CAD, CURVED SURFACES AND BUILDING QUALITY

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SUMMARY: *As Computer Aided Design has developed since the 1970s, it has enabled more complex building forms to be designed, drawn and constructed. The availability of complex curved surfaces has allowed architects, in particular, to design more expressive buildings. The question must now be asked whether these have added value or whether they are only relevant to iconic buildings, of which only a few justify their greater cost. The paper follows the development of building form and looks at its increasing complexity, since CAD was introduced, in the work of Foster & Partners, Frank Gehry and others. It considers measures of quality such as the Design Quality Index, and looks at the geometry of curved surfaces and the volumes they contain from economic and environmental points of view. The current obsession with iconic buildings may not last since being different becomes a style in itself and the current ability to pay for complex forms may not continue. The conclusion is that only in a few special buildings do complex curved surfaces offer more than a variety of expression for the designer. The additional quality that may be achieved by use of complex forms depends upon the prominence of the building and the priorities of the client. The economic benefits of CAD are more likely to lie in better models of simpler forms which enable design to be coordinated and integrated with manufacture and construction.*

KEYWORDS*: CAD, curved surfaces, building form, design quality, building models.*

1. DEVELOPMENT OF COMPLEXITY IN CAD

Computer aided design systems developed for buildings diverged from those for manufacturing industry at an early stage. The former were concerned with holding data for many simply shaped components and largely with drawing output, while the latter represented the more complex shapes of cars and aircraft. Computers during the 1970s, when the first commercial CAD systems emerged, had limited memory and storage capabilities. Now that these limitations have been lifted, the facility to model large-scale buildings with complex curved surfaces is being used, most notably in the work of Frank Gehry on buildings such as the Guggenheim museum in Bilbao.

Straight lines are represented as vectors involving only the coordinates of their end points. Simple circular curves can also be represented simply by their centre points and radii or by a line and an offset from its centre through which the curve passes. More complex curved lines require Bezier splines requiring algorithms to smooth a line passing through a series of points. This requires much more processing and, when developed from 2D into 3D surfaces, Bezier patches use much greater volumes of data and even more processing power. (Faux & Pratt 1979)

Complexity of design and construction was analysed by Bill Mitchell (Mitchell 2005). He proposed that design complexity is related to the number of decisions to be taken and that construction complexity could be reduced to the number of fabrication and assembly processes. Complexity of the whole could therefore be measured as the ratio of added design content to added construction content. Such an exercise would, in itself, be complex, but it is obvious that complex curved forms require more data therefore more decisions, unless these can be automated, and that manufacturing and assembly processes are likely to be more numerous. In fact the degree of complexity of the whole could be stated as the product of design and construction complexity.

The main concern of architects using early CAD systems was to model relationships between spaces, then convert these to rectangular forms, and produce drawings, often with large numbers of components. The economic return was in allowing alternative configurations to be considered, with some analysis of ratios of floor area to volume or usable floor space to circulation, or of energy consumption or circulation efficiency. There were also benefits from drawing repetitive elements, stored as modules, and from the ability to make alterations as the design progressed. Visualisation of these large projects also helped communication with the client, but final presentation, particularly if complex forms were involved, required taking a precisely calculated wireline view, and adding detail and rendering it manually. Nowadays it is expected that large buildings of complex form will be modelled fully, rendered in 3D and even animated or used in virtual reality displays.

2. RESEARCH CONTENT

The history of CAD has been well written up and is covered in greater detail in other papers in this issue (Penttilla 2006). The development of geometrical complexity in building form is more central to this paper and to the role of CAD in enabling more complex forms to be designed and built. Is this greater complexity providing better quality and how is quality defined? One method recently developed in the UK for the Construction Industry Council is the Design Quality Indicator (DQI 2005). This breaks down measures of quality into its elements, some of which can be quantified but others are highly subjective. Other methods deal more with value and have related design to the returns obtained by stakeholders (Macmillan 2005). The work on this current paper does not allow the stakeholders of particular buildings to be followed up and the DQIs have not been applied for long enough to offer a large body of data. However their use was tried on a single building designed by the author who could see how subjective most of the scoring was even in a known example. In relating the DQIs to a range of more complex buildings, similarly subjective decisions had to be made. However, in time, a large body of data should emerge from applications of the method and this could be used for a more thorough study of quality and form.

Complexity of form had to be reduced to several simple levels in order for the measures of the DQIs to be used to distinguish between them. Detailed analysis of all the design decisions and construction processes proposed by Bill Mitchell (Mitchell 2005) is difficult to carry out but complexity of form can be correlated with the use of rectilinear and curved geometry. The simplest level of complexity that applies to most recent buildings is orthogonality where construction assembles largely rectilinear components into a whole. Since the 1980s there has been a tendency to use components curved in one plane, often based on a circular curve to simplify fabrication, for example curved metal roofing. This is relatively easy to accommodate but, if the curves are in two dimensions, as they must be for some large buildings e.g. domes, the level of complexity becomes greater. These curves have been possible to draw by manual methods but, when curves are defined by more complex formulae than circular ones, or by the freeform lines sketched by the designer, the order of complexity becomes even greater. Sydney Opera house began with sketches of freeform curved shells but could only be built when these were rationalised into parts of the surface of a sphere. Freeform curves in two dimensions have only been possible to draw, calculate and construct since the arrival of CAD systems, and these represent the highest level of complexity of form.

The final consideration of this research study must be to ask whether complexity of form is making the best use of computer technology or whether it is exploiting it to explore complexity for its own sake. Most of the recent developments in building modelling have been to aid productivity and an important question is the effect of complex forms on the application of these productivity tools.

3. USAGE OF CURVES IN BUILDINGS

It was rather convenient that CAD was being developed while building form was going through a particularly orthogonal phase. There are obvious economies for rectangular spaces and components. They can be nested together so that furniture fits into restricted areas and components can have limited variations. More recently buildings have more generous space allowances and some are conceived as if sculpted from solid materials, even if they cannot be constructed in this way. Parametric CAD systems allow flexibility of dimensions but not of complex geometrical form.

Curves have been important in architecture at different periods: for visual or structural reasons, or as is currently the trend, for impact and variety. The ancient Greeks used subtle curves in their temples: the entasis on columns and the curve of the base to correct optical distortion. Their technology was simple, such as the use of a shell with a string wound round it to draw Ionic capitals. (Banister Fletcher, 1948) Fig 1. In the Gothic period the development of the circular curved vault into pointed vaults allowed stone roofing of bays of differing width and length while retaining a continuous surface.

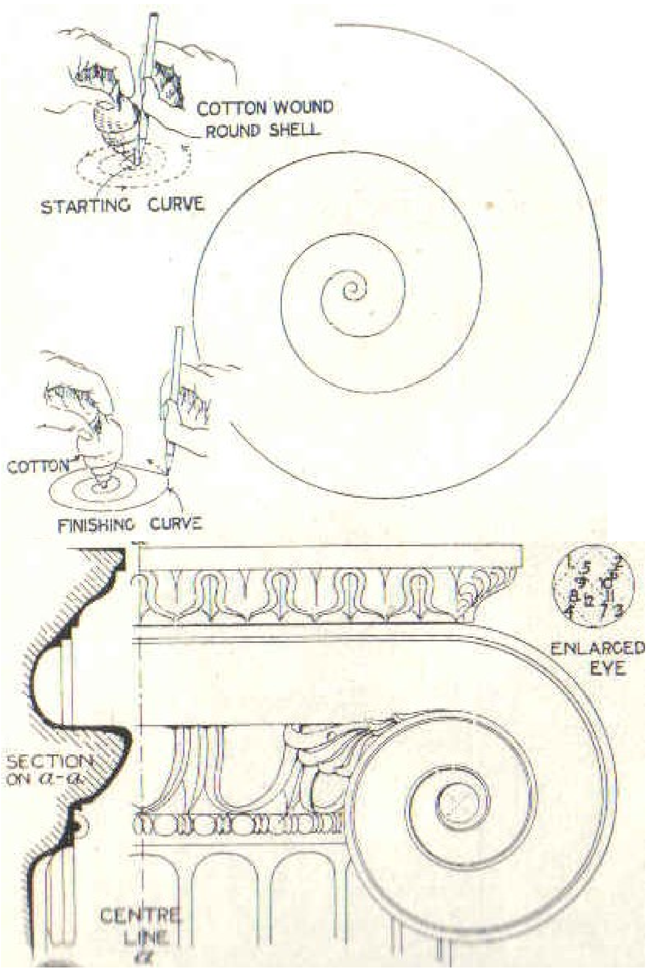

FIG. 1: Method used by the Greeks for drawing the complex curve of an Ionic column capital.

Other examples of the use of curves for expression can be seen in the romantic buildings of the early 20th century, for example the subtle curves in towers such as the city halls of Stockholm and Copenhagen. These must have been extremely difficult to set out given that they taper very gradually. Later on Alvar Aalto's buildings in Finland used gentle curves to reflect the landscape. Another Finnish building, the Dipoli centre at the Technical University in Otaniemi by Pietila, has few horizontal surfaces, and caused enormous difficulties when it was constructed in the 1960s before the introduction of CAD or laser devices for setting out.

4. A CASE STUDY OF CAD AND BUILDING FORM

The work of Foster and Partners in the UK can be used to illustrate the increasing complexity of form as their use of CAD developed (www.fosterandpartners.com). Their buildings have always been geometrically disciplined to relate to the high tech forms of construction used. Their early work was largely rectangular in plan, except for the Willis Faber Dumas building in Ipswich the shape of which followed the roads surrounding the site although the glass panels were flat. Fig 2.

Their first use of CAD was on the Stansted airport terminal opened in 1991, but the design began in the early 1980s and is still largely rectangular. In 1986 they designed an underground extension to the rectangular Sainsbury Centre for the visual arts that is gently curved. Such a large radius curve would have been difficult to draw on a conventional drawing board with the centre for the compass point being off the board. The Commerzbank headquarters in Frankfurt of 1997 is a tower with three gently curved facets and a highly complex atrium at its base. In the same year an aircraft hangar was built at the Duxford air museum using a toroidal form to allow repetitive casting of its concrete shell roof. (Martin Pawley, 2001)

FIG.2: Willis Faber Dumas office building, Ipswich, UK. Foster and Partners.

After the year 2000 Foster and Partners' work shows a complete dependence on the geometrical capabilities of the Microstation and other CAD software they use. The roof of the Great Court at the British Museum is a grid of triangular glazing that fills the space between a rectangular courtyard and the circular reading room within it. The triangles are of many different dimensions and the surface of the roof curves upwards between the edge of the court and the reading room. This is a building that could not have been designed, drawn or constructed without the aid of parametric CAD systems. Others, the shapes of which have implications for their sustainability, are the Swiss Re tower, or Gherkin as it is popularly known, which is circular on plan and tapers towards the top, Fig 3, and the Greater London Authority building which approaches a spherical form, with implications of minimising surface area for a given volume, Fig 4.

Foster and Partners' work illustrates the possibilities of using more complex geometry in buildings as a result of the developing capabilities of CAD. It is still restrained by geometrical discipline while other architects are employing CAD systems, developed for other industries such as aerospace, to produce buildings using free form curves. The best-known example of this is the work of Frank Gehry who develops his sculptural designs through models made in cardboard, which are then digitised in 3D, and modelled in the CATIA CAD system. The resulting buildings are highly complex with internal spaces and external surfaces often bearing little relation to each other, although he maintains that he designs from the inside out. They can only be constructed by transferring a 3D model to the steelwork fabricators. This is becoming known as 'Blobitecture' and uses software such as Maya, Softimage, Rhino, FormZ and 3D Studio Max. (Walters, J K, 2003) The complex forms being modelled depend upon Non-Uniform Rational Bezier Splines (NURBS) and the models are used at the earliest design stage to encourage free thinking and this has been called Waveform architecture. In future this may develop into virtual architecture since, even if the forms can be constructed, our ability to experience unbuilt spaces may become sufficient.

FIG.3: The Swiss Re office tower, London

FIG. 4: The Greater London Authority building (Architects for both - Foster and Partners)

5. ICONIC ARCHITECTURE

CAD has enabled extraordinary new buildings to be designed and built. A few of these have become landmarks and even icons encapsulating the concept of a type of building. The main intention of the designer, and often of their client, has been to create a landmark, something that could attract wide attention and transform the economy of an area. There is a limit to the number of icons that will be successful. Two recent designs: the Fourth Grace at Liverpool by Will Allsop and the Central Chinese TV tower by Rem Koolhaas, have recently been rejected or postponed although the brief was to create landmarks (Jencks 2004). Will this current concern with being different last? Jencks draws analogies with Art Nouveau at the beginning of last century. It used exotic forms at a time of relative wealth but reverted to more prosaic architecture soon afterwards. Art Nouveau was closely linked to design in other fields and to painting and sculpture. As yet the new iconic style does not appear to have equivalents in these other fields. At Bilbao most visitors are attracted by the gallery itself and are disappointed by the contents. Perhaps the designers would like their buildings to become collectable. Gehry's success in being much sought for other projects means that it is the architect who becomes the collectible item.

Contrasting the iconic building, for which there may not always be suitable projects and clients with the necessary resources, with more routine buildings such as the major school and health building programme in the UK and the needs of the developing world, the efficiencies of production are likely to be much more successful in continuous programmes based upon repetition and standardisation. This is where integrated modelling technology will produce savings when coupled with prefabrication and sustainability. The gulf in costs between the routine, series-produced and technologically advanced projects, and those designed to be landmarks, is likely to grow. Advanced CAD is still necessary to solve the complex problems that exotic forms generate, but it does not help the transfer of standard data from design through the construction process. When the economy cannot support the cost of iconic buildings, or there are so many that new ones fail to stand out, then productivity can be restored and, using new modelling and communications techniques, improved.

6. HOW TO MEASURE QUALITY IN BUILDINGS

Criteria for measuring the success of buildings have varied throughout time. They include simple measures of space usage, value for money and now sustainability. The satisfaction of the client's requirements, of the building's occupants and of the public, has always been important. Is it quality or value that should be measured? For landmark buildings quality may be the priority but for routine construction the cost, and therefore the value, according to the client's criteria, is the normal measure. A study for the Department of Trade & Industry in the UK by Eclipse Research Consultants (Macmillan 2005) categorised each of the groups for which buildings provide value as: finance, design and construction, occupants, the public and visitors. Buildings affect each of these groups in different ways and values can be assigned to different categories: exchange, use, image, social, environmental and cultural. One objective of this work is to value the more intangible aspects of design, and complexity of form. Providing iconic quality may be one of these.

The Construction Industry Council in the UK has focused on quality and developed a benchmarking tool called the Design Quality Index. This is just one of a number of benchmarks for measuring different aspects of success in the construction industry (www.dqi.org.uk). The DQI identifies three aspects of design quality based on the Vitruvian principles of 'Firmness, commodity and delight' and subdivides them into elements to allow quality comparison of different projects.

FUNCTIONALITY -	Use	Space	Access
BUILD QUALITY -	Performance	Construction	Engineering
IMPACT -	Character and innovation Internal environment	Urban & social integration Form and materials	

There is no question that these can be absolute measures, particularly with such subjective content, but they provide a framework within which to assess quality and software tools are available to apply the method and generate the circular charts. They can be used at four stages of the process: inception, design, construction and in use.

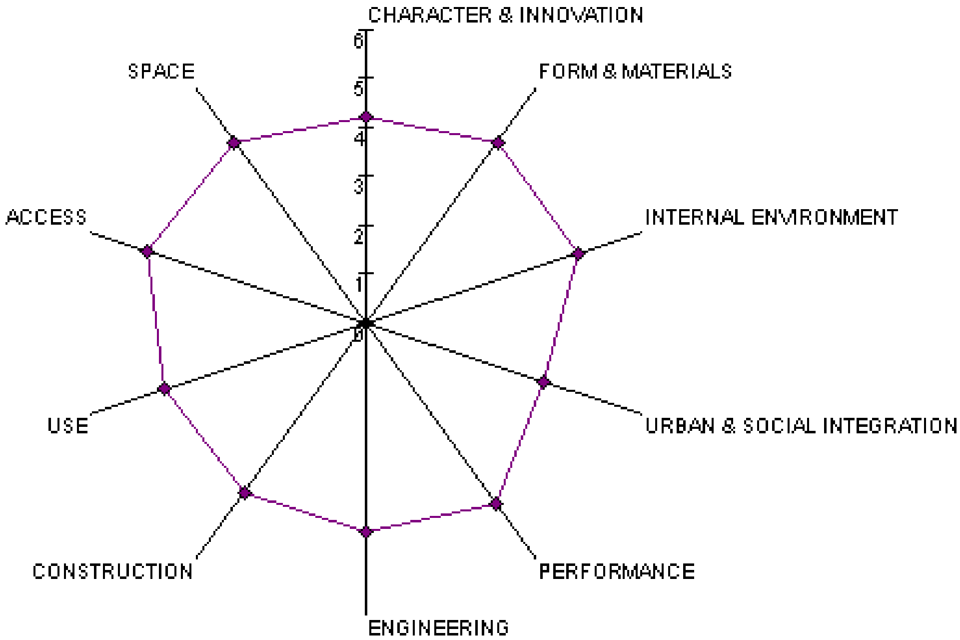

FIG. 5: DQI chart for private house extension at design stage. Construction Communications.

For use of complex forms in buildings, the effects of some criteria can be generalised. Measurement of other criteria will depend upon the particular type of building, its client's needs and its context.

Functionality with regard to ***use*** is the most fundamental aspect of building quality. Although designers have a wider responsibility to the community and even to culture, they are primarily required to meet the needs of building owners and occupants. ***Space*** can be measured by simple ratios of cost per square metre, circulation space to usable space and surface area to volume. This last measure has been the subject of much research by Ranko Bon at the University of Reading and Philip Steadman at University College, London (Steadman, P, 2005). They studied rectangular forms and, allowing for the need for natural lighting penetrating to a limited depth, have given ratios for the optimum surface to volume of buildings. If such analysis is applied to non-rectangular buildings, the fact that a sphere has the greatest volume for a given surface area is relevant, and can have implications for cost and environmental performance. The Greater London Authority building was mentioned as approximating to a sphere. It also leans towards the south so that overheating by the sun is minimised. However the space inside is largely occupied by a spiral ramp in a void over the council chamber so economy of volume is unlikely to be the main functional criterion. ***Access*** is concerned with the location of the building and its ability to accommodate disabled people.

Build quality depends upon availability of suitable materials and components and the skills and experience of construction firms. The ***performance*** of a facility is never fully tested until the building is occupied and the final reckoning cannot be made until the operating and maintenance costs are known.

Quality of ***construction*** often depends upon familiarity with the techniques used. If novel, curved forms are employed they may require new materials, such as the titanium used in Bilbao, and the workforce is unlikely to have relevant experience. However roofs using 2D circular curves have been in use for many years and the materials and workmanship are suitably adapted.

Engineering of structure and services can be modelled at the design stage although much of the software for structural and environmental analysis was developed for rectangular building forms. Approximations may have to be made for complex curved forms and structures are bound to be more demanding. However it is necessary only to look at the work of the engineer Santiago Calatrava (Lawson, B 1994) to see how curved forms can express structural needs. There are also fabric roofs to provide lightweight and economical solutions for roofing large areas such as stadia.

Impact is probably the main reason for using complex curved forms. The least measurable aspect is ***Character & Innovation***. These are of particular concern to architects. Character may reflect the style of a particular practice or the image that clients wish to project. It is highly subjective but the more complex a building form the more distinctive its character is likely to be. The Guggenheim museum in Bilbao is a highly original building that has contributed to transforming the economy of a Spanish region. On these terms it has justified its costs many times over. Innovation has been very effective in this context but in other historical cities a more contextual approach adds to quality.

Urban and social integration could argue against the use of complex forms. Most cities consist of rectilinear forms decorated in a variety of historical styles, or imitations of them. To integrate it may be necessary to respect these forms, but only if the context is of high quality. Great buildings would never have been built if architects of the past had been constrained by context. In future whole areas of cities might be built using complex forms, although fashions tend to revert after a period dominated by a particular style. Social integration has little relationship to building form apart from the needs of the public to accept a building in its context and to be stimulated by using it.

Internal environments are critical to the users and the relevance of complex, curved forms to particular uses may offer greater flexibility and richness but requires more study generally by architectural critics. ***Form and materials*** represent the basis for this exploration since complex, curved forms needed new materials. The next section will discuss the relationship between form and function and any measures that can be applied to the appropriateness of novel forms to particular types of building.

7. THE RELATIONSHIP BETWEEN FORM AND QUALITY

Without going through the DQI assessment process, which relates to specific building projects, it is possible to compare generic forms of building, using a five point scale, on the elements of the DQI process. Some elements cannot be generalised since: use, performance, urban & social integration and internal environment, depend upon the specific requirements of each building.

Three generic forms can be used for this simple comparison: rectilinear, circular curved and more complex, spline curved forms, and the latter may be applied in two dimensions or three. This provides a very simplistic, and rather subjective, measure of quality based on the DQI elements.

TABLE 1: Design Quality Indicator criteria tabulated against different types of building geometry

Building form	**Rectilinear**	**2D circular curves**	**2D spline**	**3D circular curves**	**3D spline**
Example	Most buildings	Commerzbank tower	Willis Faber Dumas office	Swiss Re tower	Guggenheim Bilbao
Use	Conventional 3	Will fit certain functions 2-4	Will fit certain sites 2-4	May suit certain needs 2-4	May suit certain needs 2-4
Space	Easily nested 3	Less perimeter Hard to use 2	Potentially efficient 3	Low surface to volume ratio 3	May fit or waste space 2-4
Access	-	Form has little	effect on this	-	-
Performance	Standard 3	May fit some functions 2-4	May fit some functions 2-4	For specific needs 2-4	For very specific needs 2-4
Construction	Conventional 4	Relatively simple 3	Many parts available 2	Complex geometry 2	Very complex geometry 1
Engineering	Structurally simple 4	Horizontal curves simple 3	May suit large structures 2-4	Complex on any structure 2	Very complex 1
Character & innovation	Average 2	High 3	High 3	High 4	Very high 5
Urban & social integration	Conventional fits street grid 3	Socially OK but may not fit 2	May be best fit for site 2-4	Distinctive 2-4	V distinctive 2-4
Internal environment	Standard 3	Reduced surface/volume 3	May reduce surface area 2	Better surface/volume 1-3	Potentially best ratio 1-3
Form and materials	Standard components 4	May not need specials 3	Probably needs specials 2	Probably needs specials 2	Will need specials 1
Totals	**29**	**25+/-2**	**24+/-4**	**24+/-4**	**22+/-5**

It is not really appropriate to total columns representing such disparate measures. Different clients or projects would put different weights onto each element so that, for instance, the clients for the Guggenheim museum might emphasise character & innovation and form & materials above all others. However the general implication, where equal weight is given to each element, is that the conventional, rectilinear form is the safest and most economic in most situations, but that more complex forms can come close to this for quality given an appropriate set of requirements. As complexity increases, the risk element also increases, but the value of iconic buildings can be of a different order to their cost in particular cases.

8. CONCLUSIONS

This paper sets the scene for a more detailed study of how CAD has enabled new forms to be designed and constructed. It applies one method for assessing quality and, under each of the headings of the DQIs, a more detailed study could be carried out, and with a greater variety of types of form. This could make use of Bill Mitchell's method of measuring complexity. Perhaps when the DQIs have been applied to a greater number of specific examples they could be analysed according to the types of form that the buildings use. Sustainability concerns and economics will be affected by the surface area to volume ratio but, where buildings have adopted forms approaching the spherical, they have often wasted space internally or needed expensive walling components, thus nullifying the benefits of reducing the external skin. This approach has benefits when the lifetime cost of operating a building is given more importance than its initial capital cost.

The context of the building is quite critical in that most new buildings have to fit into a conventional rectilinear townscape but, where the full coverage of the site is not necessary, more complex forms will draw attention to their function and may provide the iconic effects of the Guggenheim Bilbao and Sydney Opera House. This is difficult to repeat and the extra cost of complex forms may not be recovered as a result of the building's prominence. At present many clients wish to create icons that will attract attention, but this will have diminishing returns and few have been successful. They require advanced CAD technology but this is mainly solving problems created by complexity of form rather than advancing the productivity of the whole building process.

There are many reasons for the majority of buildings keeping to rectilinear, or even rectangular, forms. They are easy to build, can incorporate non-rectilinear elements, and tend to be more flexible and standardised. Where CAD is used on such buildings, the benefits for repetition, use of standard components and economy of space use, require a more fundamental modelling process. Landmark buildings of complex form are often modelled just for visualisation purposes, since their spaces and appearance are hard to imagine, while more conventional buildings may use models containing much more data on components and performance. It is these models that will help transform the efficiency of the construction process, and allow sharing of data between all those involved in it.

CAD has enabled designers to create some spectacular buildings, but the vast majority of the work of the construction industry is with routine, economic, buildable and sustainable projects. In future complex curved forms may become more usual and the economics of constructing them may improve, but they too should incorporate standard, repetitive elements to allow similar models to be built and exchanged. There will always be clients who want their buildings to stand out and who allow their architects to express themselves fully, and those with sufficient resources can do this by using more complex forms. The real contribution of CAD is through complete building models, whether these tend to be, as at present, more effective with rectilinear forms or, in future, with the more expressive forms that CAD has made possible.

New technologies, such as the capability of CAD systems to handle complex geometry, have often been use to extend the possibilities of design. They may do this at the cost of putting back the application of older technologies, such as modelling the whole design and construction process, by adding extra complexity to systems that are already challenging. Ideally, while better production processes are becoming more widely applied on conventional buildings, their use on the more complex forms that are now achievable, will also be developed to provide the richness of complex forms and the efficiency of integrated design and production methods.

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