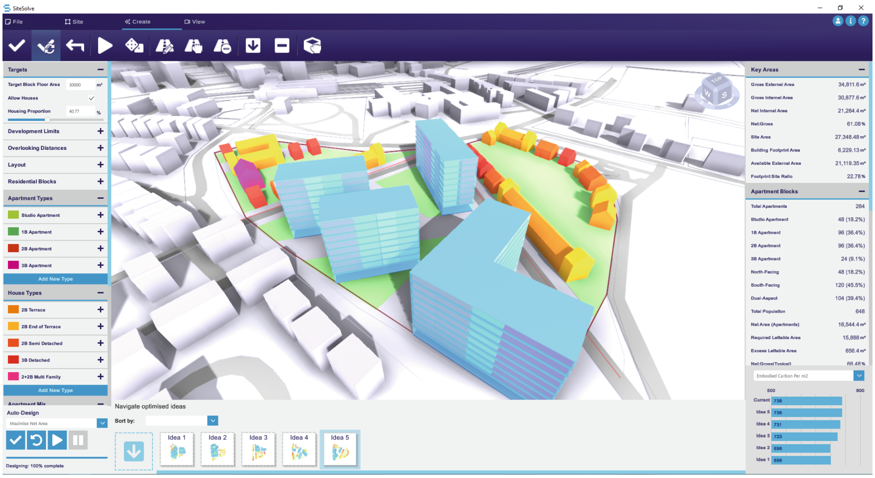


Fig. 1 SiteSolve design interface (© Ramboll)

Fig. 2 Overall project collaboration workflow (© Ramboll)

communication between all parties was key, as assumptions made during one part of the automated process had to be understood and reflected in the others.

Once the full computational workflow was in place, the full portfolio of 2200 sites could be processed and optimised automatically in only a few hours, allowing different scenarios to be considered easily.

The final output of the project was a database of site data accessible and visualised via an online dashboard (Fig. 3). This allowed TfL both an overview of the entire portfolio and the ability to 'drill down' into specific sites. For each site, this provided information on estimated unit types, cost, value and return as well as flagging up particular site-specific development risks and providing a visualisation of the generated building arrangements.

Fig. 3 Project output dashboard (© Ramboll)

Typically, such studies would be undertaken via a far simpler methodology, whereby the site area would be multiplied by an assumed density value. The SiteSolve-based approach was shown to provide significantly greater rigour and accuracy over this method [17]. In particular, many of the sites considered in this study were long but relatively thin strips of land adjacent to transport infrastructure (Fig. 4). Considering only the total area would have resulted in significant over-estimation of site capability and lead to many sites being identified as viable for development when they in fact were not.

Site access requirements were also seen to be a crucial consideration, as many sites had limited access opportunity. SiteSolve was able to consider this and produce optimised designs which ensured that all regions of the development were accessible, often with significant impact on overall unit numbers [18].

This project shows the capacity for computational design techniques not only to greatly improve the quality of information available at early design stages, but also to be applied at large scale to accomplish things that would be impossible without an automated approach.

2.2 *Smakkelaarspark*

This case study presents the competition-winning proposal for Smakkelaarsveld in Utrecht [19], which is a new 20,000 m^2 residential development. The design team, Lingotto [20], Studioninedots [21], ZUS [22] and Arup [23], had to deliver the best public space possible for the people of Utrecht. The competition was a developer

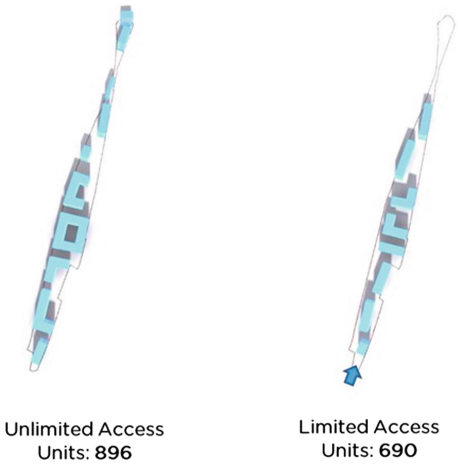


Fig. 4 Example a narrow site with arrangements assuming unlimited boundary access verses access only from the south end (© Ramboll)

competition hosted by the city of Utrecht, with the winning consortium obtaining the development rights for the 'Smakkelaarsveld'. This is an urban site next to Utrecht central train station and one of the most central and challenging plots in the Netherlands. It is also a heavily congested site, surrounded by traffic noise from major roads and railways. Other infrastructures crossing the site are bus and tram lines, waterways, overhead cabling and underground services.

Even though the master plan indicated a clear distinction between building and park, the design team decided to create a green oasis in which residential and green spaces smoothly merged. The Smakkelaarsveld area would be connected and restored with new meaning and given a new name, Smakkelaarspark.

Generative modelling methodologies were applied to the design of Smakkelaarspark, using algorithms to inform the design team of the optimal massing configurations. This modification of the traditional design process, in which engineering evaluation is normally performed once the massing design is finalised, resulted in the improvement of the design against initial design proposals.

The design was generated following three principles, as shown diagrammatically in Fig. 5.

- Step 1: The park area was to be maximised. Preferably the park would even continue over the roofs and the bus/tram track crossing the plot
- Step 2: The pattern on the plot was iteratively created by combining the initial parametric sun studies performed by Arup, with studies on the urban fabric and the existing road networks done by the architect and landscape architect

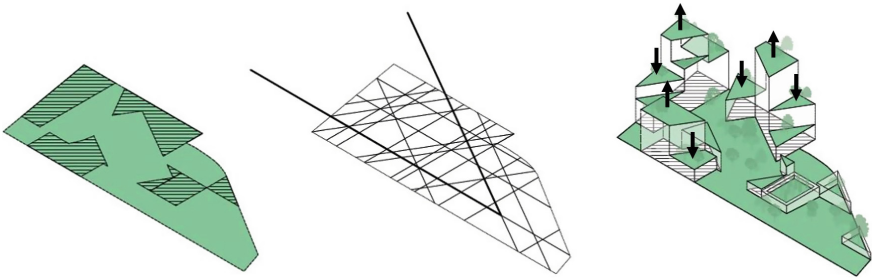


Fig. 5 Design steps Smakkelaarspark [19] (© Arup)

- Step 3: The key performance indicators (KPIs) were determined that define a healthy urban living environment and sustainable residential units. By using custom parametric definitions and building physics simulations, the performance against each KPI was quantified. Then thousands of design options were generated applying generative modelling. Using multi-objective massing optimisation, the building heights were optimised by maximising the performance of the set KPIs

In order to include all the KPIs, multi-objective optimisation was used, allowing the KPIs to be considered simultaneously.

The input variables for the design were the number of storeys per building footprint. In total, there were twelve footprints set by the design team through the aforementioned process, each of which could be four to thirteen storeys high, given the plot's maximum building height of 40 m. This means that there were 10^{12} possible design options. Given that a single iteration required 40s of run-time, the calculation of all possible options would have been prohibitively time-consuming and not feasible within the project's timeframe. This meant that an optimisation algorithm was required to reduce the number of options needing simulation and, thus, quickly find the best performing designs. Optimisation algorithms achieve this reduction through the structured exploration of the design space [9] (the range of design options) and the gradual focus on areas of higher performance with regards to the optimisation objectives. The objectives for the optimisation algorithm were the six design KPIs, which were maximised. An optimisation constraint, during the design process, is that the total floor area needs to be around 20,000 m^2.

The optimisation workflow proceeded as follows. The start was an algorithmically generated model, in which the building envelope and apartment geometries were modelled parametrically. Then the analyses were performed in order to calculate the performance with regards to the six KPIs. The overall performance was subsequently calculated and recorded. This was repeated iteratively for many geometric variations (adjusting the heights of the buildings), aiming to maximise the performance of the six design objectives.

The final competition-winning design is shown in the rendering in Fig. 6.

The main benefits of the generative workflow on this project were:

- The relatively unbiased automatic identification of areas within the design space using massing form finding where the massing would better serve the design objectives.
- The automatic generation of design options using generative modelling, facilitating the identification of high-performing alternatives based on the objectives.
- The facilitation of an informed communication among the design team, with regards to the relationship and relative performance of different design objectives.
- The quantifiable measurement of performance against the set of design objectives and the generation of simulation-based evidence, which has been used as communication material supporting the optimality of the design.
- The incorporation of health and sustainability objectives from the very early design stage as opposed to their traditional consideration later in the design process.
- The reduction of evaluation time required for multiple design iterations in multi-objective optimisation.

Fig. 6 Rendering of Smakkelaarspark winning design [24] (© Lingotto)

As used on this project, multi-objective generative massing optimisation provides a powerful means of creating improved building designs, where building performance informs and even inspires the design process from the early design stages and communicates them to the client, other design team members and the public.

2.3 Elements

Elements is a new 70-m-tall hybrid residential building in the Amstelkwartier district of Amsterdam. The design concept, developed by Kondor Wessels Vastgoed, Koschuch Architects, Arup, Boom Landscape and Buildung, draws its name from its key design considerations: optimising daylight, water collection, wind and fresh air, green spaces, energy generation and providing a considered response to the urban envelope. The development includes 70 medium-sized rental and 74 owner-occupied properties, with commercial facilities on the ground floor and a green roof garden.

With a total gross floor area of 14,800 m^2, the tower is an example of sustainable residential design, featuring innovative green design solutions. These include the integration of photovoltaic panels into the building's façade and a highly innovative hybrid timber-steel-concrete support structure, designed to reduce by the tower's CO_2 footprint by more than 50%.

However, these advanced technologies and construction techniques were not enough alone to achieve a satisfactory outcome. The design team realised that the build shape also needed optimisation in order to achieve the city's requirements for daylight, maximising it for both building's residents and the adjacent properties (Fig. 7).

Defining the building geometry parametrically, allowing for prismoidal geometric twists up the height, enables a satisfactory trade-off between the project requirements. They combined this with a parametric evaluation engine that could assess the generated designs against key performance indicators. These were:

Fig. 7 Sustainable design concept for elements (© Arup)

- Sun exposure on the building façade
- Floor plan efficiency influenced by daylight and structural core location
- Sunlight on the neighbouring buildings
- Daylight in the plinth atrium

These were selected as they ensure compliance to building codes (minimum sun hours for the elements building itself and surrounding buildings) and maximise comfort and sustainability (reduced energy usage).

A genetic algorithm was used to generate, explore and evaluate hundreds of design variants. The result was a building form that achieved a satisfactory trade-off between the conflicting objectives as well as providing a measurable improvement over a reference rectangular building (Fig. 8).

The design process highlighted interesting findings for the design team. Changing the key performance indicators and boundary conditions of the parametric model influenced the resulting optimal models. The initial optimisation of the building shape looked only at daylight levels, which produced a highly efficient form, but one that failed to give efficient floor plans for the residents. Subsequent runs included an assessment of the resulting floor plan, delivering a more balanced design.

Elements (Fig. 9) join other iconic buildings in the Amstelkwartier such as Haut, the tallest timber building in The Netherlands and the eco-chic QO Hotel. Construction of elements is expected to start in the third quarter of 2021.

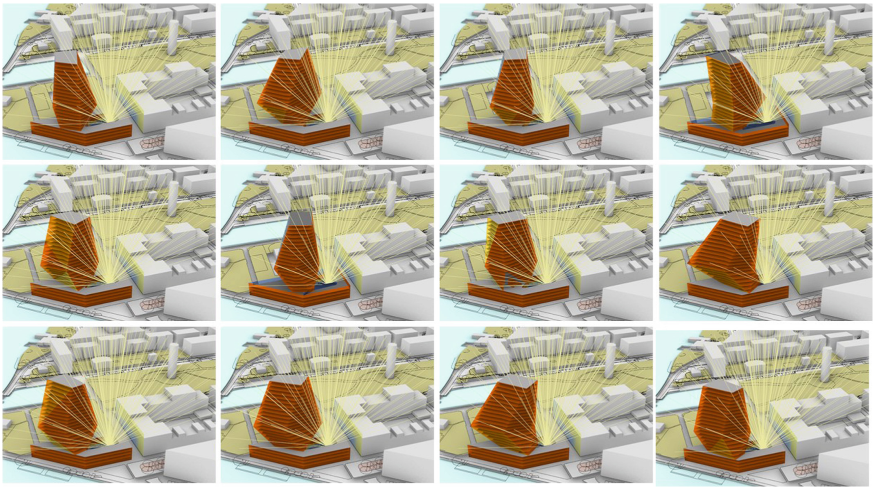


Fig. 8 Design variations driven by a genetic optimisation algorithm, gradually improving performance (© Arup)

Fig. 9 Render of the final design (© Beauty and the Bit)

2.4 Aarhus Botanical Garden Tropical Hot-House

In 1969, C. F. Møller Architects designed the iconic greenhouse in the botanical garden of the University of Aarhus, Denmark. Forty years later, plans to develop the site, by combining the renovation of the existing greenhouse complex with the construction of a new Tropical Hothouse, culminated in an architectural competition with six teams of consultants proposing alternative designs.

The author Paul Shepherd was invited to join a team comprising C. F. Møller Architects and Søren Jensen Consulting Engineers to see how a combination of parametric modelling and integrated optimization could inform the design process and help to produce a more efficient design solution. By providing a straightforward way to model complex geometrical objects and generating detailed feedback on the suitability of each design solution, the design team was able to use the software to quickly refine their parameters. The resulting structure, being both architecturally pleasing and environmentally efficient, went on to win the competition. The finished building was officially opened to the public in September 2014.

The architectural concept for the Hothouse was to produce a large domed structure to house tall tropical trees and a high viewing platform in its centre. The internal environment needed to be carefully controlled to ensure the right conditions for tropical plants to grow. In order to reduce heating requirements in winter, solar energy was to be encouraged to enter the building through the skin. However, there was a danger of allowing too much sunlight into the building during summer, which would require mechanical cooling to prevent overheating. Since Aarhus is around 57° north of the equator, there is a considerable variation in sun angle between summer and winter, so these two goals are not necessarily contradictory. The team needed a quick way of generating alternative designs, combined with a method for assessing each option's environmental performance against multiple criteria.

This investigation lent itself very well to a parametric study, combined with embedded performance measures and an automated optimization loop. The key design constraints were the footprint of the building and its maximum height, with the detail of exactly where the surface lay in-between free to be explored.

Initial ideas about structure suggested a steel frame with glazed in-fill would be an efficient way of enclosing the space and insulating it from the elements outside, so a mesh representation of the geometry was an obvious choice. For a smooth dome-like building, this could lead to many hundreds of mesh vertices, the position of which need to be fixed and treating them as independent problem variables (parameters) would be overly complex and cumbersome. It was, therefore, decided to use a subdivision surface framework [25] to represent the geometry, as shown in Fig. 10. In this way, the building envelope could be represented by a very coarse control mesh with only seven vertices; six arranged in a hexagon around the base and one above at the apex. This coarse control polygon completely defines the smooth inner mesh representing the dome by applying a recursive subdivision scheme (in this case the Loop scheme [26]). A parametric study was then carried out by changing the position of the apex vertex along the north–south axis and stretching the hexagonal base in the east–west direction. This would have the effect of leaning the dome to the north and stretching it east–west, exposing more of its surface to the southerly sun. The solar gain of each potential dome design was assessed for both summer and winter.

For speed, the approach was implemented in an existing standalone piece of subdivision surface modelling software written in C# by the author. Sun position

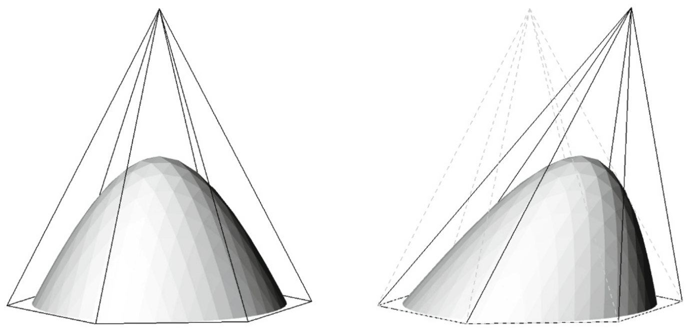


Fig. 10 Coarse control mesh defining a smooth subdivision surface inside. Moving the apex vertex north results in a building that exposes more of its surface to the southern sun (right) (© Paul Shepherd)

was automatically calculated [27] for specific days of the year (see Fig. 11), and the amount of sunlight entering the building was also calculated, taking into account self-shading and the reflectivity and absorption of glass.

To fit within the tight timescale of the competition, results were exported as graphs, and a suitable compromise between winter heating and summer overheating was made manually. Later, a simulated annealing optimizer [28] was included to explore the design space more thoroughly and identify efficient combinations of input parameters.

Combining the geometric modelling, assessment calculations and optimization engine in one single platform led to very fast design iterations. However, using bespoke software made it more difficult for the rest of the design team to interact with the model, which became something of a black box. Coloured scale models created using a 3D-printer were used to help communicate design options; but if the work were to be carried out today, a common platform such as Grasshopper [8] would make a more natural home for such collaborative parametric design software.

The success of this project was to a large extent due to the very close collaboration between the specialist researcher, expert engineering team and innovative architectural team. Conversely, involvement in this live project was immensely helpful in moving the research itself forward, by posing unforeseen questions and introducing realistic design constraints. The building was awarded the Chicago Athenaeum award for International Architecture in 2016, was regional finalist in the Civic Trust Award in 2015 and was awarded a commendation in the IStructE Structural Award (Sustainability) in 2013, with the judges being 'impressed with the truly holistic, environment-led solution to the project brief' [29], which the designers believe could not have been delivered without the integrated parametric modelling and optimization approach.

The building (Fig. 12) is open to the public all year round, with details available from https://sciencemuseerne.dk/en/botanical-garden/.

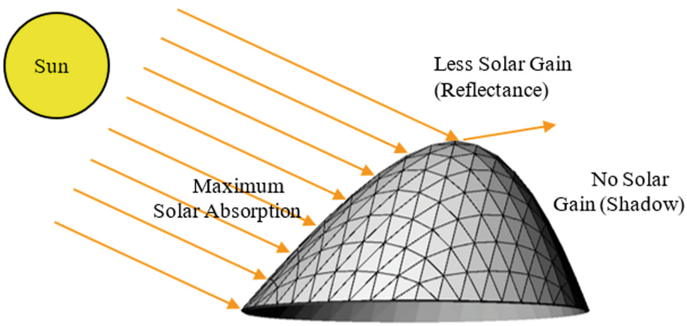


Fig. 11 Solar gain model integrated into geometric model (© Paul Shepherd)

Fig. 12 Finished building in context (© Paul Shepherd)

2.5 Camp Adventure Forest Tower

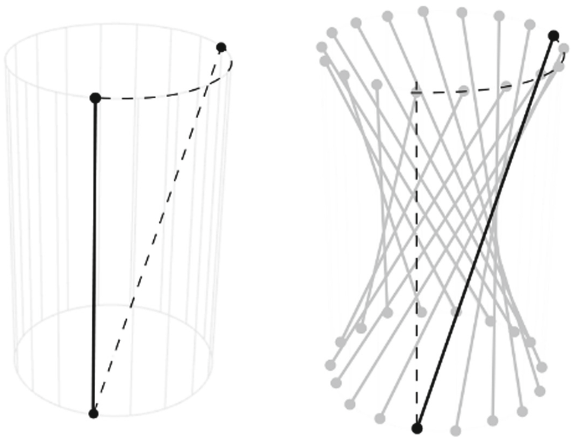
The Camp Adventure Forest Tower is a unique installation designed for users to experience the protected forest of Gisselfeld Klosters Skove, located one hour south of Copenhagen. Visitors venture along a kilometre-long boardwalk through the forest before ascending through the trees, up a striking, spiralling ramp that appears to be floating within a 45-m-tall hyperboloid diagrid tower. The tower's beauty is derived from the synthesis of architecture, structure and the surrounding landscape (Fig. 13).

The pure mathematical geometry of the hyperboloid has been used to create some of the world's most elegant and inspiring structures, from the daring communication masts of Vladimir Shukov, built nearly 100 years ago, to the concrete cooling towers of the mid-twentieth century. The Camp Adventure Forest Tower builds on this engineering heritage using twenty-first century techniques that result in a unique destination experience accessible to all.

To create the doubly curved form of a hyperboloid, a total of 36 straight tubular steel columns were used, and the position of their top nodes relative to the bottom nodes was rotated 120° about a 28 m diameter circle, as depicted in Fig. 14. Variations of this form were then derived by adjusting the primary parameters (Fig. 15).

Fig. 13 Camp adventure forest tower (© Rasmus Hjortshøj—COAST)

Fig. 14 Hyperboloid form from straight elements (© Arup)



A diagrid of this form creates an inherently stiff structure when used in combination with a radially restraining element, which in this case is a spiralling ramp ring. The ramp ring is a doubly curved element that cantilevers from the straight columns from the ground to the top at 45 m compounding to a total length of 640 m. It is used to support the ramp beams and provides the columns with radial restraint.

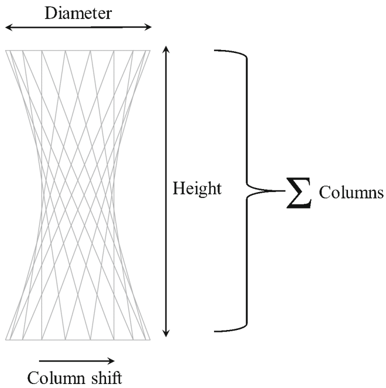


Fig. 15 Primary parameters (© Arup)

The geometry of the ramp and its connection back to the diagrid columns required the adoption of the mathematical principles to create a helical curve that mapped to a hyperboloid surface with a constant slope up the tower. This was important for the human experience and the accessibility to the platform level.

This project required both strong architect-engineer collaboration and the adoption of automation workflows in order to deliver such a novel structure. The design was conducted using a parametric workflow in the visual programming environment, Grasshopper [8] in Rhino [7], with an array of interoperable plugins, particularly Karamba 3D [30] and Geometry Gym [31].

Initial studies on form were conducted using Karamba 3D to gain immediate feedback on the structural behaviour and tonnage implications for an array of typologies, from slender to stocky towers.

A high level of integration of detailed structural analysis, design and delivery in the parametric framework was developed so that the geometry setting out and the architect-engineer coordination could be conducted in the Grasshopper code. This ensured that all consequent detailed Oasys GSA [10] analysis models, architectural depictions and BIM deliverables were accurate and perfectly coordinated.

This was particularly important for the ramp design. To achieve a slender and visually floating helical ramp up, the inside of the tower was not only a complex modelling exercise, but also a complex structural design exercise. As the ramp cantilevers from the diagrid columns, its deflection and vibration performance were critical. This way of working allowed for time to focus on the connection detailing and conducting the required complex computational analyses of the connections and the dynamic analyses in Oasys GSA. Furthermore, the connections required careful geometrical and assembly focussed detailing to enable prefabrication and coordination with the various components of the tower, such as the handrail and the timber decking (see Fig. 16).

The aesthetics and the commercial success of the project were achieved by establishing a collective digital workflow for the main geometry, allowing plenty of time to refine and develop the detailing in coordination with the contractor.

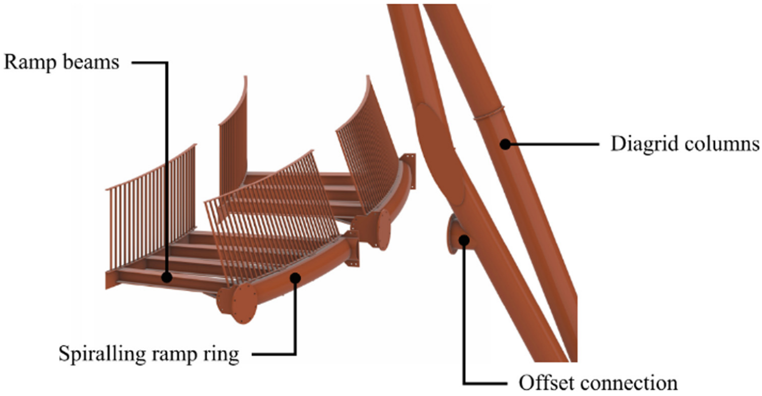


Fig. 16 Exploded view of the tower's components (© Arup)

This project is a wonderful example of parametric design and how it can enhance engineer and architect collaboration. The parametric framework allowed time to be spent where it truly mattered, such as concentrating on the detailed analyses and how to create connections that facilitated the tower's assembly. What looked almost impossible from the early architectural renderings was made quite simple to build and in addition has been a massive success for the client since its opening as the tower was crowned one of TIME Magazine's World Greatest Places in 2019 [32]. It was also awarded the Best of Best (Concept) by the German Design Council, ICONIC Award 2017 in the Visionary Architecture category and winner of South Coast Denmark's Best Tourism Initiative 2018.

2.6 Ken Rosewall Arena

In 1998, Arup designed many aspects of the Sydney 2000 Olympic venue, including the award-winning 10,000 seat Ken Rosewall Arena (show court stadium) [33]. Twenty-one years later Arup, along with Cox Architecture [34] and Fabritecture [35], was commissioned to upgrade the Ken Rosewall Arena, transforming it into a covered, all weather outdoor arena for world-class tennis events, national netball fixtures and other future sporting and entertainment events [36]. This included providing a roof over the entire arena, without compromising the original architectural vision or increasing the load on the existing structure to an extent that required significant modifications to superstructure or foundations, all within a 12-month programme.

The original stadium was a near-circular 24-sided polygon, 100 m in diameter, partially recessed into the ground to minimise building size and cost, as well as providing efficient spectator access and amenity from grade. The original raked steel framing and precast seating plate structure included a cantilever roof, the

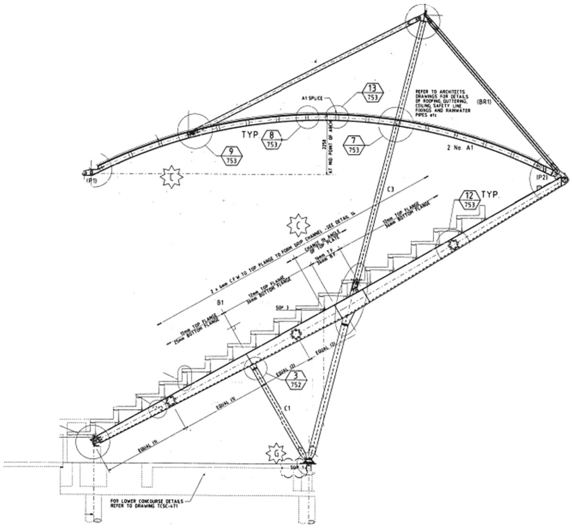


Fig. 17 Ken Rosewell Arena original structure (© Arup)

supporting structure of which also provided gravity support to the rear of the bowl (Fig. 17). This canopy was removed to make way for the new roof.

The Olympic park was a brownfield site contaminated by former industrial usage, meaning that no new foundations could be constructed within the 12 month project timeframe and applicable environmental guidelines. The existing structure could, therefore, not see any significant change in load, despite the new roof extending over the entire building.

The solution was to utilise the circular form of the existing stadium and provide Australia's first major radial cable net roof. The existing steelwork and canopy above the seating was removed and replaced with a new steel compression ring. This then supported radial cables resolved at a central tension ring, in-turn supporting the lighting and public address system and the raised vented roof. Tangential tied arch elements provided the fabric geometry between radial cables (Fig. 18). The new roof was elevated to provide a 4 m high space around the perimeter for ventilation and natural light, which can be closed using glazed hydraulic doors for stadium use in enclosed mode.

Tension structures such as this cable net roof derive their stiffness from their geometry and pretension, so it was essential to get these correct. These were determined using a method called soap film form finding, where the tensile structural elements are replaced with constant stress, zero stiffness elements. These are then free to move until they find the geometry where the pretensions are all in equilibrium. This is an iterative process as the geometry must also satisfy service and architectural constraints, such as clearance above the tennis court and sufficient roof slope for drainage. Adjusting the target pretensions then generates a new geometry.

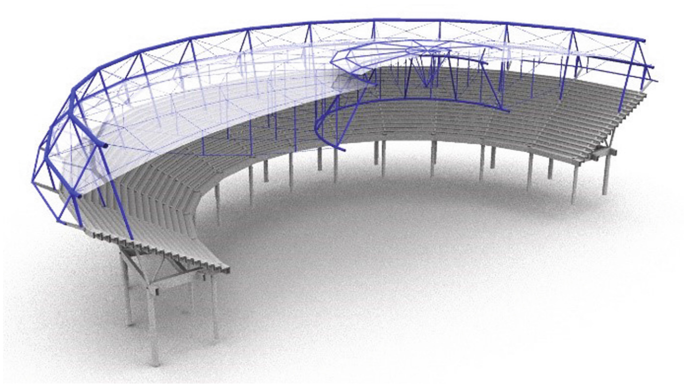


Fig. 18 Arena roof configuration (© Arup)

Due to the complex nature of the existing and new structure, the project used a fully digital workflow and delivery. This meant that the structural layout, details and connections were communicated to the project partners and procurement chain via 3D electronic files and not 2D drawings.

The design started with Rhino [7] model of the existing structure, linked into an Oasys GSA [10] analysis so that the engineers could understand the existing stressed state. The initial form finding was conducted with Grasshopper [8] together with the Geometry Gym [31] plug-in. The resulting 3D geometry was then exported to Oasys GSA for final form finding using nonlinear dynamic relaxation, determination of the cable prestresses, structural analysis and member design.

Rhino models were then used, along with the results from the analysis, to develop and check 3D finite element analysis models of the connections. These were then issued direct to the shop detailers along with annotated 3D views of the models.

Due to the tight programme and long lead time, the cables for the roof had to be ordered in the first week of the design. The rapid digital prototyping and form finding employed by Arup's design team allowed this to be done three months before the structural design was completed.

The parametric workflow allowed the structural team to tune the cable net geometry and prestress regime to 'protect' the existing structure, in a much shorter timeframe than this process being undertaken in a more traditional manner, maximising the utilisation of the existing rakers and minimising any need for local strengthening.

Despite the project restrictions, the upgraded arena was opened in January 2020 for the inaugural ATP Cup, one of the world's biggest tennis tournaments (Fig. 19). National Netball clubs, the NSW Swifts and GWS Giants were to play home matches at Ken Rosewall Arena from April 2020. The COVID pandemic has delayed this until 2021.

Fig. 19 Ken Rosewall Arena in use (© Martin Mischkulnig)

2.7 Steampunk

Steampunk (Fig. 20) is a pavilion built for the 2019 Tallinn Architecture Biennale. The scheme is a collaboration between Architects and technologists, Fologram [37], Soomeen Hahm Design [38] and Igor Pantic [39]. It's aims echoed that of the Biennale, namely that 'Beauty Matters' and that the pavilion should embody big ideas in a small structure. Format Engineers [40] were engaged shortly after the competition award to help turn a virtual concept into a physical reality and to ensure its permanence for a number of years after the festival. The project was also intended to be a test bed for the implementation of augmented reality technology on a real project on a real site [41].

The twisting and knotted installation was a hugely complex structure of interwoven steam-bent hardwood and stainless-steel connecting brackets, eight metres in length, five metres wide and five metres in height. From the outset, the designers wished to utilise primitive hand tools, augmented with the precision of intelligent holographic guides (a Microsoft HoloLens). In their own words, 'the timber elements in the structure are fabricated following the somewhat arcane and notoriously difficult process of steam bending'. No drawings or CNC code were to be generated for the fabrication. The team instead would rely upon the experimental approach of constructing entirely by hand using augmented reality design information provided to the fabricators through the Fologram holographic platform [37].

The challenges were numerous, such as how to best model the twisting form within the context of structural analysis (and hence prove it is stable), to then give

Fig. 20 Steampunk pavilion (© Fologram)

instant feedback to the fabrication model, how to use only easily procured 100 × 10 mm timber boards, what shape the connecting brackets should be and where they should best be placed to maximise structural efficiency.

The structure can be analogized to a thin shell, albeit one which twists and turns in dramatic ways. The resulting geometry leads to significant out of plane bending moments in addition to the in-plane axial forces. By changing the direction, orientation and pitch of the timber strips, as well as the stiffness and frequency of the connecting steel brackets, the structural performance changes considerably. A pattern of the strips can be generated to obey rules of minimum spacing and min/maximum length. It was also possible to gently deform the whole structure, thus allowing a more efficient shape and form to be generated at the outset whilst still retaining the original appearance of the piece.

The project team worked in a common Rhino/Grasshopper [8] script from the outset. The Architects started by defining an initial form in that script, onto to which Format Engineers then added components which automatically determined a slightly refined version, via machine learning manipulation of global control points. The refined form was represented as a solid shell at that point, and the performance measured against the structural criteria of least deflection (Fig. 21).

Once that process was complete, a 'streamline' script was added to generate continuous timber strips that flowed around the complex twisting surface. After the pattern had been agreed with the project team, further parametric geometry

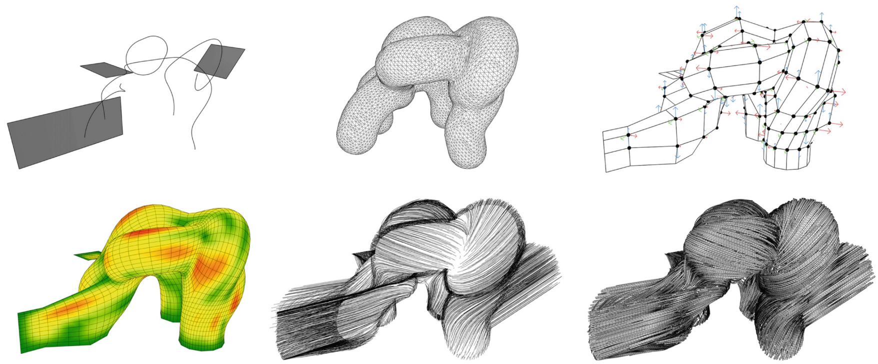


Fig. 21 Steps in geometry generation (© Format Engineers)

components split the strips into practical lengths and generated a starting pattern for the brackets. Following that, the Karamba 3D [30] finite element plug-in for Grasshopper was used to test the structural arrangement. If brackets were highly stressed, they were either automatically culled to allow stress redistribution, or reinforced by adding more. The timber pattern could also be varied, and the structural efficiency tested. The final structural arrangement was checked for quality assurance purposes with Oasys GSA [10] via a further set of commercial Grasshopper tools by Geometry Gym [31].

Fologram's own Grasshopper components were used to generate an augmented reality version of the final stable and efficient structure. Each timber strip was bagged, steamed and bent over an adaptable, mouldless formwork using a holographic model as a reference to the desired result. This fabrication process utilises two forms of feedback. Holographic models provide fabricators with clear visual feedback on the accuracy of the forming process and allow them to intuitively adapt fabrication techniques or formwork positions until parts match digital models within accepted tolerances. Physical parts can also be digitised and fed back into the digital model, allowing the design to accommodate and adapt where necessary. In each case, the feedback is a direct collaboration between designer and maker, between expected behaviour and observed results. The beauty of the project lies in this tension, in deciding when to give and take, when to adhere to preconceived design intent and when to abandon precision and begin to react.

The development was on a very tight schedule and had to be delivered to a strict budget. Both targets were met. It was proven that a highly complex form can be proven to be structurally stable, can be fabricated with simple elements and can utilise innovative techniques of augmented reality in construction. The lessons learnt can be applied to a bigger scale, and elements of the scripting can be applied to more 'everyday' developments. The project would not have been possible without digital tools and adopting a common model from the outset.

3 Conclusion

As we have seen, computational design enables the automation and iteration of design, potentially reducing production time and increasing the quality of the finished product, as well as enabling designs not feasible by other methods. It is not restricted to creating architectural forms but can be applied to all stages of the design process, from initial outline plans, via building massing, to the smallest structural detail.

Computational design is also an important working method for the design team in optimising the designs, whether for occupation levels, solar gain and shading, structural efficiency, minimising environmental impact or enabling digital fabrication and construction techniques. Computational design methodologies can also improve the efficiency of the design teams, making them more responsive to the changes inherent on all construction projects.

Computational design requires an investment in time and effort, so might not be implemented on all projects, but as designers become more familiar with the methodologies then its use will increase. It is an essential methodology option for modern construction projects.

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