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MEET OUR EXPERTS

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CK Dickson Wong began his career as an architect who completed his training at industry-leading architectural offices. Since joining Inhabit, he has overseen numerous high-end, large-scale, and complex projects from schematic design, through construction documentation and tendering, to construction administration, fabrication, and on-site coordination. As a façade consultant, CK has collaborated with world-renowned architectural offices and internationally established developers. His expertise includes architectural design, complex geometry analysis and geometry rationalization, façade system design, façade construction documentation, performance test witnessing and construction administration. Leveraging his robust knowledge of computational tools, he has been spearheading computational design initiatives within the office and developing unconventional, tailor-made façade solutions for several significant projects. He has been regularly invited to publish these solutions in major international conference proceedings in the field.

HO SUNG KIM

Ho Sung Kim is a Masters-qualified architect from the University of Pennsylvania with experience in architectural façade on projects across Hong Kong, Macau, Korea and further afield including the USA and Central Africa. He has acquired exceptional skills in BIM modelling of façade systems to model, develop, and detail façade systems to a level that allows him to automate deliverables including fabrication drawings. Utilizing his skills in parametric modelling and scripting, he is able to propose and finalize form finding, penalization, and rationalization for complex geometric designs.

ROB HADDOCK

S-5! CEO and Founder, Rob Haddock is a former contractor, award-winning roof-forensics expert, author, lecturer and building envelope scientist who has worked in various aspects of metal roofing for five decades. Together with his sons, they co-invented the PVKIT rail-less direct-attach™ solar solution, providing a simple, secure method to "lay & play" PV modules with tested, engineered, cost-saving, attachment. To learn more, visit www.S-5.com.

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Meagan Kikuta, M.Eng., B.Arch. Sci., LEED AP, RRO, is currently a Design Professional Rep for Tremco Roofing Ontario. She has over 13 years of experience in the commercial construction industry in the fields of Technical Sales, Construction Project Management and Consulting Engineering. Meagan holds a Masters in Civil Engineering from the University of Toronto and a Bachelors of Architectural Science from Ryerson University, both degrees majoring in Building Science.

MAURICE QUINN

Maurice Quinn, P.Eng., B.Eng., is a Senior Structural Engineer for Capacity Engineering Ltd. He has been with the company for over thirteen years, and often writes for CEL's blog, keeping readers up to date on various topics in the industry.

MARCO FERRAZZO

Marco Ferrazzo, B.A.Sc., is the Process Manager of Plant Production Management at Artistic Skylight Domes, Ltd. He has been an expert with the company for nearly a decade.

STEPHEN MACDOUGALL

Stephen MacDougall is a licenced Professional Engineer and Principal Forensic & Structural Engineer at Brown & Beattie Ltd. where he has worked for the past 14 years. He specializes in the assessment and repair of buildings damaged by a wide range of events, from leakage to structural collapses, fires, and extreme weather. He and his colleagues help Condominium Corporations and Insurance Companies determine the cause and best course of action to address structural and building envelope related failures.

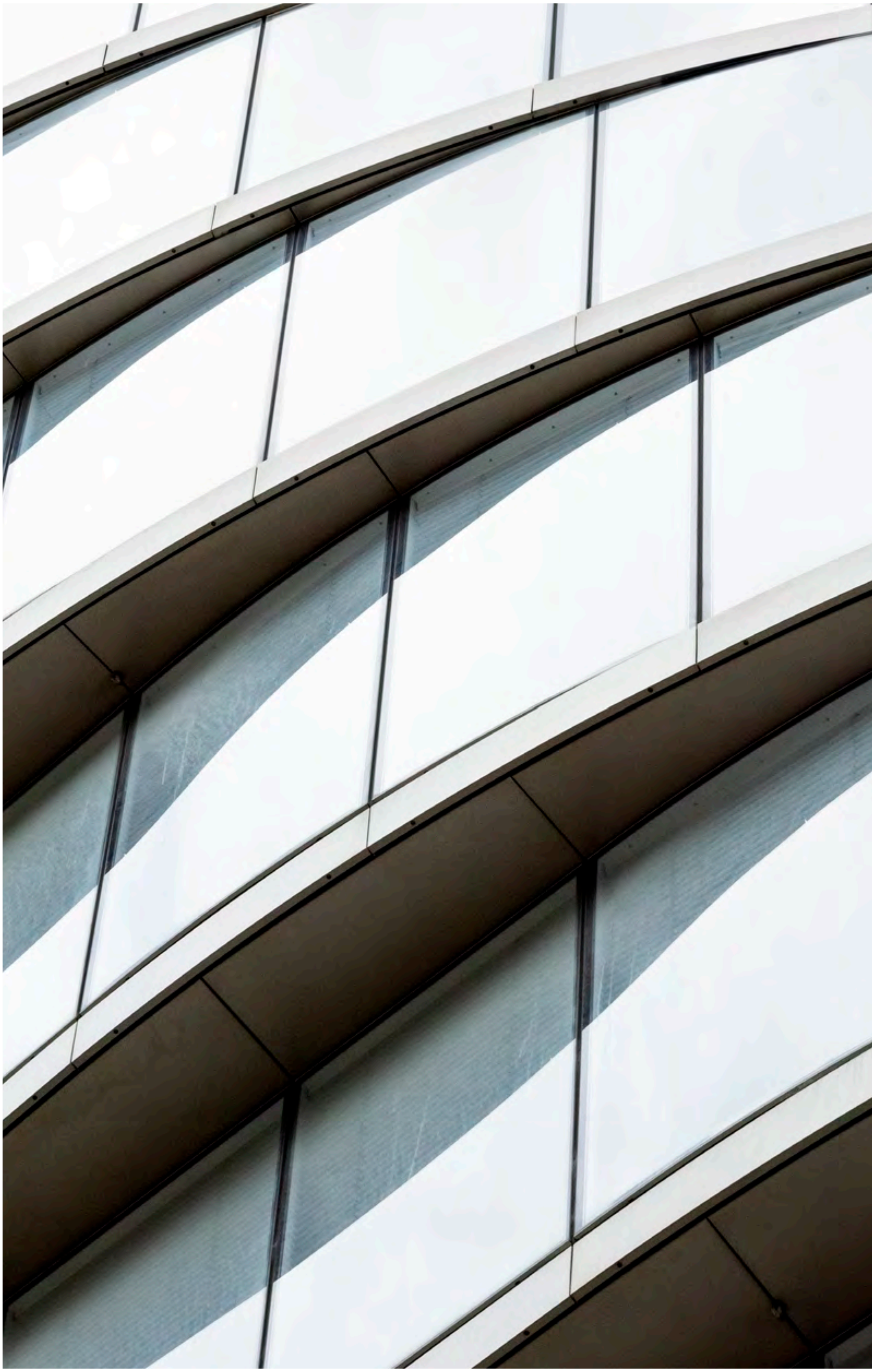
GOT SOMETHING TO SAY? WE'RE LISTENING!

We've all got stories to tell. If you're a member of the Ontario Building Envelope Council, we want to hear about your encounters while on-the-job, from a difficult or usual project, to how your company worked collaboratively to resolve an issue, to an exciting new project you're working on—or whatever you'd like to share.

We just might run your story in an upcoming issue of the magazine. Send a 100-word abstract to Daniel Aleksov (daniel@lebengineers.com) for consideration. If your idea is chosen, we'll follow up with a word count and deadline. **Submitting an idea does not guarantee publication.*

Free-form Façades:

A Survey of Optimization, Documentation, and Fabrication Methodologies



By CK Dickson Wong and Ho Sung Kim, Inhabit Group

Computationally automated standardization and planarization[1] are considered standard procedures when it comes to the design and fabrication of cladding and glazing systems on buildings with complex curved geometry. While one could argue that in the age of CNC fabrication geometrical variations among discrete elements can be accommodated and organized with relative ease, auxiliary components such as stiffeners, brackets, sub-frames etc., may need to be highly customized to accommodate the dimensional and angular variations resulted from the curvature of the curved local element. This increases the complexity of the fabrication and installation, as well as wastage in the fabrication process.

This article looks at the three approaches that one can take for computational maximization of standardization and planarization:

- *Top-down*: optimizing the global architectural surface in a way that maximizes the number of standardized and/or planar elements,
- *Bottom-up*: optimizing local façade elements (e.g., a panel) as such that they become standardized as they are being populated across an architectural surface, and
- *Bi-directional:*[2] optimizing both the global surface and local elements to achieve standardization and planarization.

TOP-DOWN

On the simplest level, this can be done by opting for specific surface classes that permits the population of standardized and/ or planar elements (e.g. developable surfaces or translational surfaces). Another common approach

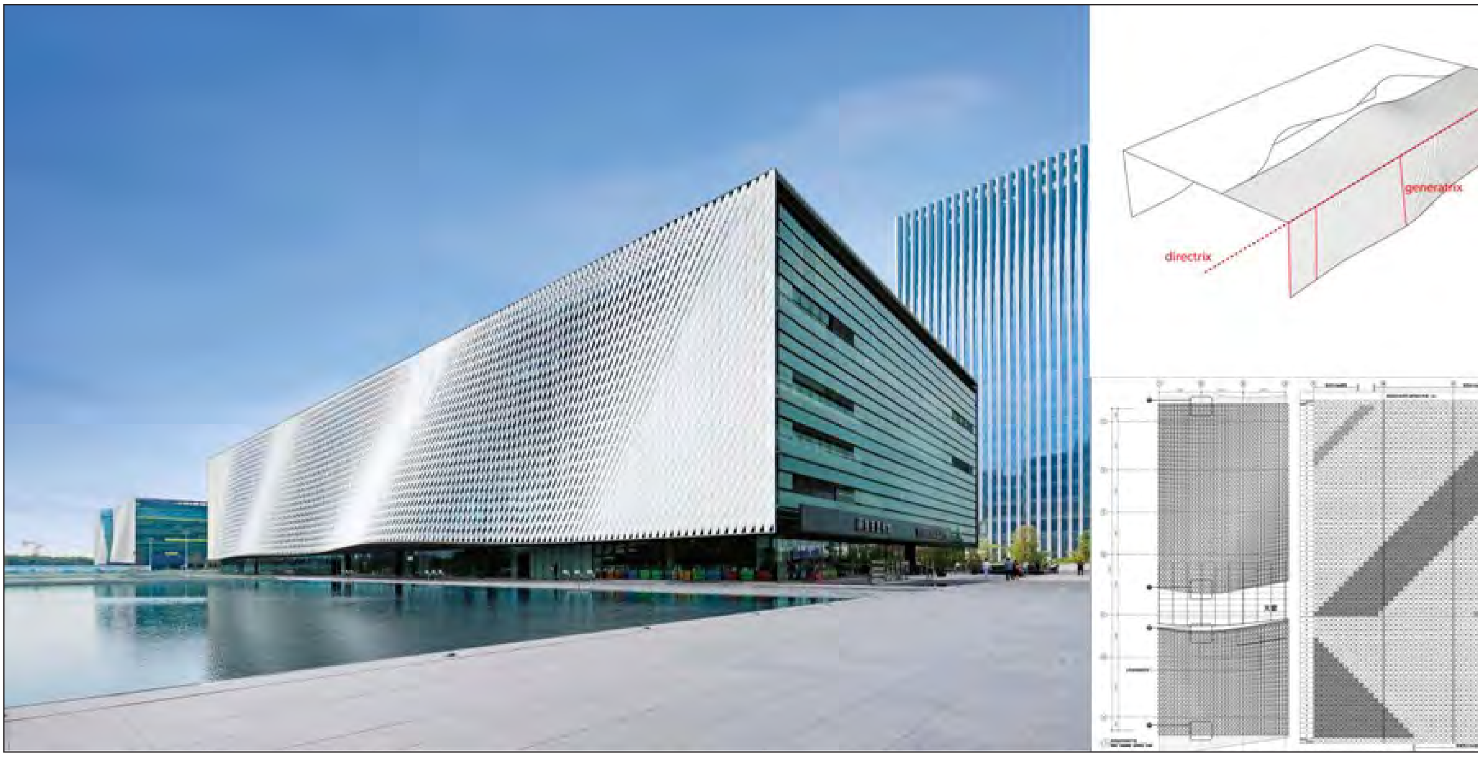


Figure 1. The Library at the Bao'An Cultural Centre in Shenzhen, China. Graphics courtesy of Rocco Design Architects Associates Ltd.

to achieve standardization and planarization is through iterative form-finding on the global geometry level, with the objective of iterative form-finding is to arrive, as closely as possible, certain mesh or surface classes that allows the global geometry to be discretized into local planar quad elements. A well-documented example of such operation is aligning a given quad mesh to some versions of a conjugate curve network, from which a Planar Quadrilateral (PQ) mesh may emerge.[3]

The external sun-shading system of the Library at the Bao'An Cultural Centre in Shenzhen, China (see Figure 1) is one such example where a top-down approach is adopted. The façade of the building features an undulating sun-shading system that 'billows' in and out of the elevation plane.

The designer opted for ruled surfaces as design surfaces because they curve only in one conjugate direction. As such, it was possible to align structural members (mullions in this case) along the direction of the straight generatrix, at a fixed spacing along the straight directrix. The generatrix, which rotated to form the surface curvature, was forced onto a plane that was perpendicular to the direction of the straight directrix (see Figure 1). More specifically, in order to control how far the façade bulges out, the second directrix of the ruled surface was formed by connecting line-arc segments.

Through controlling the chord length of the line-arc segments the bulging distance was established. It is interesting to note that the distance between each façade component along a mullion could be obtained from simply dividing the length of the mullion into equal parts. In other words, a simple two dimensional grid could be intuitively applied by the contractor. The design team used this as the basis to derive identification numbers, orientation, and geometry descriptions for the structural members as well as the diagonal sun-shading fins of the system. These pieces of information were compiled into a Geometry Method Statement (GMS) that allows the future contractor to define and set out the geometry for fabrication and site installation purposes. The GMS formed part of the design documentation.

BOTTOM-UP

Another way to arrive at a desired set of standardized, planar local elements is by instantiation based on the parameters (e.g., corner coordinates, centroid, normal direction etc.) of the curved local elements discretized from the global geometry. A popular example of this approach is fitting three vertices of a quad panel on a curved surface and allowing its fourth vertex to deviate from the global geometry. The objective of this approach would be to aggregate planar local elements to approximate the global geometry. The global geometry itself is not subject to significant adjustments with respect to standardization and planarization.

An example of the application of three-point planar quad fitting is this curved glass wall of a convention centre (see Figure 2) which, like the Library at the Bao'An Cultural Centre, also comprises of ruled surfaces.

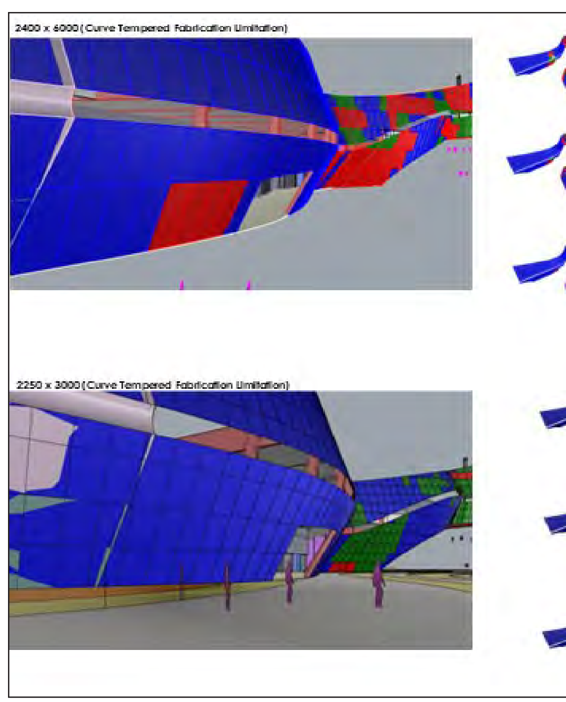
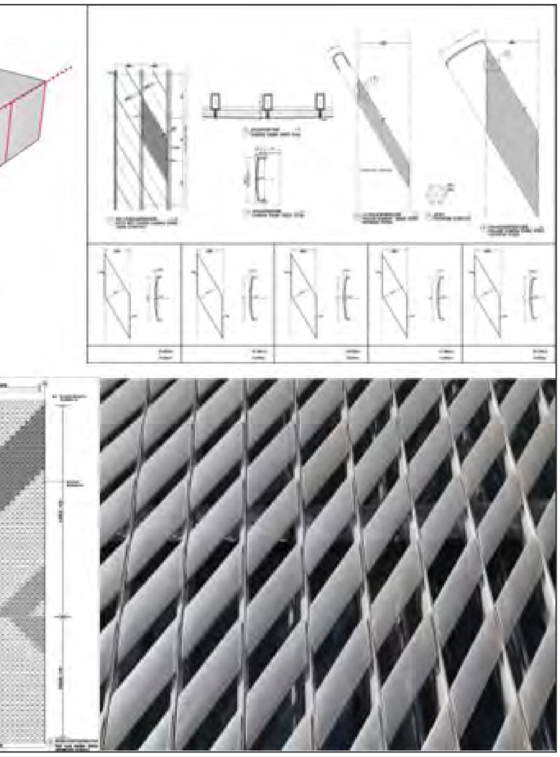


Figure 2.



However, while the Library used small metal fins fixed to parallel and equidistant mullions to form a decidedly textured appearance, the convention centre favoured a smooth appearance using planar or curved glass panels of larger modulations.

The design team also wished to minimize the number of glass panels using laminated insulated glass units (IGUs) that curve in two directions, which are fabricated using the curve annealed process (i.e., curving by slumping annealed glass into a mould under high temperature). That was because the technical complexities involved with curve annealing would have led to significant cost and time implications. (Curved annealed glass panels cannot be tempered using conventional methods. Thicker annealed glass would have to be used in lieu of thinner tempered glass in order to compensate for the reduction in glass strength. Low-e coating options for heat-formed glass are limited, with restrictions on which surface the coating can be applied on; mould customization can be costly, so is offline fabrication of large, curved, and laminated IGUs.) The optimization procedures for the system were as follows:

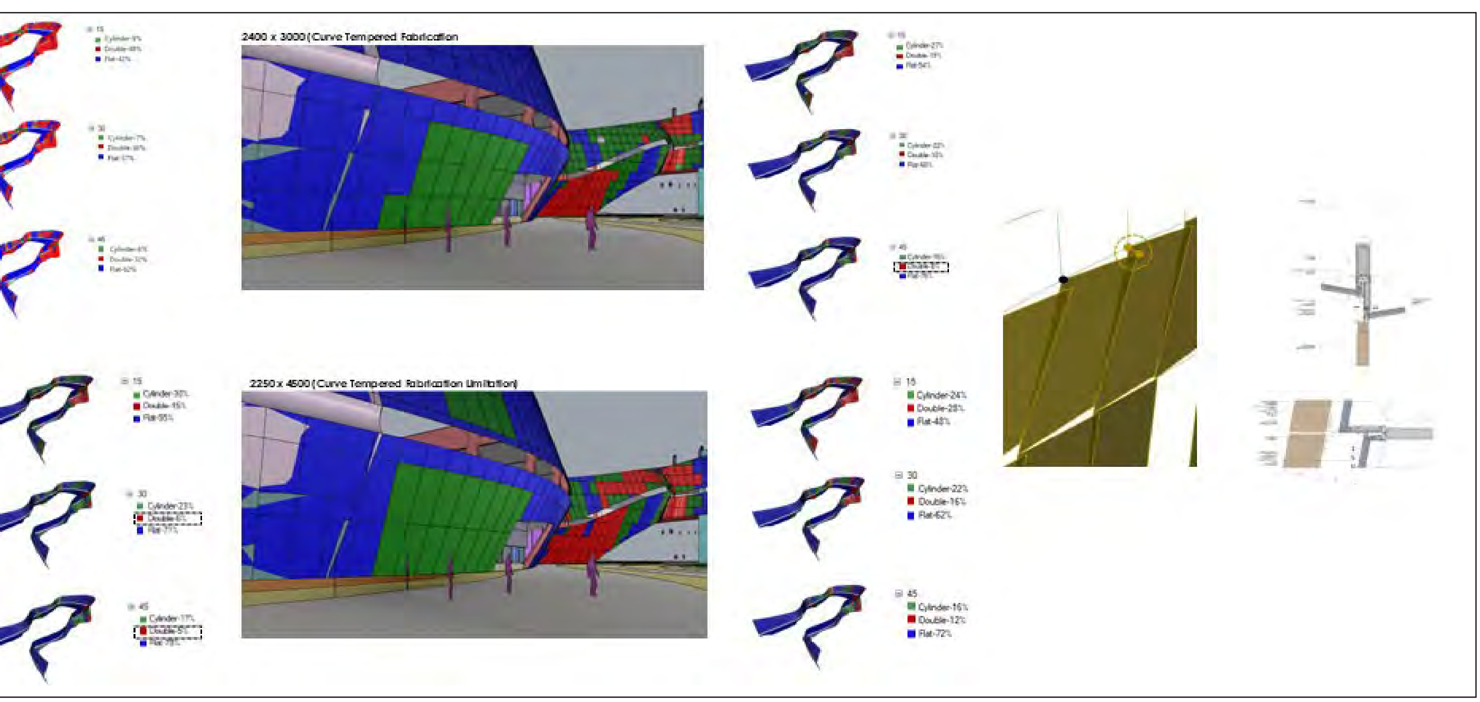
- Fitting planar glass panels of a suitable dimension to not compromise visibility due to glass division, while limiting how far the fourth vertex of the planar quad deviated from the reference surface.
- If the deviation was greater than a pre-set threshold, glass panels extracted from cylindrical surfaces of appropriate radii would be fitted to the surface instead to reduce the panel's deviation from the reference surface. Since the fabrication of glass panels curving in one direction using curve-tempering technology (i.e., heating, curving and rapidly cooling the glass to produce curved tempered glass, through a machine that can accommodate customized curves) is relatively cost-effective compared to curve annealing, it was adopted as an intermediate strategy before resorting to using curve-annealed, 'doubly-curved' glass panels.
- Curve-annealed, 'doubly-curved' laminated IGUs would only be used when planar and cylindrical panels would not fit without deviating from the pre-set thresholds.

An automated system was set up using the logic above to rapidly produce multiple options with different deviation thresholds, glass modulations and glass build-up during early design stages.

This was proven to be a valuable exercise, as the information generated from the automated exercise could be passed on to the cost consultant for real-time estimation. All stakeholders in the team were able to make informed design decisions using actionable information.

BI-DIRECTIONAL

Apart from top-down and bottom-up, it is also possible to take a bi-directional approach – while planar elements are being fitted locally on the global geometry, the global geometry itself undergoes a series of iterative adjustments using a proprietary physics engine[4] based on quantifiable optimization objectives to facilitate discretization.



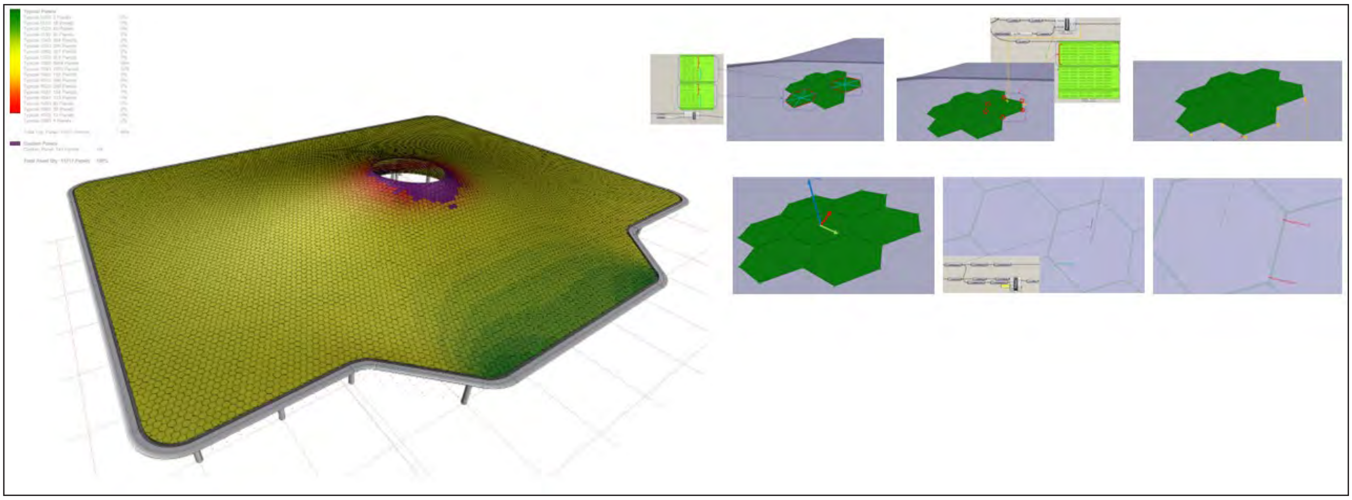


Figure 3.

An example of the application of this methodology is this airport project in Southeast Asia (see Figure 3). The reference surface generated by the designer is rectangular at the base and rises to an oculus at the centre. The architect intended to clad the roof with decorative hexagonal aluminium panels.

The objectives of the exercise, therefore, were threefold:

1. From global to local: to modify the reference surface to facilitate the instantiation of standardized hexagonal elements.
2. From local to global: to perform fitting using a pre-determined number of sets of standard hexagonal elements.
3. To assess the acceptable number of panel dimension types based on degree of deviation from reference surface.

After tidying up the reference surface provided by the designer into a base hexagonal mesh comprising of local hexagonal elements of wildly different dimensions, a physics simulation engine was used to introduce weighted force objects over the base hexagonal mesh as a spring system.

The following force objects have been introduced in the system for iterative optimization (see Figure 3):

- Equalizer: to reduce the dimensional variations among the local hexagonal elements and thereby maximize the possibility of fitting standard hexagonal elements on the surface within the prescribed tolerance.
- Planarity: to maximize the possibility of fitting planar hexagonal elements Hp in the subsequent step. If planarity cannot be achieved, panels of standard dimensions are assumed to be folded in the subsequent panel-fitting stage.
- Gravity: This force object pushes all vertices across the mesh towards the reference surface, which helped ensure that the mesh resulted from the iterative optimization would resemble the reference surface.

These force objects were plugged into a proprietary solver, which iteratively negotiated and simulated these opposing influences across the global mesh to look for equilibrium. The number of iterations required to reach equilibrium was very much a process of trial and error – in this case the results after 20,000 iterations were used for the subsequent step.

The local hexagonal elements on the output hexagonal mesh are neither standardized nor planar yet – having gone through all the pushing and pulling in the iterative process the local hexagonal elements have merely got closer, to varying degrees, to being standardized and being planarized. Using that mesh as the basis and using deviation from reference surface and joint width as fitting criteria, a set of standard-sized, flat equilateral hexagon panels were fitted at the centroid of each local hexagonal element.

The methodology described above was applied on all four surfaces concerned in the project, each with slightly adjusted parameters to suit the size, curvature, and architectural constraints of each of these global surfaces. The results above have demonstrated that the approach was highly effective (see Figure 3) – taking one of the roof surfaces as an example, 98.8 per cent of the 13,717 hexagonal panels on the surface ended up falling into 19 panel types; only 146 panels had to be customized due to architectural openings and other atypical conditions.

CONCLUSION

This article has described the three methodologies for discretizing free-form architectural surfaces for panelization: top-down, bottom-up, and bi-directional. The choice of methodology to adopt, as the case studies above have shown, varies depending on the building geometry, material selection, design intent and performance objectives. It is therefore advisable for the team to set up parametric systems that can automate multiple options early in the design stage to allow stakeholders to review, assess, and make informed design decisions based on actionable information. ■

CK Dickson Wong is a Senior Associate, and Ho Sung Kim is an Computation Design Lead for Inhabit Group.

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