Sagrada Família Rosassa: Global Computer-aided Dialogue between Designer and Craftsperson (Overcoming Differences in Age, Time and Distance)

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Abstract
The rose window ('rosassa' in Catalan) recently completed between the two groups of towers that make up the Passion Façade of Gaudí's Sagrada Família Church in Barcelona measures eight metres wide and thirty-five metres in height [Figure 1]. There were four phases to the design based in three distinct geographical locations. The design was undertaken on site, design description in Australia some eighteen thousand kilometres distant, stone-cutting a thousand kilometres distant in Galicia, with the completion of the window in March 2001. The entire undertaking was achieved within a timeframe of fifteen months from the first design sketch. Within this relatively short period, the entire team achieved a new marriage between architecture and construction, a broader relationship between time-honoured craft technique with high technology, and evidence of leading the way in trans-global collaboration via the Internet. Together the various members of the project team combined to demonstrate that the technical office on site at the Sagrada Família Church now has the capacity to use 'just-in-time' project management in order to increase efficiency. The processes and dialogues developed help transcend the tyranny of distance, the difficult relationship between traditional craft based technique and innovative digitally enhanced production methods, and the three generational age differences between the youngest and more senior team members.

Keywords
Digital Practice, Global Collaboration, Rapid Prototyping

1 Introduction

Just-in-time construction is a relatively new process where construction takes place for one part of the project while others parts are still having the detailed design finalised, and is a recent initiative taken by the *Junta Constructora* as one more means to advance the completion of the church by accelerating the building process. Of course, 'just-in-time' has always been the design-build method that has characterised the long gestation of the Sagrada Família Church, even during Gaudí's time, but its application in such a fast-track way to the Passion Façade rose window using the latest digital design and communication technology was a first for the project, and probably rates as a first for any project of this nature. It was made possible through the project management of Architect Jordi Faulí working closely with the Coordinating Architect Jordi Bonet, and Consultant Architect professor Mark Burry and his team at Deakin University. As such, and as part of an ongoing process to development techniques to increase the productivity of the design and construction of this internationally renowned yet unfinished project, the work in progress reported here yields significant insights into the 'Reinventing design, construction and operation work processes' section for Acadia 2001.

Figure 1. Position of the rose window from the interior

2 Scope

The project was in four distinct phases starting with the overall design. Mark Burry worked on site in Barcelona using a high-end computer for a period of six weeks at the beginning of 2000. Using a particular software approach commonly referred to as 'parametric design', a flexible 3D computer model was made of the whole window assembly; by flexible we refer to a model whose characteristics could be adjusted to suit known environmental conditions. For the rose window the team was departing for the first time from detailed models of windows prepared by Gaudí himself - there is no surviving concrete proposal by Gaudí for this element, and only the vaguest of ideas can be captured in his surviving drawing of the Passion Façade [Figure 2]. We do have two important clues to his intentions, however, the first being the existence of the Nativity Façade rose window on the opposite transept, and the second being the lineage of Gaudí's 1:10 scale plaster models for the lower and upper side aisle windows culminating with the central nave window in terms of design complexity (Burry, 1993). This lineage shows a developing sophistication within the articulation between the adjacent hyperbolic surfaces and accordingly we have assumed that the rose window would highlight the particularities of all three antecedents (Burry et al, 1996).

3 Parametric modelling

1:25 scale gypsum plaster studies of a proposal made by the architects Puig i Boada and Bonet Garí during the 1970s [Figures 3 & 4] proved to be an excellent starting point. Their overall composition was updated through the application of the Coordinating Architect and Director Sr Jordi Bonet's understanding of Gaudí's system of proportions (Bonet, 2000). Mark Burry was able to use this model as a first basis for the final design, and by using the system of *parametric design*, the whole composition could be altered at will. An

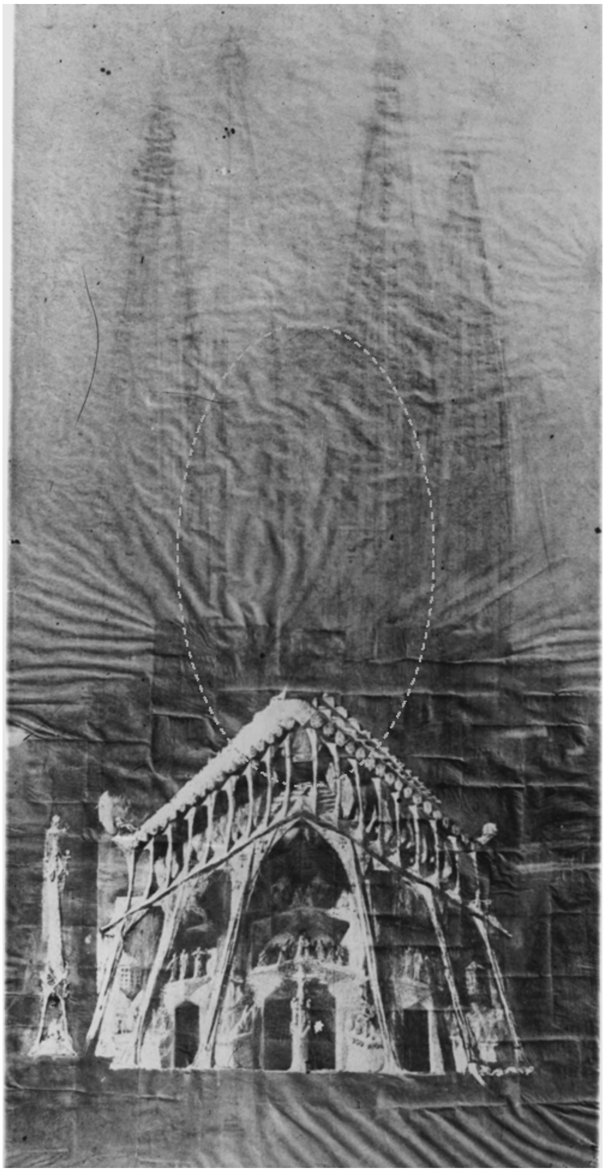

Figure 2. Original drawing by Gaudí – ellipse marks the position of the rose window

Figure 3. Provisional 1:25 gypsum plaster model (1970s)

example of this variability is the change of one or all of the mathematical constants that govern the characteristics of the component hyperbolic surfaces [Figure 5]. A particular surface, for instance, can be made more full (deeper) through changing the mathematical characteristics of the surface via the computer software, thereby affecting the nature and position of the intersections of adjacent surfaces [Figure 6]. The position of an opening, or the size of the opening itself can be changed at will with the 3D computer model automatically reforming itself without the need to rebuild the digital model through erasure and subsequent redrawing. In the case of this window, there are 3,800 events in the parametric modelling history; that is to say, for any characteristic of the model to be changed, 3,800 events need to be checked and updated before the geometry of the model can be regenerated.

Parametric design or 'associative geometry' is an approach to design that has been on the palette

Figure 4. Provisional 1:25 gypsum plaster model (1970s)

of possibilities for many of the 3D design professionals but has proved elusive for architects to date. There are very few examples where the opportunities for reconfigurable modelling based on associated geometry, which is a systemisation of geometrical dependencies whereby the designer can revisit earlier decisions and rework the model without the usual erasure and redrafting. The only example known to the authors is the roof structure for the Eurostar section of the Waterloo Station roof in London. The reason for its lack of uptake has been the prohibitive price bracket for architects, and possibly a reaction to any 'design tool' that encourages reiterative design processes. The second obstacle cannot be identified – it is more presumed and cannot be contested until sufficient architects have assessed the opportunities through practice rather than presentation. The first obstacle, however, can be challenged, and at least one major AEC software manufacturer (Bentley) is well advanced with a more affordable associative geometry modeller.

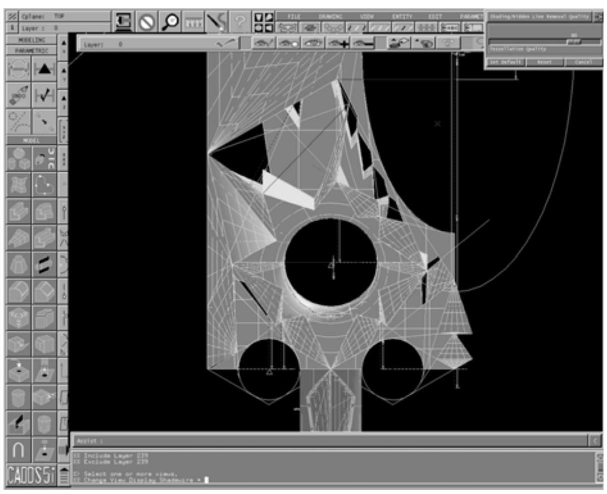

Figure 5. Parametric model of window (CADDS5)

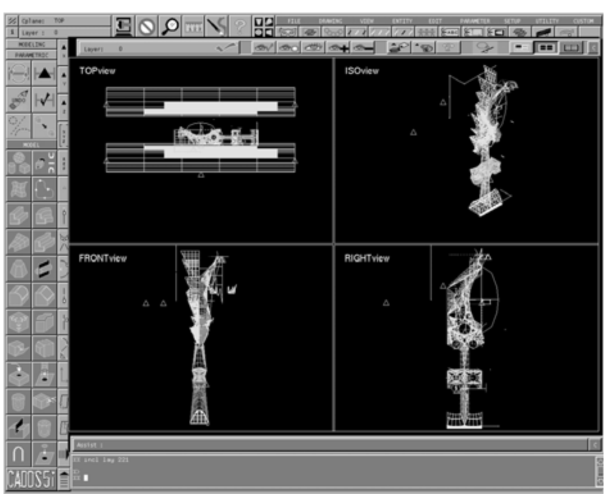

Figure 6. Parametric model of window (CADDS5)

Naturally, Gaudí had absolutely no interest in anything as esoteric as computers and software in his day. The lineage of craftspeople unbroken both during his time and in the years since his death in 1926 have alluded to his own *modus operandi*; although effective in his day, neither then nor in our time can a process based on reiterative modelling be anything less than lengthy [Figure 7]

We sense a similarity between this particular *modus operandi* using powerful digital aids and the haptic iterative design modelling used by Gaudí during the pre-digital era.

As complete as they may purport to be, high-end software packages still require some customisation, however. In the case of hyperboloids of revolution of one sheet, for example, these cannot be conveniently called-up from a library of geometries. Nevertheless, the basis by which useful geometries are sought using a reiterative design process whether it be gypsum based or digitally assisted, achieving greater efficiencies allows for more option-testing in the available time. To model a hyperboloid of revolution, test it, and refine it subsequently takes an inordinate amount of extra time if it cannot be experimented with through parametric variation on the fly. In the case of CADDS5, we resorted to an amalgam of mathematical calculation via MS Excel to derive the appropriate geometries, and MS Word via macros to convert that information into executable scripts for CADDS5 [Figures 9 and 10]. To the computer-using *aficionado*, reverting to standard desktop in order to produce the executable scripts probably seems top-heavy. On the basis of 'just getting on with the job', such purism is interesting, but not especially relevant.

After three months the design team were satisfied with the overall design composition for the window; the exterior was fully resolved while the interior had aspects that had to wait until certain measurements were made on site during construction before being finalised. Again, the use of parametric design technology allowed the easy absorption of the new information as it became available with a minimum of repeated work [Figures 11 – 13].

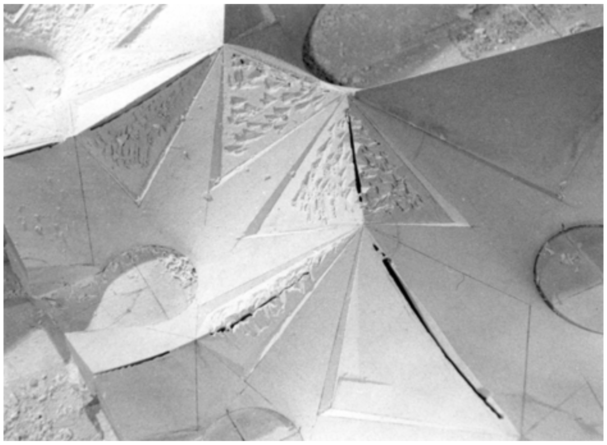

Figure 7. Gypsum plaster model showing Gaudí's method of re-iterative form finding. Here we can see a number of intersecting hyperboloids of revolution of one sheet, all of which would have been derived from drawn sections (hyperbolas) shown in figure 8.

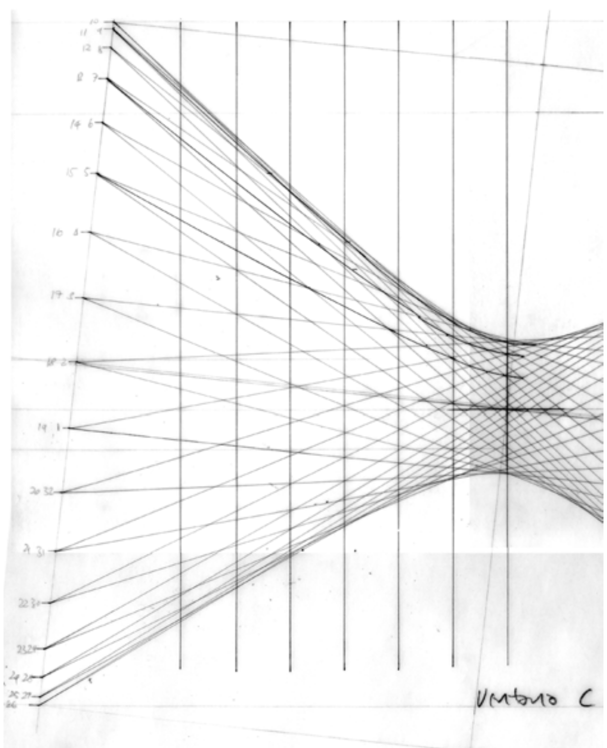

Figure 8. Graphical derivation of hyperboloids of revolution of one sheet

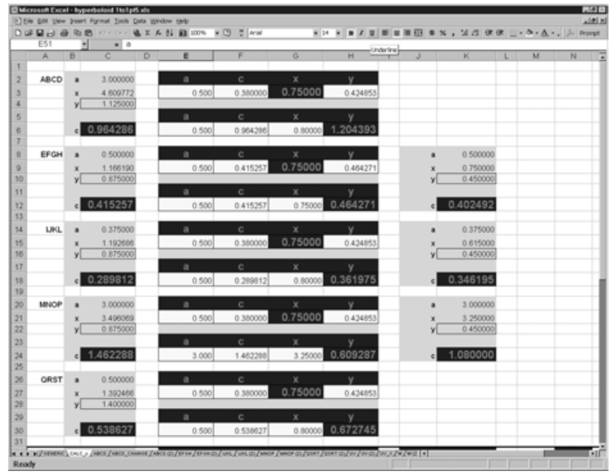

Figure 9. MS Excel is used to derive the characteristics for particular geometries.

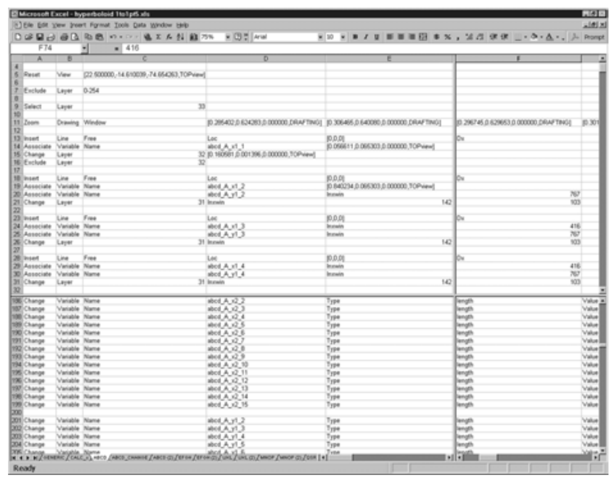

Figure 10. The calculations performed in MS Excel are then converted into tables that are then automatically processed into executable scripts to 'drive' the parametric model. The whole process of trying different variables for the geometry, producing a script through MS Word macros and running it within CADDS5 is a matter of seconds.

4 Rapid prototyping

During the creation of the overall digital design model during the first month, the stonemason Manuel Mallo made several visits from Galicia to the onsite design office in Barcelona to discuss the project in detail – his quarry and stonemason's yard are approximately 1,200 kilometres distant, and Sr Mallo himself is in his seventy sixth year. This was the first time the team had attempted to work directly from digital models to manually-based stonecutting without preparing an intermediate scaled gypsum plaster maquette. As a result

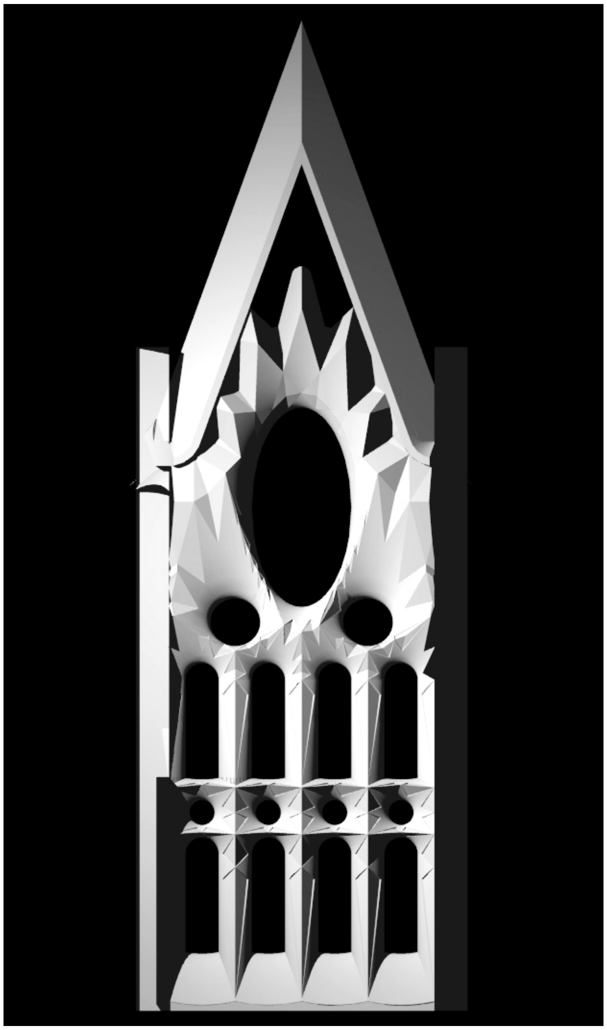

Figure 11. Computer render of exterior (Rhino3D)

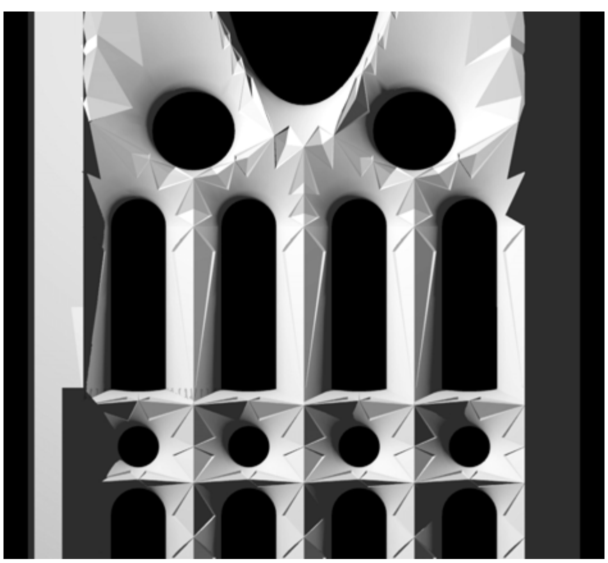

Figure 12. Computer render of exterior (Rhino3D)

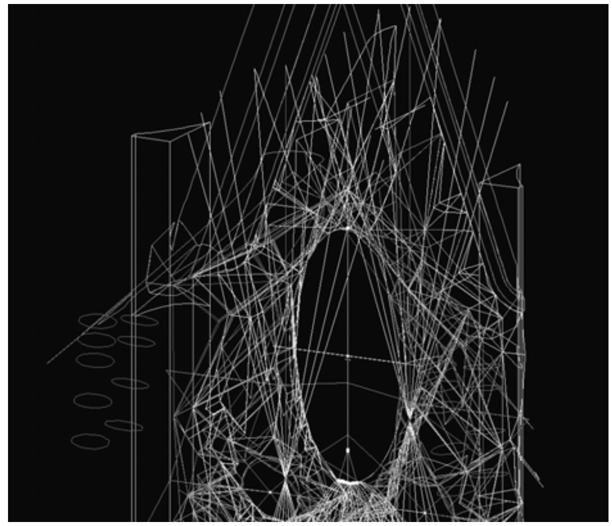

Figure 13. Wireframe of window for resolving the computer whole into individual stone pieces (Rhino3D)

the design-sculpting team had to invent an entirely new way of working together, not least through all three groups being based at inconvenient distances from each other. Through Sr Mallo's active involvement, we were able to develop the means that together could resolve the window efficiently into component pieces for cutting and shaping in his workshops on the other side of Spain. The issue here was a maximum weight to suit the cranes at both end of the operation, the sizes appropriate for trucking across Spain, and the manoeuvrability of the pieces when suspended at the working zone many tens of metres above ground level.

Included in this process was the Sagrada Família Church's first committed (as opposed to sceptical) adventure into rapid prototyping using a Themojet ™ 3D printer, which produced exquisitely detailed, accurate scaled versions of each of the stone components that typically weigh several tonnes [Figure 14].

Manuel Mallo had two observations to make during this critical phase. The first point was that the experimentation into the use of new technologies such as the 3D printer took longer than the critical path allowed and is best undertaken in a less demanding context. The second point was that his own manual method of rapid prototyping using polystyrene is in fact more rapid albeit less precise than automated rapid prototyping, with the advantage that the model maker understands more about the task in hand through the modelling than would occur with a machine made model [Figures 15 & 16].

Figure 14. Rapid prototype of individual stone piece (3D Systems)

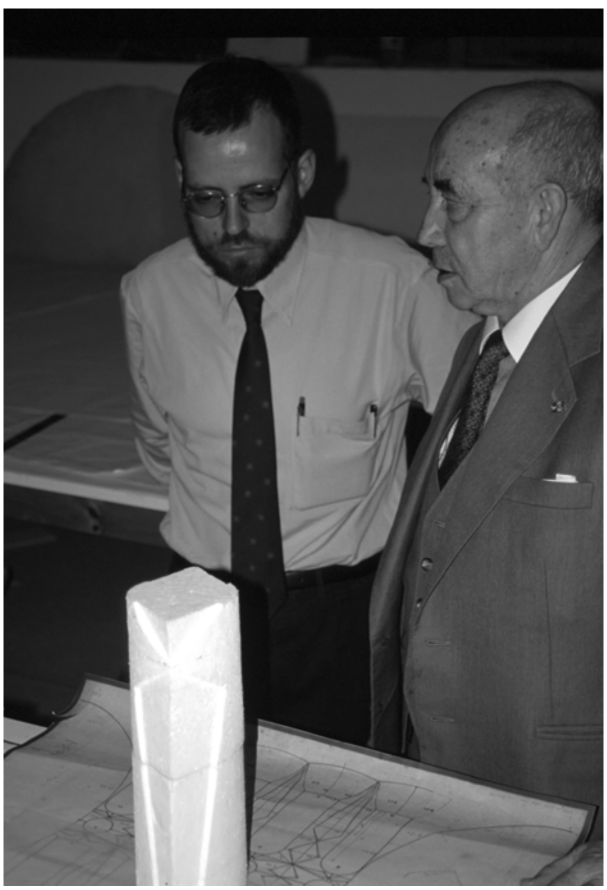

Figure 15. Manuel (stonemason) and Jordi Faulí with hand-made expanded polystyrene rapid prototype.

5 Templating, stone cutting and building

Of particular concern was the nature of the information with which Sr Mallo could direct his team of stonemasons. The lower part of the window went into production in March 2000, during the third month from the commencement of the project. This, a relatively uncomplicated part of the window, was an ideal testing bed for our new approach to design representation, rapid prototyping and production documentation. In late April, Architects Jordi Faulí and Mark Burry visited Sr Mallo's atelier near Lugo for an illuminating discussion on the lessons learned from cutting the lower window components for this first phase.

By mid year, while the lower quarter of the window was being constructed on site, the second quarter was being cut in Galicia, the third quarter being made into templates in Australia to guide the stonecutting, while the top quarter was still having the design refined in the collaboration between the Sagrada Família design office and the Deakin University team in Australia. This was the first instance of 'just-in-time' construction being put to effect at the Sagrada Família Church.

The window is more complex in design with increasing height, and the increasing complexity in design sponsored increased complexity for the template production leading to a second visit to Galicia in late summer. At this point it had become necessary for the stonemasons to first prepare full-scale prototypes for each stone piece using expanded polystyrene. These facsimiles

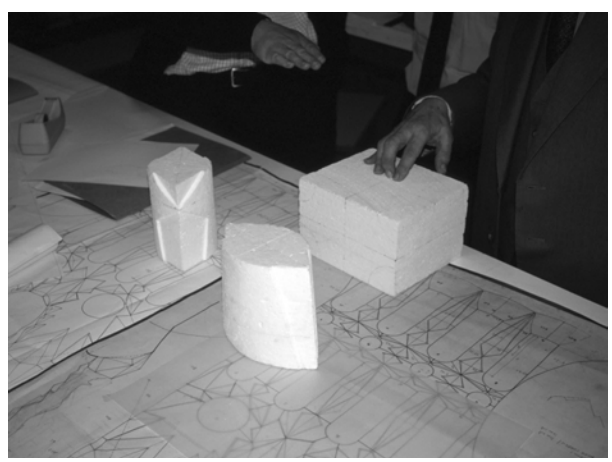

Figure 16. Manuel Mallo's hand made rapid prototype.

have the advantage of weighing only a fraction of the actual pieces, some of which weigh several tonnes, and the expanded polystyrene is certainly a great time-saving improvement on the gypsum plaster Gaudí was obliged to use for the equivalent process when building Casa Milá almost one hundred years earlier (Bassegoda, 1989).

Nearly eight hundred full-size DIN A0 templates were required to guide the stonemason's hand. These drawings were not based on any precedent this being the first time Gaudí's use of second order geometry (ruled surfaces) had been applied to the project in this way. A combination of rendered images of each piece [Figure 17] and associated full-size templates [Figures 18 & 19] were sent from Australia to Barcelona at the end of each day, printed and proofed there before being forwarded to Galicia by courier the same day. The

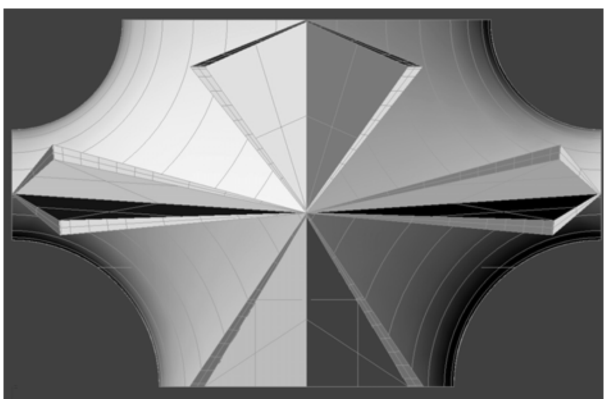

Figure 17. Computer rendering of typical individual stone piece

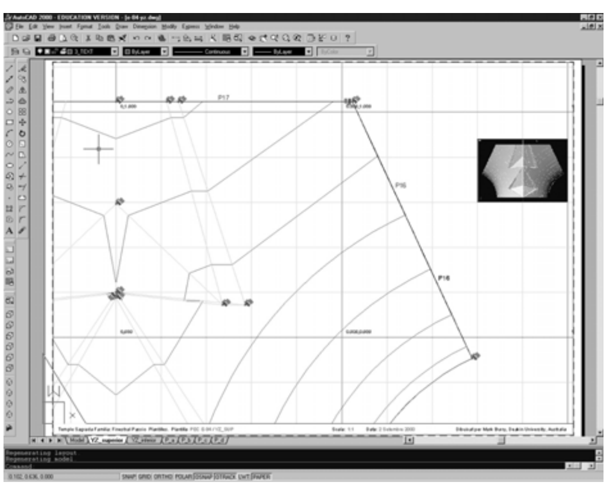

Figure 18. Typical A0 template for semi-automated stone cutting (AutoCAD 2000)

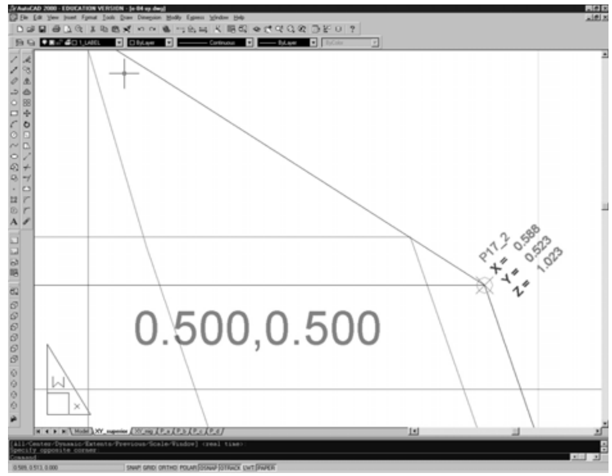

Figure 19. Detail of A0 template showing system of coordinates and contours for spatial information

system developed relied on line colour to represent the nature of each line (green lines being surface generatrices (therefore straight lines), black a template boundary between adjacent pieces, orange a curve etcetera). The drawings were supported by surface contours at separations of 10 cm (pale blue) with coordinates at critical nodes linking the orthographic projections of each piece to a common datum for each piece.

Manuel Mallo had introduced a number of innovations to his stone cutting procedures, principal of which was a semi automated cutting of ruled surfaces using an abrading wire. The piece of stone could be steered by an operative at each end of the hydraulically assisted controlling device who would each follow a path described by the templates. In this way he was able to cut warped surfaces to within a centimetre of the finished outcome, the finishing achieved relatively quickly by hand [Figures 20 – 21].

With the exception of a brief second visit by Mark Burry to Talleres Mallo near Lugo in late August, during the period June – December the Barcelona – Deakin University collaboration was conducted entirely via the Internet. Of note was the usefulness of the parametric design modelling in allowing for relatively easy adjustment of the base model to match the real circumstances of the adjacent walls. Maintained in a fairly 'loose' configuration, specific onsite information that could only be practically measured once the scaffolding had

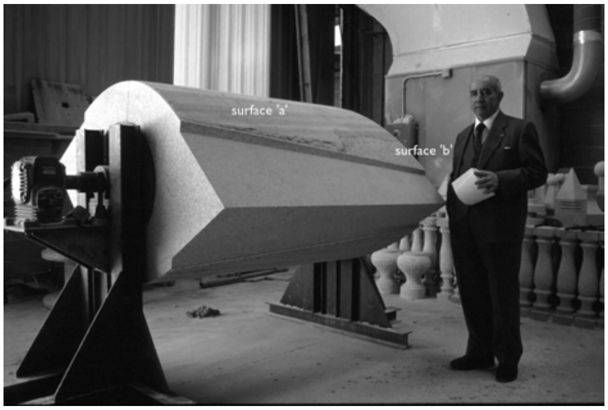

Figure 20. Manuel Mallo next to typical stone element cut by machine (surfaces 'a') and finished by hand (surfaces 'b')

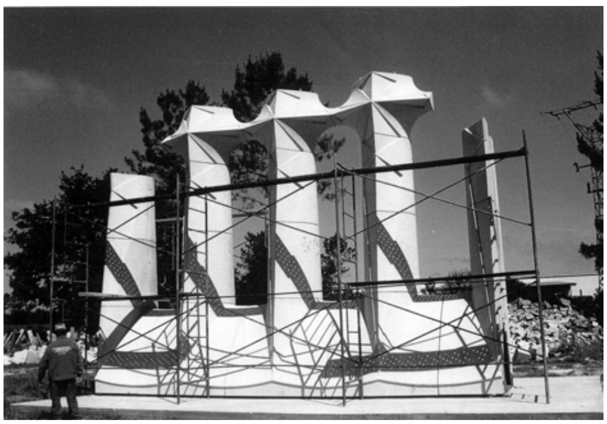

Figure 21. Lower four courses at the stonemason's yard

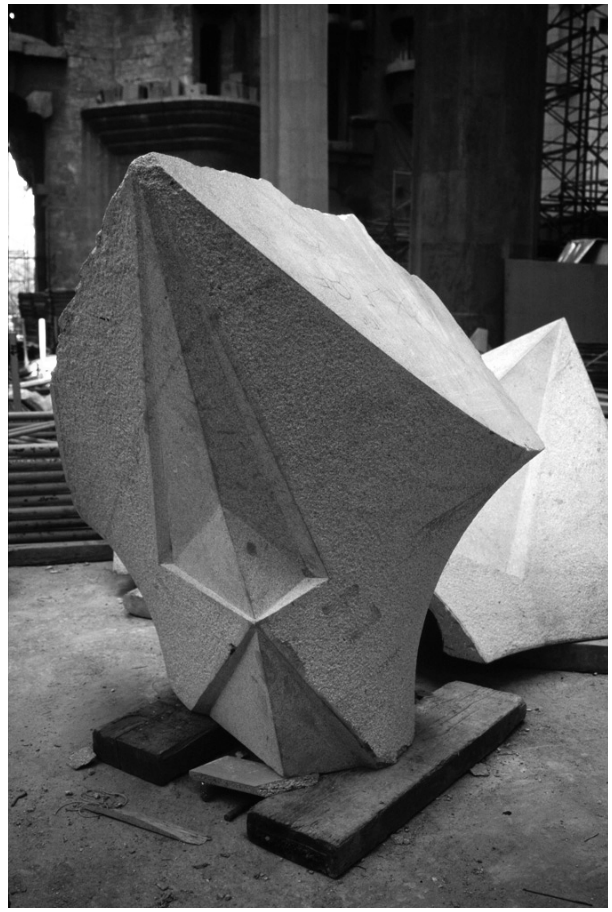

Figure 22. Individual stone piece on site

been put in place after the lower part of the wall constructed could be factored in and the parametric model retuned to match with exacting precision [Figures 23 & 24]. Following this process, and without exception, the large number of A0 templates sent to Lugo from Australia via the Sagrada Família site office were put to immediate use; none required any revision. Equally without exception, all the stone pieces from Galicia were fitted together first time on site making the whole window without any significant on-site stonecutting or revision.

6 Concluding comments

The singular trials of the one-off nature of building construction can hardly be better tested than through a Gaudí project. This short paper conceals many intriguing aspects that are published elsewhere. Not least is the fact that Gaudí invented a kind of codex by which the building's completion could be managed by others following his demise, hardly expected at the time during his advancing years (he was killed by a tram at the age of seventy-four). He nevertheless anticipated that the project would not be completed in his lifetime. The codex - a geometry based rationality – lends itself to collaboration between diverse trades and professions not necessarily tied to one location. This latest application of digital technology to manually based craft represents a considerable advance towards more efficient and cost-effective construction of this nature.

The experience of introducing rapid prototyping led, however, to two important revelations. Although subsequently established as an invaluable visualisation aid on site, trying to apply such a radical shift in process during a just-in-time 'experiment' was ill-conceived revealing, it seems, that such incursions are better tested in the academic laboratory than within a tight critical path in a real-world situation. The second revelation was the further substantiation of the premise that

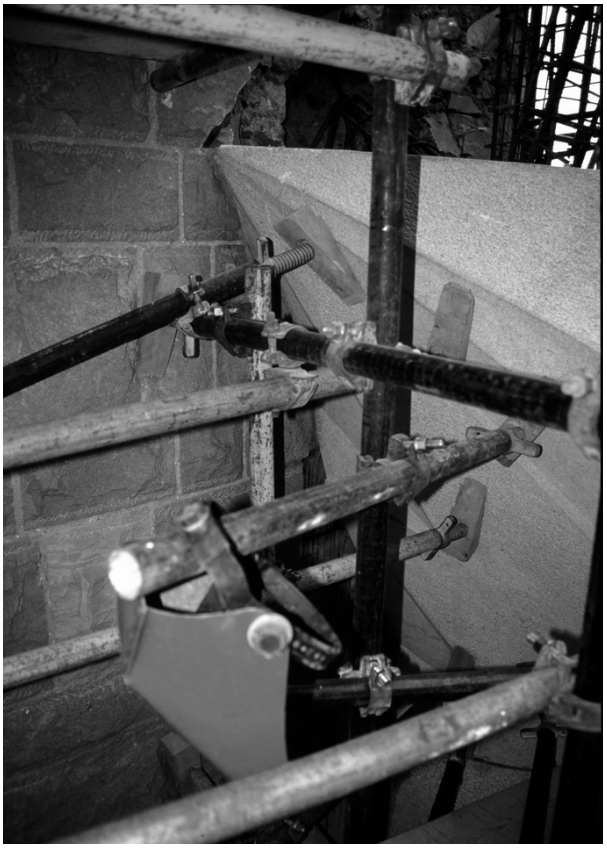

Figure 23. Example of the precision given using parametric design (refer to figure 6)

Figure 24. Close-up photograph showing of the precision given using parametric design (refer to figure 6)

the innate precision of the digital environment is sometimes costly within the relatively crude tolerances of the building industry, and that haptic engagement has its own rewards within a process ultimately as hand-driven as the craft of cutting stone.

Figure 25. partially constructed window (finished and glazed at the commencement of 2001, but still site-protected and therefore not available for full-viewing at the time of publication)

Acknowledgments

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