2/2008

The Arup Journal

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When the world's largest observation wheel, the *Singapore Flyer*, was opened on 15 April 2008 by Singapore's Prime Minister, Lee Hsien Loong, it was very much a national celebration befitting this iconic structure. Prime Minister Lee struck a symbolic beat of the ceremonial drum, and initiated a spectacular light show and fireworks display (Fig 1). He proudly stated: "I am very happy with the project; it is on time and on schedule. I think it's achieved what we hoped."

1.

The *Singapore Flyer*

Andrew Allsop Pat Dallard
Heng Kok Hui André Lovatt
Brendon McNiven

Set amidst a "necklace" of attractions, the *Singapore Flyer* has become the latest addition to the city skyline. Arup built on knowledge gained during the design of the *London Eye* to develop a "next generation" rim structure. The resulting two-dimensional "ladder truss" rim is both larger in diameter and lighter than that of its predecessor.

Inception and government support

The Singapore Government plans to position Singapore as a leading tourism hub for Asia. It has set ambitious targets for the tourism industry – to triple receipts to S$30bn, double visitor arrivals to 17M, and create 100 000 additional tourism-related jobs by the year 2015. It aims to transform the tourism landscape to realise this vision.

The *Singapore Flyer* exemplifies what is to come. This giant observation wheel (GOW) occupies a prime site in the Marina Bay area and is one of the "necklace of attractions" planned to alter the future landscape of downtown Singapore. The *Flyer* was conceived as the key element in a development-led project by Melchers Project Management Pte Ltd (MPM), a subsidiary of C Melchers GmbH & Co, an international logistics and engineering services company.

The proposal to develop the *Singapore Flyer* as a must-see, must-do tourist attraction in Asia was agreed in 2003. The huge wheel was to be an iconic landmark and a compelling draw for foreign visitors to the garden city. The Singapore Tourism Board supported the project by purchasing the land for the development and leasing it back to Singapore Flyer Pte Ltd, initially for 30 years but with an option for a further 15 years. The land was rent-free up to the first day of operation.

Overview

The *Flyer* is located on the peninsula of land that separates Marina Bay from the Kallang Basin, and is oriented to overlook the new downtown around Marina Bay in one direction and to provide a spectacular view of the East Coast and Singapore Straits in the other (Figs 2-4). As the project forms part of the government's tourism blueprint to develop Marina Bay's new waterfront, its prime location is sited close to the future Millenia Mass Rapid Transit (MRT) train station.

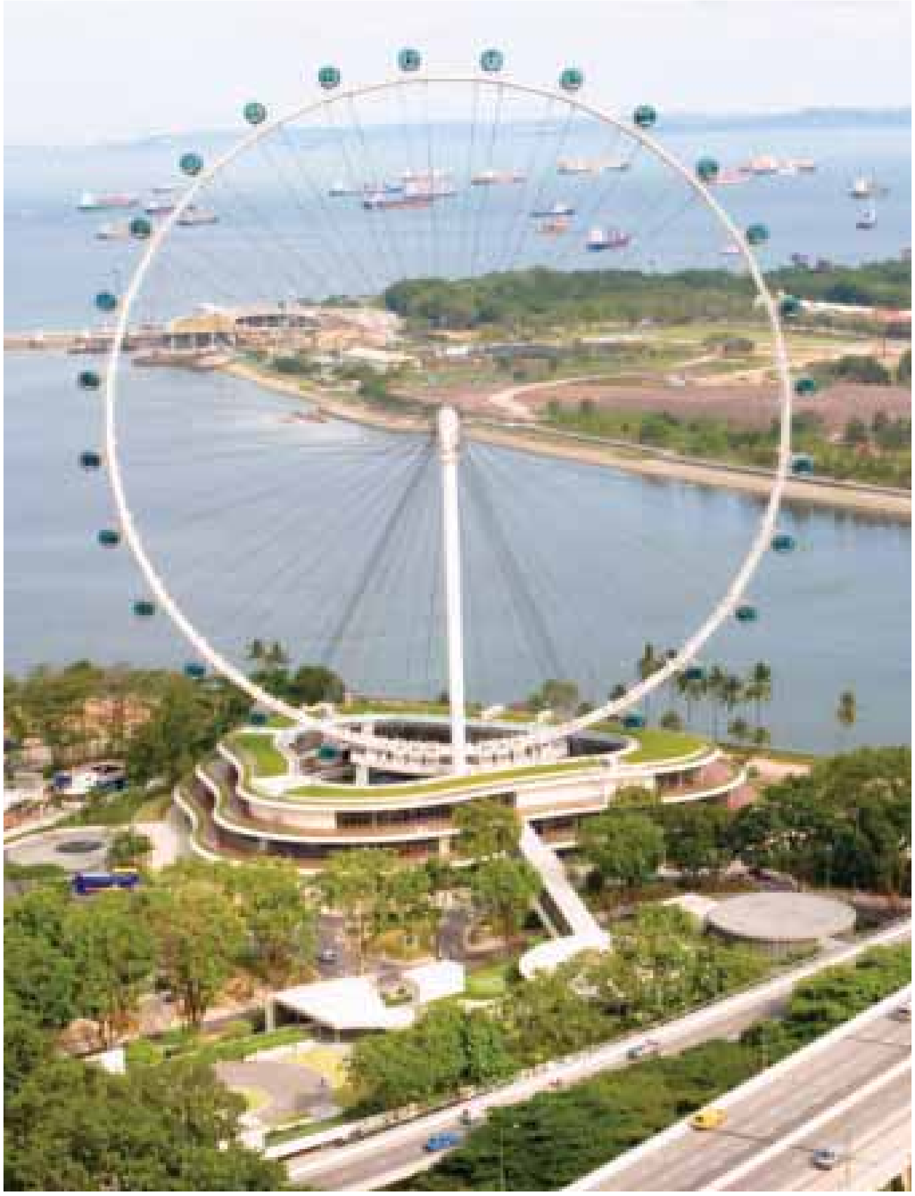
This iconic visitor attraction offers passengers a spectacular sightseeing experience. The 28 fully air-conditioned capsules, each accommodating 28 people, are attached to the outer rim of the 150m-diameter wheel, which at the top of its revolution reveals a 45km panorama of Singapore, Malaysia, and Indonesia.

Visitors board the capsules via access gantries and loading platforms on the third storey of the terminal building at the base of the wheel. The building not only houses the passenger flow infrastructure required, but also includes 15 000m² of retail shopping space. A tropical rainforest attraction replete with water features is incorporated in the courtyard space immediately below the wheel to add to the visitor experience.

A 280-lot car park space located across Raffles Avenue is linked to the terminal building by a pedestrian bridge. This fully-covered access allows visitors to appreciate the environs while making their way to the main building. The surrounding area also accommodates a concert amphitheatre for performances and other artistic pursuits.

The Japanese architect Kisho Kurokawa prepared the design concept for the building works (Fig 5), whilst DP Architects in Singapore (Fig 4) carried out all the final documentation, acting post-concept as the local architect of record.

At its highest point, the *Singapore Flyer* stands a total of 165m tall, making it the world's largest GOW. It surpasses the well-known *London Eye* by 30m, and thanks to a more efficient and innovative design, is not only larger but also lighter and slimmer than its predecessor.



2. The *Flyer* stands above the three-storey terminal building.

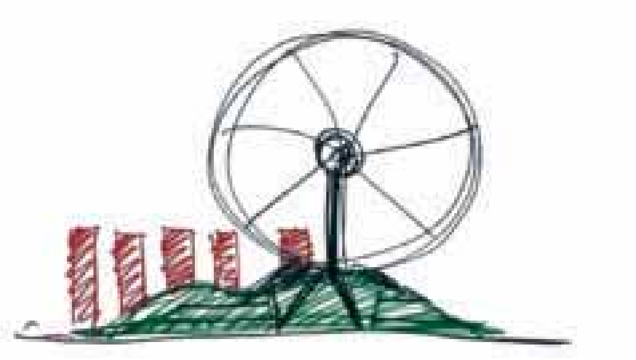
3. *Singapore Flyer* location plan.

Arup's role

The design of the *Flyer* itself was very much engineering-led. Arup built upon knowledge gained during the design of the *London Eye* to develop a thinner, lighter, "next generation" rim structure with a more efficient structural geometry and cable arrangement. The *Flyer*'s two-dimensional "ladder truss" rim structure gives it less bulk than the *London Eye*'s three-dimensional triangular rim, as well as reducing the wind loads.

At the outset of the project, Arup worked closely with MPM in a financial risk/reward partnership arrangement that involved reduced initial fees, then supplemented by success payments upon the proving of project feasibility. Arup took the design evolution from the initial conceptual ideas through scheme development up to tender stage.

4. Perspective looking north-west.



5. Architect's initial concept sketch for the terminal building.

3G design

Arup developed a "third generation" rim design, using state-of-the-art technology that makes the most of the strength and arrangement of the cables to reduce the size and visual appearance of the rim to a two-dimensional truss (which from a distance seems to disappear in relation to the size of the wheel).

"First generation": laced compression spoke wheels typical of fairground park attractions

"Second generation": 3-D box or triangular truss with tension cables as in the *Ferris Wheel* or the *London Eye*

"Third generation": 2-D "ladder" truss rim of the *Singapore Flyer.*

The detailed design was then followed through by the GOW's contractor, Mitsubishi Heavy Industries, in a design/build form of contract, with Arup acting in a novated role as the engineer of record, signing and submitting to the local authorities.

Giant observation wheels: a short history

GOWs form one lineage in a family of visitor attractions known as iconic viewing platforms (IVPs). Gustave Eiffel's Tower, the centrepiece of the 1889 Paris Exposition, was perhaps the first purpose-built IVP of modern times, and remains one of the world's most successful with more than 200M visitors since it was opened.

The founder of the GOW lineage was George Ferris's Wheel, designed and built as the principal engineering attraction of the 1893 Chicago World Fair (Fig 6), and with the intention of creating an engineering marvel to rival the Eiffel Tower's spectacular success. This original *Ferris Wheel* was 76m in diameter and had 35 cabins, each of which was able to accommodate up to 60 people. It was demolished in 1906.

Two years after the *Ferris Wheel* began operation, an 86m diameter, 40-car rival was built by the Gigantic Wheel and Recreation Towers Company Ltd for the Empire of India Exhibition, Earl's Court, London. Several more GOWs were subsequently commissioned and built around the world, characterised by their size and advanced engineering. Notable amongst them are:

- 1897: Vienna *Riesenrad*, 61m diameter (Fig 7). Burnt down in 1944 and rebuilt the following year, albeit with only 15 cabins of 12-person capacity rather than the original 30 cabins, it was immortalised in the 1949 movie *The Third Man* as the location of the famous speech by the character Harry Lime (Orson Welles) to Holly Martins (Joseph Cotten).
- 1900: *La Grande Roue*, Paris Exposition Universelle (Fig 8), approximately 80-100m diameter, 36 cabins with 8-10-person capacity. It was demolished in 1937.
- 2000: *London Eye* ("Millennium Wheel") (Fig 9), 135m diameter, 32 capsules with 25-person capacity.

Foundations

The geology of the Marina Bay area is typically recent marine and fluvial sediments of the Kallang Formation, varying from unconsolidated to normally consolidated. These materials overlay the Old Alluvium present at 15-30m depth. About 30 years ago the site was reclaimed using fill over the existing strata.

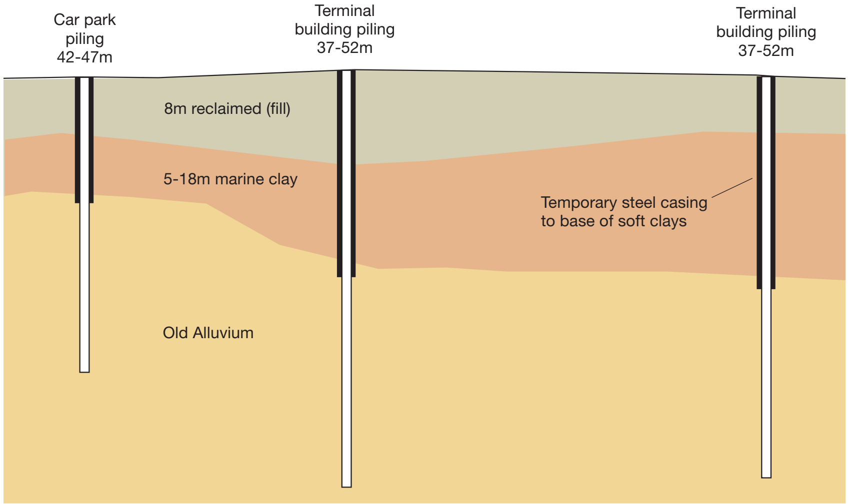
6. The original *Ferris Wheel*, Chicago World Fair, 1893.

7. Vienna *Riesenrad* ("Giant wheel"), 1896.

8. *La Grande Roue*, Paris Exposition, 1900.

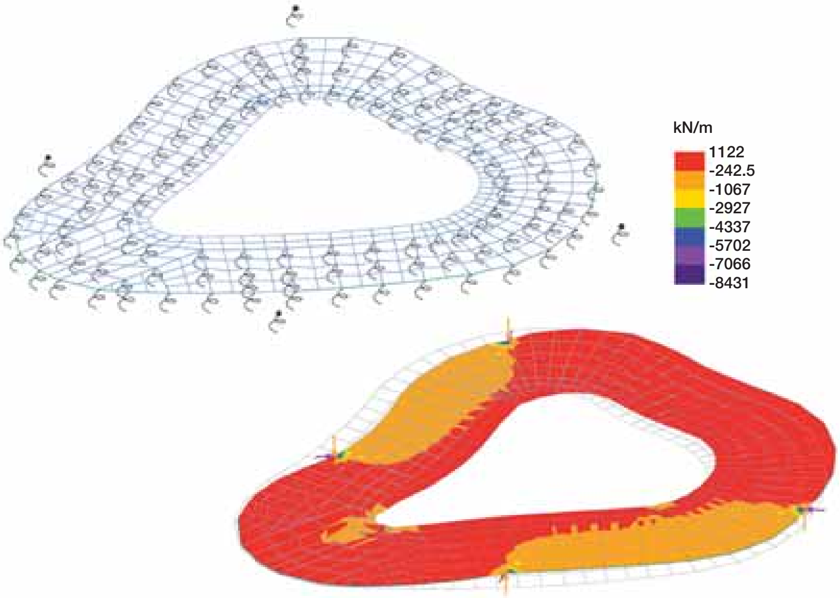
9. 2000: *London Eye* ("Millennium Wheel")

10. The wheel is supported by two 2.85m diameter columns.



11. Site geology.

12. Ground floor annulus finite element model.



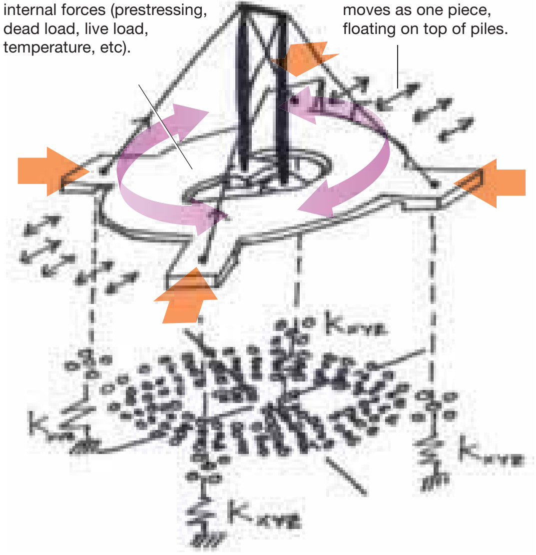
It was decided at the outset not to incorporate basements in the project, to avoid unnecessary cost and impact to the programme. The foundations for the buildings and wheel are bored piles between 600mm and 1500mm in diameter, and penetrating up to 52m in depth, socketed into the Old Alluvium (Fig 11). The piles were fully cased through the extent of the reclaimed fill and soft marine clays.

Supporting structure

The wheel is supported by two 2.85m diameter columns, founded in the courtyard of the terminal building below and stabilised at the spindle level by four cable stays. Each cable stay comprises six 100mm diameter locked coil cables prestressed to 17MN (Fig 13).

The lateral components of the stay pre-tensions are resolved through the spindle structure at the high level, and through the terminal building's ground floor structure (acting as a compression annulus), at the low level. The result is a relatively stiff closed structural system that distributes and balances the lateral components of the permanent pre-tension forces in the structure. The piles in essence are then only required to resist the vertical uplift and downwards reactions, and the net lateral force arising from wind loading, etc (Figs 12, 14).

13. Anchorages in the courtyard for the cable stays.


Ground floor plate provides "annulus" stiffness, balancing internal forces (prestressing, dead load, live load, temperature, etc).

Whole of building + GOW superstructure moves as one piece, floating on top of piles.

14. Design sketch showing force resolution for the supporting structure.

Rim and spoke design

The rim and spokes are the components that differentiate wheels from all other types of structure, and which pose some of the principal engineering challenges in designing GOWs.

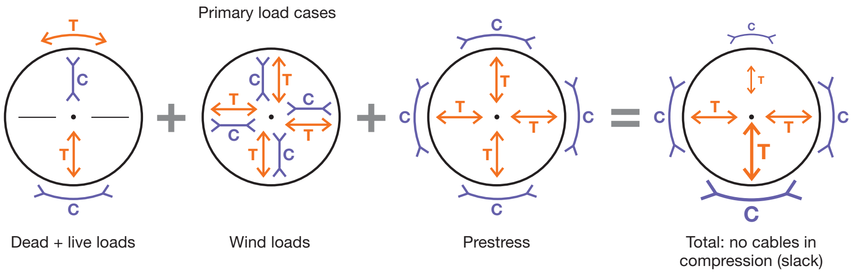
Three external load cases generate significant forces in the rim and spokes. These forces are described assuming that the spokes can resist compression. Firstly, gravity causes tension in the lower spokes and compression in the upper ones, along with compression in the lower half of the rim and tension in the upper half. Secondly, wind causes tension in spokes attached to the windward side of the hub and compression in those attached to the leeward side. Thirdly, temperature differentials between the rim and spokes cause spoke tension and rim compression, or vice versa.

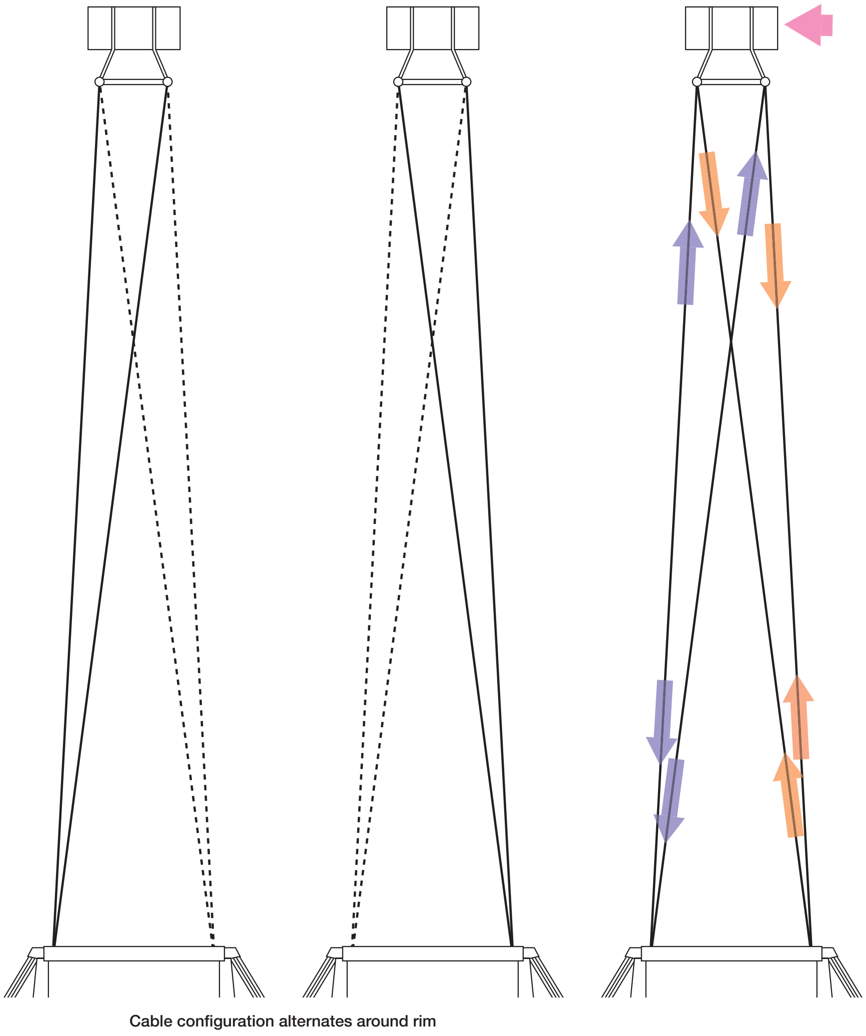
The *Singapore Flyer* uses cable spokes that need to be prestressed to resist compression. The prestress is set such that under factored loads none of the cables go slack, so they remain effective in controlling the displacement of the rim. While the prestress is necessary, the compression it induces in the rim dominates the rim design. Achieving an efficient design for the rim requires the prestress to be minimised (Fig 16).

The 2-D ladder truss helps reduce the wind load on the *Flyer* rim. This is important as, even though the wind load is only about a 10th of the weight, it generates approximately the same prestress requirement because the cable angles are unfavourable for resisting lateral load. To minimise the prestress required against wind, the width of the *Flyer* hub was maximised and cables were selectively crossed to the opposite side of the rim to increase their efficiency.

15. The *Flyer* rim is a "third generation" two-dimensional lattice truss.

16. Spoke cable components of force.





17. Rim spoke cable arrangement.

18. The main spindle is 2.6m in diameter, 25.25m long, and weighs 180 tonnes.

About half the weight of the rim, and a significant portion of the wind load, comes from the non-structural items such as the capsules, bus-bars, and drive rails. As these items fell within Mitsubishi's specialist design role, the Arup team impressed upon the various component designers the need to make these items as light and as streamlined as possible.

The final requirement is to minimise the weight of the rim primary structure. The rim needs to resist buckling under the compression (induced primarily by the spoke prestress) and to span between the lateral and radial restraints provided by the cables.

The team used purpose-written software to study rim buckling. The problem mode tends to be lateral/torsional buckling, with a critical load factor depending on the product of the lateral bending and torsional stiffnesses of the rim. In designs like the *London Eye*, the rim provides both the large lateral and torsional stiffness, and hence needs to be in the form of a substantial 3-D truss.

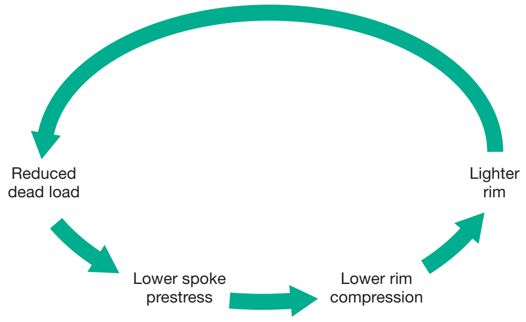
An important aspect of the *Singapore Flyer* design, however, is that it maximises the contribution the spoke cables make to the stability of the rim. The lateral stiffness provided by the cables is limited, because practical and aesthetic limits on hub width mean the cable angles will always be unfavourable. However the radial stiffness of the cables is large, and attaching them to the sides of the rim provides considerable torsional stiffness. The rim then just needs to be laterally stiff, making the 2-D ladder truss an appropriate form. Fig 17 shows how the outer cables provide torsional restraint to the rim, while the increase and decrease in tension of the inner cables transfers lateral load from the rim to the hub.

With the lateral/torsional buckling performance provided by the spokes and ladder truss, the spanning requirement determines the bending capacity of the rim in the plane of the wheel. Rim bending moments are minimised in normal operation by aligning the cables with the capsule supports. The CHS (circular hollow section) 864mm x 25.4mm chord size allows for an accident condition in which a cable is assumed to break. This also allows for cable replacement if required.

As the prestress determines the rim compression, and the rim compression is the dominant loading on the rim, a cycle of cause-and-effect is set up. If the rim design can be made more efficient and the dead load of the rim reduced, then the required prestress in the spokes decreases. This decrease in spoke prestress results in a reduced compression in the rim. This allows the rim to be made lighter, starting the cycle over again (Fig 20).

As well as spending effort to reduce the weight of the rim, the design also looked at the breakdown of the traditional code load factors in more detail. A reduced dead load factor was justified on the basis

19. Passengers mount the *Flyer* from the boarding deck at the third storey of the terminal building.



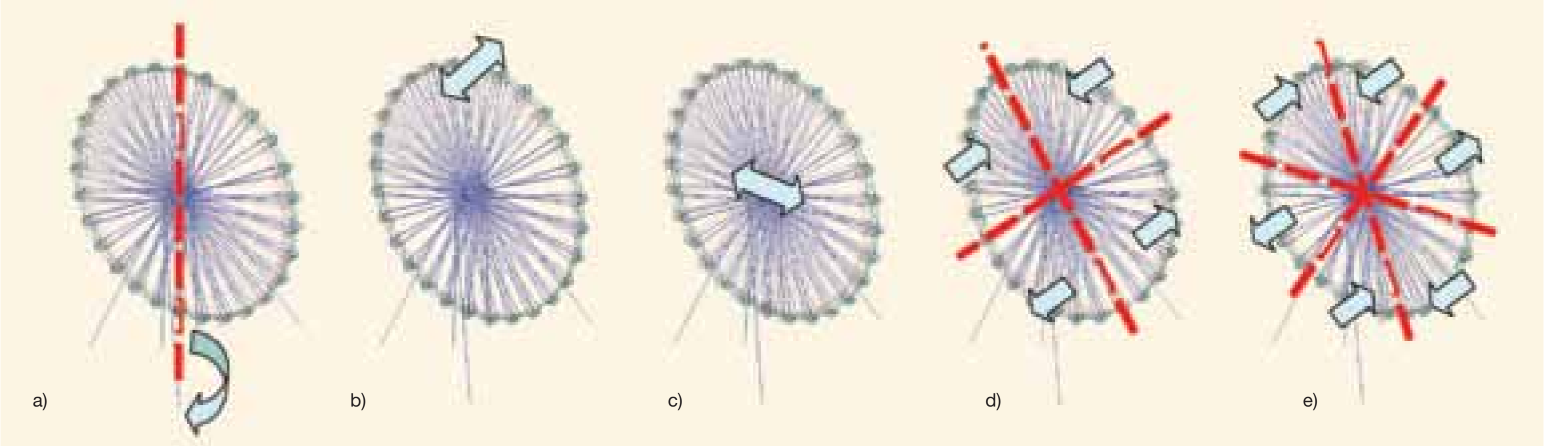
20. Virtuous dead load cycle.

that the variance in dead load that could be expected in the structure was low when compared to that of a typical building. Here, the weights of the capsules and other applied dead loads were known much more accurately than typical building dead loads. As a result, dead load factors more akin to those used in bridge design were adopted for the design of the rim structure.

Dynamics

Passenger comfort is a key design consideration for GOWs. Comfort in terms of vibration depends particularly on the wind response of modes involving movement out of the plane of the wheel. The team studied how the properties of these modes were affected by changes in lateral restraint at the bottom of the wheel, and changes in the stiffness of the support structure cable stays. The optimum level of damping to be added was also examined.

The studies showed that comfort benefits could be gained by increasing the size of the support structure cable stays over that required for strength, so as to enhance their stiffness. They also concluded that damping should be introduced at the base of the wheel, so this was incorporated into the passenger deck structures along with the drive train mechanisms (Fig 21).



21. Wind response modes: (a) in plan rotation (0.2Hz); (b) Lateral displacement at top of rim (0.42Hz); (c) Longitudinal displacement of support structure (0.60Hz); (d) Four-lobe displacement of rim (0.65Hz); (e) Six-lobe displacement of rim (1.1Hz).

22. Capsule and rim segment during wind tunnel testing.

Wind loading

Climate and design wind speeds

Singapore experiences unique wind conditions: "Sumatra" squalls blow in from the Straits, and in this mixed wind climate monsoons and thunderstorms are also commonplace.

While in general, wind speeds are low, the peak gusts in Singapore, resulting from thunderstorms, can arise very quickly and with limited warning. It is therefore difficult to reliably manage evacuations of the wheel in advance of strong winds as can be done on the *London Eye*. Fortunately such storms normally consist of only a few strong wind gusts.

The variation of wind speed with height in convective events (such as thunderstorms) is known to be quite different from the standard code profiles, and often the strongest winds occur below 100m height. Unfortunately there are currently no procedures that can be considered reliable for modelling this kind of behaviour, so in accordance with current design practice a standard wind model was assumed to fit the predicted 50-year gust speed at 10m height. This model is likely to overestimate the wind gust speeds as the top of the wheel but may underestimate the dynamic response factor - a rational compromise, given the unknowns! An allowance for the provision of dampers on the rim was made in the design should they have proven to be required under actual wind conditions.

During normal operation, a wind speed limit of 13m/sec average at 10m height was used, together with gust and dynamic response calculations based on the ESDU (Engineering Sciences Data Unit) wind model, which is compatible with British Standard code design. Given the unpredictable nature of squall/thunderstorm conditions in Singapore, however, a design acceleration limit (comparable to that experienced on the MRT trains) was imposed under the full design wind condition. Damping was also provided to ensure movement dies out quickly and any passenger alarm quickly alleviated.

Wind tunnel testing

In view of the importance of the wind loads in helping to determine minimum prestress limits, a segment of the rim and a capsule was tested in MHI's Nagasaki wind tunnel facilities to verify the assumptions made on wind drag (Fig 22). Only a segment of the wheel was tested in this large and high-speed tunnel, since the model needs to be at a scale where Reynolds' number effects can be managed. Measurements were taken for a variety of wind approach angles and rim inclinations to enable accurate application of the results in the design model.

There was some doubt about the extra drag that would result from the cylindrical shape of the *Flyer* capsules, compared to the better aerodynamic shape of those on the *London Eye*. It was also necessary to model accurately the service bus-bars and drive plates, etc, which significantly increase wind drag compared to the bare tubes of the rim structure itself.

Due to programme constraints, the foundations were designed using more conservative assumptions on overall drag, prior to the wind tunnel results being available. The more refined wind tunnel test results were incorporated into the superstructure design.

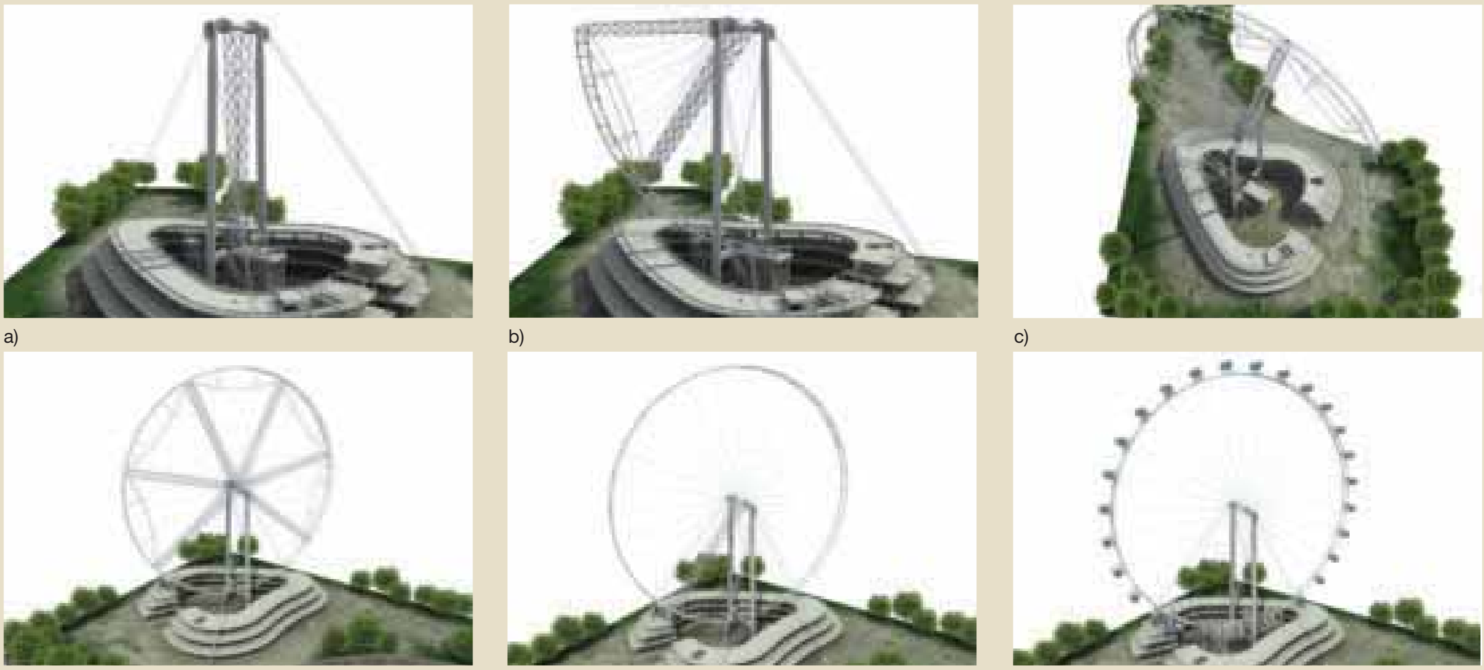
Aeroelastic stability

Questions were also raised about the risk of large amplitude vibrations due to effects such as "galloping", "vortex shedding" and "flutter". The porous nature of the rim and the low sustained wind speeds in Singapore both pointed away from problems with response of the whole wheel. Local vibrations of long slender tubular elements and cables were also considered. The main elements of the rim were found to be stable, but the possible need for cable dampers was kept on the risk register.

The main strut columns were found to fall within the range of potential vortex shedding. Tuned mass dampers were installed at mid-height in each of the columns after site measurements of the natural inherent structural damping were found to be below the values required to mitigate response.

Some vibration in the cable spokes was also observed on site during construction and ascertained to be due to wind/rain-induced responses. Rivulets of water running down the spokes alter the geometric form and result in a dynamic response. Stockbridge dampers tuned to the third and forth natural frequencies of the cables (those frequencies at which resonance was observed), were provided subsequent to operations commencing.

23. Wind tunnel tests confirmed the drag on the cylindrical capsules.



a) b) c) d) e) f)

24. Stages of erection: The wheel was erected in a “pie-slice” fashion (a). Each segment was rotated (b) until all segments had been installed (c). Once the wheel was erected, the spoke cables were stressed in two stages (d). The temporary struts were then removed, leaving only the rim attached to the central hub by cables (e), followed by the installation of the cabins (f).

Erection method

Possible erection methods (Fig 26, overleaf) were studied in detail with both client and contractor, so as to satisfy several constraints:

- limited available space on site
- limitations imposed by support structure
- programme
- achieving final dimensional and prestress tolerances
- level of acceptable risk.

The horizontal lifting method used on the *London Eye*, whereby after assembly on platforms on the river Thames the entire wheel was raised by strand jacks to the final vertical position, was not favoured for the *Flyer*. This was primarily due to space constraints on site, but also because of geometric clashes with the terminal building and the support legs during lifting. Instead, a vertical erection method was used.

First, the main support structure columns were erected in segments using bolted splices, and then the hub and spindle arrangement (180 tonnes) was lifted by strand jacks off a temporary gantry spanning between the tops of the main columns.

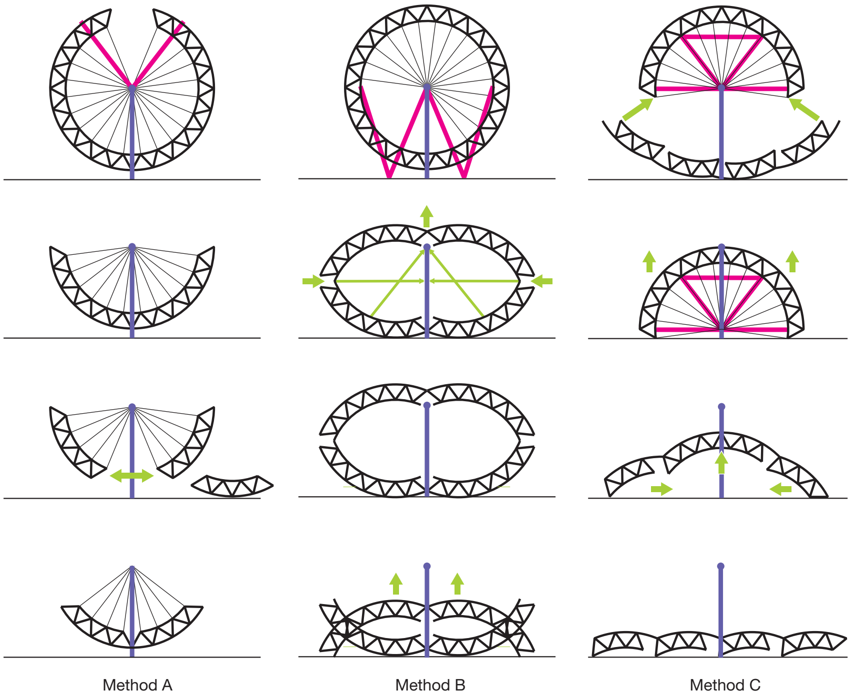
Initially the rim segments were intended to be barged to site using access from the adjacent Marina Bay and Singapore Straits. In the end, however, this proved impossible due to the barrage (a project converting the entire Marina Bay and Kallang Basin water bodies into a freshwater reservoir), sealing off access to the Straits. Instead the steelwork was sized and detailed to allow transportation by road.

25. View looking north-west during erection.

After the support columns and spindle were in place, the wheel itself was erected in a “pie slice” fashion. Rim segments were delivered to site and laid to level on a temporary stage. Cables were then installed in a slack condition. Temporary compression struts were provided between the hub and the rim enabling each segment of the rim to be stable in its own right.

Upon completion, each segment was rotated to clear the way for installing the next segment and so on (Figs 24, 25). Additional strengthening was provided to the rim in the form of lightweight chords forming bowstring trusses and maximising the size of the segments able to be built. Once the full wheel was in place, the cables were stressed in two stages, and the capsules installed.

Laser technology measuring microtremors in the cables was used to ascertain the force in each of the cable spokes at different stages in stressing. A full set of cable tensions were measured over a three-night period from survey stations at ground level, and checked against analytical predictions.



26. Alternative erection methodologies.

Passenger boarding platforms/bridges

The passenger boarding bridges are the interface where all the requirements of the GOW operation come together at one point. These requirements often conflict. They include lateral structural support and damping to the base of the wheel, catering for the forces imposed by the drive motors and braking requirements, delivery of electrical power, provision for operating equipment and operations staff, and finally the necessity for a column-free slot to allow passengers to board and disembark unhindered. These all had to be considered in arriving at the final architectural and structural form.

A curved composite steel/concrete drive deck was finally adopted. Capable of supporting the various drive motors and dampers, etc, it also affords some acoustic protection to the passengers and operators immediately below. The deck is in turn supported off a large CHS triangular truss capable of resisting the torsions generated from the eccentricities of the deck and cantilever passenger platforms. The whole arrangement was supported three storeys off the ground by steel towers acting as cantilevers to resist lateral and longitudinal loading (Fig 27).

Passenger boarding bridges span the gap between the platforms and the terminal building, and movement joints at the building interfaces ensure the whole arrangement acts independently.

Fire engineering

Arup's fire engineers used a performance-based fire strategy for the terminal building, This enabled the stairs to be reduced, yielding considerable financial benefits for the client. Compared with prescriptive methods this approach saved 6m of required egress width, the equivalent of approximately 400m^2 of floor area (Fig 28). This was classed as part of the developable floor area permitted by Singapore's Urban Redevelopment Authority, and freeing it up as lettable area improved the building's net-to-gross ratio as well as providing for a more considered fire safety strategy.

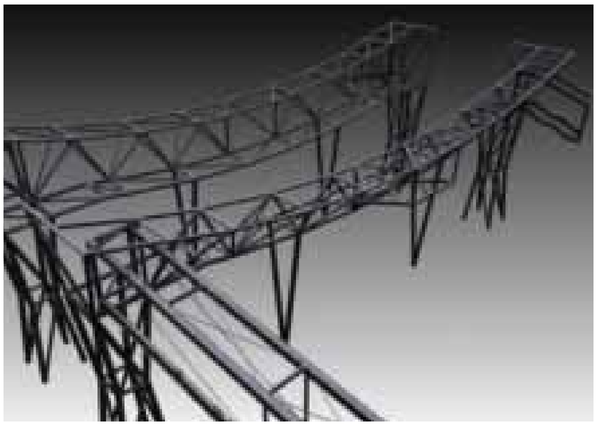
MEP engineering

The terminal building is unusual in that it is a building viewed mostly from above. With this in mind, the architects were keen to minimise the amount of rooftop clutter and services required. Most of the main services are therefore sited across the road in a compact drum area appended to the car park building and connected to the terminal building via the link bridge across Raffles Avenue.

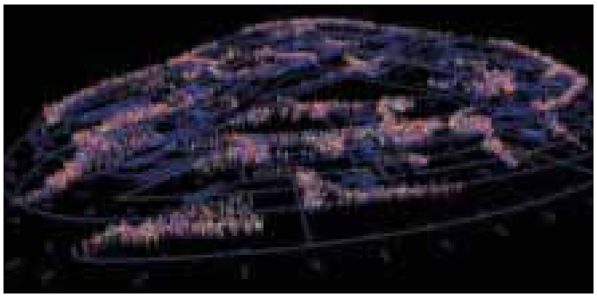
The terminal building was designed to maximise non-air conditioned open public spaces through the provision of circulation areas that provide shade and promote natural air flow. The building's "doughnut" shape also allows a high degree of connectivity to the central rainforest attraction, resulting in a comfortable tropical feel to the building environment. One of the early buildings to be so assessed, the terminal building achieved a Green Mark award under the local environmental accreditation scheme.

Traffic

Arup carried out the original traffic impact assessment required for the project. The impact on surrounding intersections during the opening year, a future case of the year 2015 (under traffic forecasts provided by the Land Transport Authority), as well as the suitability of the level of car parking to be provided, were all studied.



27. Steelwork isometric of passenger boarding deck bridges.



28. Advanced computerised pedestrian software (STEPS) was used to simulate the escape patterns and evacuation time required to aid the fire engineering design.

29.

Key facts about the *Singapore Flyer*

Project awards

- Green Mark Award 2007
- Singapore Structural Steel Society – Structural Steel Design Award 2007.

At a glance

- diameter of wheel: 150m (measured to outside of capsules)
- almost twice the height of the Statue of Liberty (equivalent of 42-storey office building)
- fills an elevational area (from the side on) of two soccer fields
- highest point above mean sea level: 168m
- total weight of steelwork: 1970 tonnes
- 28 capsules, each weighing 13.5 tonnes
- one revolution every 37 minutes
- nearest MRT station: the future Millenia station
- approximately 1260 passengers/hour.

Indicative weights

- rim: 700 tonnes
- cables: 420 tonnes
- support structure, spindle, capsule supports, etc: 850 tonnes
- total weight of steelwork: 1970 tonnes.

Other notable measurements and statistics

- 28 rim sections, 30 tonnes each
- rim diameter: 138m
- rim tube diameter: 864mm
- rim tube wall thickness: 25.4mm
- main spindle: 2.6m diameter, 25.25m long, 180 tonnes
- main stay cables: four groups of six, each 100m long, 100mm diameter, 8 tonnes

Each main stay cable can carry over 6000 tonnes of load. The main stay cables are sized to limit wheel movements and much stronger than they need to be to resist wind loads.

- 112 spoke cables, each 67m long, 75mm diameter, 4.5 tonnes

Each spoke cable is capable of carrying 450 tonnes of load.

- total length of cables: 6.8km
- main support legs: 85m high, 2.8m diameter

Each of the 28 capsules is approximately 7m x 4m x 4m (30m^2), and can carry up to 30 passengers.

The structure is supported by 38 foundation piles up to 1.5m in diameter, and bored up to 52m into the ground: nine under each of the main strut columns, and five under each of the four support cable stays.

The immense scale of development slated for the Marina Bay area means considerable increases in the traffic currently being serviced by these intersections. The land title setbacks governing the placement of the building works allow for the duplication of Raffles Avenue at some time in the future.

Subsequent to these studies a new Formula One night race event was introduced to Singapore. With the pit lanes sited immediately adjacent to the *Flyer* and with the project being ring-fenced by the track, the traffic environment will be drastically altered at least once a year!

Comparisons with the *London Eye*

The *London Eye* was an architecturally-led project formulated to mark the turning of the Millennium for the city of London. The *Singapore Flyer* was a commercially-led development supported by the Singapore government, to inject investment into the country's tourism economy. In both instances, the importance of creating a world-class attraction of exceptional quality and appearance was recognised as essential to success.

Arup developed the *London Eye* design to tender stage, when the design was for a 150m diameter wheel with 36 capsules. The design was taken forward by others at a slightly reduced size, leading to the 135m, 32-capsule *Eye* that exists today.

30. Passenger boarding bridge.

31. The East Coast, Singapore Straits vista from the top of the Flyer.

The design of the *London Eye* was strongly influenced by architectural requirements. From the outset, the architects envisaged it as being supported from one side only, and that the rim would be a triangular truss. There was a strong preference for limiting the number of spokes and for them to connect to the central inner chord of the truss.

While the advantages of a wide hub were recognised, the *Eye* hub width was limited by the distance that even a very thick walled spindle could be made to cantilever. The idea of connecting cables to the edge of the rim to increase its torsional stiffness was accepted, but they were limited to eight pairs, the minimum number that would effectively inhibit the four-lobed buckling mode.

The design of the *Singapore Flyer* was engineer-led. It was felt appropriate to support the spindle on both sides, which made it easier to achieve good support stiffness, as well as allowing a much wider spindle to be used and consequently improving the angle and efficiency of the spoke cables. This increased efficiency, together with a spoke arrangement developed to resist both lateral and radial forces and provide torsional restraint to the rim, meant that the *Flyer* rim structure could be reduced to a bare minimum.

The two differing erection methods were both effective. The horizontal lifting approach employed on the *Eye* made use of the River Thames as additional construction site area, and was well suited to the one-sided support framing. The vertical method adopted on the *Flyer* was ideally suited to the two-sided support arrangement. It also minimised the plan area required on site for erection, allowing the surrounding retail construction to proceed unhindered.

Conclusion

The *Singapore Flyer* is a private development investing in the Singapore tourism economy. Arup worked closely with developers in the first instance and subsequently as part of the consultant/contractor team to add value where the firm was best placed to contribute.

The design was an engineering-led process that recognised the importance of several geometric constraints on the structure's efficiency, and built upon knowledge gained during the design of the *London Eye*. Differing site constraints from those of the *Eye*, as well as alignment with the development driver of reducing cost, resulted in a more efficient structure being developed. The two-dimensional truss form of the *Singapore Flyer* is both taller and lighter than the *London Eye*, and brings a new lightweight elegance to the design of GOWs.

As a testament to its innovative design, the *Singapore Flyer* was awarded the Structural Steel Design Award 2007 by the Singapore Structural Steel Society, for the "distinguished use of structural steel for its creativity, value and innovation".

Andrew Allsop is a Director of Arup in the Advanced Technology and Research group in London, and the company's leading wind engineering specialist. He was the wind engineer responsible for the wind tunnel tests and other related wind aspects for the project.

Pat Dallard is an Arup Fellow and a Director of Arup in the Building London group. He specialises in advanced structural design and analysis. The buckling design approach that he originated was instrumental in the design of the *London Eye* and in this project, where he was responsible for the original scheme designs.

Heng Kok Hui is a senior engineer in Arup's Singapore office. He was the geotechnical engineer for the foundation design for this project.

André Lovatt is a Principal of Arup and the office leader for Arup in Singapore. André provided the fire safety consultancy for this project.

Brendon McNiven is a Principal of Arup, and was the Project Director for the *Singapore Flyer* project. He leads the buildings team for Arup in Singapore. Brendon specialises in architectural building structures and his expertise is in lightweight structures.

Credits

Client: Singapore Flyer Pte Ltd/Melchers Project Management **Design architect:** Kisho Kurokawa **Architect of record:** DP Architects **SMEP and fire engineer, and transportation planner:** Arup - Andrew Allsop, Easy Arisarwindha, John Brazier, Henry Chia, Mak Swee Chiang, Ho Chong Leong, Pat Dallard, Andrea De Donno, Alex Edwards, Gary Goh, Jean Goh, Andrew Henry, Liew Kim Hoe, Heng Kok Hui, Lui Vui Lee, Andre Lovatt, Peter MacDonald, Dexter Manalo, Brendon McNiven, Wong Siew Moh, Jane Nixon, Christopher Pynn, Sigrid Sanderson, Margaret Sie, Jonathan Sze, Jeffrey Willis **Associate structural engineer:** MHI **Associate building services engineer:** Alpha Engineering **Landscape architect:** ICN Design International **Contractor (building works):** Takenaka Corporation **Contractor (GOW):** Mitsubishi Heavy Industries **Illustrations:** 1, 2, 15, 29, 31 Singapore Flyer Pte Ltd; 3, 11, 16, 17, 20, 26 Nigel Whale; 4 DP Architects; 5 Kisho Kurokawa & Associates; 6 Illinois Institute of Technology; 7 Edi Mitterlechner/ Dreamstime; 8 centerblog.net; 9 Mark Arkinstall; 10, 12-14, 18, 21, 22, 24, 25, 27, 28, 30 Arup; 19 Soon Wee Meng/Dreamstime; 23 Benglim/Dreamstime.

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.

**Peter Bailey Daniel Brodkin
John Hainsworth Erin Morrow
Andrew Sedgwick Martin Simpson
Alvise Simondetti**

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.

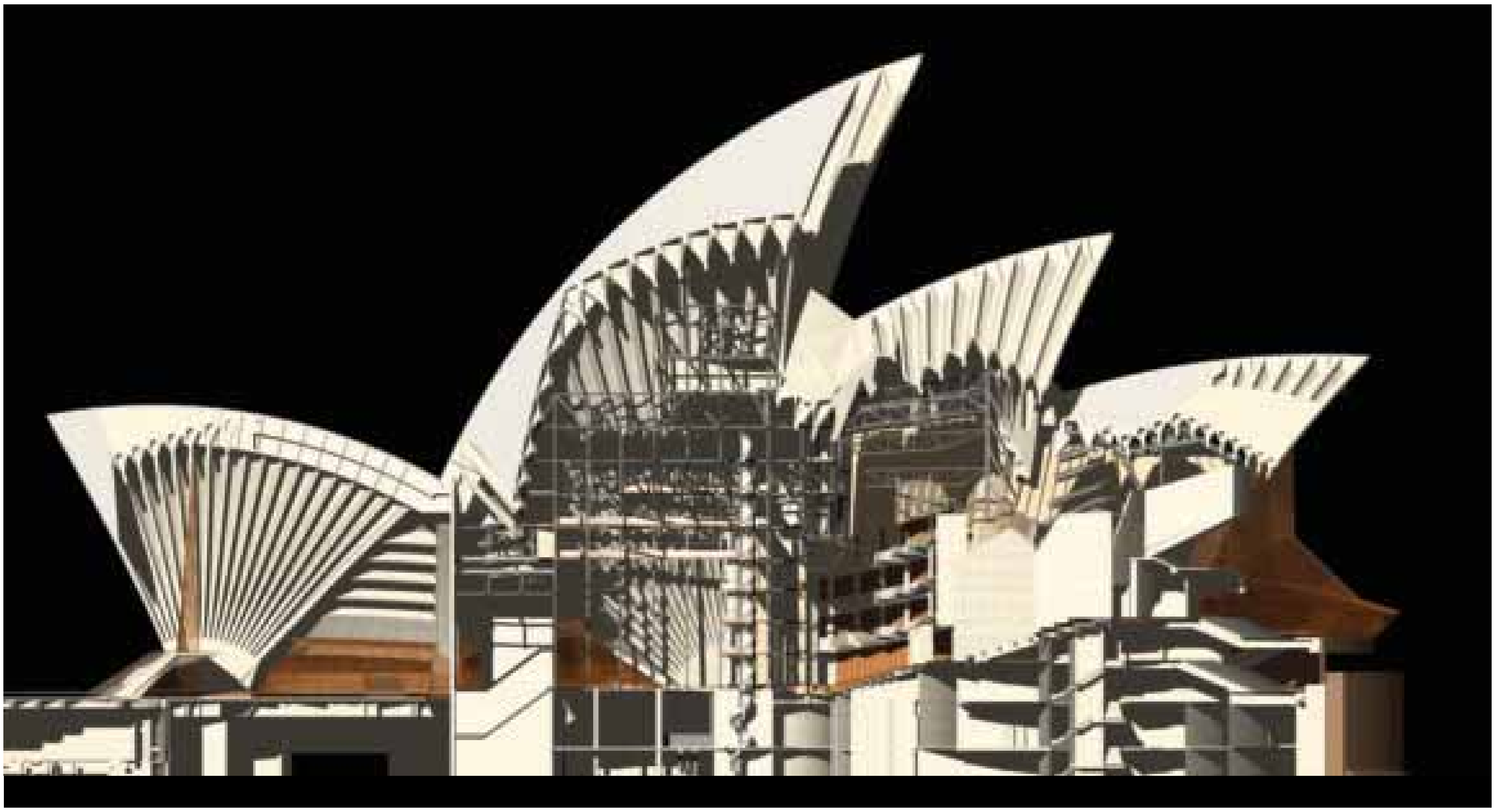
New

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.

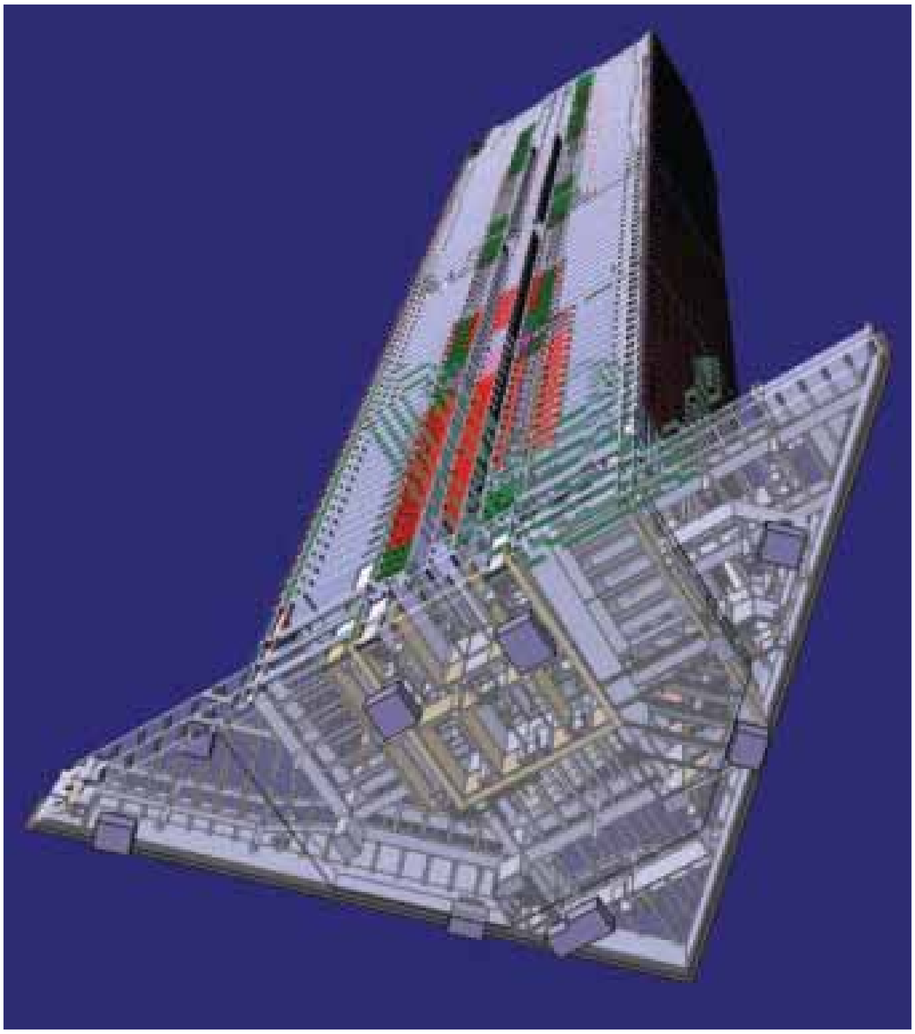
Common models

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:

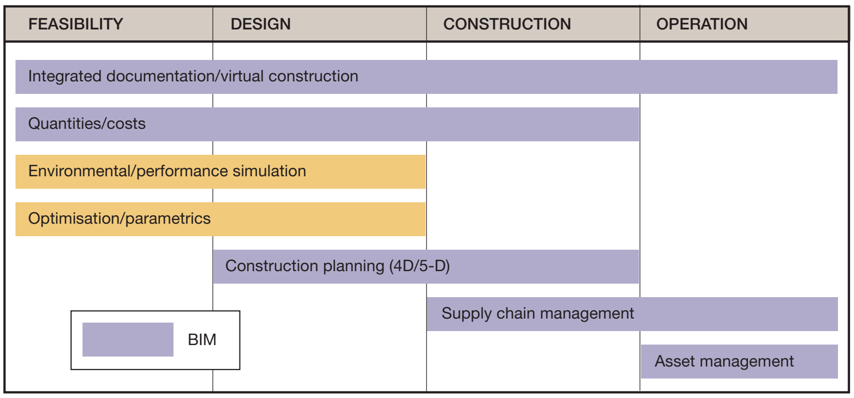
- automated scheduling of baseline quantities and costs
- construction scheduling (4-D) – for planning construction activities
- scheduling of quantities and costs over time (5-D)
- direct manufacture – automating the fabrication process.
- supply chain integration – automating the procurement process
- 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.

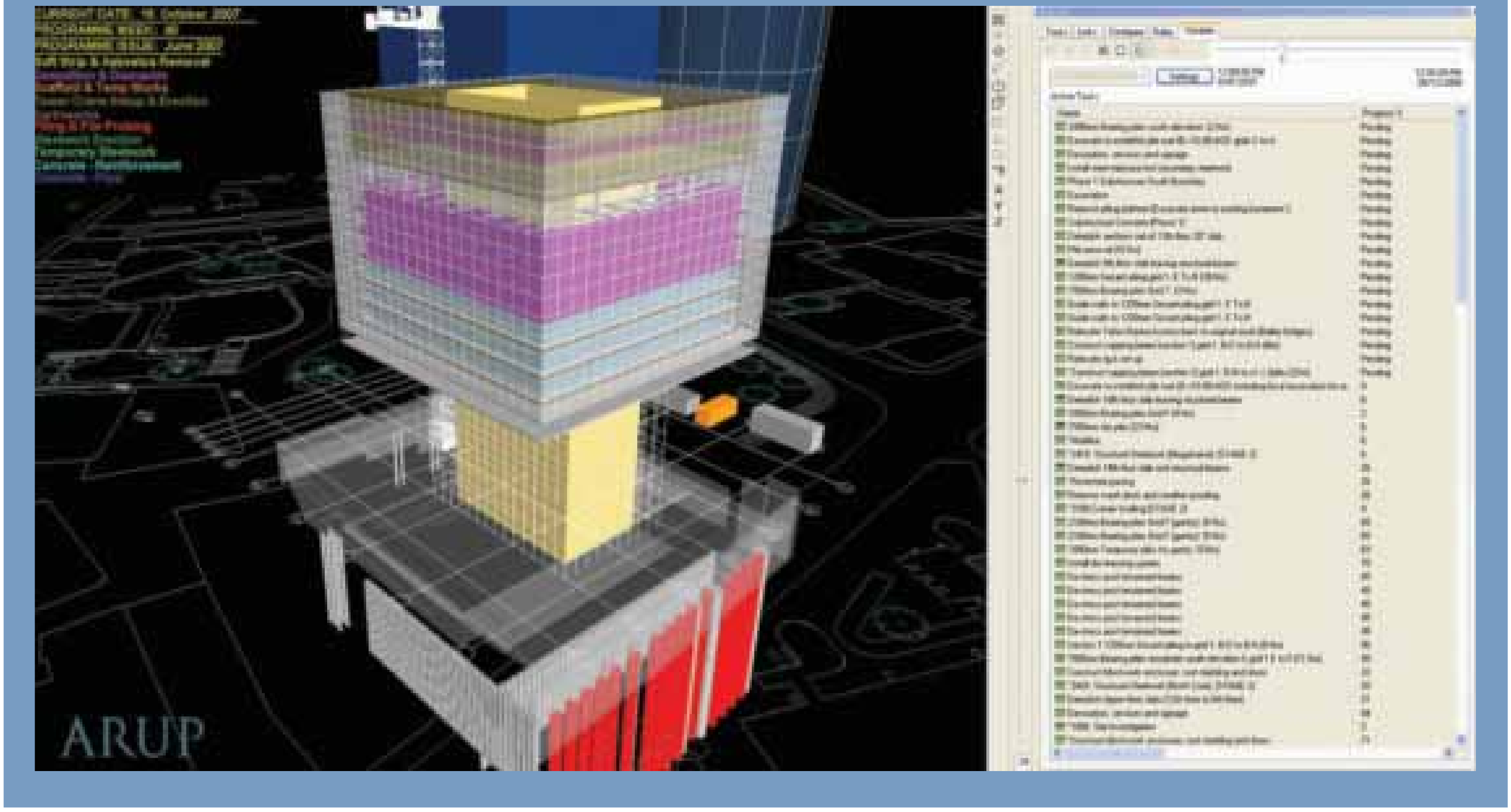
Later in the project, as more detailed programmes are required, the model can be used to describe the complex sequence of building without the need to read and understand pages of charts. The key aim is to optimise overall construction time by highlighting bottlenecks and site constraints in staging 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.

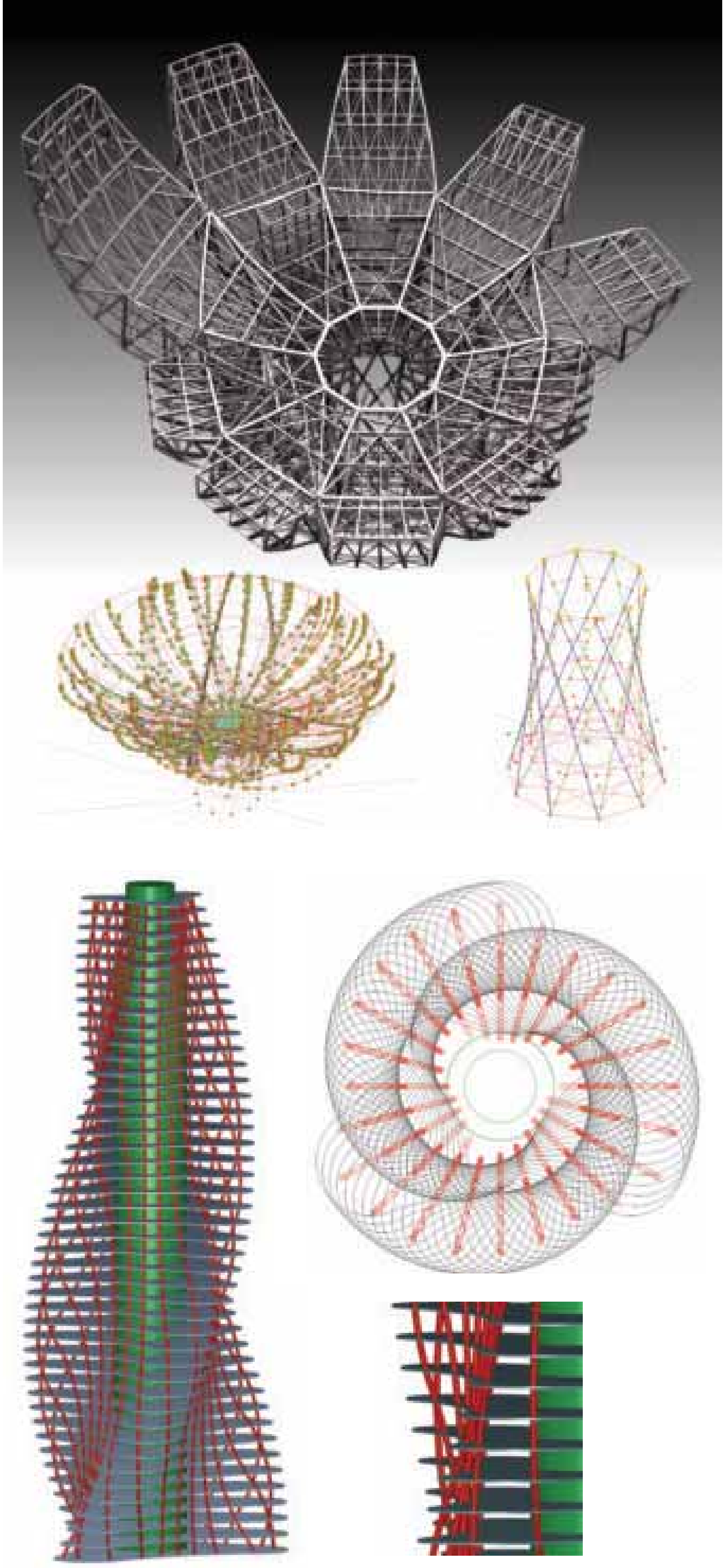
Parametric and generative modelling

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.

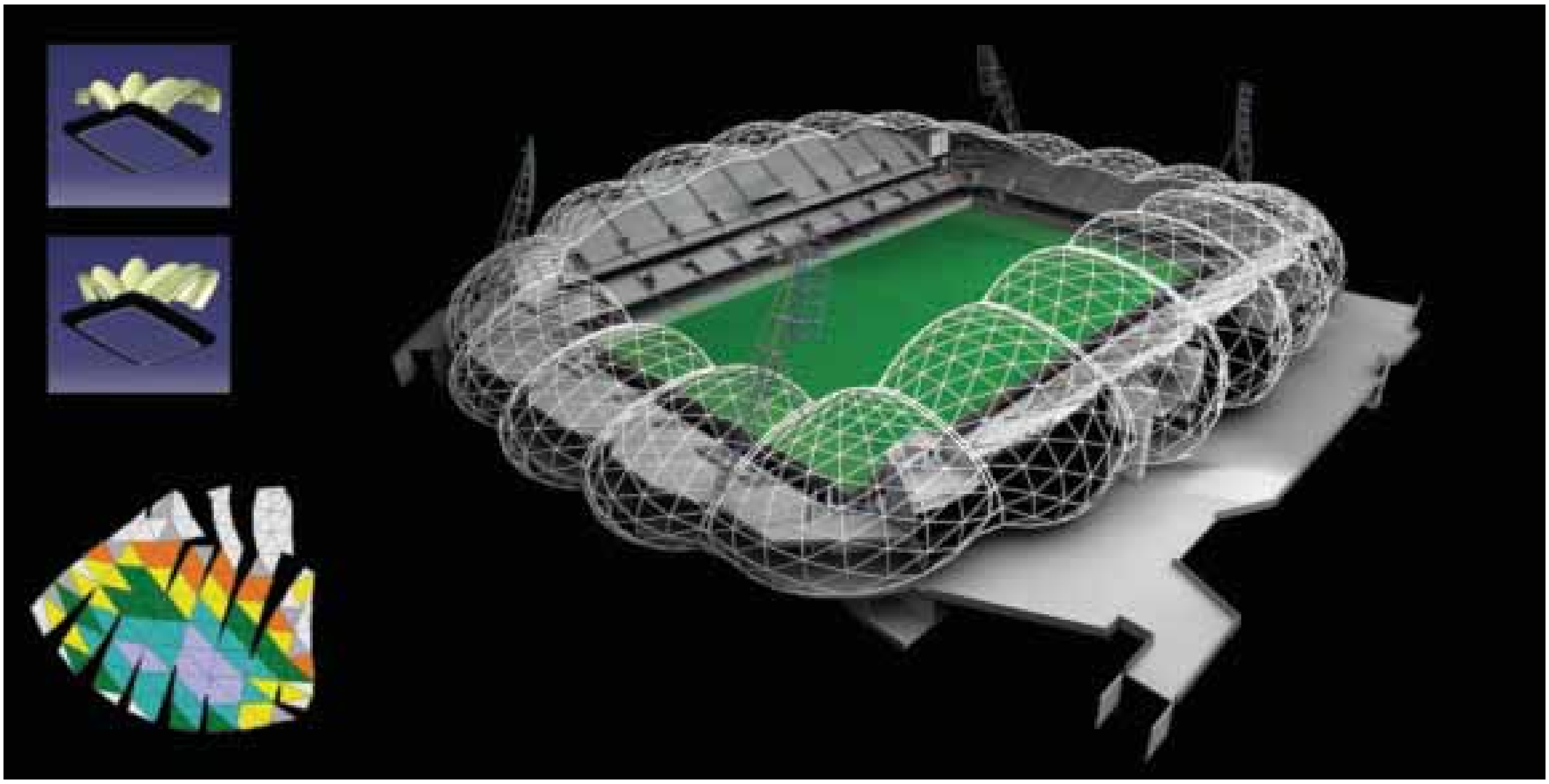
The impact on building design is liberating. For example, current trends in architecture for curving, non-orthogonal building forms are being driven by this new-found power in parametric modelling. Parametric software facilitates the design and setting-out of complex non-orthogonal building forms in 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.

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).

9. Smoke modeling in the Sydney Opera House model.

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).

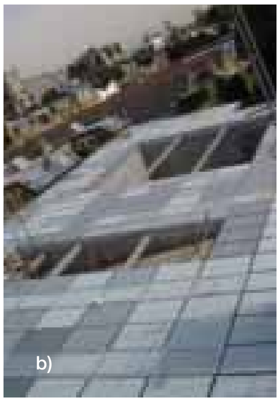
The optimisation routines used will depend on the problem to be solved. Routines are often set to optimise a single parameter (eg steel tonnage), but it is now more common to try to optimise multiple or competing parameters.

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.

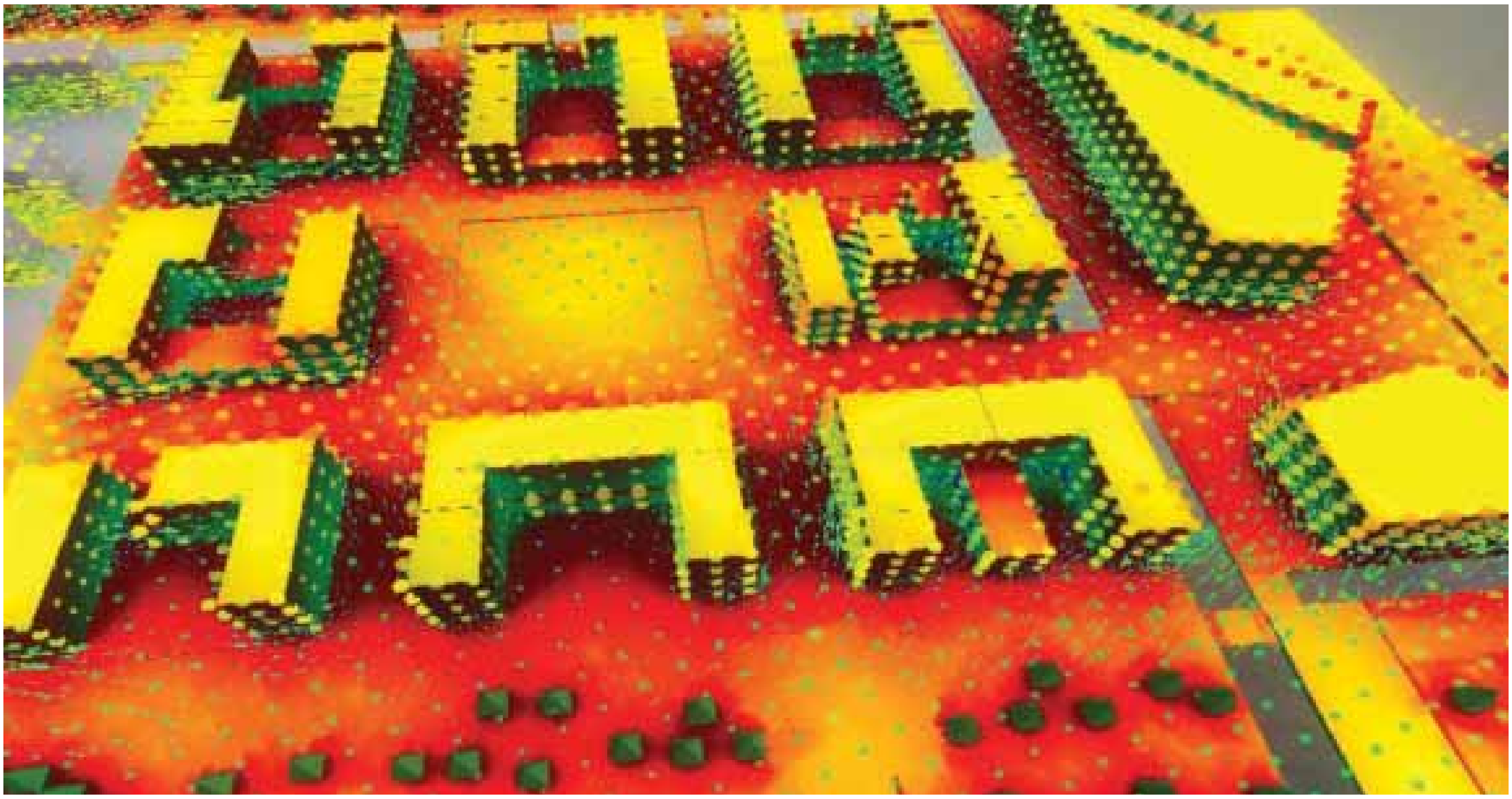
All quantitative analysis results were then integrated in a single environment that allows the user to freely navigate through the data in the 3-D environment in real time and look at all the results individually and together.

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).

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

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.

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

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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.

Designer's Toolkit 2020:

A vision for the design practice

Alvise Simondetti

Introduction

Most research that focuses on exploring the ever-shifting design requirements instigated by dramatic changes in society remains based on the assumption of unchanging tools and fabrication processes. The present study, by contrast, focuses on changing design tools, on making tools, and on the effect of this on design.

In 2006, the author conducted a review study, *Designer's Toolkit 2020*, to explore the drivers for, and what might plausibly be, the designer's desktop scenario around 15 years in the future. He interviewed 22 thought leaders* - PhD candidates to industry board members - from across the design world, with contributions from designers outside the built environment professions. Where possible, the interviews were conducted face-to-face; if not, by via video-conference or telephone.


1.

This study acknowledges changes in tools and fabrication processes for the built environment. Also, and in contrast to most designers in industry and academia alike, it considers these changing processes to be fundamental to design innovation.

Based on observation of the current position, the paper proposes, as a way forward, that a common vision should be shared by practice, industry, and academia - as one way to accelerate a much-needed transformation of design practice.

Designer's Toolkit 2020 adopts the framework proposed in the USA National Research Council (NRC) study "Beyond productivity: IT and the creative practice"[1], with four levels of research and development investment risk and return (Fig 2):

- IT produces results that could not have been predicted.
- IT enables otherwise impossible outcomes.
- IT enhances the quality of results.
- IT enhances productivity.

Unusually for a review in this field, all four levels are taken into consideration.

The designer's toolkit is rapidly changing. Design practices need a shared vision for the short, medium, and long terms.

Designer's Toolkit 2020 focused on design research projects and individuals working within a project-based research methodology. As explained by Martin Fischer[2] among others, this contrasts with laboratory-based research methodologies. Project-based research methods involve identifying a non-trivial challenge in a specific practical context, and solving that specific challenge within the project's deadline.

Researchers often use bespoke tools and protocols, and in this their methods are not different from standard project practice. However, there are further steps: revisiting the challenge; focusing on what is novel in the solution; generalising it from the specific project; rigorously testing the solution's validity; confronting the findings within the research community; and finally contributing to knowledge through publication of the results. This project-based methodology inherently guarantees the practical significance of the solution, something often questioned in design research.

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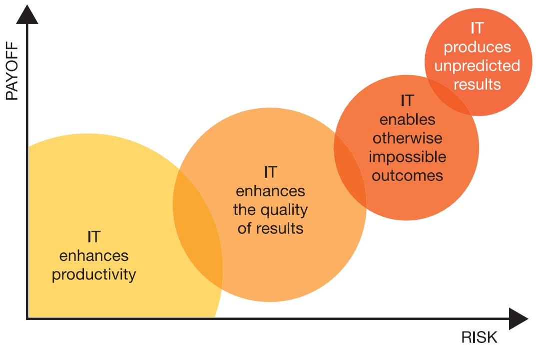
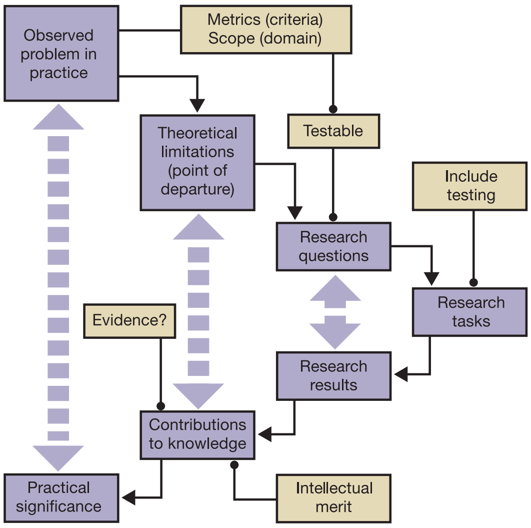


2. The NRC's four levels of risk against return.



3. Building theory in practice, as visualised by the Center for Integrated Facility Engineering (CIFE)[3].

Findings

Four "big ideas" emerged from the interviews:

(1) Transferring technologies from other industries has provided great benefits, but has generated the need to transfer processes as well - the processes by which other industries produce their designs and make decisions.

(2) Despite most of industry's and academia's focus on development of the designer's toolkit to increase efficiency, the main drivers for change are the new ways of *making*. Naturally the toolkit has developed faster and further in supporting changes at the end of the construction supply chain; however, tools for the early stages of design are creating greater gains for designers.

(3) The gains from the interaction and interplay of discipline-specific algorithms are greater than from increasing the individual sophistication of single-discipline algorithms.

(4) Designers are getting used to "just-in-time" information being available anywhere - fast, recent and relevant - and are now expecting this to apply also to design information.

The following expands on the four big ideas. All quotations in italics have been selected from the personal interviews.

(1) Process transfer, not technology transfer

Transferring technologies from other offices and/or industries has provided great benefit, allowing the design and construction of projects that couldn't otherwise have been built[4]. However, those working with new technologies, including parametric relational modelling and building information modelling (BIM) point out the limitations of this approach[5] and the necessity for a whole new one.

"Our edge comes from us and the way we think, not just our tools."

Transferring new technologies is insufficient if one doesn't also expend the energy needed to understand their methods and how to use them. Methods, unlike tools, always need to be understood and adapted to our industry, and cannot be directly translated. The same tool might be used in a dramatically different way when transferred from, say, the automotive industry to architecture - as in the case of rapid prototyping, originally developed to produce prototypes overnight and speed up the design development but, when adopted in architecture, used to produce unique designs accurately.

"Our children in their bedroom are using more sophisticated technology to make decisions within games than we're using in the planning environment."

In computer games, users make decisions based on quantitative and real-time feedback from their actions. Process transfer is the ability to learn from other offices and/or industries how they go about producing their designs and making decisions, how they think with their tools, what their protocols of interaction are, who they interact with, and who has control. For example, Toyota's lean manufacturing methods are based on accurate real-time information travelling up and down the supply chain.

"We used to have computer programmers and designers, now we have designers who can program. The ability to program what you want, when you want it, has already brought larger gains for the project, for the client, and our challenge is to turn them into designer's gains."

Traditionally, tools and methods were selected by a master designer, based on years of experience. However, tools and methods have now become disjointed, with digital tools selected by apprentices and applied to the master designer's traditional methods. Methods must also be selected with new tools in mind.

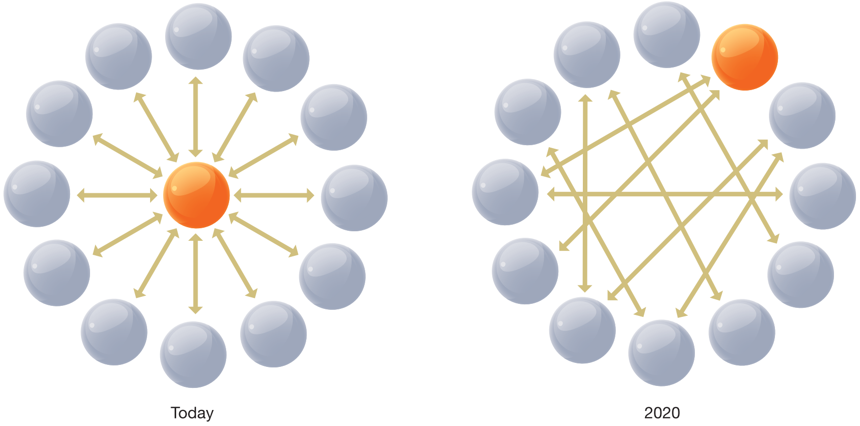
"New graduates have no fear of programming, no use for primitives."

It is a challenge for those who haven't learned how to write a computer program, even a simple one, to understand the power, and the risk, and the limitations of the work of their junior staff. How can the design director sign off the latest deliverable in the shape of a BIM automatically generated by a script where no two-dimensional section is similar to any other?

"When model managers are third parties, they take control. Project management is the ideal place to find the lateral thinking and specific understanding necessary to be a custodian, or master modeller, or model manager. This might be a temporary role."

Traditionally, the architect took control of the design. In other industries, however, model managers hold all the design information and have eroded that kind of control. The master modeller's role includes acting as the gatekeeper who gives information privileges, makes sense of information coming in, and knows what information goes out to different teams at the time they need it. Possibly "just-in-time" design information could bring similar quakes to design and construction as "just-in-time" manufacturing did to its industry. In a similar way to manufacturers seeing warehouses full of components disappear, designers might experience servers full of unusable and redundant design data disappearing too.

Designers, however, must ensure that, in the long term, control will return to them when interoperability, access control, and versioning - the current challenges in the industry - are overcome. The financial industry has automated access control methods already.



4. How the master modeller role might evolve.

"We will see a proliferation of experts, as the first rule of modelling, 'junk in, junk out', is still valid."

Master modellers aren't the only emerging specialists. Construction industry designers might take notice of the role of the mathematical modeller in the automotive design industry. The electronic math modeller, also referred to as the "digital sculptor", is the individual who takes a free form and then matches a mathematically representable form to it to create the computational representation.

"I'm now involved with people in economics, in applied mathematics, who have nothing to do with engineering, but who have little expertises that I don't have."

Computation is shifting the boundaries between disciplines, with the result that models from other disciplines are becoming of interest to designers. This is not new. What is new, however, is that these are explicit computational models that require set procedures to translate.

(2) Design for new ways of *making*, not for design efficiency

One of the greatest changes occurring in our industry is in how we *make* (or build) things, specifically our increasing ability to produce unique and complex mass-customised designs[6,7] at the same or even improved speed, cost, and quality as repetitive and simple mass-produced ones.

"We focus on novel design, not only measurable improvements."

Traditionally, designers have tailored their abstract representations (scaled plans, sections, and elevations) to communicate their ideas and solutions to various audiences including, crucially, fabricators and contractors. Now that design information feeds automatically into computer numerically controlled (CNC) machinery, novel representations are needed in the form of spreadsheets of machine commands or databases - assembly instructions, as well as interactive visualisations, that help convince the fabricator that the script as well as the machine is doing the right thing.

Traditional representations of plan, section, and elevation are becoming redundant for the fabricator and the contractor. This could have profound implications for designers who have used these representations as "tools to think with".

"Plan, section, and elevation will disappear as we know them today; however 2-D schemes will grow."

There will be implications for other disciplines that have used designers' drawings to, for example, extract quantities, provide planning advice, bring evidence in court, and calculate fees. It is possible that these disciplines may adapt to the novel representations now used to communicate between designer and fabricator. In one example, a court used an accurate representation of the 3-D design geometry to support the case of a fatal accident on a building site. In another, a High Speed 1 (Channel Tunnel Rail Link) contractor used earthworks machinery driven by on-board digital terrain models - which in turn is helping transform the rail design industry from vector to meshed representation.

Steelwork fabrication quickly adopted component-based modelling to improve its processes.
This in turn is now rapidly transforming the designer's toolkit from lines, points, and layers (inherited from the designer's hand drawings that were developed to communicate with 19th century craftsman) to components and assemblies.

Virtual prototyping of the build environment, ie BIM[8] or BEM (built environment modelling)[10], is reducing construction risk and waste. In the past, designers kept separate from construction - a business with a different risk profile. However, reducing the risk has seen the proliferation of "garage contractors" who thrive on their green credentials because of the reduced waste and reliable delivery.

"There will be something like a pre-emptive modelling of the building process that will know exactly what's going to happen with the building. Today, if you go to have your appendix out, you don't hope you're going to come out alive; it's a near mathematical certainty that today you'll survive an appendix operation."

Conversely, the current limitation of virtual prototyping is that it is unregulated. (This is to be expected and is common to all new forms of representation.) Practitioners are left with the challenge of selecting the appropriate level of detail and, most importantly, of communicating it to the team so that everyone knows what the prototype represents and what it doesn't.

"We should enhance the front end of the design process that's going on in all design offices. I think many design offices miss out on a major possibility of increased productivity or an improved design - the decisions made in the initial design stage affect 80% of what happens thereafter."

Designers should focus on developing tools that will support the conceptual stage of the design process, this first stage being arguably the most difficult of all. It is highly unstructured, and has no real algorithmic bases, at least not ones that can be readily perceived.

(3) Develop algorithms for integration, not specialised knowledge

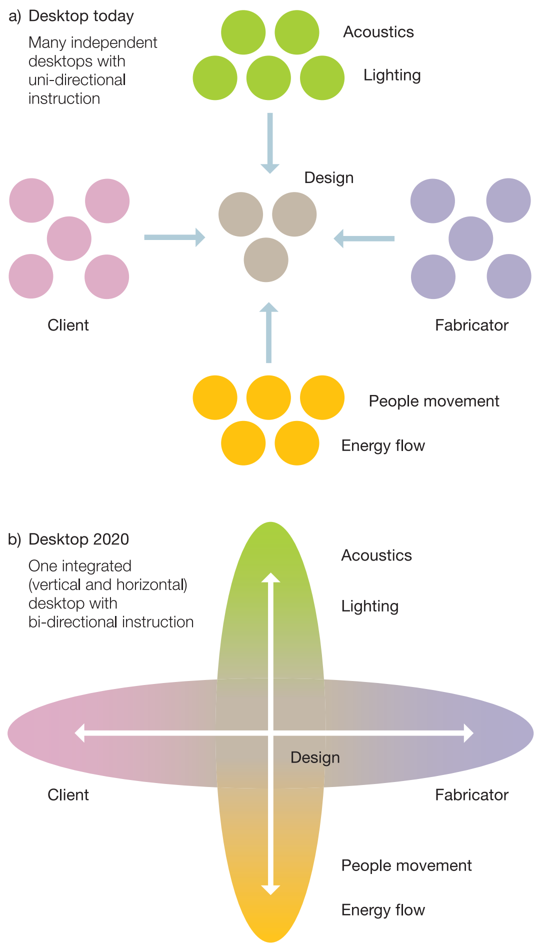
A cycle seems to be happening: we have had 20 years of developing algorithms, including finite element analysis modelling, that have made explicit our industry's specialised knowledge and greatly enhanced the development of performance-based design in engineering. However, it was pointed out that few academic papers in this area have been submitted in recent years. The current research focus is in enabling integration. Similarly in design practice, larger gains seem to accrue from optimising how disciplines interact than from how they do their tasks individually.

Integration is beginning to emerge both vertically along the supply chain and horizontally across all design and engineering disciplines. In the past, computational toolkits developed independently at the discrete level of the supply chain and in each discipline, but now considerable effort is being expended to get the tools to talk to each other, an area of research known as interoperability[10].

"There'll be more ubiquitous footprints of operating systems that'll take more and more of the day-to-day drudgery out of writing software, so that software can get more specialised."

Initially links have been developed ad hoc and unidirectional. Such links allow the integration of results from discrete analysis within one single geometric model for review and demonstration purposes. For example, simple visual checks include ensuring that all analysis is conducted on the same version of the design, or that structural and mechanical services systems do not clash with each other.

5. How disintegrated tools might evolve.



Drivers

- Hi-bandwidth connectivity
- Tighter financial margins
- Management of risk
- Online communities

Threats

- Professional protectionism
- IT viruses
- Commercial contracts
- Intellectually challenging to understand

"A holistic approach to sustainability drives multi-physics simulation? Absolutely, and with that will come a legal framework that will force you to do it. It's happening already in projects in Switzerland, also in Singapore and Finland."

"It's a multi-phase analysis; you need to do it at the conceptual design stage and at various stages all the way through. How to develop good evaluation technologies and requirements at each of these phases? It's a challenge to do that well and to be able to cross-link across phases."

Horizontal bidirectional links between the analysis and geometrical models, also referred to as "round-tripping", enables faster design cycles[11] and allows for manual design optimisation. In some projects, including stadium design, the geometry that is finally built might be as much as the 27th design version. Bidirectional links between analysis and design also allow for computational design optimisation (CDO)[12]. For example, in the design of spaceframes for long-span steel roofs, CDO is being used to reduce steel member sizes.

"The survivor will be the one who understands the need to connect."

The ultimate goal would be to take advantage of the interaction or interplay between discrete analysis as it occurs, for example in fire/structural analysis[13]. The integration of the different discrete sub-models allows the designer to identify areas of overlap and interaction, and feedback loops.

"The next drivers are going to be [from] biology and I think it is biological modelling that is going to drive the next 10 years."

Good design is holistic, and the science of biology has developed tools and methods to understand the highly complex systems of nature in which all components are related to each other; it should be no surprise that these tools and methods might attract the attention of designers.

"Integration of PDM (product data management) information containing vendor, product and consultant information, technology and industry research with CAD begins to provide automatic document-writing and even specification-writing tailored to the customer and to the manufacturer."

Fuelled by a vertically-integrated supply chain, often under a single owner, the automotive industry has developed the PDM that is now converging with CAD systems. This is an attractive precedent that might be strong enough to help the construction industry overcome the contrasting interests of suppliers.

"Vertical integration provides feedback from top to bottom (just-in-time?)"

The critical gains from vertical integration derive from the ability to have immediate information throughout the supply chain and therefore interrupt and speed up the work task as information becomes available.

(4) Where is the information? How fast, relevant and recent is it, rather than what is it?

Traditionally design information, whether drawings or 3-D digital models, was stored locally on the designer's PC. More recently designers have had a single model environment, where data are stored on a central server accessible by all the project team - access sometimes being managed according to permissions.

Designers structure project information either in folders and subfolders - structures inherited from when they had filing cabinets - or according to the way the project manager sees the world, the main goals being to retrieve the latest version of the relevant document without relying on the designer who produced it. However, with the continuous development of search engine technology, the ability to retrieve information based on keywords has made redundant some of these organisations of information. Now, search engines have been affirmed as the solution to organising and keeping track of data.

Google Earth and others offer the opportunity to arrange information according to its spatial co-ordinates, which provides an interesting alternative to the current naming convention based on chronological project number or street address of the property. Imagine a situation in which you are working on a design for a holiday resort and you "see out of your window" the first 3-D sketch model of the feasibility study for the proposed wind farm.

"All project information now resides in one single environment that can be searched, so that the history of the design process and decisions can be simply tracked down. The relational database interface is visual and time-dependent. Similar to Google Earth, every bit of information retrieved will be presented in its context, both spatial and time (versioning)."

Web-based tools have become increasingly popular for the 1-D and 2-D creation of data; we are all becoming used to the latest version "being on the web". Driven by the designers' increasingly dispersed team and the need for asynchronous working, 3-D modelling might become web-based with the security and reliability of today's on-line banking.

"We will see completely ad hoc wireless technology, where the connectivity between you and the information you need is totally random and takes place just on the basis of where you are and what time of day you go about doing your business. The difficulty with wireless right now is distinguishing between multiple frequencies. It's all right if you want to get four people, but you have to understand that there may be 1000 clusters of four or five people each, all within a half a mile of where you are, trying to do their business, too. The only way to do it might be to make each human body the determination of the frequency."

Connectivity is something we already have, for example in wireless sensor networks which reroute information according to which mote switched on within its range. Development in this technology is very advanced, as information in a sensor is cheap when compared to what is stored on the designer's laptop.

Designer's contexts

The four big ideas described above will have different implications according to different contexts. Each designer or design firm operates and will operate within a context determined by their specific social, technological, environmental, economic, and political forces. Though it may be difficult to predict what the designer's desktop will be in 2020, it is possible to analyse and measure the forces that will determine its evolution.

This section presents the criteria that might be used to measure the current designer's toolkit context and indicate its future direction. These criteria emerged as a refinement of those used in the interviews with the thought leaders. (They might also be used by readers to define their own designers' toolkit context and future direction.)

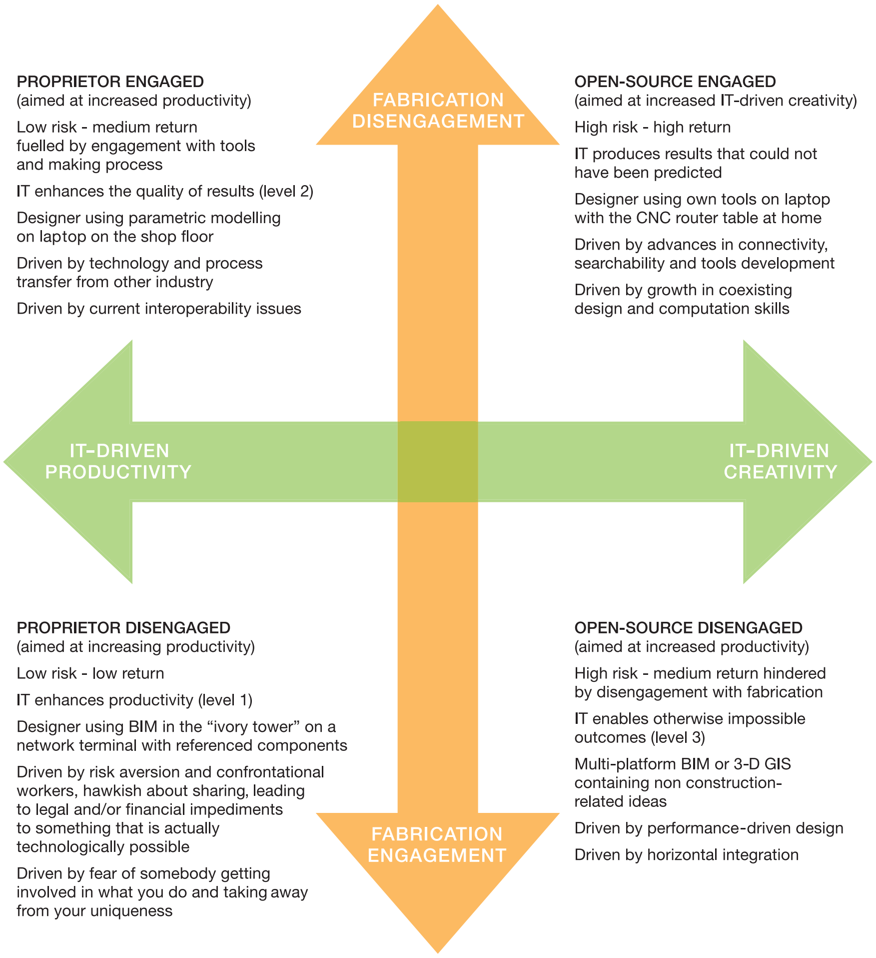
The designer's toolkit matrix (Fig 6) defines four possible contexts. The top left quadrant, "proprietor engaged", is driven by, among other forces, the enhancement of productivity - very much the way drafters have been using off-the-shelf CAD packages to produce their documentation. Similarly, designers might use off-the-shelf software for their designs. In this context the designer, though heavily engaged with novel fabrication methods in a highly integrated supply chain, is disengaged with toolmaking and is happy to use the design tools he or she is given. The risk in this process is perceived to be shared between the software manufacturer and the project team.

The top right quadrant, "open-source engaged", is driven by, among other forces, enhancement of IT-driven creativity, still highly engaged with fabrication. Designers, now fully conversant with editing and extending computer programs as a result of formal studies in both design and computation, select portions of computer code that are openly available within the firm or in the public domain, assemble and develop the code for the specific project, and finally share the computer code back with the community. This custom design system is tightly connected with fabrication of the design. This scenario is based upon trust but increases the perceived risk, which will have to be managed via a rigorous peer reviewing system.

The bottom left quadrant, the "proprietor disengaged" context, is driven by, among other forces, the risk aversion and confrontational nature of a disintegrated construction industry. Designers are afraid other disciplines are encroaching onto their territory and at the same time are afraid to change their design processes and deliverables because of the risk of attracting new liabilities. All efforts are in increasing efficiency to produce documentation even if it is not then used by fabricators.

The bottom right quadrant, "the open-source disengaged" context, is driven by the sensational growth of virtual worlds, among other forces. Designers are here providing highly constrained design tools for users or third parties to produce design instances, and thus detaching themselves from the making of designs. The designer is segregated to an "ivory tower" with little knowledge of the project and the opportunities provided by novel making processes.

6. The four selected designer's contexts.



PROPRIETOR ENGAGED
(aimed at increased productivity)

Low risk - medium return fuelled by engagement with tools and making process

IT enhances the quality of results (level 2)

Designer using parametric modelling on laptop on the shop floor

Driven by technology and process transfer from other industry

Driven by current interoperability issues

OPEN-SOURCE ENGAGED
(aimed at increased IT-driven creativity)

High risk - high return

IT produces results that could not have been predicted

Designer using own tools on laptop with the CNC router table at home

Driven by advances in connectivity, searchability and tools development

Driven by growth in coexisting design and computation skills

PROPRIETOR DISENGAGED
(aimed at increasing productivity)

Low risk - low return

IT enhances productivity (level 1)

Designer using BIM in the "ivory tower" on a network terminal with referenced components

Driven by risk aversion and confrontational workers, hawkish about sharing, leading to legal and/or financial impediments to something that is actually technologically possible

Driven by fear of somebody getting involved in what you do and taking away from your uniqueness

OPEN-SOURCE DISENGAGED
(aimed at increased productivity)

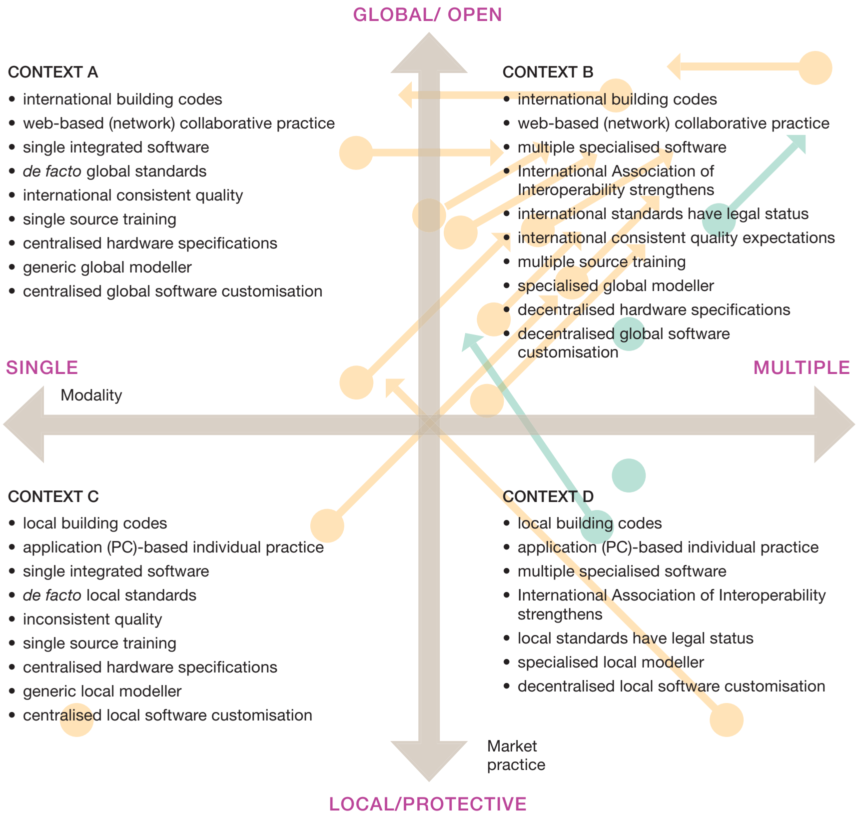
High risk - medium return hindered by disengagement with fabrication

IT enables otherwise impossible outcomes (level 3)

Multi-platform BIM or 3-D GIS containing non construction-related ideas

Driven by performance-driven design

Driven by horizontal integration



7. The four design contexts with viewpoints from 16 of the interviewees superimposed. The origin points of the arrows indicate where they think they are currently, the ends of the arrows where they think they will be in 2020 (two do not think they will have moved).

Fig 7[14] shows the results of the same exercise conducted with the thought leaders. The study conclusions were that the spectrum of criteria selected is broad enough to include the great variety of designers' current and future contexts of operations. Unsurprisingly, designers across the world operate in all contexts, with clients predicting a low-risk proprietary context and PhD candidates predicting or aspiring to a high investment risk/return context of operations. Nonetheless, the results are from a very small pool of people and therefore not necessarily fully representative.

From the discussions with the thought leaders additional pairs of criteria emerged, the mapping of which is useful for measuring the changing designer's toolkit:

- the level of production feedback and the richness of data transfer (from geometry only to including geometry, material, cost, carbon footprint, assembly, user manuals, etc)
- the type of employment (full time to collaborator) and the level of multidisciplinarity
- the dimensions of representation (2-D to 4-D) versus level of computational control in the making process (19th century craft to computer-aided manufacturing (CAM) and sequencing)
- the horizontally integrated multidisciplinary versus vertically integrated along the supply chain (from 20% to 80%)
- representation (drafting to modelling) and design performance (architectural to multi-performance)
- the generative nature of design, from design instances to design rule optimisation.

What is certain

The designer's toolkit context might be unpredictable, but everyone agrees on a few facts, known with reasonable certainty:

- Children now playing computer games will be the designers of 2020.
- Designers will not be attached to the desktop.
- Designers will be more specialised.
- There will be more collaboration between people with increasingly diverse backgrounds (biologists, economists, applied mathematicians).
- The virtual prototype is here to stay.

All the interviewees agreed with the importance of understanding the possible contexts within which the designer's toolkit will develop, as well as of identifying measurable characteristics so as to evaluate progress.

One possible scenario for the designer's toolkit in 2020

To explore all the implications of the big ideas applied to the possible contexts is important, but beyond the scope of the present study and this article. Instead, here is one possible scenario for the designer's toolkit in 2020, created by looking at the implications of applying the four big ideas to a context with a high level of fabrication feedback at the same time as a high emphasis on IT driving creativity. Equally, this would be a high risk/high return scenario that might be more suitable for some designers than others.

- It is now June 2020. The firm's designers are still at their headquarters building, which they have occupied since the firm began. The building is now 20 years old and in need of refurbishment as it doesn't perform within the current energy conservation rules.
- More then 50% of the staff are temporary - from outside the firm as well as from other offices. Their connectivity is completely ad hoc and wireless. The office has become a workshop for people to come and "perform", similar to downtown theatres or studios with a director and a small local staff to run the space and manage it.
- More designers are tasked to look at other industries and domains to learn about their innovative processes. They assess how these can transfer to the design office, as the "just-in-time" parts manufacturing method successfully transferred to "just-in-time" data for design.
- Designers have learned tool-making in university postgraduate courses, in addition to their formal education in the first principles of design. Similarly, but more rarely, they may have learned by developing their professional careers in different industries and domains.
- Fewer designers are looking at technologies, as it is not only the tools per se but also how designers use them that makes the difference. For example, designers are not being given videoconference units, electronic white board, extranet, blogs, etc; instead they are trained in how to work remotely, 24/7 and non co-located, or how to choose between solutions according to the type of work, whether commercial and on the move, or technical at the desktop.

- An increased overall level of professional training, compared to the beginning of the millennium, is in the form of "learning by doing" in a highly controlled environment, running the complete technology solution and support, and where, for example, issues of culture are specifically addressed.
- More designers have given up learning about innovative design processes from software resellers and are instead learning from other designers or researchers who are designing with different processes.
- Designers are offering consultancy in design processes to selected designers at high value-added prices, avoiding direct competition. This creates tensions with other designers who are still offering design instances.
- Designers find their inspiration from new ways of making. All design teams have a workshop in their office where they can carry out physical prototyping of their ideas directly. The computer-generated-physical modeller will initially be a specialist role similar to the digital modeller, who has now become commoditised and disappeared as a specialist.
- Design firms have begun to locate offices strategically near bigger workshops, shared with other industries like the movie industry.
- Design firms are partnering with contractors, fabricators, and owner-operators in demonstration and pilot projects to fast-forward the adoption and exploitation of novel methods in the construction industry. Design firms have developed their own making activities, aimed at enhancing designers' abilities to innovate and rethink design from first principles rather than it being aimed at the business of fabrication or construction.
- Sustainable design research has highlighted that high performance in buildings, including sustainability, can only be achieved with high-performance operation and management of the building. This is why designers are now in the business of operating their buildings and using the feedback in the design process.
- Increased specialisation is a direct result of the first law of modelling: "junk in, junk out". As a consequence of increased specialisation and globalisation, designers are now more multidisciplinary, multicultural, and mobile. Culturally specific abstractions, ie written notes in English or discipline-specific symbology like the arrows used by architects to indicate raising ramps on plans, are inadequate to ensure an effective exchange of information when working with a Chinese computational optimisation programmer, or logging onto the network to discuss the design at a fabricator's shop in Germany. As a consequence, designers are using full visual representations at all stages of design, with 100% information from all disciplines.
- Full virtual prototyping has increased the understanding and value of discipline-specific modelling and has created a strong need for algorithms that consider the interplay of parameters from different disciplines. Following a period of slow development in algorithms, there is new activity in cross-disciplinary modelling, similar to the early 2000s' evolution of fire/structure non-linear modelling. Now all discipline modelling uses CDO, and current research is in multidisciplinary optimisation[15, 16], or project optimisation.
- All the issues from the beginning of the century of integration and interoperability of explicit 3-D models have now been hammered out with the new "designer's platforms", similar to the way "plug-and-play" operating systems have sorted out hardware incompatibility and painstaking searches for drivers.
- Toolmakers, custodians, and mathematical modellers in every group are experiencing commoditisation of their specialities in the design community. Young designers joining firms are already equipped with these skills - which are now required for any designer.
- Visitors from different firms or other offices working on projects can connect their laptop (or whatever transportable hardware is called in 2020!) - irrespective of operating system - to services including internet, project folder, etc, without threatening the security of corporate firewalls.
- At the front desk, offices now have a set of procedures (or scripts) that can be run on visitors' laptops when they check in, so as to configure local printers, mailing lists, outlooks, favourites (way around town, transport services, room bookings, profiles, etc). Check-out procedures will run an "uninstall" script that will clean up and restore the original.
- Since the early 1990s we have seen commercial staff and design leaders travelling to offices, averaging one-day visits. If they were not in transit, something was wrong! Now design practitioners travel to other offices to apply their expertise for weeks at a time, their needs in terms of toolkit dramatically different.
- The office has been 100% laptop for some time. All employees have the laptop(s) appropriate to their needs. With increased literacy, new starters are asked what laptop and software they need. Only if uncertain will they be interviewed to determine what might be appropriate to their role.
- Specialist designers, isolated within their specialties, belong to global practice communities both inside and outside the firm, like Arup's Virtual Design Network, the SmartGeometry Group*, or the Radiance User Group**. Designers are as loyal to these networks as they are to their employer.


8. Children now playing computer games will be the designers of 2020.

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* Architecture is fundamentally about relationships. Many of those relationships are geometric in nature or find a geometric expression. The SmartGeometry group has been created in the belief that computer-aided design lends itself to capturing the geometric relationships that form the foundation of architecture. http://www.smartgeometry.com

** Greg Ward started developing Radiance in 1985 while at Lawrence Berkeley National Laboratory. The source code was distributed under a license forbidding further redistribution. In January 2002 Radiance 3.4 was relicensed under a less restrictive license. http://www.radiance-online.org/

- Specialised staff identify with the project more than with their employers, and similarly clients focus on project teams rather than the individual contributing design firms. The toolkit has played a key role in enabling and enhancing this change.
- All project information now resides in a single environment that can be searched, enabling the history of the design process and decisions to be simply tracked down. The relational database interface is visual and time-dependent. Similar to Google Earth, every piece of information retrieved is presented in its context, both spatial and time (versioning).
- Finally, creating digital tools is an activity encouraged and praised within the firm with "most reusable and generic tool" internal competition. Sharing of tools or toolkits is encouraged both between offices and outside the firm. The main value in creating tools is as "objects to think with" rather then the tools themselves, similar to hand drawing in traditional design.
- Each project utilises more or less bespoke design tools according to its level of innovation, ambition, and budget. For example, a project aiming at breakthrough innovation will use no middleware, as has been the case since the beginning of the millennium for games designers.

Ten actions for today

Bearing in mind the findings outlined above, and in view of the four big ideas and the possible scenarios to which they give rise, what 10 things should designers do now?

- Create the need for, not provision of, technology. For example, increase understanding on how to conduct technical (not only commercial) work on the move, remotely, 24/7, and non co-located, or how to choose between solutions according to the type of work.
- Convert meeting rooms into machining workshops to be able to "think with the new processes" and create informative scaled prototypes.
- Create graduate professional degrees in M3D or "Master of Information".
- Develop a virtual prototyping standard that outlines what is included and what is not at every stage of the design process, and which might propose types to choose from (eg light, standard, and fully-integrated virtual prototype) according to the integration ambitions of the project.
- Praise and encourage "thinking with new tools" in a highly-controlled, fully-equipped, fully-supervised environment or "sandpit".
- Enhance the office front desk to support temporary practitioners on the move, with check-in and check-out procedures, concierge, etc.
- Store all data on line according to absolute spatial co-ordinates.
- Reduce the teaching of software; increase programming training and motivation; show what can be done.
- Hire staff with computer science backgrounds to sit next to the designers, so as to automate repetitive design tasks.
- Ensure that more than one person knows how to drive BIM.

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Credits

Illustrations: 1 Amorphis/Cloki/Dreamstime.com; 2-7 Nigel Whale; 8 Jeffrey Williams/Dreamstime.com.

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Acknowledgements

The author would like to thank all the interviewees for their insights, colleagues within Arup for the informal discussions, Dr Chris Luebkeman for leadership and encouragement throughout this study, and Professor Steven Fenves at NIST for his invaluable review of this article.

Note:

A different version of this article is also being published in the Elsevier journal *Advanced Engineering Informatics*.

1. Heathrow's new air-traffic control tower in the airport context.

Terminal 5, London Heathrow: The new control tower

Jeremy Edwards Richard Matthews Sean McGinn

The size and position of Terminal 5 necessitated a new central location for Heathrow's air-traffic control tower, which introduced challenges for the project team in the tower's design, fabrication, and delivery.

Introduction

This is the third *Arup Journal* article to deal with aspects of Arup's work on Terminal 5 at Heathrow Airport, London. It follows accounts of the project's 3-D and 4-D design environment[1], and the structural design of the main building[2].

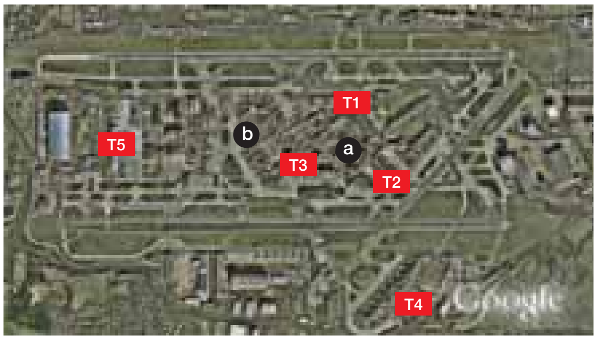
In March 2008, T5 opened, increasing further the size of the world's busiest two-runway airport, where in any one day the UK National Air Traffic Services (NATS) controls the movements of over 1000 aircraft approaching and departing, as well as managing the planes taxiing around (Fig 1).

Air-traffic controllers have to maintain constant visual contact with aircraft, and thus air-traffic control towers are crucial to ensuring that operations remain safe and efficient. T5 introduced obstructions to the required sightlines between the existing tower and aircraft using the new terminal, so a new location at a new height was needed. The optimum tower dimensions were calculated by assessing the sightlines to all taxiways and stands on the enlarged airport, whilst the best location was determined as the airport's geographic centre, at a height of 87m (Fig 2).

With the basic height and location requirements selected, the project team's task was to develop an efficient and elegant tower design, simultaneously addressing the considerable construction challenges of building on an island site surrounded by aircraft. A key requirement was to cause no operational disruption to the running of the airport; this had a significant effect on development of the design solution and the construction that followed.

Functionality

The location at Heathrow's centre necessitates full 360° views from the cab, whilst the taxiways and stands at the tower base need an extremely low viewing angle. To fulfil these requirements, the final design provides what is thought to be the largest cone of vision of any control tower in the world (Fig 3). However, the requirements of floor space for the controllers and their equipment had to be



2. Plan of Heathrow Airport showing location of (a) old and (b) new control towers.

balanced against the detrimental effects of increasing the size of the cab, which included reduced angles of vision for individual controllers, larger areas of glass, more solar gain, and wind drag on the tower. A great deal of detailed 3-D co-ordination between all design disciplines was needed to provide the most compact yet functional space possible (Fig 4).

The cab contains four levels, the highest being the visual control room (VCR), accommodating desks for 13 controllers. This floor is set back from the 10m high glass façade. At the base of this wall is a gallery space used to service the sub-equipment room containing communications and radar equipment. Underneath the sub-equipment level is the rest and recreation area containing a rest room, kitchen, toilet, and office. An external walkway here accesses a permanent cleaning cradle to service the entire cab glass wall.

The lowest level accommodates the air-handling plant as well as docking for the lift that travels up the outside of the mast. The mast structure itself contains stairs, an internal lift, and various risers for M&E and IT purposes. This rises through the middle of the cab and services every level.

Finally, a three-storey building at the base of the tower contains the NATS offices, administration and training rooms, technical equipment areas, and main plantrooms.

3. The 10m high glass façade provides a large cone of vision.

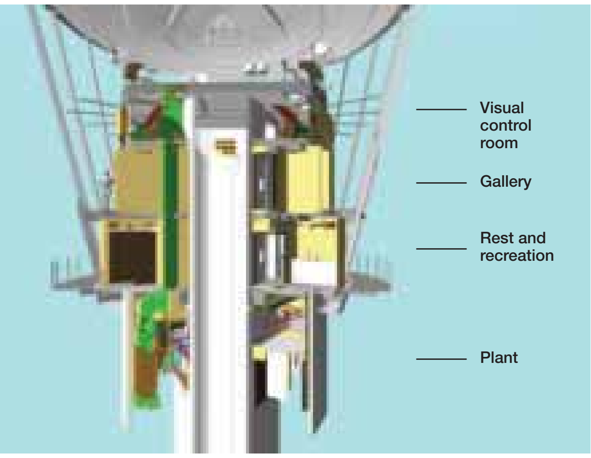
Construction method

Importantly, the construction strategy was developed in parallel with the design. A key aspect of the project was the use of the T5 agreement, the form of collaboration contract used by BAA when appointing its design consultants and contractors. This allowed the tower design to be specifically tailored to suit the erection strategy, with designers and construction team working together from the outset.

The design team considered using a traditional slip-formed concrete cantilever mast, but this would have required regular and uninterrupted concrete deliveries. Security, operations, and radar restrictions applying in the airport would also have necessitated an on-site batching plant, with cranes only usable in five-hour night-time airport closures. In view of this, the team decided on a cable-stayed steel tower, which could have half the mast diameter of an equivalent cantilevered mast structure. A steel tower could also be prefabricated and transported to site in 12m lengths, completely fitted out with stairs, lift cores, and mechanical-and-electrical risers, and then bolted together.

In addition, a small-diameter cable-stayed mast satisfied concerns about the visual impact of a traditional large-diameter concrete cantilever tower on the Heathrow skyline, as well as making it possible to construct the cab at ground level around the base of the mast, and later jack it up into position at the top. Building the cab at low level had several safety advantages, though significant challenges were also involved in making it structurally stable with the large hole through the middle for the mast.

These were met by using an idea from the petrochemical industry for erecting process plant (Fig 5). Its great advantage is that is allows the complete cab to be built at ground level without incorporating a temporary hole for jacking the cab up the mast. Understanding the prefabrication, transportation, and erection requirements was essential in defining the parameters to control the maximum diameter of the mast and the design requirements for the cab structure.

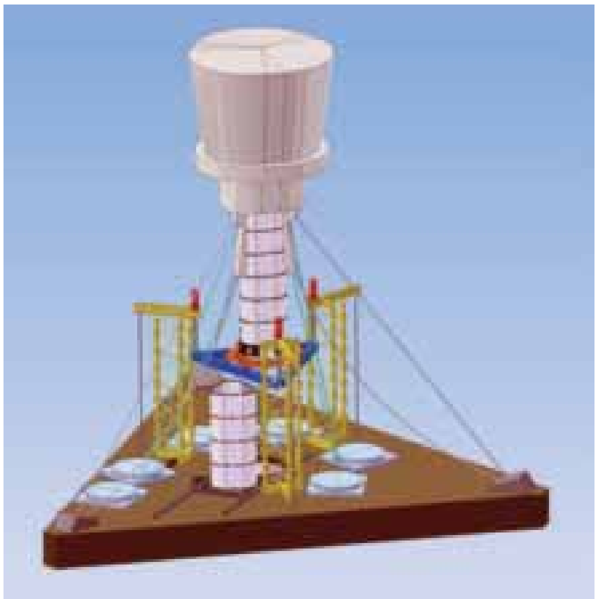


4. Section through control tower cab.

Dynamic performance

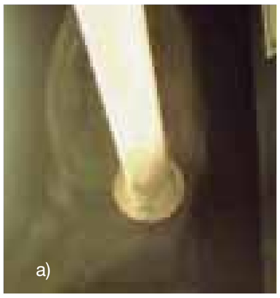
Alongside the erection strategy, another factor critical to the structural requirements for the mast was wind-induced movement of the completed tower.

Setting appropriate “comfort” criteria for tall buildings is more difficult than most design cases faced by engineers; here the tower’s dynamic performance was critical to the comfort of the air-traffic controllers. In the case of wind-induced lateral movements, acceptable performance is both time-dependent and varies with occupier sensitivity. The more often movement occurs, the less tolerant are occupiers of the level of lateral acceleration they experience. In the case of Heathrow, which often experiences fairly windy conditions, the frequent lower-strength winds formed the critical design case.

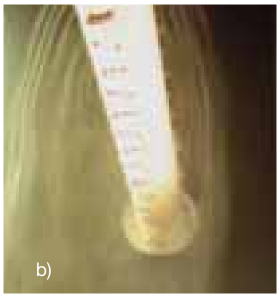


5. Tower jacking: three temporary works towers support strand-jacks and yoke system; the strands lift the yoke and mast off the ground via hydraulic jaws to allow a new section of mast to be inserted underneath.

6. Cab model in wind tunnel.



a)



b)

7. Airflow around 1:30 mast model in a wind-tunnel smoke stream without (a) and with (b) aerodynamic strokes.

During the early design stages, various levels of lateral acceleration were demonstrated to the air-traffic controllers on a motion simulator at Southampton University, and levels of acceptable movement of the control room were agreed. With these performance limits established, the design then focused on the tower's aerodynamic performance, stiffness, and damping.

Wind-tunnel testing

Extensive wind-tunnel modelling (Fig 6) was undertaken to optimise the tower's aerodynamic performance by reducing the drag and crosswind response of the design. These tests were used to develop a unique aerodynamically sculpted enclosure for the support rails and drive cables of the external passenger lift, reducing both the drag on the tower and improving the high-wind operation of the lift.

Small aerodynamic strakes (stabilisers) were also developed in the wind tunnel. Attached to the side of the mast, these control vortex-shedding and significantly reduce the cross-wind response (Fig 7).

Mast stiffness and damping

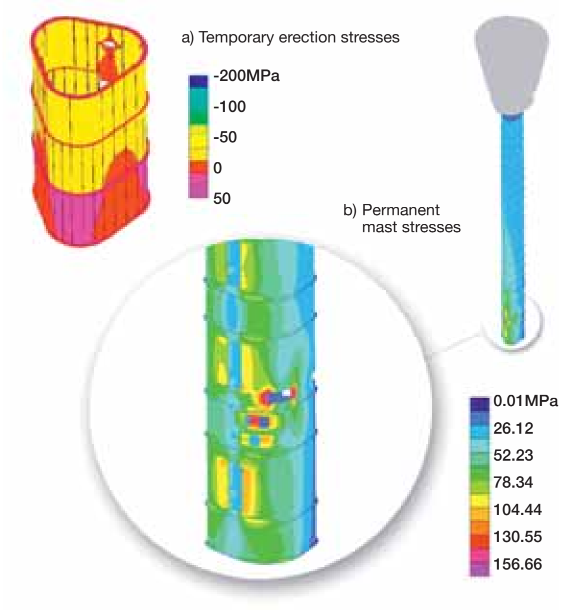
The tower's lateral stiffness and mass define its natural frequency. The amount of wind energy available to cause motion, and the sensitivity of the tower occupants, are both frequency-dependent.

In developing the Heathrow tower design, the diameter, type, geometry, and pre-tension of the main stay cables was critical to its final performance. The 150mm diameter locked coil cables, stressed to a 10th of their normal working capacity, give the axial stiffness needed to control the head of the mast and also provide considerable reserves of strength, allowing the tower to operate safely if cables ever need to be removed for replacement. The cable natural frequencies are governed by the cable mass, axial stiffness, and the degree of pre-tension. Coincidentally, the optimum pre-tension for overall tower stiffness resulted in cable natural frequencies very close to those of the tower system as a whole. De-tuning the cable pre-tension would have resulted in a much less efficient structure.

The final engineering factor that determines the tower's dynamic performance is its damping. The natural damping of the steel mast and cables is low (0.5%), so small viscous dampers were attached to the main cables to damp their lateral vibration, to prevent unpredictable and uncontrollable transfer of energy between the cables and tower dynamic modes, and to and lift the overall tower damping to 1.5%.

Finally, two hybrid mass dampers (Fig 12) were installed at the head of the mast immediately below the control room floor. These have both passive and active operational modes. In normal higher-wind situations, accelerometers in the cab detect tower movement and the control system then activates the dampers, moving the 5 tonne suspended masses in the appropriate direction to counteract the wind-driven tower movement. These raise the overall damping of the tower to levels in excess of 10% critical damping. Arup was instrumental in developing the design and validation of both the passive and the active damping systems.

8. Prefabricated mast section before installation of stairs and lift risers.



9. Mast stress diagrams.

Structural design

The steel mast was built in eight sections, normally 12m in length, with a 30mm thick outer steel skin, vertical longitudinal stiffeners, and horizontal stiffener hoops. The stresses induced in the steel mast during the temporary jacking cycles (Fig 9a) were very different from those it experiences in its permanent erected state (Fig 9b), and so it was designed to resist these considerable stresses during erection. Apart from the obvious compression loads carried by the mast, the critical additional design loads were generated by concentrated load from the lifting jaws during erection and by locked-in thermal stresses in the permanent state.

The high axial stiffness of the cable stays generate unusually high thermal stresses, as they restrict the tower's natural tendency to sway sideways under differential solar-induced thermal expansion on one side of the mast. A grey glass-flake epoxy paint, with low solar absorption, was used to limit the locked-in thermal stresses in the mast.

Thermal-stress modelling by Arup also showed that even a small air velocity makes a big difference to the steel temperature gradient around the mast. Back-analysis of UK Meteorological Office data showed that, even on the hottest days, there is always a small amount of background wind, and this was duly added to the thermal model.

To maximise usable floor space, the cab has no internal columns. Radial trusses in the roof act with each of the 24 façade mullions to form a 3-D portal frame. Floors within the cab span between the perimeter mullions and the steel mast. At the lowest cab level, structural loads in the mullions are transferred to the red-coloured structural steel skin spanning between the three support points offered by the main cable anchorages (Fig 11).

Construction co-ordination

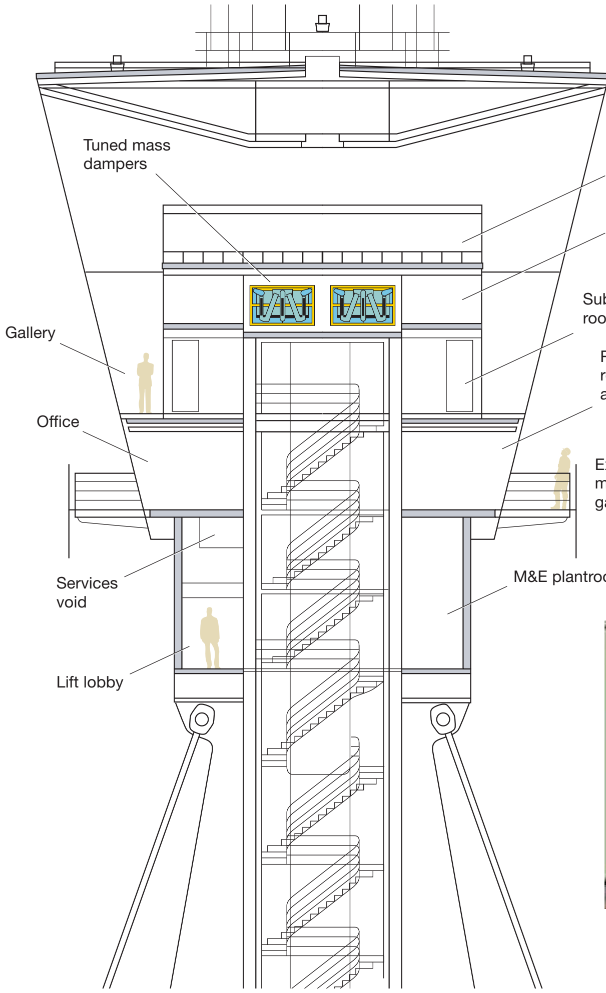
One construction issue remained: prefabrication of the cab structure at ground level would require cranage. This would limit construction to night time only as cranage limitations were in force during airport operations. However, it was realised that as the cab structure was designed to be lifted by strand jacks attached to three points on the temporary works jacking frame, the same points could be used to lift and transport the cab from a remote site using multi-wheeled transporter units able to lift and transport large loads, as is the case in the petrochemical industry.
The client, BAA, identified a suitable open site near Terminal 4 that would enable cab construction and fit-out to start early and progress in parallel with installation of the main foundations on the control tower site. These foundations comprise 1050mm and 750mm diameter piles, and pile caps up to 4.1m deep that support the tower, the base building, and permanent guy cables. The site had to be cleared in order to construct the main foundations.

Mast fabrication

As site work progressed, the first 12m long mast sections were fabricated. To achieve satisfactory alignment and force transfer between adjacent mast sections, careful control of tolerances in each was required.

The initial fabrication method used on the two top mast sections did not give adequate steel tolerances, but fortunately they could still be used because the compressive forces at the top of the tower are low, and the lower tolerances

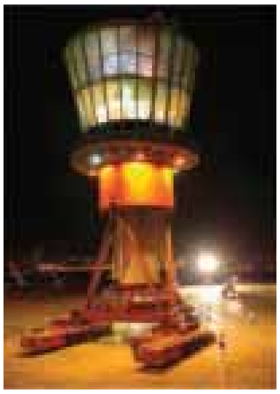
11. Cross-section through top of tower.



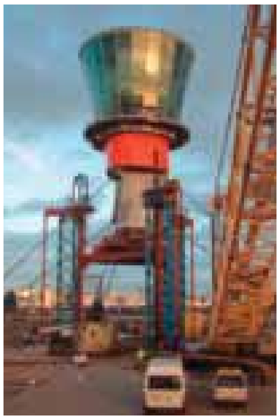
12. A 5 tonne active mass damper located at cab level.

12. Erecting the two top mast sections for cab construction.

13. Locating cab roof onto 24 mullions.



14. Moving 900 tonnes 1.5km across the airport.



15. Jacking the cab to 87m height.

were acceptable. In the revised procedure, precision jigs were used to fabricate 3m long sections of mast tube, which were heavily braced during fabrication to control weld shrinkage effects. Before removal of the bracing, the sections were heat-treated to stress-relieve them and ensure that fabrication accuracy was maintained. The 3m sections were then stacked and welded into the final 12m lengths. Prior to painting, the bolted interface flanges at the ends of the mast sections were milled and CNC (computer numerically controlled) drilled to ensure precise fit and alignment on site. Before transport to site, the mast sections were fitted out with the steel stairs, service risers, and the lift enclosure.

Cab construction

Cab construction on the remote site began with a temporary piled foundation, off which the 32m high cab was built. The top two sections of mast were used as a core from which all the floors were suspended (Fig 12). The main cable anchorages, stressed steel skin, and structural mullion systems were added to create a coronet of 24 mullions to which the roof would connect.

The roof structure, complete with internal acoustic lining, access walkway, decking, and waterproofing was constructed at ground level. The entire 50 tonne roof was craned into place (Fig 13) and connected to the ring of mullions. Before being moved from the temporary site, the cab was fully fitted out with M&E plant, walls, and ceilings.

Moving the cab

Preplanning the cab's 1.5km journey across the airport took considerable effort. The route crossed over the southern runway and involved using the main taxiways to get to the final site. The entire route had to be meticulously assessed for its load-carrying capacity because at close to 900 tonnes, the transported load greatly exceeded the 400 tonnes of a fully-loaded Boeing 747 for which the pavement was designed. Damage to the runway or breakdown of the transporter en route could cause effective closure of the airport - with resultant damages likely to exceed half the value of the entire control tower project. Detailed contingency plans were put in place to cover all eventualities.

After a 24-hour delay due to thunderstorms, the overnight move (Fig 14) was achieved without incident in less than two hours amidst a sea of press and TV cameras. At the control tower site, the 32m high, 750 tonne cab was manoeuvred and placed onto its foundation to within 10mm of dead centre.

Mast erection

Once the cab was successfully moved, the mast jacking towers were installed and the first of five mast lifts commenced, each mast section being successively added to the underside of the tower (Fig 15). Software developed by the jacking contractor was used to ensure that the lift was always level by controlling the strand jacks and guy cables. Prior to its use on site, the control logic of this custom-written jacking software had been tested and refined using a small-scale test rig.

To ensure verticality of the tower during the lift, both optical and GPS surveying were used to monitor the plumb of the mast. In general the top of the tower was maintained within 25mm of plumb throughout erection (Fig 16).

During the jacking cycles a procedure linking regional weather forecasting and local wind measurement was put into place to predict and monitor the weather conditions during each lift. The erection procedure had various wind limits placed on it but in the case of the most severe predicted weather, the tower was to be lowered onto its foundation and supported on multiple interconnected jacks forming a hydraulic pin at the base. In this situation, a second set of guy cables (Fig 5) were to be tensioned to give the mast additional strength and stiffness. Fortunately no weather severe enough to need these precautions was experienced. As well as eliminating non-uniform compression stresses in the mast, the hydraulic pin also served as a damper to absorb energy from wind-induced oscillations and remove the risk of aerodynamic instability during all stages of erection.

As the lifts progressed, a cycle of mast jacking during the day was followed by preparation of the next mast section during a night shift. Although the rig could raise the mast to the required height for each lift in a day, the process demanded so much preparation that it took about three weeks in all. However, all five mast lifts were completed without incident while airport operations continued uninterrupted around the site (Fig 17).

Completion

With mast erection complete, the project immediately progressed to the erection and fit-out of the base building and the connection of services between it and the cab. Once this was complete, the temporary guy cables were removed and the permanent 150mm diameter locked coil cables installed from a crane and tensioned during a further series of night-time operations.

The final installations and commissioning in the tower included tuning the hybrid mass dampers to suit the tower's final as-built natural frequency. Also installed was a 100m pedestrian bridge link from the control tower base building to the end of Terminal 3's Pier 7. Each section of the glazed bridge, designed by Thyssen, was prefabricated in 30m lengths, brought directly to the tower site, and rapidly craned into place during night time operations.

16. Jacks controlling guy cables during the lift.

Conclusion

The new tower went "live" in February 2007 when full airport operations transferred and the old tower was closed after 52 years of service.

Building a new air-traffic control tower in the centre of Heathrow's airside operations involved unique construction and operational requirements that largely dictated its architectural and engineering form (a more detailed description of the project has been published elsewhere[3]). This tower satisfies the air-traffic controllers' requirements, yet was constructed with no disruption to the airport's daily operations and no accidents. Its successful completion demonstrates the value of T5's integrated design and construction philosophy.

17. Tower and base building under construction.

Jeremy Edwards is an Associate of Arup with the Building London 4 group. He is a structural engineer and has had several roles on T5, including assistant structural engineer for the air-traffic control tower.

Richard Matthews is a Director of Arup with the Building London 9 group. He leads the structural engineering team for T5, and acted as Project Leader for BAA on the air-traffic control tower.

Sean McGinn is a Senior Associate of Arup with the Buildings Melbourne, Australia, group. He was lead structural engineer of the air-traffic control tower.

Credits

Client: BAA (building owner, airport operator, overall project manager) **Building operator:** NATS **Architect:** Richard Rogers Partnership **Project manager, structural engineer (superstructures), acoustics, façade, wind and dynamics engineer:** Arup - Andrew Allsop, Mike Banfi, Francesco Biancelli, Nick Boulter, Anita Bramfitt, Simon Cardwell, Jeremy Edwards, Rob Embury, Matteo Farina, Graham Gedge, James Hargreaves, Richard Henderson, Roger Howkins, Angus Low, Richard Matthews, Chris Murgatoyd, Daniel Powell, Sean McGinn, Nils Svensson, Ian Wilson, Peter Young, Andrea Zelco **Engineer (substructure):** Mott Macdonald **Temporary works designer:** Dorman Long Technology **Infrastructure engineer:** TPS **M&E engineer: DSSR** **Cost manager:** Turner & Townsend/EC Harris **Construction integrator:** Mace **Steelwork supplier:** Watson Steel **Substructure contractor:** Laing O'Rourke **Jacking and cab transportation:** Faggiolli **M&E and infrastructure contractor:** AMEC **Façade supplier:** Schmidlin **Lift supplier:** Schindler **Fit-out supplier:** Warings **Logistics:** Amalga **Illustrations:** 1-10, 12-17 BAA/HATCT project team; 11 Nigel Whale.

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CCTV Headquarters, Beijing, China:

Building the structure

Chris Carroll Craig Gibbons Goman Ho Michael Kwok Richard Lawson Alexis Lee Ronald Li Andrew Luong Rory McGowan Chas Pope

1. Architect's illustration of the completed building.

Erecting two massive leaning Towers, and connecting them with a 9-13 storey Overhang suspended 36 storeys in the air, presented the structural engineers and contractors with unprecedented design and construction challenges.

This is the third *Arup Journal* article about the CCTV (China Central Television) building in Beijing; it covers the construction of this unique project. The previous two articles dealt with the structural[1] and services engineering[2] design.

Introduction

China Central Television (CCTV) had been expanding greatly, in competition with major international television and news service providers, and early in 2002 it organised an international design competition for a new headquarters. This was won by the team of OMA (Office for Metropolitan Architecture) and Arup. The team subsequently allied with the East China Design Institute (ECADI) to act as the essential local design institute for both architecture and engineering. The first *Arup Journal* article[1] outlined the design collaboration process.

The unusual brief, in television terms, was for all the functions of production, management, and administration to be contained on the chosen site in the new Beijing Central Business District, but not necessarily in one building.

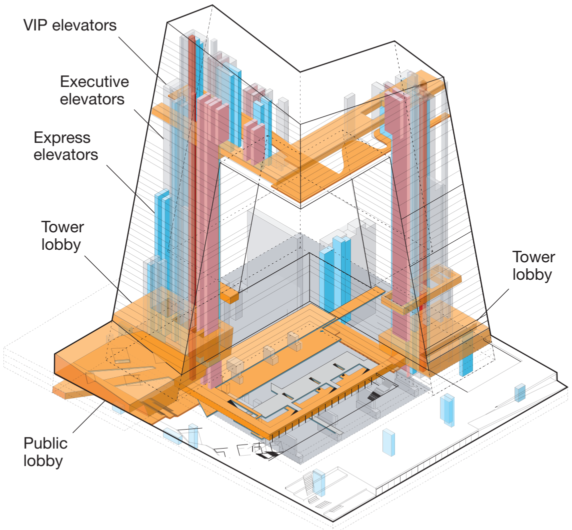
In its architectural response, however, OMA decided that by doing just this, it should be possible to break down the "ghettoes" that tend to form in a complex and compartmentalised process like making television programmes, and create a building whose layout in three dimensions would force all those involved to mix and produce a better end-product more economically and efficiently (Fig 1).

The winning design for the 473 000m^2, 234m tall CCTV building thus combines administration and offices, news and broadcasting, programme production, and services – the entire process of Chinese television – in a single loop of interconnected activities (Fig 2) around the four elements of the building: the nine-storey "Base", the two leaning Towers that slope at 6° in two directions, and the 9-13 storey "Overhang", suspended 36 storeys in the air. The public facilities are in a second building, the Television Cultural Centre (TVCC), and both are linked to a third service building that houses major plant as well as security.

The whole development will provide 599 000m^2 gross floor area and covers 187 000m^2, including a landscaped media park with external features.

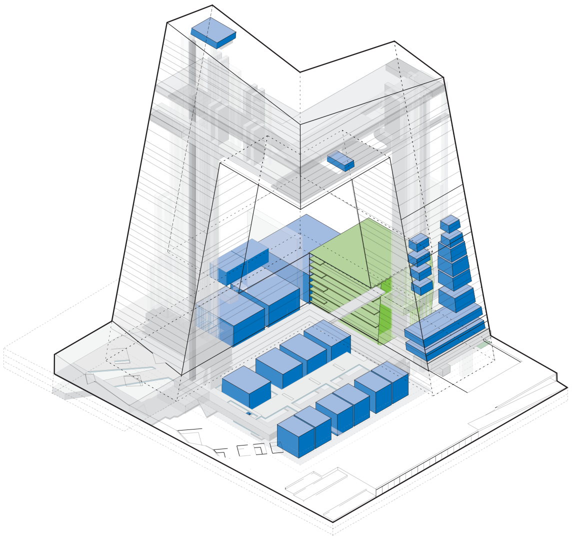
Construction Documents phase

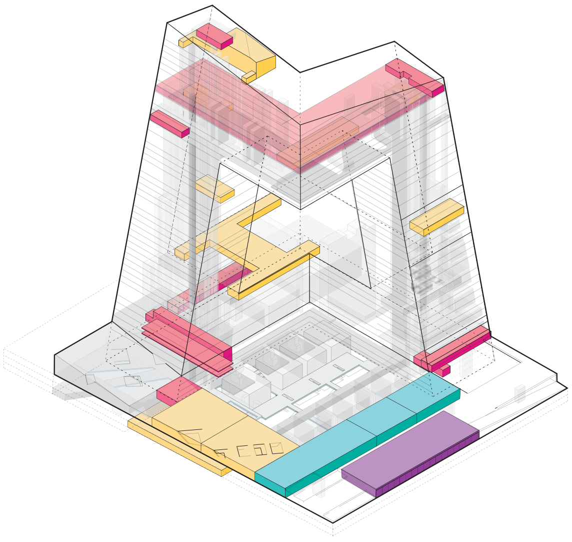
In August 2004, after receiving approval for the structural design from the Chinese Ministry of Construction, Arup handed over the extended preliminary design (EPD) documents to ECADI, which then began to produce the Construction Documents (CDs). Arup, however, maintained an extensive involvement on completion of the EPD design phase, including production of tender documentation for the main structure and interaction with the tenderers for the works, as well as being part of the tender review process. Together with the architects OMA, Arup also had a continuous site presence during construction, working with the contractor in implementing the design (Fig 3).



Public space and circulation

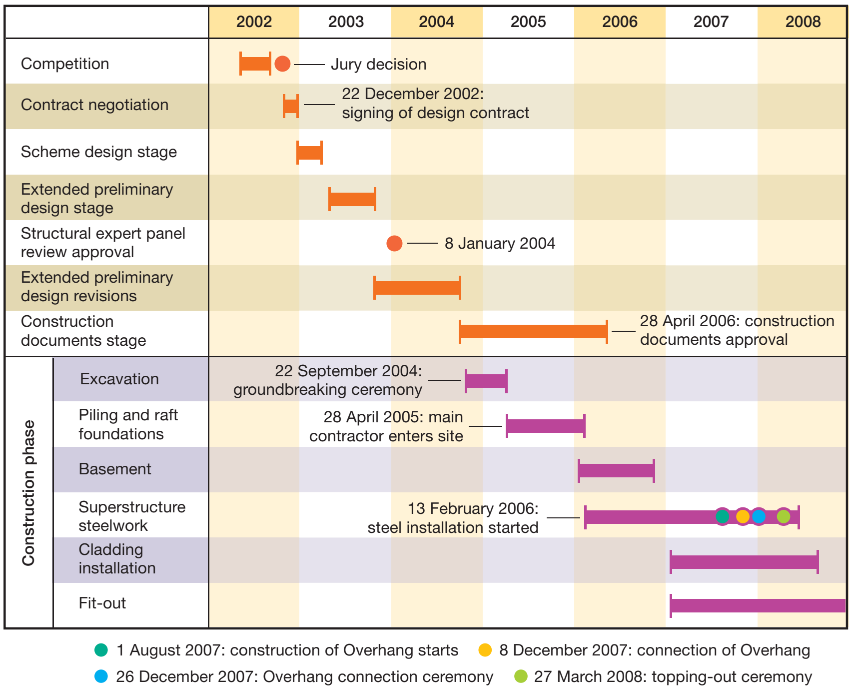
Sky studio





Staff and VIP facilities

2. Functions and layout within the CCTV building.



3. CCTV timeline.

As previously described[1], the building's shape and form meant that it fell outside the prescriptive codes for buildings in China. In consequence, a rigorous series of meetings was required with an assembled expert panel comprising 12 professors from around China, appointed by the Ministry of Construction. Dialogue with these experts influenced the approach to the design and determined the extent of analysis required to justify the seismic performance of the building.

As part of the expert panel approval process[1], several suggestions were made that Arup and ECADI subsequently addressed during the CD phase. These included a requirement for three physical tests to be carried out, in order to verify the analytical calculations:

- Joint test ("butterfly plate"): Beijing's Tsinghua University tested a 1:5 scale model of the column-brace joint to confirm its performance under cyclical loading, in particular the requirement that failure takes place by yielding of the element rather than at the connection.
- Composite column: Tongji University in Shanghai carried out destructive tests on 1:5 scale models of the project's non-standard steel reinforced columns. These tests resulted from concerns that the high structural steel ratio might lead to reduced ductility.
- Shaking table test model: A 7m tall 1:35 scale model of the entire building was constructed to test the structural performance under several seismic events including a severe design earthquake (known as Level 3 - average return period of 1 in 2475 years). The tests were undertaken by the China Academy of Building Research (CABR) in Beijing, using the largest shaking table outside America or Japan (Fig 4 overleaf).

This large-scale shaking table test was of particular interest. In China it is the norm for buildings that fall outside the code to be thus studied, and the CCTV model was the largest and most complex tested to date. The nature of the testing required the primary structural elements to be made from copper (to replicate as much as possible in a scale sense the ductility of steel). The model also included concrete floors (approximately 8mm thick) to represent the 150mm thick composite floor slabs.

Interestingly, in a scaled model test the duration of the earthquake is also scaled, so that the severe design earthquake event lasted less than four seconds when applied to the model.

In all cases, the physical tests correlated closely with the analysis. It is arguable that computer analysis is now more accurate than a physical shaking table test, which is still the standard practice in China. Due to the amount of scaling required, the accuracy of such models and tests may be significantly less than the proven accuracy of the analytical software used to design the building. Nonetheless, a shaking table test helps to corroborate the computer model and provides a demonstration that the design has safely accounted for seismic issues.

Tender, excavation, and foundations

As noted already, Arup had a major role in the tender process for appointing the main contractor, including the production of the steelwork drawings and specifications. One key document was the Particular Technical Specification, which placed several requirements on the contractor that were specific to the design of CCTV.

Some of the specific issues identified in the Particular Specification included:

- weight audits – ie onus on the contractor to convey the weight added to the building at stages during the construction
- specific monitoring of the Tower deformation (married to the construction weight assessment)
- specific monitoring of deformations (including dishing) of the foundations
- presetting of the structure
- monitoring of daily variation in the difference between the position of connection points as the Overhang construction advanced prior to linking
- the requirement to connect when the relative movement between the connection points of the Overhang were manageable (suggesting connection when the two Towers were at an even temperature, ie at dawn)
- a means of showing that the extent of connection was commensurate with the daily movement measurement, so as to prevent the connection ripping apart once it had been firmly made
- a requirement for post-installing certain key structural elements.

In addition to regular gravity and lateral forces acting on the structure, there are significant additional construction stage forces due to the fact that the building comprises two separate leaning Towers with cantilevers up until the point at which they are joined to become one structure. The additional bending and overturning stresses that get "locked" into the Towers and foundations prior to joining depend on the amount of structure and façade completed at the time of connection.

In essence, the greater the construction load applied to the building prior to connecting the two Towers, the more this would manifest itself as increased locked-in base moments in the Towers.

4. Shaking table model.

5. Three alternative methods of constructing the Overhang.

After the connection was made, any added weight would result in a thrust between the two Towers via the Overhang. The final stresses in the building were therefore very much linked to the construction sequence. The Particular Specification defined an upper and lower bound range of permissible locked-in stress, allowing the contractor some flexibility in choosing his final construction sequence.

Another interesting feature of the process was the proposals put forward by different tenderers to meet the Particular Specification requirements and the particularly challenging aspects of the Overhang construction. One of the three shortlisted tenderers proposed a temporary tower the full 162m height to the underside of the Overhang, providing a working platform to build the Overhang connection in situ. The second tenderer opted to build a partial cantilever from the Towers and then construct the lower part of the Overhang at ground level and strand jack the assembly into position. The third tenderer proposed to construct incremental cantilevers from each Tower until the two met and connected at the centre of the Overhang (Fig 5). This latter approach was as described in Arup's documentation, though any construction approach was deemed acceptable provided it could satisfy the locked-in stress limits defined in the Particular Specification.

The Particular Technical Specification approach has become a leading example of best practice for high-rise construction within Arup.

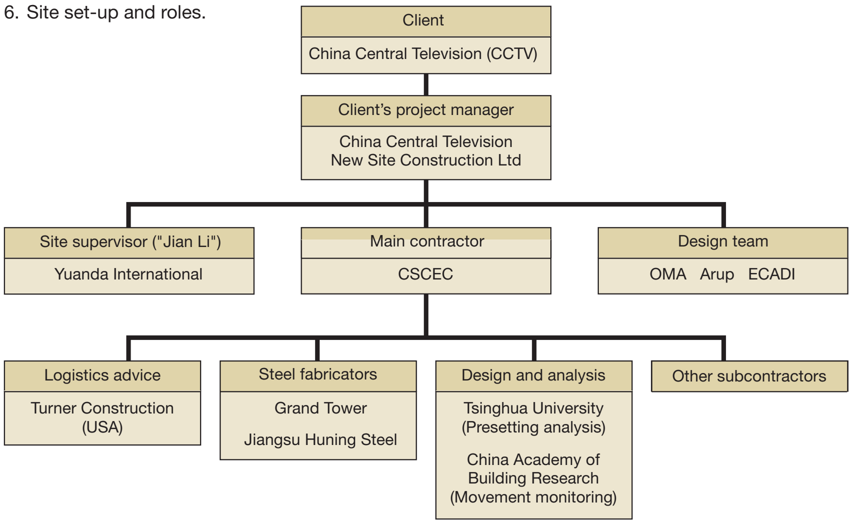
China State Construction Engineering Corporation (CSCEC) was awarded the main contract in April 2005. CSCEC tendered on this third approach.

Construction team

CSCEC, a state-owned enterprise under the administration of the central government, was established in 1982 and is China's largest construction and engineering group. CSCEC now enjoys an international reputation, having completed an increasing number of projects abroad including the Middle East, South America and Africa. The steelwork fabricators were Grand Tower, part of the Bao Steel group based in Shanghai (China's largest steel manufacturer), and Jiangsu Huning Steel, based in Jixing, Jiangsu Province.

Other members of the team were Turner Construction (USA), providing support to CSCEC on construction logistics, China Academy of Building Research (CABR), one of the major design institutes in Beijing, and Tsinghua University, which carried out the presetting analysis and is one of China's foremost universities. The independent site supervisor was Yuanda International, established in 1995 (Fig 6).

6. Site set-up and roles.



Excavation and foundations

The ground-breaking ceremony took place on 22 September 2004, and the excavation of 870 000m³ of earth began the following month under an advance contract. Strict construction regulations in Beijing meant that spoil could only be removed at night: nonetheless, up to 12 000m³ of soil was removed each day, the entire excavation taking 190 days. Dewatering wells were also installed, since the groundwater level was above the maximum excavation depth of 27.4m below existing ground level.

7. Cutting down piles by hand.

8. Preparation of foundation raft.

9. Delivery of column baseplate, April 2006.

The two Towers are supported on separate piled raft foundations with up to 370 reinforced concrete bored piles beneath each, typically 33m long and up to 1.2m in diameter. In total, 1242 piles were installed during the spring and summer of 2005. In common with many other Beijing projects, the piles were shaft- and toe-grouted (in accordance with an alternative design by CABR). The top 2m of the piles were then topped off by hand rather than with machinery (Fig 7) - one of the few occasions when sheer numbers of workers had to be mobilised to carry out the work: such unskilled, labour-intensive tasks were few on this project.

The Tower rafts were constructed over Christmas 2005 (Fig 8). The 7m thick reinforced concrete slabs each contain up to 39 000m³ of concrete and 5000 tonnes of reinforcement. Each raft was constructed in a single continuous pour lasting up to 54 hours. At one stage, 720m³ of concrete was being delivered every hour, using a relay of 160 concrete trucks from three suppliers. Chilled water pipes were embedded inside the pour and temperatures were monitored for more than two weeks to ensure that the concrete did not experience too high a temperature gradient during curing. The two rafts, poured within days of each other, were the largest single continuous concrete pours ever undertaken by China's building industry. In total, 133 343m³ of concrete went into the foundations of the Towers and podium.

The seismic analysis indicated that some columns and their foundation piles could experience tension during a severe design earthquake. Some of the perimeter columns and their baseplates were therefore embedded 6m into the rafts to enhance their anchorage (Fig 11). Certain piles were also designed for tension.

Steelwork construction

The first column element was placed on 13 February 2006 (Fig 12). In total, 41 882 steel elements with a combined weight of 125 000 tonnes, including connections, were erected over the next 26 months, at a peak rate of 8000 tonnes per month.

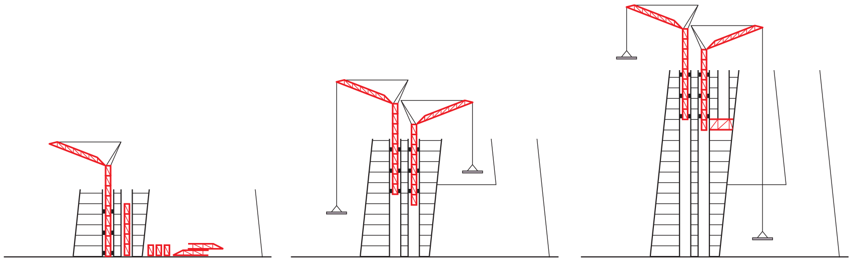
During the design it was thought that some high-grade steel elements would need to be imported, but in the end all the steel came from China, reflecting the rapid advances of the country's steelwork industry. Steel sections were fabricated at the yards of Grand Tower in Shanghai and Huning in Jiangsu, and then delivered to site by road (Fig 9), with a size limit of either the tower crane capacity (80 tonnes at a distance of 12m) or the maximum physical dimensions that could be transported (18m length). Inspections generally took place prior to shipping, with further checks prior to installation. Only minor fabrication work was carried out on site.

The size of the site enabled many elements to be stored after delivery (Fig 13), although heavier ones were kept on the backs of trailers until they could be craned directly into position. Due to the many different elements, each was individually coded to identify its location and orientation.

The elements were lifted into place by two tower cranes working inside each Tower. These were *Favco M1280D* cranes imported from Australia – the largest ever used in China's building industry - plus a smaller *M600D* crane. Even so, care was needed when locating the temporary ground-level working platforms to which the elements were delivered for craning, to ensure that all parts of the sloping Towers stayed within the cranes' operating radius as their height progressively increased.

Each crane not only had to be raised up to 14 times during construction, but also slewed sideways up to four times when it reached the upper levels, to maintain position relative to the edges of the progressively shifting floorplate (Fig 10).

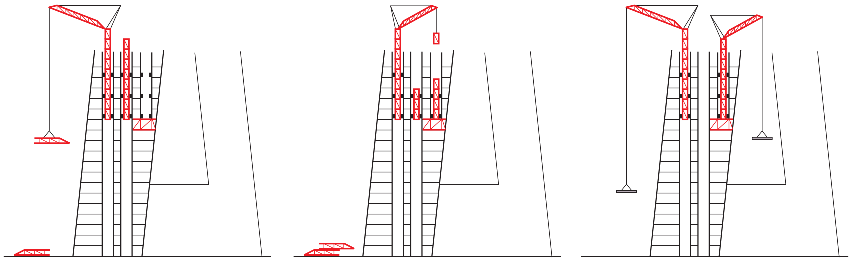
10. Crane slewing process.



(a) Cranes erected (in lift shafts) at ground level.

(b) As building height increases, cranes progressively lifted by jacks.

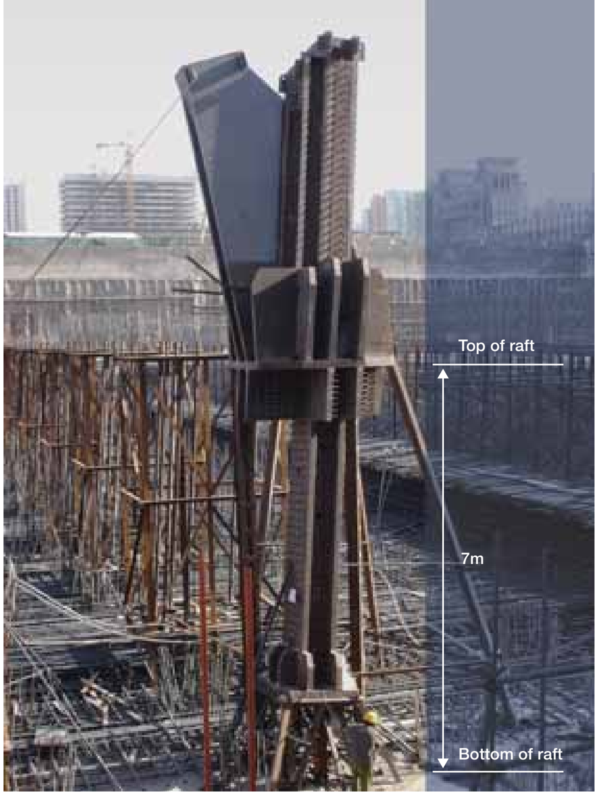
(c) Due to shifting floorplate, crane must be relocated horizontally so as to reach extremity of building.



(d) First crane used to dismantle second crane.

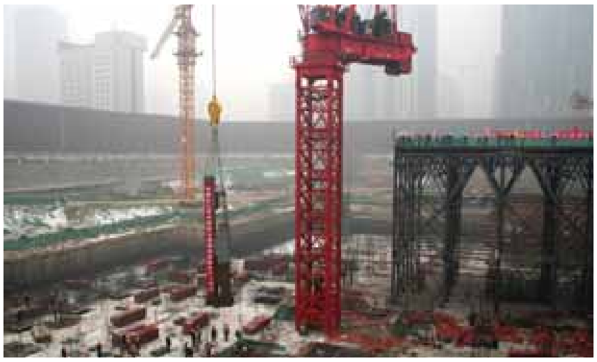
(e) First crane used to reassemble second crane in new position.

(f) Both cranes resume work.



11. Column embedded in raft.

12. Installation of first column.



13. Prefabricated elements stored on site.

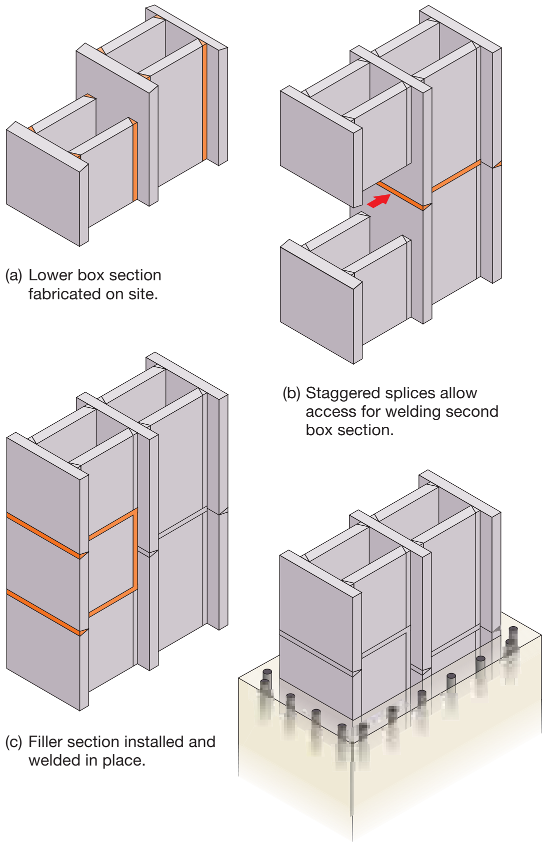
14. Craning in action.

Due to the 6° slope of the Towers, the perimeter elements needed to be adjusted to approximately the correct installation angle after being lifted a short distance off the ground, using a chain block. This simplified the erection process at height.

The vertical core structure was generally erected three storeys ahead of the perimeter frame. This meant that the perimeter columns could be initially bolted in place and braced to the core columns with temporary stays, then released from the tower crane before final surveying and positioning. The welders could then start the full-penetration butt welds required at every connection: a time-consuming task requiring shift work to achieve a continuous 24-hour process.

The maximum plate thickness of the columns is 110mm and the volume of weld sometimes reaches as much as 15% of the total connection weight. At the extreme case, a few connection plates near the base of the Tower required a 15m long site splice of 100mm thick plate, each taking a week to complete. The plate thickness of some elements exceeded the maximum assumed in design, which had been determined by likely steel availability. Onerous material specifications were laid out for thick sections to ensure satisfactory performance.

The welders had to be specially qualified for each particular welding process. Before the start of a given weld, the welder's qualification, the electrodes, scaffolding safety, the preheating temperature, and the method would all be checked. Procedures were laid down for monitoring preheating temperatures, the interpass temperature, and any post-heating treatment. Non-destructive testing 24 hours after completion was carried out by the contractor, site supervision company, and third parties employed by the client.



(a) Lower box section fabricated on site.

(b) Staggered splices allow access for welding second box section.

(c) Filler section installed and welded in place.

(d) Box sections encased in reinforced concrete.

17. Weld process for complex section.

Though, following standard Chinese practice, all quality control was carried out by the independent site supervisor, Arup maintained a site presence to observe progress and provide a liaison with the architect and client, due to the project's complexity.

Some of the most complex sections required careful thought to achieve a full weld, with staggered splices used in some cases to reduce concentrations of weld stresses where possible (Fig 17).

The geometrical complexity made construction slower than for other steel-framed buildings. Although the rate of erection increased as the contractor became more familiar with the process, CCTV has no "typical floors". Nevertheless, up to six storeys per month was achieved for the relatively uniform levels at Tower mid-height.

Concreting the composite columns and floor slabs took place several storeys behind steel erection, off the critical path.

Life on site

An average of 1200 workers were on site at any one time, rising to 3500 at peak of construction. They ranged from unskilled migrant labourers to experienced welders and top-level management. CCTV actually employed far fewer labourers than other large projects in the city, since the building contains a limited amount of conventional reinforced concrete construction (by contrast almost 50 000 were employed on Beijing Airport's new terminal). The men, and a few women, usually worked 8-10 hour days. In 2007, construction workers in Beijing could typically earn up to £120 per month - a considerable sum by rural income standards - with workers sending much of this home to support their families. Accommodation and food were usually provided by the contractor. Most lived in dormitories on the outskirts of Beijing, provided by the contractor, although some actually lived on the site.

The workers hail from all parts of China, and generally return home for two weeks once a year during the Spring Festival (Chinese New Year). The site meeting minutes recorded some unusual working concerns: for example, productivity being affected by homesickness in the lead-up to the Spring Festival, or by workers suddenly returning to farms in the surrounding provinces during the wheat harvest season between May and June.

15.

Mealtimes are possibly the most important part of the day, with the site almost coming to a standstill at lunchtime, except for the non-stop sparks from welders. During summer evenings, outdoor film screenings were arranged for workers in public squares near the site.

16. Welding in process.

18. Basic concept of presetting for a sloping Tower.

(a) Tower deflects under its own weight.

(b) Preset upwards and backwards.

(c) Resultant: no deflection under self-weight.

19. CCTV under construction at times presented almost surreal vistas from surrounding streets.

Movements and presets

Arup's calculations included a "construction time history" analysis to take account of the effects of the predicted construction method and sequence on the completed building's deflections and built-in forces. This indicated that the corner of the Overhang would move downwards by approximately 300mm under the building's dead weight. For there to be no overall downward deflection under this load case, the whole structure needed to be preset upwards and backwards to compensate (Fig 18), and the contractor continuously monitored construction to ensure that the actual movements corresponded to analysis assumptions and predictions.

The presetting process was further complicated by the fact that when completed, almost all the columns have different stresses, depending on the ratio of gravity to seismic loads, unlike in a conventional building where all perimeter elements will be similarly stressed. As a result, different presets were required on different sides of the Towers, the exact values also depending on the final construction sequence. In practical terms, this meant fabricating the columns longer on one side of each Tower, so that they would eventually shorten to the correct geometry under load.

Presetting was in two stages: at the fabrication yard, based on the results of the analytical modelling, and then at installation, if required, to suit the actual building deformation as monitored during the course of construction. Progress of floor plate concreting was also controlled to suit the assumptions made in the presetting estimation.

The contractor commissioned CABR to carry out the movement monitoring, while Tsinghua University performed the building movement prediction and presetting analysis as required by the Arup specification. This required a more detailed time history analysis of the final construction sequence, dividing the process into 53 assumed stages based on estimated progress for the perimeter tube, core, slab concreting, façade, services, and interior fit-out. This was compared with the results of the movement monitoring, and checks and adjustments were made as necessary.

The studies found that the movements during Overhang construction would be far more significant than those at the earlier stages caused by the Towers' lean only. Due to the large number of variables needed for the presetting calculation (variable axial stiffness, final construction sequence, foundation settlement, thermal movements, etc), the main focus of the analysis was on the critical Overhang construction stage. By the time Overhang erection commenced, there was already much movement data from the Tower construction that could be used to calibrate the analysis.

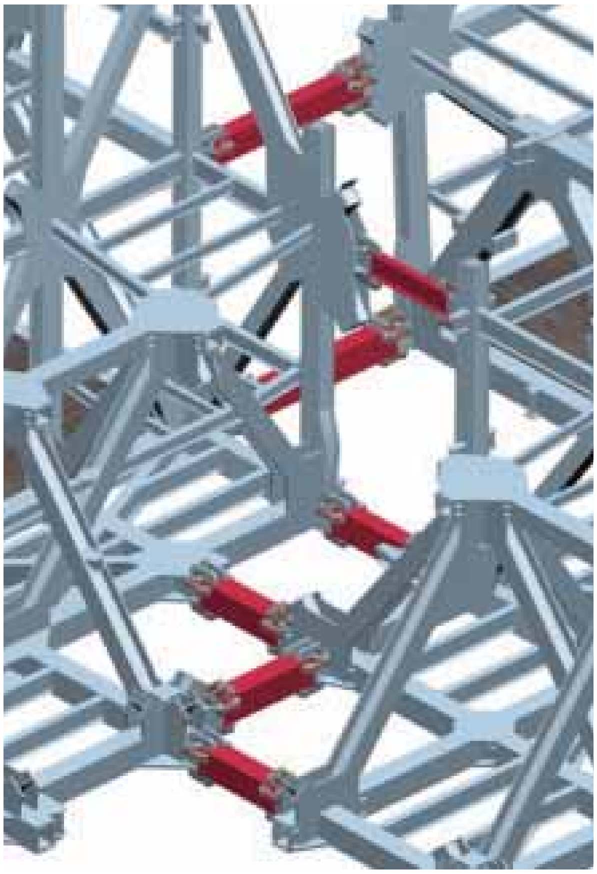
20. Large "butterfly" plate.

Overhang construction

Construction of the Overhang began after the steelwork for the two Towers was completed to roof level. Tower 2 Overhang began first, in August 2007, and the structure was cantilevered out piece-by-piece from each Tower over the course of the next five months (Fig 22). This was the most critical construction stage, not only in terms of temporary stability but also because its presence and the way it was built would change the behaviour of those parts of the Tower already constructed. The forces from the two halves of the partly constructed Overhang would be concentrated in the Towers until such time as the two halves were linked and the building became a single continuous form, when the loads would start being shared between all of the permanent structure.

The bottom two levels of the Overhang contain 15 transfer trusses that support the internal columns and transfer their loads into the external tube. In the corner of the Overhang, these trusses are two-way, resulting in some complex 3-D nodes with up to 13 connecting elements, weighing approximately 33 tonnes each.

Fabrication accuracy was therefore crucial for this part of the structure, with erection being carried out piece-by-piece 160m above ground level. Trial assembly of these trusses at the fabrication yard prior to delivery was essential to ensure that minimal adjustment would be needed at height.



21. The seven initial connection elements.

24. The completed Overhang structure, showing the three 3m diameter circles punched in the deck to create glazed viewing platforms for the public viewing gallery.

22. The Overhang before connection.

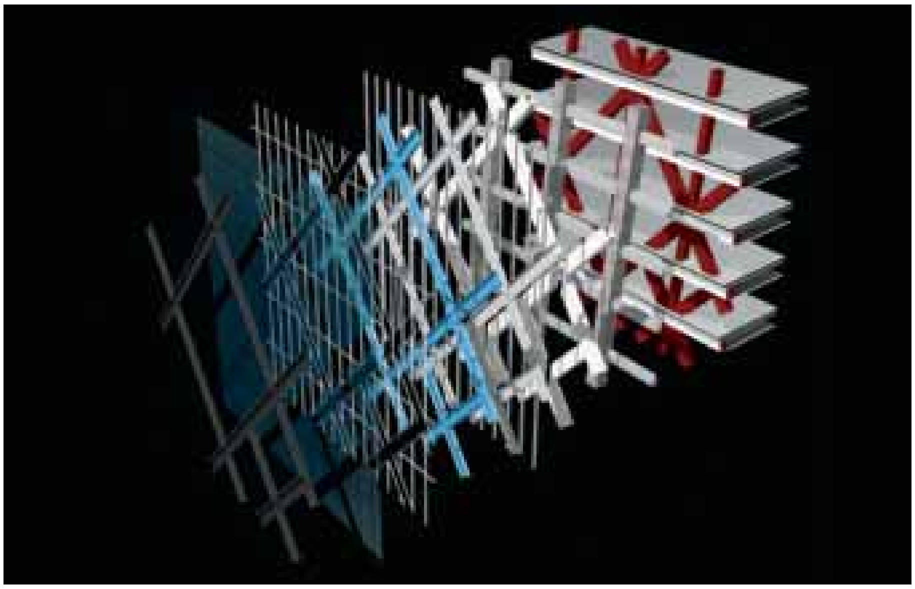
23. Installation of first connection element.

Prior to connection, the two Towers would move independently of each other due to environmental conditions, in particular wind and thermal expansion and contraction. As soon as they were joined, therefore, the elements at the link would have to be able to resist the stresses caused by these movements. As a result, the connection strategy required a delay joint that could allow a sufficient number of elements to be loosely connected between the Towers, then locked off quickly to allow them all to carry these forces safely before any relative movement took place. Arup specified that this should take place early in the morning on a windless day, when the two Towers would be at a uniform temperature and the movements at a minimum.

In the lead-up to connection, Arup's specification required one week of monitoring of global and relative movements so that the correct dimensions of the linking elements could be predicted. The relative movements of the Towers during the day were found to be around ±10mm. The contractor made the final measurements of the gap exactly 24 hours beforehand (ie at identical ambient conditions) so that final adjustments could be made to the length of the linking elements while they were still on the ground prior to installation.

The contractor chose to connect seven link elements at the inside corner of the Overhang during this initial connection phase (Fig 21). These were lifted into place – to less than 10mm tolerance – and temporarily fixed with pins in the space of a few minutes at 9.00am on 8 December 2007, before the Towers started to move relative to each other (Fig 23). The pins allowed them to carry the thermal loads while the joints were fully welded over the following 48 hours.

The specification originally called for the connection to take place while ambient temperatures were between 12-28°C (ie close to the standard room temperature assumed in analysis). Since the connection took place during winter, the temperature at the time was around 0°C, so further analysis of the structure was carried out by the design team to check the impact of the increased design thermal range.



25. Façade build-up.

Once the initial connection was made, the remainder of the Overhang steelwork was progressively installed. With the building now acting as one entity, the Overhang was propping and stabilising the two Towers, and continued to attract locked-in stresses as further weight was applied. In addition to the primary steelwork elements, a continuous steel plate deck up to 20mm thick was laid down on the lowest floors of the Overhang to resist the high in-plane forces that were part of this propping action. The steel plate is not, in fact, fully continuous – three 3m diameter circles were punched into the deck to provide glass viewing platforms for the public gallery at the Overhang's bottom level (Fig 24).

The concrete floor slabs were only added once the entire primary structure had been completed, so as to reduce the loads during the partially-constructed stage. Again, the construction stage analysis needed to take account of this sequencing.

A topping-out ceremony on 27 March 2008, on a specially-constructed platform at the corner of the Overhang, marked the completion of the steelwork installation.

Post-installation of key elements

Arup's early analysis showed that the corner columns on the inside faces of the Towers would attract a huge amount of dead load from the Overhang, and thus have little spare capacity for resisting seismic loads. Increasing the column sizes was rejected since they would become stiffer and hence attract even higher loads. Instead, the corner column and brace elements directly below the Overhang were left out until the end of construction, forcing the dead loads to travel via the diagonals down adjacent columns and enabling the full capacity of the corner elements to be available for wind and seismic loads in the as-built condition.

Key elements at the intersection of the Towers and podium were also post-fixed for similar reasons. In addition, this process enabled the architectural size of the elements to be controlled, while giving the contractor additional flexibility to deal with construction movements.

Delay joints were introduced between the Towers and the Base to allow for differential settlement between the two structures' foundations. It should be noted that over half the predicted settlements were expected to take place after the Towers were constructed to their full height, due to the disproportionate effect of the Overhang on the forces in certain columns. These were fully closed after completion of the main structure. Further late-cast strips were also provided at several locations around the basement to control shrinkage.

Follow-on trades

Installing the façade began once the structure had reached mid-height, so the façade design needed to take account of significant movements subsequent to installation. This sequencing also created tricky interfacing problems due to the need to share tower crane use with the steel erection, and cope with protecting workers – and completed cladding – from work taking place above.

The lean of the Towers meant that workers on the re-entrant sides of the Tower would be protected from falling objects above (albeit with additional installation hurdles to overcome), while extra care would be needed to protect those on the other faces which were subject to higher risk.

Services installation also began while the structure was in progress. This fast-track process was in marked contrast to many other projects in the city, in which façade and MEP installation would sometimes only start once the structure had been completed.

26. Construction progress at March 2008.

27. The façade design includes large diagonal “diagrid” elements that span between each primary floor, mirroring the structural braces.

Novel construction solutions for a novel building

The challenge of constructing a vast, cranked, leaning building made the contractor devise some other intriguing solutions.

Cutting down piles

The wide availability of unskilled labour in China means that many operations are carried out in a very different manner from the West. On CCTV, for example, piles were cut down by hand, with hammer and chisel, to expose the reinforcement (Fig 7).

While this avoided workers suffering from Vibration White Finger, a condition that often affects those working with vibrating machinery like drills, this was still a very time-consuming process, and other methods were developed to speed things up. Once the outer part of the pile had been broken back, a notch was cut into the central part, and cables were tightened around the remainder of the section. Then, with the help of a *Tirfor* winch, the mass-concrete pile top could simply be snapped off.

Façade installation

The façade design includes large diagonal “diagrid” elements that span between each primary floor, mirroring the structural braces (Fig 27). These heavy pieces had to be lifted with the tower cranes, but on the re-entrant faces, the slope of the Towers meant that it was impossible to get them close enough to the edge of the floor to fix them in position. The contractor came up with an ingenious system of supporting the element off a counterbalanced “mini-crane”, hanging on the end of the main crane cable. This allowed a team inside the Tower to manoeuvre the piece laterally into position.

The other faces also involved challenges. The glazing panels were lifted up individually by rope, but on the outer faces of the Towers, men were needed on the ground to pull the rope sideways to keep the panels away from the Tower as they were lifted, to prevent damage to glazing already installed.

Surveying

Not one of the 121 columns in either Tower’s perimeter frame is vertical, and many of the pieces in the Base and Overhang are aligned in completely different directions. To ensure every element was positioned correctly, the contractor continuously monitored the control points throughout the building, reaching 670 in number at the most critical stage around January 2008 after the linking of the two Towers. Monitoring included vertical movements of Tower circumference at particular floors, corner column movements at the Overhang soffit, internal levelling, stress, raft settlement, and Overhang movement.

Reinforcement bars

Spare reinforcement is used for almost everything on a Chinese construction site - handrails for temporary staircases (and sometimes the staircases themselves); impromptu hammers and other tools; drain covers. Very few offcuts go to waste. Meanwhile, almost all reinforcement used in the permanent works is coupled rather than lapped – material costs are still the main driver in China.

Recycling

As is standard in China, virtually nothing from the site demolition or new building went to waste. Every brick, nail, pipe, and piece of timber and reinforcement was meticulously extracted and collected by a team of workers, before being used again on site or sent away for reuse or recycling.

28. The TVCC building, to the left of the CCTV headquarters, April 2008.

TVCC and the Service Building

The other buildings on site, TVCC (Fig 28) and the Service Building, were built simultaneously. Construction of the Service Building began in April 2006, and it was handed over in June 2008.

The Service Building was actually the critical path item, as it had to be complete and fully commissioned in advance of CCTV and TVCC. Service tunnels running between the three buildings introduced a significant element of civil engineering works to the site.

The contract for TVCC was given to a separate contractor, Beijing Urban Construction Group. Work began in March 2005, and the structure was complete by September 2007. TVCC and the Service Building will be described in detail in a future issue of *The Arup Journal*.

Conclusion

The structure of the CCTV building was completed in May 2008, with the façade due to be finished by the start of the Beijing Olympic Games. Within weeks of structural completion, China was struck by its most violent earthquake of recent years. Although the epicentre was nearly 1000 miles from Beijing, the tremor was felt on site. Like other structures in seismic regions, CCTV is designed to resist a certain level of earthquake during construction, and no damage was reported. However, this served as a timely reminder of the importance of the building's rigorous seismic design and approvals process.

That the contractor could construct such a vast and complex building with few delays was a credit to the design team and to CSCEC, in particular the attention paid to devising a feasible construction sequence from an early stage, and the careful thought about the buildability of the primary structural elements and connections.

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Credits

Client: China Central Television **Architect:** OMA Stedebouw BV, Ole Scheeren and Rem Koolhaas **Structural, MEP, geotechnical, fire, and security consultant:** Arup - Abdel Ahmed, Cecil Balmond, Carolina Bartram, Chris Carroll, Wayne Chan, Mark Choi, Dean Clabrough, Paul Cross, Roy Denoon, Omar Diallo, Mimmy Dino, Xiaonian Duan, Gary Ge, Craig Gibbons, Sam Hatch, Colin Ho, Goman Ho, Jonathan Kerry, Michael Kwok, Richard Lawson, Alexis Lee, Jing-Yu Li, Ronald Li, Zhao-Fan Li, Peng Liu, Man-Kit Luk, Andrew Luong, John McArthur, Rory McGowan, Hamish Nevile, Jack Pappin, Steve Peet, Dan Pook, Chas Pope, Andrew Smith, Stuart Smith, Alex To, Felix Tong, Paul Tonkin, Ben Urick, Bai-Qian Wan, Yang Wang, Yi-Hua Wang, Will Whitby, Robin Wilkinson, Michelle Wong, Stella Wong, Eric Wu, Lucy Xu, Angela Yeung, Terence Yip, George Zhao (geotechnical, structural) **Main contractor:** China State Construction Engineering Corporation **Steelwork contractors:** Grand Tower; Jiangsu Huning Steel **Construction logistics:** Turner Construction **Building movement monitor:** China Academy of Building Research **Presetting analyst:** Tsinghua University **Independent site supervisor:** Yuanda International **Illustrations:** 1, 2, 25 OMA; 3, 6, 10, 17 Nigel Whale; 4, 12, 14, 16, 19, 23, 27, 29 Chas Pope; 5, 8, 18 Arup; 7, 9, 11, 13, 15, 20 Rory McGowan; 21 CSCEC; 22, 24, 26, 28 ©Arup/Frank P Palmer.

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29. The scale of the completed structure is emphasised by the quantity of site works that were still in progress around its base in August 2008.

The European Extremely Large Telescope enclosure design

Davar Abi-Zadeh Philip Bogan Jac Cross John Lyle
Pieter Moerland Hugo Mulder Roland Trim

Introduction

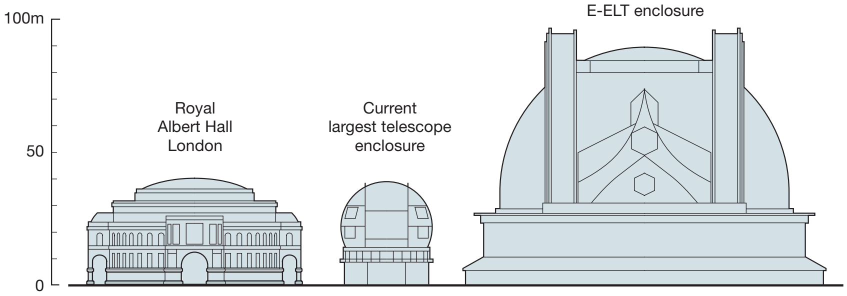
Modern astrophysics is tackling some fundamental questions. What was the origin of our universe? What will be its fate? Are we alone in the universe?

An important component in world-wide astrophysics strategy is the deployment of huge ground-based optical-infrared telescopes[1]. In the last quarter-century there has been a resurgence in large terrestrial telescopes, driven by the development of computer-controlled adaptive lenses that reduce the atmospheric distortion normally associated with ground-based telescopes. This technology, when applied to so-called Extremely Large Telescopes (ELTs), will vastly further astrophysical knowledge, allowing detailed studies of planets around other stars, the physical evidence of the earliest history of the universe, super-massive black holes, and the nature and distribution of the dark matter and dark energy that seem to dominate the universe.

Several ELT projects are currently being pursued around the world, including the Giant Magellan Telescope[2] and the Thirty Meter Telescope in North America[3]. Development of the European ELT (E-ELT) is being led by the European Southern Observatory (ESO). With a 42m diameter primary mirror, adaptive optics, and a large capacity for powerful post-focal instruments, the E-ELT (Fig 2) will offer image quality that is quite literally incredible - around 100 times better than that from the Hubble Space Telescope.

Arup was commissioned by ESO to develop a preliminary design for the E-ELT enclosure, the structure that houses the telescope (Fig 1). Drawing together a multidisciplinary team, Arup took advantage of its wide experience to develop innovative solutions to some of the unusual demands of the brief. These included a nesting door arrangement - unique among telescope enclosures and inspired by work on movable stadium roofs - and a novel design of crane.

> **“A telescope of this size could not be built without a complete rethinking of the way we make telescopes.”**
>
> Catherine Cesarsky, former Director General of ESO.



1. Relative size of E-ELT enclosure.

ESO

ESO is the pre-eminent intergovernmental science and technology organisation in astronomy. It is funded by 13 European countries and has a remit to build and operate large astronomy facilities for use by European scientists.

Existing facilities include several telescopes around the 3.5m diameter range and the unprecedented array of four Very Large Telescopes in Paranal, Chile.

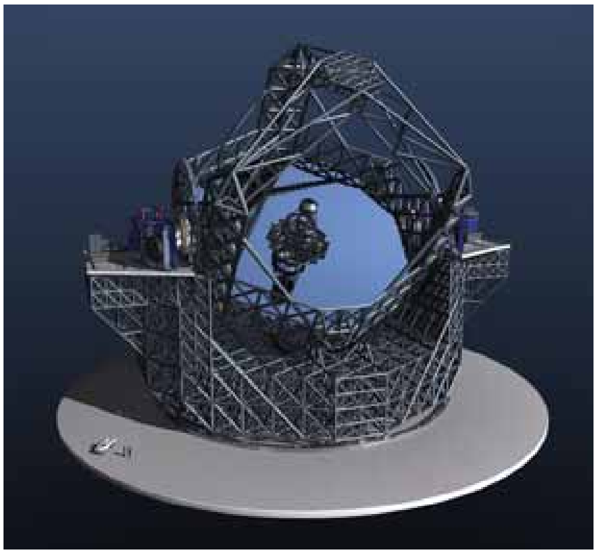
As well as the E-ELT project, ESO, in collaboration with North America, East Asia and Chile, is constructing an array of 66 antennae in the Atacama Desert, Chile for observation at sub-millimetre wavelengths.

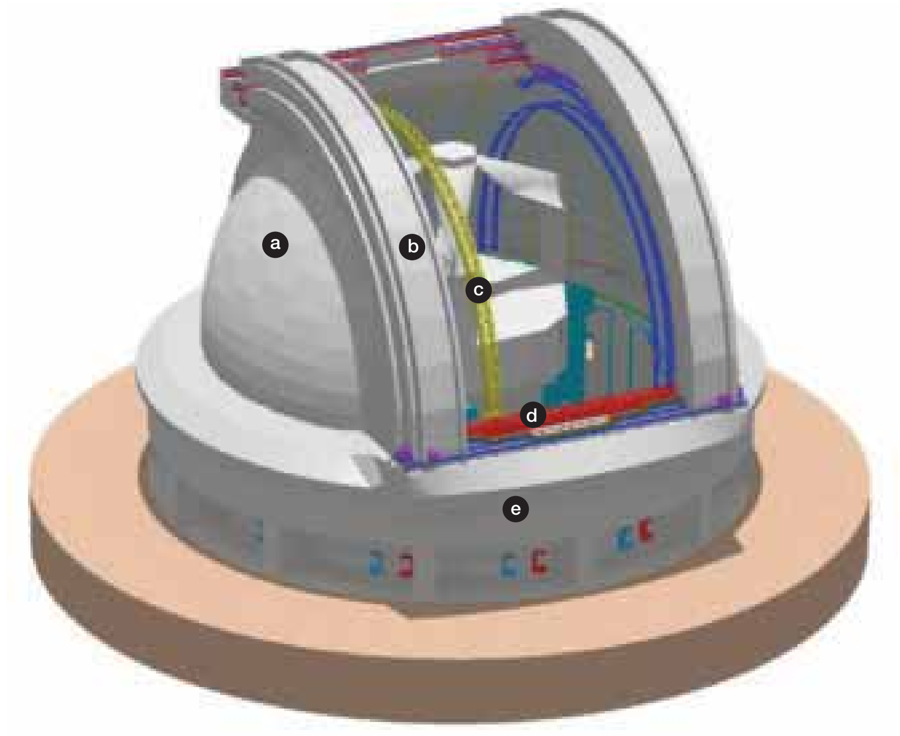
Purpose of the enclosure

The world’s best sites for astronomical observations are at high altitudes (typically 2500-3000m above sea level), where the effects of atmospheric distortion are lower. As well as being difficult of access for construction, however, such sites form a harsh environment for telescopes, which therefore need to be protected by enclosures when not in use.

During the day the enclosure is closed and sealed in order to protect the telescope as much as possible from dirt and dust, the levels of which are far higher during the day than at night. This reduces the required frequency of cleaning the telescope mirrors, an expensive and time-consuming operation. The enclosure also closes to protect the telescope from adverse weather, like high winds or snow.

2. Artist’s impression of the E-ELT. The telescope itself and its mount structure do not form part of Arup’s design study.





3. Enclosure overview showing: (a) dome, (b) doors, (c) crane, (d) windshield, (e) concrete substructure.

4. Starfield in the central bulge of our galaxy, some 26 000 light years distant, photographed in 2006 by the Hubble Space Telescope. In this survey, called the Sagittarius Window Eclipsing Extrasolar Planet Search (SWEEPS), Hubble discovered 16 extra-solar planets by detecting the slight dimming of stars as the (Jupiter-sized) planets pass in front of them. The resolution of the E-ELT will be such that it will be able to observe such planets *directly.*

In addition to its protective function, the enclosure facilitates telescope maintenance. It provides access, and contains handling facilities for instruments, mirror segments, and other telescope components.

At night the enclosure must open to allow the telescope a clear view of the sky. In addition, it must minimise as much as possible image distortion, of which there are two main sources relevant to the enclosure. “Enclosure seeing” refers primarily to the distortion of the image due to thermal effects that affect the refractive index of air (an extreme version of this is the heat haze seen above roads on a hot day). If the enclosure releases significant heat into the air during observations, the warmed air may pass across the telescope’s line of sight causing image distortion. One approach to this problem is to completely remove the enclosure - for example roll it downwind of the telescope during observations - but that does not address the second role of the enclosure at night.

The image can suffer from telescope vibration due to wind buffeting, and so to enable its use in a greater range of conditions, on what are typically quite windy sites, the enclosure is used as a wind break to protect the telescope when winds are relatively strong.

Overview of the enclosure

The primary mirror of the E-ELT is supported in a steel frame that can be rotated about a horizontal axis, referred to as the “altitude axis”. This frame is in turn supported in a second steel structure, which can be rotated about the vertical axis, or “azimuth axis”. These two degrees of freedom allow the telescope to be pointed anywhere in the sky, typically 30° above the horizon.

Arup’s design for the E-ELT enclosure (Fig 3) comprises a steel-framed dome with a viewing slot covered by a set of arched doors that move on straight, horizontal tracks at the top and bottom of the slot and nest together in the open position. The dome is mounted on wheeled bogies running on circular tracks fixed on a concrete substructure. This enables the dome to rotate independently to the telescope structure about the azimuth axis, and helps minimise vibrations when the telescope tracks stars or planets. The dome rotation is usually carried out periodically through the night.

The enclosure houses a deployable windshield, which can partly cover the slot to protect the telescope during observations in high winds, and an arched, gantry crane and lifting platform for equipment handling. The enclosure is also clad with insulating panels, making it air, light and watertight, and is actively cooled during the day to maintain night-time temperatures inside, to minimise “enclosure seeing”.

Dome and doors

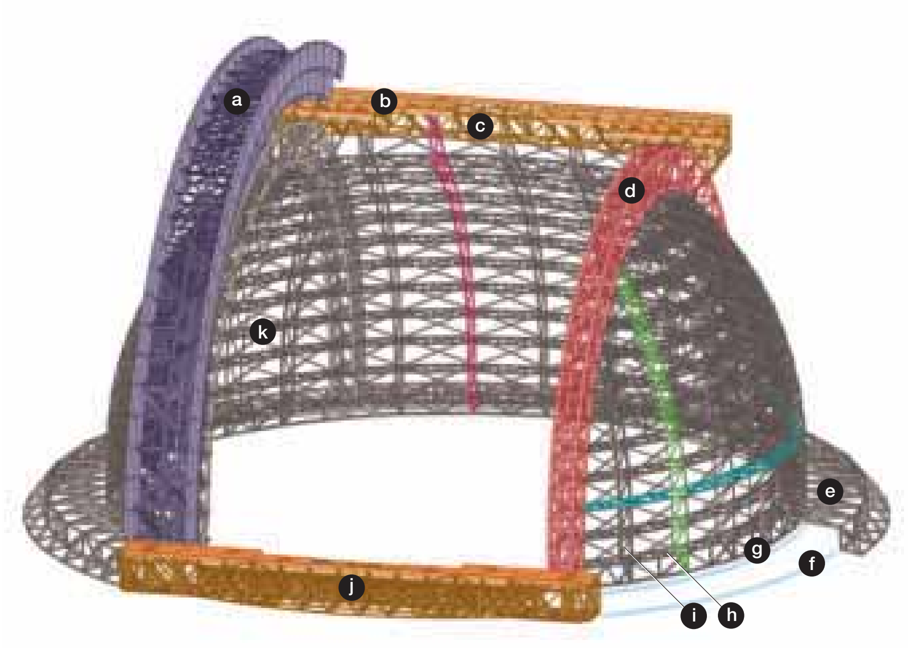
The dome is a hemispherical steel structure some 90m in diameter with a 45m-wide viewing slot running from the base of the dome to about 22.5m past the zenith (Fig 5).

Two rectangular box trusses form main arches that run along both sides of the viewing slot and span from the front to the back of the dome. Although the structure looks like a dome (and is referred to thus), its structural behaviour is rather different, due to the large relative size of the viewing slot. The dome sides behave structurally as shells, which under gravity "lean" towards the centre. This effect is countered partly by the lateral stiffness of the main trusses and partly by the shell behaviour of the sides, both resulting in large support reactions under the main arches.

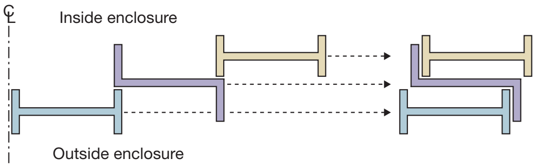
At the sides of the dome, vertical radial trusses extend from the circular track to the main arches at regular intervals. At the rear, between the main arches, vertical trusses with equal horizontal spacing run from the circular track to the viewing slot's back edge, which is formed by the support structure for the upper tracks of the doors. The lower tracks of the doors are supported at the front edge of the viewing slot. This structure spans between bogies on the main circular track and a second concentric track, which has a radius some 10m larger. This second track is needed to carry the load of the doors which, when open, sit outside the main circular track by approximately 10m radial distance. Without the second track, the doors would have to be supported on some form of structure cantilevered from the main track, which would drastically increase the size of the lower track support structure and the loading on the bogies beneath it.

Horizontal trusses supporting walkways along the inside of the dome run around the structure and stop at the sides of the viewing slot. The frame formed by the horizontal and vertical elements is braced with diagonal members.

The arches together with the radials generate a radial thrust load which is taken by the bogies and in turn by the concrete base structure. The vertical and horizontal reactions at the tops of the doors are carried by the top track support structure and distributed to the bogies through the main arches and the vertical trusses at the back of the enclosure. At the bottom of the doors, the vertical reactions are taken by the front track support structure and distributed primarily into the outer circular track. Horizontal reactions at the bottom of the doors are carried to the main circular track further inwards. Because the doors act as an arch, their thrust loads increase the total horizontal reactions of the dome significantly.



5. Dome structure showing: (a) shutter panels, (b) panel tracks, (c) top track support, (d) main arch, (e) track cover, (f) offset track, (g) main track, (h) horizontal truss, (i) radial vertical truss, (j) front track support, (k) vertical truss back.



6. Section through nesting door arrangement in the open and closed position.

Six door panels, three on each side of the viewing slot, close the enclosure during daytime and in poor weather conditions. Each ca.8m wide panel spans from the front to the back edge of the viewing slot, running on horizontal tracks to allow it to move sideways. The shapes of these panels allow them to be packaged as close to the dome structure as possible. The pair with the largest span, and most distant from the dome, are central in the closed position. In horizontal cross-section, these are H-shaped. From the centre outwards, the next pair are Z-shaped, whilst the outermost – those that travel the shortest distance – are also H-shaped, allowing all six to nest when in the open position (Fig 6).

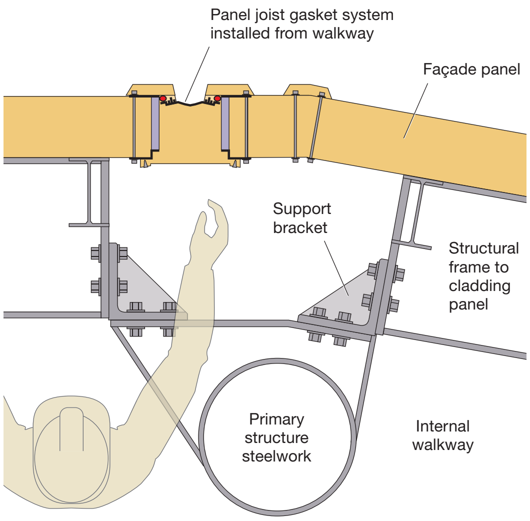
The design of the nesting arrangement of the doors draws on Arup's experience of stadium roof design[4], achieving a more economic solution than would have been possible by simply scaling up existing telescope doors.

The panels' structure consists of two deep plate sections on either side, and standard rolled steel sections to couple the plate sections and support the cladding. As previously noted, the panels arch between their supports so that both the vertical and the horizontal loads must be accommodated at the supports.

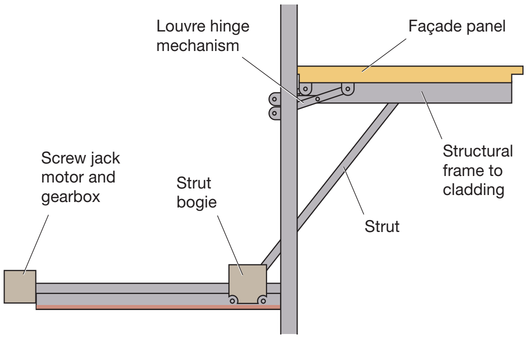
Façade

The façade panels must insulate the enclosure, allowing the temperature of the structures inside to be controlled so that when the enclosure is opened for viewing, heat release and consequent image distortion are minimised. The 150mm thick composite panels comprise a steel inner skin, insulating core material, and an aluminium outer skin. The latter is a client requirement; aluminium has suitable absorptivity and emissivity properties that reduce solar gain during the day and avoid excessive cooling of the façade at night by radiation to the sky.

The bays formed by the dome structure are all planar, so that flat façade panels can be used throughout. Each façade panel edge abuts those of its neighbours to create a sealed enclosure. Due to the scale of the enclosure and the exposed nature of the site, the composite panels would be assembled on site, at ground level, into larger, bay-sized façade panels, supported on a steel frame. The largest size of prefabricated façade panel would be approximately 10m x 4m.

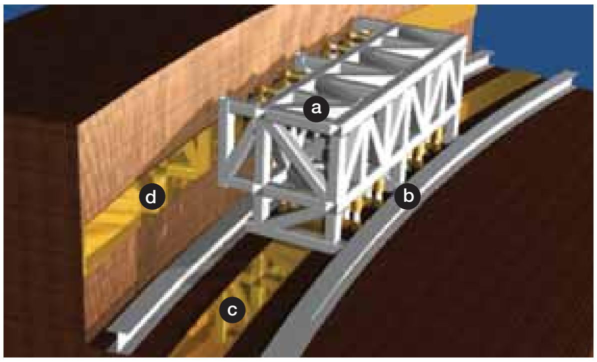


7. Typical panel joint.

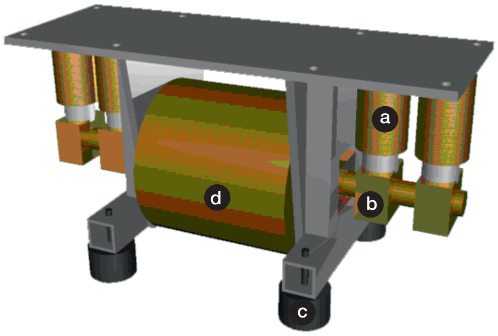


8. Ventilation louvres.

9. Typical enclosure support bogie showing: (a) bogie frame, (b) anti-uplift rail, (c) track for vertical loads, (d) track for lateral loads.



10. Roller module: (a) hydraulic jacks, (b) guided axle bearing, (c) guide rollers, (d) roller.



The panels at the sides of the enclosure are set out to a radial grid, which allows for repetition in their construction; apart from where they intersect with the main arches, horizontal panels will be similar to each other. This repetition will make the façade system easier to construct and simpler to install, with obvious cost benefits.

To allow the pre-assembled façade panels to be lifted more easily and in a wider range of wind conditions, Arup proposed a system of rails on the enclosure, to allow the large panels to be guided into position. This combination of ground level prefabrication and guidance system allows the façade to be installed in less time.

The prefabricated panels can be sealed together from the internal walkways of the enclosure using an EPDM (ethylene propylene diene monomer rubber) gasket. The panels cantilever beyond the primary structure, providing easy access to their joints (Fig 7).

The façade is perforated by about 100 opening louvres, each approximately 2m x 4m and independently actuated by a screw-jack to enable optimisation of the enclosure's ventilation at night (Fig 8). This is needed to ensure that the temperature of the telescope and enclosure structures tracks the ambient air temperature throughout the night, to reduce "enclosure seeing".

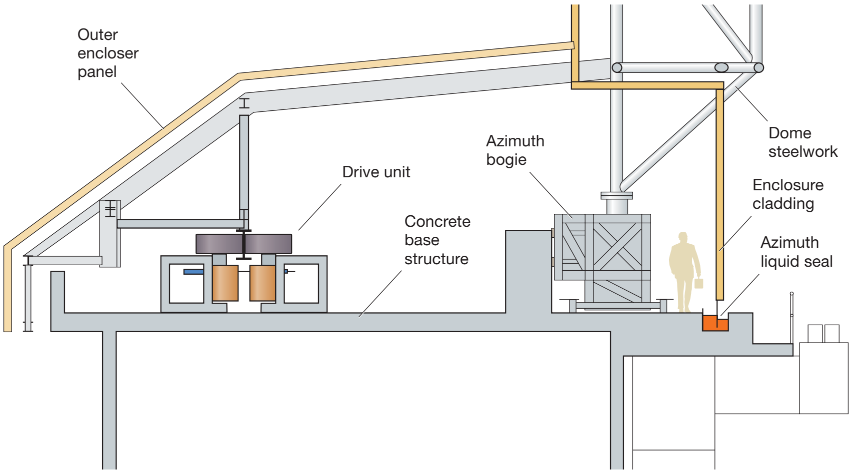
Azimuth mechanisms

Several drive units rotate the dome on its tracked wheeled bogies about the azimuth axis (Fig 9). The steel bogie frames distribute loads from the dome through a passive hydraulic system to up to eight steel rollers, four to carry vertical loads and four to carry thrust loads (Fig 10). The hydraulic system ensures even distribution of load between the rollers, and allows the reaction at each bogie location to be measured using a pressure transducer. The bogies are fitted with uplift protection to prevent them lifting significantly under extreme seismic or wind loading.

The space between the inner and outer circular tracks is covered with a skirt. The outer edge of this skirt is supported at regular intervals by a single roller module fixed directly to the skirt structure without any hydraulic load spreading (Fig 11).

The dome is driven about the azimuth axis by 48 drive units equally spaced in the area between the inner and outer circular tracks. The units are fixed to the concrete base structure and engage with a driving surface on the dome structure (Fig 12). Each unit consists of two sub-modules of a tyred wheel, driven by an electric motor mounted on a steel chassis connected to the concrete base structure by brass-lined sliders oriented to allow the chassis to move freely in the radial direction. The two sub-modules are clamped together by spring units so that in turn the tyres clamp the drive bar between them. The drive units are clustered in groups of four, and serviced by a power conditioning station supplied with electricity and cooling fluid to dissipate the heat generated during deceleration of the dome.

11. Section through azimuth drive and support zone at the perimeter.



The drive tyres are standard heavy truck tyres with an operational normal contact force of 40kN and a coefficient of friction at low speed of at least 0.25 in low temperatures without visible ice, and 0.6 on dry track at 20°C.

The telescope enclosure position will be read from an encoder mounted on the drive bar to return the aggregate position to within 0.5mm accuracy (+/- 0.0006°). The position will be confirmed by a further system of magnets fixed to the drive bar at 5m intervals, read by reed switches (electrical switches operated by an applied magnetic field).

The drive units are torque controlled, with an encoder on each axle to ensure that the wheels do not slip; the control system uses traction control algorithms to maximise traction and braking forces. The control system will operate the enclosure position to within +/-50mm for compatibility with viewing requirements.

The telescope enclosure and door structure is designed to withstand the ultimate loading conditions without the extra restraint of locking pins. Adding these could induce local loading into the structure and require the enclosure to stop precisely to enable the locking pins to be inserted. Instead of locking pins the enclosure utilises brake units that engage with the web of the drive bar. The clamp will only provide restraint in the direction of the drive bar.

Door mechanisms

A compact recirculating roller bearing system was chosen for the mechanisms that support the door panels at the top and bottom and allow them to be opened and closed along their straight horizontal tracks (Fig 13). This bearing is a commercially available product typically used for moving heavy structures. For the configuration in the chosen design, the supports could generate a drag load of up to approximately 5% of the support reactions during initial operations. This drag load reduces during the operational life of the door tracks and decreases the amount of power needed to open the doors.

Before opening the panels in snow or ice conditions, exposed tracks may require de-icing, either manually or through trace heating, to prevent additional load on the drive system. If trace heating is used the track sections outside the enclosure when it is closed would need to be heated.

As the door panels are tied arches, irregularities in the track could induce extra forces in the arch structure and supports. These loads were evaluated by performing a parametric analysis on the support conditions using Arup's GSA program, including altering connection stiffness and applying enforced displacements on the structure.

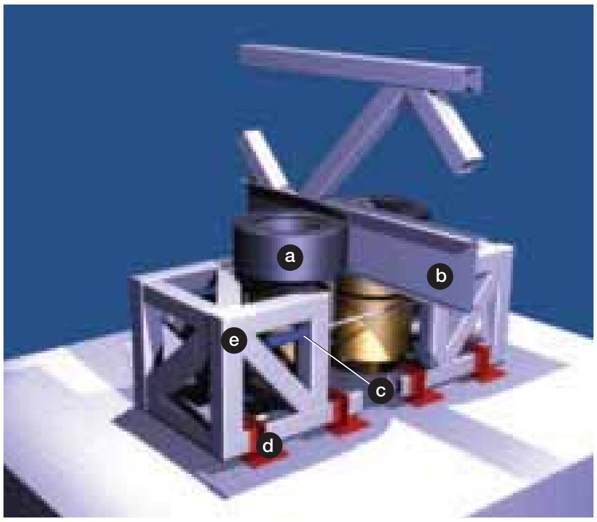
The drive mechanism for the doors has to overcome friction, wind loading, any residual ice and snow, and any sticking effects of seals – forces which combined indicate that the use of a simple rack-and-pinion drive would be beneficial. These drives will be located at the top and bottom of the door panels, so that each panel is driven from both ends simultaneously. 10m lengths of standard rack are bolted to a steel H-section, which is connected to the door track support structure. The rack is engaged by a pair of pinion drives, mounted on the door panel, which can generate up to 280kN thrust from a three-phase 45kW fan-cooled motor. Each door panel is supplied with power via a 70KW umbilical at the top and bottom locations.

The door panel locking mechanisms use a similar device to those used to hold the telescope enclosure against azimuth rotation. Each door panel requires a brake unit that can develop 500kN braking force at the top and bottom of the panel. Application of this lock will be carefully controlled by control systems so that the doors can be accurately parked. This is important for adequate sealing of them.

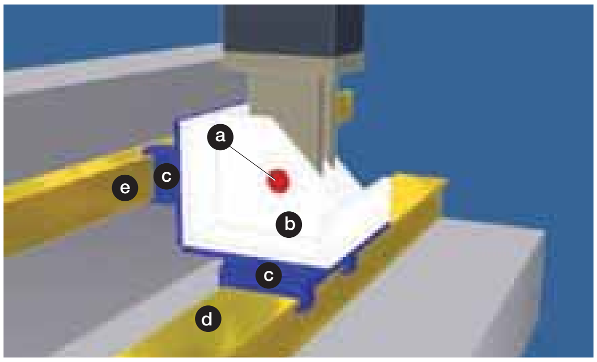
The base structure

The structure of the enclosure base follows from both the task of carrying the loads from the enclosure dome, and from some functionality requirements in the client's specification.

Vertical loadings from the steel enclosure are directly supported by an inner ring wall some 22m high above ground and extending 5m below ground. This is stabilised by 12 radial walls of the same vertical dimensions and radial width of around 10m.



12. Drive unit showing: (a) tyres, (b) drive bar, (c) spring unit, (d) sliding connectors, (e) drive chassis.



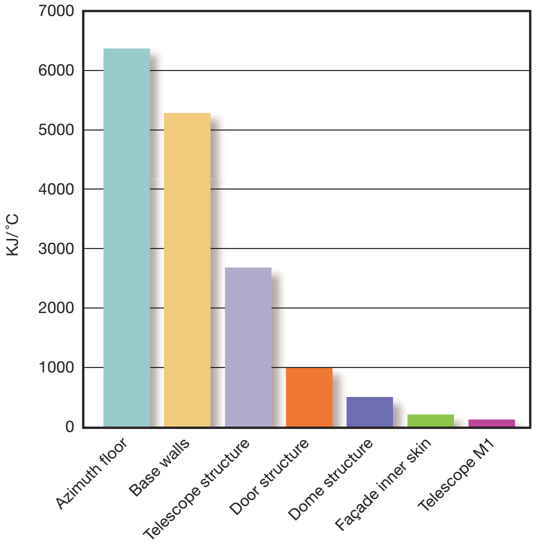
13. Door support bogie showing: (a) structural pin, (b) steel transfer structure, (c) re-circulating bearing, (d) track for vertical loads, (e) track for thrust loads.

Lateral loadings from the dome are transferred through a top slab into the inner ring wall and into the radial walls. The top slab is supported by a 10m deep beam, underneath the outer track, which also carries the vertical loads from the bogies under the door track support truss. Vertical and lateral loading from the structural elements is transferred into the ground by a bottom slab. Perpendicular ribs are added so as to reduce the sensitivity to buckling of the free outer edge of the radial wall.

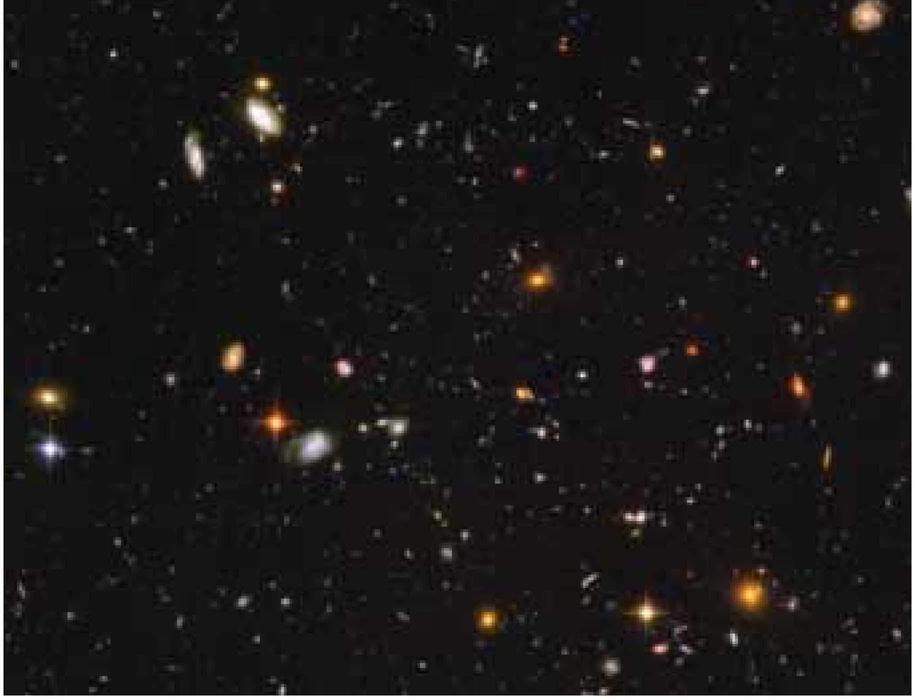
Thermal control

To minimise night-time release of heat into the air passing across the telescope's line of sight with resulting deterioration of image quality, the enclosure interior is actively cooled during the day. The aim is to maintain the temperature of the telescope and surrounding internal structures at the following night's predicted external temperature.

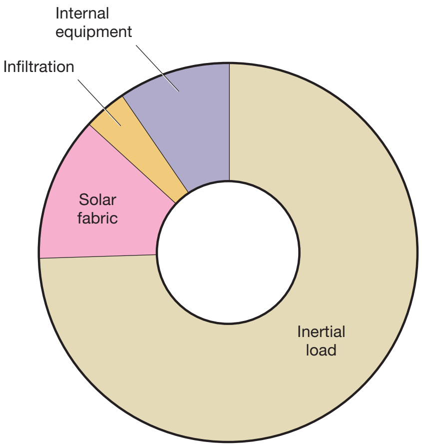
Variations in the temperature of air passing across the telescope around the enclosure can change the density and refractive index of the air, giving rise to optical distortions. If this occurs within the telescope's line of sight the effect can be detrimental to the quality of its seeing.



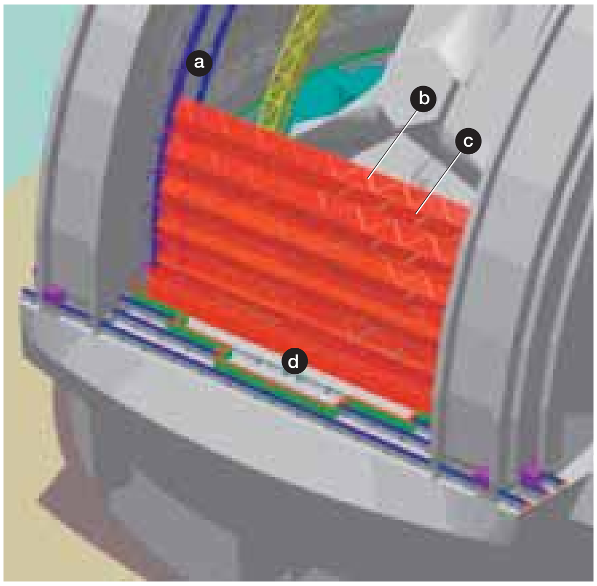
14. Thermal inertia of main enclosure systems.



17. E-ELT's resolution will enable it to "see" even further back into the early history of the universe than Hubble's most distant images, eg these galaxies only about 1bn years after the Big Bang.



15. Proportion of cooling load from different sources.



16. Windshield showing: (a) tracks on main arches, (b) hinged plane trusses, (c) fabric infill panels, (d) windshield retracting to space below telescopic sightline.

ESO's main design requirement for the cooling system required the temperature of all internal structures to be within 1°C of the external night-time temperature for a temperature difference between the inside and outside of the enclosure of 10°C. A secondary design requirement related to the advent of a cold weather front, ie the internal structures needed to be cooled to within 1°C of external temperature when it dropped by 10°C between the end of one night and the start of the next night.

The cooling system was therefore sized to remove heat from the following sources:

- solar gain of the enclosure
- warm air infiltrating the enclosure
- internal sources, eg motors, lights and people
- outside air deliberately introduced into the enclosure to provide a positive pressure in the enclosure volume
- thermal inertia of structures in the enclosure, eg telescope structure and enclosure steelwork (Fig 14).

Where possible, the large thermal masses in the enclosure are rendered inactive – by insulating the enclosure doors, the concrete walls, and floor. The telescope itself, being outside Arup's remit, is not insulated.

The total cooling load of 1405kW (Fig 15) gives a requirement for a volume flow rate of 290-320m³/sec, depending on the site altitude.

Air is supplied to the enclosure by 10 air-handling units through a series of three concentric ring ducts at the top and midway up the enclosure wall, and around the base of the telescope. These supply air to many nozzle units which jet cooled air over the telescope and the enclosure surfaces. Nozzles are used because they can supply cool air to the enclosure dome without the need to pass cooled air through ducts across the moving boundary between the dome and the enclosure base structure.

The windshield

During observations, the viewing slot can be partially covered by a deployable windshield (Fig 16) to protect the telescope from wind buffeting, which degrades the image. The windshield is a concertina, formed from a series of hinged plane trusses infilled with fabric to block the wind. These trusses are supported on yet another set of wheeled bogies, running on tracks fixed to the main arch.

When required, the windshield is lifted by cables running over the main arches to winches at the rear of the dome. When not in use, it folds below the telescope view into a space just inside the doors at the front of the dome. The windshield height can be adjusted when necessary throughout the night to provide maximum protection to the telescope without impinging on its view.

The handling facilities

The enclosure requires handling facilities for maintenance tasks, provided by an overhead crane and a lifting platform. The 20 tonne SWL (safe working load) crane will be used primarily for swapping out primary mirror segments for cleaning, but also to handle instruments around the secondary mirror and in the mast structure at the centre of the telescope.

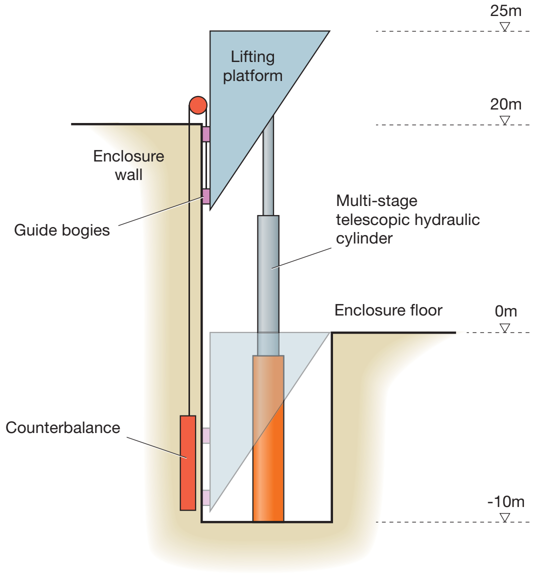
The crane is of a novel arched gantry design (Fig 18) which, combined with a lifting range of 70m, allows loads to be hoisted from the azimuth floor and carried clear over the telescope working volume. When in use, the crane moves across the viewing slot on straight, level rails on the door track support structures, giving immediate access to much of the enclosure volume. By rotating the dome, on which the crane is mounted, the remaining enclosure volume can be accessed. During observations the crane parks against a main arch, out of view of the telescope.

The 30 tonne SWL lifting platform (Fig 19) will be used to lift instruments from the azimuth floor to the 25m high Nasmyth platforms at the side of the primary mirror. As is characteristic of the Nasmyth type of reflecting telescope, the light beam is directed along the altitude axis into these instruments.

The lifting platform is horizontally constrained by bogies running on a pair of vertical rails fixed to the enclosure wall, and also counterbalanced with the additional lifting force provided by a pair of multi-stage, telescoping hydraulic actuators. When not in use the platform retracts level with the azimuth floor, the platform structure and actuators being accommodated in a 10m deep pit beneath.

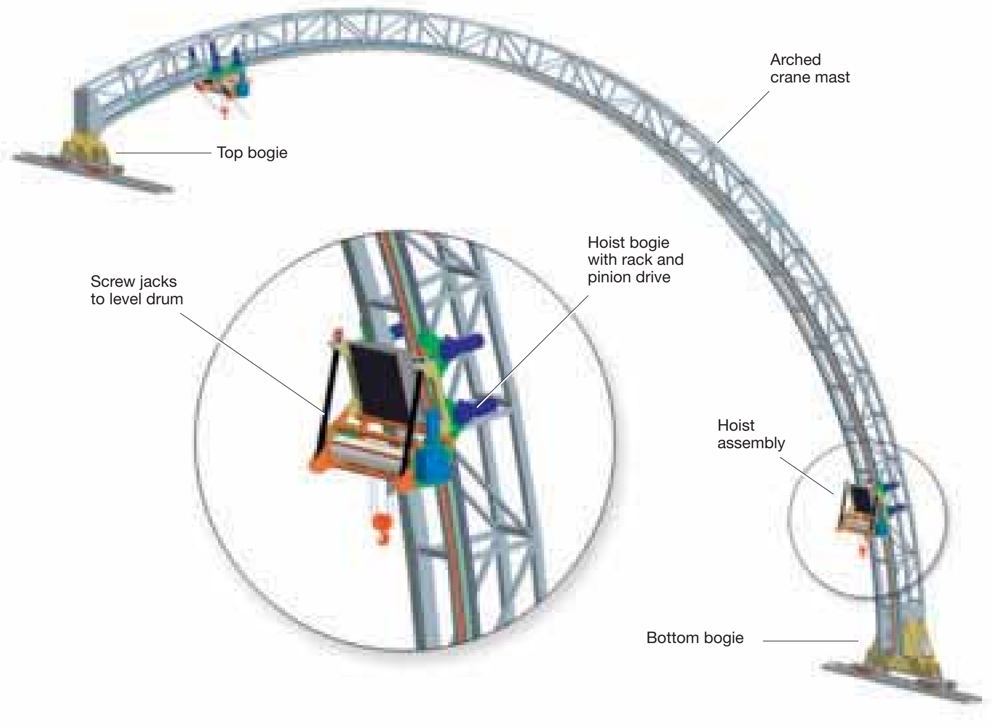
The next steps

Arup's work formed part of the detailed design phase of the E-ELT, which began in December 2006 with the approval of the € 57m, three-year programme, and is ongoing with a further design iteration before tender. This will pave the way for beginning construction of the facility in 2010, provided that the necessary funding is secured. The target is for the E-ELT to be operational around 2017.



19. Lifting platform schematic.

18. Novel arched crane design.



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(4) CHAN, J, *et al*. Miller Park. *The Arup Journal*, *37*(1), pp24-33, 1/2002.

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Roland Trim is a senior engineer with Arup's Advanced Technology London Group. He designed the E-ELT enclosure's azimuth rotation mechanisms and door opening mechanisms.

Credits

Client: European Organisation for Astronomical Research in the Southern Hemisphere (ESO) **Architecture, SMEP, mechanisation, wind, control systems, and façade engineering, lighting and cost consulting:** Arup - Davar Abi-Zadeh, Pavlina Akritas, Andrew Allsop, Dan Bergsagel, Phil Brogan, Mike Clifton, Jac Cross, Graham Dodd, Christina Fell, Chris Fulford, Tony Greenfield, David Griffiths, Chris Harvey, Florence Lam, John Lyle, Daniel Meiner, Pieter Moerland, Strachan Mitchell, Hugo Mulder, Ender Ozkan, Dipesh Patel, Adam Pearce, Roland Trim, Felix Weber **Crane design:** Arup *and* SCX Ltd **Lifting platform design:** Arup *and* Weir Strachan & Henshaw **Illustrations:** 1, 6-8, 11, 14, 15, 19 Nigel Whale; 2 ©ESO; 3, 5, 9, 10, 12, 13, 16 Arup; 4 NASA, ESA and K Sahu (STScI); 17 NASA, ESA and N Pirzkal (STScI/ESA); 18 Daniel Pickard ©SCX Ltd; 20 Chris Fulford.

20. Graphical rendering of the E-ELT enclosure at site.

About Arup

Arup is a global organisation of designers, engineers, planners, and business consultants, founded in 1946 by Sir Ove Arup (1895-1988). It has a constantly evolving skills base, and works with local and international clients around the world.

Arup is owned by Trusts established for the benefit of its staff and for charitable purposes, with no external shareholders. This ownership structure, together with the core values set down by Sir Ove Arup, are fundamental to the way the firm is organised and operates.

Independence enables Arup to:

- shape its own direction and take a long-term view, unhampered by short-term pressures from external shareholders
- distribute its profits through reinvestment in learning, research and development, to staff through a global profit-sharing scheme, and by donation to charitable organisations.

Arup's core values drive a strong culture of sharing and collaboration.

All this results in:

- a dynamic working environment that inspires creativity and innovation
- a commitment to the environment and the communities where we work that defines our approach to work, to clients and collaborators, and to our own members
- robust professional and personal networks that are reinforced by positive policies on equality, fairness, staff mobility, and knowledge sharing
- the ability to grow organically by attracting and retaining the best and brightest individuals from around the world - and from a broad range of cultures - who share those core values and beliefs in social usefulness, sustainable development, and excellence in the quality of our work.

With this combination of global reach and a collaborative approach that is values-driven, Arup is uniquely positioned to fulfil its aim to shape a better world.

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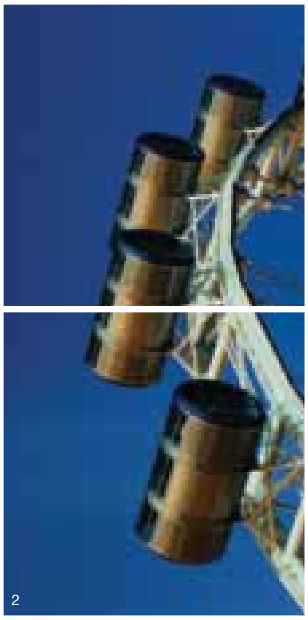

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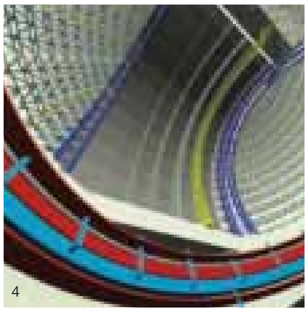

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Illustrations: 1. Plan view of a twisted building created using the parametric software *Generative Components*: Matt Clark, John Legge-Wilkinson and Stuart Bull; 2. Pods on the *Singapore Flyer*: Singapore Flyer Pte Ltd; 3. *Designer's Toolkit 2020*: Hemantraval/Dreamstime.com; 4. Viewing slot of the European Extremely Large Telescope enclosure: Arup; 5. Cab of new air traffic control tower, Heathrow Airport: Fleyeing/Dreamstime.com; 6. Installation of brace element, CCTV headquarters, Beijing: Chas Pope.

Front cover: The view towards the centre of Singapore from the top of the *Singapore Flyer*: Singapore Flyer Pte Ltd.

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The Arup Journal Vol.43 No.2 (2/2008)
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