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Parametric design and the Sagrada Familia

Mark Burry
School of Architecture and Building
Deakin University
Geelong
Victoria
Australia 3217

Parametric design is a paradigm for the more effective use of computers in architectural design and practice. Rather than focus on design as a holistic process of formal synthesis, the more localised issue of design development will be discussed, especially with regard to the resolution of complex geometry. The triforium of Gaudí's Sagrada Familia is taken as a case study. Parametric variation is used to define surface geometry consistent with the surviving fragments of plaster models, and what we know of Gaudí's technique.

I suspect that most who have attempted to design real buildings using CAD will concede, in spite of the persuasive talk (mostly from within universities), that there is still no practical design role for the computer, despite its performance in draughting and representation. For those hoping for more meaningful 'design opportunities' there are improving environments for the expert user (and closet programmer) and a useful increase in both the general knowledge of computing and the friendliness of software. Most products now offer productivity gains through macros and scripting languages. Sophisticated languages exist within particular products which allow the basic program to be adapted very substantially towards a particular design methodology.

A disjunction occurs when the software developer's metaphor, couched in terms that the practitioner half understands, is used to sell the product. The jargon is transformed, for the user, into an expected and unquestioned functionality. Thus the term 'parametric design' is valued more for the word 'design' than for 'parametric', with the assumption that the computer is actually going to assist the design process. The developer meant to say simply that the design could be varied by changing numeric parameters. To the designer used to using materials to hand in order to encapsulate a passing idea, the notion of resolving a design into a number of known but variable parameters will seem unusually restrictive and disciplined.

Parametric design, explained in detail below, is not a 'latest and greatest' but actually harnesses the logic behind most computer graphics programs. A drawing or model on the screen is derived from algebraic representations of shape organised with a common syntax. In this way a line is defined by its two ends, shapes by common vertices between lines (or arcs etc.), and models by shape adjacencies. The notation of 'shape' in this way dominates most of the principal texts on computer graphics during the last 20 years although the research behind it goes further back. Mitchell, for instance, opens his introduction to *The Electronic Design Studio* with a 'provocatively reductionist' definition of design as the 'computation of shape information that is

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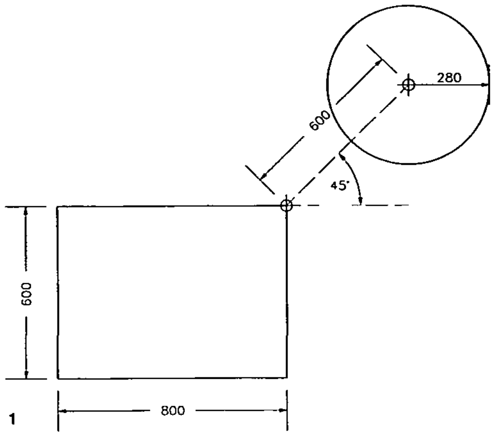

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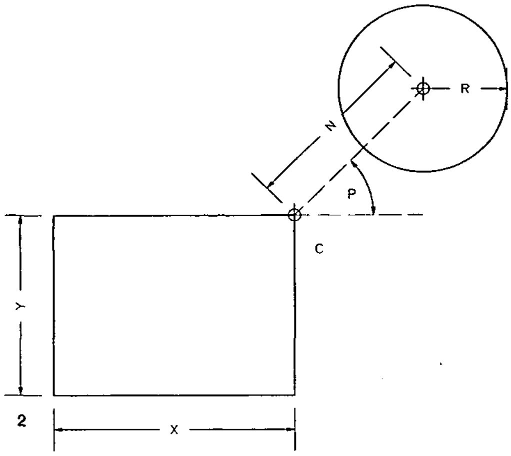

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1. **Explicit geometry.**
2. **Associative geometry.**

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needed to guide fabrication or construction of an artefact' (Mitchell, 1990b).

The end points which describe a particular line are parameters and if those parameters may be changed interactively they are said to be variable. The information about the ends of a particular line (for example) are held in the computer's database. If information about co-ordinates is linked to the screen, the database can be altered through direct manipulation. A simple example is provided by the 'grip-points' in recent versions of AutoCAD; more sophisticated software offers almost total access to the database via the screen.

The idea of parametric design is intrinsically linked to graphics programming; the possibilities have been recognised in academic literature for some time. However, the theoretical possibilities seem often to be reduced to rather banal exercises such as '101 ways to reconfigure a Palladian Villa' or 'design a Doric column to order'; useful examples, no doubt, but tied to precedent in a way which frustrates a more creative leaning. On the other hand, serious consideration is given to explaining the structure of parametric variation (Mitchell, 1990a) and entry-level graphics programming has also been made relatively accessible (Mitchell, Liggett & Kvan, 1987). Programming can, of course, redefine the supplied user-interface – but it is a resource unlikely to be available to most practices.

When the theory is related by practitioners to their working environment, opinions differ. There are elegant and relatively contemporary descriptions which promote the potential for parametric design (Aish, 1992) which can be compared with others which dismiss any wider relevance, especially in 'the realm of preliminary design' (Miller, 1990). There is little effective debate about the use of parametric design in architecture, outside academia.

Parametric design: rules and constraints

Parametric design, then, has a distinguished inheritance from a number of theoretical research streams. Parametric design or variation differs from explicit design through the alliance between descriptive and associative geometry. With explicit design an entity is 'what it is'. Typical CAD packages are used to draw entities with their interrelationships mapped in absolute terms: a circle of given radius and a rectangle of given dimensions placed in a position defined by given co-órdinates or dimensions, for example [Fig. 1]. High end software packages, aimed, it would seem, at 3D designers other than architects, offer a more fluid approach where entities are defined by a series of changeable parameters. Relationships between entities are defined as algebraic expressions representing geometrical constraints. A simple example is a rectangle of x by y units placed at a distance n units from a circle of variable radius at a location of p degrees with regard to a point c on the rectangle [Fig. 2]. These variables and relationships can be changed at will (within certain topologically derived limits) allowing the computer-user to perform an operation, assess it and make definite or experimental changes, by simply changing the parameters.

Other than values expressed as lengths, angles and positions the variable parameters include constants, constraints and dependencies. Two unconnected lines might have a relationship such that one is always half the length of the other, or one line might be constrained to being never more than a certain length. A window opening can be a given width but with a height which is a variable proportion of the width: the proportion is expressed as a constant and the composition of the window altered by changing its value and regenerating the drawing. An entire architectural facade could be composed in this way and reconfigured almost instantly by changing combinations of values, constants and constraints.

With constraint comes the possibility of over constraint: an irregular polygon might have one set of conditions, such as angles between sides, in conflict with another, such as lengths of sides. The designer has to become skilled in anticipating the unintentional over (or under) constraint as well as the inadvertent fixing of a condition by a decision made much earlier in the parametric design process.

The advantages to the product designer are perhaps

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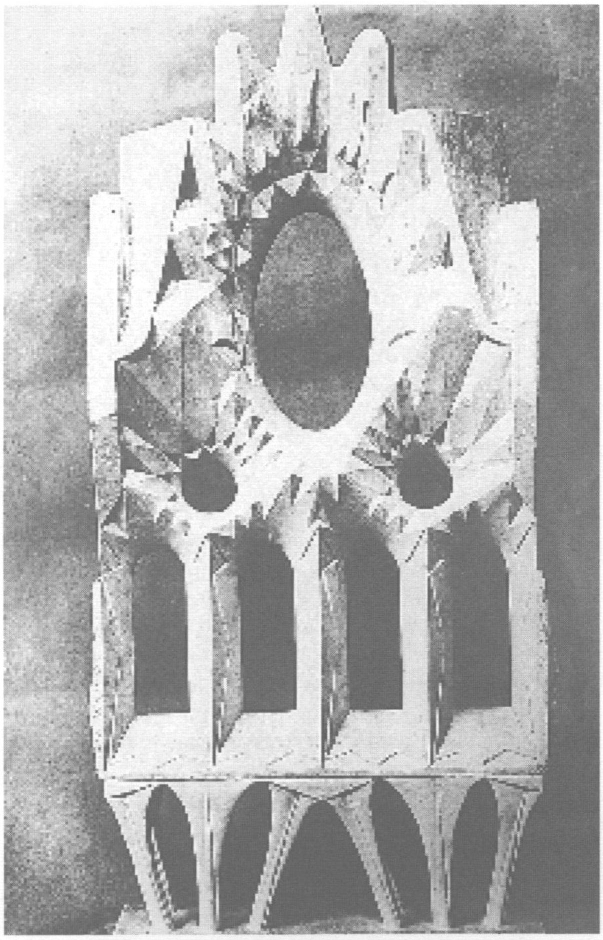
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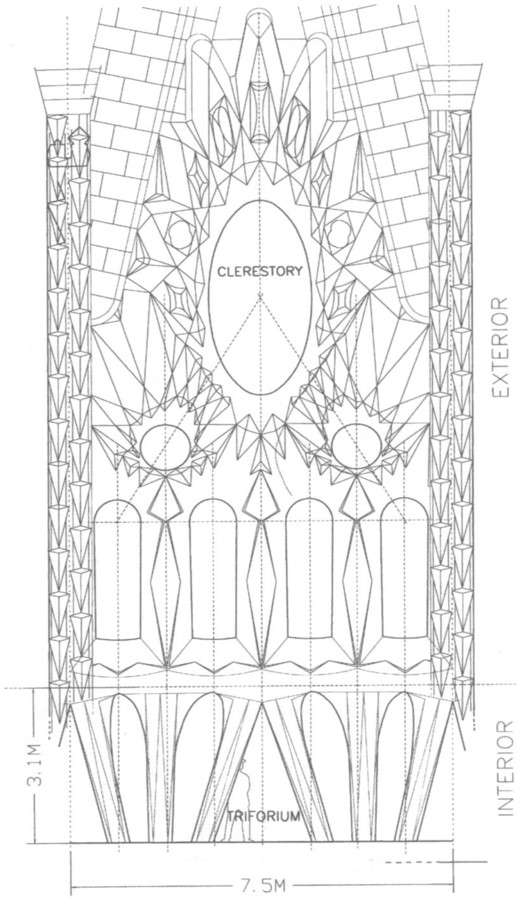

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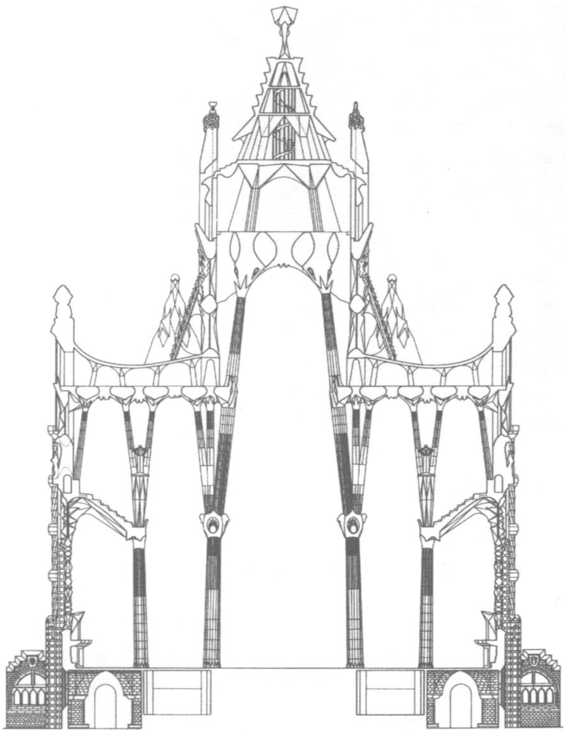
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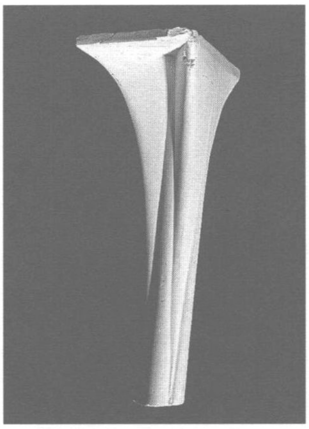
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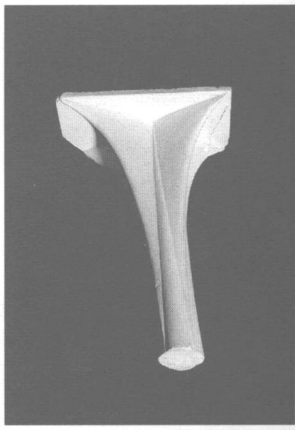
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3. Photograph of Gaudí's 1:10 model of the central nave clerestory.
4a. Elevation drawing of triforium and clerestory based on original model.
4b. Cross-section.

5a and b. 1:10 model (restored) of triforium column.
6. Surface geometries of typical column.

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more obvious than those to the architect. The design of a wine glass, for instance, may be driven by maintaining capacity as a constraint. The various lengths, angles and positions can be constrained or liberated at will, and if a particular combination is incompatible with the capacity constraint the 'design solution' will fail. Compared to traditional techniques, this process of iterative evaluation and re-evaluation is a major opportunity for productivity and quality gain.

The *columnetes* for the Sagrada Familia church nave

The Sagrada Familia has always been funded by donations, and it became clear to Gaudí himself that the building would never be completed in his lifetime. A rigorous system for surface composition presented incontestable advantages, especially when compositions formed in this way lack nothing of the movement found in earlier free-form work.

Parametric design has been used to interpret part of a relatively small, but elaborate, unrealised design by Antoni Gaudí. In this case study, parametric design will be shown to have assisted the search for an effective solution to an unusual but defined design 'problem'. This evidence will be used to support the potential of parametric design as a valuable intermediary in a range of architectural design issues, some of which are only beginning to emerge with an architecture more difficult to build.

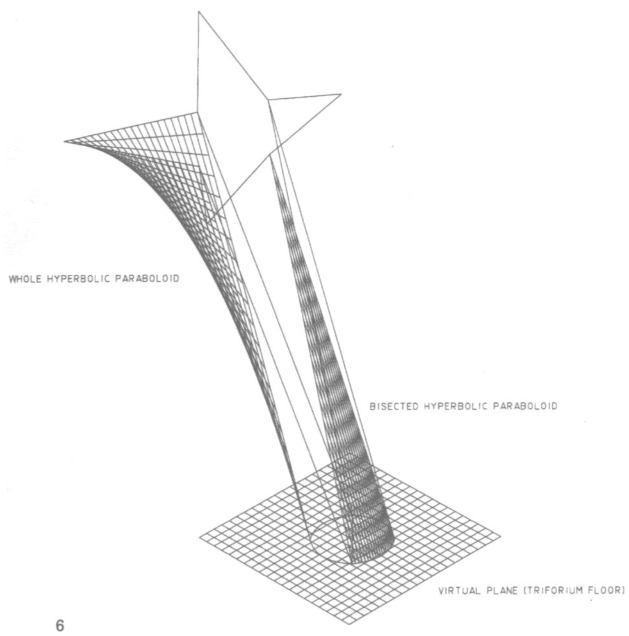
The triforium columns support the Sagrada Familia central nave clerestory and were designed by Gaudí in the years immediately preceding his death in 1926. A photograph of the whole triforium-clerestory assembly exists from the time of the window's design [Fig. 3]. It is undated, but as it appeared in publications during Gaudí's life-time, it is evidence of his intentions, which are being used to direct current endeavours, rather than (as often assumed) those of faithful but deluded Gaudí-style successors. The position of the triforium relative to the clerestory, with notional dimensions, is shown in a drawing of the model [Fig. 4a] and in a cross-section [Fig. 4b]. The occupation of the church by vandals during the Spanish Civil War led to the partial destruction of the models, which have been painstakingly restored during the decades following Gaudí's death. Not all the scattered pieces were recovered, but there were sufficient to afford a faithful reconstitution.

The sinuosity and responsive plastic morphology of the columns [Figs. 5a and 5b] do not give any obvious sense of their composition: in this case a selection of ruled surfaces (hyperbolic paraboloids) are joined at their seams, which are lines, not curves. There are 12 columns for each 7.5m window bay. The individual column is comprised of four full surfaces and a further four which are bisected by a plane, referred to as the virtual plane but in reality the triforium floor [Fig. 6]. The reason for this is that both the computer modelling and the geometrical construction involve manipulations where gravity and orientation have no relevance, and a neutral name for this plane, critical for the explanation of the formal geometrical composition, avoids misunderstanding.

Until sufficient time is invested in each part of the model, with a precision commensurate with the objective behind the use of such geometries, that is, for building, the restoration will be no more than a good approximation. The composition of ruled surfaces means that there is at least a comprehensible geometry by which the shattered pieces may be associated. The need to restore the 1:25 and 1:10 scale gypsum plaster models would hardly have been anticipated during their making, so the relative ease with which the thousands of fragments can be reformed is an unforeseen bonus.

The constructional advantages of using ruled surfaces to describe form are explained in detail elsewhere (Burry, 1992), but it is their apparent disadvantage, a non-negotiability of the various surfaces, which is central to this discussion. The interpretation of the models' geometry is either right or wrong; there is no room for any licensed impressionism or equivalent free-form work from the posthumous collaborator. Gaudí's systematic approach which emerged during the last (and relatively silent) 12 years of his long career, bequeaths a language which allows his successors to work in a manner akin to that of his contemporary assistants.

Over and above the aesthetic subtlety and liveliness of the combination of surfaces, these plaster-modelled intentions have been formulated in a pragmatically knowing way. Motivated by constructional advantage – the straight lines that make ruled surfaces have easily defined start and end points on the templates central to the craft operation – these surfaces resist corruption by the designer and, subsequently, by the executant. While the importance of the creative seed emanating from one fertile mind is not disputed, there is a world of difference between the sole progenitor (Gehry for instance), being necessarily and properly involved in all subsequent design refinements, and the leadership of Gaudí in the



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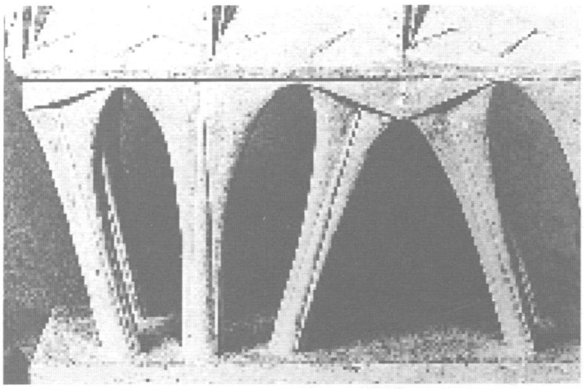
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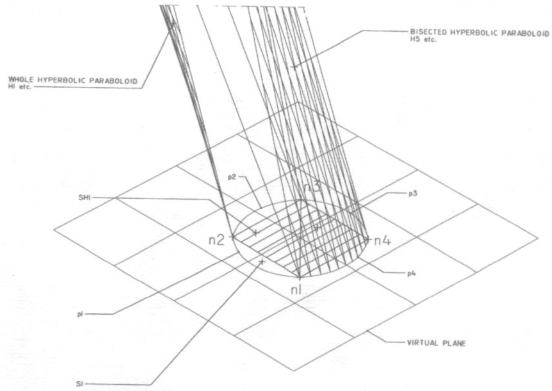

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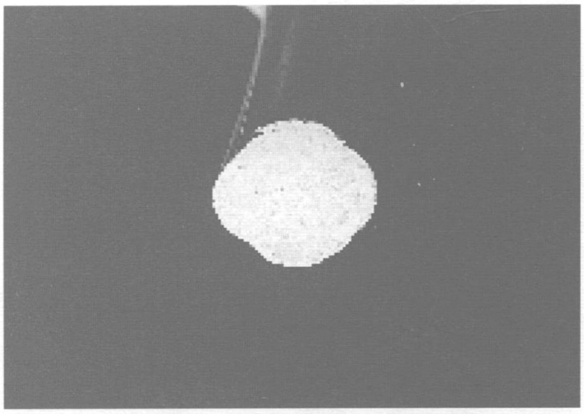
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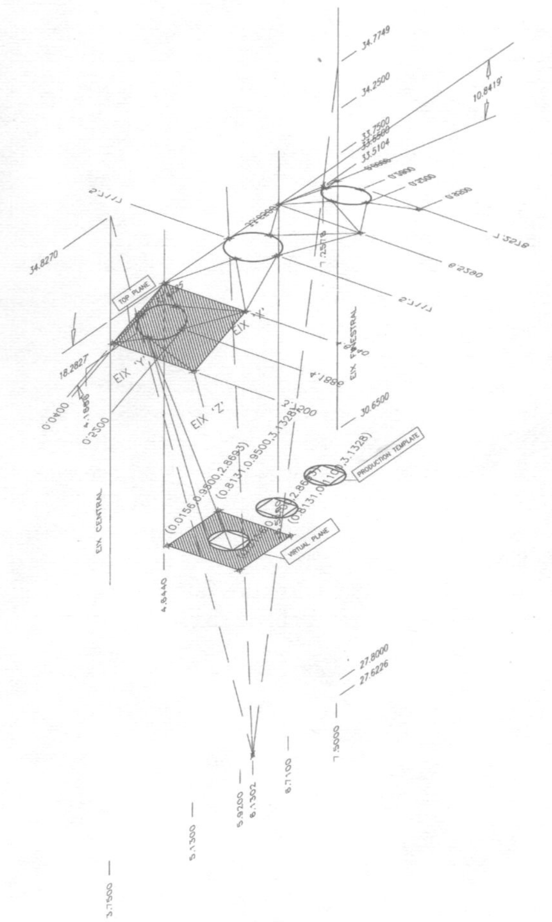

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7. Detail from photograph of original model prior to its destruction.
8. Detail of restored column 'quatrefoil' base.
9. Aspects of geometry governing the column base profile.
10. Initial briefing drawing showing the spatial arrangements for prototype group of three columns.
11. Detail of briefing drawing.
12. Parametric set-out based on briefing drawing.

case of the Sagrada Familia. Imagine the problem for successors, struggling to work from a similarly shattered plaster model, if Gaudí had died before the completion of one of his earlier free-form buildings, La Pedrera (Casa Milà), for example. There would be no meaning to the disconnected myriad of randomly shattered pieces, no coherence or order from which the whole could be reformulated. The restoration of a scale model of La Pedrera would be dependent on the continued existence of the sole author; few could claim to have Gaudí's touch.

Parameter derivation

The implications of the approximation in the restored model can be seen by comparing [Figs. 7 and 8]. Only the top halves of the modelled columns were recovered and the restoration relied upon the restorer's eye for the downward extension of the column to the virtual plane, that is the location of points n1-n4 for hyperbolic paraboloids HP1-HP4 [Fig. 9]. The points n1-n4 are the vertices of a notional shape SH1 as well as the intersections of the parabolic curves p1-p4, formed where the hyperbolic paraboloids HP5-HP8 are cut by

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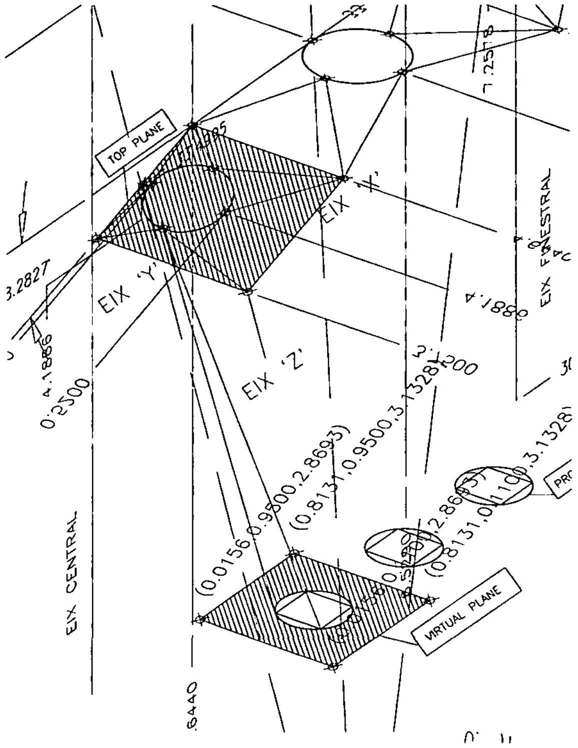

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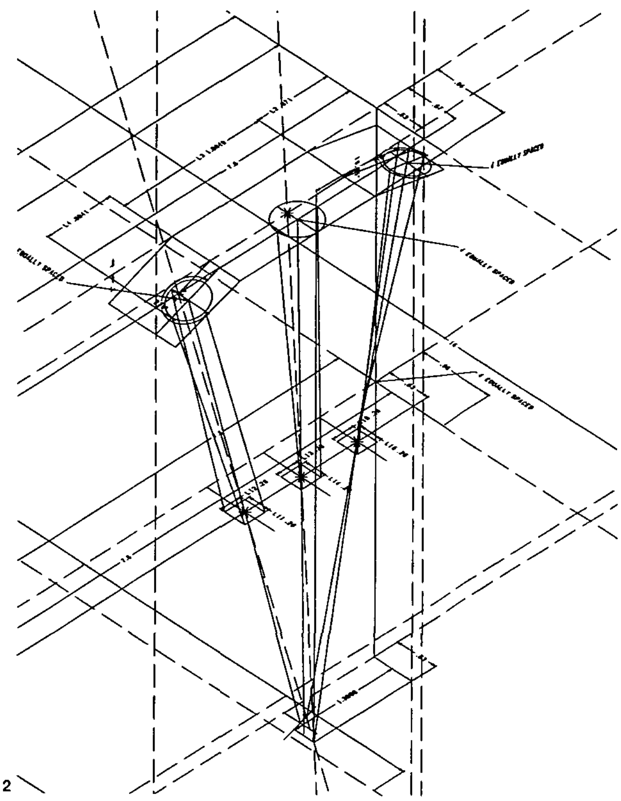

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the virtual plane. The four curves p1-p4 circumscribe the cross-section of the column base at floor level (i.e. in the virtual plane), the area denoted S1. While the bounding of SH1 is determined by structural considerations and remains a hidden figure contained within S1 (with only points n1-n4 in common), the profile for S1 itself is determined by fundamentally aesthetic considerations. The plasterwork restoration of the model base shows that SH1 is a square circumscribed by four parabolas forming a quatrefoil [Fig. 8]. However, an enlargement of the photograph of the original model prior to its destruction reveals reasonably clearly a cylindrical rather than a quatrefoil base profile: it would seem that some aesthetic sensibility had entered the restorers' craft at odds with the photograph [Fig. 7]. But what criteria could be used to decide the true derivation of the column morphology?

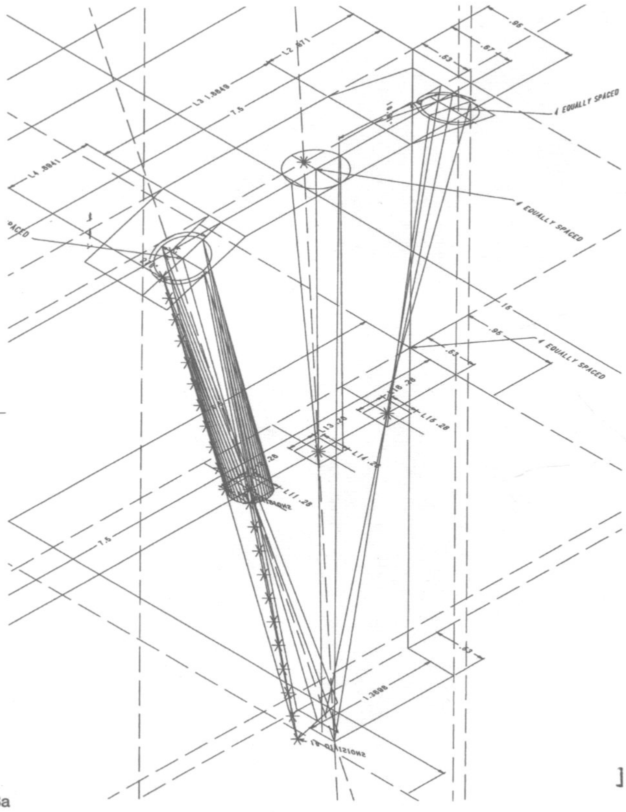
Parametric change

The 12 columns for each 7.5 metre bay are based on three prototypes duplicated by reflection about the x and y axis. Without being certain of the geometry there is nevertheless no obstacle to defining a spatial strategy for the positioning and inclinations of the column axes. [Figs. 10 and 11] show the briefing document where every position and dimension is an explicit statement, a best-guess without the assurance that the end result would produce a satisfactory base profile.

Experimental configurations, tested iteratively, produced the desired result. The explicit statements were made into parametric inputs in the 3D modelling software from ComputerVision's 'CADDS5' [Fig. 12]. [Figs. 10 and 12] do not appear dissimilar. The difference is that every entity in [Fig. 12] is governed by the parameters shown as intersections between entities, dimensions or configurations such as 'four equally spaced'. This works well so long as the design intention is clear from the outset; that the solution is known even if the route to it is not.

The parametric adjustment process is straightforward as shown [Figs. 13a-c]. Each column is built up conventionally as if it were an explicit one-off design. In this example the principal adjustments concern the parameters that influence the shape of base-profiles p1-p4. There is actually more to making the model than a cursory explanation allows, but the principle of making the changes is as simple as it looks. As each notation or number is selected, a calculator appears in which a new value or arrangement is typed, and the model regenerates itself attempting to accommodate the changes. If there is a solution the user is asked to accept it or to return to the unmodified version. If there is not, the user is informed at what point the model became impossible to reconfigure, providing an insight into the limits of the various parametric changes.

With a suitably powerful work station the process is extremely fast. Changes can be applied at once and, providing there is a solution, it takes less than 40 seconds to regenerate all 12 columns together. With real-time rendering and view manipulation the process is very convincing.



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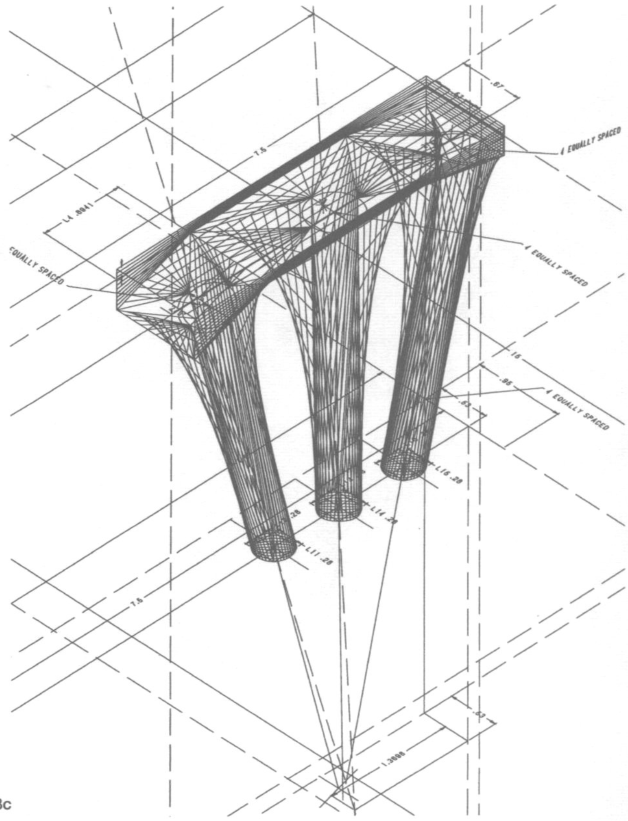

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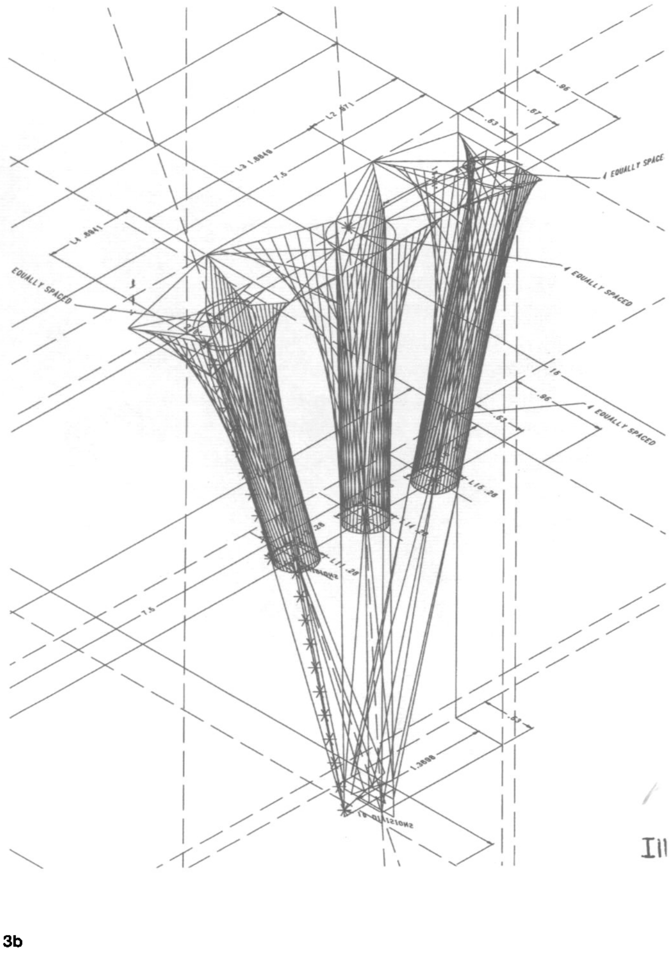

13b

13a-c. Build-up of parametric model. Once assembled the model can be reconfigured by changing any of the parameters shown in the model.
14. Derivation of bisected hyperbolic paraboloid.
15. Location of a single virtual point, the basis for the derivation of the fourth vertex for each bisected hyperbolic paraboloid.
16. An alternative to the bisected hyperbolic paraboloids is the sectored conoid – not a convincing alternative although easier to make.

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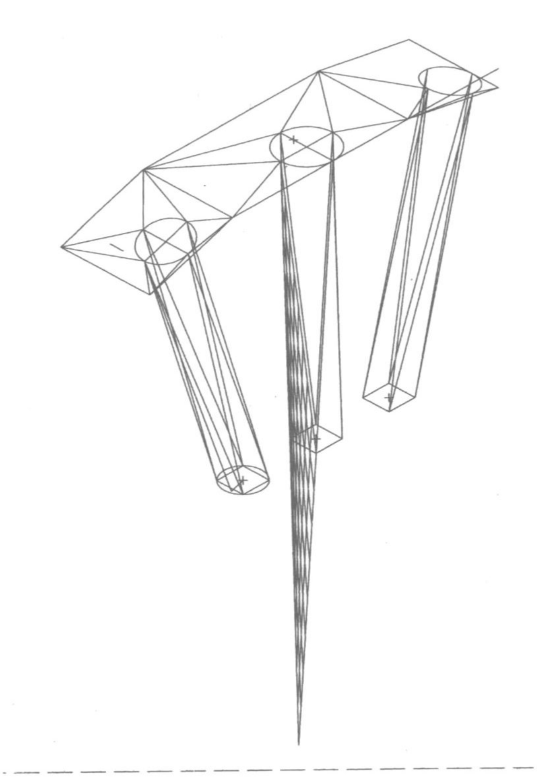

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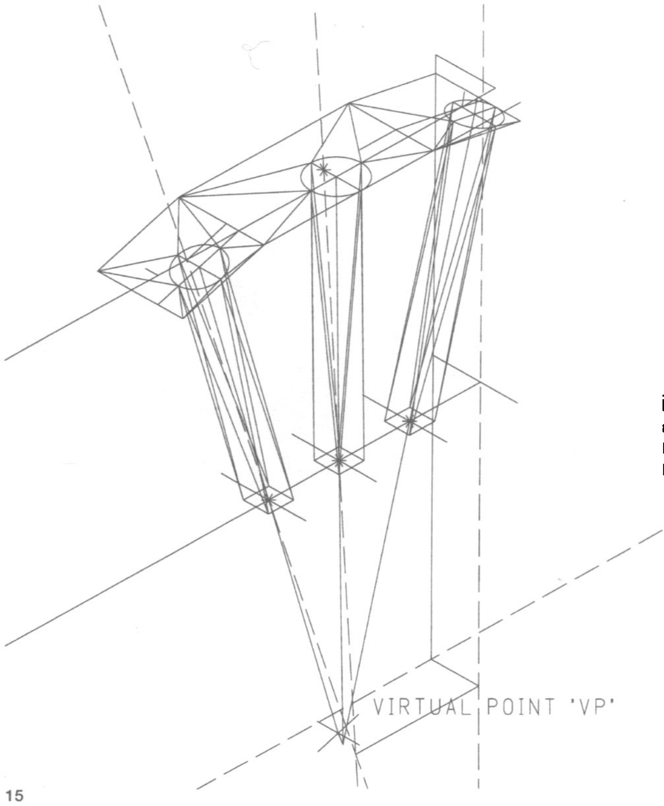

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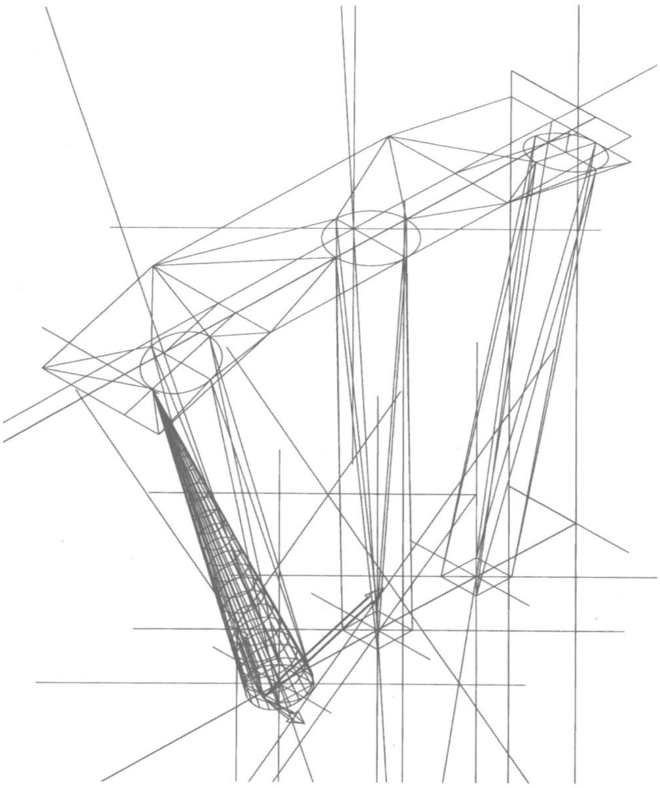

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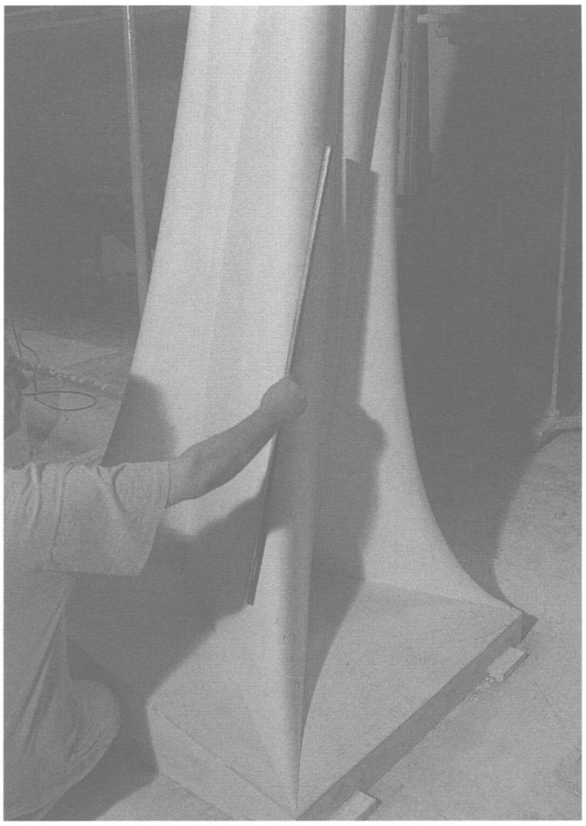
Constraining influence

Although I have stated that the column is composed of four complete and four bisected hyperbolic paraboloids, there is no physical evidence that the bisected hyperbolic paraboloids are, indeed, hyperbolic paraboloids. Hyperbolic paraboloids HP1-4 are incontrovertible on the basis that Gaudí, at the time that this particular assembly was being designed, worked exclusively in combinations of ruled and planar surfaces. Logically, in the opinion of the latter-day collaborators, the bisected forms ought to be hyperbolic paraboloids like their entire neighbours, but with their fourth points being virtual [Fig. 14], so conforming with the implied interconnectedness characteristic of the structural synthesis manifested in all of Gaudí's work. This virtual point 'VP' [Fig. 15] is the convergence of the three prototypical column axes more or less coincident with the capital of the single column below supporting the upper triforium. The form of the bisected surfaces, however, could equally be surmised as sectors of conoids [Fig. 16], an easier form to deduce and to make. The argument against this formulation is the fact that as at least one of these columns has a pronounced inclination, the arcs (equivalent of p1-p4) on all four sides of the column base would be ellipses with exaggerated eccentricity. This particular solution would mean that each of the three bases would have marked distortions, the severity being determined by the degree of inclination.

In choosing the parametric design strategy for any particular problem, the single most influential determinant to any component needs to be inserted as late in the process as possible. If we commence with the derivation

17a and 17b. Full-size gypsum-plaster masters from which glass-fibre moulds can be made. The parametric model took less than a day to prepare, each variation less than a minute to regenerate. In contrast it took two crafts people one month to make one of six columns.
18. Example of working drawing. All that is required by the plaster technicians is a full-size template of the column base and co-ordinates of the position of the template relative to start and end points of the lines that are the edges to the hyperbolic paraboloids.


17a


17b

of curves p1-4 as being 'conoid' at the beginning of the process, and decide subsequently to make use of hyperbolic paraboloids, there is no solution other than to completely disassemble the model and restart at that critical decision.

The dilemma of having to choose between different geometrical strategies for interpreting Gaudí's intentions, without written or oral record, exemplifies a fundamental problem of parametric design as a design strategy. The problem is as follows. Of the two geometries most likely to be the generator of the curves p1-p4, one has to be adopted; there is no twilight zone of either/or. The choice may well be a parameter within the intellectual process of form synthesis, but it is not permitted as a parameter within the linear process employed by parametric design software: a choice has to be made at the time that the particular geometry is inserted into the model, and cannot be varied subsequently. Parametric modelling is likely to result in retrospective knowledge of optimum strategies – a tendency towards being wiser after the event. Unfortunately, each non-parametric design decision can be a parameter in a greater parametric design, the overall design process. I do not believe that any of the commercial products properly cater for parametric design within parametric design, but they rely on the dissolution of major design strategies to a series of interrelated tactics. This is not inconsistent with the view that a building is made up of components.

Locating parametric design in practice

While there is hardly any debate on the subject in practice, even those uninitiated in this most interactive design medium will see that here is a tool which, while it comes closer to the popular conception of what a computer ought to do, nevertheless could trigger a disaster were it to be used to promote programmatic formal design methods.

The real or imagined potential for parametric design software is not at all clear-cut, and it would seem that very few architectural practices have tried it. Despite having the product in their office, Frank O. Gehry & Associates have seen no need to use parametric design: a stark contrast between theory and practice from one of the world's most creative exponents of architectural modelling using the computer. The case study, however, points to and can be used to speculate on an improved role for designing in tandem with the computer.

The contrast in the use of the computer between Frank O. Gehry & Associates and the latter-day Gaudí collaborators is indicative of the richness and diversity of high-end computer use in practice; it does not necessarily signal any other form of value judgement. Gehry, designing both conceptually and in detail in a world where the computer is established, can justifiably claim to be exploiting it to its full potential. Both Gaudí and Gehry rely on the physical model as their primary design device. Gehry, by digitising surfaces from 3D physical models, precludes the opportunity of parametric design with its attendant reliance on analytical geometry. Gaudí, by introducing second order geometries (ruled surfaces), has contrived to do exactly the opposite [Figs. 17-19]. Both seem valid when the authors and their times

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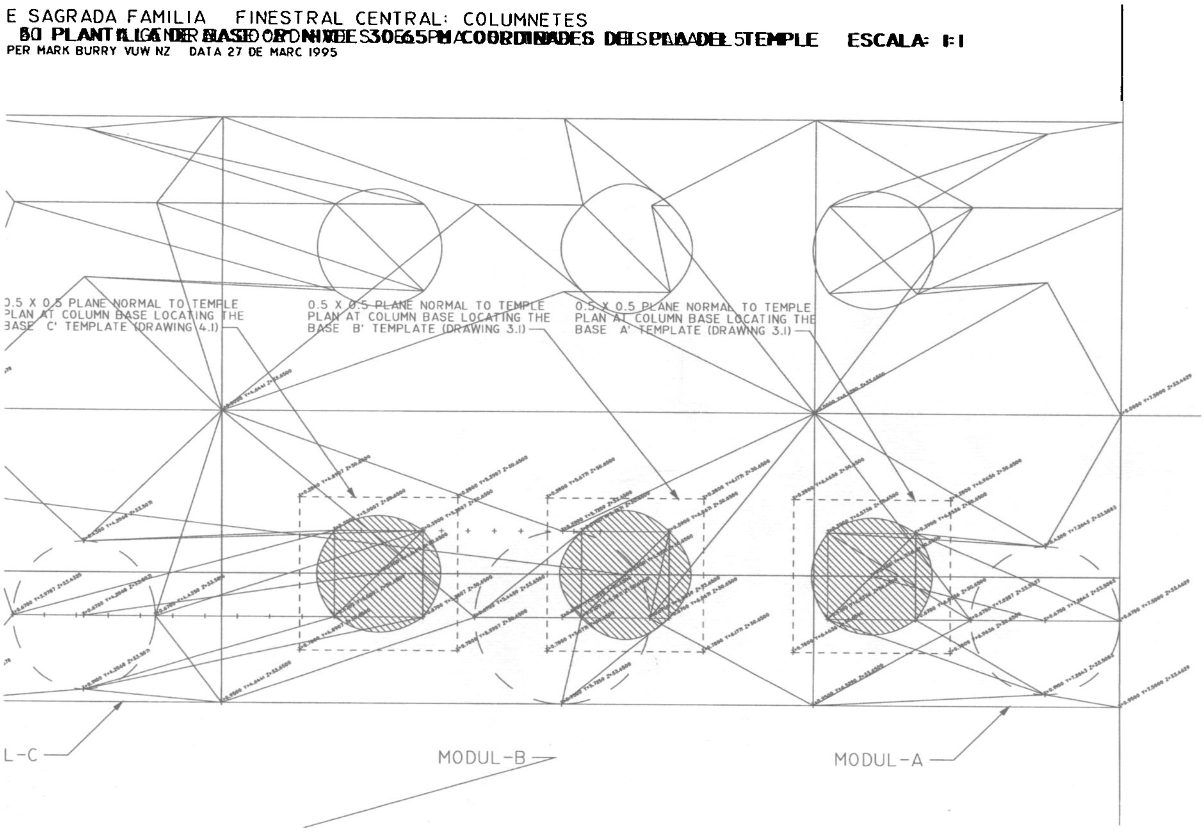

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are taken into context. My suspicion is that we are waiting for the artificial intelligence of computers to be raised to a level where we can interact more readily with 'givens' (such as the digitised model, the sculptor's output) rather than controlling the givens from the beginning of a design sequence, the situation encountered with the case study presented.

As matters stand, and beyond graphite, paper and physical modelling, design may still benefit from this entirely different *modus operandi*, bringing in the computer only when it comes to production description. At the very least, parametric design can make a unique contribution to fine tuning reasonably well-formed ideas which still lack the commitment of measurement necessary for building. And if the architecture being proposed is formally 'difficult', any device which promotes ready refinement and implementation must have its place.

The privileging of the 'big picture' in design education at the expense of the detail seems to ignore a routine undertaking in the practice of architecture: the resolution of the whole into coherently detailed parts. Fine architecture has been produced in the past without the aid of parametric design, but within a codex of forms and assemblies which have been simplified when compared to the output of other manufacturing industries. Cultural theory which successfully isolates the building of buildings from more weighty architectural discourse is now being tested in quite an insidious fashion: a generation of buildings which will need a deeper theoretical explanation than the tectonic issues seem to demand. High-Tech, in the main, and especially earlier work, does not reflect the precision found in other contemporary engineering output where the equivalent clunkiness is smoothed out through the influence of automation. Form-warpers such as Frank O. Gehry & Associates are dancing between the crudeness of both hand modelling and traditional building, and absolute reliance on the computer to describe form with numerical cogency.

As a paradigm for a useful design methodology, parametric design will always be in conflict with the comfortable looseness of architectural thinking. Mechanical engineers have had to develop a more sophisticated spatial sensibility than architects; their problems of constraining oddly-shaped, weirdly-moving parts have led to tools that aid the optimisation and containment of discrete parts and identify potential interferences between closely associated components. If it becomes a more accessible tool for the resolution and refinement of architectural detail, parametric design may yet have its place in less esoteric architectural production than that characterised by Gaudí.

At an educational level I have been surprised how quickly students learn to develop sophisticated word-processing macros and CAD scripts. As a practitioner I retain a level of dismay at how little time is available to experiment with software, as opposed to its immediate practical use. Paradigms that treat at least part of the process as parametric design begin to allow the computer to make a richer contribution. For most architectural practices, the incorporation of a fully-configured parametric design module in their CAD repertoire, remains unlikely. I would hope that its

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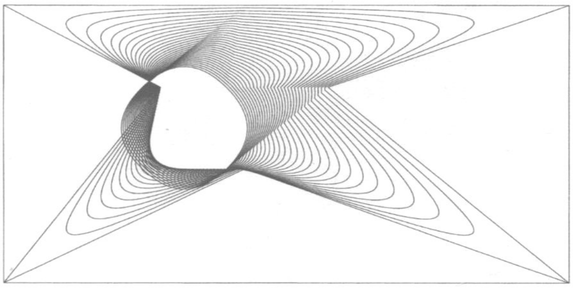
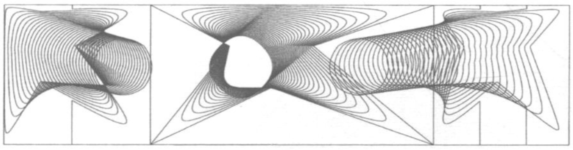
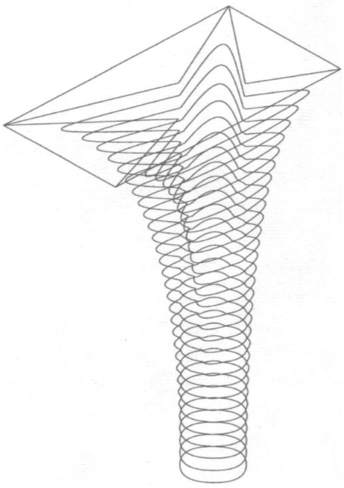
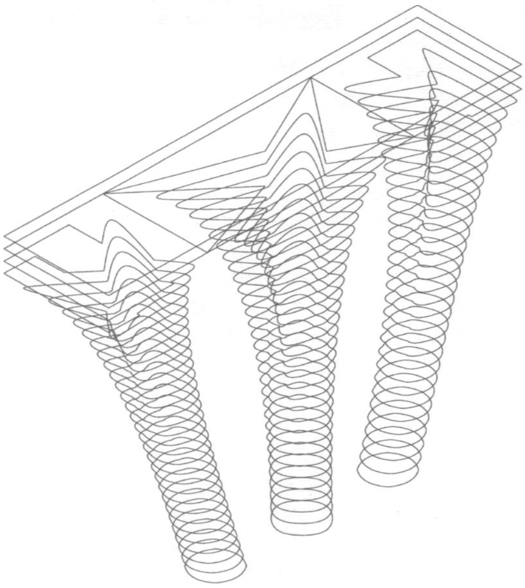
emergence as a more affordable tool will allow greater complexity and precision to components and assemblies, if not to the whole design. The case study shows that although the geometry of an assembly may not be complex, the manipulations may be. Any 'tool' which allows hybridisation to occur at an experimental but controllable level has a potential, still to be widely recognised, in current architectural practice. Others have commented on the need for an entirely new computer-aided design approach (Mitchell, 1992); as matters stand parametric design is a stop-gap for the adventurous. The tail does not need to wag the dog, for, by applying the medium to a small part of Gaudí's design, human invention is shown to remain at the forefront.


19a


19b


19c


19d

19a–d. Fringe benefits. The parametric modeller can section the model at given intervals, in this case 0.1 metres, essential for deriving satisfactory cover for reinforcement within sculpted surfaces.

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Acknowledgements

Jordi Bonet (Architect Director), Jordi Faulí (Project Architect); Professor Josep Gómez Serrano, Jordi Coll, Juan Carlos Melero (UPC). Victoria University of Wellington for research grants, Universitat Politecnica de Catalunya for various visiting appointments, FGH in Australia and CV in Spain for supply and support of CADDS5 software and SUN (New Zealand) for hardware support.

Biography

Mark Burry lectured at Victoria University in Wellington until June this year when he took up the Chair of Architecture and Building at Deakin University. He is an architect in private practice and is Consultant Architect to the Construction Committee of the Sagrada Familia Church where he has been responsible for much of the interpretation of Gaudí's original models for current construction purposes.

https://doi.org/10.1017/S1359135500003092 Published online by Cambridge University Press