Two Case-Studies of Freeform-Facade Rationalization

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Abstract. This paper will demonstrate two effective facade rationalisation patterns developed at Gehry Technologies for mitigating the tradeoffs between project constructability constraints vs. project aesthetic constraints. The two Case-Studies will present, firstly a method for dealing with large amounts of component instantiations and second with the economical delivery of complex project geometry through panelling. Both projects use design technology as a strategy for the integration of specialized knowledge and trades, through an effective use of information technology. The Case Studies will present the development of the Gridshell Digital Mock-Up of the Yas Island Marina Hotel in Abu Dhabi designed by Asymptote Architects and secondly the Museo Soumaya facade system in Mexico City designed by Fernando Romero LAR. This document will report the development process for obtaining relevant construction information, essential for the assembly of the facade systems by a third-party sub-contractor in support of the facade system coordination. The report concludes on the implementations of bespoke tools in support of the coordination and geometry description tasks. The tailored tool making process extends the parametric modelling system Digital Project™ in the design support role of obtaining aesthetically pleasing decompositions of the buildings Master Design Surface MDS into feasible constructible components

Keywords. Facade Rationalization; Integration; Parametric Design; K-means Clustering.

INTRODUCTION
This paper will outline the outcomes of two projects where the use of digital design technology as an integration device allowed the coordination of the projects for their successful delivery. The first case study will show the outcomes of the delivery process for the Yas island Marina hotel Grid Shell Assembly, this project will address how the use of digital mock-ups and their compulsory automation, support the decision-making phases at the intersection between the upstream tasks of designing for construction and the downstream tasks of analysing assemblability. The second case study will show the process of obtaining relevant construction documentation for the Museo Soumaya Facade Assembly this project will demonstrate by exemplification a successful mitigation of the tradeoffs between constructability and aesthetics, through the use of advanced methods for decision making support.

Both projects will show how through the appropriate use of Building Lifecycle Management Software in this case Digital Project™, a Catia™ V5 BLM solution tailored for the architecture industry,
architects can manage the coordination and integration task of delivering complex freeform facades while maintaining control over the quality of the overall outcome specially when projects require the involvement of various specialists with knowledge outside the domain of architecture. In both projects the BLM solution served as a platform for the centralization of repositories used for the integration of fabrication specifications for manufacturing and assembly constraints. The platform enhanced the synchronization of concurrent engineering practices and the consolidation of heterogeneous data among dispersed teams and disciplines during the modelling for fabrication process. Through the effective use of this platform both projects benefited from the advantages of a digital environment that fostered a tight integration of the design, fabrication and construction teams.

**BACKGROUND: RATIONALISATION**

As architectural projects become increasingly more complex, the original role of the architect as the sole author and integrator of all trades, is slowly being marginalised by the inability of the architect to cope with the complexities of a new way of practice, while not too long ago the architect contributed the majority of the information required to fabricate buildings, today this is certainly not the case, more and more architects are becoming integrators, consolidating the data from the silos of other trades involved in the delivery of complex projects. This increase of complexity in delivering a building is independent of the building geometry, a project with complex geometry, complicates further the already difficult task of delivering a building.

During the last 10 years we have seen an expanded use of new tools in proposing architectural outcomes, this plurality of new forms and methods of shaping comes as a result of a progressive integration of computation into the architectural practice, complex geometries have broadened through computation the domain of design expression (Dritsas, 2005). The new expressions of architectural outcomes are not compatible with our existing frameworks for executing and delivering projects, our institutions are outdated and our models of practice are becoming obsolete. An Attempt from the firm to rectify the misalignments between these two incompatible ways of working is through the use of a rationalisation strategy, a rationalisation strategy is a heuristic device used to reduce or simplify the complexity of fabrication in a particular aspect of the building, the most popular methods seen have been methods for panelising a large surface into smaller constructible components. The introduction of a rationalization strategy early in the planning for fabrication and assembly phases could potentially have a dramatic impact in reducing the increased cost and risks introduced with the use of unconventional geometry (Shelden, 2002).

Determining where to introduce the rationalisation strategy within the design process, is crucial in exploiting the use of this heuristic device. In the best-case scenario the rationalisation strategy is embedded from day-1 into the design logic (pre-rationalisation). Although not advantageous to all parties and the least optimal of all, a rationalisation strategy can potentially be introduced late in the design process allowing the appropriate handling or management of the design consequences of earlier decision making (Post-Rationalisation) and lastly parallel decisions affecting the rationalisation of form can be made alongside of the design process (Co-Rationalisation) (Fischer, 2007).

As exemplified by the Miran Galerie of dECOi Architects in the post-rational method geometry must be reconstructed through the use of a degenerative geometric transformation process, where the complexities of the design are abstracted into simpler fabrication constructions, in the Miran Galerie for example the geometry is reconstructed by a process of contouring, reducing the original geometry. This abstraction process is convenient for decoupling design intent with the final methods of construction. (Dritsas, 2005). Due to the unique circumstances of each project, both of the case studies presented in
the following sections, had to be executed using post-rational strategies.

In the *Bishops Gate Tower*, Hesselgren et al. (2007) suggest a required shift in thinking from designing objects to the design of the systems that generate designed objects. A running theme of the strategies presented above and later in this paper, is the consistent use of a *coherent geometric schema* with built-in guarantees of *constructability*, it follows that simple geometry should provide a simple construction method. Glymph et al. (2002) refer to a similar concept, where a “Geometric Strategy” is established as a design constraint, enabling the embedding of fabrication rules through the use of a restricted geometric solution space.

**CASE-STUDY 1: YAS ISLAND MARINA HOTEL**

While managing large model assemblies, high component counts are conveniently maintained by using wireframe data. Although wireframes are sufficient geometric constructs for conveying a limited set of dimensional properties of the design intent, wireframe geometry fails to address the thickness of elements, making it ultimately impossible to visualize or measure whether all components in the assembly fit together. During the integrated delivery of the Yas Island Gridshell shown in Figure 1, wireframes took place as placeholders for Panels, Beams and Nodes represented through surfaces, lines and points respectively. The placeholder wireframes where effectively used as a coordination device between all stake-holders, allowing the coordination of quantities through a bill of materials, lengths, alignment vectors for beams normal to the Master Design Surface, alignment vectors for the nodes normal to the MDS surface, the nodes centre of steel coordinates, the node’s top and bottom of steel coordinates, offset on a normal vector from the MDS, and lastly through the use of parametric modelling technology the geometric dependency between elements was used to manage the topology of the Gridshell. The topology of the panel was
maintained as list of the names of the four beams required to enclose a panel, the topology of the beam was maintained as a list of the names of the two points required to limit the length of an infinite line, and lastly the nodes where maintained as a list of the name and coordinates of the points in space required to build all other elements in the assembly.

When coordinating the construction of a project with sculpted parts and high component counts, early in the design decision making stages a consensus must be made as to how much resolution should the model for fabrication have, naturally this will tend to converge to the minimum optimal, allowing for all stakeholders to coordinate their given trades with a minimal upfront investment in modeling. Unconventional geometry has also increased the cost of producing relevant construction documentation information (Shelden, 2002). Wireframes allow mitigating the tradeoffs between the cost of producing information and the minimum amount of data necessary to describe design intent to other members of the construction team. In the Yas Island Marina Hotel project, the need for evaluating the rain-screen facade assembly prior to submitting data to the fabricator was crucial to avoiding potential clashes and misfits of components on site, wireframes are not sufficient for investigating “assemblability” issues and misfits. The development of a strategy to build a digital Mock-up DMU of the assembly became evident.

The Yas Island Marina Gridshell required a series of design-study tasks prior to the development of the Digital Mock-Up assembly, these tasks ranged from the re-parameterization of the original NURBS surface imported from the animation package Maya into rational surfaces derived from translational surfaces along an ellipse shown in upper left area of figure 2, as well as mapping gridlines over the Master Design Surface in order to embed an appropriate panelling shown on the lower left area of figure 2, and later the involvement of the consultancy firm Evolute to optimize the panels and beams over the MDS for various fabrication constraints, such as the minimization of beam torsion. While these tasks deserve mention on this paper, the Focus of this case-study is on the automated development of a Digital Mock-Up through an automated method for “Dressing-Up” the wireframe geometry with high-resolution components as shown in figure 3.

**Automation**

The Yas Island Gridshell Digital Mock-up assembly required the instantiation of more than 200,000 components in the assembly, this was a sufficient justification for developing an automation strategy for the massive instantiation of the sculpted parts pertaining to the Panel Assembly, the Beam Assembly, the Node Assembly and the Node Stem Assembly.

![Figure 3](image)

*Left: non-exhaustive display of available components in the Gridshell. Right: beam / node instantiation close-up.*
The Digital Mock-Up instantiation is managed through an unsupervised visual basic script controlling Digital Project™ and Excel™, the bespoke tool iteratively examines each node and queries the existence of its immediate neighbours, and with this map determining where the node in question is in relation to the grid shell, after identifying the relative location type (Top, Middle, and Bottom) the tool queries the type map of the node neighbourhood to determine which rule has been met, if the condition matches any of the rules in the rule-set, the appropriate hand modelled bottom-up assembly is instantiated shown in figure 3.

The Yas Island DMU required the use of more than 20 smart assemblies, these assemblies where re-used and arranged spatially by the tool described above in over more than 200,000 different unique configurations, through a rule-checking algorithm that follows the resemblance of a generation zero cellular automata. The tool needs to be able to query a node and obtain information from its neighbours, the tool needed to perform various lookups of different key-value pair attributes associated with the nodes in the parametric model. With the data the tool gathered from the node in question and the data of its surrounding neighbours, the tool could determine which assembly to instantiate in the nodes and then how to gather the correct construction geometry from all nodes to build trimmed beams between them.

**Search strategy**

Even when dealing with fast computers, large quantities of components are difficult to manage and search, gridshells have large quantities of elements, when performing tasks that depend on the lookup of data, if the techniques used for searching are inefficient it will render the task unreasonably slow. Understanding the computational complexity of algorithms and their relationship to the size of the datasets they manipulate, offers insights into developing faster search strategies.

The speed of searching an element within a massive dataset is proportional to the number of cycles required to find the element. The best case scenario is when the search time is always a constant time regardless of the size of the dataset.

By maintaining the Vertices of the Grid Shell in Hash Maps, we can search any node in linear time regardless of the number of Nodes in the grid shell, searching for a node and its neighbours takes no longer than one cycle, computationally this means there is no speed penalty for querying about the existence of a node and retrieving its coordinates or any other key-value pair attribute from the model.

**Gridshell name expansion**

If we follow the thinking process of hashing functions, from reading the index of a node we should know how to locate the node within the grid shell and any of its surrounding members. The index of the vertex is mapped using an indexing pattern
that encodes the topological spatial situation of the node in relationship to the grid shell.

A Node in the grid shell is defined as the intersection point of a H Gridline and a V Gridline. In the Yas Island Grid shell the virtual diagonal gridlines inclined forward are named V lines and the Back Inclined diagonal Gridlines are named H lines.

So it follows that the vertex is named using the nomenclature (“H” + H grid-line number + “_” + “V” + V gridline number) for example a vertex indexed as H100_V350 is located where Grid-line H100 intersects Gridline V350.

**Computation and instantiation performance**
The same complexity problem of managing large lookup tables and algorithms, replicates symmetrically to the notion of the execution runtime performance of the tool, the more beams and nodes we had to instantiate, the longer it would take to complete. Even if we executed the tool on the fastest available machine in the office (a Dell Precision Workstation with quad core Xeon processors and 30 gigabytes of Ram) the execution would have a taken weeks to complete.

A typical solution to the problem had been solved by Google, they referred to the problem as “map-reduce”. A very large time-consuming task is split into smaller manageable chunks which output their results to a final process which collects the values and compiles them into a single result. In our case we executed the same tool on 10 low-end laptops simultaneously running only a segment of the Gridshell on each laptop, the first laptop would run beams from 0-250 and then the second laptop would run beams from 200-450, etc in chunks of 250 with a 50 beam buffer of overlap, to allow for redundancy in the event of failure. Through the use of this method the 10 gigabyte parametric model of the massive Gridshell was instantiated in a lapse of hours as opposed to days or even weeks, allowing the identification of assemblability misfits and discrepancies early in the project. Given the speed of instantiation afforded quick iterations of the Digital Mock-Up, the DMU became an active component of the decision making process.

**CASE-STUDY 2: MUSEO SOUMAYA**
The facade rationalisation strategy of the Museo Soumaya was guided by a finite set of rules imposed by the design team mostly dealing with desired aesthetic qualities in the design outcome of the rationalisation. The Rationalization used a geometric strategy involving the use of a parametric sphere-packing algorithm for mapping hexagonal planar panels onto a doubly curved surface while preserving the isometries of lengths and the conformality of angles.

![Figure 5](image)
Left: installation of panels. Right: finished facade paneling.
Early in the project the design team opted in using a pre-rationalised turn-key solution patented by the consultancy firm Geometrika for the fabrication of freeform space frame structures, as the panel positioning device and the support structure for the panels. The rationalisation strategy also inherited a fixed non-negotiable MDS Master Design Surface; due to concurrent assembly processes within the interior of the project completing at a faster pace than that of the exterior facade engineering exercises, the Master Design Surface had to be frozen.

As a design consequence of selecting Geometrica’s space frame strut and node system, the rationalisation strategy was reduced substantially, triangular configurations of same size circles produce hexagonal intersection patterns, each node in Geometrica’s space frame holds the centre of gravity of a single hexagonal panel and three incoming struts, forming a secondary triangular aluminium structure over the primary steel of the project providing support for hanging the outer aluminium panels and the inner waterproofing panels developed by Geometrica.

While this class of problem has been previously explored as a mathematical optimization of a fixed surface using triangular meshes where the in-circles of the triangles form a packing of circles and spheres on surfaces (Pottmann, 2009), the methods employed by Pottmann require an optimization algorithm that dynamically relaxes the values in the coordinates of the triangular mesh nodes in response to a cost function, minimizing the cost function makes the mesh conform to the surface and meets the hexagonal properties desired.

Our approach arrives to a similar result without the use of an iterative method, and can be easily mapped through a parametric modeller namely Digital Project, we wanted to explore the packing through a geometrical strategy, a geometric heuristic, Inspired from research on cellular aggregate structures, the intersection of circles and their inscribed hexagonal patterns resemble closely the formation of tissues or cellular aggregates in nature. Thompson (1961) modelled the morphological growth of cellular aggregates as the boundary conditions of intersecting spheres; Thompson (1961) identifies a “geometrical strategy” (Glymph 2002) for reconstructing the emerging hexagonal patterns found in natural forms. Through intersecting analytical sphere surfaces with the free-form surface of the facade, we obtain quasi-circular embeddings in the uv space of the surface, the self intersections of the quasi-circle embeddings are the vertex nodes of our hexagonal packing. While the hexagons produced are not pure hexagons with interior angles of 60 degrees and equidistant edges, the measurable distortions are below an acceptable threshold, the discrepancy is hidden with the incorporation of a gap in the edge between panel to panel, the gap also absorbed the visual discrepancies produced from using a low number of unique panels.

Figure 6
Left: Gaussian Curvature analysis.
Right: Sphere-Packing tool, User can specify radius of sphere, number of vertical and horizontal spheres, start curve, start point and surface.
The Museo Soumaya initially contained more than 16,000 unique panels, the high panel count increases complexity and cost of manufacturing. Through a series of cluster analysis exercises, the unique panel counts where reduced until the panel to panel edge discrepancies where not discernible, the easiest clustering algorithm to work with is the “Lloyd” k-means clustering, this clustering analysis is available in most statistical packages, such as Revolutions R, with the invocation of four lines we can sort all 16,000 panels into 49 clusters and output the result of the cluster as well as the cluster centres:

```r
mydata <- read.table("C:/paneldata.csv", header=TRUE, sep=",", row.names="UniqueID")
fit <- kmeans(mydata, 49,100,1,"Lloyd")
write.table(fit$cluster, "C:/panel_cluster.csv", sep=",")
write.table(fit$centers, "C:/panel_centers.csv", sep=",")
```

While the cluster analysis can inform us of how to cluster the packing of panels, to visualize the true-outcome of building the 16,000+ panels with 49 or less moulds, we must also replace all panels with the panel in the centre of the family it belongs as shown in figure 7. Increasing the family count reduces the panel to panel gap discrepancies and approximates more faithfully the Master Design Surface.

While the Museo Soumaya exemplifies the use of a sphere-packing algorithm for producing a conformal mapping of a two dimensional hexagonal-mesh, the sphere-packing can be used in many other situation where we know nothing of the surface class and its construction and require to wrap a two dimensional embedding on the surface. The k-means clustering algorithm can be used to conveniently reduce large number of unique components reduced into groups by measuring their similarities, how precise the sorting algorithm works, depends on the relevance of the data per instance provided to the algorithm.

**CONCLUSIONS**

We have exemplified with the two case studies above, how design rationalisation heuristics can be employed to handle large amounts of data and how Digital Mock-Ups allow to anticipate errors during assembly. The panelisation system of Museo Soumaya, shows a method for packing planar hexagonal panels over a doubly curved surface without the use of an optimization algorithm, and the subsequent k-means clustering for the reduction of large quantities of unique components during fabrication and assembly. Both projects provide efficient methods for the digitally supported delivery of large complex projects mainly through an efficient use of information and secondly by investigating rational strategies for the reduction of complexity through a coherent geometrical strategy.

Though there isn’t a silver bullet for rationalising projects from the burgeoning emergence of architectural expressions, the examples illustrated above in addition to the two case-studies shown in the previous sections, demonstrate how simple innovations in the way we use design technology and geometry in the service of decision making and coordination have an enormous impact over the quality and constructability of complex freeform architectural projects.
REFERENCES


