COMPUTER AIDED ARCHITECTURAL DESIGN FUTURES 2005

Computer Aided Architectural Design Futures 2005

Proceedings of the 11th International CAAD Futures Conference held at the Vienna University of Technology, Vienna, Austria, on June 20–22, 2005

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Foreword

MARTENS Bob and BROWN Andre
Co-conference Chairs, CAAD Futures 2005

Computer Aided Architectural Design is a particularly dynamic field that is developing through the actions of architects, software developers, researchers, technologists, users, and society alike. CAAD tools in the architectural office are no longer prominent outsiders, but have become ubiquitous tools for all professionals in the design disciplines. At the same time, techniques and tools from other fields and uses, are entering the field of architectural design. This is exemplified by the tendency to speak of Information and Communication Technology as a field in which CAAD is embedded. Exciting new combinations are possible for those, who are firmly grounded in an understanding of architectural design and who have a clear vision of the potential use of ICT.

CAAD Futures 2005 called for innovative and original papers in the field of Computer Aided Architectural Design, that present rigorous, high-quality research and development work. Papers should point towards the future, but be based on a thorough understanding of the past and present. This book contains a selection of papers presented at the 11th CAAD Futures conference which took place at Vienna University of Technology; the following categories of double-blind peer-reviewed papers are included:

- Building Information Modelling and Construction Management;
- Design Methods, process and creativity;
- Digital Design, Representation and Visualization;
- Form and Fabric: Computer Integrated Construction and Manufacturing;
- Human-machine Interaction: Connecting the Physical and the Virtual;
- Knowledge Based Design and Generative Systems;
- Linking Education, Research and Practice;
- Virtual Heritage, Reconstruction and Histories

Over recent years the grouping of papers under headings of Virtual Environments, and Collaboration (or cooperation) has been common, but we have deliberately resisted the temptation to use these categories. These days the topics of virtual environments and collaboration are so common to much of the research undertaken that we need to be more specific in order to produce helpful classifications. We hope that the headings listed above do that.

Two decades of CAAD Futures conferences can be regarded as a quest for "Learning from the Past" (in line with the conference theme!). Up to the 2001 conference, paper-based proceedings were published in collaboration with renowned publishing houses. Since 2001, a limited number of CD-Roms were distributed to the conference participants. There are hardly any individual teachers, researchers, librarians, etc., who can claim to have a complete set of CAAD Futures proceedings, since some of the earlier works are out of stock. Making nearly two decades of teaching and research work in this specialized field of CAAD available would therefore be of great importance (approx. 5.500 pages) and allow the identification of a more tangible historical and developmental record. For authors this would encourage and enable wider dissemination of their published papers. eCAADe ("education and research in CAAD in europe" - www.ecaade.org) served as a collaborating partner with the CAAD Futures foundation to get this idea put into practice and took over the financial risk for the cost of digitisation. As soon as the complete "rough material" was available in the pdf-format the next step was to create two different final versions. The wider availability of CAAD Futures Proceedings for the period 1985 to 2003 has been accomplished on one hand by means of an off-line-version (CD-Rom) and on the other hand by an on-line-version in CUMINCAD (Cumulative Index on CAD - www.cumincad.scix.net). Considering the effort involved it could have been rather tempting only to scan-in the total package without separate text recordis, But this would have meant that a full-text search would not have been possible. In this aspect the Digital Proceedings differ considerably from their paper-based originals. Doubtless, a digital publication can be designed according to specific appearance requirements from the very beginning provided the paper-based form is only to act as a mere by-product.

ACKNOWLEDGEMENTS

We are indebted to Henri Achten, Urs Hirschberg and Ardeshir Mahdavi for their support to this conference as program Chairs. Hannu Penttilä provided boundless efforts concerning the maintenance of the web-based reviewing interface, which allowed us to stay within the tight deadlines.

Keynote Papers

Digitally Sponsored Convergence of Design Education, Research and Practice

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Keywords: transdisciplinary design, convergence, design practice, collaboration, post digital design

Abstract: This paper looks at examples of successful transdisciplinary design projects that oblige a departure from the typical assertion of sub-discipline distinctions. In doing so a case is made for a new convergence between architectural design education, research and practice. A case for post digital design will also be made, defined here as the comprehensive assimilation of the computer within traditional modes of design practice, offering a more natural and productive state of affairs than the exclusively digital office promulgated especially during the previous decade. The paper concludes with a demonstration of transdisciplinary design teaching and practice, offering a post digital design framework that require radical new approaches to education and practice. It is contended here that only when CAAD research is undertaken conjointly within teaching and practice can the links be properly formed between the two.

1 BACKGROUND

The history of computer-aided architectural design is now more than a generation in length. Given how far CAAD has come in this time, it is perhaps surprising that CAAD still means 'CAD' to many, and its presence in the architectural course is tolerated only through its apparent usefulness as CAD in the contemporary office. The status of CAAD has been primarily one attuned to the fortunes of early adopters on the quest for digital equivalents to traditional practice paradigms. Implicitly at least, the emphasis has been on extending the architects' range of commercial opportunity: increased efficiency as the prime motivator over the quest for design excellence in itself. For much of this period CAAD education has therefore been located at the program fringe with varying levels of interest from each academic community, but seldom touching the curriculum core. The critics of CA(A)D in the academy regard its insinuation into the program as an inexorable thief of time better devoted to other more valuable intellectual engagements.

Where CAAD is synonymous with design experimentation – the "*exciting new combinations*" referred to in the 'Conference Theme'- it runs contrary to the desires of conservative members of the teaching and practicing fraternity. These are often

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senior colleagues with a tighter grasp on the reins of power. Their misgivings become manifestly obvious during design reviews, for instance. A major unexpected challenge to the proselytising of those committed to progressing the work of the first generation CAAD pioneers is a younger set of reactionaries more inclined to oppose than progress the cause. 'Younger', in this context, refers to a significant cohort of potential movers and shakers who, whilst only in their thirties now, are unlucky enough to have just missed the easy access to more sophisticated software running on cheaper and considerably more powerful computers currently available to students – unless they have made strenuous counter-current steps gain access. In other words, not having been able to get their hands dirty in the way that 'studio' traditionally allows, can force designers with an otherwise reasonable disposition to tend towards a corner. It is one thing to accept a water colourist making a better go of it than oneself: at least we can judge our worth through our personal experience of a relatively familiar task. When the work is not only rather difficult to interpret against conventional composition, but has also emerged from a process that is quite foreign to the critic, special difficulties arise. We can see that our schools today are in a mode change that has no historical precedent for the practice of architecture, at least since the Industrial Revolution.

"*Learning from the past*" as a means to set "*a foundation for the future*" is thus a more loaded conference theme than might first appear. Through making a case in this brief paper for a digitally sponsored convergence of design education, research and practice, I shall try and sidestep any trite reverence for what has gone before, even that sufficiently robust to survive or thrive in today's context. Alignment with a trajectory of foregrounding the role and status of architectural rendering, faster and ever more accurate costing, tighter project management with the great strides in ICT (Information and Communication Technology) is a manifestly positive benchmark. But *only* to focus on ICT would risk missing some of the great benefits that we are beginning to derive from other shifts in thinking and action. The entry of "*techniques and tools from other fields and uses*" into our repertoire, as the conference theme notes, is surely the true stuff of innovation? This desire to borrow tools and techniques from elsewhere can only be satisfied effectively when we fracture inviolable discipline boundaries, a change requiring a significant cultural shift. This definition of innovation – the lifting of a skill set or tools from one discipline and applying it within another, is especially effective when one foot is kept in the past. This allows for the rediscovery of previously highly valued, latterly overlooked, transdisciplinary relationships whose worth has been judged irrelevant in a recent context. Moving forwards needs to be complemented by looking quizzically over our shoulders at what is being left behind.

Three case studies are offered here as examples of transdisciplinary advantage. Details of one historically grounded research project (Gaudí's Sagrada Família Church) are compared with two recent case studies (urban sculpture and student collaborative work). In all three examples I shall identify where the academy <-> practice <-> design research convergence emerges as a new enterprise, not merely a continuation of what we assume always to have been in place. In doing so, a shift in thinking and action is provoked, offering an essential new link between practice and the classroom – through the addition of CAAD 'research' into the traditional mix.

2. HISTORY

The history of the Sagrada Família Church in Barcelona, the architect Antoni Gaudí's *magnum* opus hardly needs to be told here. The building commenced in 1882 and was inherited by the young Gaudí a year later when the original architect, del Villar resigned on a point of principle: the client had asked the architect to build in a particular way in order to save money, which he regarded as unacceptable interference. Del Villar's proposal was for a relatively modest Gothic Revival church, whereas the young Gaudí quickly persuaded his client to be more ambitious.

Gaudí worked on this project for 43 years until his accidental death in 1926: he was mortally injured by a passing tram. In terms of Gaudí's ambition, the project was inadequately funded from the beginning, and as the project made at times very slow progress, he had the unusual luxury of being able to focus on aspects of the design that ordinarily would not be possible. In a way, notions of rapid process at that time were self-defeating. The complexity of Gaudí's design made the cost go up relative to del Villar's original design, placing increased demands on the limited funds available. Rather than simplify the design to meet the budget constraints, Gaudí used the time to seek means to rationalise the description of the building without compromising the plastic expression. Ironically, what he was proposing for his time was never practically achievable, which more or less remained the case until the arrival of the computer. The direction the project took during his last twelve years – the period when he had eschewed all secular commissions, devoting himself entirely to the project, was one of rigorous application of geometry. All the surfaces of the building from that point onwards were based on second order geometry, more commonly referred to as ruled-surfaces. The surfaces themselves are easy to describe and comprehend: the helicoids, the hyperboloid of revolution, and the hyperbolic paraboloid. Their articulation as a community of intersected forms is far more problematic from a representational viewpoint.

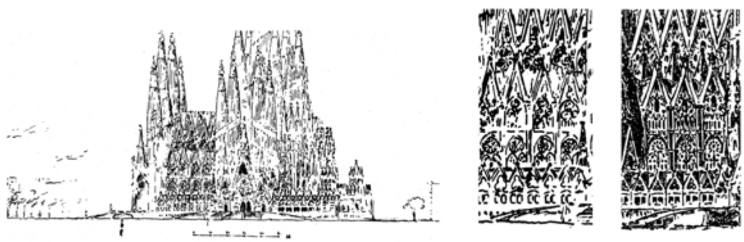


Figure 1 The first drawing to appear of the whole of the Sagrada Família Church, drawn by Gaudí's assistant Rubió in 1906: Gaudí died in 1926. Twenty years later we can see that the Gothic Revival moulding has been replaced by a more plastic surface treatment. In fact, Gaudí had spent the last twelve years of his life exploring second-order (ruled) surfaces, from aesthetic, philosophical, and practical points of advantage

Figures 1 show the project and the migration from freeform to rational geometry. On the left hand side is the first definitive drawing of the project by Gaudí produced by his assistant Rubió under his direction in 1906 – 23 years after his commission, that is, approximately half way through his work on the church. The drawing went through a series of iterative changes but remained the definitive statement of the overall composition right up to Gaudí's death in 1926. It is when we compare details of the first and last version of the sketch that we can see subtle changes, which are in fact the transition from freeform to ruled-surfaces, shown in the two excerpts that are side by side. This can be seen most clearly when we compare the clerestory window (the uppermost row); the window shown in the photograph of the 1:10 scale plaster of Paris model made by Gaudí (Figure 2) has been incorporated into the design. This photograph was taken before Gaudí's death, and is especially important as the models were subsequently smashed during the occupation of the incomplete church during the Spanish Civil War.

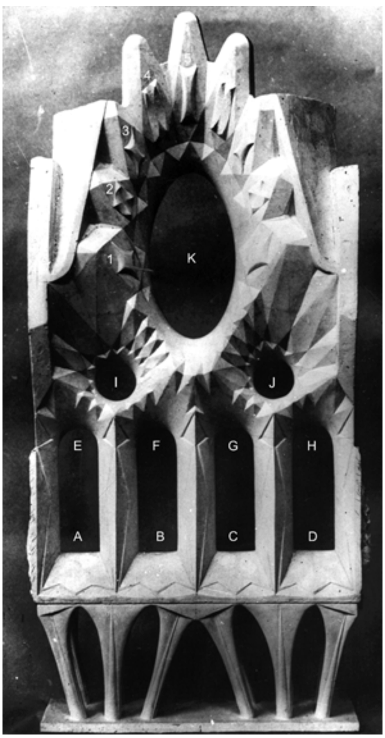


Figure 2 Sagrada Família Church clerestory window made at a scale of 1:10 during the years immediately preceding Gaudí's death in 1926. Each letter refers to the Boolean subtraction of a series of hyperboloids of revolution from a notional solid

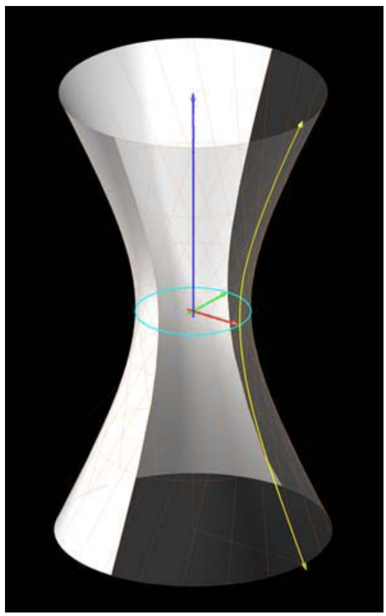


Figure 3 Hyperboloid of revolution showing the 9 parameters that can alter its relationship between neighbours. These are 3 Cartesian coordinates, three axes of rotation about each Cartesian axis, two constants th at determine the 'waist' (collar) dimensions, and a third that defines the asymptote that determines the hyperbolic curvature

Overlaid in the photograph are a series of letters referring to hyperboloids of revolution: ruled-surfaces which have been subtracted from the notional wall mass as a Boolean operation. The formal description of a hyperboloid of revolution is shown in Figure 3. Each hyperboloid of revolution has nine constituent parameters that govern its relationship to neighbouring hyperboloids in a geometrical array. When the values of these parameters change *inter alia*, not only is there an extraordinarily detailed disguising the underlying rationalist composition, there is also and extraordinary range of possibilities. The nine parameters are shown in Figure 3.

What makes this project transdisciplinary, a research project, and why would a university be involved?

3. PRE-DIGITAL INTERVENTION

I have worked as consultant architect to the Sagrada Família Church since 1979, commencing as a 'year out' student. During this time I worked on most of the nave construction which has been developed with archaeologically derived geometrical precision from the surviving fragments of plaster of Paris model such as the clerestory window shown in Figure 2. Gaudí had a highly original working method whereby he personally intervened with the craftspeople working with him. In interpreting his design for the nave his successors did not have the advantage of actually composing the building with all the possibilities of direct engagement with the model makers and a slow timeframe within which to cogitate – the latter-day task was essentially one of reverse engineering. My role was to attempt to speed-up the process from one of haptic engagement with rapidly setting plaster of Paris to the cleaner process of descriptive geometry analysed on paper. Predating any thoughts of computers, solid geometry, Boolean operations, or even wire frame representations, the work was fundamentally a mapping exercise. Intersecting these forms in space graphically was a challenge only when interpreting the task from a purely architectural focus. Indeed, while in that mindset, and having only just emerged from my late Modernist chrysalis, my resolution of the task was proceeding nowhere until the quantum leap into cartography. Only when each form was conceived as a terrain with contours could an effective method of intersecting adjacent geometries be derived. Figure 4 shows the side view of a hyperboloid of revolution raised typically to meet the source of natural light thereby distinguishing the exterior (left hand side) and making for richer architectonic expression. Combining inclination of forms with elliptical rather than circular inducing parameters no doubt enlivened the composition; it also has to be admitted that this confounded the cartographical quest many times over.

Figure 5 shows the notional area view of the hyperbolic terrain, effectively the façade. The map shows the positions of each hyperboloid of revolution collar or throat relative to each other, the curves of intersection between the adjacent forms, and more acutely, the points of intersection between any three such curves known as *triple points*. As the composition was based on a system of proportion relatively

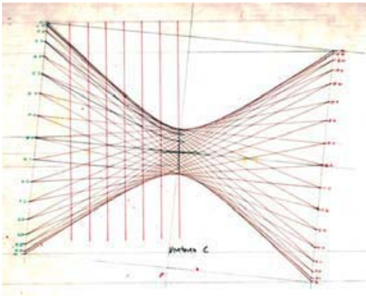


Figure 4 Graphical representation of the parameters

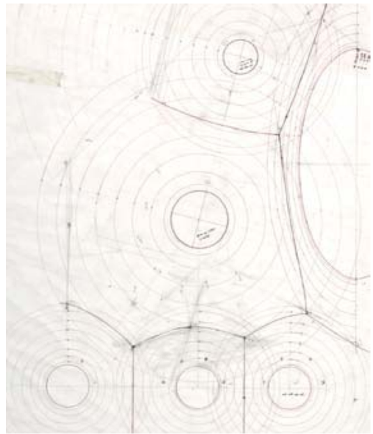


Figure 5 Contours are derived in order to find the intersections

easily derived from the surviving photographs, the fact that the models were in fragments was not the same problem that the team would have been faced with if, say, we were confronted with a similar scenario for the *Casa Milá (La Pedrera)*, the nearby freeform Gaudí apartment block, that mercifully was completed in Gaudí's time. As in any genetic puzzle, with sufficient triple points providing an x, y, and z coordinates common to three intersecting hyperboloids of revolution, the task of reverse engineering was rendered 'not impossible'… but relatively impossible if we continued working using graphical analysis and cartographical constructs.

4. DIGITAL INTERVENTION

In 1989 the first real application of Gaudí's sophisticated ruled-surface geometry was nearing a point of being programmed for building and we were obliged to look at the computer as an aid to speed-up an otherwise unremittingly slow process. At that time it was not clear how these digital explorations might take place, still less where. The investment at that time into an emerging technology without any clear idea of which, if any software would be able to adequately advance the task appeared to be too great, so the opportunity of taking the work into the academic research environment appeared to be a good first move. Within three months it became clear that there was no proprietary software package dedicated for architectural use anywhere in the market capable of doing the tasks, despite many confident assurances to the contrary by the manufacturers concerned. In fact today, whilst the architectural software has come along very significantly, there is no single package that we are aware of that can perform all the tasks required, which is why a significant proportion of the research work undertaken to advance the project takes place in the academy. And it is this essential paradox that makes the Sagrada Família Church such an interesting subject in the debate that connects the fortunes of the future with the experiences of the past.

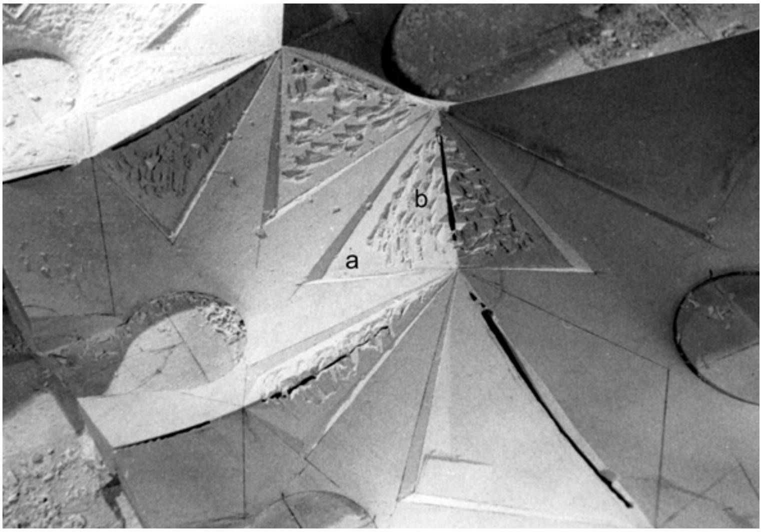


Figure 6 Gaudí probably derived all his large scale models from an iterative hands-on process working more with plaster of Paris than with a pencil

Figure 6 reveals the 3D translation in plaster of Paris from the 2D drawn abstractions, typified by the drawing shown in Figure 5. The curves of intersection and associated triple points can be seen, and the system of decoration allied to the ruled-surfaces' rulings are clear. The translation from Gaudí's hand-making research techniques, through the descriptive geometry to the computer was not an obvious one. Where the relatively weak demands of the architect on 3D spatial modelling had failed to stimulate a market for sophisticated product, the demands of the aero, auto, and marine designers had. Software directed to all three sectors revealed just how sophisticated their needs for complex surface and spatial representation were in comparison. Their software, which quickly revealed its usefulness, was and remains in a cost structure far beyond the reach of most of the construction sector, and today we are still waiting for such product to emerge at an industry appropriate price point. This point is rapidly being reached, fortunately. Fifteen years earlier than the time of writing, software with the capacity to make a series of progressive Boolean operations was esoteric within the architects' world to the point of obscurity. Figure 7, being read from top left to bottom right, however, reveals the power of such operations in the production of Gaudinian form. It is fascinating that the use of software at the time of its first contribution at the Sagrada Família Church was as atypical then as the intellectual and conceptual processes that Gaudí was able to apply to his work in his time. It seems very apposite that he proposed a design methodology initially perceived as quirky by most of those I demonstrated it to in the early days of its use. Yet it appears highly contemporary now.

Figure 7 shows but one iteration in the search for a precision version of the clerestory window that was needed to match the original. While the process was far more rapid than my earlier pursuit by hand drawing, and quicker still than the modelling from Gaudí's time, it was clear from the beginning that we were only making minimal use of the softwares' potential, which led to Project Architect Jordi Faulí's suggestion that we engage directly with the mathematics underlying the ruled-surface geometry.

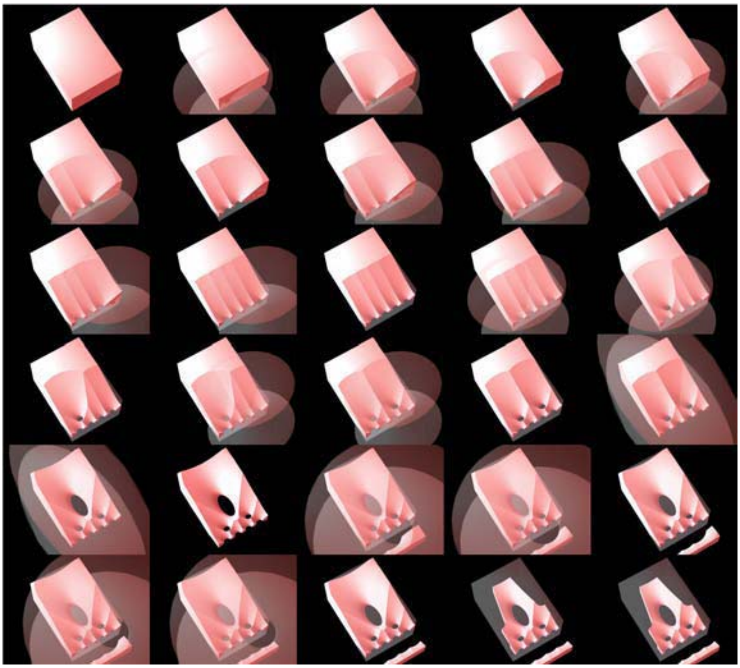
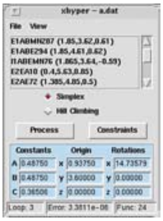


Figure 7 series of Boolean subtractions echoing through the use of the computer an analogue process. The process reads from top left to bottom right

Figure 11 (LHS) shows a detail of a restored fragment of Gaudí's 1:10 model of the clerestory (Figure 2). The surviving fragments of the exterior and interior faces of this window together offer over five hundred points in space. With painstaking care, all these were measured using homemade equipment giving us a series of data files with the 3D coordinates relating to each hyperboloids of revolution. It took twelve person weeks to take these measurements and record them in 1992, this being a year or two ahead of the office of Gehry Partners and their access to medical measuring kit. As a point of interest, in 2003 this work was repeated using a laser scanner returning a point cloud of coordinates in the millions for the same surfaces, such have been the advances during the last decade.

5. BESPOKE SOFTWARE

To find the combination of hyperboloids of revolutions that would match the data extracted from the models, each data file was read into a program *xhyper* written by Peter Wood at Victoria University of Wellington in 1994.



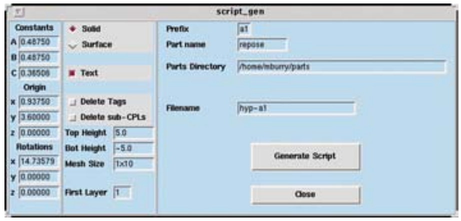


Figure 8 (LHS) The Program *xhyper* written by Peter Wood. Figure 9 (RHS): The data coming from *xhyper* is then post processed by another program *script_gen* written for the purpose of generating an executable script

The data files (Figure 8) identified the points as being crucial, such as the triple points and points around the throat (collar). The next level of importance were the points on the intersection curves while the points on the surfaces (around the borders of the facetted decoration, for example) were regarded as the least accurate, especially as we suspected most of the surfaces to be from elliptical hyperboloids of revolution, and therefore manually interpolated rather than specifically 'found' in space. The points that are listed in the upper window of Figure 8 show the distinction: the letter commencing each descriptor identifies whether the point is exterior or interior, and the sequence that follows identifies the weighting for each point along with its unique identifier. The program Xhyper then used one of two algorithms 'Simplex' or 'Hill Climbing' (depending on the number of variables and/or unknowns in terms of the 9 parameters shown in Figure 3).

At that time the only opportunities that existed for this level of number crunching was to use the Unix platform and x windows – we had tried a very primitive prototype using Basic with DOS, and again it seems that little details like this remind us just how far we have come in a relatively short time.

Having produced a program that was able to match hypothetical but accurate hyperboloids of revolution to the data sets gathered from the laboratory measurements of the surviving models, the next logical step was to tie the output directly to a 3D digital model. This we did by writing an executable script *Script_gen* which output a CSV text that would make each hyperboloid in space for subsequent Boolean operations (Figure 7). A further script performed the sequence of subtractions, labelled and dimensioned the model. The whole operation took just one hour to run for each iteration which was the equivalent of several months of 'cartography' with further months of plaster modelling. Having said this, ninety six iterations were required: the rotation parameter only had to change by 0.25^{o} for a substantial change to result in the curves of intersection, and more importantly the triple points. Just at the time when we felt that as a team we could congratulate ourselves on the finesse we had brought to the task, we would pull ourselves up short as we realised that Gaudí managed this finesse in his head, without the need for ninety six variations. In fact, we know of only two.

Figure 10 compares the trimmed hypothetical surfaces resulting from *xhyper* with the points and connecting lines measured in space on the original models, and the close match can be appreciated.

Figure 10 Comparison of trimmed ruled-surfaces as intersected 'optimised' hyperboloids of revolution shown against the wireframe of actual data

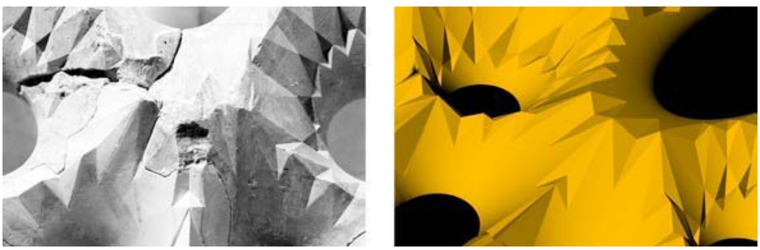


Figure 11 Final computed and digitally represented outcome

Figure 12 Digitally modelled exterior to the Sagrada Família nave clerestory

Finding the parent surfaces was actually just the beginning; the decoration and other embellishment contingent on the abilities of the software at that time in being able to trim surfaces, and ultimately build competent solids. Figure 12 shows the 3D digital model completed in 1994, and can be compared with the photograph (Figure 2), which we suspect dates from 1922.

For the last decade we have been experimenting with parametric design, the first instance of its direct application to the Sagrada Família Church being the row of columns that form the triforium below the clerestory. This detailed account for the design of the now constructed window along the length of the central nave is to provide insight into how a diverse team first had to be formed in order to accommodate Gaudí's unique way of working, provoking a resident expertise in ways to get the best out of collaboration with the computer.

An assertion that the Sagrada Família Church is one of the world's most progressive projects, and not the anachronism that so many have presumed, requires some justification. Rather than posit the analysis, interpretation, and resolution of the models, followed by the synthesis and ultimately the application of the ruled-surfaces described above as being the main innovation, I believe that there are other more fundamental values being established through the project. Principally, it is the actual teamwork behind the project that offers an alternative model of practice. The way the digital opportunities have been approached, and what this represents in a context extending far beyond the particular idiosyncrasies and needs of the Sagrada Família Church offers some new foundations firmly rooted in the past. The project has embraced a dialogue with research groups at several universities, and stimulated (almost) a generation of students on that basis.

6. TRANSDISCIPLINARY DESIGN COLLABORATION

The following table delineates the contribution from the transdisciplinary design team, outlining their contribution and the phases of the project that they contributed to.

Table 1 Transdisciplinary design collaboration (Sagrada Família Church)

Discipline	Contribution	Phase of project
Architects (prior to 1989)	Conceptual design – Gaudí died in 1926 leaving the design for the remaining two transepts based on the almost completed Nativity Façade, the nave fully modelled at scales of 1:25 and 1:10, the whole composition sketched (Figure 1) as a plan, section and elevation, and models for the sacristies designed to be prototypes for the remaining towers (other than the transepts).	The client regards the building as 'Gaudí's project', and Gaudí is referred to today as the Sagrada Família Church's architect.
Archaeologist	The models were severely damaged with the fragments dispersed around site such that they are still being recovered. These have	From 2000 the project has moved to the central crossing and apse area that was documented by Gaudí only

	had to be looked for, then identified, catalogued and stored.	as sketches. Vital pieces of his known experimental work that can be seen in photographs are still sought and profited on when found.
Archivist	All Gaudí's drawings and models were burnt during the Spanish Civil War. The handful of surviving drawings and photographs had to be looked for and assessed for their usefulness	This role has been essential and maintained on site since Gaudí's death.
Draftspersons	Basic information needed to be extracted from the model fragments, initially as measured drawings, more recently as 3D scans	Essential in Gaudí's day, now increasingly irrelevant as the direct modelling to production opportunities increase
Model makers	The surviving fragments of model had to be reassembled into as close an approximation of the original model as possible. The model makers have also had to invent machinery and techniques to allow Gaudí's haptic experimentation to continue. Ultimately the model makes need to make the precision versions of the applied geometry at scales of 1:25 and 1:10 to 'test' the proposals prior to actual building. Rapid prototyping contributes to this process but has not replaced it.	Despite the heavy use of rapid prototyping on site via 3D printers, the number of model makers has risen on site indicating their prominent role, not just as scale modellers but as production modellers for 1:1 moulds etc.
Historian	Because of the cultural significance of this building, and the many mysteries that surround it, almost all moves have to be qualified by an historical perspective. Significant material continues to turn-up such as the urban plan for the 'star-shaped plaza' surrounding the building, lodged with the Town Council in the 1910s, and only just located during recent years.	The building's historical context manifestly becomes more complex with the passage of time
Cartographer / descriptive geometers	All the surfaces are based on a rational geometry, principally ruled-surfaces. Their interrelationships are not in the typical province of the architect although it is noted here that the School of Architecture in Barcelona retains a Department of Descriptive Geometry (recently renamed to fit the times).	Always important, the arrival of 3D laser measuring and other scanning techniques makes the topographers' role evermore prominent
Mathematicians	To rely on graphical analysis alone, while substantially speeding-up the process, is not enough, especially once digital assistance is sought. In order to enter the geometry into the computer, while possible through mimicking the hand drawn techniques, it is far more efficient to do so as mathematical formulae. While recognising that this task is relatively trivial for the mathematician, it is well beyond the skill set of a typical architect	Mathematicians have only entered the project once it became clear that efficiency through the use of software depended substantially on direct mathematical input
Programmers	If we are going to work with formulae, it is not enough to rely on proprietary software	Once mathematics became a core component to software use,

	interfaces, and necessarily programmers are required to adapt such packages to the particular needs of the project.	programming was required to make full use of their contribution given the potential of any given package was significantly enhanced beyond 'out-of-the-box' capability.
Structural engineers	Every move made at the Sagrada Família Church has to be qualified structurally as Gaudí has setup the whole building as a piece of equilibrated design.	As the building becomes higher, and regarding making use of existing foundations, the role of the structural designer becomes more significant, especially in the pursuit of increased material strength and performance.
Architects (after 1989)	The role of the Sagrada Família Church architects since 1989 have necessarily encompassed the use of the computer, and with it necessarily are quite different from any that went before. Points of commonality remain the sketch pad and the gesture. In all other respects the working practice is entirely different, as are the relationships between the architects and collaborators which are probably far less hierarchical than used to be the case.	The shifts in the role of the architects and the particularities of the construction evolution seem to be intimately tied and co-dependent. The role of the architect is changing significantly, with the emergence of specialist 'project design architects' and 'detailed design architects'
Boat builders	Much of the building needs to be prototyped at full-scale for the purpose of testing the design visually or making moulds. He architects have relied on the nautical industry for many of the techniques, just as Gaudí himself used boat builders for the structure of his 'La Pedrera' apartment building.	It is clear that Gaudí has relied on peripheral and improbably connected skill-bases outwith the construction industry from the first, as much as he drew deeply from the oldest traditions.
Topographers	The nature of the design requires topographers to measure the building as much in the air as on the ground, and connect almost on a daily basis with the architects.	This role has evolved from surveying to 'spatial collaboration', and is expected to become more so as the project becomes more complex.
CAD/CAM Auto engineers	All work that can be practicably undertaken by CNC techniques is done so using a skill base imported directly from the auto and aero industry.	Once the shift to manufacturing processes has been made it is assumed that the new processes will acquire their own AEC identity.
Stonemasons	It is impossible to work on this project without engaging the stonemasons from the moment of inception. All aspects today push the use of stone to new limits both in terms of production and performance, which has been the case since Gaudí first led the building project.	Towards the end of his involvement Gaudí himself experimented in composite materials, notably with the design and execution of the Nativity Façade belltower finials. At this point the history of the project shows new materials and techniques being added to the mix rather than replacing any.

7. POST DIGITAL TRANSDISCIPLINARY DESIGN COLLABORATION: 'SHOAL FLY BY'

Table 1 shows the various core disciplines, the role their members played, and the stages of the project that they contributed to. If the story ended there it would be an interesting piece of history. However, the project that follows shows that the methodologies and new research relationships with the academy are as potent for contemporary projects, and that they do not have to be 'cathedral scale'.

In 2002 two architects / artists from a small town outside Melbourne Australia contacted our research facility based at RMIT University. They had heard of our work with the Sagrada Família Church and wondered if we could provide some assistance with building a competition piece that they had won. When they visited the brought with them a maquette of the piece 'Shoal Fly By' – one of five intended pieces to adorn the new waterfront of the Docklands urban renewal project in Melbourne (Figure 13). The pieces, inspired by the idea of engaging the passer by with a shoal of fish, at the scale of the maquette, were relatively miniature delicate assemblies of twisted wire with the odd pink 'shape' being held aloft.

Our first step, under project leadership of Andrew Maher, was to engage the tube benders and fabricators at the beginning, and in every conversation involving ways and means to construct the pieces with the designers. This was a direct lesson from the Sagrada Família Church, and one that yielded immediate dividends.

Figure 13 Post digital teamwork: artists Michael Bellemo and Cat Macleod discuss their maquette for a 90 metre long sculpture 'Shoal Fly By'

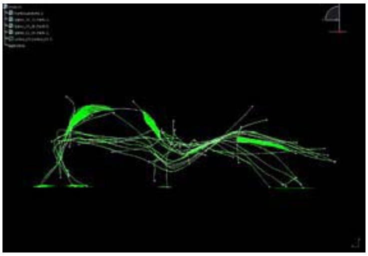


Figure 14 The maquettes were scanned in 3D producing a cloud formed from millions of points in space

We scanned the model (Figures 13 and 14), and took the point cloud into a parametric modelling environment, with which we produced a 3D digital model for the designers to sign off. From this point, the 3D digital representation of the model held no further interest to us. Each strand of the model was extracted as a tube following a nurbs curve.

There being no facility in Melbourne remotely capable of bending a nurbs curve, we had to find a way of working in a series of cotangent arcs (Figure 15). Peter Wood in Wellington was again the computer programmer who provided an interface between us and our instrument.

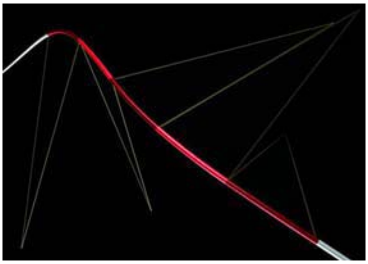


Figure 15 Each strand has to be rationalised as a series of cotangent arcs that seamlessly join

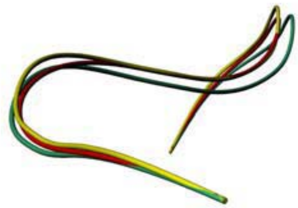


Figure 16 Using more arcs per strand raises the cost but closes the gap between the original and its rationalised equivalent

We worked with a model of each strand, and in discussion with the tube benders and the fabricators, were able to establish a 'so many arcs per strand' agreement. If we had a large number of arcs with which to engage, we could seamlessly approximate the original nurbs curve very closely, but the cost would be relatively high. Figure 16 shows that by reducing the number of cotangent arcs lowered the overall cost but downgraded the degree of match. Our program allowed us to tinker in the presence of the builders and architects / artists resolving the project to acceptable margins to all concerned. The characteristics and kinks of each strand that were important to the projects authors survived their digital translation perfectly. Figure 17 is a view of the digital project.

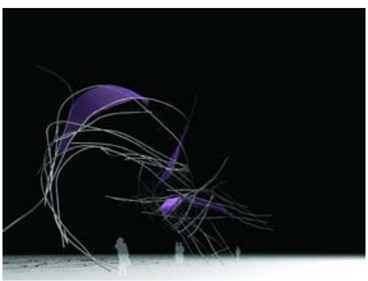


Figure 17 Digital rendering

Figure 18 The arcs become strands

Three other innovations added value to this project. The first was the absence of any drawings. Once the strands had been resolved into arcs using our program, their detailing was entirely by spreadsheet. The tube benders and fabricators worked entirely from this source, the columns providing respectively the radius, length and curvature of the arcs, and the positions in space and relative rotation.

The second innovation was inadvertently hitting upon the escape route of the bread and salami approach to 'blob solving'. It seems that one of the greatest digital triumphs today is fabrication based on the digital resolution of sufficient 2D profiles to provide a structural solution to any weird shaped building. With the method described above, the structural layout may be considered as 3D curves based on any criteria and not solely on a slicing routine within the software. The isoparms on the surface, for example, can be extracted and be used as the guides for appropriately sized structural members composed of cotangent arcs. Although we have since discovered two other teams hitting upon this method for solving the 3D curved edge to a spatial element, we believe that this the first structure of its kind conceding completely to the spatial design, and not the more typical *vice versa*.

Finally, the third innovation was to involve two senior students in this project firstly as an elective study during semester, and then as summer scholars. Rather than simply being on the payroll (which of course they were), the emphasis was on co-ownership. And in working in this way, the power of the analogue balanced very well the digital intervention, providing a powerful post digital experience for all.

The project has two of the intended five pieces built along the new waterfront (Figures 19 and 20). The longest will be approximately 90 metres, somewhat larger than the model that came in a shoebox, the essential analogue constituent to what was otherwise a purely digital progression to completed artefact.

Figure 19 The sculpture was made and first erected in an industrial building

Figure 20 The first of five 'Shoal Fly By' sculptures in place

Table 2 Transdisciplinary design collaboration ('Shoal Fly By')

Discipline	Contribution	Phase of project
Architects / artists	Conceptual design – the project was fully developed from the outset as an analogue physical model.	The project originators were fully involved through the entire project.
Draftspersons (research assistants)	Basic information needed to be extracted from the model fragments as 3D scans	Skills in scanning required for the initial digital design phases only

Model makers	A dummy model had to be made initially top perfect the scanning techniques given the combination of the original model's fragility, and the fact that the authors wanted it to remain intact	Despite the heavy use of rapid prototyping on site via 3D printers, the number of model makers has risen on site indicating their prominent role, not just as scale modellers but as production modellers for 1:1 moulds etc.
Tube benders	The tube bender needed to be consulted from the beginning to reach a common position on hows and when	Crucial at the early stages they were nevertheless fully involved right up until fabrication
Fabricators	The fabricators were consulted from the beginning to reach a common position on the ways the project would be built. The dialogue with the fabricator remained steady and crucial throughout the project.	
Mathematicians	To rely on graphical analysis alone, while substantially speeding-up the process, is not enough, especially once digital assistance is sought. In order to enter the geometry into the computer, while possible through mimicking the hand drawn techniques, it is far more efficient to do so as mathematical formulae. While recognising that this task is relatively trivial for the mathematician, it is well beyond the skill set of a typical architect	Mathematicians entered the project at the commencement since we realised from the Sagrada Família Church project that efficiency through the use of software depended substantially on direct mathematical input.
Programmers	As with the Sagrada Família Church, if we are going to work with formulae, it is not enough to rely on proprietary software interfaces, and necessarily programmers are required to adapt such packages to the particular needs of the project.	Mathematics was a core component to software use from the outset, programming was required to make full use of their contribution given the potential of any given package was significantly enhanced beyond 'out-of-the-box' capability.
Structural engineers	Involved from the commencement with a certain amount of risk taking being undertaken, given the desired slenderness of the tubes selected.	More involved at the outset with the project originators, and not especially involved with the digital design development at all, as far as we could discern.
Design development architects (after the conceptual design phase)	The role of the design development architects commenced after the conclusion of the conceptual design. This would on paper appear not to be ideal, but in fact worked fine in that there were no discernable tangled egos or vanities throughout the project, the biggest killer to post digital design shared authorship projects such as these.	The design development architects came in after the competition had been won, so there was never any competing agenda: the design, as a winning concept, belongs to the competition winners.
Topographers	The nature of the design requires 'topographers' to measure the structure as much in the air as on the ground, and connect almost on a daily basis with the architects.	This role has evolved from surveying to 'spatial collaboration', and is expected to become more so as complex projects such as this place far greater demands on the spatial 'fixer'.

8. POST DIGITAL TRANSDISCIPLINARY DESIGN COLLABORATION: 'THE POLITICS OF WATER'

The final transdisciplinary post digital project to be described here, the *Politics of Water*, is one of the outcomes from a studio we ran last year with a mixture of architecture and industrial design students. Features of the studio were derived from the very positive experience we had with the *Shoal Fly By* project the year before.

The *Politics of Water* studio was conceived as a semester long project in three stages – two research-through-design focused and one more conventionally applied research. In t he first stage the class worked individually coming to terms with the designer's opportunities to express the physical and political attributes of water. There were no expectations of difference in approach anticipated between the architects and the industrial designers. In the second phase, however, a distinction was expected as each student worked on a project based on or around water at any scale that suited them. An architecture student Tatu Parsinnen, for instance, proposed a grid-shelled concrete swimming baths on the water where the tide movement outside manifested itself inside (Figure 21 LHS). Industrial designers worked on projects such as a new kind of umbrella to objects of a far more esoteric nature.

Figure 21 Original proposal for a public baths (LHS); modified with window opening sizes are determined by the activities within the swimming pool (RHS)

For the final phase, the students formed into groups from both disciplines, each working on a project that did not come from any of the group members – the role of author and the concept of authorship was questioned through the detailed design development of someone else's baby. Figure 21 RHS shows the effects of the major conceptual leap the inheritors made to Tatu's project, ultimately blessed by the original author, I hasten to point out. Why, they asked, given the various levels of privacy required in the different areas of the pool, were all the windows the same size?

This question was dealt with using *Photoshop* where the group did nothing apart from coaxing the grid into more generous areas of glass, and others into tighter areas. Stung (perhaps) by the criticism that they had locked the 'developer' into a project requiring umpteen unique pieces of glass, they set about resolving this challenge parametrically. This they achieved through an analogue parametric model shown in Figure 22. The theory runs thus: each exterior opening is set by the expanding and contracting distortion of the original grid. Using a range of only 5 rectilinear sheets of glass, these would be moved in space until a workable opening to the interior of the space was found through experimentation – shown in the model through the rubber band quadrilaterals stretched by the parametrically alterable positions for the edges to the reveals. Figure 22 LHS and centre show two solutions to the exterior opening, and RHS shows them both superimposed. In seeking to provide evidence for a digitally sponsored convergence of design education, research and practice, I believe that this project along with the other four companion projects from the studio provides a compelling case for fusing architecture and industrial design students and their respective design sensibilities.

Figure 22 There are five sizes of glass proposed for the swimming pool, but many more variants for the actual opening sizes can be found using this analogue parametric model

9. CONCLUDING COMMENTS

Motivated by the observable practice uptake (predominantly 3D rendered images and animations, 2D drafting and associated text management), investigations into the extent to which the computer actually assists in the design process have been secondary to more pragmatic goals in most schools and practices. 'Design' software development has been progressively providing a more persuasive exposition of the design outcome – such as the precise 2D drafting that describes the building to the builder, and a broad range of value added services including virtual 3D modelling, model rendering, image manipulation, animation, and production management. Software dedicated to each or several of these tasks continues to dominate in practice, which is less inclined to take up the design exploratory tools favoured by some sectors of the academy.

Much is made of the ongoing debate in which the possible augmentation of design process through digital intervention is pitted against the presumed ability of the computer to take an eventual lead in design synthesis. The dilemmas about the desirability and viability of CSAD (*computer sponsored architectural design*) have perhaps masked tendencies that are becoming ever more manifest, which represent quite different opportunities for architectural designers regardless of individual software development strategies: convergence between design education, research and practice. This convergence not only offers fluency across all three areas of activity within the discipline, it also erodes the preciously guarded delimitation of architecture as a discrete and professionally protected discipline.