The Geometrical Processing of the Free-formed Envelopes for The Esplanade Theatres in Singapore

JAIME SANCHEZ-ALVAREZ, MERO GmbH & Co. KG, D-97064 Würzburg, Germany

INTRODUCTION

Geometry can be used as an abstract tool to describe and represent the form and the structure of physical objects, such as the supporting and cladding systems of architectural envelopes and engineering structures. In the computer based context of building design, elements of Geometry, such as points, lines and surfaces assume the tangible nature of a physical tool and they lend the designer means to draw and generate virtual models of an object for the various tasks leading to its materialization. For instance, the geometrical model containing the metric and topological properties of a structure or a cladding system provides the system's description for structural analysis and also the basis for construction detailing and fabrication.
Due to their unconventional free-form and their complex constitution and size, the two dome-like envelopes designed by the Singaporean office DP-Architects for the new centre for the performing arts at the place called The Esplanade in Singapore constitute an excellent example to highlight the instrumental role of Geometry in the technical processing of complex building envelopes. Figure 1 gives an impression of The Esplanade Theatres.

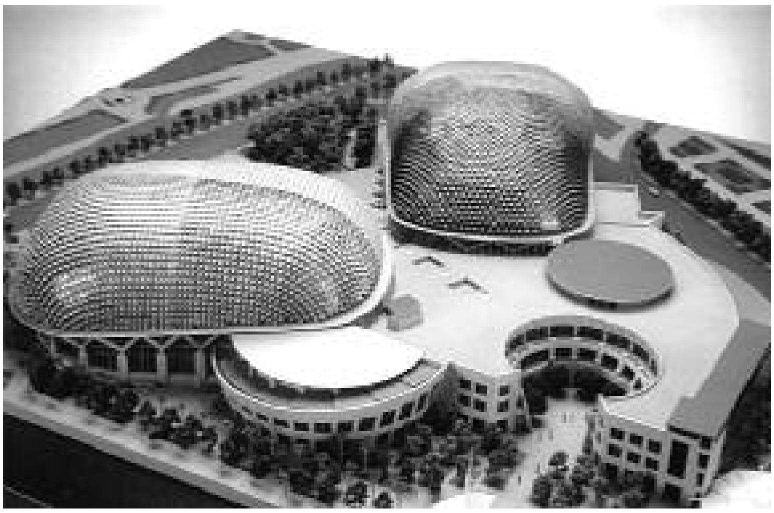


Figure 1. Left: Physical model of The Esplanade Theatres, with the Concert Hall on the left and the Lyric Theatre on the right-hand side.
Right: Interior rendering of Concert Hall's Foyer (photos courtesy of DP-Architects)

The overall dimensions of these domes are, for the Concert Hall: length, 93 m; width, 59 m; height respective inclined base edge, 26 m and for the Lyric Theatre: length, 102 m; width, 61 m; height respective inclined base edge, 24 m.

THE BASIC NURBS-SURFACES

The global geometric shape of both theatres envelopes falls into the category known as "NURBS"-surfaces, where NURBS stands for "Non Uniform Rational B-Splines". NURBS-Surfaces represent an advanced state of the numerical techniques, which have been developed for the description of free-form surfaces in the computer-based design of ship hulls, car bodies and aircraft fuselages. NURBS-surfaces cannot in general be defined by the classical formulae of analytical and vector geometry and this substantially complicates their construction processing. As in the design of a car body, the development of the NURBS-surfaces for The Esplanade has not been a simple modelling procedure within a CAD program, but the final forms of the domes have been the outcome of a relatively long process of shape improvement. The London-based design office Atelier One was appointed to work on refining and modelling accurately the envelopes that the architects had conceived to house the core activities of both theatres at The Esplanade. Aiming always to satisfy formal and aesthetical aspects, the domes had to be tightly shaped around the boxes of the theatres to keep the surface to a minimum. The envelopes had to fulfil also structural, natural lighting and sun protection requirements.

Modelling the surfaces involved setting up a framework of splines, which are a class of free-form curves, and then generate free-form surface areas known as "Coons patches" within every four-edged region in the framework. The final form of a NURBS-surface was achieved by literally pulling around its “weights” and “control points”, which are in turn virtual devices to modify interactively the shape of the surface in a CAD system, until the final form fulfilled the design requirements. Once a surface was defined, it was possible to develop on it a regular network with a constant mesh length of 1.5 m. This grid was geometrically constructed using a “virtual compass” to draw the mesh on the NURBS-surface. Figure 2 presents the two CAD models given to MERO (the specialized sub-contractor for the structure and the cladding) as raw material defining the geometric shape and the basic structure of The Esplanade’s grid-shells. It must be pointed out that the mesh lines in these grids are not curves but straight-line segments which could be readily used to represent straight structural members.

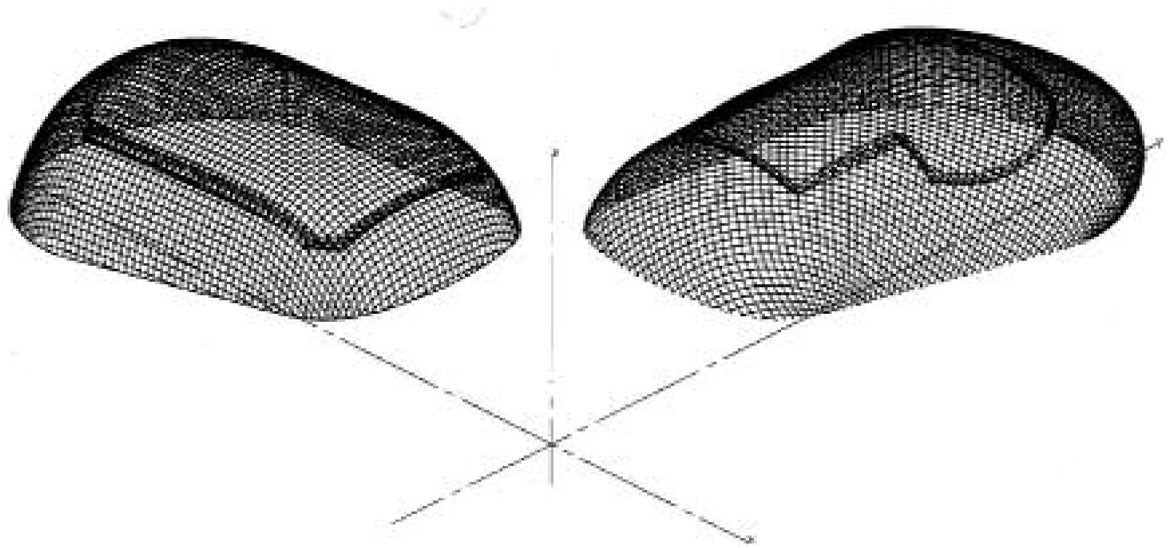


Figure 2. Initial basic rhombic grids for the Concert Hall (left) and the Lyric Theatre (right)

For the sake of abbreviation, these basic networks will be referred to as basic rhombic grids. A basic difference between the rhombic grids of the two shells is the orientation of their meshes. In the Concert Hall the main polygons run either along or across the base edge of the shell, whereas in the Lyric Theatre these polygons run diagonally to the base line.

THE SPACE TRUSS

Preliminary feasibility studies favoured the selection of a double-layered space truss against a single-layered grid structure, as represented by the basic rhombic grids. The chosen combination of external and internal grids corresponds topologically to the so-called square-on-diagonal double-layered grid. This type of geometrical arrangement is often used when the more common square-on-square layout turns to be too dense and larger transparency of the structure is required. In the space trusses for The Esplanade, the regular geometry of the square-on-diagonal grid has been distorted or transformed to fit the basic free-form surfaces. Thus, the external grid matches the lines of the basic rhombic grid and the nodal points of the internal diagonal grid lie at a constant distance of 90 cm inside the external grid. The principle used to determine the nodal points of the internal grid was the so-called dual- or reciprocal-net method. Here, if the midpoints of neighbouring meshes of a network are connected with lines, the resulting network is the reciprocal or dual of the initial net. The procedure in the MERO-software (Geometry program KONDAR, Ref. 2) has been implemented in such a way, that the new points of the dual grid can be located at a given distance of the initial grid and the inter-layer diagonals connecting a new point with the corresponding vertices of the source face are also generated. It must be noted, that in the case of the square-on-diagonal grid, not all the meshes of the initial grid have been used for generation of the dual-net, but a subset of faces arranged in a chessboard layout. Figure 3 shows the transition from the single-layered rhombic grid to the square-on-diagonal space truss in a portion of the basic grid for Lyric Theatre. The figure also shows the polyhedral components of the structure and the introduction of additional lines turning the external rhombic grid into a triangulated one, which provided the required continuous edge support for the triangular glass panes.

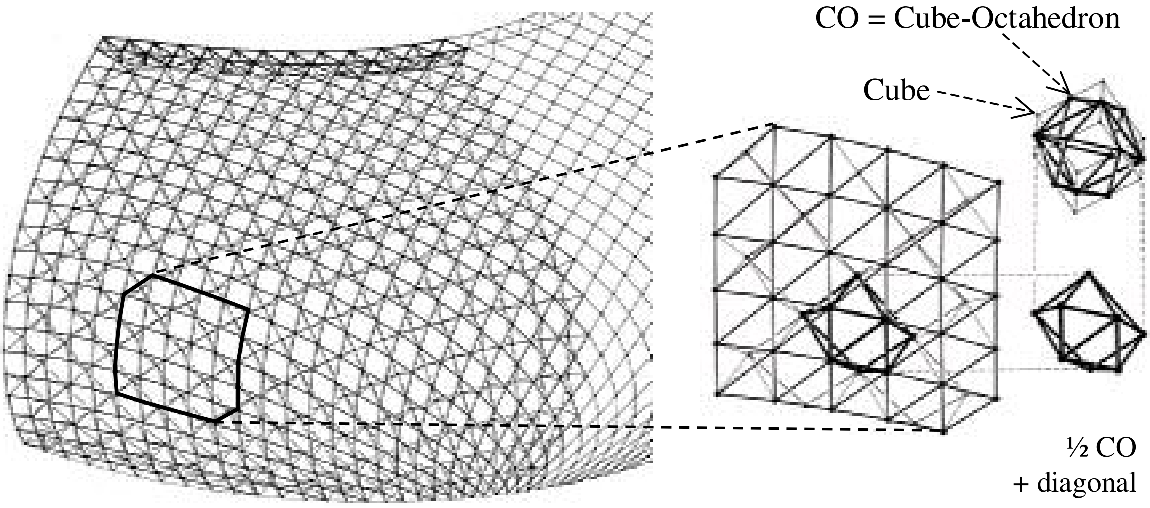
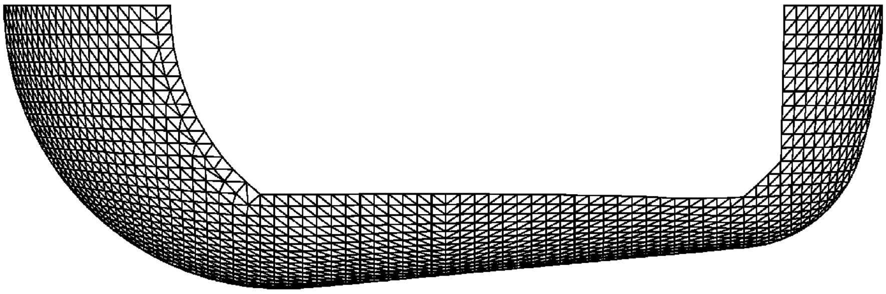
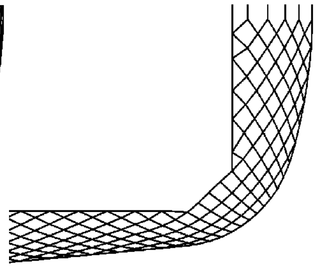


Figure 3. Square-on-diagonal double-layered grid and its polyhedral components.

Figures 4 and 5 illustrate the final state of a series of improvement cycles for the geometry of the space trusses for both envelopes. It most be noted, that the upper and base edge regions had to be locally corrected to follow certain forming principles given by the designers. This correction was performed with the aid of user-written procedures or macro-commands, which systematized the modifications in a consistent and time effective way, minimizing also the risk of what may be called “interactive” mistakes.



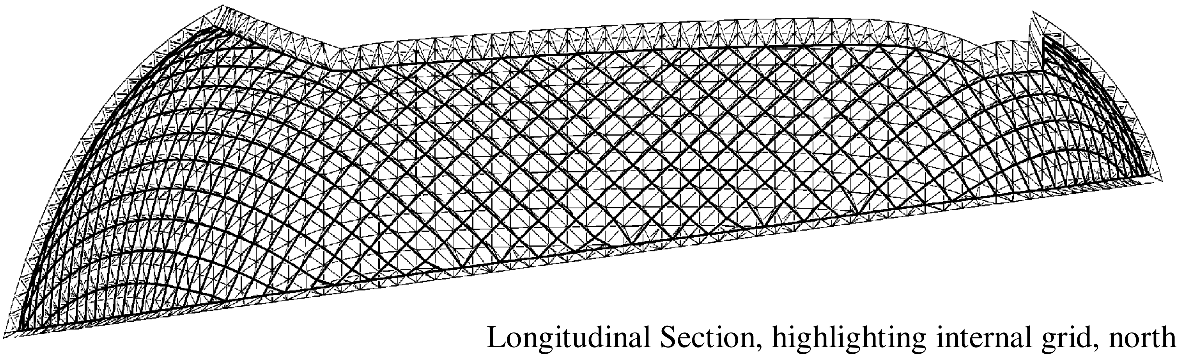


External grid, ½-Plan

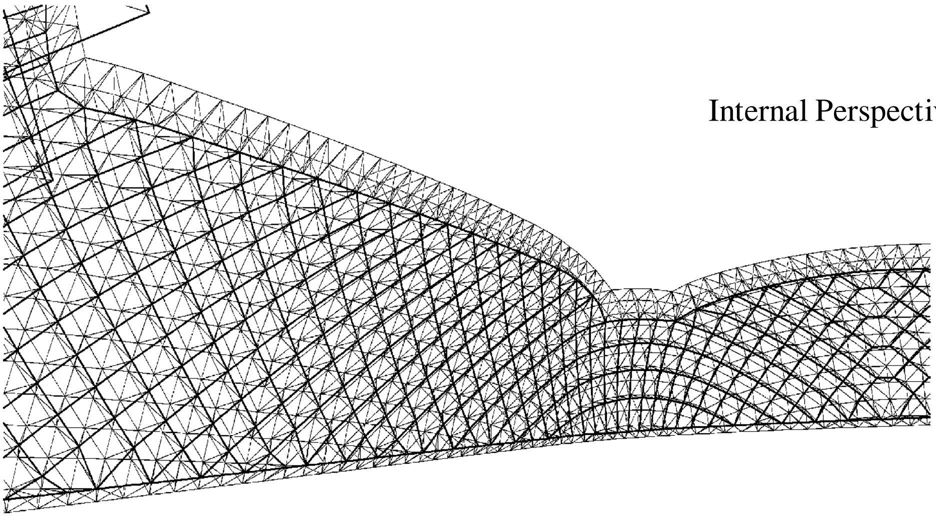
Internal grid, portion

West

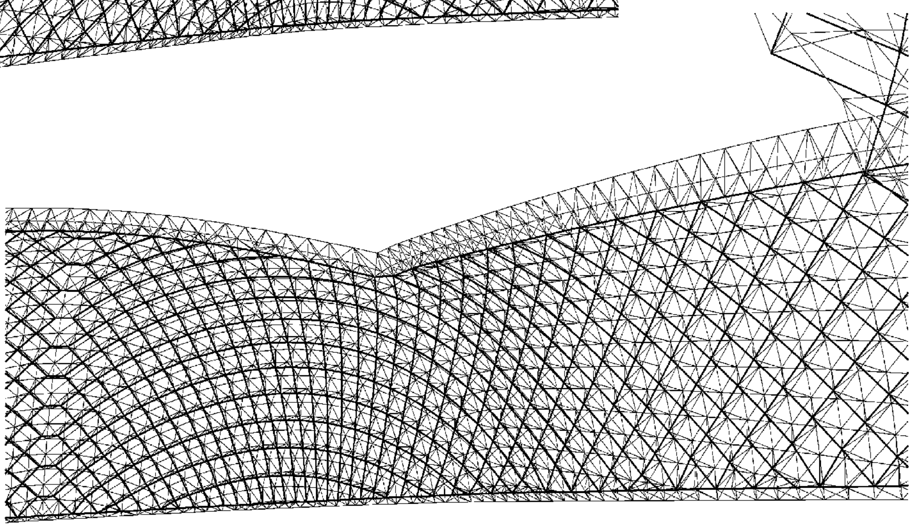
East



Longitudinal Section, highlighting internal grid, north

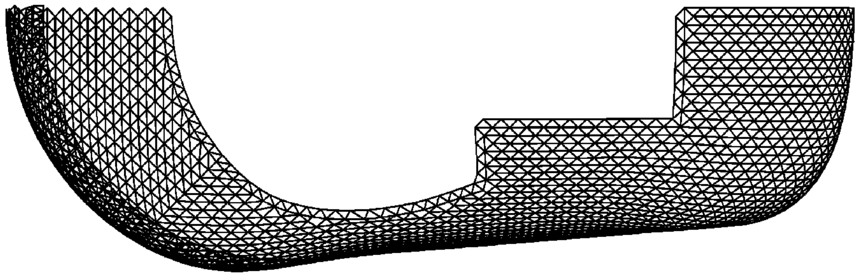


Internal Perspective, viewing northeast

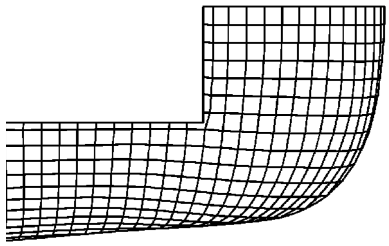


Internal Perspective,
viewing northwest

Figure 4. Concert Hall, space truss geometry.



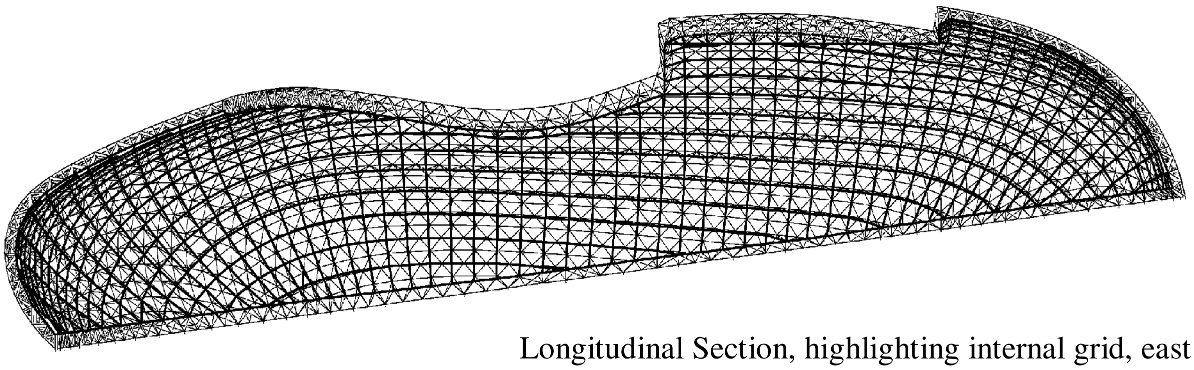
External grid, ½-Plan



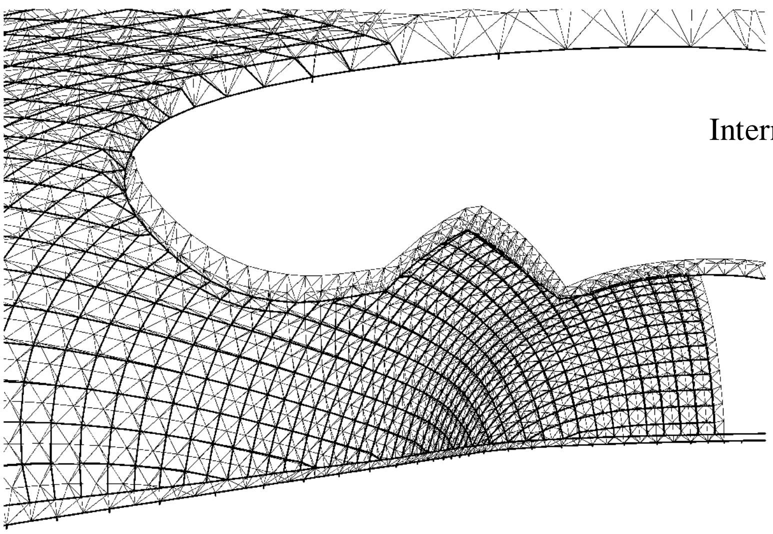
Internal grid, portion

North

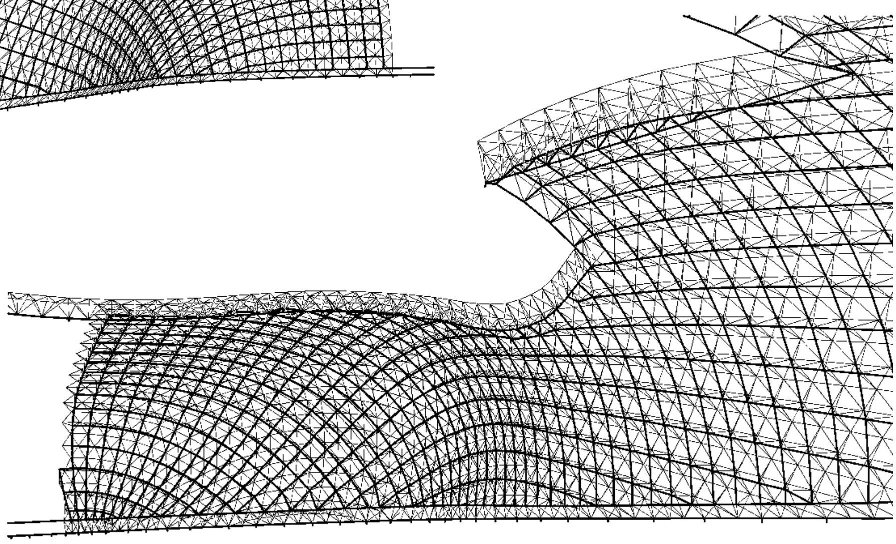
South



Longitudinal Section, highlighting internal grid, east



Internal Perspective, viewing southeast



Internal Perspective, viewing northeast

Figure 5. Lyric Theatre, space truss geometry.

STRUCTURING THE GEOMETRIC MODEL

The bulk of elements bound to form both structural models of the domes at The Esplanade and the complex space interrelations among the components demanded from the very beginning a structured modelling approach. To have an idea of quantities, the space truss for the Concert Hall ended up with 3671 points and 14180 line elements, while the Lyric Theatre amounted to 4710 points and 18232 lines. Also, when the geometric model of a structure is created to transcend the modelling environment, it is very important that the model is organised having its further usages in mind. Thus, every model of The Esplanade was broken down in sub-groups of elements likely to be treated in the same manner or having common initial attributes.

The use of colour and point markers

In the geometry program KONDAR (Ref. 2), colour and point markers provided means to organise the models in sub-groups of elements, which were thus easier to handle. Here, every sub-group of points, lines and faces was given a different colour, which could in turn be addressed by a colour number. Point markers, which are graphical symbols used to make points visible on a computer screen, were employed in the same way to organise these elements in further groups with corresponding marker identifiers. The marker number was integrated within the colour number of a point, thus creating the possibility of assigning the element to two different groups, for instance the external grid and also a certain wind pressure zone on this grid, as Figure 6 suggests. The elements sub-groups constituted the basis to organise not only the model itself, but structural analysis, construction detailing, fabrication, packing, transportation and installation of the construction elements.

Additional geometric information

Structure, glazing and sunshades constitute an integral envelope system in The Esplanade's domes. The three-dimensional models of the structures were extended with additional line elements that were primarily used to place and orient the non-symmetrical structural components in the global coordinate system of the complex. In addition, these auxiliary lines were employed to relate the cladding components and their fixtures to the structure. These kind of additional entities are usually grouped in two sets, namely, the set of "local coordinate systems", which are related to the structural members, and the set of "normal-to-the-surface vectors", which correspond to the nodal points of a given grid. Figure 7 illustrates the way in which normal vectors were attached to the nodes and local systems at the midpoints of the line elements on an area of the external structural grid for the Lyric Theatre.

In the grid-shells of The Esplanade, the integration of the glazing edge support in the external rhombic grid of the space truss made necessary the introduction of a third family of lines dividing every rhombus of the grid in two triangles. The exact geometry definition for the triangular glazing panes was obtained with the aid of the normal vectors on the external grid of the structure. These were used to make a copy of the external grid at the level "base of glass panes" by displacing the system's nodes outwards, along the normal vectors, by a distance determined at the construction detailing. The MERO-software has special functions that can automatically generate faces or panels, local coordinate systems and normal vectors on a given network and the latter can be used to copy and "explode" a grid in a prescribed way. Incidentally, the Concert Hall and the Lyric Theatre have 4599 and 5913 glass panes, respectively, amounting to a total surface of 10731 m^2.

The application of grouping by colour and the practical value of additional geometric elements are further dealt with in the paper "The Envelopes of the Arts Centre in Singapore" in the proceedings of this conference, see Ref. 3.

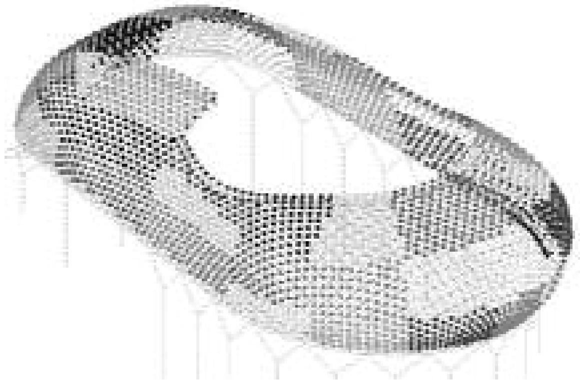


Figure 6. Lyric Theatre, point colouring and point markers defining wind pressure zones (here in grey tones)

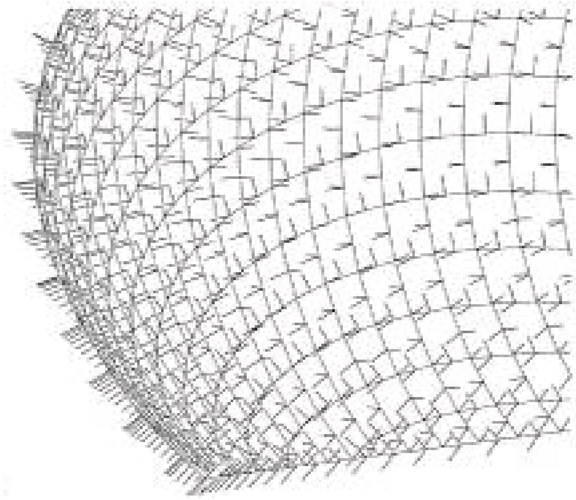


Figure 7. Lyric Theatre, portion of external grid showing normal vectors at nodal points and local systems at lines midpoints.

THE SUNSHADES ENVELOPES

The tiled skins of the theatres envelopes, composed of thousands of aluminium sunshade pyramids, constitute one of the most distinctive design features of The Esplanade Art Centre. For the purpose of geometrically modelling these cladding hulls, it was essential to identify the minimal component and its parameters. An individual sunshade element was reduced to a rhombus, folded (in general) about its shorter diagonal to form a triangular pyramid with two empty faces. One of these faces is the base lying on the glazing grid and the other empty face is the opening to let light in. The fold in the middle of the rhombus can be seen as a hinge, which allowed fitting the same element on base rhombic meshes of various widths, while keeping the constant edge length of 1.5 m. The idea behind this was to realize a smoothly changing cladding surface, with elements rising and opening, falling and closing, using a minimum number of different element types. Except for the special edge elements, the two domes required finally not more than twenty five different rhombic cutting patterns. The folding angle constituted a further criterion to create sub-types of sunshades at the subsequent construction detailing.

The distribution and orientation of sunshade elements on one symmetric half of every grid-shell was provided in the form of a spreadsheet, which was organized as a map of the real grid. Each cell of the table represented a mesh of the basic rhombic grid and it contained the value of the corner angle of the rhombus in flattened form, which was chosen to define the type of sunshade. The remaining task was then to translate the spreadsheet into a geometric model. It should be noted, that construction detailing required the generation of the basic rhombic grid carrying the base points of the sunshades 30 cm outside the structure's external grid and that was obtained with the use of the formerly explained normal-vectors technique.

Special attention has to be drawn again to user programming within the context of a general Geometry or CAD program. Initially, the actual geometric construction of the individual sunshades was systematized in the form of macro-commands in the Geometry-program KONDAR (Ref. 2) and these performed rather well from the very beginning. The main procedure required as input data only the typical angle of the sunshade and the ordered sequence of the three points on the carrying grid defining the position and orientation of the sunshade. Figure 8 gives an idea of the compact listing of this procedure together with a sketch of the geometric construction parameters. Figure 9 shows, in turn, a few sunshades placed in position on the carrying grid and Figure 10 some special edge situations. The initial interactive input for a large set of sunshades, however, proved to be time consuming, tedious and prone to errors. To wit, some 1650 sunshade elements had to be generated and placed on the global rhombic grid for a half of the Concert Hall and 1920 for a half of the Lyric Theatre.

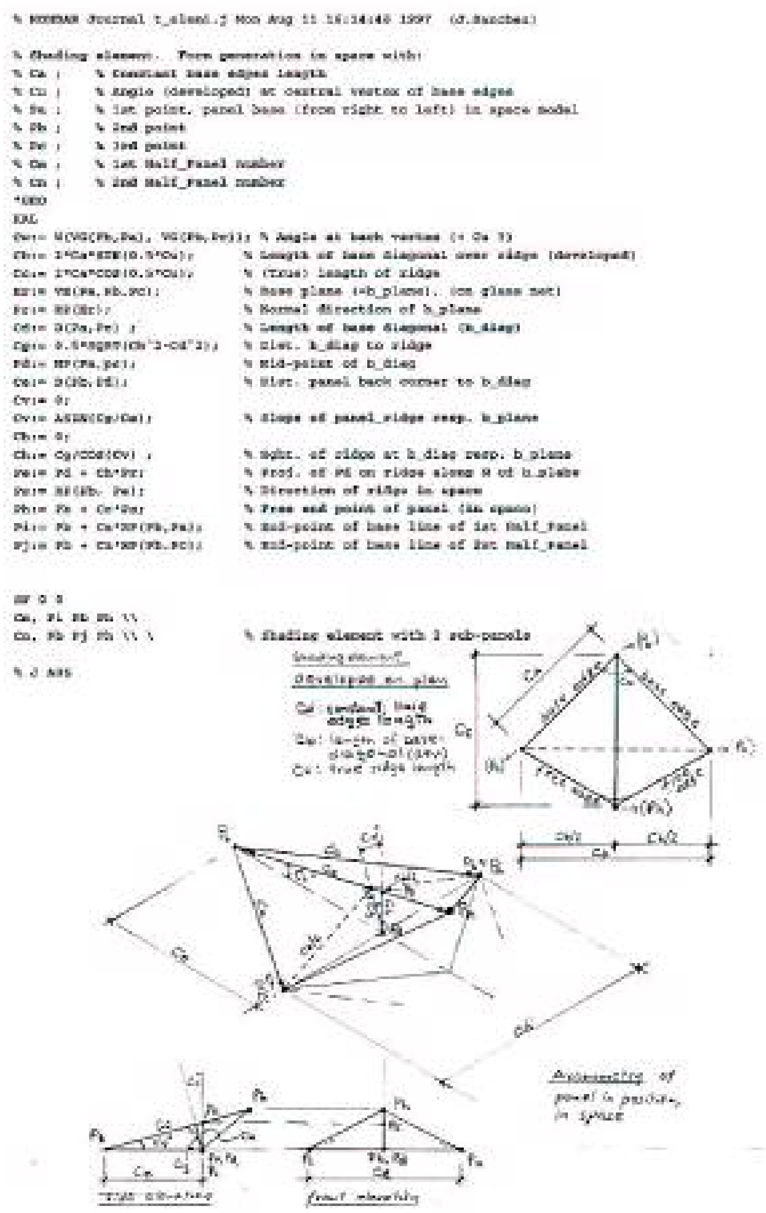


Figure 8. Basic construction macro-command for a typical sunshade element.

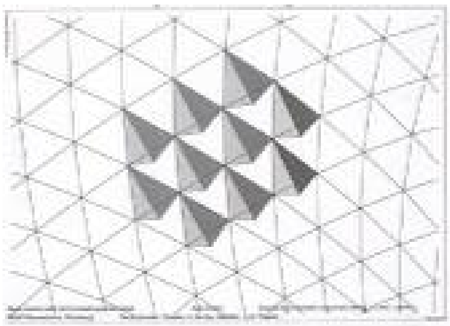


Figure 9. One run of the construction macro-command positions one individual sunshade element on the external grid

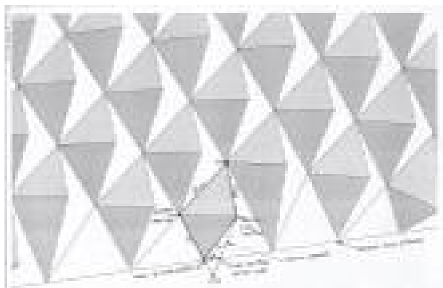


Figure 10. Special situations at the edges required special construction procedures.

After the initial modelling experience and with an undefined number of optimisation revisions in view, a considerable effort was dedicated to plan a generation strategy aiming at the substantial simplification, reduction and automated generation of input data. The effort was worth of it, because the final form of the sunshades envelope for the Concert Hall went through four modelling-assessment-correction cycles and the Lyric Theatre required six.

Figure 11 shows the essence of the exercise of smoothly “profiling” the sunshades envelopes with various sunshade types.

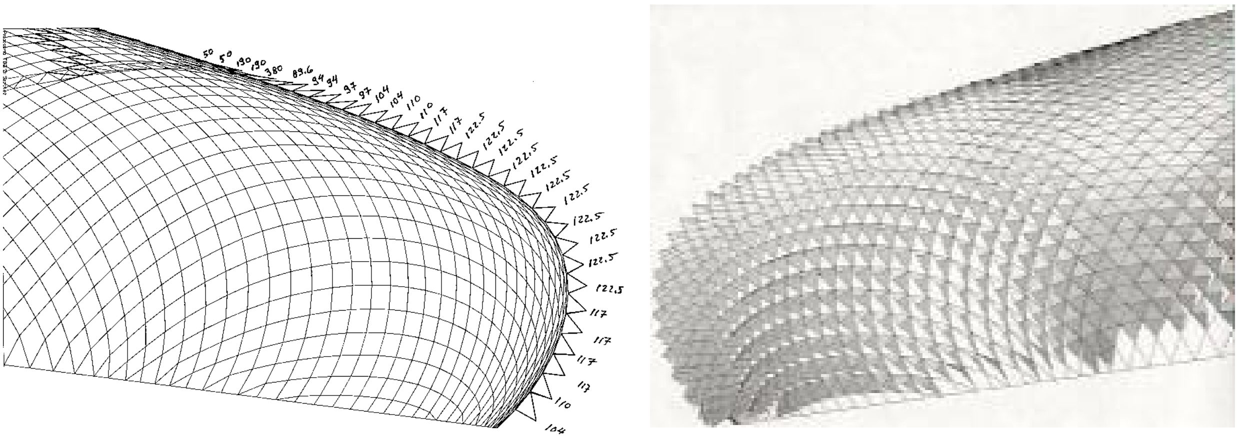


Figure 11. “Profiling” the sunshades envelope for the Lyric Theatre

The first device towards rationalizing the input was to colour the carrying rhombic grid according to the sunshades distribution specified by the corresponding spreadsheet, where a colour represented a sunshade type. The idea was to move from the table full of numbers to a geometric model containing the distribution of elements and the basic metrics of the envelopes. Next, a list of rhombic facets was automatically derived from this coloured model, where every line of the list had the rhombus number followed by the four point numbers locating the face on the rhombic grid and the colour number identifying the type of sunshade. A complementary list of numbered node coordinates defined the actual metric properties of the coloured rhombic grid. A further program read this list to generate in turn the next table with the input for the actual geometric construction macro-command. In this last list, every line contains the ordered sequence of three point numbers defining the base of a sunshade and the “call” for the construction macro-command. This list was practically used as a macro-command itself, which generated a set of oriented sunshades of the same type. Finally, the sunshades sub-groups were added together via a higher-level KONDAR-procedure, which gave rise to the complete sunshades model. Figure 12 shows renderings of the final sunshades models for the Concert Hall and the Lyric Theatre and photographs of the real sunshade envelopes.

CONCLUDING REMARK

Geometry alone is not the answer to all the problems in the technical processing of engineering and architectural objects, but try to find an area where Geometry does not play an underlying essential role.

REFERENCES

1. GORE V , www.vikas-gore.com, website in Internet for architectural design aspects.

2. EMDE H., Dialog-Handbuch zum Programmsystem KONDAR 2.0, Technical University Darmstadt, Germany, 1990-92

3. KLIMKE H, SANCHEZ J, VASILIU M, STÜHLER W, KASPAR C, The Envelopes of the Arts Centre in Singapore, Proceedings of the 5th International Conference on Space Structures, Surrey, GB, August 2002.

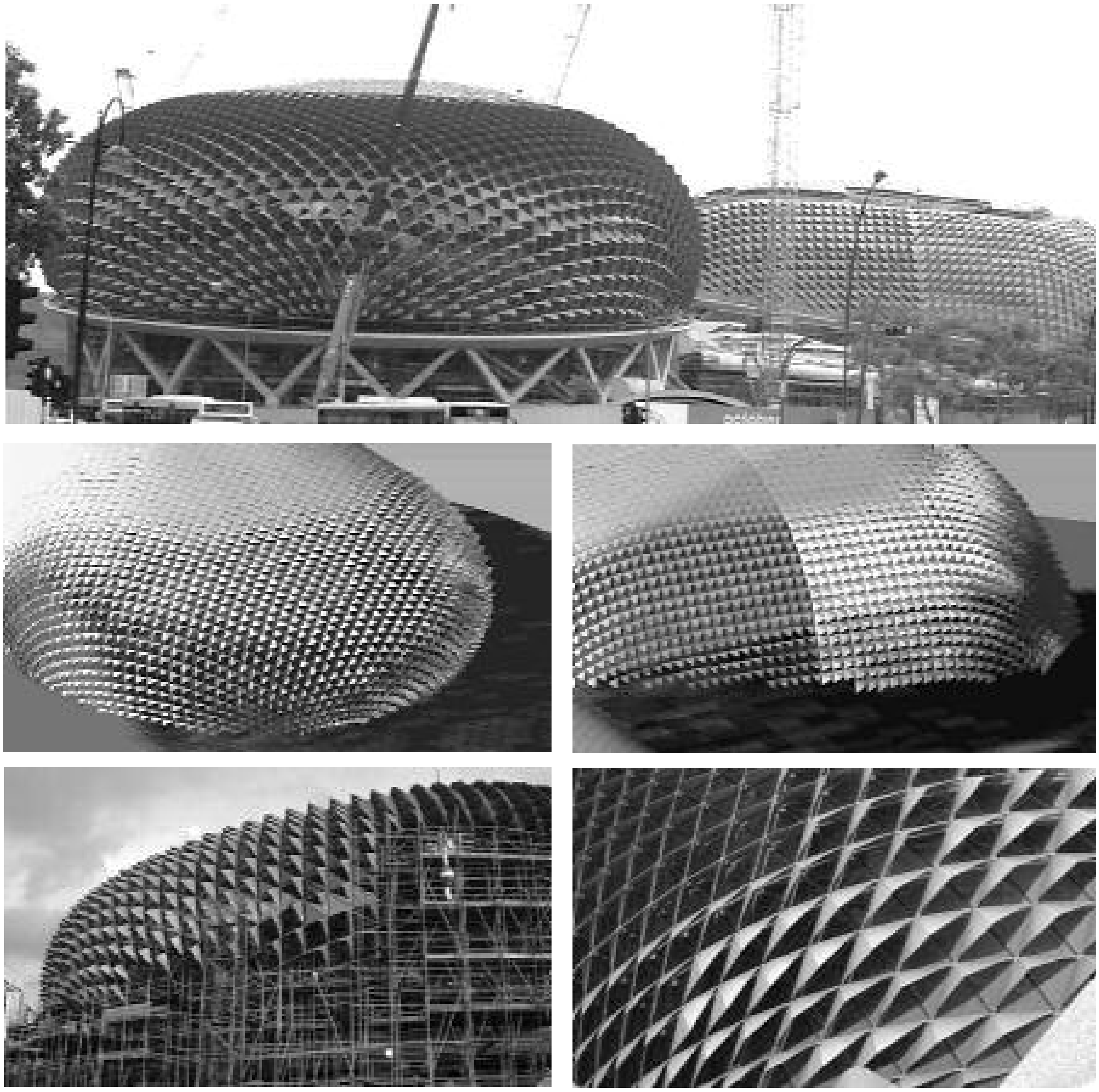


Figure 12. The sunshades envelopes of The Esplanade Theatres in Singapore.

PARTICIPANTS

Client:	**The Esplanade Company Ltd. Singapore**
Architect:	DP Architects Pte. Ltd., Singapore
General Contractor:	Penta-Ocean Construction Co. Ltd., Singapore
Project Manager:	Public Works Department (PWD), Ministry of National Development; Arts Centre Development Division (ACDD), Singapore
Cladding Consultant:	Atelier One, London / U.K.
Cladding Contractor:	MERO GmbH & Co. KG, Würzburg and MERO Asia Pacific Pte. Ltd., Singapore