1. The structure of the Beijing Aquatics Centre ("Water Cube"): projects like this are now beyond conventional two-dimensional design and documentation methods.

The Virtual Building

Emerging technology is moving us closer to the dream of the "virtual building": a fully defined, integrated and operationally tested virtual prototype of the finished building.

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Introduction

For at least the near future, the intuition and know-how of experienced designers and builders will remain fundamental to successful building projects. However, much more can be done in the virtual world both now and in the future to help designers, builders, and owners avoid some of the time-consuming and costly trial-and-error approaches currently accepted within the industry.

The next decade will see the emergence and application of a holistic, technology-driven approach to the building process - a revolution in the making.

Thanks to the new virtual technologies, the potential exists to rely more on hard facts rather than just design intuition. The concept of the "virtual building" will eventually enable designers to develop a fully-tested building solution with confidence not just in the building's constructability but also in its long-term operational performance. The emerging virtual process is becoming fundamental to design innovation, producing results that could not have been predicted before the advent of these technologies. This process will include and supplement current cutting-edge use of 3-D computer-aided design/drafting (CAD) and building information modelling (BIM).

What is the "virtual building"?

Answer: a concept in which all design, construction, environmental performance, and operational problems are visualised, solved, and optimised using integrated computer simulation. The virtual building is intended to support stakeholders throughout the project's lifetime in the following areas:

- *Exploration:* a constantly evolving tool for exploring new directions in design and construction
- *Communication:* enabling project teams to quickly and accurately communicate design forms, functions, and behaviours to other team members and the broader collection of stakeholders
- *Integration:* providing an environment where design and facility team members can share and co-ordinate project information quickly and efficiently
- *Optimisation:* facilitating analysis tools that are capable of optimising performance, sustainability, and costs to meet both short-term and long-term goals.

Tools and techniques used in the virtual building are constantly evolving. This paper focuses on the possibilities for virtual design in the building industry *now*, what is *new* and cutting-edge, and what can be expected to come *next* that will change the way we design buildings in future.

Now

2-D drafting vs 3-D modelling

Drawings in two dimensions are still the construction industry's main form of contract documentation. They are also one of the main causes of conflict, with poor documentation estimated to cost billions of dollars each year. The problems with 2-D documentation usually relate to poor co-ordination and poor detailing, due to the limitations of designers in fully representing a physical object, ie a building described only in two dimensions on documents produced by separate disciplines.

3-D modelling, on the other hand, is the building block of the virtual building, offering significant improvements over conventional drawing production (Fig 2).

A 3-D model of a building created early in the process forces the designer/drafter to think and resolve the proposed solutions in all three dimensions and in all parts of the building. In essence, 3-D modelling pulls the activity of co-ordination forward into the process of design, creating a vehicle for true design integration. Once the spatial arrangement and detailing are resolved, then 2-D drawings can be extracted directly from the 3-D model.

As the drawings are a "by-product" of the model, almost limitless permutations of sections, plans, elevations, and isometric views can be produced in any direction. More importantly, as the drawings reflect the model, they are fully co-ordinated with one another and will only present consistent information.

Through 3-D representation, the building can be far more easily understood not only by the design disciplines, but by clients and builders as well. As a communication tool, the 3-D modelling approach is thus far superior to 2-D and is already showing results in producing better products with less rework. Once a basic 3-D model is set up, the possibilities of how this information can be developed, utilised, interrogated, and supplemented are endless.

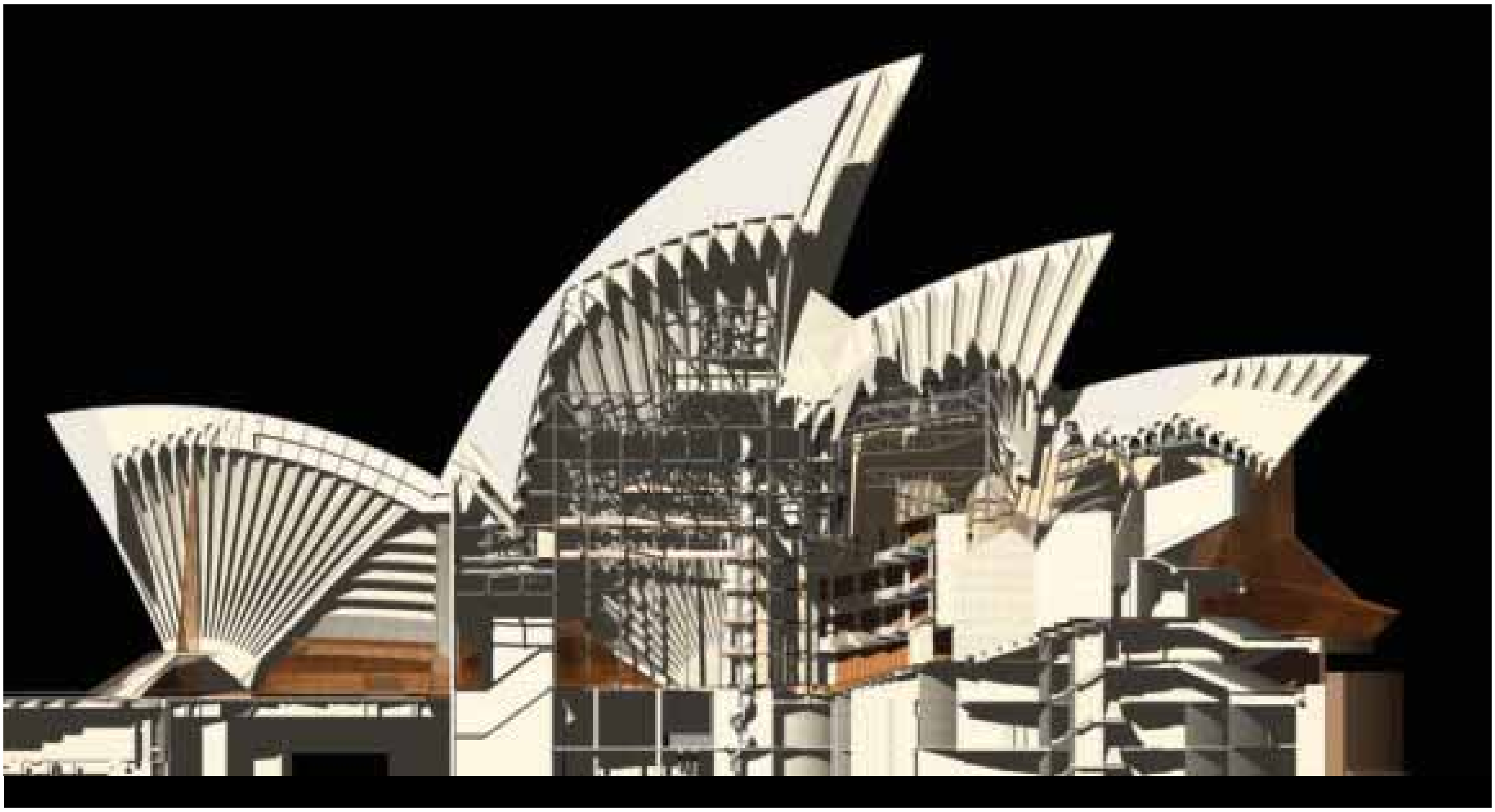
New

Virtual construction

As the density of systems increases, space management becomes increasingly important in producing an efficient and well-integrated building. By combining 3-D models from the various design consultants, the architectural and engineering design can be co-ordinated by overlay and visual comparison. This process can be aided by clash detection software, but is most effectively implemented at virtual construction workshops. By producing a virtual model of building system components, it is possible to effectively visualise and manage design co-ordination, thereby improving confidence in the design and reducing the chance of late changes and clashes between building systems on site.

This process is best enacted if all consultants use the same software. If this is impossible, data can be exchanged using Industry Foundation Classes (IFC) interoperability standards[1]. Alternatively, software such as *NavisWorks*[2] can be used to import and view models from different software platforms and run virtual design workshops. During the review process we can rotate and zoom in on issues, isolate them, redline, add appropriate comments, and then assign

2. 3-D model of the Sydney Opera House.



actions, resulting in a Word document annotated with 3-D views from the model. Closer collaborative working practices should develop, using these tools.

One benefit may be to avoid duplication of effort. For example, Arup is currently working with industry leading architects to integrate the structural and architectural models, leading to significant time and cost savings for architects through not having to continually redigitise structural frame information.

During construction, subcontractors' models can be added to the process to provide further assurance on fit. In cases where subcontractors do not yet have 3-D modelling tools, information can be taken from their 2-D drawings and developed in 3-D by a modelling team. In this way, full 3-D co-ordination by clash detection, or "virtual construction", can be carried out before physical construction commences. This can be considered a virtual dress rehearsal for the construction process, saving potentially costly remedial works on site, and estimated to reduce construction costs by between 2-10%.

A combination of the architectural, MEP, façade, and structural designer and subcontractor models within a single interactive, free-to-view model offers a very powerful design review tool. The ability to combine 3-D models over one another in the virtual building environment (Fig 3) may promote a "right first time" approach to the design, procurement, and construction process.

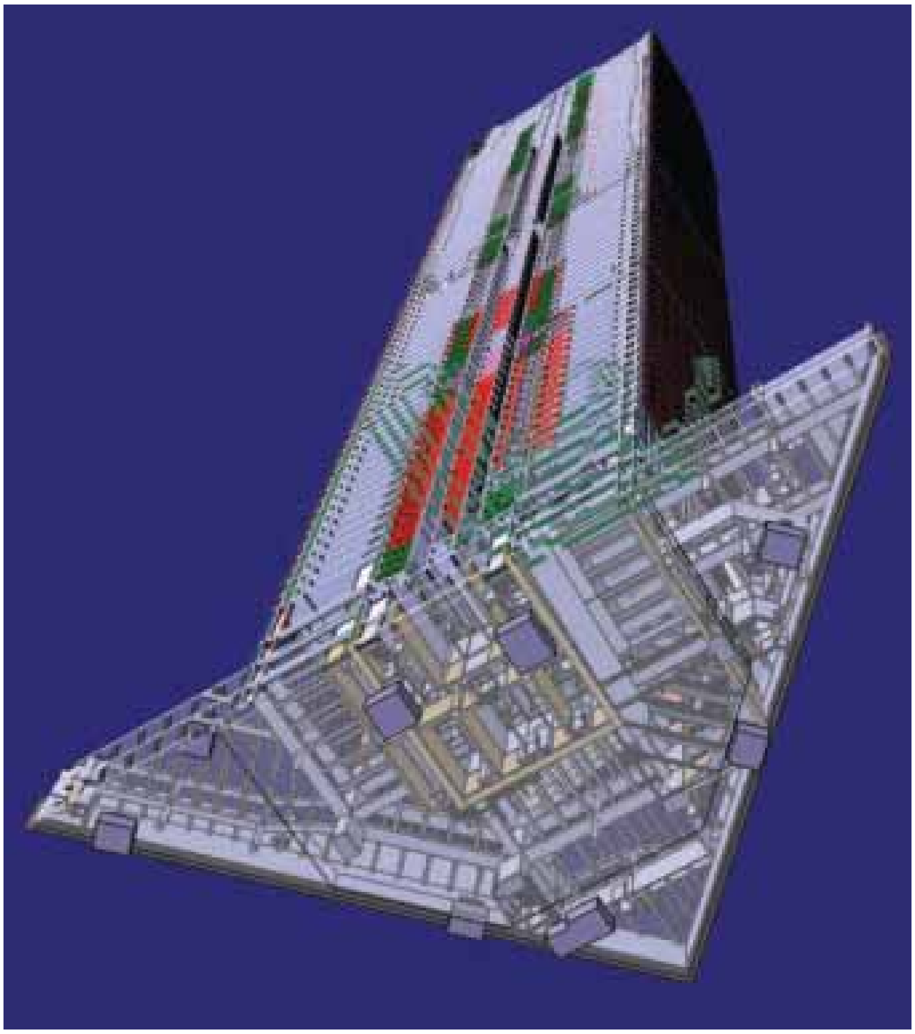
Common models

The next step beyond virtual construction is to introduce a common model approach from the outset of the project - this is where a 3-D model is shared centrally with all members of the design team. A shared central model requires agreed protocols regarding who can alter what and how, and when it may be updated. The model will need to be hosted on a central server located at the office either of the client or any member of the design team, or by a specialist modelling firm appointed to the project.

This process has been trialled on very few projects around the world. One example in which Arup was involved is the One Island East project for Swire Properties in Hong Kong (Fig 4), which was entirely designed and procured using the *Digital Project* platform. The client bought hardware and software for the entire team to use to ensure a consistent approach. A central 3-D co-ordinator was appointed to oversee and supervise the central model all through the design and construction process.
The client sees this as a way of rationalising his approach to all the projects in his portfolio, with benefits flowing into how he manages his assets.

3. Princeton University Chemistry Laboratory: overlay of all engineering disciplines.

4. One Island East, Hong Kong, designed using a central model.



Simpler versions of the central model, such as centralised database modelling, are already being used. For example, the architect's extruded shape geometry can be fused with the engineer's analytical centreline geometry with scripted links for software interoperability, facilitating the comprehensive inclusion of design changes on a single parametric platform.

In practice, the central model approach is not yet perfect and the project team can expect numerous procedural problems. But though the approach may not save design and documentation time, it can be expected to considerably reduce effort and save money during the site phase. In order to maximise the benefits, centrally controlled models will require a transformation in the way project teams work, with "master modellers" expected to assume control of all design information on projects in the near future.

Building Information Modelling (BIM)

BIM is a tool for adding information other than geometry to a 3-D model, its main purposes including:

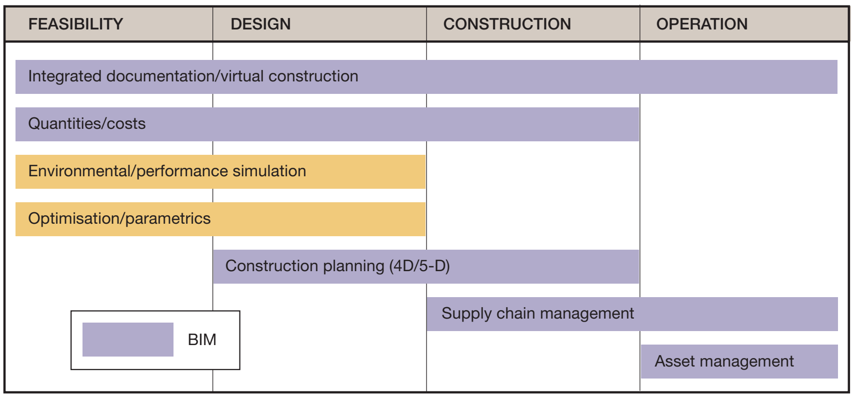
- automated scheduling of baseline quantities and costs
- construction scheduling (4-D) – for planning construction activities
- scheduling of quantities and costs over time (5-D)
- direct manufacture – automating the fabrication process.
- supply chain integration – automating the procurement process
- facilities management – for managing the asset using the model as an interface.

Right now, BIM is proving useful (as stated by *Autodesk*) "in providing continuous and immediate availability of project design scope, schedule, and cost information that is high quality, reliable, integrated, and fully co-ordinated". The ability to attach this type of information already exists within the common 3-D software packages, but we are still developing an understanding of how to select and organise the data. BIM offers the potential to vertically integrate the entire construction supply chain, as well as horizontally integrate the design team (Fig 5).

Quantities and costs

It is already becoming common practice to extract the precise measurement of materials or components from 3-D models we produce. All the geometric information needed has already been used to create the model, so it is a simple extension to extract that information in summary form once complete. The benefit of this is that the manual take-off of quantities - often prone to human and scaling error - can be verified, or indeed may become superseded.

Once the quantities are extracted in a usable format, it becomes a simple extension to add unit costs to the quantities measured to extract a representative cost plan. One of the great benefits of this is that rapid assessment and reassessment of costs is now possible once the 3-D model is set up. Any changes to the model and its impact on cost can be quickly (and automatically) assessed.



5. Virtual building processes cover the full cycle of a building's life.

Construction scheduling (4-D)

Planning a construction process is notoriously difficult. Industry reports suggest that resources are only used at 40-60% efficiency. 4-D modelling is a powerful new tool that provides an interactive ability to visualise, inform, and rehearse construction sequences, driving more efficiency into the construction process.

"4-D" is an acronym that has developed in the industry to represent the addition of the time dimension to a 3-D model. In simple terms, the 3-D model contains "objects" controlled and driven by a Gantt chart[3] timeline. The application of the "fourth dimension" allows the sequence of objects to be manipulated with almost limitless permutations. If we wish to amend the staging process, we amend the Gannt chart, not the "3-D images" (which are simply a by-product of the process).

In the early stages of a time-critical project it can be useful to produce simple visualisation/ AVI presentations of the construction and site management sequencing. Sequential stills and movies of the process can be produced to help disseminate the information clearly.

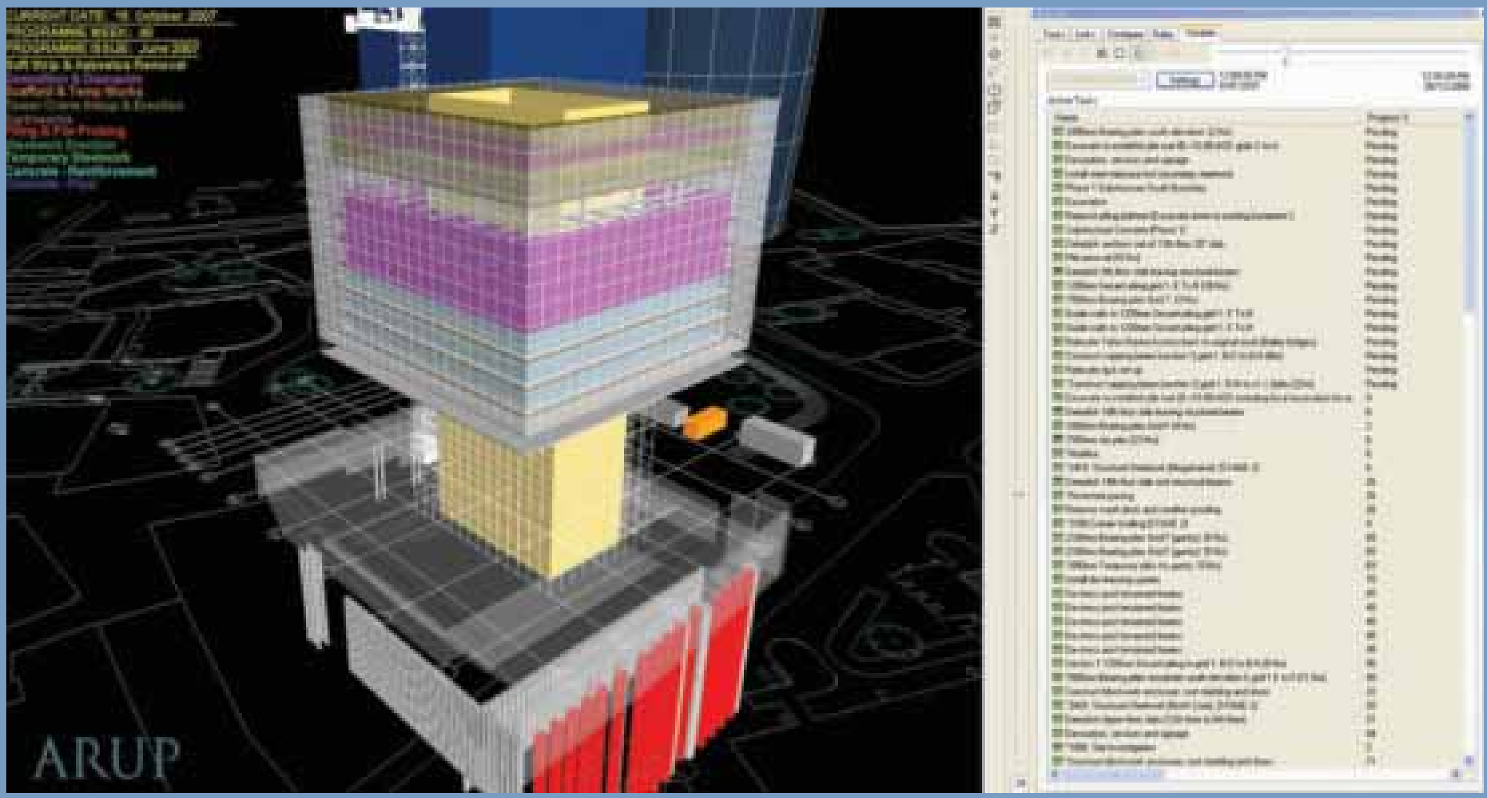
Later in the project, as more detailed programmes are required, the model can be used to describe the complex sequence of building without the need to read and understand pages of charts. The key aim is to optimise overall construction time by highlighting bottlenecks and site constraints in staging the works. Site management is assisted by illustrating the true scope of works and the staging necessary to solve key constructability issues. It is a highly effective planning communication tool for disseminating construction impacts to stakeholders, or to overlapping and multiple subcontractors.

This approach has already been used with great success by Arup on many projects, including demolition scheduling on the Leadenhall Street project in London (Fig 6), and major works staging for Kings Cross and St Pancras stations.

5-D scheduling

When we combine the automated extraction of quantities over a timelined 4-D model we add a fifth dimension, commonly known as "5-D". The power of 5-D scheduling allow us to exploit the relationships between the objects' timeline within the 4-D environment, and then report on their subsequent quantity or cost at particular points in time.

In simple terms, the consequence of task occurrences (or not), and their relationships to one another, allows us to investigate limitless permutations of quantum at any point in time. Some examples of this would be to extract cubic metres of concrete to be poured in the following week onto a dayworks schedule, or a $ value of work complete in a monthly cost plan forecast. In a recent shopping



6. 122 Leadenhall Street, London, project: 4-D construction modelling.

centre project, moving the bars on the Gantt chart ripples over the 4-D model and onto the 5-D documentation, presenting the number, location, and availability of car park spaces available at any point in time during the refurbishment. Such methods are ideal for optioneering and assessing the client's risk and financial implications.

The clear downstream benefits of 4-D and 5-D during the construction phase of a project means that selection of design consultants with the requisite modelling skills is now more important than ever.

Direct manufacture

The virtual building process enables advanced manufacturing technologies which extract fabrication data directly from 3-D models using computer numerically controlled (CNC) technology, eliminating the need and risk associated with interpreting 2-D drawings.

Digital fabrication can be used for routine assemblies, but can also enable more complex shapes and assemblies that would not be possible using conventional methods. This technology is used extensively in the steel industry, but can be adapted for precast concrete construction as well. A recent example is "The Travellers" sculptures in Melbourne[4] for the 2006 Commonwealth Games, where no drawings were produced. All components were fabricated direct from the 3-D design model and associated spreadsheets.

The potential to save money and time by eliminating the design drawing and/or workshop drawing process is self-evident – a pointer to the potential for a "drawing-free" future, and a key step towards the "virtual building".

Supply chain management

Having guided a collaborative design and planning effort, the virtual building model can be manipulated and interrogated to further effect during construction. Interactive project review meetings with builders and subcontractors can be hosted, and discussions documented with views from the model. This promotes cross-trade co-ordination through the trial construction, and helps maximise the benefits of the collective specialisms offered by the subcontractors. Interactive and free-to-view models can be distributed to all, offering quick and effective project visualisation; this helps subcontractors immediately understand what is required of them and reduces much of the risk aspect of their pricing.

During the early stages of a project, designers tend to use generic components to represent the building systems. Such components can be used to produce accurate tender information, but eventually will be replaced by specific components that the general contractor and subcontractors intend to use for construction. The object-oriented nature of the virtual building model means that components at varying levels of detail can be easily inserted or exchanged at any stage of the process.

The virtual building process thus enables alternative layouts and building system strategies to be modelled quickly and accurately, including final clash detection and installation procedures. The digital model can also be linked to order information, allowing components to be tracked from production to delivery, storage on site, and final installation.

Asset or facilities management

The virtual building is not only useful during the design and construction process, but will soon be an effective tool for facility management throughout the building's lifetime. By linking components in the virtual building to a facility management database, the building manager could operate and run the asset using a visual interface. The virtual building database can be designed to hold drawings, specifications and maintenance history for the components within the model. Hence an asset manager could simply "click on a room" to find relevant information for it. Alternatively, the manager could move directly from the database to the location in the model to identify a component in question, or the model could be set up to warn of faults or scheduled maintenance, or monitor energy usage.

The process of reordering components or scheduling maintenance becomes greatly simplified, as the manager only need point to the element in question in the model for all relevant specifications to be brought up from the database. This could be particularly powerful for façade elements where breakages are common and geometric and performance data must be precisely adhered to when reordering.

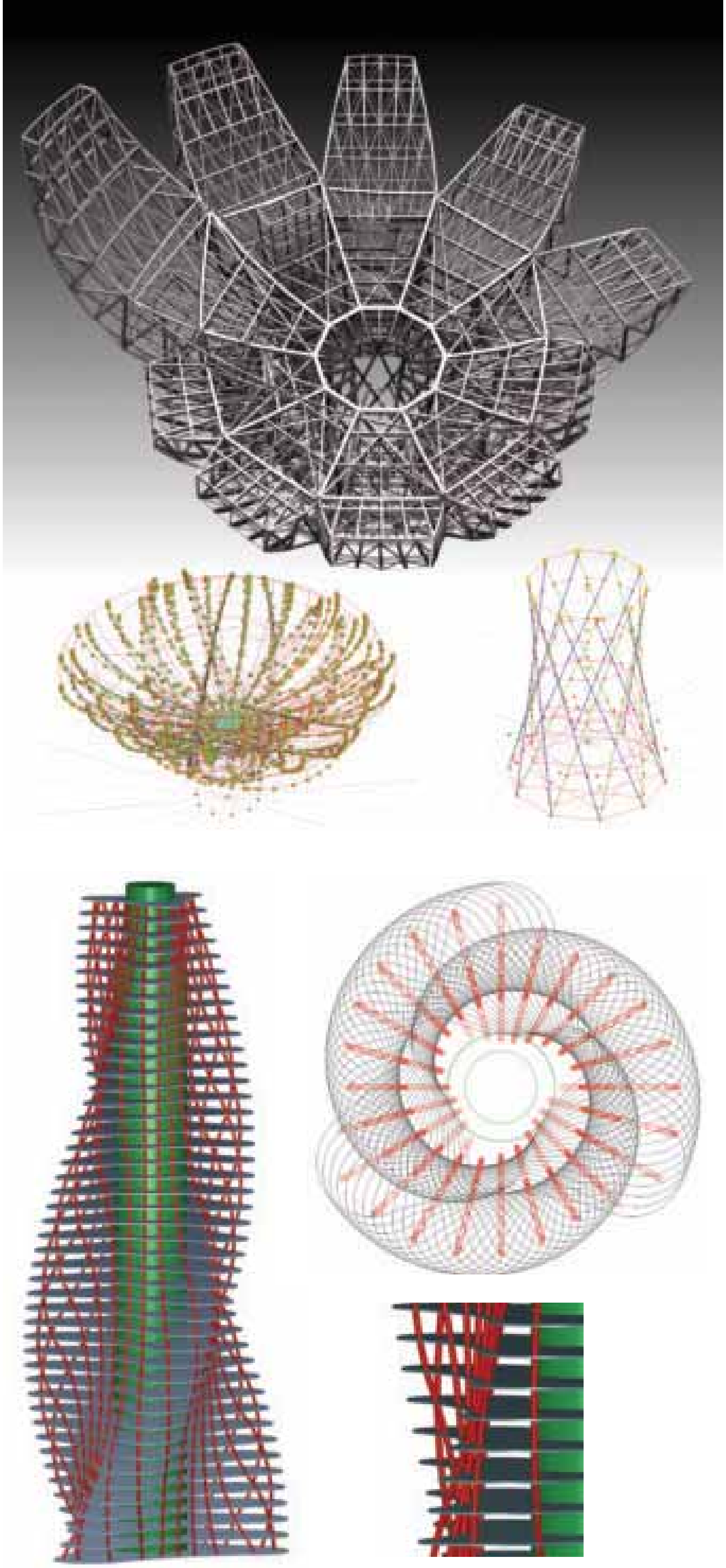
Parametric and generative modelling

Parametric modeling is a process using associative modelling software which, according to Bentley Systems, “captures and exploits the critical relationships between design intent and geometry” via scripts, algorithms and rules. By capturing the defining parameters of a building, ie geometric constraints, environmental issues, or material limitations, and their relationship to the building form, the design process can be automated and design iterations accelerated. Designers are thus empowered to explore limitless expressions in form that are not arbitrary, but instead responsive to the critical needs of the project.

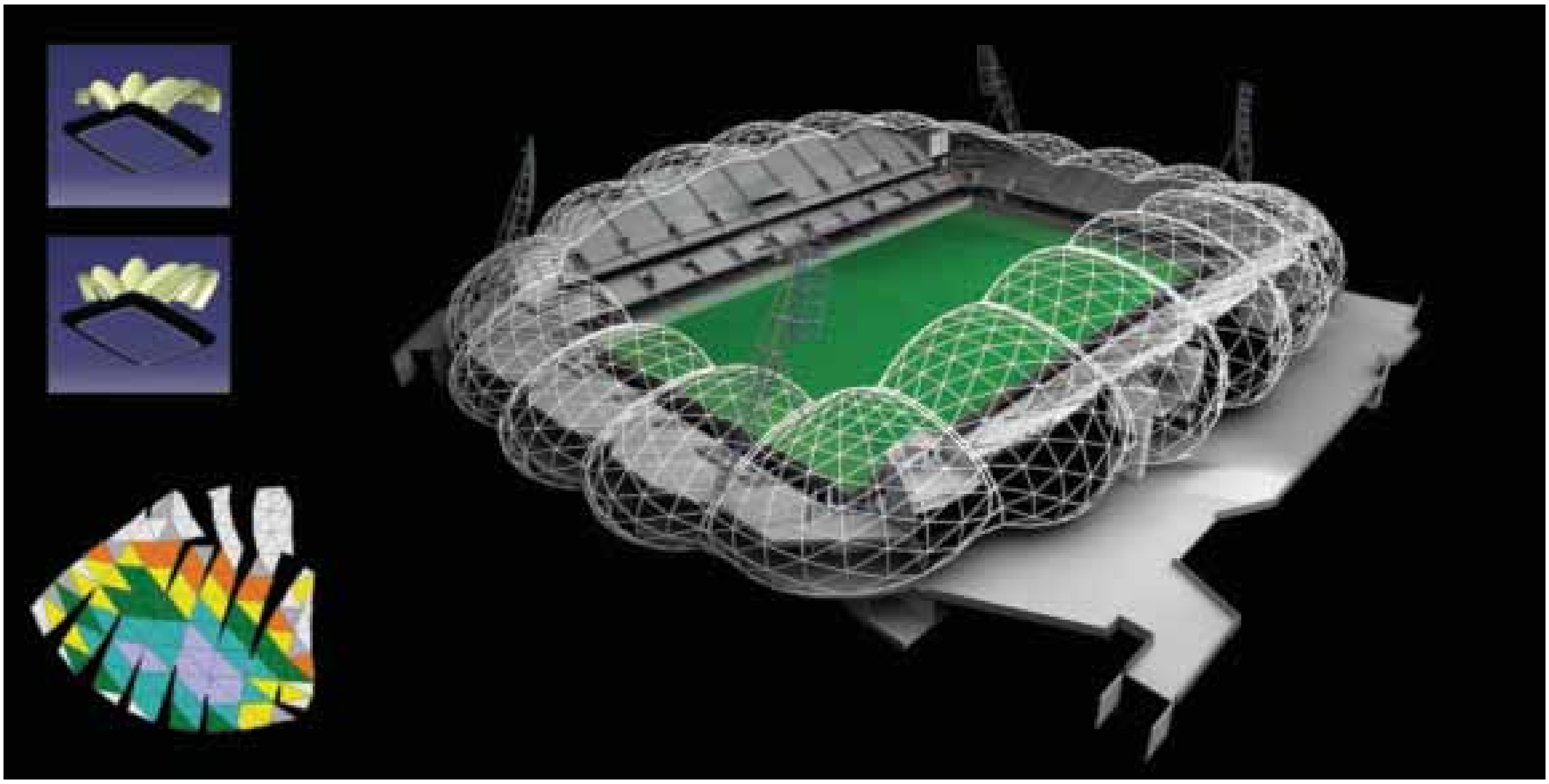
The impact on building design is liberating. For example, current trends in architecture for curving, non-orthogonal building forms are being driven by this new-found power in parametric modelling. Parametric software facilitates the design and setting-out of complex non-orthogonal building forms in two respects. Firstly, it allows users to generate the first form, which is often too complex to derive using simple computer programs or scripts. Then, since the form is generated from a system of rules applied to a few key variables, the shape can be changed rapidly by adjusting the variables, and tested for efficiency, aesthetics and performance.

Programming and scripting have, it is true, been used in various forms for many years, such as generating geometry and analysis models, or for specific uses such as venue sightline analysis. In the past, however, scripting was only accessible to those with computer programming skills, but now simpler scripting languages, and more compatibility between languages and new programs that use the same scripting principals but present the user with a graphical user interface, have made parametric and generative modelling more accessible.

Proprietary parametric software include *Digital Project* by Gehry Technologies[5] and Bentley Systems’ *Generative Components*[6] (Fig 7).



7. A sculptural arts centre and a twisted building created using *Generative Components.*



8. Parametric modelling of Melbourne rectangular pitch stadium roof, including roof panels and structural forms.

As an example, the proposed roof of the new Olympic Park stadium in Melbourne was studied parametrically to find the optimum shape, performance, and cost by varying the height of the leading edge of the roof and thus causing an automatic update of the key geometry of the rest of the roof. Structural and façade element variation could thus be studied to find the optimum set from a cost and visual point of view (Fig 8).

It is not difficult to imagine how multiple variations of buildings could be designed from standard components. A predefined façade suite could be programmed to populate the building face automatically, knowing its geometric and environmental limitations, as the geometry changes. Other components could also respond to their inputs. The designer would then select the preferred combination depending on client, site, environmental requirements, and individual preference. This has enormous possibilities in reproducible or adaptable buildings such as schools and apartment buildings, especially when combined with direct manufacture.

9. Smoke modeling in the Sydney Opera House model.

Environmental performance modelling

The principles of virtual building lend themselves to exploring project improvements through quick assessment and comparison of alternative environmental performance options. Pioneering methods are emerging that will assist in planning optimal space, material and energy utilisation, allowing teams to assess the optimum sustainable design outcome. These design options can be maintained throughout the design period, with the rapid ability to schedule, analyse, and compare options concurrently as they develop. For instance, a 3-D model now offers a central database from which compliance reports for environmental rating systems such as LEED[7] in the US and Green Star[8] in Australia can be automatically created.

Sustainable design assessments can focus at a micro-level - for instance, embodied energy in the concrete - or at a macro-level, to determine, for example, urban amenity, over-shadowing, or street acoustics in whole precincts. In either case, changes and improvements can be readily interpreted using visual and aural models.

There will be no more important development in this regard than the integration of thermal/energy, air quality, and daylight modeling into a central virtual building model. Using these tools we can hope to achieve more sustainable buildings and have confidence in their performance. Small steps have already been taken towards assessing the acoustic performance of spaces defined by 3-D models. Simplified models can now be extracted from a detailed central model and tested and refined, as Arup has done in modelling the upgrade to the Sydney Opera House Opera Theatre. Further development is needed on the direct interrogation of central models.

Similar testing levels are possible for smoke modelling as part of an overall performance-based fire engineering approach. Smoke modeling can now use geometry directly from the design 3-D model, providing a more precise assessment of evacuation times and smoke control performance (Fig 9).

10. City model of Ancoats Village, Manchester.

City modelling

Whole cities can now be modelled to demonstrate client and community-wide benefits - a "virtual city" of virtual buildings. The existing city is modelled by gathering geographic spatial information, either from existing information or aerial or terrestrial sampling, and storing it in a manageable format. The virtual building model for the new development is then inserted into the city model (Fig 10), where it can be accessed for such uses as integrating and assessing new developments for planning purposes, accessibility assessments, and visual and other environmental assessments.

Next

Real-time analysis

Currently, design is a time-consuming iterative process whereby design teams meet, conceive options, and then go away to investigate and test those options. A week or two later the team meets again and the process repeats. Tools are now being developed to enable design to be optimised quickly in "real time" in the design studio with the whole design team. Computational fluid dynamics (CFD) is used to assess the environmental performance of a space, but to date has been very time-consuming to set up and run, often taking days or weeks. But computer power and memory are developing rapidly, and hence the ability to run these routines on the spot and help the design team work through options more rapidly.

Optimisation

This process uses computational routines to assess and sort options to find an optimal set of solutions, providing a support to design intuition rather than replacing it. Any number of parameters in a design can be varied, including for example, views, daylight levels, thermal efficiency, and costs (Fig 11).

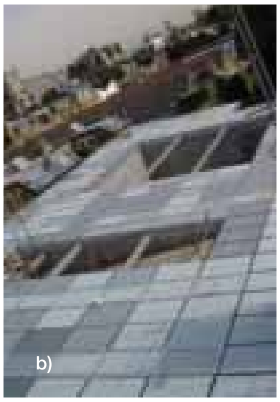
The optimisation routines used will depend on the problem to be solved. Routines are often set to optimise a single parameter (eg steel tonnage), but it is now more common to try to optimise multiple or competing parameters.

In these cases, one process is based on "ant colony" optimisation. Ants find the optimum route through unknown terrain by emitting pheromones; similarly, sets of solutions are developed that best meet the design team's objectives. Once a computational solution set has been built, alternate designs can be explored by varying the parameters.

Design parameters can be incorporated into complex algorithms that will find the best set of solutions to meet the objectives set by the design team. Once a computational solution set has been built, alternate designs can be explored by varying the parameters.

This approach has been widely used in the aerospace and automotive industries, and is only now beginning to take hold in the building industry. Optimisation's appeal for architects is that is provides an objective basis for design, but is in no way a replacement for design itself.

The design team and client must control the subjective process of selecting and weighing the parameters. The strength of this approach is that project solutions can be assessed without any presupposition about form, and confidence increased of finding the best solution.



11. The Light House, Notting Hill, London: arrangement of façade and roof panels optimised to fulfil a set of internal environment parameters.

Integrated 3-D urbanism

Our understanding of urban environments is becoming more critical than ever in our quest for a low-carbon, low-consumption future. Using virtual modelling to understand the interaction between all the components of a city and how the whole organism performs is a critical part of this journey.

Arup is taking the first steps towards a multi-parameter real-time quantitative simulation of urban environments. The aim is to partially automate the process of bringing discreet quantitative analytical solutions (urban design, moving vehicles, moving people, acoustics, lighting and climate) into a unified real-time interactive environment to demonstrate performance-based design to designer, client, and city planner.

The pilot project (Fig 12) studied a section of the planned eco-city at Dongtan in China. The process involved:

- creation of a 3-D urban design geometric model from the urban design in the GIS database
- CFD analysis of the prevailing wind flow
- analysis of daylight factors
- analysis of people and vehicle movement, taking into account the predicted land use destinations in the masterplan, and
- acoustical analysis of the urban space, taking into account design parameters including the noise emitted by vehicles and mechanical systems.

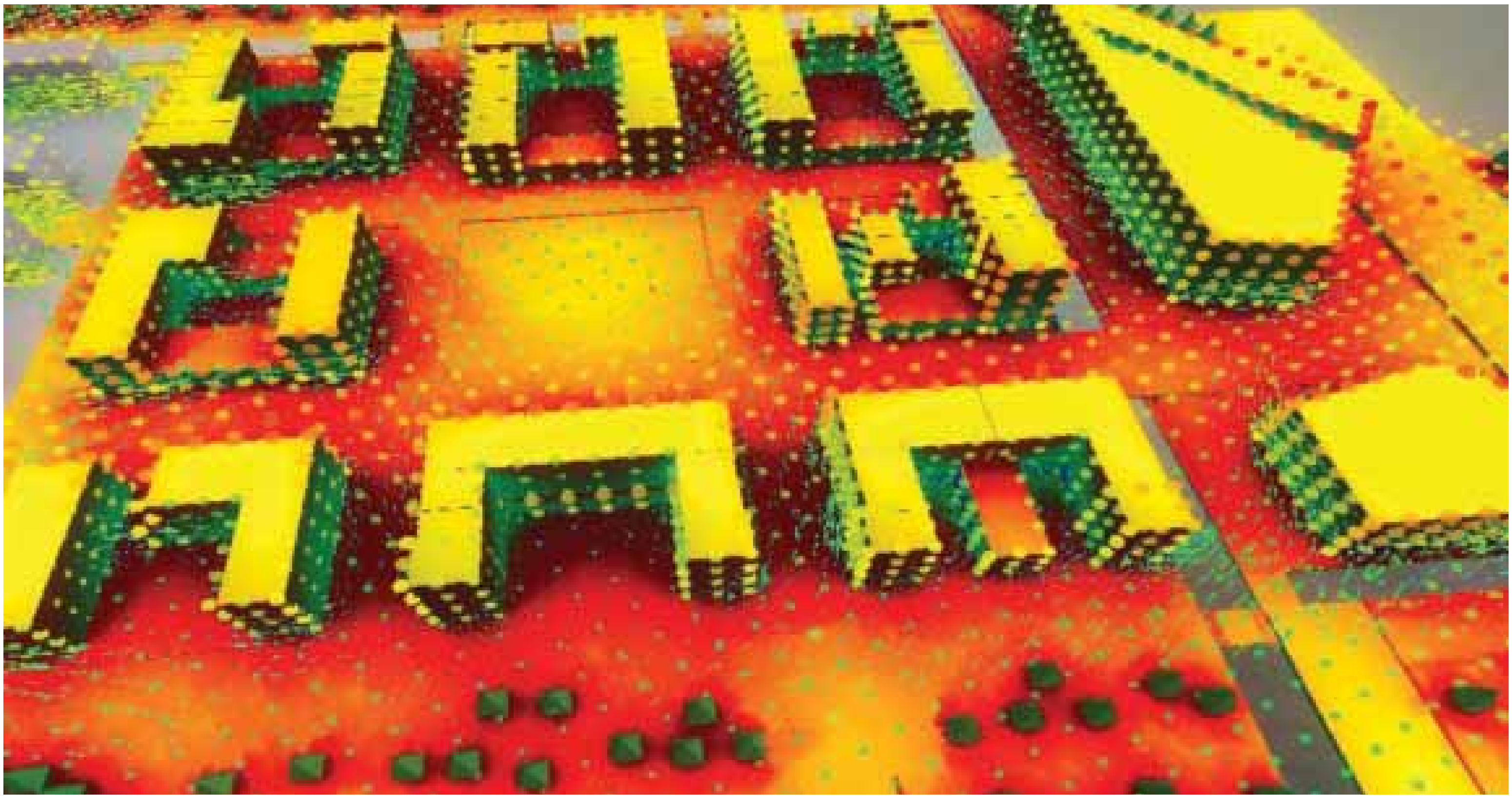
All quantitative analysis results were then integrated in a single environment that allows the user to freely navigate through the data in the 3-D environment in real time and look at all the results individually and together.

With further development, the interactive environment could become a masterplanning deliverable alongside sustainability guidelines. City planners, clients, and designers will all be better informed about prevailing local conditions and the impact of proposed developments. Designers will put forward their designs confident that the urban environment has been optimised despite competing parameters. The process provides a first step in our quest to design the sustainable city of the future.

Immersion (aka virtual reality)

High degrees of intuition and judgement currently exist in the design process. Past experience and years of design training go into producing a good design with the right feel to the space that, it is hoped, performs well. Wouldn't it be powerful to be able to experience the space *before it is built* in order to refine design choices and provide more certainty in the outcome?

At the most basic level, a "fly-through" view of a model provides some feel for the space and sense of proportion. This is proving a very useful tool in current practice, but it does not truly engage all the senses.



12. Integrated 3-D urbanism demonstration project.

It is now possible to provide an accurate aural footprint of a space using acoustic simulation rooms such as Arup's *SoundLab*. In *SoundLab*, the acoustic performance of a space can be demonstrated at any position inside the space using surround speakers, with visual clues provided by a 3-D model on a screen. It is thus possible to demonstrate the view and sound at any given seat in specific performance spaces.

Engaging the visual senses is also being explored using 3-D projections or virtual reality goggles, which provide some ability to immerse yourself within a space modelled in 3-D. There are shortcomings, however, as current screen and projection technologies are unable to closely replicate the visual bandwidth perceived by the human eye, and hence form a barrier to true "reality", particularly when in varying shades of light and dark. These tools are still under development and far from mainstream. As for air temperature and movement, attempts have been made to provide a visual representation so that we can see how a space is behaving. CFD is the current tool; experiments to present the results in 3-D have not so far proven successful.

The goal is a room that can simulate the appearance, sound, air movement, and temperature performance of a space, providing a true immersive experience. This might be formed by creating a box in which the building model is projected onto the inside walls to simulate standing or walking in the room in question, while surround speakers, fans, heaters, and air-conditioners simulate the planned environmental conditions direct from the virtual model (Fig 13).

Populating virtual buildings

Software now exists that permits the virtual building space to be inhabited by agents, preprogrammed with human behavioural patterns to see how they will react to different physical environments. One such program is Arup's *MassMotion*, an internally-funded research and development initiative that staff in the firm's Toronto and New York offices developed in response to the needs of the Fulton Street Transit Center (FSTC) project in New York City. Since then, further development has taken place in Toronto with technical input from staff in the New York, Melbourne, Westborough, and San Francisco offices.

Developed relatively economically in comparison with other comparable programs, *MassMotion* is a completely new suite of tools, though the developers leveraged commercially available 3-D software from *Softimage* to streamline development and rapidly build out functionality. *MassMotion* is also very cost-effective.

MassMotion produces highly instructive animations of pedestrian flow, and it should be stressed that these are not merely animations, but the results of analysing the cumulative effect of the decisions of the individual agents. In addition to the animations, *MassMotion* produces flow and occupancy counts, queue sizes, and density maps; all of which inform the design.

The process involves the creation or adaptation of a 3-D model with all the primary physical and spatial features that one would find in the final built form. Then the agents can be programmed to behave in ways that mimic human behaviour, for instance pausing at a café for a cup of coffee or stopping at a travel information board, passing through a turnstile or going up an escalator, based upon destination preferences. The FSTC model agents were given attributes from the field surveys, ie male/female ratios (as women on average walk at a slightly shorter step and pace), and whether they were commuters (know where they are going) or tourists (not sure where they are going).

The agents are then left free to populate the model, enabling the users to observe and assess how the space performs. The result is the potential for a realistic assessment, as true pedestrian systems are more random and chaotic than previous modeling tools allowed. The performance of the space can then be assessed against level of service metrics and to identify bottlenecks, as well as egress assessment. Traffic simulation can also provide further opportunities.

13. Immersion in a virtual reality room modelling sight, sound and comfort.

The breakthrough with this technology is that it opens up endless possibilities for testing any sort of spatial interaction. For example, the likely success of retail layouts could be proven.

Since its application for FSTC, *MassMotion* has been developed further. It can now simulate a broad range of pedestrian activities including emergency evacuation, navigation by familiarity or by signage, behaviour in access-controlled areas such as fare gates, and dynamic response to scheduled events.

A wide range of project types, including train stations, bus stations, and airports, as well as stadia and office towers, have now been designed with the help of *MassMotion*.

Conclusion

Full virtual prototyping of buildings is no longer a dream for the distant future. Powerful tools are being implemented in the virtual building environment that allow us to partially simulate the performance of a building before it is constructed. As the technology develops, the potential exists for the creation of a complete virtual building in which all its aspects and internal relationships can be tested and understood in an automated fashion.

The challenge for the property and construction industries today is to embrace and accept the 3-D-enabled technology now on offer, to produce a more streamlined, right-first-time approach to building design, construction, and operation.

Forward-thinking clients already expect 3-D-based design. As technology advances these are the clients who will expect the model's object content to be packed with all conceivable aspects of data to give them financial or operational certainty. The resulting virtual building models will open far-reaching opportunities within the future management and business operations related to the building industry, and Arup will contribute a key role in this process.

14. Fulton Street Transit Center, New York: *MassMotion* modelling.

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Credits

National Aquatic Centre, Beijing
Client: Beijing State-owned Assets Management Co Ltd
Architect: PTW (Australia) & CSCEC & Design

One Island East, Hong Kong
Client: Swire Properties Ltd
Architect: Wong & Ouyang (Hong Kong) Ltd

122 Leadenhall Street, London
Client: British Land Co plc
Architect: Richard Rogers Partnership Ltd

Melbourne Olympic Park rectangular pitch stadium
Client: Melbourne & Olympic Park Trust
Architect: Cox Architects & Planners

Sydney Opera House Opera Theatre refurbishment
Client: Sydney Opera House Trust
Architect: Utzon Architects/Johnson Pilton Walker

Princeton University Chemistry Laboratory
Client: Princeton University
Design architect: Hopkins Architects Ltd
Executive architect: Payette Associates Inc

Marina Bay Sands Integrated Resort, Singapore
Client: Marina Bay Sands Pte Ltd
Design: Architect: Moshe Safde *with* Aedas

Al Raha tower, Abu Dhabi
Client: Aldar Properties Pjsc
Architect: Asymptote Architecture

Fulton Street Transit Center, New York
Client: Metropolitan Transit Authority Capital Construction New York
Architect: Grimshaw Architects

Illustrations: 1 Ben McMillan; 2 Stuart Bull; 3 Vincent Fiorenza; 4 Swire Properties; 5 Nigel Whale; 6 Simon Kerr, 7 Matt Clark, John Legge-Wilkinson and Stuart Bull (© Arup + Marina Bay Sands Pte Ltd); 8 John Legge-Wilkinson 9, 10 Simon Mabey; 11 Gianni Botsford Architects; 12 Alvise Simondetti; 13 Tristan Simmonds; 14 Robert Stava.

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Acknowledgements

The authors would like to acknowledge the key contributions to this article from the following Arup experts:

Americas: Matt Clark, Anthony Cortez, David Farnsworth, Vincent Fiorenza, Ken Goldup, Zak Kostura, Murat Kurakas, Robert Stava, Ben Urick

Australasia: Peter Bowtell, Stuart Bull, John Legge-Wilkinson, Chris Pynn

East Asia: Maverick Chan, Kelvin Lam

Europe: Francesco Ànselmo, Gavin Davies, Alexej Goehring, Anne-Marie Gribnau, Alejandro Gutierrez, Peter Head, Andrew Jenkins, Scott Kerr, Vahndi Minah, Aston Wisdom, Braulio Morera, Tristan Simmonds, Steve Walker, Neill Woodger, Darren Woolf, Russell Yell.