GAUDÍ AND CAD

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SUMMARY: *The presence and uptake of the computer, so omni-influential in approaches to design and architectural representation over the last decade, has begun to have an effect on built form and design quality. The computer has a reciprocal involvement in a revolution in thinking about space and time that has created a shift from the stable and metric (Euclidian) concepts inherited from the Classical through Renaissance and Modernist world to a more dynamic, unstable and unpredictable model, more closely aligned with our understanding of natural systems of growth, form and evolution. This paper focuses on a similarly reciprocal relationship between the developing use of computer-aided architectural design (CAD) and the detailed design and construction of the greatest work of a forerunner of this contemporary shift in spatial theory in architecture, the Catalan architect Antoni Gaudí. For fifteen years the introduction of the computer has contributed to the realisation of the highly complex Sagrada Família church based on the design bequeathed from Gaudí. While it has impacted on the speed, precision, research and design process, and undoubtedly the built outcome, the use of the computer has also contributed to the depth of understanding of the conceptual design system underlying Gaudí's formal expression. Conceived long before the possibility of electronic computation and still beyond the powers of conventional architectural software, the implementation of this systemic approach to design is a rich source in the quest for meaningful use of computation in design and construction today and tomorrow. It promotes experimental uses of computing in both reverse engineering the design from the original architect's gypsum plaster models and scant surviving images, and streamlining the communication and construction.*

KEYWORDS: *Gaudí, Sagrada Família, associative geometry, seriality, CAD CAM, organic architecture.*

1. INTRODUCTION

What are the most fundamental changes that rapid electronic computation has wrought on all forms of creative output?

We can create copies very easily, large numbers of duplicates or replicates with small differences or refinements. The evidence is even to be seen in our junk mail: the unsolicited and irrelevant items which arrive with a personalised name and address. We can reuse material very easily, whether it is text, spatial representations or formatting templates. We can automate repetitive sequences with ease or represent a whole sequence of logical functions by an icon that evokes the haptic equivalent in the physical world. How does this powerful facility to copy, reuse and automate, through ultimately binary re-representation and computation of everything we do, impact not only on what we do and how we do it but on the built product of our endeavour? Clearly it has influenced the focus in design practice, powerfully so since the 1960s. The interest in emergent design is to some extent the product of the ability to set up system behaviour, link it to geometry and apply the algorithm in the computational black box to explore the changing formal or spatial configurations generated over time or spatial field. Emergent design practice sets up the conditions under which things emerge. This is happening in the context of a new understanding of space coloured by changing emphasis in our understanding of nature. (Fraser and Fraser, 1996, 1998).

CAD has also given the designer the opportunity to emulate free form geometrical surfaces and curved structure using NURBS. (Kolarevic, 2003) Algorithmic approaches to rationalisation allow description and construction of irregularly changing surfaces, for instance, the panellisation of the free form surfaces of Frank Gehry's Disney Concert Hall or the use of 2D arcs welded co-tangentially to emulate a free form 3D curve, in other words approximating irrational shape by resolving it into a whole series of rational bits. (Maher et al, 2003) Significantly, it is possible to work directly in three dimensions whether through digital modelling or scanning physical models to create editable digital replicas. We have software or can develop software that easily resolves this into traditional 2D description and we can link it to other forms of output information for construction (Maher et al, 2003). Of course design in which 3 dimensional models are privileged over 2 dimensional graphical projection predates the support of the computer (Evans, 1995) Nowhere is this more apparent than in the work of Antoni Gaudí. The subtle and highly plastic nature of the work defies easy description through drawing and conventional projections. The construction of the Pedrera (Casa Mila) and the crypt of the Colònia Güell are two notable examples of his work between 1900 and 1910 in which the communication between designer and craftspeople on site was fundamental to the execution with precise fitting and fine tuning of the components taking place through hand craft on site or in situ (Bassagoda, 1989, 1990). In his work three dimensional models, notably the gypsum plaster casts from clay masters for the Sagrada Família church and the funicular model for the Colònia Güell church, were a principal design tool and medium of communication. In the case of the Sagrada Família Church, these models provide the evidence of his highly original but coherent language for the construction of the church in his corporeal absence.

2. GAUDÍ'S MODELS FOR THE TEMPLE SAGRADA FAMÍLIA

Gaudí worked on the design for the Sagrada Família Church for 43 years from the time he inherited the commission from the first architect for the church in 1883. His predecessor del Villar resigned after a disagreement with the client over construction of the crypt, the church having commenced based on a Gothic plan, the crypt and apse already underway. Gaudí's design for the church and the progressive emergence of its architectural language builds on his work on other commissions undertaken throughout the period. (Bonet, 2000) From 1914 onwards he devoted all his attention to advancing the design and construction of the church and even lived on site during the later stages of this period. It became clear by this time that the work would not be brought to completion within his lifetime - only one transept, the lower apse and the crypt beneath it were built when he died in 1926. The importance of resolving and communicating the design intentions for future execution assumed increasing significance. The significantly larger and more complex Sagrada Família demanded a more systemic approach than either La Pedrera or the incomplete Colònia Güell church.

In the Sagrada Família, Gaudí revisited the principals of Gothic architecture and sought ways to continue its evolution both with regard to structural efficiency and to the gains for admittance of light and its play on the interior surfaces of the church. His work with funicular models in designing the church for the Colònia Güell are well known as an interactive design tool harnessing statics as a generator of form and his regard for structural efficiency is also seen in the inclination of the branching columns of the nave of the Sagrada Família.

Another great innovation with its roots in his close observation and knowledge of natural growth and form was his use of a family of ruled surfaces: hyperboloids of revolution of one sheet, hyperbolic paraboloids and helicoids. These are all doubly curved surfaces. Close approximations of all these can be seen in natural structures for instance the hyperboloid in bone shafts, the hyperbolic paraboloid in the web between fingers and tree roots, and the helicoid in the DNA molecule and the cell growth in trees. Moreover, the permutation of individual parameters of each of these shapes and the combination of these surfaces leads to a very rich formal and structural palette with much greater variety in their qualities than spherical surfaces for instance, which can only be scaled. The details of Gaudí's application of these surfaces throughout the Sagrada Família are outside the scope of this paper (Burry 1993, Bonet 2000). However, it is significant to note the way in which these curved surfaces can be formed in wet plaster by the use of a swept straight edge between guides, the stereotomic opportunities for the stone mason to sculpt them similarly by cutting straight lines between corresponding endpoints on 2D templates or to automate this cutting process using contemporary robot stone cutting equipment. Also, the opportunity for intersecting two or more doubly curved surfaces, though they may be different surfaces (a hyperboloid and hyperbolic paraboloid for instance) along a shared straight line opens up the possibility of extensive complex surfaces and forms from a highly rational process. In this sense it bears some relation to contemporary interest in emergent processes and genetically generated form. Gaudí developed a codex for rich organic form generation in a way that could be repeated, infinitely varied within the rules, and both described and built with clarity and precision.

The process of creating and assembling the gypsum plaster models is illustrated in Fig. 3. A flat zinc template cut to a hyperbola of particular parameter values is revolved in wet plaster to create the circular hyperboloid master. From this a series of similar dish like hyperboloid surfaces are cast, then cut and assembled.

FIG. 1: Sagrada Família Church in context from South East

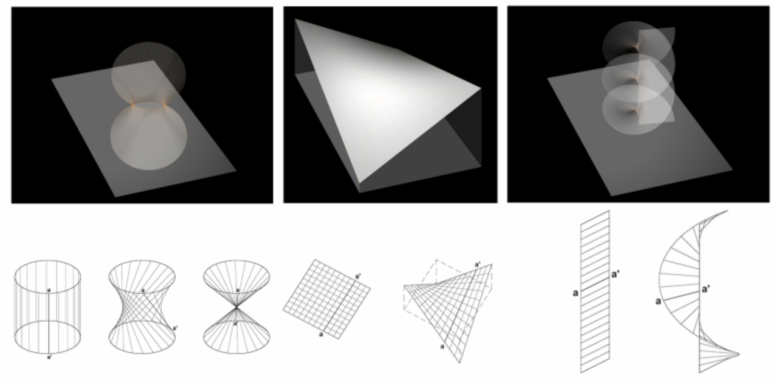

FIG. 2: Ruled surfaces: hyperboloid, hyperbolic paraboloid and helicoids

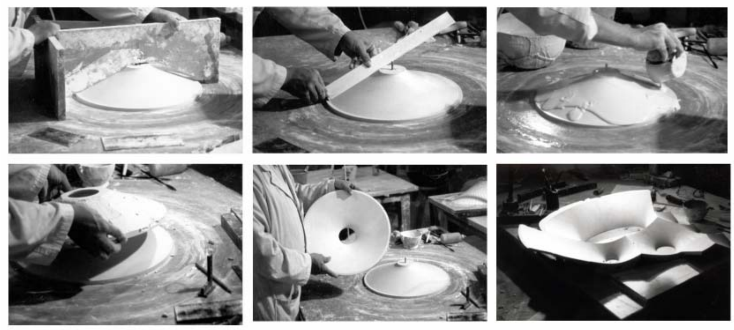

FIG. 3: Making and assembling the base hyperboloids of the window model in gypsum plaster

3. THE TEMPLE SAGRADA FAMÍLIA: CONTEMPORARY MODELS

3.1 Digital modelling

The construction of the Sagrada Família church has continued more or less continuously but at different rhythms at different times, since the 1880s, despite Gaudi's death in 1926, with the exception of a hiatus throughout and after the Spanish Civil War. At this time the church was raided, the drawings burnt and plaster models smashed.

Immediately after the war, work was delayed by a further decade of painstaking collection, cataloguing and restoration of the models from the surviving smashed fragments. None of the drawings could be recovered.

Until 1990 all the work was undertaken as physical models supported graphically through complex mapping drawings, tracing the projection of intersections between adjacent surfaces in three dimensions. All the source material was the restored plaster models prepared for almost all of the church during Gaudí’s lifetime. The screen walls of the upper nave (or the windows) can be created as a series of Boolean subtractions of hyperboloid solids from a block of material . Interestingly, in the early 1990s when the computer was first brought to bear on the process of modelling these windows for detailed design for construction, this process of Boolean subtraction was well beyond the scope of any architectural software and largely remains so. In the early research into CAD application to the work of continuing the realisation of the church, aeronautical software in combination with scripting provided a means both to model the geometry of the challenging surface compositions and to find the geometrical description that best conformed to measured plaster surfaces from Gaudí’s original models. By the mid nineties the task of varying the parameters of the individual component geometrical surfaces within the composition to hone the fit to the various conditions measured from the physical plaster models could be achieved within the software itself, which was by then parametric, providing associative geometric modelling. This meant that the two dimensional proportional system of the centres of the various openings in the window screen could be manipulated within the model, while simultaneously achieving the triple points of intersection between three adjacent hyperboloid surfaces appropriately in space by selectively altering the values of multiple parameters of the hyperboloids. The measurements from the plaster surface will not scale up to a completely uncompromised full scale piece. The appropriate parameters of the individual surfaces must be reverse engineered to conform as closely as possible to all the geometrical inputs. Traditionally resolving the best fit solution at larger scale in plaster would involve a laborious process of remaking the individual hyperboloids with slightly altered shape parameters, cutting these up, refitting and reconstructing the whole plaster model . The precision and relational opportunities of the digital representation allow a change of parameter and regeneration of the whole or affected part in just a few hours a decade ago, and more recently, in minutes. The extent of possible iteration even in a compressed program is transformed. This will be discussed further in the next section.

Next the carving up of the whole screen into component blocks of stone could also be varied parametrically, linked to volumes, weights as well as compositional considerations and ultimately to the centroids of the stone components calculated for determining points of suspension from the crane when positioning. (Burry, 2002).

In the contemporary site office at the Sagrada Família virtually all work now involves the use of the computer. CAD CAM robot stone cutting using digital files to describe the pieces has been employed since 1991. Since 2000 there has been a 3D wax printer on site to allow rapid prototyping of individual stones or whole building assemblies at the familiar scales of 1:25 or 1:10 scale. Throughout this period, the plaster workshop has continued to work, growing rather than contracting with the increased pace of design and construction, becoming increasingly involved in the construction of full scale moulds for the actual construction of the vaults of the church in addition to continuing to restore the original Gaudí models and make new plaster maquettes of design work in progress.

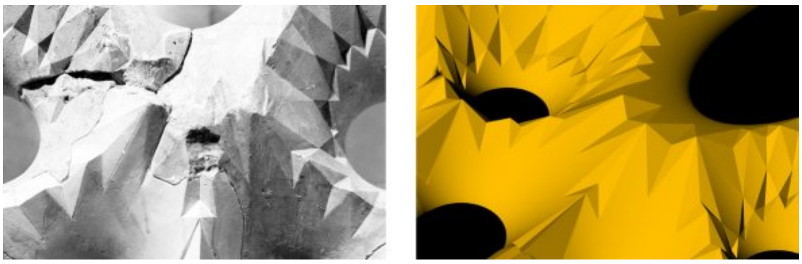

FIG. 4: Original plaster model showing the triple point between surfaces and image of the digital model

3.2 Iteration

The construction of the Sagrada Família church has always proceeded without the detailed resolution or documentation of the whole building. To this extent it conforms to the ‘just in time’ philosophy. However in past decades ‘just in time’ was signified by the production of two dimensional full-size templates for the stone mason for the stones of the lower nave window ten years in advance of their use in construction. Today the pace is different; the demand is for production information for immediate use. The introduction of CAD and CAD/CAM into every aspect of the work has had a role in this. Regardless of the increased urgency within the technical office, versioning is still an exhaustive process in its contribution to design decision making. The responsibility of bringing to fruition the appropriate realisation of church designed by Gaudí almost eight decades after his death necessitates not only extensive research for each part of the building but also extensive discussion and exploration through modelling of the possible variants at a detailed level of interpretation of the models for construction. This has become an even more demanding process since the work progressed from areas of the church represented by original Gaudí plaster models to the current work on the upper colonnade of the Passion Façade for which there is no surviving plaster model built during Gaudí's lifetime. The only original evidence is a photograph of the final drawing for the west elevation of the church and the surrounding parts of the church in their modelled and built form: the transept and towers. It is clear from the photograph, for instance, that there is serial growth through the columns, hexagonal prism frieze and stepping gable above towards the centre of the colonnade but reverse engineering the precise nature of this growth from this two dimensional image becomes the subject of experimentation. Constructing an associative geometrical model that allows for variation not only in the values of dimension, angle and constants but, in this case, for the replacement of the growth functions and the number of step instances within the gable, allows this experimentation and versioning to occur within a single virtual model with the opportunity for physical prototyping of versions.

During the construction of the Passion Façade rose window or "Rosassa" in Catalan (2000- 2002), the parametric model for the whole 35metre high window assembly could be selectively constrained so that the lower portion already being cut from stone at the quarry or under construction on site could be "fixed" while the higher reaches of the window could still have the geometry fine tuned to take into account precise measurements of the built surroundings as the scaffold reached the height to be able to obtain these measurements. This continuation of versioning of the window after documents have been issued (in this case 1: 1 templates issued to the stone quarry) and construction is underway would be beyond the scope of the modeller outside a computational environment because the flow-on effect of a single change of parameter value to one of the hyperboloids is so extensive in its impact on the intersections with neighbouring hyperboloids, changing the profile of all the templates in the effected zone of the window.

3.3 Measurement

One of the most intriguing aspects of developing detailed models for the construction of the colonnade for the upper Passion Façade was the system of growth through the repetitive elements towards the centre of the assembly. Working from the photograph of the two dimensional west elevation drawing, an atmospheric render of the whole, the only definitive guide to depth and three dimensional characteristics are the shadows cast by the columns. There is also a plaster model and several generations of plan section and elevation drawings developed between the 1950s and 1980s. As a starting point this plaster model was digitised using a Microscribe© with Rhino© modelling software. This four day process was laborious in comparison with the repeat run as a test with a hand held laser scanner subsequently. But compared to an earlier model-measuring procedure using a manual, relief map approach taking the measurements with weighted strings from a retort stand on wheels to the surface of the nave window model laid flat on a level marble slab, weeks of work were reduced to a few days.

While the digitiser and scanner offer rapid data collection and a high relative level of precision - and there is software to automate the extraction of a mesh from the point cloud generated by the scanner, the next step of finding the geometry from the scanned surface still presents a challenge. Whether approached computationally or through intuitive trial and error, it demands the privileging of some of the geometrical data over others. Points, lines and curves of intersection between adjacent surfaces can be recorded using a stylus overcoming the tendency of the laser scan post processing to interpolate between points resulting in the blurring of curved or linear edges. Should the edges recorded with the stylus be regarded as definitive in reconstructing the surfaces? What if the surfaces derived from these boundaries are not the best fit to the scanned point cloud? How can the errors in collecting the data and level of precision be built into the post processing analysis?

The digitised data for the colonnade plaster model was collected by an arm with a 700mm radius, and similar range from its transmitter (the electronic coordinate system origin in real space) which, given the overall size of the model, created many overlapping partial models in varying coordinate systems that had to be rotated and stitched back together. Inevitably the level of accuracy of plus or minus one millimetre implied that there was some variation between the same point collected in two or three of these sub models. In this case the interpolation and reconstruction of the surfaces was carried out manually within the modelling software.

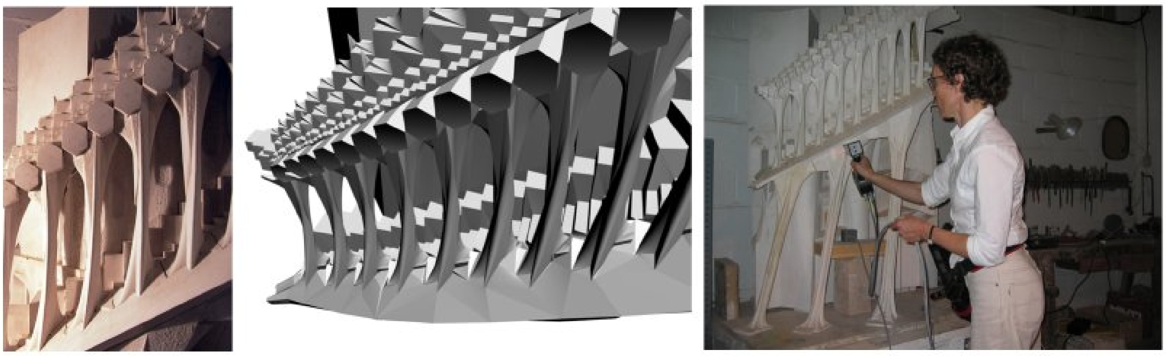

FIG. 5: a) Detail of the 1980s plaster model b) digital near-facsimile of the 1980s Cardoner plaster model of the colonnade by point digitising the model in sections 2002 c) comparative digitising using a laser scanner 2003

3.4 Serial Variation

Within the limitations noted above, the digital model was the closest possible replica of the 1980s plaster interpretation of the colonnade by Cardonner. The process of constructing it provided insights into the composition of the parts and their possible relations. It also allowed for easy comparison between three two-dimensional images. The first of these was the original photograph image, the second, an orthographically corrected photograph of the façade as built to date from the surveyors in the Spatial Sciences School in UPC and the third, the equivalent view of the digitised model to the same scale. There were steps at this point to establish whether the original photograph was a true orthographic projection using photogrammetric techniques.(Maher and Burry, 2002) In Adobe Illustrator this could be extended to comparative vector information. While it is difficult to derive detailed information from the photograph, there were obvious differences that had been introduced in the plaster model. The whole gable is much taller and there are differences in the numbers of instances in the frieze and gable for instance. On the other hand the digitised plaster model provided information about the plan that could not be derived from the photograph. With the ultimate objective of achieving a very close resemblance to the rendered drawing in the photograph, we commenced on the construction of a parametric model of the whole assembly in which the parts are related by a clear system of relations and constraints but the overall configuration can vary through varying parameter values. In doing this we sought to find a systemic approach to the serial variation in the frieze and gable. Measurements from the photograph and plaster model for instance, hexagon widths and heights or step depths in the gable were plotted as curves against the “number” of the hexagon or step and the sequential change in these measurements were also plotted. The resulting curves were then analysed for fit to various types of curve. The hexagonal prisms of the frieze clearly grew in a linear fashion and, given that the number of prisms and their approximate relationship to the intercolumniation could be read from the photograph, the only further question was to estimate the extent of growth. For the stepping gable there was a good correlation with quadratics or parabolic curves in the growth of the steps. In the plaster model interpretation, the three dimensional curves described by the edge of each layer of steps was linear when projected in the front elevation and parabolic projected in the plan.

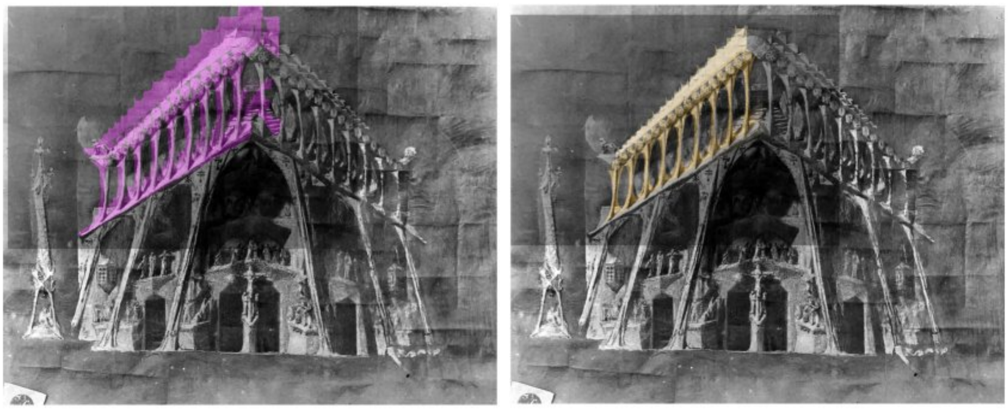

FIG. 6: a) front elevation view of the digitised plaster model overlaid on the original photograph b) front elevation view of a version of the parametrically constructed digital model of the colonnade overlaid on the photo

3.5 Rationalisation

One of the principal aims of parametric modelling is to defer design decision making to be able to progress many impacting aspects of the design in parallel. In this regard the linking of the growth in the upper colonnade elements to a quadratic relationship was not regarded a definitive but rather as a starting point for structuring a model that would be sufficiently flexible to substitute an alternative relationship is it was found to be better to use, for example, an exponential or catenary relationship subsequently. A mathematical formula is attached to the growth to make global algorithmic change possible subsequently. As already noted, to achieve this level of flexibility in the process through physical modelling of graphical representation implies sacrificing several orders of speed in being able to see the impact of changes on the whole. In fact the development of the 1980s plaster model was a long and painstaking process during the previous two decades with many iterations of individual column design. So within the digital model values for the inclination, the overall length, the number of steps and three constants of the quadratic equation controlling the rate of change of step size can all be altered at will to fine tune the assembly to better "fit" Gaudí's original image or accommodate the view shaft to the rose window from the park opposite the Passion façade or respond to constructional concerns.

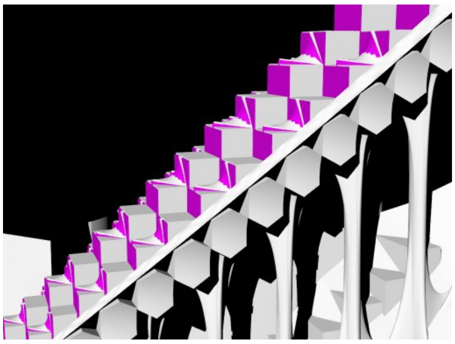

FIG. 7: A subtle example of changing one of the constants in the "growth" quadratic for the steps, the number of steps remains the same, the start and end point remain the same but the rate of change of growth is altered (second version: dark steps superimposed on original)

This process of rationalisation may be seen as analogous to other work, such as Frank Gehry's freeform sculptures that are scanned, remodelled and then subject to a process of 'rational' subdivision for penalisation and construction. Or a recent Australian example the *Shoal Fly-By*, a series of large public sculptures for the Melbourne docklands waterfront designed by artist Cat McLeod and architect partner Michael Bellemo as a series of 1:100 scale models made from electrical wire. Conceptualised as a shoal of fish 'flying' by through the glinting waves, these small fragile models had had every kink in the fine wire considered and created. How could this level of handcraft be constructed at full scale in which the wire becomes stainless steel tube in three dimensional curving, snaking paths through the air over up to 40 metres? In this case the complex curves had to be rationalised into a series of cotangential two dimensional arcs, arc length variable to suit to extent of curvature variation (Maher et al, 2003).

Although examples have been given of working from handcrafted plaster models towards rational mathematically defined and repeatable digital models to resolve the construction of Gaudí's work at full scale, this work is essentially different from the examples of working from "free form" in the previous paragraph. In this case we are working within the ambit of Gaudí's own rationalisation of the surfaces arising in nature. His use of ruled surfaces, albeit a codex that encompasses infinite subtle formal and spatial variation, nevertheless provides a system, intentional or otherwise, for description and construction. The work is essentially one of "decoding" rather than overlaying a rational process. What Gaudí's work has in common with the contemporary examples is that the rationality is in the description and production rather than in the aesthetic of the outcome. The logic is powerful but the outcome far from predictable.

3.6 Pattern: the limits and beyond

The central nave window has a series of decorative motifs, now built and resplendent in gold and coloured Venetian glass mosaic. At the time of modelling the window parametrically, working from the gypsum model made by Gaudi between 1920 and 1926, these motifs did not immediately seem to fit within the family of hyperbolic and planar surfaces used elsewhere in the composition. Nor was the relationship between the individual motifs immediately legible until they were denoted as "a single species with two genders: an alpha and a beta." (Burry, 1998). Their individuality within these two genders could then be seen as a consequence of their composition upon the parent elliptical hyperbolic surface of the window opening where their diagonals are coincident with the opposing straight lines through the larger ruled surface. They were represented by a single digital model and the process of moving parametrically between the two "genders" was animated in a series of frames to demonstrate the relationship between them. This powerful analogy of frozen life within the stone led to experimental investigation into the virtual forms that exist beyond the alpha and beta archetypes. Through changing two numbers in the algorithm producing the series of morphing forms, likened to applying "growth extender" and "age accelerator", the form progressed to a far more complex self intersecting "monster" not readily re-representable in stone. (Burry, 1998) This work most graphically illustrates the sophistication of Gaudí's choice of ruled surfaces for this very refined systematisation of the organic in architecture, his conceptual powers in the absence of digital means of representation and the opportunity the computer provides to enter and explore this process-driven spatial and formal world.

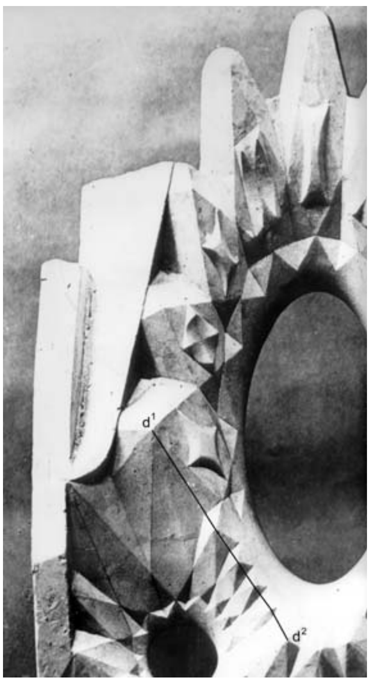

FIG. 8: Restored plaster model showing a detail of the motifs around the principal opening of the central nave window.

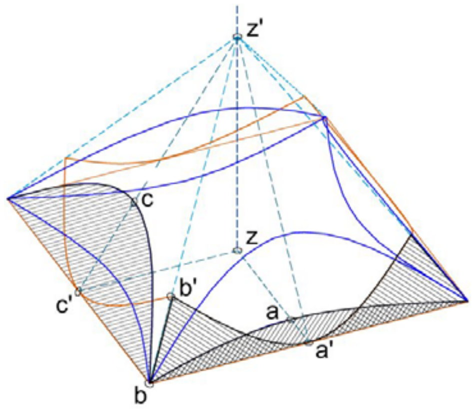

FIG. 9: Schema for the algorithm to generate the form of the motifs (both types, all variants)

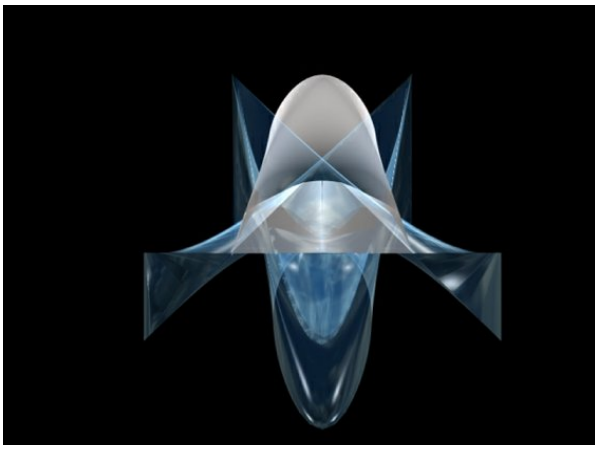

FIG. 10: Render of a computer generated 'monster' motif or teraton where growth hormone is applied and the parameter values are taken beyond the stable alpha or beta state

3.7 Exchange

Finally, it is only through the introduction of the computer and related digital communication technologies that it has been possible to work on the project from the opposite side of the globe since 1990. The traits for the stones of the Western transept rose window, over 700 A0 1:1 template drawings providing the information for cutting the stone were, for instance, all prepared in Australia as required, transferred electronically, printed and checked at the technical office on site and couriered the same day to the stone mason in Galicea, on the other side of Spain. Already this workflow pattern is so ubiquitous and familiar so that it is hard to comprehend for how few years it has been so.

4. CONCLUSION

The paper gives a series of examples of ways in which CAD, through its digital facility to copy, reuse and automate has informed and changed the process of translating Gaudí's design for the Sagrada Família church for its continuing construction. To say that CAD has impacted directly on the *building form* would be to admit that we have been less than true in our participation to the intentions of 'the Master'. However, we believe that it is possible to make an unequivocal case for the contribution of CAD to the design quality. In this case the contribution is not to the original conception, but to its fine-tuning and realisation. Clearly there is a new level of precision in measurement, modelling, description and production but this may not be the greatest contribution to realising the essence of the design. Perhaps it is in our opportunities for rapid iteration and for construction of flexible models that are always open to the inclusion of new evidence or insights up to the moment of construction. These models allow new levels of scrutiny, dedication in seeking the best interpretation within the latitude that the surviving design models and images afford. The possibility of modelling a domain of possible outcomes rather a single formal outcome without the huge time cost of rework in plaster is a compelling computational contribution. In this work the design process has never been limited by time and cost but it is now possible to work to a program and yet explore the subtlest of variations in resolving the detailed design. This is illustrated no where more clearly than in the investigation into the serial variation in the upper colonnade of the Passion Façade. Could the complexity of the geometry of the colonnade have been conceived and realised without the computer? Clearly it could and was. The conceptual complexity is the product of a great creative mind and dedicated work of a small team working earlier in the medium of gypsum plaster. Conversely the enhanced opportunity to experiment and find different ways to structure models, to visualise the underlying processes generating the forms and to prototype has undoubtedly contributed to the conceptual understanding of Gaudí's work. Moreover the challenge of reproducing the plaster modeller's plastic facility digitally has extended the reach of computer aid to design in architecture, moving it at an early stage outside the normal choice and application of software in the discipline in order to meet the challenges of Gaudí's conception. This seems as it should be - a feedback loop in which the creative demands of the designer challenge the tools and the use of tools in new ways promoting in turn new creative output.

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