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architectural design based

on parametric variation

and associative geometry

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ARCHITECTURAL DESIGN
BASED ON PARAMETRIC
VARIATION AND ASSOCIATIVE
GEOMETRY

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Abstract. This paper considers the role of the computer for detailed design within the wider architectural design process. The central proposition is that parametric modelling software is invaluable for both preliminary and developed design where there is a need for the definition, manipulation and
visualisation of complex geometry. The paper begins with a definition of ‘parametric design’ followed by a consideration of its potential to assist or hinder the designer. A worked example will demonstrate how the elements that make up a model can be referenced to each other using a number of clearly defined constraints, the completed model being changed, modified and regenerated while conforming to pre-set conditions. This will be followed by a report on research into the implications of parametric design modelling applied retrospectively to Jørn Utzon’s documented design process for the Sydney Opera House. The study analyses how conventional modelling coped with the manipulation of these forms and compares this with the potential of computer-aided iterative design refinement.
Although parametric design (also known as 'associative geometry') has been available commercially for at least a decade, it is not used in the typical architect's office. It is expensive and requires high-end computers; a typical installation could approach $US100,000 for software and hardware placing it beyond the reach of most architects. Parametric design software has been developed principally for mechanical engineers, civil engineers, industrial designers and for the transport industry all of whom make good use of products that allow the 'whole' to be resolved into a large number of associated and adaptable parts.

[Figure 1] shows a set of two objects with their dimensioned relationships. This example can be referred to as an explicit design. Any of the dimensioned parameters can be changed, but only through a sequence of erasures and redrawing. A parametrically generated model can be 'updated' by identifying one or more of the parameters and changing their values. [Figure 2] is an example of a parametrically generated model and shows the difference in philosophy between explicit and associative geometry. [Figure 3] shows the topological effect of reconfiguring the parameters.
Figure 1
Figure 2
Figure 3
[Figure 4] can be compared with the previous figure in order to illustrate an immediate problem. The original design intention was based on a circle and a rectangle. A problem occurs if the designer wishes to reconfigure the geometry to, say, a rectangle and an ellipse. When the circle is the last element to be inserted into the model it can be readily changed to an ellipse by deleting the circle and substituting it with an ellipse. If the decision to insert a circle is made earlier on in the design sequence it cannot be simply changed subsequently to an ellipse: the computer does not have the necessary artificial intelligence with which it can predict what effects the change will have on later decisions. It does not appear to be possible to revisit the decision-path even though, in retrospect, the subsequent decisions are known. The parametric design modeller records all decisions in a logical path. When the diameter of the circle is changed, for example, it will revisit every decision in sequence and look for any linked implications. A relationship that enjoys a wide range of variability and is possible at the time that it is implemented can become unexpectedly constrained by later and apparently unrelated decisions. The designer can paint himself or herself into a corner, as it were, especially if they have not prepared a clear structure with which they can assemble the parametric model. In other words, the designer needs to be organised in a way that
traditional media place no such demands.
Figure 4
If the designer can identify the degree of flexibility that they require for each decision, they can make arrangements within the construction of the model. The ellipse example, depending on the way it is constructed can be changed to a circle later by making both axes the same length. This is not possible, obviously, if the original geometry is inserted as circle defined with a radius or a diameter. [Figure 5], however, shows how the ellipse might avoid becoming too over-constraining should the designer decide to base their work on an egg-shape rather than the original circle or the subsequent ellipse. The construction of the ellipse can be made in such a way as to allow different lengths to be given to the four lines whose free ends define locations on a spline. These can be equalised to allow an ellipse to be reconfigured parametrically. [Figure 6] shows how eight parameters might be required to allow the designer to provide greater definition and control.

The geometry can be contrived to allow an approximate circle, or an ellipse, or an egg. A further change will be needed as shown in [Figure 7] and [Figure 8] to allow a more precise definition of the three options discussed and, additionally, a fairly convoluted free-form. This suggests that with sufficient forward planning, the designer can keep their options open but for every sophisticated and apparently open-ended
configuration, new constraints will be found. None of the paradigms above, for instance, will convert a figure from being curve-based to rectilinear.
Figure 5
Figure 6
Figure 7
The Sydney Opera House took eighteen years to create. The polemical nature of the relationship between the architect, builder and public purse stimulated many debates at almost every level of architectural, social and political life in Australia during that time (1955-73). The removal of Jørn Utzon from the project, and the work subsequently undertaken by the architectural panel that replaced him is still a contentious issue within professional and public circles thirty years later. These unfortunate circumstances make it difficult to extract precise information on the geometrical forms of the roofs and the way that their shapes developed although the broad development is well known [Figures 9 &10]. It is clear from what we know of Utzon's design process, a question suggests itself: could parametric modelling have helped Utzon in his quest for an appropriate solution had it been at his disposal at the time?

Although the building's subsequent resolution to simpler geometrical forms might suggest a prescient sympathy for the opportunities provided by contemporary computer technology, it must be conceded that the architect's design methodology managed an awkward situation regardless of later opportunities [Figure 11]. The building nevertheless offers a fertile subject for research into design and modelling. Utzon's systematic approach, his inspiration, design methodology and final design product appear
to have much in common with the properties of parametric modelling. We can assert this for two reasons:

- The building is of complex but regular geometry, consisting of a number of sub-systems that are related.
- The building has relationships that can be calculated such as the volume (for acoustic performance analysis); the desired sound paths; maximum and minimum reverberation time; number of seats; lighting; stage and stage machinery.

Utzon's system of design, that is to design-for-construction by breaking down the whole to composite elements and distributing them to manufacturers is more common among industrial and mechanical design and manufacture. It is not surprising, then, that parametric modelling is well established in those disciplines. As a "model man" (Yeomans, 1968), Utzon is interested in taking 3D and spatial relationships to their limits. He would commit himself completely to explore every angle of a schema (Nobis 1994), yet be ready to drop it and start from scratch if it proved inadequate. He had well established research methods but can be shown to be open to new opportunities (Utzon letter 14/3/97).
"... One cannot make such a complex of forms without being clear on the geometry, without having found some form of harmony between them. I have worked a lot with various forms... ...for instance, generated volumes made of ellipses and parabolas, but I ended up by taking these forms from a sphere..."
Figure 11
A computer model has been used to assess the impact parametric modelling might have had on the design; retrospective analysis of the design process for the Sydney Opera House is offered as a means to benchmark the viability of parametric design in this context (Murray, 1997)

The model consists of 4 spheres [Figure 12]. These were sectioned and became the roof segments for each of the two theatre halls. [Figures 13 & 14]

To attain the full benefit of parametric design, one must first identify the constants and the variables. In this case study the number of shells was set at four. Each shell is part of a sphere, each of which having the same radius, two of the shells meeting to form a ridge [Figure 15].

The finished model can be manipulated and analysed. Changes can be made to the radius of the spheres and the location of their centres as well as the angles of their cutting planes. By moving the spheres the four shells can assume new heights [Figures 16 & 17].

While the making of the model has proven somewhat complex, once made its manipulation is very simple. Typing different co-ordinates can change the centre of the spheres. The angle of the cutting planes can be modified through the end-points of the
definition lines. After one or any number of changes in one operation, the model regenerates itself trying to accommodate all the new values for the parameters. It gives the user the option to accept the changes, or cancel them and return to the previous version.
Figures 13 & 14
Figure 15
Figures 16 & 17
The regeneration is rapid, a matter of seconds rather than minutes. The model can be shaded and rotated allowing inspection from any viewing point [Figure 18].

The significance lies in the fact that through using the computer in this way, the model is composed using the principles of descriptive geometry. The main advantage of this methodology is that the designer can use the principles of descriptive geometry, without being distracted by formulae and calculations. The critical common point of the two back shells, for example, is determined as the intersection between the original spheres and the plane of symmetry. Its position is defined by geometrical method not by an equation [Figure 19].

The model does not prescribe how to design by using parametrically manipulated geometry; it simply presents a possible way of using parametric design, once a system of geometry is chosen. It assumes that the designer's intentions were clear such that parametric manipulation can be adopted as a tool for formal refinement.

Two additional fields where parametric design models may be used for the Sydney Opera House are the glass walls and auditoria ceilings. Utzon planned the glass walls to have a conical geometrical structure while the ceilings were based on cylinders. Even more challenging would be the
construction of a model that included all three systems and allowed modification and investigation simultaneously in all of them. This is a subject for further investigation.
Figure 18
In their book of Visual Notes for Architects and Designers (Crowe and Laseau, 1989), Norman Crowe and Paul Laseau state that habit or training in just one mode of thinking can cause us to ignore many other ways of looking at a problem. Being aware of alternative thinking and technique allows us to take full advantage of our creative potential. Effective use of parametric modelling tools provides a fertile medium for teaching architecture and research into design processes. This study provides a view on the way that geometric modelling and constraint definition can help in the creation, manipulation and resolution of complex geometrical forms by placing it the context of a problem that predates the computer-based solution. It also tackles problems resulting from the way in which design is influenced by the form of communication and abstraction used by the designer, and in the different phases of the design process (experiencing, recording and manipulating). Although software and hardware at prices architectural practice can afford is some way off, it is useful to note that 'soft parametric design' has already emerged such as the 'grip points' in AutoCAD, for example. The greater ease with which all-comers can adapt their preferred software by programming is also helping designers to customise their CAAD engine, often in a way that is inherently parametrically based and quite within the context of this discussion.


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design for making

The first task where this approach was exploited was with making the roof-shells. Each shell is a triangle sectioned from of a sphere; the sphere made prefabrication more feasible. The success was such that Utzon used the same approach for the glass walls, the auditoria ceilings and all the cladding. He used other geometrical forms, specifically cones and cylinders. A look at the way conventional modelling coped with the manipulation of these forms is quite revealing.

In his report to the Sydney Opera House Committee, Professor Ashworth states:

"The more one is associated with the Opera House, the more one associates the obvious necessity and difficulty associated with thinking in three-dimensions, on this scheme and it would be quite impossible to ensure satisfactory results without constant recourse to three dimensional models." (Ashworth, 1960)

Utzon built a number of sketch and large-scale models. Indeed, it became a characteristic of Utzon's working methodology. He used both simple exploration and detailed models as tools to ascertain the exact form before the construction began. He also believed that making life size models best solves awkward shapes while insisting on developing ideas through direct contact with the manufacture. Cohen (quoted from 'The Opera House'
1984) likens his methodology to a design of a motor car, where the designer subdivides the overall form into a series of reproducible units for manufacture.
The Government of New South Wales organised a competition for a design for the design of Sydney Opera House. The winning entry was Jørn Utzon design for an art complex. He proposed a complex of two theatres on a masonry podium. Each of two theatres, (a larger and a smaller) is covered by a group of concrete vaults. A restaurant is housed under similar shells as an adjacent building on the platform.

A series of political circumstances led to a building on Bennelong Point distinct from the one that Utzon designed. Utzon was dismissed from the project a year before the exterior was complete. The evidence for this paper is based on a combination of the documented design for both Utzon's built and unbuilt Opera House. The complete documentation is held in the Mitchell Library (Nobis, 1994).

From the outset, Utzon conceived the Opera House as one entity (Nobis, 1994). He wanted a complex building where everything had its place within a structure that would act as a single organism. Though the work had been divided into three Stages he insisted on the unity of the project, by developing all its elements simultaneously.

There were contrasting influences on Utzon's work. The industrialised architecture of the Modern Movement (Smith, 1979) was considered along with his private study of the natural structures of algae, plants and shells...
(Tobias, 1994). Through his architecture, Utzon was linking single elements into complex structures as occurs in the natural world: "A Palm leaf - this is a kind of thing in nature that gives you ideas and that was exactly what inspired me." (Utzon speaking in 'Skyer' Tobias, 1994). The Sydney Opera House was to be created as an organic form but by using industrial processes.

Through the design process of the Opera House, Utzon became increasingly fascinated by geometry and realised the potential for basing his whole design on geometrical principles, probably as a result of his co-operation with Ove Arup the structural engineer (Arup and Zung, 1969). He also wanted to ensure a high quality of workmanship. Strict geometry was preferred for prefabrication many of the elements off-site.
A design strategy, then, is essential for parametric design to be able to make an effective contribution. Even if designers continue to do their broader thinking using graphite and paper, one assumes that some degree of commitment to a detailed description has to be made. The co-ordinated resolution from general to specific is a *sine qua non* to communicate to their colleagues and, subsequently, to the building contractor. Regardless of the role given to parametric design in the more conceptual phases of the design process, there is a clear case to be made for its value in iterative design refinement in the overall translation from idea to building. A case can also be made for formulating a design strategy that suits parametric design software in order to obtain full value. Rather than make this case here, we will revisit a project to evaluate how parametric design might have been of significant assistance to the designer.
The ability to define, determine and reconfigure geometrical relationships is of particular value. In the example given, the relationship between 'X' and 'Y' can be determined by an equation such as:

\[ x = 1.5 \times y \]

Relationships such as the angle 'P' between the rectangle and the circle can be linked as, for example:

\[
\begin{align*}
\text{if } x < (2 \times y) \text{ then } P &= 45 \text{ degrees} \\
\text{else } 30 \text{ degrees}
\end{align*}
\]

This is known as constraining the model. It is easy, however, to over-constrain such that by unilaterally attempting to change the length of one side of a rectangle otherwise constrained by all angles being 'set' to ninety degrees, an impossible form is attempted.

Does parametric design suit the way designers design? There is an argument that parametric design offers a sound procedure appropriate for the resolution of a design to a detailed level. It may also have a role in initial design thinking. Nevertheless, before presenting a case study that discusses the potential for parametric design in architectural design, it is necessary to present some limitations.

As long as we continue to ponder over what constitutes the design process, the suitability of parametric design to the designer is a matter of debate not easily resolved. It has
enjoyed both early support (Aish, 1992) as it has pre-emptive dismissal (Miller, 1990). There are obvious implications for a design protocol that depends on structured decision making for those who have a more loose approach to synthesis.
Commercially available software allows the parameters to be expressed and altered in a number of ways. The most immediate, and probably the more intuitive method is via the mouse and screen. The screen is the graphical link to the model represented internally by a database with an information flow in two directions. Information is obtained from the database and displayed on the screen in a manner similar to all CAD packages. Additionally, information can be submitted back to the database from the screen representation itself. The user can pick a dimension or variable from the screen, for instance, and request that its value be changed in the database via a screen-based numerical keypad. The computer assesses the viability of this change and acts upon it. If the change in value results in a conflict, the feedback to the screen will show the point at which the conflict occurs obliging the designer to look for a more successful alternative value to the parameter(s).

The database can also be controlled and changes effected through a text-based interface. Parameters whose values can be changed are variables. They can also be components to equations whose expressions can be varied. Whether the database is accessed from the screen or from a text-based interface, the model has to be regenerated to a new reconfigured state; the package we use - CADDS5 - is not able to do this on the fly.