RETHINKING COMPLEXITY: VLADIMIR SHUKHOV'S STEEL LATTICE STRUCTURES

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ABSTRACT

This paper presents a critical review of the advantages and disadvantages of contemporary digital architecture, in retrospect to Vladimir Shukhov's design techniques, applied in the early twentieth century. After investigating Shukhov's structural systems, the paper explores the relationship between performance and form, questioning the necessity of structures of high complexity. It presents unpublished archive material of Shukhov's early work and stimulates a valuable discussion by comparing it with contemporary projects designed by renowned architects. The study focuses on Shukhov's tessellation method of creating double-curved surfaces using simple standardised elements. The study of current digital approaches revolves around leading architects using computational tools (e.g. Foster+Partners, Buro Happold, Arup) who have materialised high complexity structures composed of irregular units. Our findings highlight advantages and disadvantages of contemporary computational approaches.

Keywords: *Fabrication and Material Studies, Architectural History, Design Concepts and Strategies, Performative Design*

1. INTRODUCTION

Technology, materiality and construction are three interdependent components that have an enormous impact on architecture. Today's construction technology emerged during the industrial revolution, introducing the serial production of new, standardised construction components made of new materials such as metals, glass and plastics. However, in recent decades, digital tools and techniques have become the next significant impetus in architectural evolution [1]. Emerging technologies are redefining the practice of architecture, and mass customisation makes serial production of non-standardised building components possible. Designing without using a computer has become something unthinkable. The use of algorithmic, generative and parametric applications in the design process is increasing. As a consequence, form has been liberated from the boundaries of the Cartesian system. As Peters and Peters state:

'*If you find a nice curve of surface somewhere with interesting properties you can incorporate it in your design* [2].'

On the other hand, the gap between designers and the digitised building process seems to be increasing. Even though more and more practices are operating so-called in-house 'parametric units', the vast majority of them still design in conventional ways and only occasionally outsource 'optimisation' to digital specialists. But how efficient is this approach? Incoherence between form, function and performance seems to be increasing.

Looking back to the past century, there were various visionary designers such as Isler, Otto, Candela and Shukhov using design methods comparable to today's computational design, operating in a pre-computational parametric set-up. They applied mathematical algorithms and principles observed in nature to develop pioneering buildings which stood out as milestones of architectural production. Vladimir Shukhov, a Russian engineer, was one of the first to embrace such an innovative approach.

This paper is aimed at rethinking and evaluating the advantages and disadvantages of today's computational design techniques by comparing contemporary performative design methods with Shukhov's analogue approach, undoubtedly one of the most efficient of the pre-computational era. In order to narrow down our research field, this investigation focuses on metal gridshell structures, a commonly known construction type invented by Shukhov and widely used in contemporary practice. We try to answer the following main research questions:

- What were Vladimir Shukhov's design techniques?
- How do Shukhov's manufacturing and assembling processes differ from contemporary digital design techniques? How does their design logic differ?
- How can today's advanced performative design techniques benefit from Shukhov's design heritage?

Our research method is based on the analysis and comparison of two contemporary gridshell structures (constructed using digital design and fabrication techniques) to two designed by Shukhov using his own method: 30 St Mary Axe (commonly known as the 'Gherkin') and the Great Court of the British Museum designed by Foster+Partners, versa the Radio Tower on Shabolovskaya St (1921) and Viksa Works (1897-8) by Shukhov. All four case studies have similar characteristics in terms of size and construction type. The comparison is based on the design process applied, as well as the efficiency of the chosen gridshell structure unit and the assembly process. How similar are they? How do they differ? How coherent and efficient are they? Could a contemporary computational approach be informed by a much older precedent? Although the technology available was different in both periods and had an obvious impact on the entire design and construction process, we try to cast light on the philosophy and mindset behind these projects. Our data collection is derived from literature review, as well as from site visits and research in the archives of the Russian Academy of Science.

2. LITERATURE REVIEW

The history of steel structures started in the mid- to late nineteenth century, when iron and steel were introduced into the building industry as construction materials. Wyatt explains the reasons for this, as well as the circumstances related to this turning point in architecture in *Industrial Revolution* [3]. Steiner emphasises the further development of metal constructions in *French Iron Architecture* [4]. Loyrette focuses on the Eiffel Tower, the most famous monument of its time in the developed world, describing it in his book *Gustave Eiffel* [5]. Furthermore, engineers Sundaram and Ananthasuresh offer some interesting insights in the article 'Gustave Eiffel and his optimal structures' [6], published in the *Resonance* journal, where they analyse how Eiffel & Co cleverly optimised the tower through a combination of parameters and shape hierarchy.

Sourcing the literature about the origins of metal diagrid lattice structures and its inventor Vladimir Shukhov has been challenging. Shukhov's active creative period coincided with a dramatic historical crisis in Russia: the end of the Russian Empire, the Revolution and the Civil War. During this time a significant amount of Russian cultural heritage was lost or destroyed. Fortunately, Shukhov's family managed to save some of his photographs, drawings, sketchpads and other working materials, most of which are now stored in different national archives.

Alongside Shukhov's drawings and sketchpads, the most informative document was a typescript produced by Shukhov's former employee Grigory Kovelman [7]. Kovelman managed to put together an extensive overview of Shukhov's inventions and projects, both as a biographer and as a specialist who had worked with Shukhov and who had insider knowledge of the engineer's design processes. Elena Shukhova, the grand-daughter of the genius engineer, presents extensive biographical details in *Vladimir Grigorevich Shukhov. The First Engineer in Russia* [8]. *Art of Construction* [9], edited by Murrat Guppoev, Ralner Graefe and Ottmar Pertchi, is a valuable collection of articles about Shukhov and his various inventions, written by different specialists. It includes illustrations and information about Shukhov's structures and some examples of his calculations. Shukhov's own book *Rafters* [10] discusses the mathematical investigations which led him to conceptualise the spatial lattice structure, describing it as 'an optimisation process'. In 2010, the journal *Detail* published an analysis of Shukhov's constructions, calling his approach to design 'an early example of parametric design' [11].

A new stage of lattice structure development is presented in *Finding Form* [12], where Frei Otto, one of the most renowned engineers working with such structures, explains his way of modelling and calculating grid surfaces. Otto's writings are particularly interesting because he started working with lattice structures at the dawn of the era of computational engineering and was one of the first to have collaborated with computational designers in realising complex lattice structure projects.

Since computational technologies started to become an essential part of contemporary design practice, numerous articles and books have highlighted different aspects of digital architecture. For example, *Animate Form* [13] by Greg Lynn (among the first comprehensive books on digital form generation) introduces new design techniques based on computational animation, and a new formal vocabulary including blobs, hypersurfaces, and polysurfaces. Lynn establishes three basic properties of digital architecture: topology, time and parameters. Branko Kolarevic's *Architecture in the Digital Age* [14] provides useful background knowledge on the process of developing the computer-aided design approach. This book emerged from the symposium on designing and manufacturing architecture in the digital age held at the University of Pennsylvania in March 2002, and is among the first to describe the emergence of digital design and fabrication techniques. It presents the differences between the notions of parametricism, algorithmic design and generative design, as well as related fabrication techniques.

In addition, for the last ten years the series of *AD* journal has been systematically presenting current trends in the field. The issue *Computation Works: the building of algorithmic thought* [15] raises an interesting debate: even though design is shifting from conventional drawing to parametric modelling, architects continue to have an insufficient understanding of algorithmic concepts. At the same time, the role of computational designers is significantly increasing; they do not merely create 3D models, but '*distil the underlying logic of architecture and create new environments*'.

Inside Smartgeometry: Expanding the Architectural Possibilities of Computational Design [2] edited by Brady and Terri Peters is a collection of articles dedicated to innovative computational geometry. In 'Geometry: How smart do you have to be?', Chris Williams, a structural engineer known for his innovative work on the Great Court of the British Museum, speculates about the irrelevance of particular mathematical knowledge for architects aiming to model complex geometries using computational tools: "You don't need to be Bradley Wiggins… to ride to the shops". The vocabulary of new geometric objects and working principles in the field of computational design is presented in *Architectural Geometry* [16], written by Helmut Pottmann, Andreas Asperl, Michael Hofer and Axel Kilian. In this book, the authors describe the elements of new computational geometry applied in the contemporary practice of modelling gridshell structures, including freeform surface, mesh and the logic of its formation.

Written sources on the Great Court of the British Museum and 30 St Mary Axe tower, designed by Foster+Partners for their client Swiss Re, are plentiful, due to the perceived cultural value of these structures and the public discussion around them. *The Great Court and The British Museum* [17], published by the British Museum Press, documents the Great Court's design and construction processes. More construction details are presented in Hart's *The Brilliant Shell Game at the British Museum* in the *Architectural Record* [18].

Form finding process and development, and construction of the tower at 30 St Mary Axe is described in *30 St Mary Axe: A Tower of London* (2006) by architecture critic and journalist Kenneth Powell [19], as well as in *London will never look the same again* (2002) by Pearson in *Building* magazine. Many other journals have covered this prominent building; detailed construction and design information, however, is not usually included.

3. SHUKHOV'S LATTICE STRUCTURES

One of Shukhov's most significant architectural inventions was the thin metal lattice (or 'diagrid shell') structure. This was developed after intense research into the most rational type of rafters which weighed and cost the least and which could be assembled quickly. Shukhov suggested a formula to define the proportional relationships between structural elements, which at first sight seemed senseless:

$$\alpha = e = c$$

where a- length of panels, e - minimal distance between frames, and c - distance between two purlins, dependent on the actual situation [10].

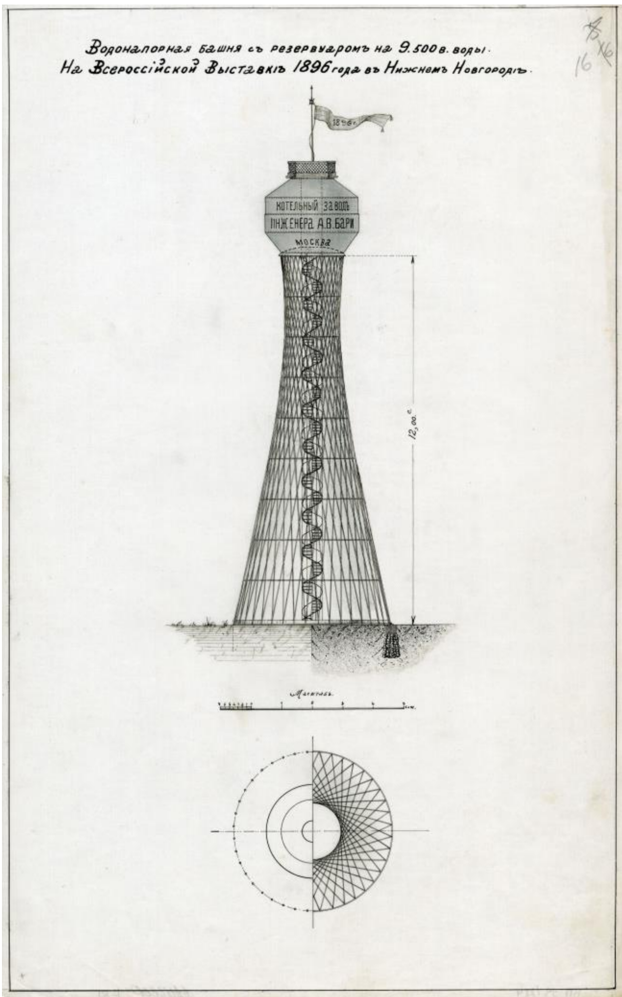

Figure 1: *The first Shukhov hyperboloid water tower erected at the 1896 Nizhniy Novgorod exhibition. [Archive of the Russian Academy of Science, F.1508/Op.2/81(16)]*

According to the formula, the minimal covering weight could be achieved only if the construction had no purlins and if the distance between trusses was equal to the distance between the missing purlins. The answer to this riddle was the spatial lattice structure, where trusses and purlins were the same, and the distances between trusses and purlins were equal. In 1895 Shukhov obtained a patent for the invention. The new structures were first presented to the general public at the All-Russian Industrial Art Exhibition in Nizhniy Novgorod in 1896 (figure 1), where Shukhov designed a number of objects using three types of lattice structure: suspension, vaulted and rigid spatial shell.

Suspension lattice structures (figure 2) were based on tension, the most advantageous type of stress for metal constructions. These structures were designed according to Shukhov's elaborate investigations of material properties. The grid surface comprised overlapping tensile elements: that is, rolled metal plane or angle-section rods riveted to each other. They were called '*roofs without trusses'* [21], and the clear, extremely simple suspension structure system and the easy-to-perform node conjunction made on-site construction fast and straightforward.

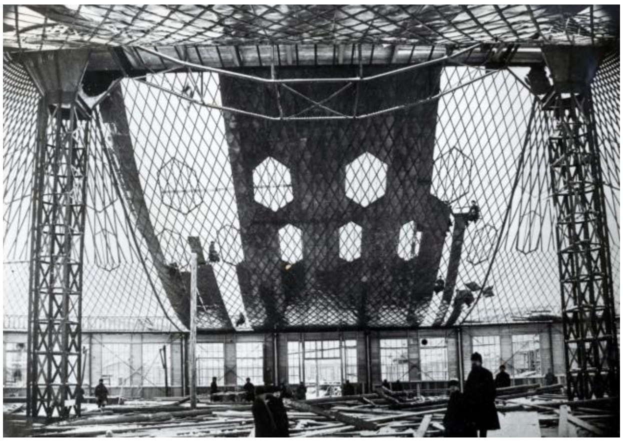

Figure 2: *Suspension lattice structure. [Archive of the Russian Academy of Science, F.1508/Op.2/37, 49]*

Vaulted gridshell constructions (figure 3) did not attract much public attention; however, they brought commercial success to the Bari office [22]. The vaults were formed with thin metal arches turned away from the frontal position at a particular angle. They thus worked as one continuous resilient truss. The optimal angle of intersection was considered to be 68°; one professor, a contemporary of Shukhov, proposed instead an angle of 90° which would have meant a 31% increase in the structure's weight [8].

Each arch was made with rigid metal strips of equal length, or with angle pieces set edge to edge; during the assembling process, each piece was bent equally. The most interesting example of a vaulted lattice shell was the covering for the Viksa Works built in 1897–8. It was the first time in the world's building practice that double-curved spatial vaults were created with single type rod elements [23].

Shukhov's lattice-suspended and vaulted structures represented a carrying surface, which could be shaped in any form. It was made of intercrossing rods, and combined the function of trusses (the main floor structural system) and purlins. The density of the grid made it possible to attach it to the shell without additional structures. Due to the rational distribution of material along the shape, the grids were two to three times lighter than roofs with conventional frames [21]. The difference was proportionate to the span of the construction.

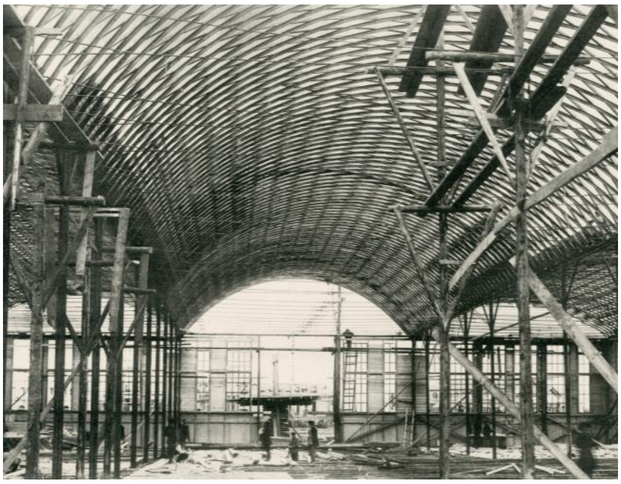

Figure 3: *Vaulted lattice structure, Viksa Works. [Archive of the Russian Academy of Science, F.1508/Op.1/49, 18]*

The final and most unusual of the gridshell structures presented at the Exhibition was the 32-metre-tall lattice hyperboloid water tower. *'Everything was amazing in that first Shukhov tower – everything in it was some structural and geometric puzzle: straight rods and the external silhouette double curvature, the openwork lightness below and the solid heaviness above.*' [23]

The water tower was a unique structure of its time, with an unprecedented shape and construction properties. According to Cooper, the idea of such a new structure came directly from an imaginary hyperboloid geometry, invented by the Russian mathematician Lobachevski in 1829 [24]. Shukhov's biographer Grigory Kovelman writes that Shukhov told him he had been thinking about the properties of hyperboloid structures for a long time, that he had studied hyperboloid forms at the Technical School, and that apparently the moment of enlightenment came about when he saw an up-ended wicker wastepaper basket with a focus on top of his desk. According to Shukhov, this was when he understood clearly how a hyperboloid structure with its curved surface generated by straight rods [21].

As well as gridshell coverings, the structure of the lattice tower was a spatial system, where the load was equally spread along the surface. It was formed with angle rods and horizontal hoops embracing the structure, with the dense intersections between elements and wide cross sections granting the tower stability. Aiming to optimise the design process, soon after building the tower Shukhov presented the standardised elements of the tower structure in a table format (figure 4), with the aid of which it became possible to design a new water tower according to a client's requirements in twenty-five minutes [21]. Despite this standardised approach however, each tower had an individual appearance, as Shukhov's method was based not on unification as much as it was on optimization.

After the exhibition Shukhov continued developing hyperboloid towers, trying to increase their height. The tallest hyperboloid structure he designed was the the 150-metre-tall ComIntern Radio Tower on Shabolovskaya Street in Moscow, built to celebrate the international collaboration of Communist parties.

As a result of the use in recent decades of computational technologies by engineers and architects becoming increasingly common, new gridshell structures have been developed where the structural units do not pre-determine the building shape, allowing formal freedom and infinite geometric complexity. At the same time, mass customisation is making non-identical construction units more affordable. However, digital structures remain just a small percentage of the entire architectural production. The construction cost of high complexity projects is still considerably higher than conventional projects, making commissions accessible only to large practices who can afford the required knowhow and research resources.

Nevertheless, complexity and formal freedom are often applied stylistically, rather than aiming for structural performance or efficiency in construction. Striving to cast light on this debate we compare a contemporary computational approach with the one invented by Shukhov at the end of the nineteenth century.

4. SHABOLOVSKAYA TOWER AND 30 ST MARY AXE TOWER

4.1. Design process

The Radio Tower in Moscow (figure 5) and the Swiss Re building (later rebranded 30 St Mary Axe) are two towers of similar height (150 m and 180 m respectively) with respective diameters of 40.3 m and 56.15 m. The Radio Tower in Moscow is a gridshell which aims for structural efficiency. Its minimal surface and open lattice structure help in reducing the wind load, one of the main challenges in high-rise building design. It comprises six hyperboloid blocks formed with angle rods and horizontal hoops. The dense intersections between elements and wide cross sections grants the tower consumption [9]. Shukhov's design logic focuses on structural stiffness. The rings between the different segments offer additional reinforcement to create an equilibrium between minimal material consumption, structural efficiency and geometry. It is a generative formula, embracing structural interdependences between a standardised unit, building shape and performance.

The elliptic shape of the Swiss Re building (figure 7) was also aiming for a structurally efficient geometry able to reduce wind loads. Foster+Partners architects collaborated with Mark Burry, a specialist from the Arup Group, to optimise the final shape according to aerodynamic principles, using wind simulation software; the final design required hundreds of card and plastic scale models [25]. Its structure consists of a central core and a perimeter steel gridshell joined by rolled steel radial beams.

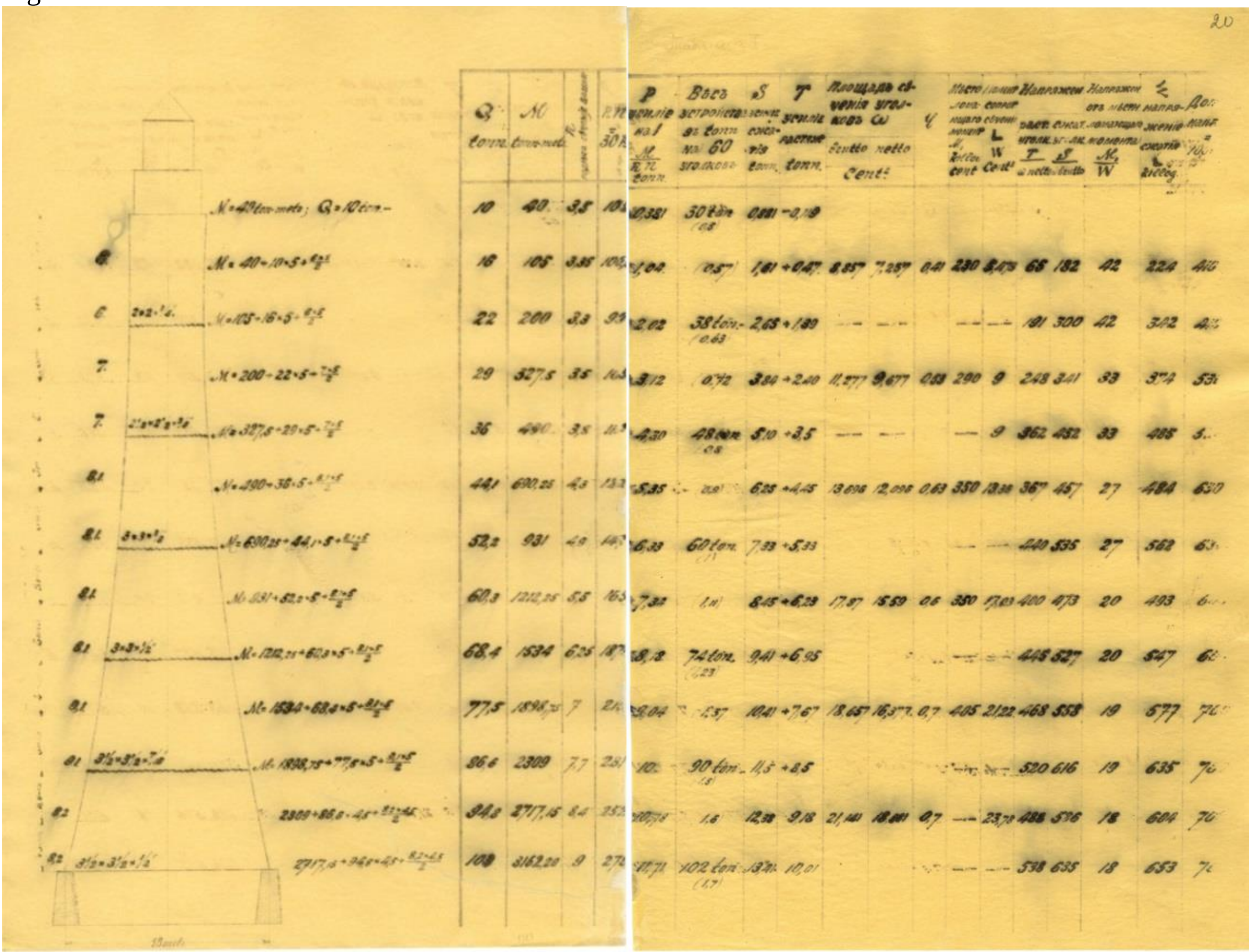

Figure 4: Table of standardised elements by Vladimir Shukhov. [Archive of the Russian Academy of Science, F.1508/Op.1/83, 19 and 20. (first time published)]

The grid's interlocking horizontal hoops turn the structure into a stiff, triangulated shell with a lateral working load, which resists wind force and makes the whole construction stable [20].

4.2. Grid-shell structure type

The most significant difference between the Shabolovskaya radio tower and the ‘Gherkin’ is revealed by the design logic of their gridshell structures. The main idiosyncrasy of Shukhov’s lattice was that he never used equal rings and regular intersections: the intersection points between straight lines in the upper and lower parts are not symmetrical [23]. Rod connections were also shifted from one to another, trying to create as much small-scale inter-crossing as possible, like in a knitted garment, whereas the Swiss Re diagrid system represents a polyhedron composed of diagonal columns and nodes. The lattice mesh of the hyperboloid pylons in the Shabolovskaya tower is made of two layers of diagonal double 140 mm U-section rods aligned

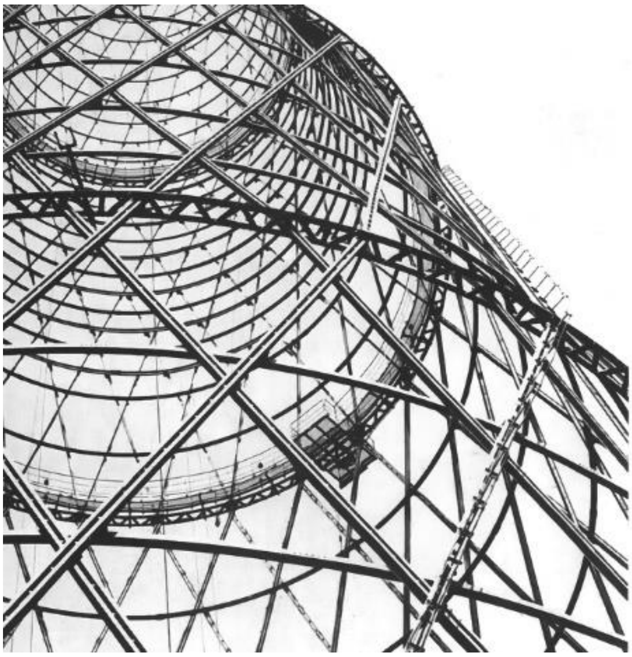

Figure 5: *Radio Tower Moscow. [© Elizaveta Edemskaya]*

between two rings. These rings have a truss structure comprising two L-section rods, which simplifies the pylons’ connections and makes it possible to fix the rods securely. Intermediate U-section rolled metal holding rings fix the rods between the main structural rings. In the process of connecting the diagonal rods to the rings, they were slightly twisted along the whole length, which could be done quite easily due to high material flexibility and because the rod section was relatively small. This granted additional structural stiffness to the construction. In order to stabilise the construction, the number of the rods were reduced gradually from the bottom of the lower pylon to its top.

The Swiss Re diagrid system comprises a series of two-storey steel A-frames. Each frame consists of two tubular diagonal columns bolted with a two-metre height node. Nodes connect the diagrid shell to the radial beams of the central core and govern the curvature of the building, making them crucial to the overall structure of the construction. Due to the building's elliptical shape, the geometry of each node is different; the Arup team thus designed each individual node in detail during the computer modelling stage [19]. In addition, in order to stabilise the tower Arup designed two column types: bigger and heavier for the bottom levels and smaller and lighter for the upper floors.

4.3. Fabrication and assembly

The fabrication and assembly of the Radio Tower was quite simple due to the elements being identical throughout the building and the highly original 'telescopic' assembly method implemented by Shukhov. Each section was assembled and lifted in large blocks inside the structure to fit the five basic wooden cranes and pulleys [19]. The only issue was bending horizontal U-section rings according to the structure, as this was an expensive process at the time [8].

The simplicity of the design and the method of assembly made it possible to build a complex structure using primitive equipment and relying on low-skilled workers. Besides this, the telescope assembly method was highly accurate. In another famous hyperboloid tower with similar structural features to the Radio Tower, the leeway from dead centre was only 24 mm [8].

Galankin [26], Shukhov’s former employee, writes that Shukhov used to make calculations in a unique way, in that they were so laconic (figure 6) that other specialists found them difficult to understand. In spite their brevity however, if Shukhov was asked about load, rod stress, rod profile and section, rivet quantity, material weight, temperature impact or any other specifications, he always had an answer, because his concise calculations covered all these aspects, but nothing that was irrelevant [7].

The main issue in assembling the gridshell structure for 30 St Mary Axe was that it depended on accurate fabrication [16]. *'With a triangular grid, there's nothing you can do if all goes wrong'* [18].

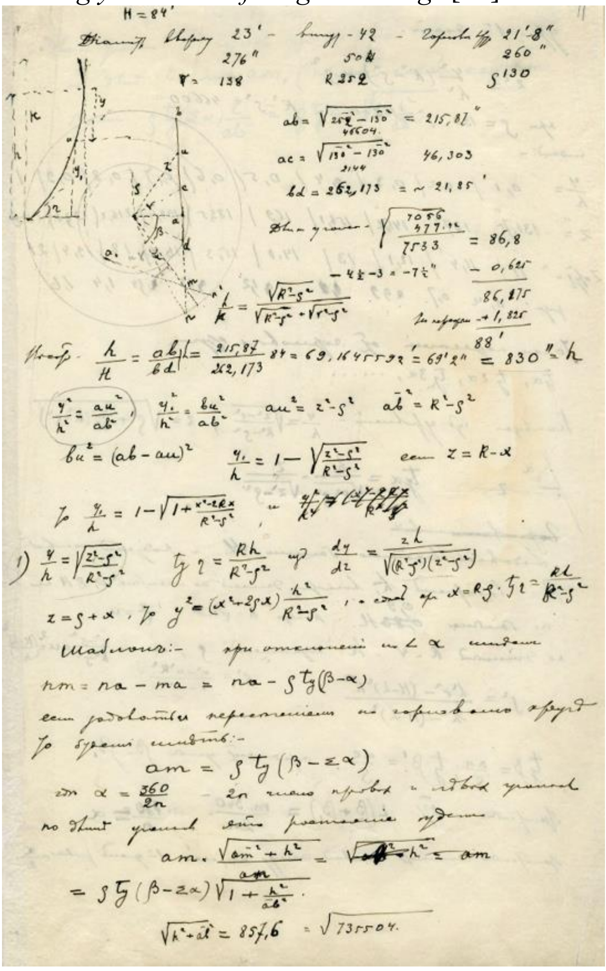

Figure 6: *Calculation for Shabolovskaya Tower. [Archive of the Russian Academy of Science, (first time published)]*

Building such a structure was possible only with the aid of advanced 3D modelling and modern computational fabrication technologies which enable accurate calculation and construction element production with minimum defects and errors. The most difficult part of construction was when the point when all eighteen nodes were in place around the circumference forming a horizontal hoop and tie sections were added to link the nodes. To cover all the boltholes, the tie sections had to line up, a high precision process.

5. THE GREAT COURT OF THE BRITISH MUSEUM AND VIKSA WORKS

5.1. Design process and grid-shell structure

The Viksa Works roof (figure 8) represents the world's first building precedence applying double-curved spatial vaults, composed of single-type rod elements [23]. The roof is subdivided into five segments by three-pinned arches and is covered with symmetrical, double curvatured shells. The single curvature system was transformed into a double-curved surface simply by bending the longitudinal beams. From the cross to the long sections, the circular-cut dome edges have a bend size equal to one-sixth of the span. The symmetric shape of the double-curved domes made it possible to form them with identically bent rods [22]. Sixty-eight degrees was considered the most optimal angle of the rods' intersections.

Figure 7: *Swiss Re Building, London. [© Ian Beedy, Freeimages.com]*

The Great Court roof structure is much more complicated (figure 8). The covering works as a lattice-glazed canopy stretched between the dome's drum of the Reading Room and four sides of the Museum's quadrangle. Its design was generated in two stages. First, engineers from Buro Happold calculated its geometry using standard static (or linear) computer programming. Then, Chris Williams, a computation specialist, was invited to study the deformation of the roof structure. Using simulation software, he designed a 3D simulation model and optimised the gridshell's mesh. The grid size was determined by the maximum glass panel size available; as a result, the structure consists of 3,312 unique double-glazed panels. The total weight of the canopy without glazing is 478 tonnes.

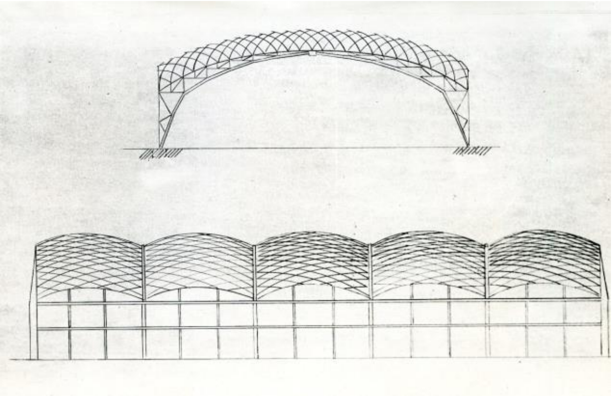

Figure 8: *Viksa Works covering.* [*Archive of the Russian Academy of Science (first time published)*]

5.2. Fabrication and assembly

The final shape was a complex structure, consisting of thousands of unique elements. However, although the gridshell details were successfully prefabricated according to 3D models, the process of assembling the non-standardised structure was somewhat time- and cost-consuming. The final grid construction was formed of radial hollow steel sections (box beams) welded to 1,826 structural nodes, each node having a unique design [17]. The engineers expressed great concern about the reliability of the structure; as a result, Happold, instead of using lower grade steel which might have contained impurities, chose Grade D steel material, usually used in marine and offshore applications [18].

In contrast to the canopy of the Great Court, the construction system of the Viksa Works roof, while highly original, was relatively simple and used no extended scaffolding, usually essential in the assembly of complicated spatial shell structures. This construction system was forty per cent lighter than other roof structures. Kovelman [7] writes that initially, builders refused to climb on the roof as they were unable to believe that such a light lattice structure would sustain their weight.

Despite both projects being built at different times and under very different conditions, examining their specifications and statistics allows for interesting comparisons to emerge:

Viksa Works [4]

- Construction period: 1897–8 (one year)
- Dimensions: 75 m (length) x 38.3m (width)
- Area: 2,795.9 sqm
- Span: 14.5 m
- Minimum roof height: 6.8 m
- Maximum roof height: 13.25 m
- Rods: Z-section rolled metal: 60.5 mm x 45.6 mm
- Budget: 40,568 rubles

Queen II Great Court [18]:

- Construction period: 1998–00 (two years)
- Dimensions: 73 m (length) x 97 m (width)
- Area: approximately 3,692.5 sqm
- Nodes: 1,826
- Polygons: 3,312
- Total structure weight: 800 tonnes, 478 tonnes of steel, 315 tonnes of glass
- Steel beams: minimum steel section depth: 76 mm; maximum steel section depth: 178 mm
- Budget: £100 million

6. DISCUSSION AND CONCLUSION

The case studies present constructions built at different times and under different conditions, and which served different functions and used different technologies; an attempt to compare them might thus seem inappropriate. However, the design logic behind each of these buildings could constitute a subject of comparison.

Even though all four projects aim for structural efficiency and aerodynamic behaviour, a closer look reveals their differences. Each of the four buildings was designed following fundamentally different principles. Shukhov's design logic, based on crossed rods, minimal asymmetry and displaced detail interconnections is similar to the logic of a wicker basket structure, with thin fragile elements joined together to form a strong elastic spatial construction.

In contrast, Foster's computational structure is composed of polyhedral beams. It is easy to trace their origin back to computer modelling, where the most straightforward way to design and calculate a smooth form is by using a polygon mesh. Each logic is almost the exact opposite of the other: one is based on a standardised, structural unit leading to a pre-determined form (e.g. hyper paraboloid); the other is based on form, which dictates the need for a mass customised unit.

Figure 9: *Great Court of British Museum, London.*
[© Pablo Rodriquez, Freeimages.com]

An examination of the assembly process also reveals major differences. The Shabolovskaya Tower's rods are modular, planar and linear, with all the joints repetitive and simple. Its assembly required no high-tech equipment or specially trained workers [8]. On the other hand, the Gherkin's assembly relied on mass customised units. This was thus a complicated process, requiring intense logistics, high-tech equipment and specialised workers.

Shukhov's structures were as laconic as his calculations [7]. Each element – rod size, thickness and angle, building geometry and construction assembly time – was in a specific place: nothing was irrelevant. His calculations (figures 4 and 6) are equivalent to today's algorithms created in Grasshopper, Dynamo, or any other scripting software. They define the relationship between unit and overall shape, whereby the unit generates the overall form. One could argue that rebuilding Shukhov's projects using today's technology would require no changes to improve them. The design logic would be described later by Buckminster Fuller as coherence between form, structure and material as a type of structural minimalism [27].

Foster's Gherkin follows the principles of a typical computational design path, where polygonal tessellation follows form generation. Polygonal geometries are used by current 3D CAD software to represent double curved shapes, which often become a building's structural system in the next planning phase. Optimisation comes even later and re-informs the polygonal geometry. This is a process dictated by the way software operates. Irregular construction units, joints and cladding panels emerge by default. However, although today's construction technology allows us to fabricate and assemble such complexities, one could question the overall necessity and efficiency of such a process, as it remains more time- and energy-consuming than a standardised solution.

This discrepancy poses a question: do we use computer technology as a supporting tool, or has it begun to dictate the design process? Computational technologies make multi-complex shape generation possible; Lynn, however, stresses another issue:

'The computer is not a brain. Machine intelligence might best be described as that of mindless connections. When connecting multiple variables, the computer simply connects them, it does not think critically about how it connects... Even in the most scientific applications of computer simulations it is argued that first an intuition must be developed in order to recognize the nonlinear behaviour of computer simulations.' [20].

Current CAD-tools are able to adapt to almost any type of design process that an architect chooses to follow, making it unreasonable to blame technology for human decisions. Star architect Patrick Schumacher for instance [28] manifests his view on parametricism as a new style:

'Contemporary avant-garde architecture is addressing the demand for an increased level of articulated complexity by means of retooling its methods on the basis of parametric design systems. The contemporary architectural style that has achieved pervasive hegemony within the contemporary architectural avant-garde can be best understood as a research program based upon the parametric paradigm. We propose to call this style: parametricism.'

Schumacher is a characteristic example of an architect using computational tools in a form-driven manner, representing the total opposite of Shukhov's understanding of parametricism and algorithmic thinking. According to Schumacher, today's profession appears divided between those who use computational tools in order to address the so-called 'high demand' of complexity and those who do not. Looking at the current social, economic and environmental problems worldwide, Schumacher appears to take a rather elitist approach. Emerging technologies have so much more to offer than making high complexity structures buildable: they could help us to improve a building's environmental performance, decrease its construction cost and construction time, and save building material.

Our comparison between the four case studies demonstrates that many current designers are not utilising the possibilities offered by technology. If computational architecture is supposed to produce 'smartgeometry', perhaps engineers and architects should strive for 'wisegeometry', that is, geometry based not so much on calculations as on an optimal construction logic of the physical world, such as that of Shukhov's structures. Perhaps wisegeometry should start by addressing Chris Williams's reflection in Smartgeometry:

'Computers are no longer a new technology, but their implications for the ways in which people will work are still unclear' [2].

We appear to be living in a period of technological transition, which has the potential to revolutionise our way of building even further. Current achievements in robotic fabrication might eliminate human labour on site [29], thus allowing even more complexity by making construction even more affordable. Even if this occurs however, understanding Shukhov's laconic algorithmic philosophy could help us to channel robotic innovation to create a more efficient, sustainable and affordable building environment, rather than a merely in a manner which might be considered stylistic but lacking in any truly worthwhile innovation.

7. IN FAVOR OF SHUKHOV'S ARCHITECTURAL HERITAGE

In 2016, Shukhov's architectural heritage is in a compromised state. Although the Bary office built thousands of constructions across Russia, only a few survive. In spite of numerous discussions regarding the importance of Shukhov's constructions, one of his most famous buildings, the Radio Tower in Moscow, is at risk of collapse because it has not been renovated for twenty-five years. Following the international *Heritage at Risk* conference held in Moscow in 2006, 170 specialists from 33 countries declared the Shabolovskaya Tower a masterpiece of Russian avant-garde architecture and proposed that it be placed on the UNESCO World Heritage list. Sir Norman Foster also interceded for the structure, which he described as 'neglected' and which would 'd[ie]' without 'faithful restoration.'

Figure 10: *Viksa Works in 2016. [© Vladimir Fedorovich Shukhov*]

Of the numerous lattice roof structures designed by Shukhov, only the Viksa Works (figure 10) with its unique double-curved roof has survived. This historical monument of Russian architectural achievement is also in a poor condition, having been left without a covering for years. Its urgent restoration is also required to prevent it from falling into decay. The most innovative of designers are only permitted to look to the future through reference to the past, which we as curators must not fail to maintain

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