Concurrent Geometric, Structural and Environmental Design: Louvre Abu Dhabi

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Abstract. *Sophisticated contemporary design projects are constrained by the multi-objective requirements of architects, engineers, and specialty consultants. The Louvre Abu Dhabi represents a step forward in the concurrent engineering of multi-objective geometry conditions for environmentally informed envelope design. The project takes advantage of associative and generative modeling technology to create a framework for multi-constraint problems in which all stakeholders can embed their own requirements and design rules in a real-time and collaborative way. At the same time, the creation of a globally shared, web-hosted, versioned model provides a dramatically more open and transparent way for designers and engineers to converge toward a shared solution for the geometric and environmental challenges. Thus the Louvre Abu Dhabi provides a case study for a new concurrent design approach to multi-constraint geometric problems in architecture.*

1 Introduction

Every building is naturally subject to the demands and desires of many constituents, each of which hopes to achieve certain objectives with a project. To satisfy these multiple and often divergent objectives, building design has become an increasingly collaborative activity, often drawing on the knowledge of dozens or hundreds of experts to achieve a successful result. Today the historical design team of architect, structural engineer, and mechanical engineer may be joined by a myriad of new consultants for facade, maintenance, museography, accessibility, sustainability, and more. The staggering range of rules, constraints, and requirements brought to bear on a project by these consultants often has direct impact on building geometry. New technologies, particularly parametric tools and concurrent design platforms, provide a means to synthetically optimize designs for these various geometric objectives.

A paradigmatic project to illustrate this multi-objective approach to geometry is the design of the Louvre Abu Dhabi (LAD). The Louvre Abu Dhabi is a new classical arts museum in the United Arab Emirates planned as a central feature of the cultural district of Saadiyat Island. Consisting of 22,500m² of gallery space and supporting programs, the museum buildings are arranged in a micro-city floating on the sea, shaded by an iconic shallow dome (Figure 1).

At the heart of the design concept, this giant dome structure performs environmental, aesthetic, and structural functions. Environmentally, it provides shade and cooler temperatures to the outdoor public spaces connecting the multiple buildings of the museum village. Aesthetically, it functions as an external open-air canopy, filtering the natural light of the sun and creating a dramatic and constantly transforming lighting effect beneath the dome. Architect Jean Nouvel stated: "*This micro-city requires a micro-climate that would give the visitor a feeling of entering a different world. The building is covered with a large dome, a form common to all civilizations. This one is made of a web of different patterns interlaced into a translucent ceiling which lets a diffuse, magical light come through in the best tradition of great Arabian architecture.*"

Figure 1: Site plan and perspective view beneath the dome.

To achieve this effect, the dome is conceived as a layered series of geometric patterns, superimposed in a manner that appears haptic although it is highly controlled. The role of the interdisciplinary design team was to bring to reality this vision, taking into account a series of constraints:

Aesthetic. The pattern of the floating, filigree canopy is intended to be, in effect, a marvellously dynamic installation, equal parts mystery and precision.

Natural lighting. Below the canopy, the design vision calls for a "rain of light:" visible rays of light and dynamic light patterns on the plaza and walls. This demands the careful control of perforation levels and diffuse light.

Environmental. To achieve a comfortable microclimate beneath the dome, a cumulative target level of only 1.8% light transmission must be achieved, and a low emissivity material is required for the interior surface.

Museography. Natural lighting of the galleries is achieved with variable, specifically prescribed levels of perforation in the dome.

Structural. The dome spans 165 meters between only 4 supports, generating large cantilevers. Individual pattern elements span up to 5 meters.

Fabrication, Assembly and Maintenance. The brief required a design for buildability, accessibility and durability over a 100 year lifetime. As much as possible of the fabrication planning needed to be automated in order for the project to be feasible.

Ultimately, these constraints were translated into specific geometric rules for the design. To achieve these disparate and sometimes competing requirements, the team used advanced parametric tools and concurrent design systems to find optimal solutions to shared challenges.

2 An Iterative Integration Process

The process of concurrent design for LAD leveraged the flexible collaboration of multiple disciplines. The principal design team consisted of the architects, Ateliers Jean Nouvel (AJN) in association with HW Architecture, and the engineers, Buro Happold (BH) in association with TransSolar. Multiple sub-contractors were deployed, including Gehry Technologies who provided expertise, software, and infrastructure for the parametric control of the dome, CERMA research laboratory for advanced lighting analysis, and One to One GmbH to manage the production of the large scale model for design verification. At each level performance requirements were translated into geometric rules embedded in the core parametric model.

2.1 Geometric origins

A base geometric pattern to create the filigree web of the canopy was fundamental to all later design and analysis decisions. This pattern consists of an isosceles triangle repeated and rotated to form a system of squares and hexagons (Figure 2). The pattern is mapped to the dome surface following an underlying “great circle” grid, resulting in a tessellation that is true at the apex, whilst it distorts nonlinearly towards the perimeter. The same pattern would later be repeated, rotated, and scaled to achieve the density and intricacy of the final design.

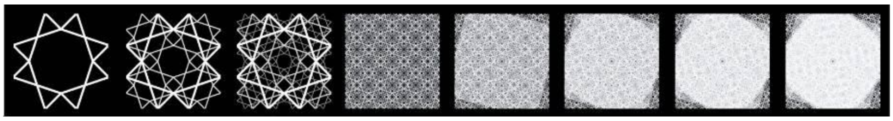

Figure 2: Base pattern applied to dome, with studies of derived patterns.

2.2 Structural iterations

Early in the design process there were investigations into the potential structure of the dome, including concrete, tensegrity, and steel. With steel selected, an extensive period of workshops and design iterations were undertaken, experimenting with different structural typologies, evolving the structure away from a rectilinear arrangement. Ultimately, the geometric base pattern of the dome and the primary structural grid were fused, creating a structural space-frame that itself acts as one of the many shading layers of the dome. One important effect of this deep structural system is that two skins are created, inner and outer surfaces approximately 6 meters apart, thereby creating a more dynamic light effect under the dome due to the phenomenon of parallax (Figure 3).

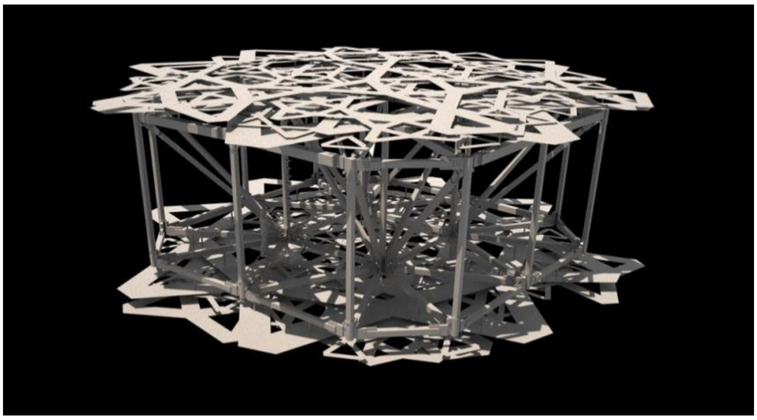

Figure 3: Partial digital model illustrating structure and cladding relationship.

In order to meet these specific, complex engineering and architectural requirements, a process of research and development further extended the team's existing structural optimisation capabilities. Building on Buro Happold's SMART Sizer technologies, a novel iterative approach to structural optimisation was developed for the project enabling a fine balance of a number of interrelated constraints: structure self-weight, aesthetics, cost and buildability. Details of these techniques can be found in [Shrubshall and Fisher 2011]. Thus exploiting this approach enabled an efficient, elegant solution which equally meets all the multi-objective design criteria.

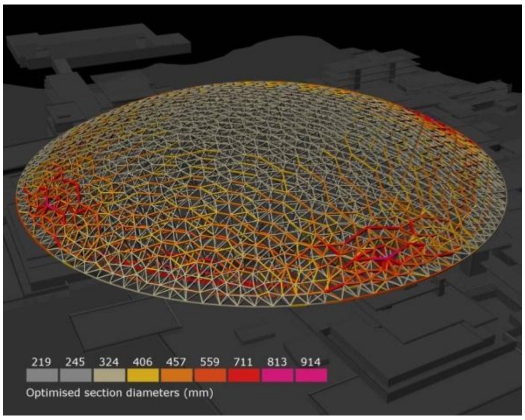

Figure 4: An initial deflection optimisation controls the stiffness distribution in the dome, enabling the designer to closely sculpt the global behaviour of structure, before then continuing to satisfy all the specific local stress criteria. In utilising this approach, stiff regions within the dome naturally emerge arching between the supports.

2.3 Cladding iterations

With the fundamental base pattern established, a set of parameters controlled its transformation into the ten distinct, superimposed layers of the dome cladding. The key relationships to manage were relative scale, rotation and translation of the pattern components. A series of trials ultimately resulted in a combination of parameters which provide variation and perceived intricacy whilst still maintaining consistent, predictable points of connection between layers and sufficient density for microclimate effects.

Each cladding layer has not only a distinct pattern scale and orientation relative to the others, but also mass-customized member widths in order to achieve the necessary apertures for daylighting across the dome surface. By varying these widths within an established range, the dome achieves areas of greater and lesser perforation (Figure 5). These perforation levels were calculated and ultimately controlled using a process of inverse lighting analysis.

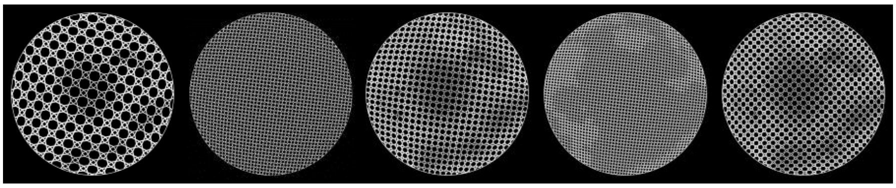

Figure 5: The five outer layers of cladding of various scales, rotations, and member widths.

2.4 Inverse lighting

CERMA, an architectural and urban ambient environment laboratory, undertook the challenge of computing the perforation variations on the dome, taking into account the natural lighting intentions given by the architects. As the perforations of the dome are small compared to the dome size, the perforation ratio over the dome can be seen as a transparency map. In a performative design approach [Kolarevic and Malkawi 2005], the inverse lighting paradigm applied to the architectural design is used in order to produce this transparency map. Several steps ensured the precision and fidelity of this inverse lighting model.

The inverse natural lighting model. Several methods allow the inversion of lighting simulations in architecture [Patow and Pueyo 2005]. In the case of Louvre Abu Dhabi, the dome is a light filter which can be seen as a set of intermediary light sources. These intermediary light sources have an anisotropic feature which is essential in the solving of the inverse problem. The emittance property of these intermediary light sources is bound to the transparency properties of the filter. Therefore the inverse problem can be seen as an emittance research of anisotropic light sources. The integration of this approach into the collaborative design process is achieved through the use of a light-based parametric design tool: EEL, which is developed to handle such complex features as a heterogeneous light distribution. The detailed case study can be found in [Tourre and Miguet 2010].

Computing the transparency map. The process of the inverse lighting study can be summarized as follows:

- Preliminary lighting simulations on the 3D model, in order to aid the description of lighting intentions
- Definition of the lighting intention map
- Inverse natural lighting with the EEL prototype
- Computing the transparency map
- Verifying the dome configuration with a forward lighting approach

The definition of the lighting intention map is essential to the inverse lighting process. This intention map shows explicitly where designers hope to achieve various light and temperature levels. In the case of the Louvre Abu Dhabi, the lighting intention map developed by the architects contains three areas: plaza, galleries having roof lights, and other buildings and water (Figure 6). The intended illuminance levels (in lux) were based on a report by the microclimate specialists

TransSolar, preliminary lighting studies, and meetings between AJN, BH, and CERMA. These intention maps are very complex because they must cover the range over the course of a year.

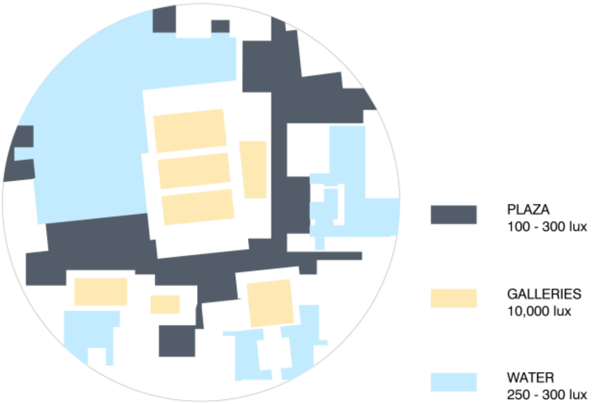

Figure 6: Lighting intention map used as input data for the inverse lighting model.

The resulting perforation ratio, interpreted from the computed transparency map, ranges from 2% to 8% over the “natural lighting” areas (galleries), and from 0.1% to 1% over the protected areas (plaza, water surface, and other buildings). Therefore, the inverse lighting model responds to this design problem by analysing the lighting intentions and applying the results to compute the member widths of the cladding. The transparency map then becomes the basis for the data-driven approach to the parametric variation of the dome.

3 Parametric Model

3.1 Computational infrastructure

With these simultaneous design processes under way, it became apparent that the project would benefit from a shared parametric model for design optimization and fabrication automation. Using Digital Project software and SVN, a web-based model repository, Gehry Technologies put in place an infrastructure that allowed the concurrent collaboration on the LAD Dome model between the architect, engineer, and consultants. This allowed architects and engineers to work simultaneously with the same model on different problems, while each adhered to project-critical constraints that had been agreed upon by the team. The same system provided a natural way to distribute content, facilitating studies, collaboration, and training.

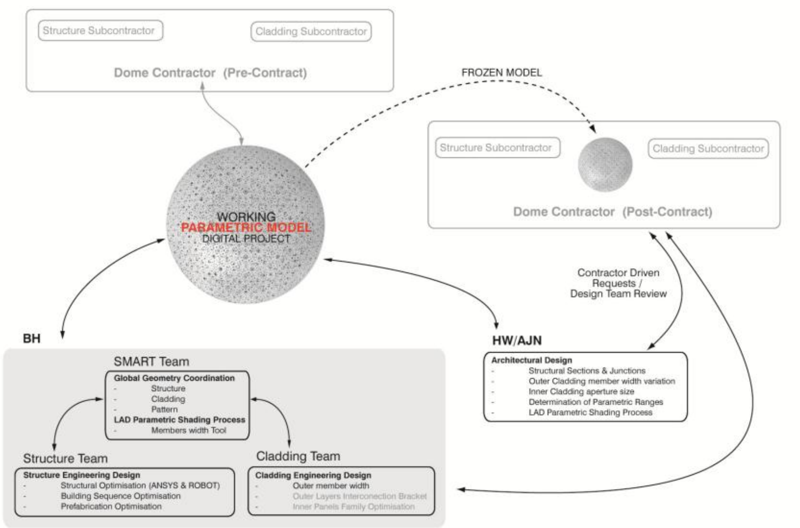

Figure 7: Diagram of parametric workflow, detailing how various constraints of the project were folded into the central parametric model of the dome.

3.2 Parametric process

The Digital Project model served as a base for continuing development of the structure, cladding, lighting, and details of the dome. All of the key constraints of these various disciplines were embedded in this concurrent web-distributed model. The structural model took advantage of the semantic architectural objects in Digital Project to generate key analysis wireframe and metadata. The structural team continued to use Ansys and Robot for their analysis, but the Digital Project model held the wireframe base that was shared amongst the team. The parametric system allowed easy control and testing of variables in the cladding layers, which were first instantiated as wireframe centrelines and eventually linked to the inverse lighting map to drive member thickness and achieve the desired level of perforation. In this way, the central model became a responsive data-driven tool for synthesizing both external light information and structural analysis metrics. The model adapted itself to each data set, providing reciprocal feedback for the interrelationship between the two.

3.3 Mathematical opacity control

A major design challenge was to link the geometry to the precise environmental requirements, realizing true performance-based design. With the centralized parametric model established, this was achieved by integrating the specific lighting simulation data with the geometry generation.

An approach was developed by which the required overall opacity of the dome is decomposed into individual translucency maps for each separate layer of cladding. Ratios specified the extent to which each cladding layer contributes to the whole opacity of the roof. Thus the parametric model is driven by a series of distribution functions weighting the dome solidity between the top and bottom skins and then between each sub-layer. For instance the translucency of layer i, t_i is:

$$t_i = \left(\frac{cT}{t_s}\right)^{\frac{\rho_i}{\sum_{j=1}^{8}\rho_j}}$$

where cT is global translucency at a point on the dome, t_s is translucency of the structure, ρ_i is translucency ratio of layer i.

Starting from the initial physical simulation (as conducted by the inverse lighting studies and described above), the translucency decomposition formulas were integrated into the parametric dome geometry, to calculate opacity values for each of the layers of the dome. These layer-wise translucency values are defined in zones across the surface enabling the local variation within each layer to be described (Figure 8). Each member of every layer detects its proximity to the closest analysis zone, and by taking on the assigned thickness within a given range, the layer achieves the necessary level of perforation (Figure 9).

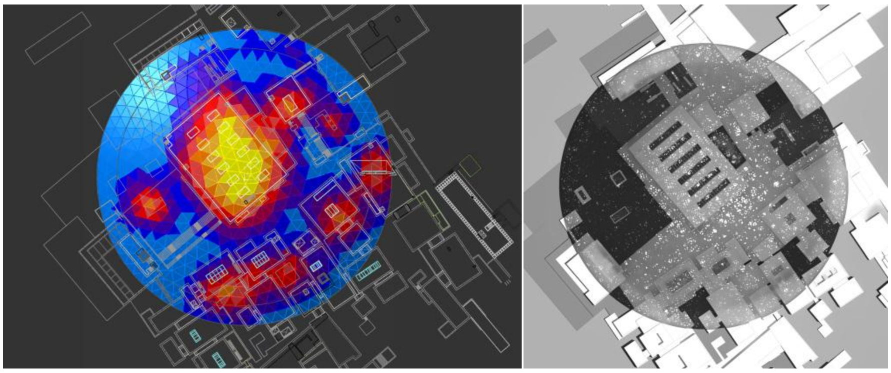

Figure 8: Overall translucency map with resulting shadow effect beneath the dome.

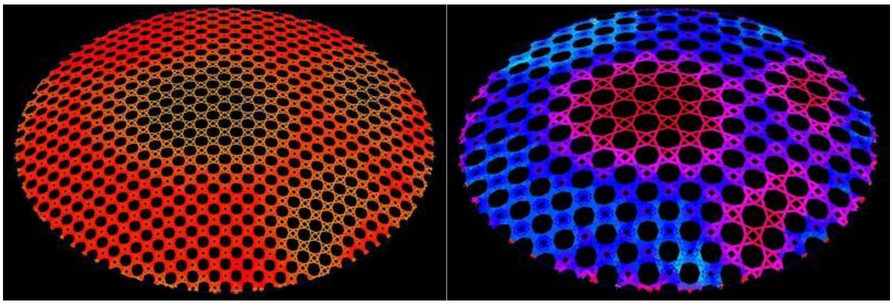

Figure 9: Two examples of the translucency map applied to cladding layers.

3.4 Detail studies

As the design developed, the challenges of detailing the metal cladding members and connections across the entire dome (approx. 12,000 preassembled modules) were also addressed collaboratively with the parametric model. The construction documents for the dome were fully automated from these detail studies, producing over 300 pages of detail drawings and 3000 pages of numeric quantities for the tendering of the dome. These quantities included not only lengths and widths of members but also vertex-wise angle defects, which helped to generate accurate end cuts for each irregular shape while inducing the proper curvature for the global dome.

Octagon, triangle and square families. Ultimately, the method of assigning member widths drove the cladding construction details. Geometric families of congruent parts were developed to smooth the transitions between individual elements of varying widths. The result was a central single or double rail that could also be used as a joint for fixation. Member widths are controlled independently on either side of the rail, making it possible for asymmetric combinations to result. Also with this system, a subtle change in member orientation had to take place. Rather than each linear element being oriented normal to the surface of the sphere, each orientation had to be defined by new planes established within each octagon, triangle and square family (Figure 10). The slight surface angle that results is variable, but the differences are small enough to be considered constant for fabrication. The folds also contribute to the visual nuance of the surface when reflected by the light.

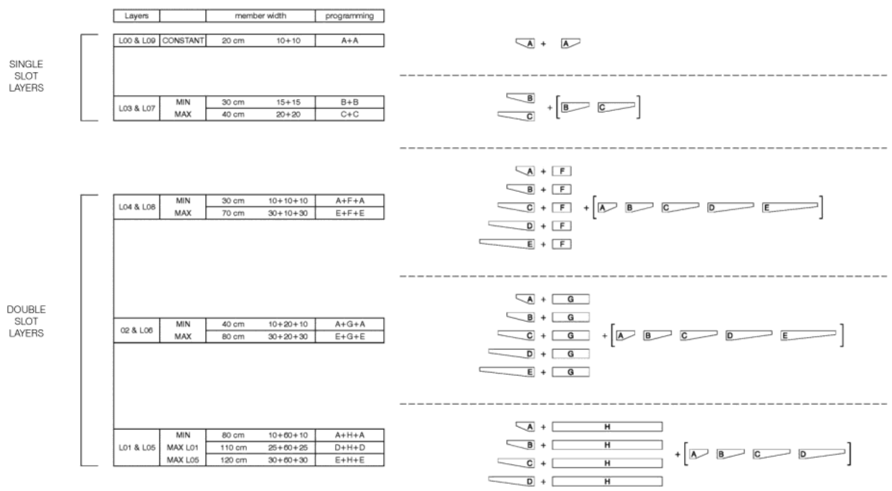

Figure 10: Cladding member width catalogue. Families of extrusions provide a semi-standardized method of adaptively accommodating a range of member widths.

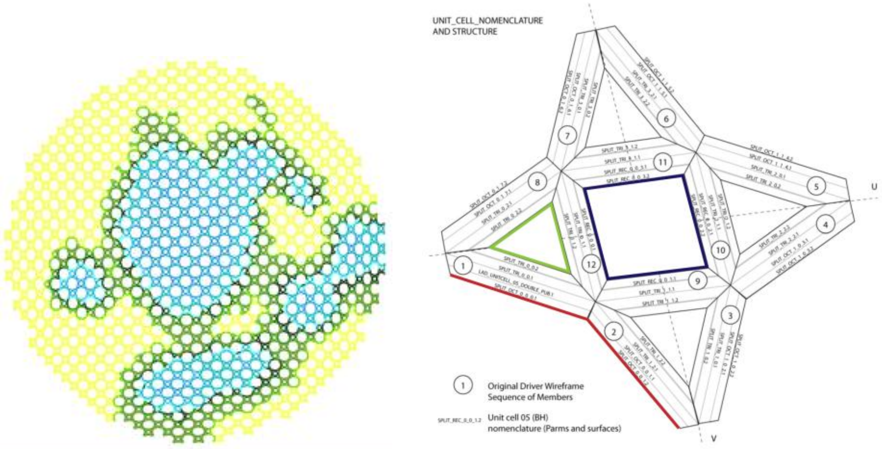

Figure 11: Construction documents produced from parametric model: Sorting member widths over a single layer (left) & detail showing octagon, triangle, square families (right).

4 Results

At each step, physical simulations were used to supplement and validate the digital models, as in the shadow rendering in figure 8. In addition, a series of progressively more detailed prototypes were constructed, including a partial 1:1 scale mock up on the site and a 1:33 scale prototype of the entire dome.

4.1 Large scale prototype

The fabrication of a 1:33 model, built primarily for light-testing purposes, served also as a precursor to the forthcoming full-scale dome erection, as many of the issues relevant in construction had to be addressed for the first time. The model was far outside the realm of traditional architectural model-making due to its large dimensions, inherent geometric complexity, precise material specifications and convoluted assembly logistics (measuring 5.50m in diameter and being constructed out of 15280 aluminum and stainless steel parts in less than 6 months). The task of the model’s construction, as well as the concurrent design process leading up to that point, necessitated the engagement of an interdisciplinary collective. Three cooperating firms were appointed, combining the expertise of computational geometry, state-of-the-art manufacturing and assembly facilities and traditional model-making skills, respectively.

Primary Structure. Initially, basic structural analysis specifically for the 1:33 model was carried out in order to evaluate construction alternatives. The chosen approach was an all metal structure consisting of non-standard stainless-steel nodes, laser-cut out of flat metal sheets, and lathe-manufactured aluminum bars. A parametric plug-in for Rhinoceros was developed which enabled the generation of the entire primary structure, taking the Digital Project wireframe data as input. An integrated optimization algorithm that reduced 2,497 unique members for each quarter of the dome to 44 standard bar types by varying the length of nodes' arms within a range of 12mm - visually almost imperceptible and structurally irrelevant. Each node is unique, 1,079 different types for each quarter, and was automatically flattened, labelled and nested. All relevant information for assembly was engraved on each individual connection: the node's number, the neighbouring node numbers and the bar types to be attached.

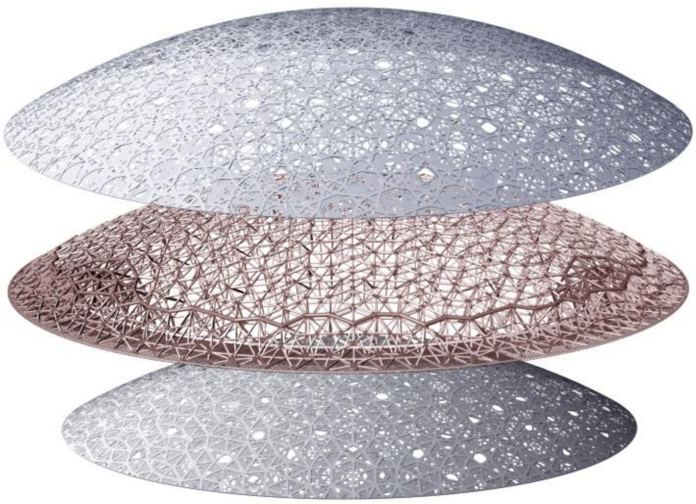

Figure 12: Components of 1:33 scale dome prototype

Cladding Layers. The 1:33 model had to withstand a temperature difference of approximately 70°K. Due to the thermal expansion of the structure the only viable solution for the dome cladding was to apply the same material, Aluminum (AlMg3, H111). The cladding was produced in small modules of approximately 600x600mm, assembled with a gap of 0,8mm between each to allow for heat expansion. For reasons of time and cost, three of the five layers of the interior and outer cladding were merged into one. The layers of each module were individually pressed into double-curved spherical segments, the pattern of the cladding water jet-cut, and the layers glued together to form a complete module, which was then screwed onto spacers attached to the primary structure.

For the large scale prototype, as with the full scale dome, the process of further rationalizing the geometry was a crucial step in the development of an efficient, practical and viable solution for its construction.

Figure 13: Prototype in progress.

4.2 Full scale mock-up

A full scale portion of the dome was constructed on site beginning the summer of 2009. Temporary wooden cladding permitted light testing and validation to be carried out and the results incorporated early into the parametric model. The space around the mock up was fully enclosed to block out light from the sides, and the structure was equipped with a moving platform to simulate the conditions at the centre of the dome (30 meters above the plaza) as well as the edge (9.5 meters above). In early 2010 the temporary cladding was replaced with multi-layer cladding prototypes, testing the finishes, joints, connections, and fabrication procedures. As an on-going point of reference during the design period, the mock-up served as a valuable tool for concurrent design.

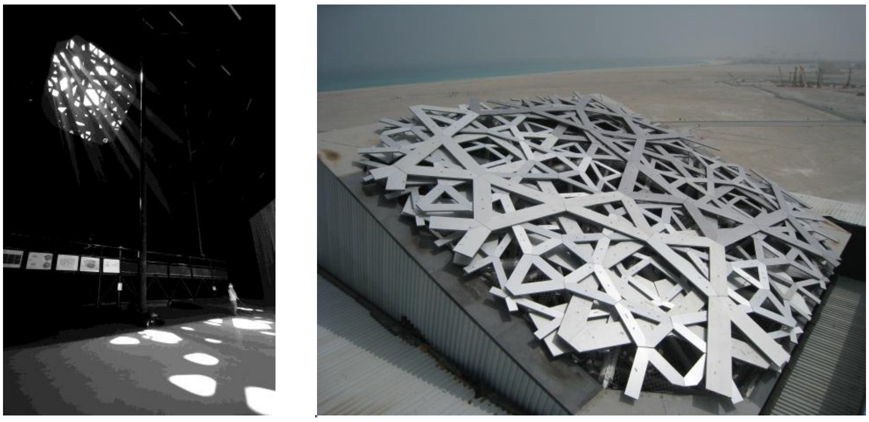

Figure 14: Photos of full scale mock-up. This full scale section of the dome could pivot to simulate any lighting condition on the dome. Photo credits: Neil Francis (left) and Stefan Zopp (right)

4.3 Looking forward: convergent design

Thus far, the twofold optimisation process to define the dome geometry for both structural and environmental performance illustrates how seemingly complex geometry can be achieved, and in fact emerges naturally, from the interaction and concurrent design of specific engineering requirements. Integrating into this design process the standardisation and fabrication constraints means that a complex architectural aesthetic can be realised whilst meeting practical engineering limitations.

The Louvre Abu Dhabi is now entering construction the phase and preparing for fabrication and assembly of the dome. Given the complexity of the geometry, the scale of the dome, and the number of parts, a rigorous system for cataloguing, fabrication, and installation is essential. The wealth of information contained in the shared parametric model will be a critical resource as the project becomes a reality.

Ultimately, the Louvre Abu Dhabi represents a step forward in the reciprocal integration of environmental, structural, and architectural geometry constraints. The dome is a step beyond even concurrent design to convergent design - iterative optimization of multiple constraints toward a synthetic objective. It illustrates the rich intersection of collaboration and geometry, and the profound evolution towards simultaneous variation and control that is possible with new parametric and concurrent design systems. As the case of the dome shows, the competing, multi-objective constraints of complex projects can be resolved holistically, elevating the capacity of multidisciplinary teams and the quality of unprecedented projects.

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