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Front cover: Detail of BIQ House at IBA, Hamburg — the world's first bio-responsive façade.

This page: Rear façade of the refurbished Rijksmuseum in Amsterdam.

Revitalising Amsterdam's museums:

an introduction

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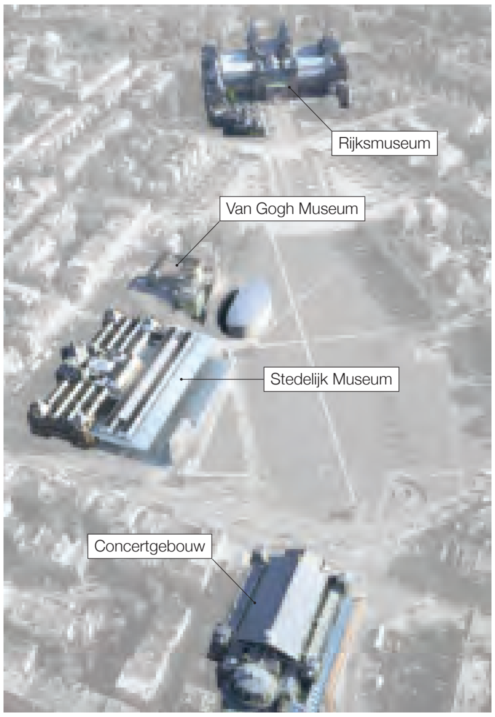

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1. The Museumplein in Amsterdam.

2–3. Aerial image of Museumplein showing relative positions of the Rijksmuseum and Stedelijk Museum.

Author
Joop Paul

Introduction

In the 23 years since 1990, The Netherlands has invested some €1.5bn in over 40 museums. Around half of this budget has been spent in the city of Amsterdam, with about €500M of that for two museums of international importance. These are the Rijksmuseum, celebrated for its Golden Age art collection, and the Stedelijk Museum, which houses the city's leading collection of contemporary art. The Rijksmuseum was closed in 2003 and the Stedelijk in 2004 for renovations and significant extensions, and both have now been reopened by Queen Beatrix: the Stedelijk in autumn 2012 and the Rijksmuseum following in spring 2013.

These extensive restorations — together with the 2007–2011 renovation of the Scheepvaartmuseum (the National Maritime Museum, focusing on Dutch nautical history), the opening in 2009 of the Hermitage Amsterdam (a branch of the St Petersburg Hermitage, focusing unsurprisingly on Russian art) and the 2012 opening, also by Queen Beatrix, of the new EYE Film Institute Netherlands — have enabled Amsterdam to regain its status as an international cultural destination alongside its other well-known attractions to both inhabitants and tourists.

The area

Amsterdam's Museumplein (Museum Square) is situated immediately south-west of the outermost canal forming the perimeter to the city's historic centre, the unique concentric semi-circular rings of streets and canals built on reclaimed land in the 17th century (Fig 1).

Until the second half of the 19th century only a handful of peasants' houses were situated where the museums now stand, but with the presence here of the 1883 International Colonial and Export Exhibition, the city governance allocated this area to be a new art and culture zone for Amsterdam. To underline this goal the streets were named after famous painters. Nowadays the main cultural institutions sited on the Museumplein are the Rijksmuseum, the Stedelijk Museum, the Van Gogh Museum (1973) and the Concertgebouw (Concert Hall, 1881) (Figs 2–3).

The Rijksmuseum

Designed by the long-lived and prolific Dutch architect Pierre Cuypers (1827-1921), the Rijksmuseum was opened in 1885 as the home of the country's national museum. The collection initially comprised collections from the Dutch regents and objects from state institutions, but was soon extended to include paintings and illustrations of the City of Amsterdam. Due the ever-growing collection and changing visions for its overall concept and direction, the Rijksmuseum was renovated several times over the years. Between 1904 and 1916, new galleries to the south-west of the main building were added — today known as the Philips Wing — and later used to accommodate and exhibit the collection of 19th century paintings and drawings donated by Mr & Mrs Drucker Fraser. Between 1950 and 1960 the original patios were changed into galleries, creating even more space.

The latest renovation, based on the designs of Cruz y Ortiz, has reinstated the building's original layout. The built-in galleries in the atria have been demolished, so that the atria now offer copious daylighting and a sense of space. Paintings, craftsmanship and history are no longer separated, but show in one chronological circuit an integrated account of Dutch art and history. A new pavilion has been added, also designed by Cruz y Ortiz, to display the Asian collection.

The museum has been modernised in many ways, but at the same time Cuypers' original architectural details have been brought back, illustrating the Rijksmuseum's new adage: "Continue with Cuypers". The Rijksmuseum is now a fitting attraction for 21st century visitors, the numbers of whom have far exceeded expectations. The museum welcomed 500 000 visitors in the first two months after reopening, compared with the 2M per year expected.

Stedelijk Museum

The Stedelijk Museum was founded toward the end of the 19th century, initiated by several committed and well-to-do citizens to meet their desire to promote and exhibit contemporary art. The original building, designed by Adriaan Willem Weissman, was opened in 1895.

The original building underwent various phases of modernisation, and from 1945 to 1954 its total usable space was extended by the insertion of intermediate storeys (entresols). In 1954 the Sandberg wing (named after the then director) was added alongside, but this has subsequently made way for the new extension (nicknamed the "Bathtub"), the design for which was presented in 2004 by Benthem Crouwel Architects. Their plan also included an extensive renovation of the Weissman building, in which various 20th century modifications like the entresols were removed and the building restored to the original state. As with the Rijksmuseum, there have been more visitors than expected. In the first six months after reopening the Stedelijk was visited by 500 000 people, whereas 800 000 per year were expected.

Transforming the square

With these transformations of the Rijksmuseum, the Stedelijk Museum and soon the neighbouring Van Gogh Museum, the Museumplein has gained another dimension, as the main entrances of all the buildings now point towards the square. It is the city's focus for all kinds of cultural and social events — for example the annual Queen's Day, sometimes described as the "world's biggest street party" (to become King's Day in 2014 following the abdication of Queen Beatrix and the accession of King Willem-Alexander), and the Uitmarkt, the annual opening of Amsterdam's cultural season at the end of August.

Catalyst for Arup in Amsterdam

Both projects have not only helped to transform the city, but have also been a further catalyst for the growth of the young Arup office in Amsterdam, following earlier key projects like the Amsterdam Public Library and the Nescio Bridge. These important museums have led to a growing reputation and portfolio for the firm in the world of Dutch arts and culture, to which Arup is proud to contribute.

Author
Joop Paul is a Director of Arup, and a member of its Europe Board. He was Project Director for the redevelopments of both the Rijksmuseum and the Stedelijk Museum.

Image credits
1 *Nigel Whale*; 2–3 *Benthem Crouwel.*

Refurbishing the Rijksmuseum

Location
Amsterdam, The Netherlands

Authors
Karsten Jurkait Siegrid Siderius

1.

Introduction
For generations every Dutch child has been taken at least once in its life to the Rijksmuseum. For Amsterdam tourists a visit is an obligatory item in the itinerary, to marvel at Rembrandt's *The Night Watch* and other masterpieces of the Dutch Golden Age (Fig 1). In addition, the museum houses a vast collection of Dutch and Colonial art from the 15th to the 20th centuries — from paintings and Delft chinaware to dollhouses, ship models, armour, furniture and garments — visited by over a million visitors per year.

The building itself is also a work of art, purpose-designed by Pierre Cuypers in the late 19th century to house and display the royal collection of Dutch art, and covered with frescoes by renowned contemporary artists (Fig 2). Already during its construction the building was extended to exhibit more of the ever-growing collection, and had further additions (the South "Philips" Wing, Drawing School, and Director's Villa). In the 1960s the two original courtyards within each of the east and west wings disappeared under new floor areas and an auditorium; at the same time the original high vaults were hidden by false ceilings to accommodate distribution for lighting and air-conditioning (Figs 3–6).

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1. *The Night Watch* in the refurbished Rembrandt Room.

2. Intermediate level gallery before any refurbishment.

3–5. The 1960s refurbishment in progress.

6. Upper level gallery after 1960s refurbishment.

The new areas provided more exhibition space, but the building became less transparent and more difficult to navigate; the original spaciousness was lost, and the frescoes covered by layers of paint. With yet more growth, increasing numbers of visitors, and demands for better restoration and storage facilities, the Dutch Parliament decided in 1999 that the building should be substantially refurbished to the standards of a 21st century museum.

The objective was to:
(1) resolve the access problem caused by the public passage (the "Museumstraat") incorporated in Cuypers' original design, which ran through the building between the east and west wings and effectively divided it into two disconnected halves;
(2) create a completely new building for the various restoration workshops (the "Atelier Building"); and
(3) incorporate appropriate spaces for a museum shop and catering.

Forming the team

Three main stakeholders were to manage the task: The Rijksmuseum itself as building user; the then Ministry of Spatial Planning, Housing and the Environment as building owner; and the Ministry of Education, Culture and Science as owner of the collection. Members from each of the three thus came together to form their own client body, the Programmdirectie Het Nieuwe Rijksmuseum to manage the design and construction process.

In 2001 the internationally renowned Spanish practice Cruz y Ortiz from Seville won the architectural competition. It had designed, among other projects, the Spanish Pavilion at the Hanover Expo 2000, train stations for Seville and Basle, and stadia at Madrid, Seville and Huelva. For the restoration aspects, the Dutch practice Van Hoogevest Architecten joined the team under Cruz y Ortiz's lead to advise on where and how to recover the original design. Later, in 2004, the French designer Wilmotte completed the architectural team, undertaking the exhibition design.

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In a separate competition in 2002, the three main engineering contracts, for structural and services design and building physics advice, were tendered. Arcadis, already structural designer of the adjoining underground parts of the Museumplein, was commissioned for the structure, while the services design and building physics went to Arup, for which the firm formed joint ventures respectively with the Dutch practices Van Heugten (now part of Royal Haskoning), and DGMR. Arup/Van Heugten was commissioned to advise on the specialist installations of groundwater thermal storage, IT/communications, security, and exhibition lighting, while Arup/DGMR was consultant for fire safety, daylighting, and material studies. The Atelier Building was not within Arup's commission.

With the team established, a series of workshops was held to agree strategies to achieve the demanding brief and determine how members would work together. Alistair Guthrie (Arup Fellow and museum expert) coined the expression "best overall compromise", and this carried through the project.

Best overall compromise

As each team presented its objectives, it became clear that some aims were in direct conflict (eg modernising the building and at the same time bringing back its old design, or having an open building but also providing close ambient control).

To achieve the best overall solution, all had to agree what would work best for the museum, in some cases accepting solutions that were not the optimum individual design for one discipline but would allow others to function satisfactorily too, and meet the overall criteria of a world-class museum in a historic national monument.

This approach was actively embraced by the whole team, and produced some truly remarkable solutions that would not have been possible otherwise. This article highlights some of them.

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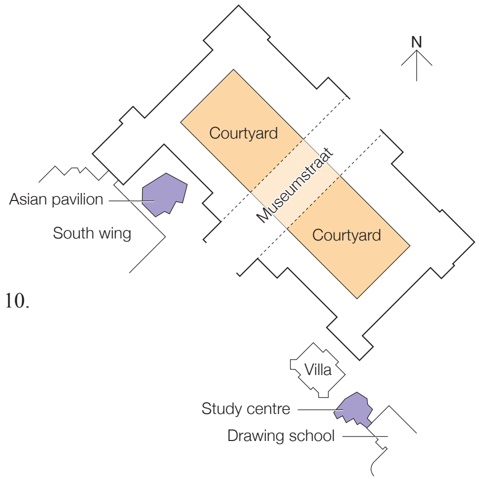

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7. Original architect's sketch showing design concept for linking courtyards beneath Museumstraat.

8. Museumstraat between the east and west courtyards.

9. New area linking courtyards beneath Museumstraat.

10. Elements of architectural concept.

11. Asian Pavilion.

12. Study Centre.

Overall architectural concept

The architectural design resolved the division of the building by restoring the two original courtyards and connecting them underneath the Museumstraat, from which they are also accessed (Figs 7–10). The recreated courtyards would incorporate the museum shop and restaurant, with new basements beneath accommodating a new auditorium and conference facilities.

In addition, a separate building was to be created for the museum's important collection of Asian art (Fig 11), and a further annexe, the Study Centre, would provide facilities for studying some of the art that cannot be exhibited to the wider public (Fig 12).

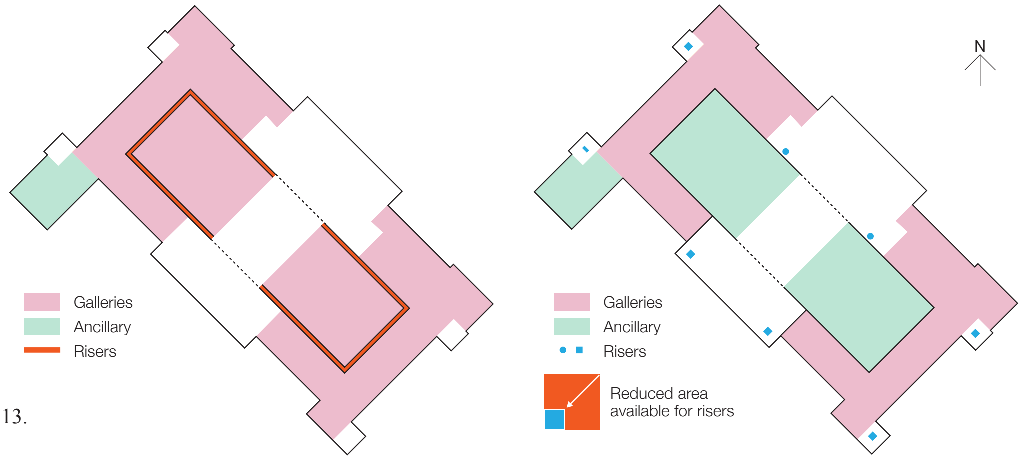
Building services

Main services distribution within the building

One of the design team's principal challenges was to integrate the new services installations with the recovery of the building's original geometry and spaces. These had of course not allowed for modern-day services, and the new space needed to be found without interfering with the vision of restoring the building's original glory (Fig 13). The team had to integrate the services invisibly without modifying the original geometry, which required a multidisciplinary solution with contributions from all team members.

Recovering the original courtyards and vaulted ceilings was the first challenge, since neither the distribution routes behind the 1960s false ceilings and in the gap between the old shell and the new core, nor the original plantrooms under the old courtyard roofs, were now available (Figs 14–15).

The solution was two-fold. First, vertical distribution was reduced by locating plant as close as possible to the area it served. This included integrating it in the roof spaces above the galleries, which required careful co-ordination with the cast iron roof trusses (where Cuypers had tried out new structural concepts, and which were all different as a result), and creating new underground plantrooms at the building perimeter and in the new basements to serve the lower galleries (Fig 22).



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The intermediate-level galleries are also served from here, with the corresponding vertical distribution running in the (originally over-dimensioned) walls, which in the original design also housed shunts to distribute warm air for heating throughout the building (Fig 16).

Second, to further reduce the need for vertical distribution, the return air from the galleries is allowed to drift into the courtyards via the original window openings (Fig 21), where it is collected and returned to air-handling units (AHUs) via underground ducts (Figs 16, 44). This has the benefit of tempering the courtyards, providing both a comfortable environment for this transient space and creating a buffer zone between the exterior and the closely controlled conditions of the galleries.

Close collaboration between disciplines was particularly needed in dealing with both the roof spaces and the galleries. The available spaces in the roof had to be defined individually with the restoration team, and the equipment sized accordingly by the building services team. The structures team then had to check the load capacity of Cuypers' original innovative cast iron roof trusses, the building physics team calculate how the daylighting of the galleries below could be affected, and the architectural team devise the integration of access gantries and intakes in the roof (Fig 51).


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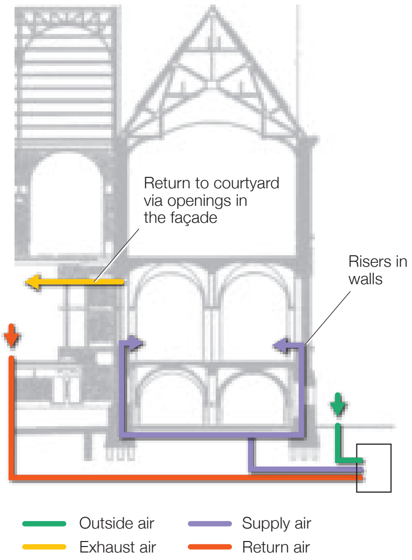
13. Distribution of spaces (*left*) before and (*right*) after refurbishment.

14, 15. The 1960s refurbishment introduced false ceilings that were removed in the restoration, thereby making the concealment of services routes more challenging.



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16. Internal services distribution: integrating the new air supply (intermediate level).

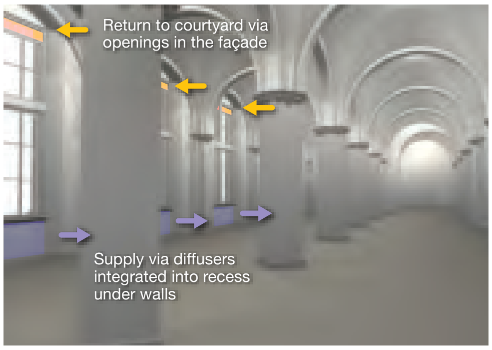
17. Wall riser at the ground floor during construction.

18. Internal services distribution: integrating the new air supply.

19. Diffuser in wall recess.

20. 18th Century Gallery: restored space discreetly ventilated.

21. Courtyard window, showing openings above for return air.



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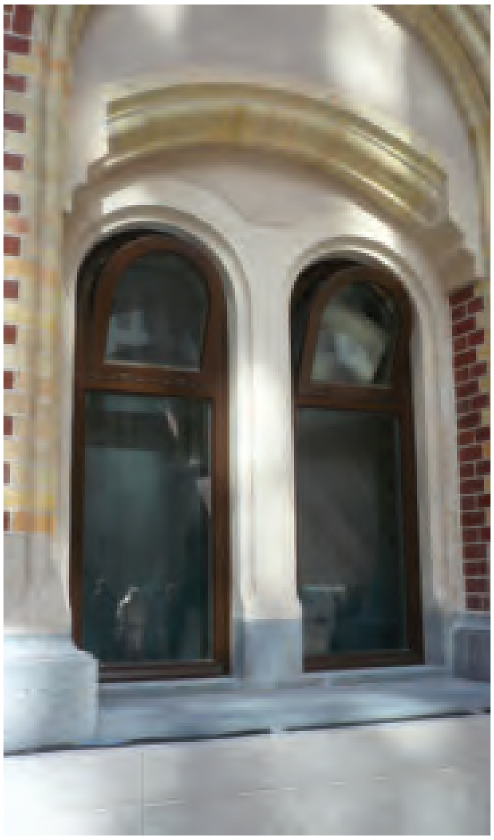

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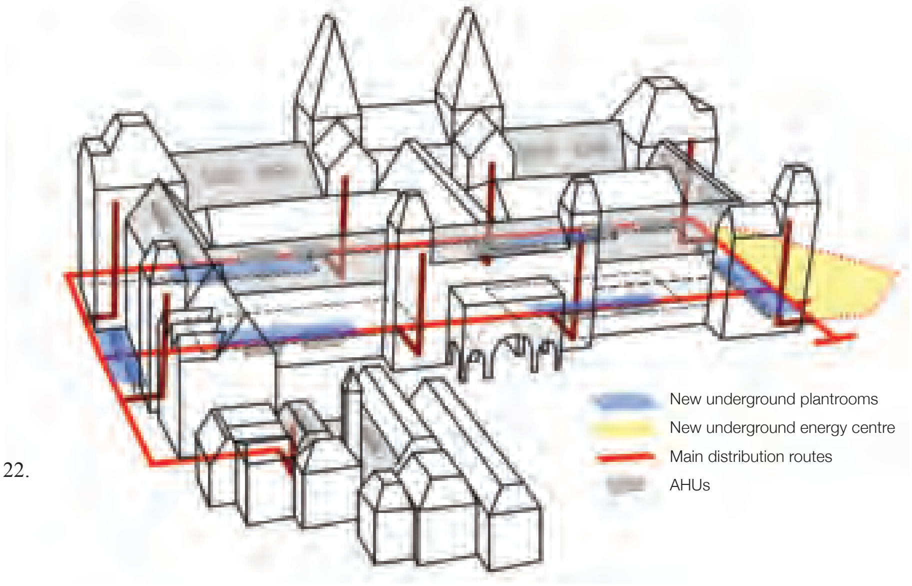

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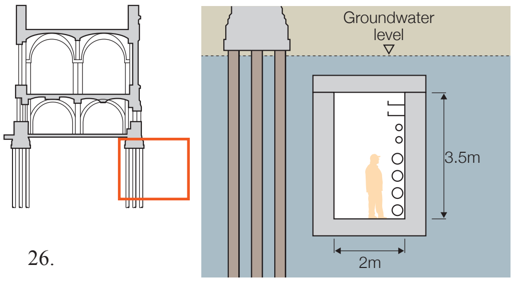

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22. Overview of main services distribution.

23. The underground energy centre, with Study Centre in the background.

24. Ring main tunnel.

25. Plantroom in tunnel pocket.

26. Tunnel cross-section.

In the galleries, the air supply had to be integrated within the existing geometry and co-ordinated with the proposed exhibition design (which required adaptable solutions for special cases), as well as with the detailing of the critical thermal insulation of the walls (Fig 39). At the same time, for the connections between the ground and intermediate floors, the load-bearing walls had to be analysed to identify where holes could be cut (Fig 17).

In the final result the original geometry of the galleries has been brought back, without compromising the required ambient conditions for the artwork. The services engineering design allows visitors to enjoy the splendid art and architecture with no hint of how much effort went into making the installations invisible (Figs 18–21).

Central plant and distribution

For the central plant and its distribution, the team decided to go beyond the boundary of the original building and create a new underground energy centre at the east side (Figs 22–23). A perimeter tunnel connects to four new underground plantrooms (each around 20m x 7m on plan), as well as to the plantrooms in the new courtyard basements, and distribute the mains supplies in a ring around the building (Figs 24–25). As a result, no space in the building needed to be compromised, with penetrations of existing fabric kept to a minimum and the energy supply for the building mostly invisible.

For the remaining vertical distribution the old stair cores were recreated, thus again integrating all distribution elements almost invisibly, and in the least possible space.

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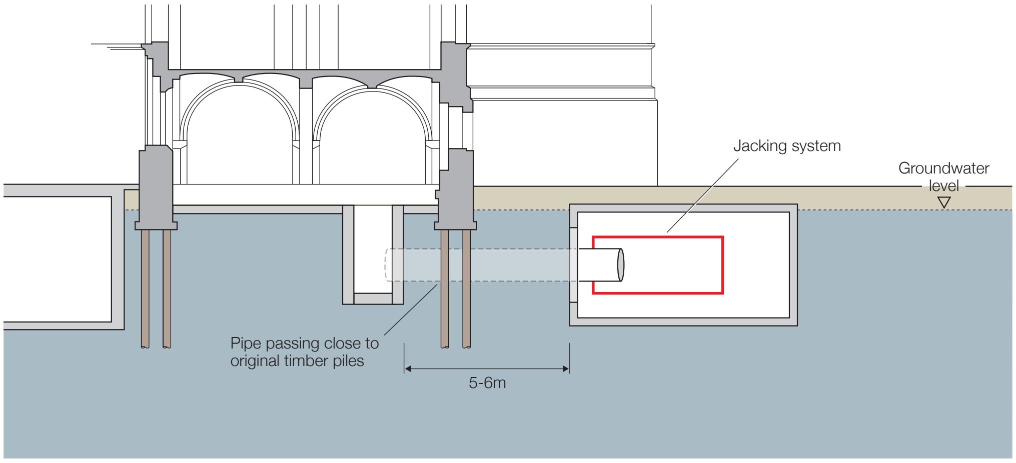
What seems simple in concept, however, required considerable efforts from the team to become a reality, and posed various important challenges.

To start with, the tunnels and the new external plantrooms had to be built below groundwater level, which in Amsterdam lies just a few centimetres below the surface (Fig 26). These spaces — one on each of the east and west sides and two on the north side — sit in "pockets" between pairs of towers.

A particular challenge lay in connecting them to the building from below its ground floor and under the groundwater level; this again required a multidisciplinary approach from the building services, structural, and architectural teams, and the involvement of geotechnics and infrastructure specialists — a true combination of quite different technologies.

The solution, which allowed construction under water without digging beneath the existing foundations, was to create "receiving chambers" under the building and connect these to the plantrooms by a pipe-in-pipe system. This system carries conditioned air from the AHUs to the galleries via the receiving chambers, a distance of 5m–6m depending on position. Air is then exhausted via the atria and returned the 12m–13m distance to the plantrooms under the building again (Fig 27).



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The thick, robust outer pipes, varying in diameter from 500mm–750mm, were sized and placed individually so as to fit between the timber piles that support the whole building. They were jacked from the plantrooms (Fig 28), pressed into the ground section by section, and then welded together until the connection to the receiving chamber under the ground floor galleries was complete. Constant checks had to be made that none of the piles were being damaged during this process.

When the outer pipe was in place, the inner pipe was inserted. These, in much lighter sheet metal ducting, are around 30mm narrower than the outer, thus allowing a small air gap of about 15mm which was sealed after fitting when the final system connection was made.

A further challenge lay in connecting the services in the existing building with the services in these new structures; the existing building had already settled for more than a century and was experiencing hardly any movements, but the new structures were expected to settle various centimetres in their first years, which would cause the connections to fail. The team had to find solutions that would allow such movements without failure, at the same time withstanding the surrounding groundwater conditions; again an integrated approach and the involvement of infrastructure technology resolved the issue.

The final result is again remarkable. None of the timber piles or foundations were damaged or weakened, the connections are watertight, and the "invisible installations" function as predicted without impacting on the original geometry of the building.

Secondary services distribution

Yet another challenge for the services integration was the secondary distribution, from risers to the terminal equipment. Before the refurbishment, the secondary circuits of the services installations ran in a services corridor between the original galleries and the spaces in the courtyards, and behind false ceilings in the galleries; both options became unavailable with the return to the building's original geometry. The idea of a raised floor also had to be discarded in most areas, since it would have hidden many of the historic skirting details that the refurbishment was to bring back.

As a compromise it was decided to remove the first layer of the existing floor — avoiding where possible areas with original terrazzo flooring — and cast in the services. This required a considerable co-ordination effort between the different services (electrical supplies, data cabling, fire detection) and the varying floor levels, as well as finding a layout that suited the exhibition design and offered flexibility for modifications between exhibitions.

At ground floor level the ground slab was lowered and the finished floor reinstated at the original level, thus creating a space for both air and services distribution.

Air supply to galleries

As with the different approaches for the central mains, the distribution concept for each gallery type was tailored to best fit the building. The upper galleries are supplied from above via diffusers integrated in the original laylights, the intermediate galleries via consoles integrated in the window niches, and the lower galleries via the raised floor created by lowering the original floor slab and thus maintaining the original finished floor level, as noted above.

To suit the desired aesthetics of the ceilings in the main floor galleries, a combination of two diffuser types (jet nozzles to overcome buoyancy effects in heating conditions, and linear slots to avoid this effect in cooling conditions) was used. Depending on the room and supply conditions, air is supplied at varying percentages through one diffuser type or the other (Figs 30–31).

All solutions were tested and fine-tuned using CFD (computational fluid dynamics) analysis tools, giving the client confidence that the demanding targets set for the ambient conditions in the galleries would be achieved (Fig 32).

27. Pressing pipes into the ground under the building for the pipe-in-pipe system.

28. Jacking system in action.

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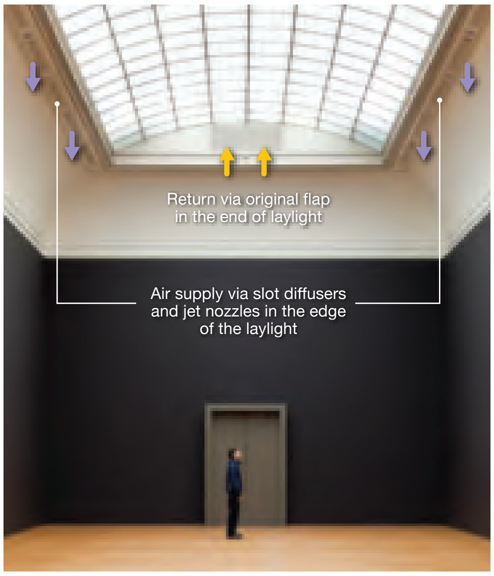

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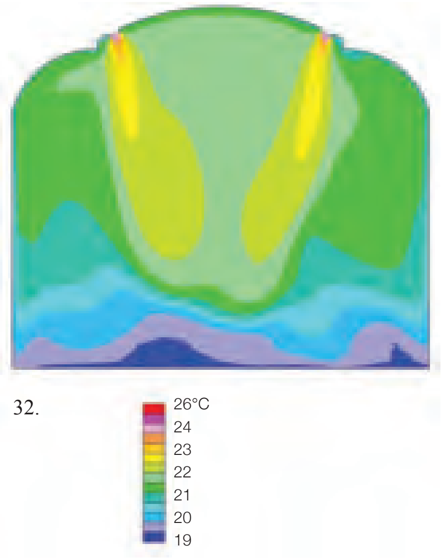

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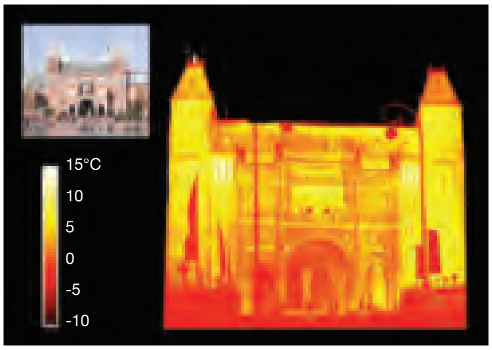
29. 17th Century Ship Gallery.

30, 31. Use of jet nozzles and slot diffusers in upper galleries.

32. CFD analysis for upper galleries.



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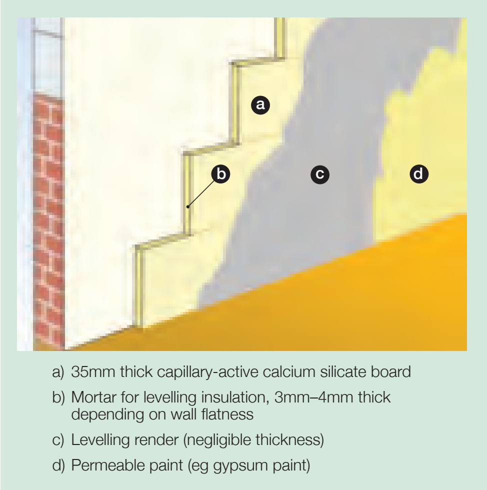

a) 35mm thick capillary-active calcium silicate board
b) Mortar for levelling insulation, 3mm–4mm thick depending on wall flatness
c) Levelling render (negligible thickness)
d) Permeable paint (eg gypsum paint)

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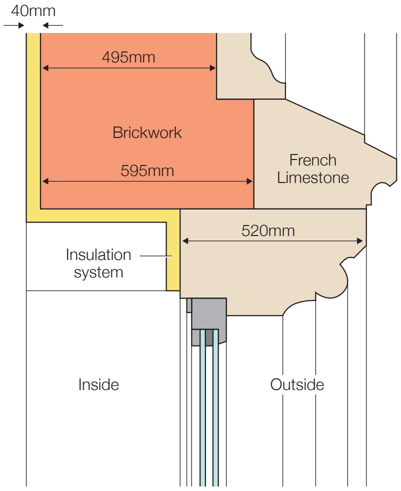

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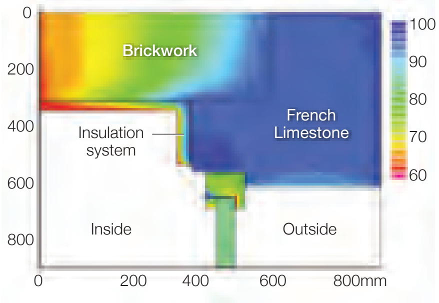

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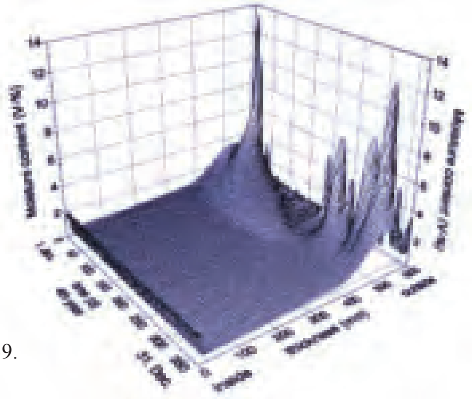

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33. Thermal imaging of south façade.

34. Internal façade insulation system.

35, 36. Application of calcium silicate boards.

37. Analysed detail of window recess.

38. Predicted temperature distribution in the analysed wall section.

39. Predicted moisture content in the analysed wall section.

40. The Cuypers Library, the Netherlands' largest art history collection.

Thermal insulation

A further aspect to be taken into account during the refurbishment was the building fabric, which affects both the ambient conditions for the artwork and the building's energy consumption and running costs.

The original building was constructed without insulation, which caused considerable heat losses through the façade (Fig 33); since the installation of air-conditioning in the 1960s the building had also repeatedly suffered from condensation on the walls and behind the paintings during the winter months, when the environment was artificially humidified.

An investigation indicated that this was due to both interstitial condensation within the walls and exposure to rain. After evaluating various options and balancing the importance of ambient conditions versus the value of the monument, the team decided to insulate the exterior walls from the inside and improve the thermal performance of the windows.

The system chosen was a dramatic departure from conventional methods, where a vapour barrier is created to avoid interstitial condensation. It consists of a calcium silicate plate that, while offering insulating properties, allows the walls to "breath" — drying out both outside and inside due to its diffusion-open, capillary-active structure (Figs 34–36). This permits the moisture in the walls to evaporate, and thus also had minimum impact on those of the original frescoes that had survived. As an added value it also acts as a buffer for the relative humidity in the space.

To complete the wall build-up, the selected finish was a lime-based paint, which allowed the plaster to breathe. This was again an original material choice, further contributing to the remit of bringing back the original design.

Although this solution had been used for over a decade in Germany, its application was not widely known in conservation circles, and raised concerns among the client bodies. The team therefore decided to carry out two-dimensional hygrothermal analyses of typical details in the building, and then test the paint on part of a wall during a hot and a cold season. The tests validated the solution, which was implemented throughout (Figs 37–39).

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The courtyards

The recovered courtyards are the centrepiece of the refurbishment. The west courtyard functions as the new main entrance, but both are accessible from the street and form a single space. The original façades have been restored to their original glory, and the original glazed roof has been reinstated (albeit in modern double-glazing) as has the interior, secondary, roof layer that is now used to reduce the solar loads in the space.

Since the courtyards are working spaces for the museum staff, the thermal conditions, lighting and acoustics had to be designed accordingly. The spaciousness of these areas required special treatment, but again without imposing on the aim of bringing back the original structure.

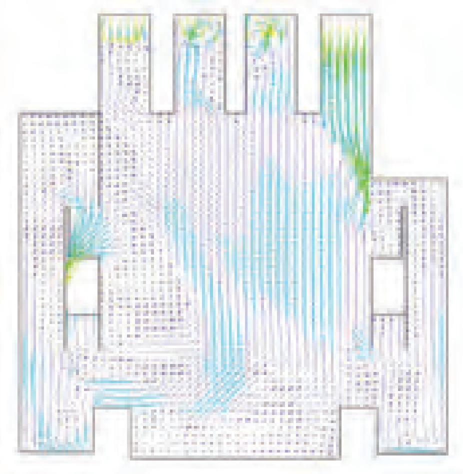
This ambient control was achieved by a two-fold approach. A basic tempering of the ambient conditions is derived from the gallery return air that flows from the ground and intermediate floor galleries, and thus allows the courtyards to function as both super-sized plenums and high-efficiency heat recovery devices (all excess energy from the gallery return air is used here); unwanted infiltration is reduced by using revolving doors at the entrances. This tempering is supported by an underfloor heating system and a balancing of the high-level shading between the desired natural lighting and the limitation of solar thermal loads.

Locally, areas where staff work permanently have been treated with further measures (fan-coils, infrared emitters). Here, local control has been enabled (Fig 43).

Fresh air is supplied to the space via transfer grilles in the newly-created windows to the passage; at the same time unwanted infiltration is reduced by the revolving doors. The resulting ambient conditions from these solutions were first tested in a 3-D CFD model to ensure that draft and cold spots in populated areas would be avoided (Fig 45).

With great reverberating volumes, numerous hard surfaces, and many sources of ambient noise from the visitors, the courtyards were also at risk of forming an acoustically unintelligible environment, unacceptable both for the museum operations (eg ticket sales) and visitors (eg tour guides).

Once again, a 3-D study of the spaces was undertaken to establish the effects and evaluate the impact of possible solutions. Here the features of the design were used to achieve the desired acoustic effect, by constructing the ceiling sculptures in absorbent material, and by finishing the upper parts of the walls with acoustic material. The final result maintains its sense of spaciousness without the acoustic effects (echoes) that are normally encountered in such a large space.



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41. Refurbished east courtyard.

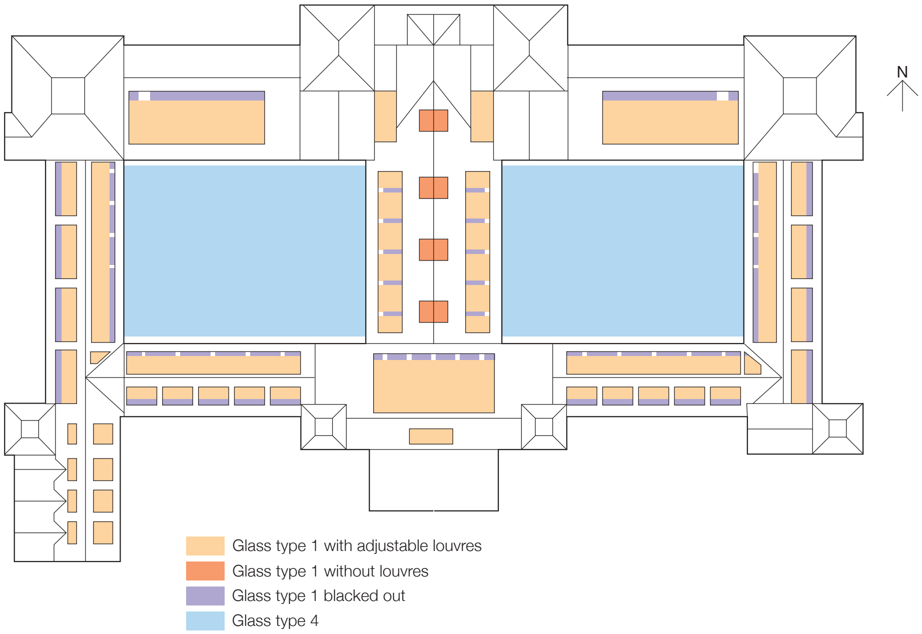
42. Refurbished west courtyard.

43. Servicing restored courtyards:
(a) Special materials and detailing to improve room acoustics;
(b) Make-up air via transfer grilles in passage façades with integrated convectors;
(c) Manifolds for underfloor heating;
(d) Information desks treated additionally by fan-coil units;
(e) Underfloor heating in all areas.

44. Return air inlet in the west courtyard.

45. CFD analysis of ambient conditions in the courtyard.

46.



47.

Lighting

As in any museum, lighting plays a central role in bringing exhibitions at the Rijksmuseum to life; at the same time it is a critical factor in preserving the art in the museum's care, necessitating adherence to strict limits on the extent and type of illumination. In an additional commission, Arup's lighting team was brought on board to deal with the daylighting and the design of the electrical lighting system, both for feature lighting to spaces like the courtyards and staircases, and for the exhibition spaces.

Daylighting

Cuypers' original design relied heavily on daylight, but over the decades since the building was first completed this had been progressively reduced by windows being blocked up and by the introduction of suspended ceilings. The design intent for the refurbishment was to make the Rijksmuseum a daylit museum again (Fig 47).

In pursuit of this goal, the lighting design team analysed the expected daylight levels and evaluated the various options for maintaining appropriate vertical and horizontal illuminance levels in the galleries. This was done by comparing static and adjustable window treatments, with the aim of avoiding over-exposure from natural light throughout the year but also maximising the daylight experience in the spaces, and then studying, together with the architectural and restoration team, how this could be best achieved within the building (Fig 48).

The galleries

On the upper floor, daylight is admitted through laylights in the ceilings and transparent skylight sections in the roofs. To determine the effect of this on the galleries beneath, the daylight uniformity on the glass of the laylights was analysed. The team took on-site measurements, studied various options by the use of scale models, and visualised and calculated the daylight using *Radiance* finite element analysis software for 3-D modelling (Fig 49).

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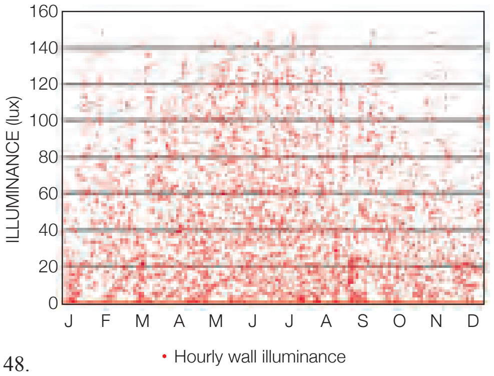

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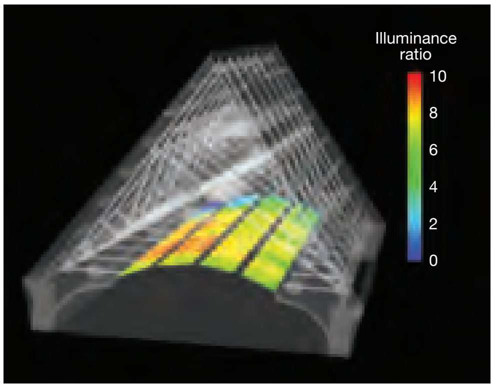
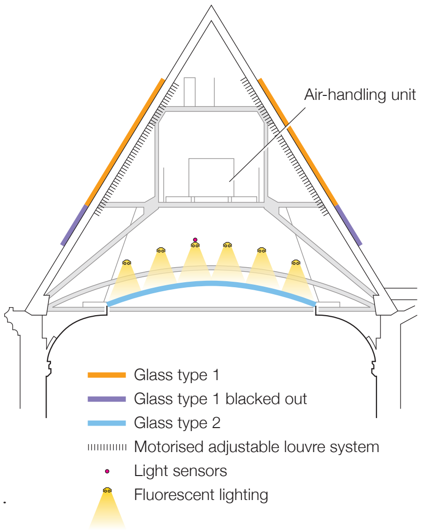


49.

The final solution consisted of replacing the glazing of the horizontal laylights above the galleries and the skylights in the roof above, and fitting the skylights with adjustable louvres on the interior; these are set four times a year according to seasonal daylight availability. In the cavity between the laylights and the skylights, fluorescent lighting fixtures are mounted to ensure even light distribution and the required light levels when there is insufficient daylight; these luminaires are linked to a daylight sensor. The result is gallery spaces with homogenous light spilling into them from above (Fig 51).

The original design foresaw the intermediate level galleries to be side-lit; at that time the lower level spaces were used as plant and storage spaces, with much smaller windows. The museum's requirement for ever more wall space for the artworks resulted in the vertical windows on the intermediate and ground levels being maintained only at crucial viewing points from the building to the outside or across the courtyards; other windows were closed and used as surfaces for hanging paintings or to exhibit other artwork. As a result, daylight came to play only a minor role in lighting these spaces, with artificial light as the main focus.



51.

46. The Gallery of Honour.

47. Roof layout, showing types of glazing and location of louvres.

48. Daylight levels throughout the year with seasonally adjusted daylight control.

49. Uniformity analysis.

50. 17th Century Gallery.

51. Typical roof section showing louvres and lighting installation.

52.

53.

52. 19th Century Gallery.

53. Vaulted gallery with suspended lighting racks.

54. Zone for mounting fixtures for ideal lighting angle.

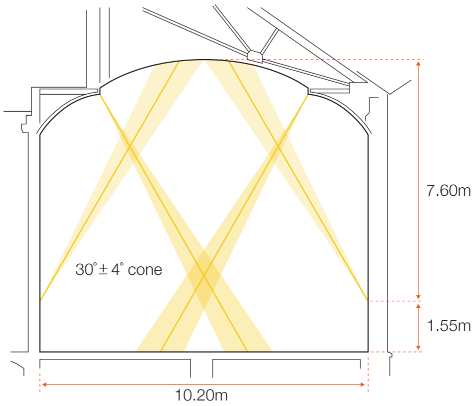
55. 20th Century Gallery on upper level.

Artificial light

With the renovation the original vaulted ceilings in the galleries are again exposed, and the electric lighting had to be designed to work with their geometry. This was achieved by putting suspended lighting rack systems in each individual vault (Figs 52–53). On the intermediate levels these racks have a square footprint, while on the ground floor they are round (Figs 64–65).

Each rack has an indirect uplighting element which accentuates the vaulted spaces and creates a homogenous, shadow-free, overall illumination; it also functions as emergency lighting. On the undersides of the racks, individual spotlights are mounted to accentuate the various art objects.
The design for the racks was developed by the exhibition designer Wilmotte specifically for the project, and uses LED light sources by Philips, the museum's sponsor and founding partner.

For the upper galleries the artificial lighting supplied by the fluorescent lighting behind the laylights is supported by recessed tracks along the edge and in the centre of the laylights. These three tracks allow for flexible fixture mounting and ensure that the correct angles for lighting the artworks can be achieved (Figs 29, 54–55).



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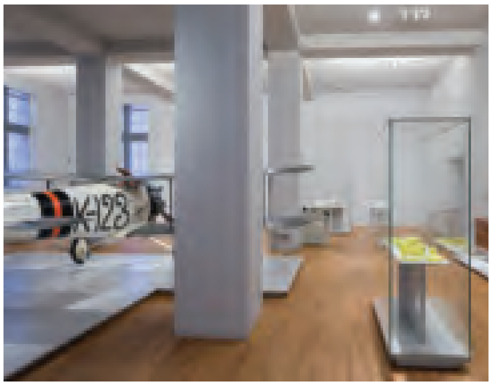

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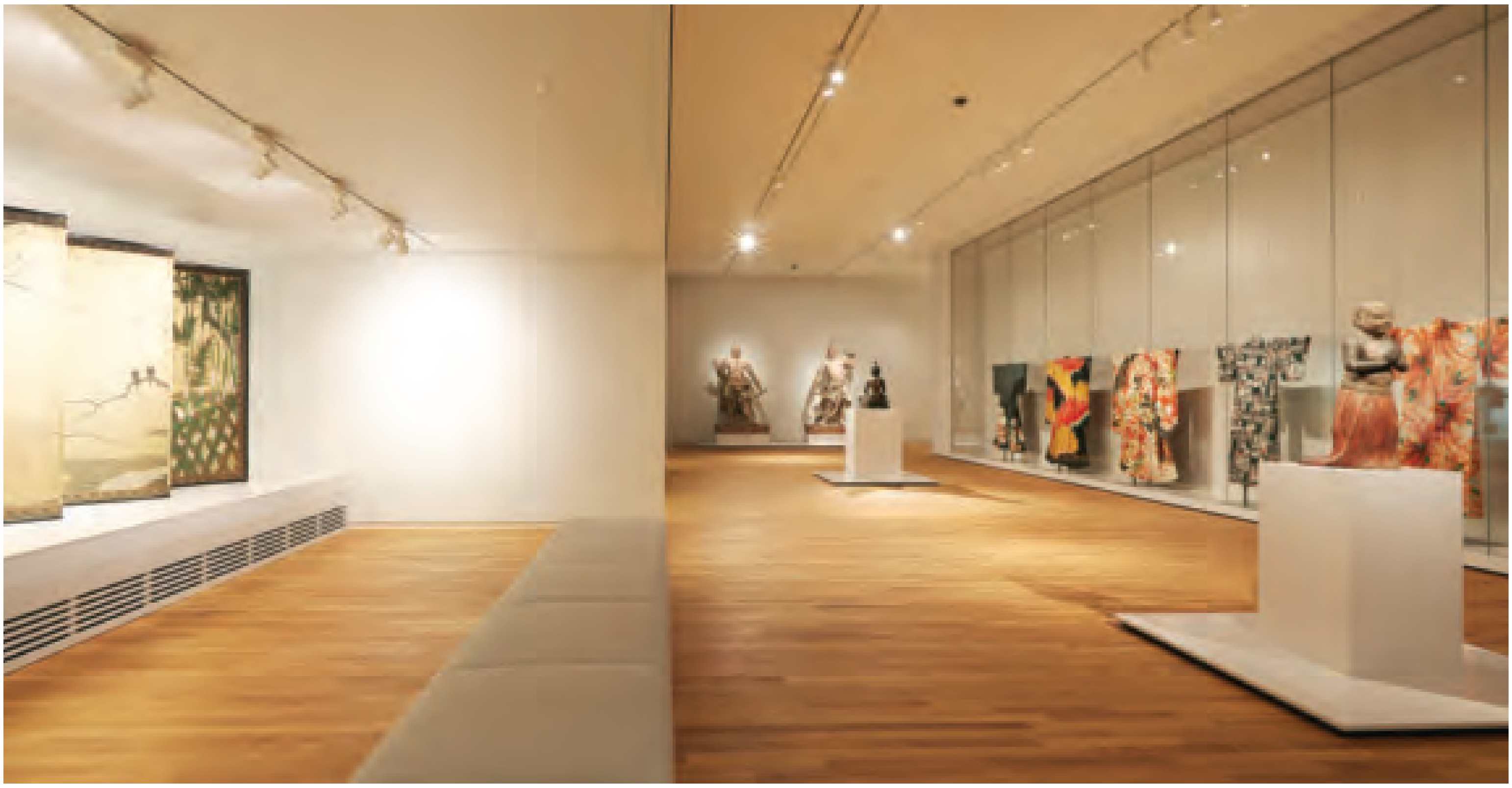


56.

57.

For the new Asian Pavilion designed by Cruz y Ortiz, only recessed linear tracks in the ceilings are used to supply the artificial lighting (Fig 56).

The display case design by Wilmotte does not include integrated lighting, but relies on the artworks inside being lit from the rack and track systems above; to facilitate this, the cases were designed to be as transparent as possible, with special non-reflective glass (Fig 57). The display cases in the Asian Pavilion do have integrated lighting with a diffused glass top that makes the edges seem to disappear.

56. Recessed linear tracks for lighting in the Asian Pavilion.

57. Display cases using special non-reflective glass, in the 18th Century Gallery.

58. Daylight factor in the courtyard.

59. Plan and detail of lighting in the chandelier.

60. Courtyard roof showing suspended ceiling structure — the “super-sized chandelier”.

61. The east courtyard.

62. Courtyard window.

Courtyards

In the courtyards, daylight was less critical in terms of conservation, as light-sensitive artwork is not exhibited here; the focus was rather on creating attractive environments for visitors and employees, as the courtyards contain the entrance halls, visitor information booths, ticket sales, ticket control, and similar functions.

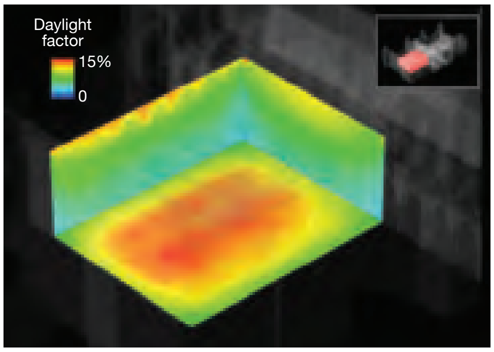
During the day the courtyards get ample light through the skylights, as demonstrated by the corresponding daylight factor calculations (Fig 58). At night the challenge was to incorporate artificial lighting but discreetly, in a way that enhanced the attractive setting but without damage to the original façades.

The solution was to use the suspended ceiling structures — envisaged by the architectural design as “super-sized chandeliers” made of lightweight acoustic panels – to incorporate small uplight fixtures so as to form a large glowing volume (Figs 59–60). Together with spotlights mounted in the underside of the structure, they provide lighting down onto steps, counters and the courtyard space in general (Fig 61).

The connection between the courtyards underneath the central entrance houses the coat check and ticket office; it is lit with recessed lines of light that accentuate the connection between the two courtyards, turning this relatively low space into a comfortable area to be in (Fig 9).

ICT

Certainly not envisaged at the time of the Rijskmuseum’s original design, IT and communications (ICT) play an important role in this as with all modern museums, starting with a web presence and internet ticket sales, through on-site ticketing and ticket controls, to interactive tours and wireless asset management.



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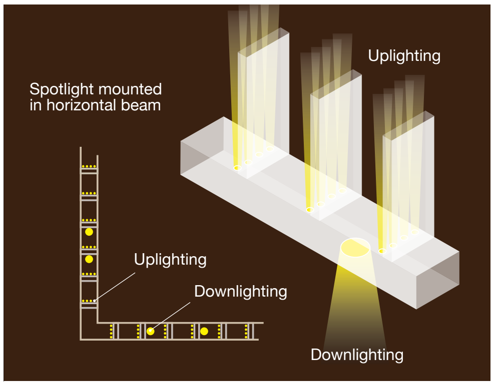


59.

60.

Before the refurbishment, ICT technology had only been installed in an ad hoc manner to meet the most urgent needs; the refurbishment was the opportunity to start afresh, and consider how it could be used to enhance the operation and user experience of the museum.

Arup was commissioned to support the museum in this process, and the first step was to produce an agreed set of ICT needs through a series of consultative stakeholder workshops, where the requirements for the visitor experience envisaged by the museum, the architectural vision, and the building services concepts were all established.

In the process the role of ICT at the Rijksmuseum (in learning, teaching, entertainment, etc) was discussed, and likely enabling technologies, recent examples and experiences — plus opportunities for revenue generation, funding and sponsorship — were presented.

The team addressed the appropriateness of budgets, comparing the investment costs with related running costs, revenue generation and operational savings, contingencies and opportunities for sponsorship, branding and marketing. An important factor was the museum’s operational structure; the team had to assess whether the formulated requirements aligned with the existing, or whether new operational structures had to be created to support the newly emerging requirements.

The results from the workshops were distilled into a “roadmap” that defined the vision and opportunities for ICT and outlined the scope of the systems and services deploying ICT in the museum. The document also contained an indication of when key decisions had to be made and how the technology affected project design issues. This formed the basis for all further development activities related to ICT infrastructure, systems and services.

61.

Fire

Museums pose special challenges in fire safety design. Apart from the requirements of "normal" buildings to prioritise the safe evacuation of occupants, protection of the priceless artwork is a driving factor.
In addition, the security needs for safeguarding the artwork from theft sometimes contradict the needs of fire protection. And here in the Rijksmuseum, restoring the building's original geometry and finishes added a further level of complexity to the challenge.

As many elements of modern fire safety design could not be used in the historic building, alternative solutions had to be found and agreed. The final fire safety strategy again evolved from a results-oriented collaboration of all disciplines, and a close co-ordination with the City of Amsterdam Fire Department from the start of the process.

62.

The first task was to reduce the risk of fire in the building; for this purpose the statistically most frequent causes of fires developing in museums were studied and addressed one by one to reduce the corresponding risk.
This involved, for example, special details in the electrical installations, and highly sensitive fire detection systems adapted to the geometries of the various spaces, as well as a review of the museum's operational procedures.

A particular challenge was the compartmentation of the building; the courtyards had to be kept separate from the galleries in case of a fire, but the ventilation concept relied on the spaces to be connected. The solution lay in developing custom-made windows (Fig 62) which met the need to provide an air path between galleries and courtyards, an acoustic attenuation, a security barrier between the spaces, and fire and smoke resistance in case of a fire.

Energy sources

A further "masterpiece" of the museum is the central energy production, based on a seasonal energy storage system (aquifer), with warm and cold wells providing heat or coolth as required to the air-handling equipment. The system is boosted by a series of reversible heat pumps with heat recovery, and backed up by conventional boilers and cooling towers, which also enable balancing of the energy flows through the year (Fig 63).

This system, together with the improvements in thermal insulation and airtightness, makes the refurbished Rijksmuseum much more energy-efficient than before, even though the improved ambient conditions and air quality require a higher energy input per m^2.

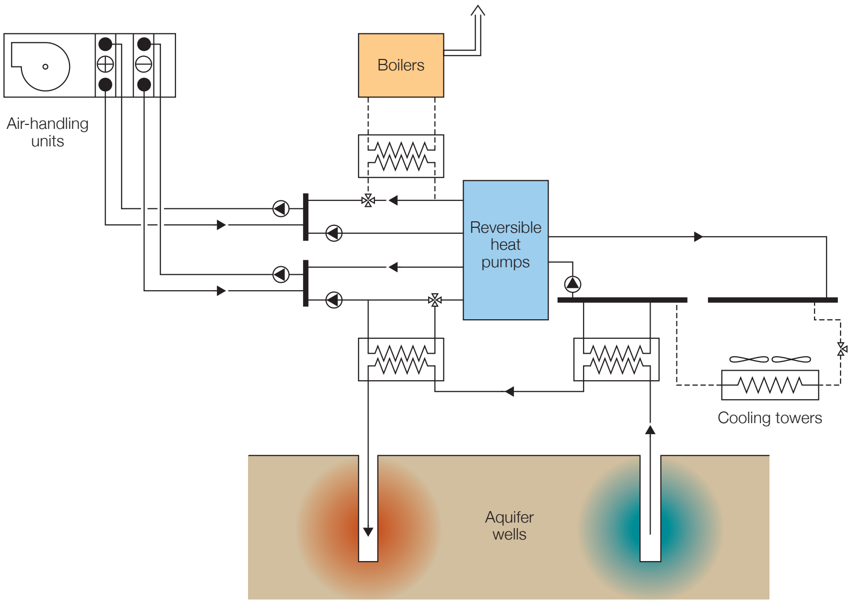
A further advantage of the system is that it considerably reduces the space required for heat rejection, again contributing to the overall "invisible installations" concept.

Conclusion

On 14 April 2013 the Rijksmuseum was finally returned to the public, opened the day before in a formal ceremony by Her Royal Highness Queen Beatrix. The event had been eagerly awaited by the whole nation and was widely covered in national and international media (Fig 66).

The reopened building stands witness that a challenging brief can be met if the team truly collaborates to find holistic solutions that take the individual contributions from each discipline to a higher level. The results speak for themselves, and have been acclaimed by both visitors and the museum staff. Cruz y Ortiz were awarded the Abe Bonnema Architectuurprijs 2013 for the project in October 2013. In its comments, the jury explicitly included other consultants in the award, stating that without them the design could not have been made to happen.

Since the completion of the main building, Arup has been commissioned for the Philips Wing, which functioned as interim accommodation for the museum and will now be refurbished to form the final element of the building, providing further catering and temporary exhibition spaces.



63.

64.

65.

66.

63. Energy concept.

64. Delftware exhibition in the special collections gallery on the ground floor.

65. Special collections gallery on the ground floor.

The new Rijksmuseum has been highly successful with the public since its reopening.

66. Fireworks for the formal opening by Queen Beatrix on 14 April, 2013.

Authors

Karsten Jurkait is an Associate Director in the Düsseldorf office, and led the design team for the Rijksmuseum restoration.

Siegrid Siderius is an Associate Director in the Amsterdam office, and led the lighting design team for the Rijksmuseum restoration.

Project credits

Client: *Het Nieuwe Rijksmuseum* Promoters: *Netherlands Ministry of Spatial Planning, Housing and the Environment/Netherlands Ministry of Education, Culture and Science* Architect: *Cruz y Ortiz Arquitectos* Structural engineer: *Arcadis Bouw & Vastgoed BV* Mechanical, electrical, public health, civil, ICT, and exhibition lighting designer in JV (with Van Heugten); building physics, acoustics, fire, daylighting designer in JV (with DGMR): *Arup — Giulio Antonutto-Foi, Aitor Arregui, Monica Bamogo, Johan Beudeker, Remco Boukens, Marco Briede, Javier Caselles, Pablo Checa, Mark Chown, Simone Collon, Steve Done, Tom Fernando, David Gilpin, Alexej Goehring, Alistair Guthrie, Rupert Inman, Chema Jimenez, Karsten Jurkait, Ben Kreukniet, Carmelo Lacayo, Florence Lam, Javier Pinan, Mani Manivannan, Andrew McNeil, Jesus Moracho, Wolfgang Muller, Robert Murphy, Rouven Nieuwenburg, Nieves Perez Pacios, Joop Paul, James Quinton, Jim Read, Robert Senior, Siegrid Siderius, Alex Thomas, Rogier Van Der Heide, Daan Van Konijnenburg, Imke Van Mil, Jaap Wiedenhoff, Darren Woolf* Local architect: *ADP Architecten* Restoration consultant: *Van Hoogevest Architecten* Exhibitions designer: *Wilmotte & Associés* Building services JV partner: *Van Heugten* Building physics JV partner: *DGMR* Landscape architect: *Copijn Tuin- en landschapsarchitecten* Construction manager: *BRINK Groep*.

Image credits

1, 20, 41–42, 46, 61, 64–65 *John Lewis Marshall*; 2–6, 14–15, 17, 35–36 *Courtesy Van Hoogevest Architecten*; 7 *Courtesy Cruz y Ortiz Arquitectos*; 8–9, 30, 53, 60 *Pedro Pegenaute*; 10, 13, 16, 26–27, 37, 47, 51, 54, 59, 63 *Nigel Whale*; 11–12, 19, 21, 23, 31, 44, 62 *Karsten Jurkait*; 18, 43 *Indigo;* 22, 25, 32, 34, 45, 48–49, 58 *Arup*; 24 *Rouven Nieuwenburg (Royal Haskoning)*; 28 *Arcadis*; 29, 40, 50, 55, 57 *Iwan Baan*; 33 *DGMR*; 38, 39 *University of Dresden*; 52, 56, 66 *Erik Smits.*

Enhancing the Stedelijk Museum

Location
Amsterdam, The Netherlands

Authors
Marcel de Boer Mariëlle Rutten Siegrid Siderius Frank Van Berge Henegouwen

Introduction

To maintain and consolidate its key position in the world of contemporary art and design, the Stedelijk Museum in Amsterdam has been renovated and extended with the new addition designed by Benthem Crouwel Architects. The rejuvenated Museum was opened officially by Queen Beatrix on 22 September 2012. Museum Director Ann Goldstein commented: *"With this long and eagerly awaited reopening, the Stedelijk Museum Amsterdam re-establishes its powerful position among the great and leading art institutions. It puts Amsterdam in the limelight as a centre of artistic renewal and breathes new life into Museumplein – one of the foremost cultural landscapes in the world. Above all, with the completion of Mels Crouwels's bold and brilliantly functional building, we are adding another major new work to our collection of Dutch home-grown modern design."*

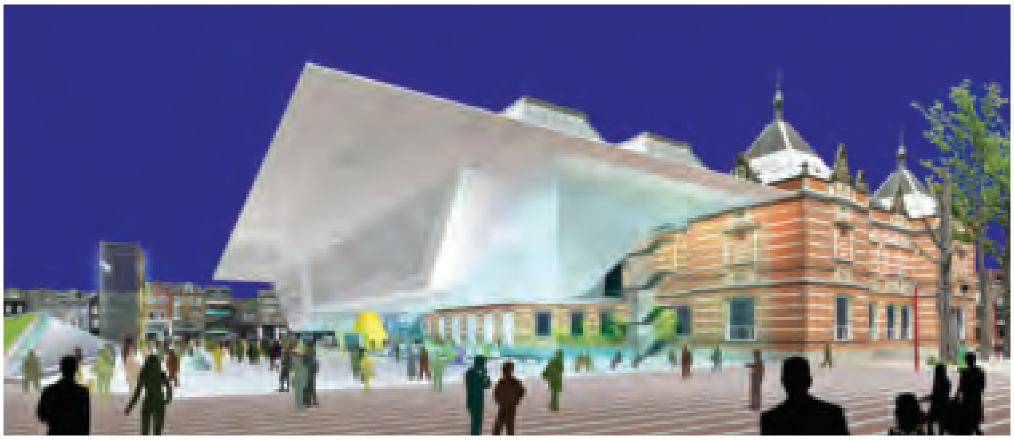
1.

Architect's concept and Arup's role

Benthem Crouwel's award-winning design was submitted in 2004. Though the project comprised both the refurbishment of the 1895 Weissman building and the addition of a new building (the "bathtub") that was radically different in external appearance, the architect's conception reflected the wishes of the client — that it should respect the existing building and that the end result should form a single unit (Figs 3–4).

The starting point for the restoration was to reveal the neo-Renaissance character of the original 1895 building, celebrated for its majestic staircase, grand rooms and use of natural light. During the renovation some non-original intermediate floors were removed, and new connections made between exhibition spaces. At the competition stage, Arup advised Benthem Crouwel on the structural design (Fig 5) and undertook the lighting design, the aim of which was to maximise the use of natural light in the museum, within the constraints of art conservation.

A key part of the concept was the relocation of the main entrance. The team determined that the entrance in the existing building, with all the functions associated with it, could no longer function as such, and so the museum as a whole was reoriented to face south-east, with the entrance now accessed via the new building from Museumplein.



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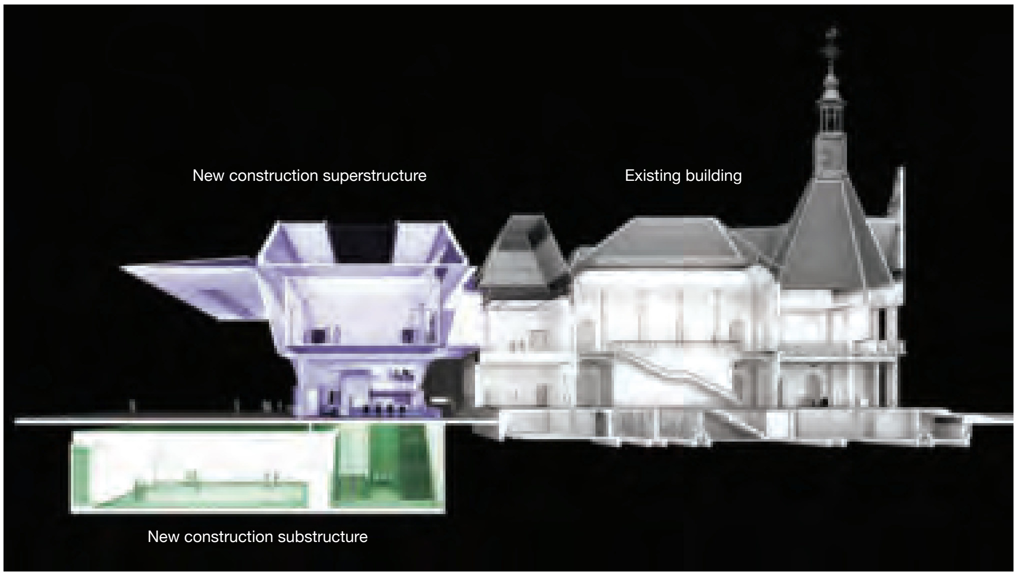

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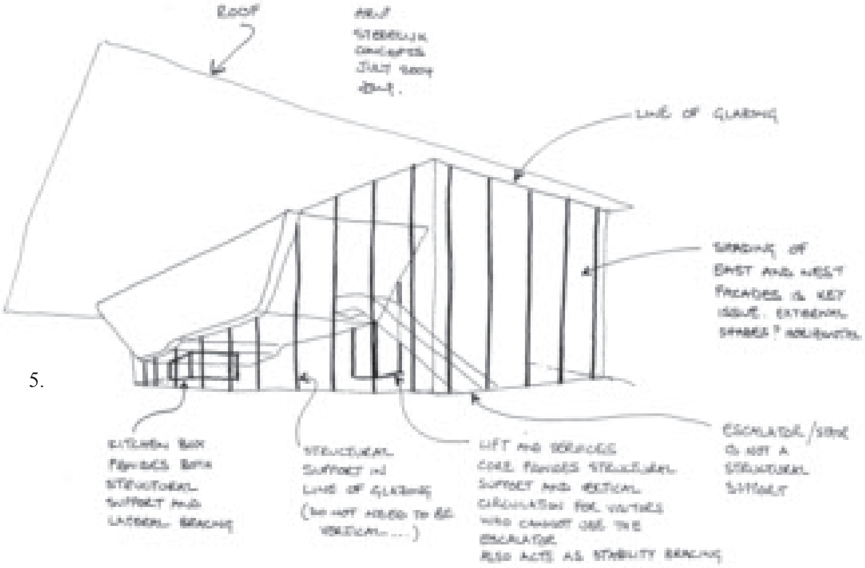


5.

1. Museum shop in the transparent ground floor of the new building.

2. The original building under construction in 1893.

3. Architect's impression.

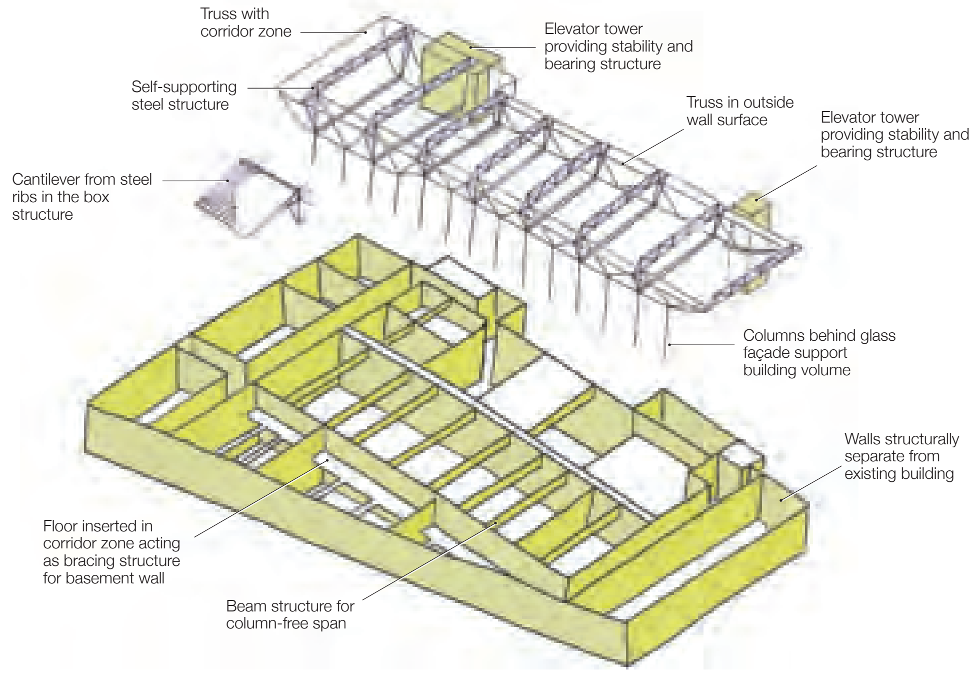
4. Relationship between new and old.

5. Arup's initial structural concept for the new building.

6.

6. The new entrance area.

7. Structural design at the competition stage.



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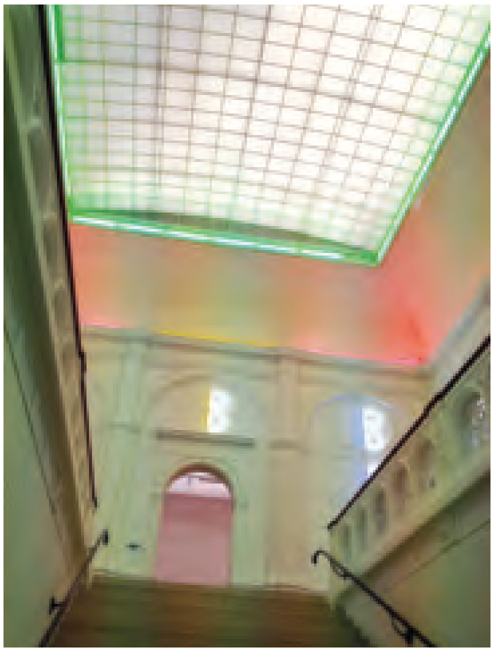


8.

9.

For the "bathtub", Arup designed a steel structure with load-bearing columns behind the glazed curtain walling, trusses within the exterior walls, and trusses in the transverse direction in various grid patterns (Fig 7). Stability is provided by wall elements and steel portals. By having only part of the new building above ground and sinking two floors of it below ground level, the existing building was kept virtually intact and its original aspect preserved as far as possible, the glazing on the new building's ground floor allowing the façade of the old building to remain visible. Arup also carried out the lighting design for the new building.

The Weissman building

The 1895 building is known for its symmetrical layout, its central staircase (Fig 8), its diversity of rooms and galleries, and above all for the rooms on the upper floor, with its magnificent (natural) overhead light and fabric ceilings. All these defining features were retained in the new design. Mezzanine floors that had been installed during the 1950s were removed, and various recesses were created for the new installations.

Air supply and extraction are routed through recesses in the arches of the vaulted floors. In the basement the air is conveyed through ducts to various riser points, made possible by cutting a large number of recesses in the basement and a ground-level intake to draw in air from the exterior. The new positioning of pillars as a result of the 1950s refurbishment was taken into account when creating the recesses in the interior walls. Also, the high level of the water table meant that watertightness was an important design factor.

Another challenge was to prevent distortion of the original wall murals by Karel Appel. As with the sinking (drilling) of the sheet piling and the foundation piles, the particular conditions at each location had to be taken into account.

Substructure

A two-level basement was built under the square and the new superstructure, down to a depth of 8.5m below ground level and locally 12m at the goods and truck lift. The basement is a 90m x 45m concrete shell with outer walls varying in thickness from 500mm to 800mm depending on the lateral forces. The basement floor is 500mm thick, built on an under-water concrete floor.

The walls at ground floor level are supported by system floors, matching the span of the installations. The floor systems employed are hollow-core slabs, I-beams and heavy-duty girders, featuring a continuous compression layer. The interior walls are also 500mm thick concrete. Stringent requirements were imposed for watertightness (crack width) in the basement floor as well as the basement walls, on account of the museum functions located in the basement (Fig 10).

10.

8. The head of the central staircase in the refurbished Weissman building.

9. The large exhibition space in the basement can be subdivided by temporary walls to suit specific requirements.

10. Building below the water table for the new basement.

11.

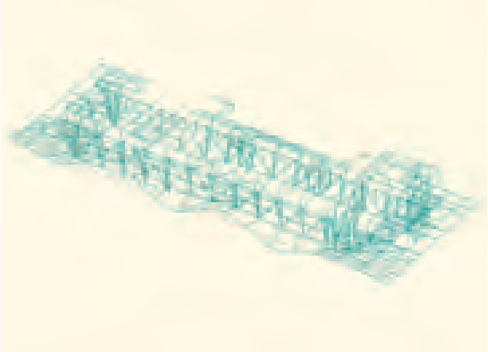
Superstructure of the new building
In addition to the basement, the new construction comprises a glass-enclosed ground floor as well as the opaque, seemingly solid, bathtub-shaped superstructure above that seems to hover over the ground level (Fig 11), through which the original building is visible. Together with the new entrance to the museum, this transparent ground floor houses an information centre, library, shop, and restaurant with terrace. The two upper levels accommodate a large exhibition space and auditorium on the lower level, and offices above. A large canopy cuts through the new structure at the height of the gutter of the original building.

The superstructure comprises steel lattice structures with hollow-core slab floors, and the steel façade trusses make it possible for the superstructure to be supported at only six points, five columns and one concrete wall, a solution that allows for a large open exhibition space. Arup and Benthem Crouwel collaborated on optimising the structure, including the location of the bearing points and the trusses.

During the contract award stage, the contractor introduced some refinement to the steel superstructure from the specification design that Arup had supplied.

12.

13.



14.

11. The signature "bathtub" shape of the new building.

12. New entrance exterior.

13. The original specification design for the superstructure, showing the four bearing points.

14. Dynamic analysis of canopy.

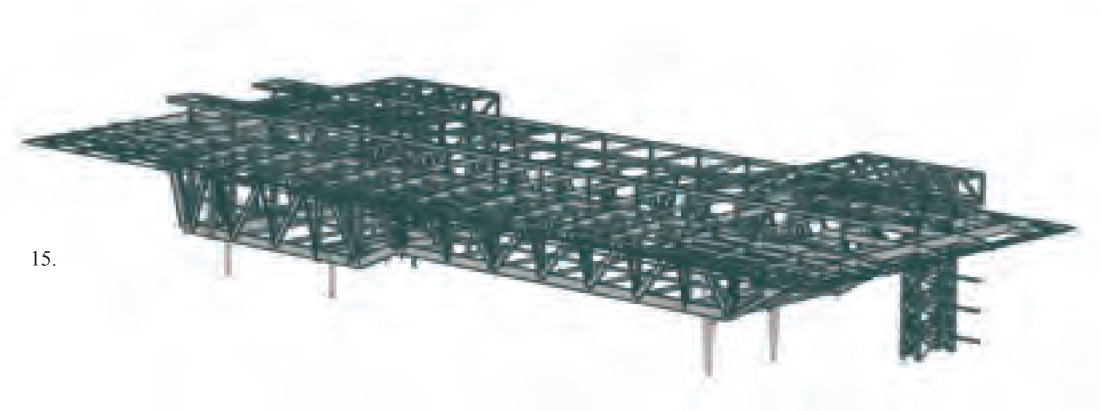
Specification design

The superstructure was originally designed to be carried on four bearing points, those to the east consisting of two columns with a box girder above, stabilised by a concrete wall, and a stabilising portal to the west, 14m in height up to the underside of the office floor. The east and west bearing points support two lattice trusses at 15m centres. Each has a centre span of around 48m and extends 20m either side. The museum floor is located between the lattice trusses at 4.72m and 6.92m above ground level, the hollow-core slabs having unsupported spans of 15m. These hollow-core slabs are centred on heavy wide-flanged I-beams (HD profiles in European nomenclature). These HD profiles can also be used as steel columns.

The office floor, 14m above ground level, incorporates *LightCatchers*[1], proprietary apertures through which natural light enters the museum hall directly from the outside. Due to the location of these, the team decided to position the hollow-core slabs for the office floor span parallel to the trusses. The plate girders for the canopy are continuous from truss to truss and carry the hollow-core slab floor, 200mm thick and spanning 6m. The roof also consists of hollow-core slabs, supported by trusses in the transverse direction perpendicular to the façade lattice trusses. The columns for these trusses bear the canopy girder (Fig 13).

In addition, Arup conducted an analysis of the canopy structure, to gauge the dynamic effect of this very large projection on user comfort (Fig 14).

In the specification Arup laid down a construction methodology in which the superstructure was to be built in layers due to the small number of bearing points, and limiting the load on the basement roof. The bottom rail of the truss was supported temporarily until the hollow-core slabs were laid and the trusses completed. The trusses were self-supporting thereafter.



15.

15. Revised superstructure concept, with six bearing points.

16, 17. Truss erection.

18. Construction of hollow core slabs.

19. Support to hollow core slabs by truss, including extra steel floor beams at 6m centres.

The optimised design

At the start of the execution phase, Arup and Benthem Crouwel were asked to consider, jointly with the main contractor, reducing the quantity of steel in the superstructure. Two optimisation proposals were examined: (1) to make the outer wall on the ground floor loadbearing, or (2) to increase the number of bearing points under the superstructure. In the end it was decided to raise the number of bearing points from four to six (Fig 15).

The use of six bearing points changed the form of the trusses and reduced their weight. The new row of bearing points consists of a concrete wall and a column with a box girder above.

This optimisation resulted in the following alterations to the specification design:

- replacing the wide-flanged I-beam profiles (HD sections) with regular I-beams (HE sections), and so reducing the self-weight
- changing the span direction of the hollow-core slab at the office floor and roof floor locations
- forming the continuous canopy in sections ending outside the lattice trusses
- combining the trusses with a quarter girder between the office floor and the roof floor (Figs 16–18).

In addition, the optimisation also caused changes to the installation design. In the specification design there was space between the hollow-core slab floor and the lattice trusses, whereas in the optimised design the girders are configured with duct feed-through apertures in the web.

Using six bearing points enabled the lattice trusses to be formed in two sections. The columns, box girders and portal were installed first, and the trusses were assembled on the basement roof and hoisted into place in two sections. The bottom rail, now constructed in the heaviest available regular I-beam profile, was too high to lay the hollow-core slabs over it, so these were ultimately laid off-centre next to the I-beams. This had benefits for hoisting into position, but drawbacks on account of the eccentricity. To cope with this, extra beams were fitted at 6m centres between the bottom rails of the lattice trusses and between the hollow-core slabs (Fig 19).

By grouting the reinforced joints between the hollow-core slabs and the lattice truss, the hollow-core slabs provided transverse stability during construction. The disc action of the hollow-core slab floor compression layer ensured horizontal transfer to the concrete walls and the stabilising portal, as previously noted.

Modifying the specification design of the canopy resulted in an increase in distortions and the consequent dynamic effect, which were countered by using additional struts to the roof. The installation recesses were placed in the webs of the top rail. Due to the dimensions of the recesses it was impossible to absorb further deflection in the top rail of the lattice trusses, so hinges were fitted locally in the top rail to eliminate bending moment. The bearing reaction of the office floor was transferred away directly to the truss verticals through an additional steel structure. The flanges of the top rail were designed to locally absorb the tension.

The use of regular I-beams (HE 1000M) also resulted in the connecting paths between the existing and new buildings being blocked, so the sections were lowered locally by around 200mm. This modified construction method resulted in more temporary connections during construction (Table 1).

16.

17.

18.

19.

20.

Table 1: Differences between the specification design and the optimised design

Specification design	*Optimised design*
Lattice truss lower rail HD400/509	Lattice truss lower rail HE 1000M
Four bearing points	Six bearing points
Office floor and roof floor hollow-core slab span parallel to lattice trusses	Office floor and roof floor hollow-core slab span perpendicular to lattice trusses
Canopy as a continuous construction	Canopy supported on outer wall girder outside lattice trusses only
Museum floor hollow-core slabs laid centrally on bottom rails of trusses	Museum floor hollow-core slabs laid between the HE 1000M members; linking beams fitted between lattice truss bottom rails due to the eccentric bearing
Trusses to support the roof	Continuous outer wall girder in lieu of trusses; the outer wall girder is stabilised by using it in double configuration
Ducts running over the lattice truss girders	Ducts running through the lattice truss girders

21.

20–21. The brick façade of the Weissman building provides both a warm backdrop to functions in the new entrance area, and a striking contrast to its architecture.

The lighting design

As already mentioned, the original design by Weissman of the original Museum was always noted for its daylighting, and when it closed for renovation one of the main lighting considerations was to maintain the feeling of it being flooded with daylight. However, analysis and testing showed that the existing daylight levels were in fact much too high for the health of the artworks.

Arup was commissioned to design the lighting, and help resolve the potential conflict between user experience and conservation by designing both the daylighting and artificial lighting installations, working closely with Benthem Crouwel to ensure that the lighting was integral to the architectural design.

Existing building

The existing museum has two main daylight systems. On the ground floor the gallery spaces are lit from vertical windows, while the first floor galleries are mostly illuminated from above through the museum's pitched roof, via a horizontal laylight. To determine the optimum daylighting approach, Arup studied the sun's path and the number of hours of daylight availability in combination with the museum layout and orientation. This revealed two key factors:
(1) for conservation of the artworks, the light entering the vertical windows needed to be reduced, but (2) at the same time visibility to the outside had to be maintained, to keep the connection with the city of Amsterdam.

To meet both requirements, the vertical windows were fitted with flat, translucent scrim, which in combination with the glazing itself ensures the correct light transmission. The scrim was architecturally designed to exactly fit the window frame, creating the impression of a continuous wall that allows soft daylight in, and gives an only slightly obscured view out, due to the heaviness of the scrim fabric.

22.

23.

As the Stedelijk exhibits much modern art, spaces are often required to be blacked out. When this is the case the scrim is replaced with an identically detailed blackout screen.

Underneath the laylight a diffusing vellum layer has been installed with integrated recessed track to allow for accent lighting with adjustable spots (Fig 22). This vellum ensures a smooth white architectural finish to the space, allowing just a subtle visibility of the original daylight construction frames.

For the ground floor galleries, and those first floor galleries without the laylight, suspended track lighting is provided. The illumination from this is indirect, aimed upwards to the ceiling and casting diffuse reflected light back down into the spaces (Fig 23).

22. Beneath the gallery laylight, a diffusing vellum layer has been installed with adjustable spots on integrated recessed tracks to allow for accent lighting.

23. First floor galleries without a laylight have been given suspended lighting racks, with indirect lighting aimed upwards to cast diffuse reflected light down into the space.

24. Section through the galleries in the original building showing the daylight entry sequence.

25. Louvre on the pitched roof windows can be adjusted according to the availability of natural light throughout the year.

26. The art installation by Dan Flavin now provides the artificial lighting for the first floor landing in the original building.

To ensure maximum daylight without overexposure to the artworks, the daylit galleries on the first floor have a louvre system installed underneath the windows in the pitched roof (Fig 24). These louvres are adjusted according to the available daylight: less open during the summer and more open in winter, to ensure the appropriate levels of light exposure.

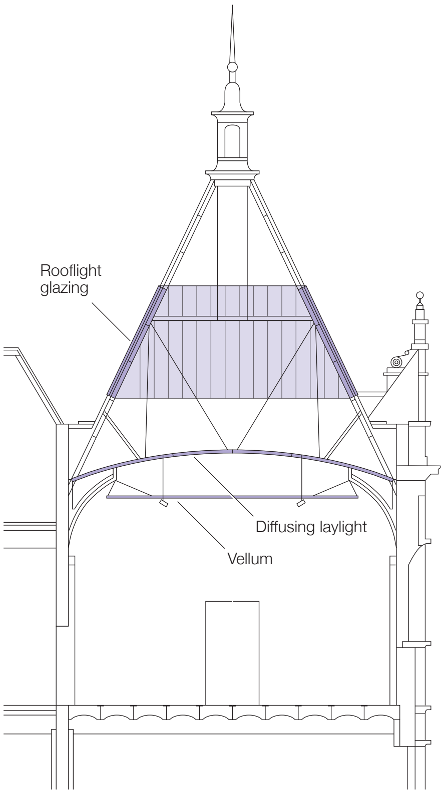
When blackout is required, the louvres can be completely closed; between them and the horizontal laylight an array of fluorescent fixtures is provided to achieve additional and constant light levels in the galleries (Fig 25).

As part of the design brief, a scale model of one gallery was made to test the lighting relationship between the skylight, laylight and vellum to ensure that the architectural intent would be met. During construction a full-scale mock-up of the louvre system was placed in one of the corner galleries to test the accuracy of the computer modelling and the acceptability of the lighting. This enabled the client to see in advance what the effect would be.

Existing building main stair

The main stair in the existing building was carefully restored and is the only interior area where original 19th century architectural details have been retained. As this area contains no light-sensitive artworks, the daylighting levels can be higher, so this space also has its original skylight visible without a vellum screen.

In 1986 the American artist Dan Flavin (1933-1996) was commissioned by the Stedelijk to create an art installation including light fixtures. This was bought back for the reopening of the museum and now provides the artificial lighting for the first floor landing, which functions as the main photo opportunity location in the museum (Fig 26).



24.

25.

26.

New building

Daylighting at the ground floor level of the new building is abundant due to the glass façade on all sides. In the evenings, ceiling fixtures ensure appropriate light levels in the space, recessed to avoid any cluttering effect.

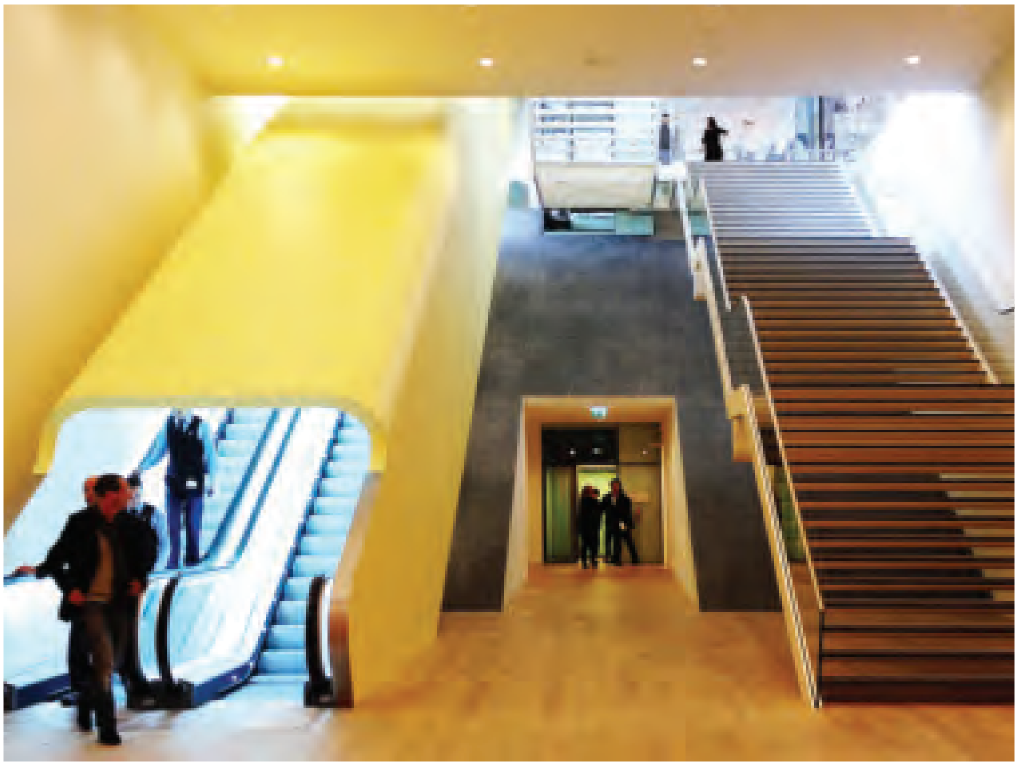
From the ground floor entrance, the main stair takes visitors down to the basement level, which contains the most extensive clear-span exhibition gallery in the Netherlands (Fig 27). By the use of temporary walls, this single large space can be subdivided to suit specific exhibition requirements.

Its location below ground level means that this gallery has no daylight access, which makes it ideal both for video installations and particularly light-sensitive artworks. The lighting design here is again a recessed track system, which allows for flexible mounting of spot and floodlights.

The other galleries in the new building are on the first floor, within the "bathtub". To allow visitors to move between exhibitions without the distraction of others entering and using the various ground floor facilities, an enclosed escalator runs directly between the lower level and the first floor, skipping the ground floor. This escalator tube has already proved to be a prime visual/ photo opportunity feature of the refurbished museum, the enclosed space with its bright lighting transporting visitors between "artistic worlds" and enhanced by the audio art incorporated within it (Fig 28).

To allow some daylight into the first floor gallery space, two linear slots of skylights were introduced along the length of the spacer (Figs 29–30). Due to the building's orientation and the limited size of these apertures, daylight does not light the space uniformly here, but adds a dynamic element to the gallery. As with the skylights in the original building, these can also be blacked out if the exhibition requires this.
The artificial lighting is by recessed track, similar to the solution in the lower level.

27.



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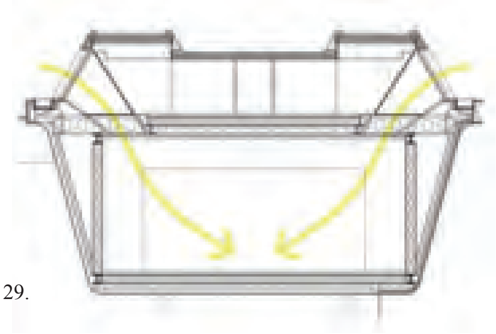

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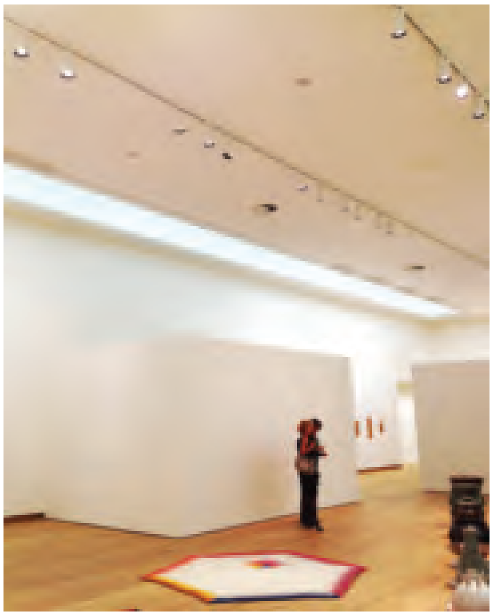

30.

27. Large basement exhibition space.

28. The brightly lit escalator tube.

29. Daylight path into galleries.

30. Linear "daylight catchers" run along the gallery edge.

31. Lighting at night emphasises the transparency of the ground floor.

31.

Conclusion

The architect deliberately created a very strong visual contrast between the exteriors of the new and the existing buildings, but in their interiors the new and the old are seamlessly connected, allowing visitors to experience the museum as one continuous structure. The lighting does the same through the use of similar solutions, with just subtle differences to match the changing architectural context.

In the first three months following its opening, the refurbished Stedelijk Museum welcomed over 300,000 visitors, well in excess of the estimated quarter-million. The result shows that the new museum has been embraced by the audience.

Reference

(1) www.econation.be/en/what-is-lightcatcher/

Authors

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Project credits

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Promoter: *Gemeentelijk Grondbedrijf Amsterdam*
Architect: *Benthem Crouwel Architects*
Structural engineer and lighting designer: *Arup — Johan Beudeker, Sander Boogers, Linda Bukman, Melissa Burton, Jeroen Coenders, Marcel De Boer, Thijs Gielleit,Stefan Greven, Arjan Habraken, Michele Janner, Ger Jonker, Ben Kreukniet, Paul Marchant, Andrew McNeil, Joop Paul, Zhiwei Qian, Reinier Ringers, Mariëlle Rutten, Jeff Shaw, Siegrid Siderius, Edwin Thie, Frank Van Berge Henegouwen, Petra Van De Ven, Wesley Van Der Bent, Rogier Van Der Heide, Clarissa Van Der Putten, Imke Van Mil, Joris Veerman, Peter Vermeij, John Wooter, Yuguang Yang, Talal Zmarrou* Building services engineer: *Huisman & Van Muijen* Façade engineer: *Solico BV*
Specialist consultant: *Imtech NV*
Main contractor: *Royal Volker Wessels Stevin NV*.

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Image credits

1, 6, 9, 12, 20, 22–23, 26, 31 *Jannes Linders*; 2 *Stadsarchief Amsterdam*; 3 *Benthem Crouwel*; 4–5, 7, 10, 13–15, 19, 24, 29 *Arup;* 8, 25, 28, 30 *Siegrid Siderius;* 11, 21, 27 *John Lewis Marshall*; 16–18 *Phillip Nijman.*

The Bill & Melinda Gates Foundation Campus

1. The North Building of the Bill & Melinda Gates Foundation campus, with the atrium on the right.

2. The campus Design Precepts.

3. Reception area.

1.

Location
Seattle, WA

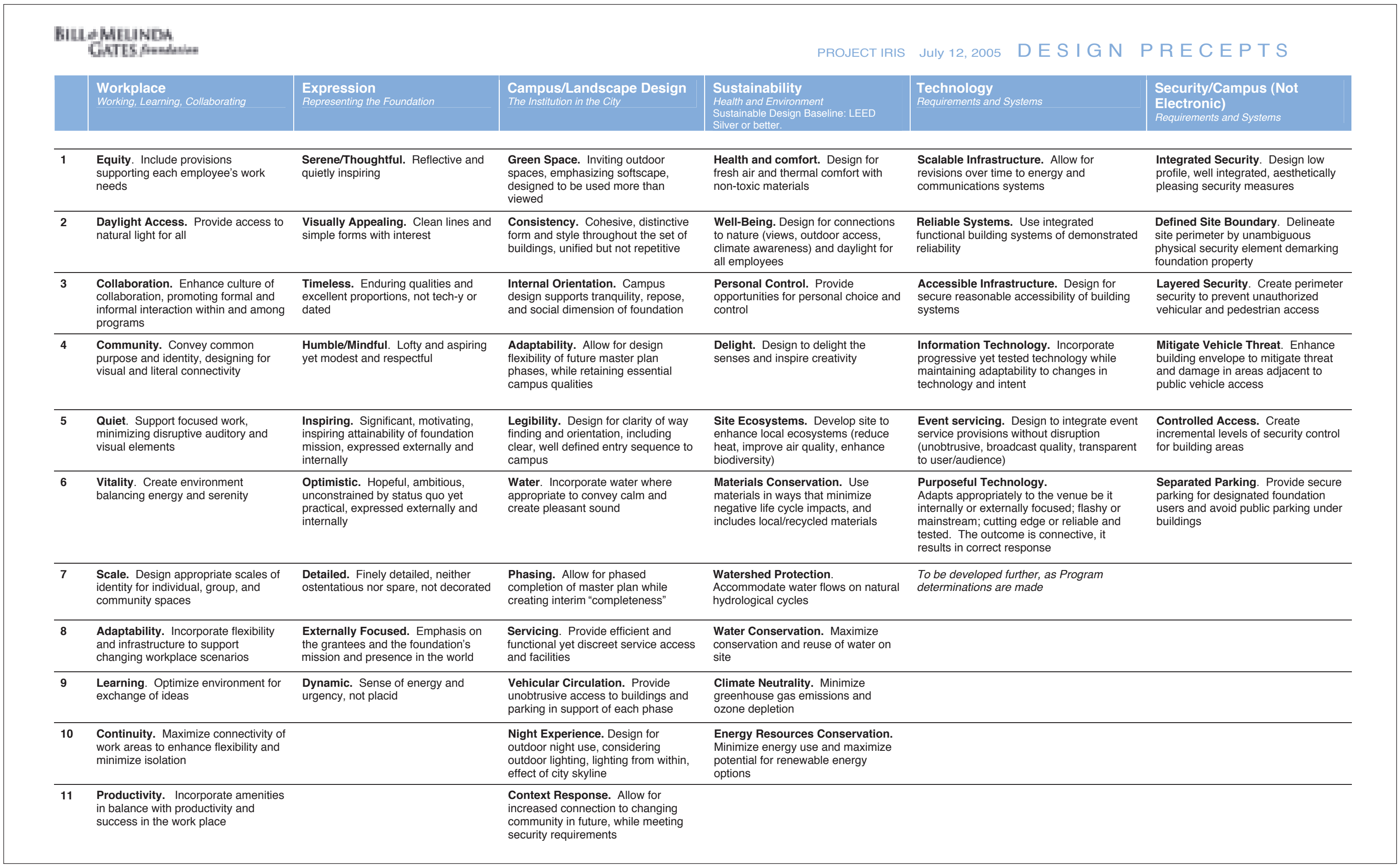
Authors
Peter Alspach Hans-Erik Blomgren
Cormac Deavy Steve McConnell
Anne Marie Moellenberndt Jay Oleson
Sara Paul Betsy Price Simon Reynolds
Jesse Vernon

Introduction
In 2005, a team from the Seattle architectural firm NBBJ met with Melinda Gates to discuss design and planning for the new Bill & Melinda Gates Foundation headquarters in the City's downtown. The Foundation had originally been established in 1994 as the William H Gates Foundation, but this was changed to its present name five years later.

The Foundation's ambitious goals range far and wide, from eradicating age-old scourges such as malaria and polio, and producing the first HIV vaccine, to preparing every student in the United States to graduate from high school ready for college and a career.

Melinda Gates took the lead in planning the US$500M campus, and for inspiration she toured a host of notable buildings, from the Wellcome Trust charity in London, UK, to biotech giant Genzyme in Cambridge, MA, to the Finnish Embassy in Washington, DC. She envisioned the new headquarters as a model of durability, green design, and workplace efficiency.

Arup worked with NBBJ on the masterplan, and one of the firm's first critical steps was to help generate the campus Design Precepts (Fig 2), a guiding document covering all the Foundation's design aspirations, including its sustainability goals. Later in 2005 Arup


BILL & MELINDA GATES foundation

PROJECT IRIS July 12, 2005 DESIGN PRECEPTS

	Workplace *Working, Learning, Collaborating*	**Expression** *Representing the Foundation*	**Campus/Landscape Design** *The Institution in the City*	**Sustainability** *Health and Environment* Sustainable Design Baseline: LEED Silver or better.	**Technology** *Requirements and Systems*	**Security/Campus (Not Electronic)** *Requirements and Systems*
1	**Equity**. Include provisions supporting each employee's work needs	**Serene/Thoughtful.** Reflective and quietly inspiring	**Green Space.** Inviting outdoor spaces, emphasizing softscape, designed to be used more than viewed	**Health and comfort.** Design for fresh air and thermal comfort with non-toxic materials	**Scalable Infrastructure.** Allow for revisions over time to energy and communications systems	**Integrated Security**. Design low profile, well integrated, aesthetically pleasing security measures
2	**Daylight Access.** Provide access to natural light for all	**Visually Appealing.** Clean lines and simple forms with interest	**Consistency.** Cohesive, distinctive form and style throughout the set of buildings, unified but not repetitive	**Well-Being.** Design for connections to nature (views, outdoor access, climate awareness) and daylight for all employees	**Reliable Systems.** Use integrated functional building systems of demonstrated reliability	**Defined Site Boundary**. Delineate site perimeter by unambiguous physical security element demarking foundation property
3	**Collaboration.** Enhance culture of collaboration, promoting formal and informal interaction within and among programs	**Timeless.** Enduring qualities and excellent proportions, not tech-y or dated	**Internal Orientation.** Campus design supports tranquility, repose, and social dimension of foundation	**Personal Control.** Provide opportunities for personal choice and control	**Accessible Infrastructure.** Design for secure reasonable accessibility of building systems	**Layered Security**. Create perimeter security to prevent unauthorized vehicular and pedestrian access
4	**Community.** Convey common purpose and identity, designing for visual and literal connectivity	**Humble/Mindful**. Lofty and aspiring yet modest and respectful	**Adaptability.** Allow for design flexibility of future master plan phases, while retaining essential campus qualities	**Delight.** Design to delight the senses and inspire creativity	**Information Technology.** Incorporate progressive yet tested technology while maintaining adaptability to changes in technology and intent	**Mitigate Vehicle Threat**. Enhance building envelope to mitigate threat and damage in areas adjacent to public vehicle access
5	**Quiet**. Support focused work, minimizing disruptive auditory and visual elements	**Inspiring.** Significant, motivating, inspiring attainability of foundation mission, expressed externally and internally	**Legibility.** Design for clarity of way finding and orientation, including clear, well defined entry sequence to campus	**Site Ecosystems.** Develop site to enhance local ecosystems (reduce heat, improve air quality, enhance biodiversity)	**Event servicing.** Design to integrate event service provisions without disruption (unobtrusive, broadcast quality, transparent to user/audience)	**Controlled Access.** Create incremental levels of security control for building areas
6	**Vitality**. Create environment balancing energy and serenity	**Optimistic.** Hopeful, ambitious, unconstrained by status quo yet practical, expressed externally and internally	**Water**. Incorporate water where appropriate to convey calm and create pleasant sound	**Materials Conservation.** Use materials in ways that minimize negative life cycle impacts, and includes local/recycled materials	**Purposeful Technology.** Adapts appropriately to the venue be it internally or externally focused; flashy or mainstream; cutting edge or reliable and tested. The outcome is connective, it results in correct response	**Separated Parking**. Provide secure parking for designated foundation users and avoid public parking under buildings
7	**Scale.** Design appropriate scales of identity for individual, group, and community spaces	**Detailed.** Finely detailed, neither ostentatious nor spare, not decorated	**Phasing.** Allow for phased completion of master plan while creating interim "completeness"	**Watershed Protection**. Accommodate water flows on natural hydrological cycles	*To be developed further, as Program determinations are made*	
8	**Adaptability.** Incorporate flexibility and infrastructure to support changing workplace scenarios	**Externally Focused.** Emphasis on the grantees and the foundation's mission and presence in the world	**Servicing**. Provide efficient and functional yet discreet service access and facilities	**Water Conservation.** Maximize conservation and reuse of water on site		
9	**Learning**. Optimize environment for exchange of ideas	**Dynamic.** Sense of energy and urgency, not placid	**Vehicular Circulation.** Provide unobtrusive access to buildings and parking in support of each phase	**Climate Neutrality.** Minimize greenhouse gas emissions and ozone depletion		
10	**Continuity.** Maximize connectivity of work areas to enhance flexibility and minimize isolation		**Night Experience.** Design for outdoor night use, considering outdoor lighting, lighting from within, effect of city skyline	**Energy Resources Conservation.** Minimize energy use and maximize potential for renewable energy options		
11	**Productivity.** Incorporate amenities in balance with productivity and success in the work place		**Context Response.** Allow for increased connection to changing community in future, while meeting security requirements			

2.

3.

Decision making and collaboration

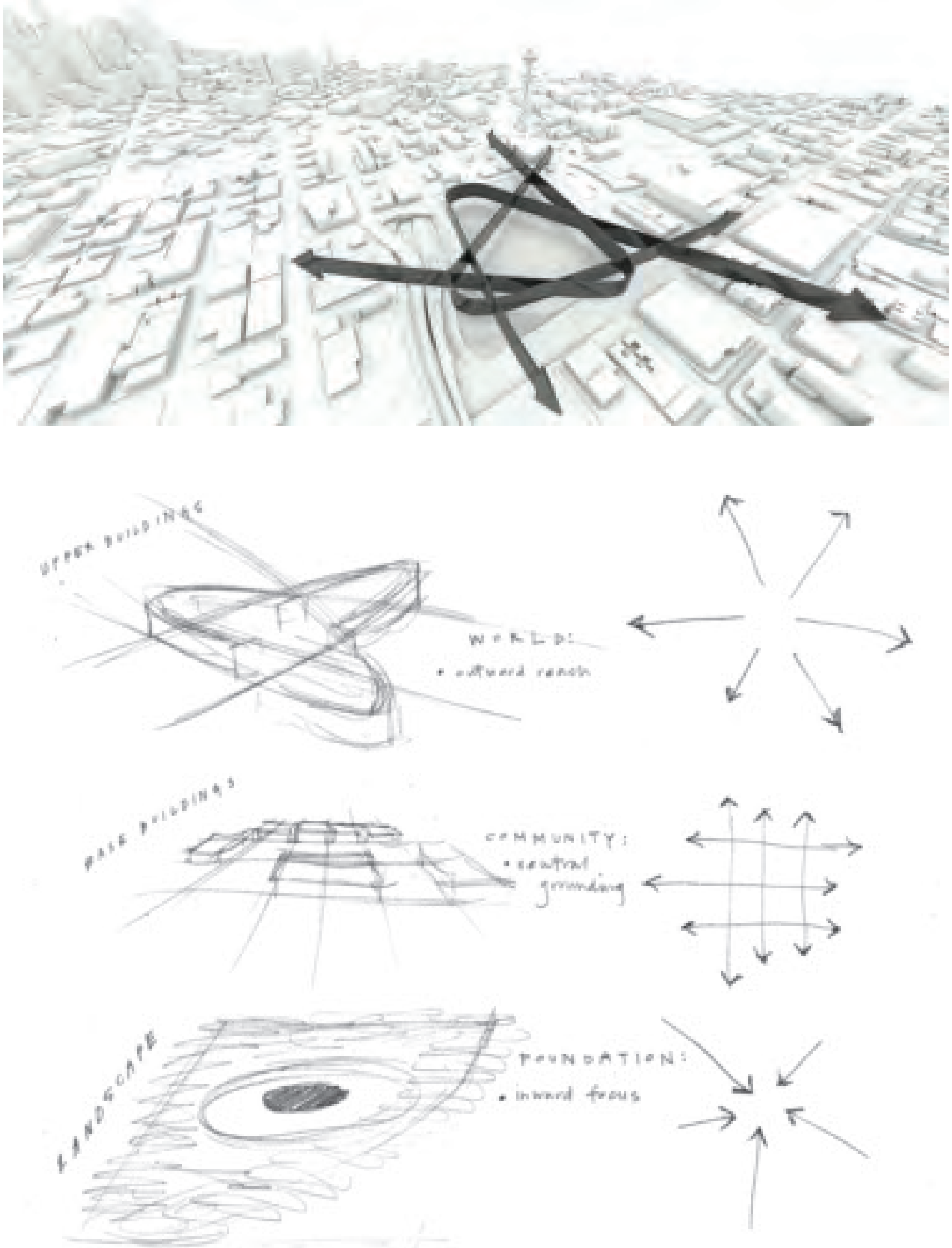
Decision making for the campus was driven by two key factors — the Foundation's Design Precepts and a spirit of collaboration. The Design Precepts served as a constant reminder of the Foundation's values and overarching goals for the project and the team referred to them constantly when evaluating design solutions — particularly so when facing the tough choices sometimes necessitated by budget challenges. By having a clear client vision articulated for the whole team, decision making was relatively straightforward for all its members.

The joint team of architects, engineers and contractors approached major decisions together to ensure buy-in from all parties and thorough constructability reviews. A total-cost-of-ownership life-cycle evaluation was performed for major systems; this accounted for the Foundation's expected 100-year life while maintaining the client's remit that all decisions be economically sound. The total-cost-of-ownership approach included first costs, operational and maintenance costs, capital equipment replacements, and commodity costs. This financial analysis was then supplemented by a non-financial evaluation to capture some of the aspects of performance that are not as easily quantified financially.

joined the NBBJ-led design team to provide structural, mechanical, electrical, and plumbing (SMEP) engineering services, and subsequently added acoustics, audiovisual (AV), information and communications technology (ICT), façades, and materials consulting. As well as NBBJ and Arup, the team included Sellen Construction Co, Seneca Group, Gustafson Guthrie Nichol (GGN), McKinstry, KPFF, and Cochran.

In 2006, a meeting was held with Melinda Gates to review NBBJ's initial architectural concepts based around the Design Precepts. When plans for a set of unassuming rectangular buildings were unveiled, she thanked the team for delivering what she had asked for, but sent them back to the drawing board. The space initially envisioned as "humble and mindful" also needed to be bold. It had to make a statement reflective of the Foundation's own expansive ambitions. *"I wanted something that's rooted in the Northwest,"* Ms Gates said, but it also needed *"to be iconic and represent the work we do. And the work we do is global; it reaches out to the world."*[1]

The campus duly embodies connections between the Foundation's global mission and its local community, with structures that represent both local roots (commitment to the Pacific Northwest) and global values (the belief that every life has equal worth). The masterplan's three prominent office wings cantilever above the campus grounds, rotated in different directions like arms reaching out to the world (Fig 4). The base buildings support the neighbourhood context, aligning with the orthogonal City grid, providing wide new pedestrian walkways and returning nearly half the site to green space. With its curved glass walls and City-centre site, the Foundation is visible to and linked with the community and neighbourhood.



4.

4. Concept diagrams of a "bolder" campus.

5. Site masterplan.

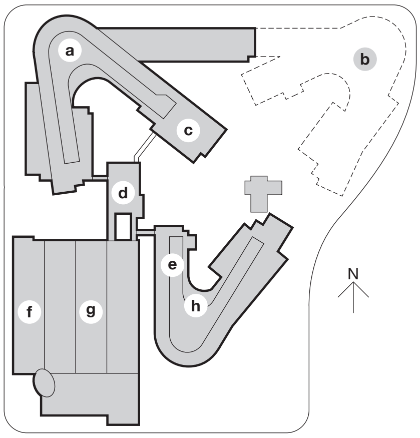
6. Solar control blinds help maintain thermal efficiency.

7. The Visitor Center.

Project overview

Completed in spring 2011, this new home for all the Foundation's staff occupies 12 acres (4.9ha), replacing an asphalt parking lot with a campus that includes two acres (0.8ha) of living roofs and native plantings.

The masterplan (Fig 5) comprises four main above-ground structures and was split over three phases: (1) the garage, incorporating the Visitor Center; (2) the seven-storey North (A) and South (B) Buildings connected by a basement; and (3) the East



5.

a North Building
b Future East Building
c Atrium
d Reception Building
e South Building
f Visitor Center
g Garage
h The Knuckle

6.

7.

Building (currently in design, and which will add an additional 400 000ft^2 (37 200m^2)). The museum-style Visitor Center opened in May 2012 and includes hands-on exhibits about the Foundation's mission (Fig 7).

At 900 000ft^2 (83 600m^2) gross for phases 1 and 2, the project — incorporating offices, an atrium, a data centre, a commercial kitchen, service spaces, loading docks and below-grade parking — demonstrates how large-scale sustainable architecture can be delivered at the highest level.

The multifunctional basement, which runs under most of the site, includes car parking, a loading dock, MEP equipment rooms, and more specific programme requirements such as fitness rooms, catering kitchens, storage, the data centre, and security kiosks. The buildings above have consistent architectural styling and detailing, and building systems. At its east end, the North Building flows into a lightweight glass and steel atrium.

The Foundation needed a workplace environment that supports the unique needs of its partners and staff. Each office "neighbourhood" accommodates 20-25 people, with conference rooms and informal seating areas creating intimate, cohesive team spaces. Shared amenities encourage exchange of ideas and the 60:40 split respectively between open and private areas allows for both collaborative and heads-down work.

8.

Melinda Gates said she hopes that all this helps the Foundation's employees, who hail from 37 countries, to do their best work: *"If having a space where people can collaborate better leads to that, then I think we've achieved our mission."*

The core purpose of the campus is to create a workplace environment that supports the unique needs of the Foundation's partners and staff. Face-to-face connections are a priority for its constantly travelling workforce. A curved, glass breezeway along the inner curve of each building serves as the main circulation corridor, offering visual connections to anywhere on the campus. Standing at the end of a building, the viewer can see all six floors of staff and partners working, collaborating and traversing.

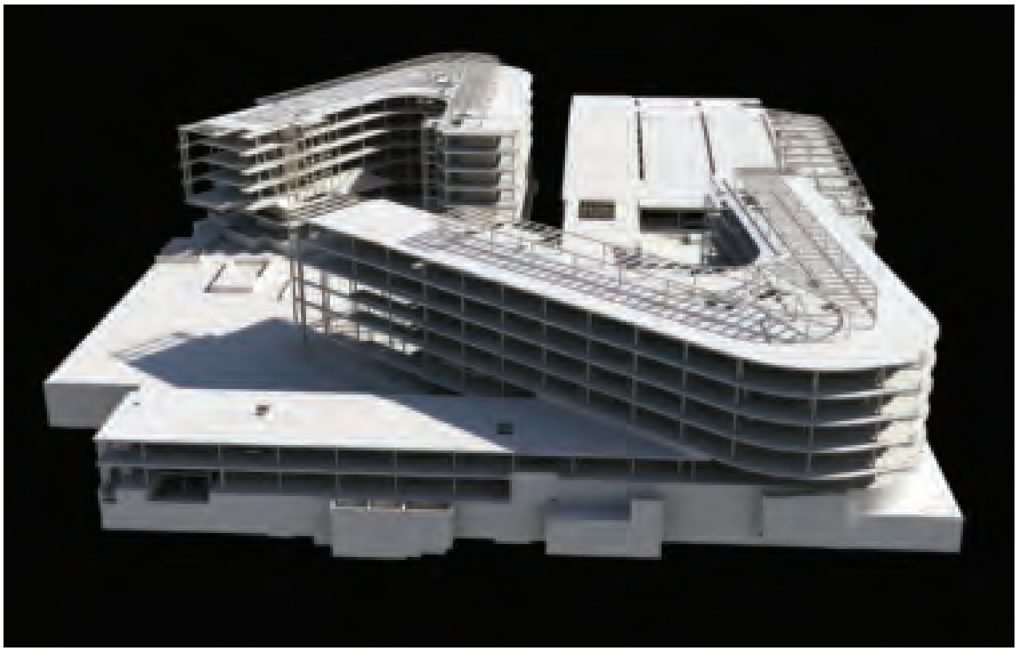
A central staircase is used to encourage informal interactions, and the atrium is designed as the social hub, where staff and partners enter each morning, grab coffee, and start their day. The entire campus is designed to serve as an extended workplace for a highly flexible workforce.

The site

Early use as a trolley and bus barn had left local high concentrations of soils contaminated with hydrocarbons. This was taken into account in the building's early planning and orientation, locating the below-grade spaces to minimise the excavation and subsequent off-site treatment and disposal of the contaminated ground. To prevent gaseous intrusion into the building, the slab on grade and perimeter basement wall over the entire site were constructed with an impermeable vapour barrier system in addition to a waterproofing membrane.

Above ground, the landscape design integrates the site with the buildings and serves as a visible reflection of the project's sustainability. The water features, sourced from rainwater, provide local habitat for birds and other wildlife.

The site is also an extension of the office workplace, creating outdoor environments where staff can work amidst a peaceful oasis within the City, aided by an IT infrastructure designed to maximise workplace efficiency by providing wireless and cellular network availability throughout the campus; the goal was to be able to work online anywhere — informal gathering spaces, conference rooms, atrium, within elevators, and outdoors — without disconnecting from the network.



9.

10.

Workplace design

Planning the spaces

Ultimately, the building is about its occupants and their mission in realising the goals of the Foundation. The main buildings comprise 64ft (19.5m) wide, four-storey offices above a deeper podium structure that houses additional office space and support functions including a convening centre, training centre and servery/dining facilities.

As already noted, the office workspace is organised around "neighbourhoods" of 20-25 people. These needed to be highly flexible: though they were basically designed around a 60:40 ratio of open/closed offices, the Foundation wanted the flexibility to accommodate layouts ranging from 90:10 to 10:90 open/closed. This desire for flexibility extended throughout the design of the building systems.

The brief was to create a column-free and flexible space, and at the same time maximise clear heights. Given the need for flexibility in programming the office space, the team selected a 50ft x 30ft (15.2m x 9.1m) column grid, and a composite steel gravity frame (Fig 9), with three separate concrete shear wall cores for lateral stability (Fig 10), as the structural system for the North and South Building towers.

A 30in (760mm) depth allowance for the composite beams and slab achieved this, and also allowed for and incorporated mechanical, electrical, plumbing and fire protection distribution. The floor beams cantilever off each column line, creating the total 64ft (19.5m) building width, versatile enough for multiple interior office layout arrangements. As part of the focus on the users, the team undertook finite element analyses to assess human-induced vibrations of complete floor plates, ensuring adequate occupant comfort and client satisfaction while maintaining an economic structural steel floor solution.

8. The campus is visible to and linked with the community and neighbourhood.

9. Digital structural model of the first two phases of the Campus, showing the North Building *(foreground)*, South Building *(behind left)*, and garage *(behind right)*.

10. The three concrete cores, showing the scale of the construction.

11.

Windows to the creative inspiration

“Could you explain the case for value, given the design team’s recommendation for a premium curtain wall system?”

12.

That was the question posed by the Foundation to NBBJ to validate its proposal to invest $8M above the standard curtain-wall benchmark on glazing for the project. NBBJ sought floor-to-ceiling, argon gas-filled, double-glazed units with interior laminated glass lite windows for the office wings to enable a 30% increase in façade energy performance and glass units twice the typical width — mullions 10ft (3m) across instead of the standard 5ft (1.4m). Conveying the integrity of this specification was crucial to NBBJ’s vision for a workplace design that wasn’t just the backdrop to innovation, but that actively courted it.

Transparency — one of five “vision critical” design strategies NBBJ employed to signify the Foundation’s culture and values — included the expansive glazing, which would allow employees to see one another across the campus courtyard while working in separate buildings. The strategy of connecting employees visually arose in part out of the fact that Foundation employees, global experts in their fields, travel frequently. Demanding schedules can make teamwork more difficult to orchestrate, and visual connections could abet this.

Besides providing further visual signification of the Foundation’s mission and its openness toward its urban Seattle location, transparency would also create a new standard in high-performance workspace design through the penetration of daylight and the views afforded. These windows would also reduce energy costs and contribute to a consistent distribution of heat, and hence greater comfort, for employees. Goals such as eradicating some of the world’s most pernicious diseases demand a space that enables brilliant thinking and creativity, space that literally works to connect and inspire employees. In the service of that, NBBJ’s recommendation would allow daylight deep into circulatory spaces — areas known for bringing people together in both planned and serendipitous ways. The designers sought to leverage the possibilities of employees hatching and building on great ideas in the staircases as well as at their desks.

But to accomplish that required designers to make the case for value to Melinda Gates, who was responsible for ensuring the judicious use of design and construction funds for the building. NBBJ asked Arup to present the benefits of this solution. Arup offered its quantitative cost-benefit analysis of window walls and mechanical systems, which compared the inverse relationship between up-front glazing costs and long-term energy savings. What truly created the moment where the Foundation understood the importance of the design solution was when Arup presented qualitative information derived from researching a wide range of building typologies — hospitals, schools, corporations — where views and expansive daylighting has been documented, largely anecdotally, to increase productivity and engagement.

Arup’s development of the technical and anecdotal information from their experience creating systems for a wide range of building types is what helped The Bill & Melinda Gates Foundation truly understand that this wasn’t just about aesthetics, but it was a strategy to increase employees creative productivity and intellectual capital. Yes, windows can do that, and Arup’s sophistication helped us execute our design vision to its fullest.

Steve McConnell, Managing Partner, NBBJ

Façades

The façade design was another important factor in the overall architectural design. The Foundation wanted a façade that signified its particular culture and values rather than that of a typical office building. A 5ft (1.5m) wide module is commonly used in commercial façades because it co-ordinates well with internal space planning, but NBBJ observed that use of this tends to proclaim "office" however it is dressed up. Narrower modules of 4ft (1.2m) express curving plans well by the way they form small facets, but they are associated with residential schemes or, worse, older offices. A module width of 10ft (3m) was preferable to create wide windows and a façade rhythm with spacious horizons. From an early stage it was clear that the width of the façade panels would be a significant design factor in the importance it had for expressing the Foundation's culture and values.

The panel width not only established the character of the façade but also had a significant impact on the building's —overall energy performance and internal environment. The panel width is the same on both the inward-facing breezeway and the outward-facing façades. On the breezeway the large floor-to-ceiling glass panels, accentuated by an elevated ceiling with tapered cantilevered beams, highlight the inner transparency of the campus, bringing office activity and life to its heart.

The higher ceilings also allow for increased daylight penetration to the workspaces by the breezeway circulation zone. At the outer façade a more traditional 30in (760mm) sill provides more external privacy while still allowing for views and daylight to the opposite perimeter. The 10ft (3m) panel width also reduced the thermal bridging of the façade, allowing for improved thermal performance.

Panels 10ft (3m) wide and 6ft 7in (2m) tall may not sound difficult to make for a breezeway, but they needed to be heat treated for strength and thermal shock resistance, and laminated for security reasons. The team realised that nearly all glass tempering machines in the US at that time were less than 10ft (3m) wide, which meant the glass would have small waves of distortion running up and down the pane. That looks bad from the outside, and even worse to occupants, whose view out is distorted by the lens effect created when two wavy panes are laminated together.

Given that some distortion was inevitable, it would be much less noticeable if the waves ran from side to side — but that necessitated a machine over 10ft (3m) wide. Arup's UK-based glazing specialists worked with global and American suppliers, the contractors, and NBBJ to provide several procurement options to keep pricing competitive while achieving the critical glazing vision for the campus.

Incorporating the services

An underfloor air distribution system works in concert with access-flow power and data distribution to allow for a highly reconfigurable workspace; the system also enables flexible reconfiguration of cooling and more individual control of thermal comfort than typical HVAC solutions.

An 18in (460mm) deep access floor at the podium levels accommodates the higher demands associated with conference and meeting facilities, while a 16in (410mm) deep access floor is used at the upper office floors due to reduced loads and the desire to keep floor-to-floor distance as low as possible. A 2in (50mm) clearance between the floor beams and the suspended ceiling creates the return air path.

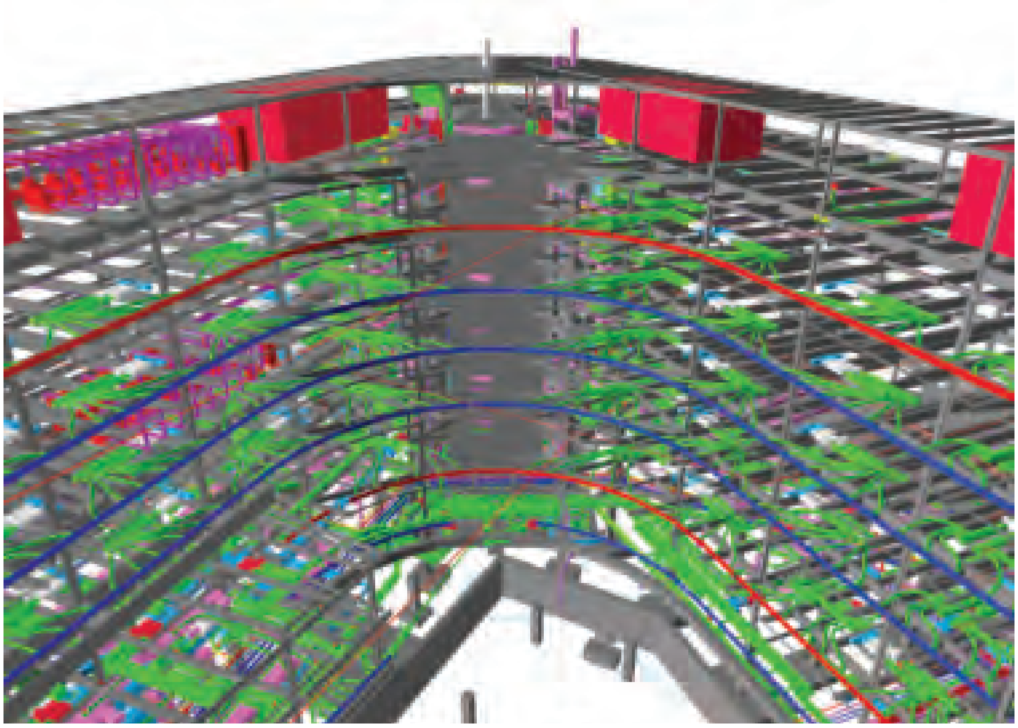
The underfloor electrical distribution system, for both power and data, uses pre-manufactured flexible cables with quick-connect fittings for each workstation and to plug into floor boxes. Spare capacity at the distribution points accommodates the need for any future increase in workstation density, while spare cable length at each floor box allows small moves for them as needed to co-ordinate with furniture over the life of the facility. Spare capacity in the HVAC system allows for up to a 20% increase in cooling output.

Integral to the structural beams are pre-co-ordinated service openings with spare capacity for future overhead distribution, with an extra opening at the roof beams to allow for rainwater leader routing without impeding future penetration capacity.

11. Open space in front of the North Building.

12. The tall, wide glazing panels accentuate visual connections across the campus.

13. Structure/building services 3-D co-ordination model.



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Cantilevers, knuckles and cowls

At the building ends and central sweeping curved regions or "knuckles", raking columns (approximately 25˚ from vertical) and wide-flanged hangers create cantilevers of up to 60ft (18.3m) that allow floor levels 3–7 to project over and be visually distinct from the lower two-storey, steel-framed podiums (Figs 14–16).

At each level where a corridor runs along the inner edge of the floor plate, the steel cantilever beams and ceiling are tapered to allow for increased floor-to-ceiling height and more favourable natural daylight through the exterior façade. During construction, each steel hanger was supported off temporary shoring columns that were removed after the steel framing was completed.

At the building ends, the hangers also support exterior 30ft (9.1m) steel box cantilevers at level 3 and a roof and connecting side walls that frame out the architecturally expressed building cowls.

16.

14. Digital model of composite structure, showing raking columns at building end.

15. Raking columns and hangers under construction at "knuckle".

16. The sweeping curved portion or knuckle of the North Building, where raked columns enable the cantilever of levels 3–7, visually distinct from the two-level steel-framed podium.

17. South Building cowl under construction.

18. Interior of North Building cowl

19. Completed South Building cowl.

17.

18.

19.

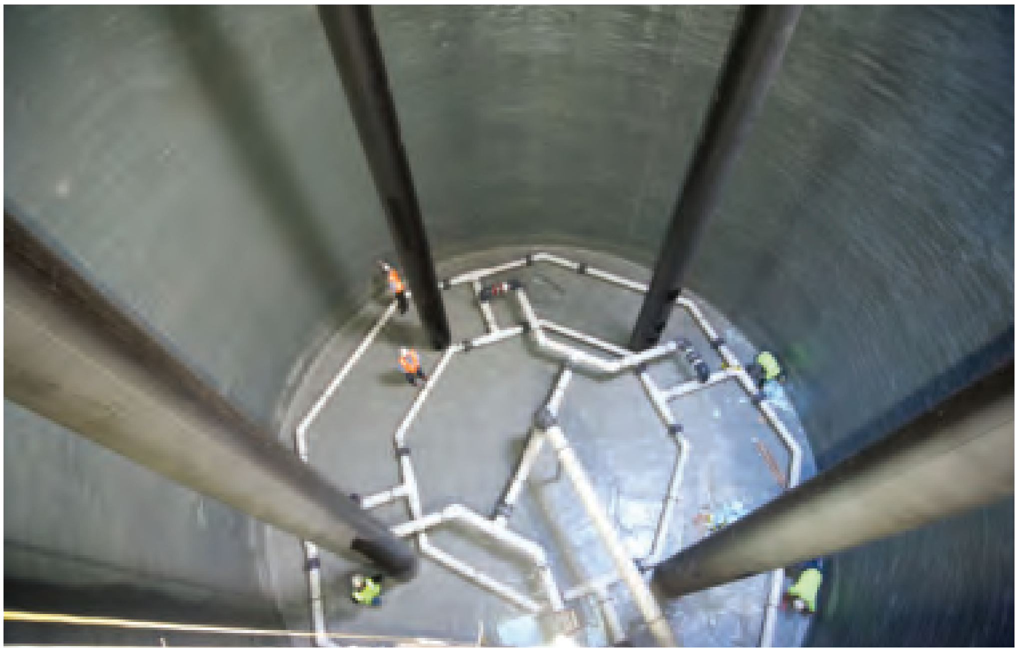
At the cantilevered cowl tips, 2.5in (63.5mm) upward cambers were required to ensure that the cowl in its unshored final state would reside within the building envelope. Diligent, co-ordinated detailing of the cowl structure with the architectural stone and copper finishes was necessary to achieve the desired result (Figs 17–19).

At the roof level, the horizontal forces from the raking columns are transferred back to the seismic core via steel diaphragm plates field-welded to the top flange of the roof beams. This structural approach allowed for unimpeded building services routing in the office ceiling plenum below.

The cantilevered structure intruded into the access floor zone at several areas, requiring co-ordination with the HVAC distribution. In these areas the beams used intumescent paint instead of typical spray-on fireproofing to reduce the blockage of airflow at the perimeter, while sheet metal plenums were constructed around the steel to allow the diffusers to sit within the floor above the beams and align with the continuous band of linear perimeter grilles along the breezeway.

20.

21.



22.

Transformer cooling code variance

In Seattle's building code, transformer cooling is prescribed to use exhaust fans to draw outside air in whenever the space temperature exceeds 70˚F (21˚C). While efficient, this approach requires a three-hour rated separation for both the intake and exhaust air paths and dumps the heat to the outside.

The Foundation's two transformer rooms are in the basement, beneath a highly designed landscape integral to the function and aesthetic of the campus. The intrusion of rated intake and exhaust terminations was thus a major design challenge. That physical constraint made Arup look at alternatives to the code's prescriptive approach to transformer room conditioning, and realise that the challenge presented an opportunity — to capture the waste heat from the transformers and harvest it to heat the building.

The team worked with the City of Seattle and Seattle City Light, the local electrical utility provider, to develop the solution: each transformer room served by two recirculating chilled water AHUs. Heat recovery to the heating hot water and domestic hot water systems is via a heat recovery chiller that captures waste heat from the transformer rooms and other cooling loads, such as IDF closets and kitchen refrigeration systems.

CFD simulation demonstrated cooling effectiveness to the utility, and the team worked with the Seattle fire department to address life safety concerns — an illuminating process for all parties as to the real intent behind many of the code requirements. The final system eliminated the vertical rated shafts and terminations, saves energy, and met all the aesthetic goals. The City liked the solution so much that it is considering modifying future versions of the code to explicitly allow for implementing the Arup approach.

Energy systems

A distributed central plant energy system provides heating, cooling and power back-up to the campus. This central plant is distributed between the two buildings, based on available roof space and load matching.

The hot water plant is on the roof of the North Building, and provides both space heating to the entire campus and domestic hot water heating to the large loads (kitchen, dining, fitness, and convening centre) within the North Building itself. The main heating hot water plant consists of eight high-efficiency condensing gas boilers with a supply temperature of 120°F (49°C) and a combined thermal output of 15 000MBH (4400kW). The heating hot water boiler plant is supplemented by a 120 ton (422kW) heat recovery chiller that recovers heat from the data centre, IT closets, transformers, and kitchen refrigeration systems.

The domestic hot water plant serving the North Building uses a 1000 MBH (290kW) gas-fired condensing boiler, supplemented by a solar thermal array — 47 evacuated tube solar collectors — that is estimated to contribute around 37% of the domestic hot water heating energy.

A central chilled water plant in the South Building provides cooling for the campus. The chilled water plant utilises 960 tons (3376kW) of air-cooled chillers combined with a 750 000 gallon (2.84M litre) thermal energy storage (TES) tank (Fig 22). The TES tank is located below grade at the south end of the South Building, with the air-cooled chillers on the roof and pumping plant in the basement adjacent to the TES tank.

The chilled water plant design was driven by several key variables, one being the Foundation's desire to be a responsible consumer of water. The team evaluated six

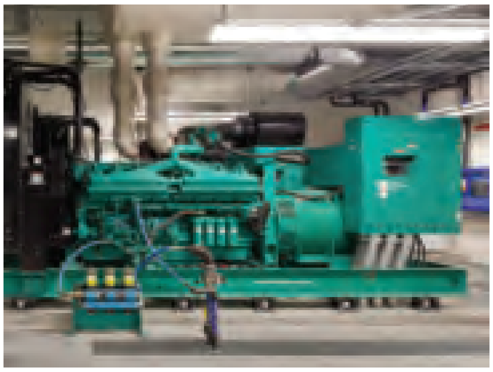
20. Rooftop AHU with coil piping connections and roof level distribution.

21. TES heat exchangers and pumps in the main TES pump room.

22. The TES tank.

23. The generator plant.

24. Reflecting pools.



23.

central plant technologies, ultimately settling on air-cooled chillers with thermal energy storage as the optimal blend of energy conservation, water conservation, and operational savings. By using an air-cooled chiller plant with TES, the chillers run predominantly at night when outdoor temperatures are cool.

The cool outside air eliminates much of the energy penalty traditionally associated with air-cooled chillers, while the lack of cooling towers eliminates the use of about 2.6M gallons (9.9M litres) of water per year compared to water-cooled chillers. The chilled water plant can be adapted for future expansion or energy rate structure changes by simply changing the TES tank's operational strategy.

The electrical supply is provided from the City utility to two transformer vaults, one at each of the main buildings. The electrical system is designed to allow the Foundation to switch over seamlessly from the current radial supply to a more robust network supply from the grid when it becomes available.

If an electricity outage occurs, the generator plant (Fig 23) provides the data centre and other campus elements with standby power, and with n+1 redundancy (one generator more than necessary to keep the data centre and life safety loads operational). Arup implemented a strategy that allows the generators to be properly tested, saves space on site, and puts the energy produced during the tests to productive use.

24.

Diesel generators used as standby power sources often end up with operational electrical loads well below generating capacity, which can in time lead to engine maintenance problems. This is often addressed by using temporary load bank equipment (imagine a hair dryer the size of a shipping container) to impose a large load on the generators, alleviating the low-load maintenance concerns. The load bank discharges the energy produced by the generator during the test as hot air.

To maintain the data centre operations during outages, the team decided to connect the entire chiller plant to the generator plant, and thus use the entire chiller plant electrical load to load-test the generators. This allows generator testing with permanently-installed equipment only, eliminating the need to find space for temporary load bank equipment. A final benefit of this approach is that power produced during the generator test is put to productive use — the chilled water from generator testing is used to charge the TES tank and eventually to cool the buildings the following day.

Water systems

Water programs are one of the Foundation's key missions and water conservation is a key focus of much of the campus's sustainable solutions. Embracing a recent ruling by the state Department of Ecology that permitted rainwater collection within the City of Seattle (where served by a combined sewer/storm water system), the team developed one of the country's largest rainwater harvesting systems.

Despite its reputation for rain, Seattle actually has a two to four-month summer dry period, which coincides with peak water consumption from landscape irrigation, cooling use, and evaporation from water features (Fig 24). To meet the initial goal of 100% of the irrigation and water feature make up from harvested rainwater Arup, GGN and KPFF looked at a balanced supply-and-demand approach to bridge the dry period.

To minimise the storage tank size, the team looked at non-traditional water sources, including the capture and use of nearly 250 000 gallons (950 000 litres) of condensate from the 20+ air handling units (AHUs) on the project that typically get dumped during the summer — exactly when a source was needed.

Given this additional water source, Arup determined that toilet flushing and water feature needs could also be met with collected rainwater, if a place could be found for a 1M gallon (3.8M litre) water tank. The team identified an unused void in the basement excavation that met the size requirements and would simplify the basement construction as it reduced shoring and slab stepping.

The basement structure contains the 14 200ft^2 (1320m^2) rainwater harvesting storage tank (Fig 25), which has a 30in (760mm) thick concrete slab on grade and 18in (460mm) thick perimeter concrete walls. As there are occupied spaces around the tank perimeter at the basement level, a waterproofing membrane was applied to its interior surfaces.

To further mitigate the risk of leaks, additional measures were taken including water stops at all concrete construction joints, use of proprietary corrosion-resistant reinforcing bars, and a proprietary concrete mix with integral waterproofing and corrosion protection admixture for casting the tank's base and walls.

The final campus rainwater system harvests 2.5M gallons (9.5M litres) per year from approximately one-third of the 12 acre (4.9ha) site, meeting 100% of the irrigation demand and 95% of the overall non-potable demand. The storage tank doubles as a stormwater overflow volume to help minimise flooding of local sewers, helping to alleviate surcharge issues on the local combined sewer/storm water system that discharges surcharges to the Puget Sound.

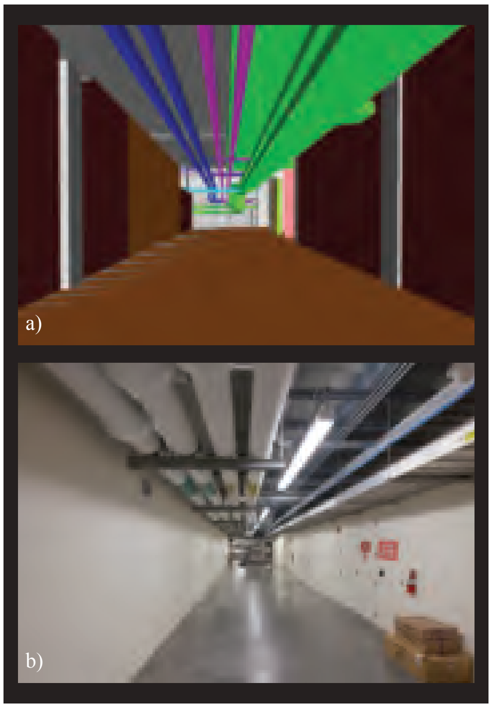
Basement

The basement of the Foundation interconnects all the buildings on the campus, providing parking as well as utility routing and support services such as the fitness centre, kitchen, loading dock, shipping and receiving, data centre, and a large portion of the MEP spaces. As the basement is thus a major service route for the building, early co-ordination was critical to set out the correct dimensional allowances and get the main routing paths co-ordinated between major load centres (Fig 26).

At grade, the steel office towers bear on a two-storey cast-in-situ basement structure that encompasses the entire site and provides an additional 400 000ft^2 (37 000m^2) of floor area. Beyond the towers, the grade level accommodates a landscaping buildup allowance of 5ft (1.5m) for water features, soil, paving and large tree pits. In addition, the design required a large live load allowance for fire truck access.

These loads, totalling over 750lb/ft^2 (3660kg/m^2), are supported on 16in (400mm) two-way flat plate slabs with drop caps on a 30ft (9.1m) square column grid. The slabs were cast monolithically without movement joints, but with 28-day delay pour strips to mitigate in-plane restraining forces from shrinkage and creep.

All below-grade parking areas were kept outside the tower building footprint, which allowed for all the large tower column loads to carry directly down to spread footing foundations without the need for transfer beams, while at the same time maintaining an efficient car parking layout.



26.

25. Rainwater storage tank.

26. Access route in the basement: (a) digital model; (b) built reality.

27. The garage (*see following pages*) was the first element of the campus to be completed, and its 1.4 acre (0.6 ha) green roof, by far the largest in Seattle, is now well established.

25.

27.

The Garage

Prior to overall demolition on the campus site, a new five-storey underground post-tensioned (PT) concrete parking garage with 2000 vehicle spaces was built to replace the large surface parking lot used by the Seattle Center (SC) (Fig 28). The garage had to be operational before campus construction could begin.

The garage design, incorporating the shell and core design for the Visitor Center, began in early 2006 and excavation commenced in January 2007. It was an aggressive schedule — construction of the parking levels, including foundations and basement walls, was finished in 12 months, while a further six months was needed for the one-storey steel-framed, 1.4 acre (0.6 ha) living roof.

Only one of the five levels is above ground, yet the most common, efficient structural system for parking in the Pacific Northwest was used — cast-in-place PT concrete beams, in this instance 60ft (18.3m) long and typically 18in (460mm) wide x 34in (864mm) deep, supporting a 6in (150mm) thick PT slab. The building's footprint is 240ft (73.15m) x 347ft (105.8m), surrounded by 14in–18in (355mm–460mm) thick perimeter basement walls and supported on spread footings.
Underground PT concrete is uncommon, but with careful detailing and construction it can be successful.

The structure features reduced energy use and advanced lighting design for a parking structure. Skylights bring natural light into the upper levels, and glass-housed elevators, used as the main pedestrian entries, draw daylight deep into the lower levels.
The mechanical system includes the use of two small exhaust fans wherever one large fan would be typically used. Only one of the two needs to be turned on when exhaust demands are low; smaller fans run more efficiently than large fans running below capacity. Computational fluid dynamics (CFD) analysis was used to optimise their locations. As a result, the garage uses 37% less energy than a typical code-compliant garage.

28.

The garage was awarded LEED-NC (Leadership in Energy and Environmental Design for New Construction) Gold (Version 2.2) certification, among the country's first LEED Gold freestanding garages. It also boasts the region's largest "green" roof (Figs 27, 29–30).

Structural movement during and after post-tensioning

The large PT forces applied to the ends of the beams and slabs caused them to shorten due to strain, and subsequently shrinkage and creep continued this shortening. If the walls and columns were rigidly fixed to the PT beams and slabs, this would have restricted the free shortening of those elements, leading to severe cracking and migration of the PT forces from full application where intended. Details were therefore developed to provide for shortening of the PT elements wherever they would connect to others. Sequences of concrete casting, PT application, and formwork stripping became vital to the design's success.

To stop the basement walls restraining (1) the movements necessary for application of PT force to the beams and slabs and (2) shrinkage and creep of the whole floor plate, they were shotcreted at least 21–60 days after the beams and slabs were post-tensioned (Fig 31). In effect they formed delay strips all around the structure, allowing the beams and slabs to receive PT and to shrink and creep away from the basement walls. Wall construction was thus no longer on the critical path and this helped focus activities on the floor framing.

Most PT beam jacking was done along ramp lines where the ends of PT beams were accessible. To allow movement during and after PT, a special horizontal slip plane detail was used above each beam at column joints adjacent to ramped floors. Foamed plastic sleeves were placed around each column reinforcing bar above each slip plane to allow the bars to bend slightly.

Delayed casting joints between adjacent pieces

Casting new concrete adjacent to previously cast concrete required delay — which varied according to types of element and location — so as to allow shortening, creep, and shrinkage. Each floor was divided into five separate casts (Fig 32), arranged and sequenced to allow maximum delay time between adjacent casts. The basement perimeter was enclosed with a delay pour strip, usually provided by the basement wall or a shored strip left open along the wall. Major delay pour strips cut each floor in half; with a 60-day delay, these were some of the last concrete to be cast for the garage.

Construction sequence and PT jacking access

Access for PT jacking proved necessary in several areas not planned in the original concepts, with blockouts and stressing pockets to allow the contractor to access the jacking locations prior to casting the area solid. Blockouts were sized not only for the jacks and personnel, but the necessary rebar detailing to place the bars within the blockout when it was cast back (Figs 33–35).

29.

30.

28. Interior of parking garage.

29, 30. The garage "living roof".

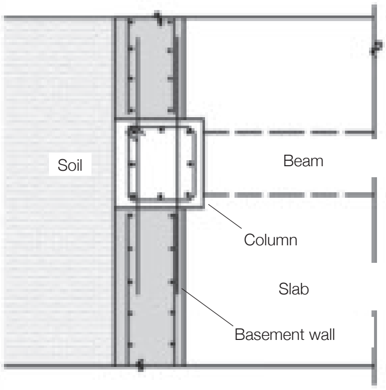
31. Basement walls were shotcreted much later than the casting of the post-tensioned beams, slabs, and reinforced concrete columns.

32. Areas for casting on each floor (five numbered), major construction joints, and the major delay pour strips in the middle of the floor plate. The 240ft (73.2m) dimension for areas 1 and 3 were post-tensioned with jacks from each end, equivalent to a one-ended PT jacking pull of 120ft (36.6m), the maximum allowed by the specification.

33. Garage cross-section showing individual casting of beams and columns: construction joints represented by lines across the columns. Beams along the ramps were generally cast with the short column below them.

34. Where PT jack access was needed at a concrete beam end adjacent to a basement wall, an end portion of the beam was left open on shoring (hatched), and cast after jacking. PT jack access at the ends of concrete slabs was similar.

35. For PT jack access at a concrete beam end along the ramp, where the beams were almost in line, the area hatched was formed, shored, but left open for access to the jacking end.



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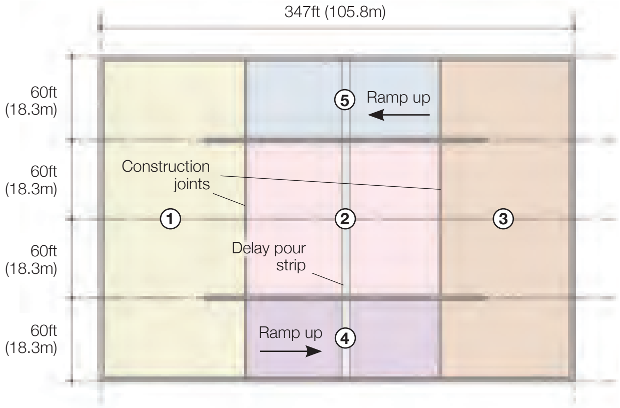

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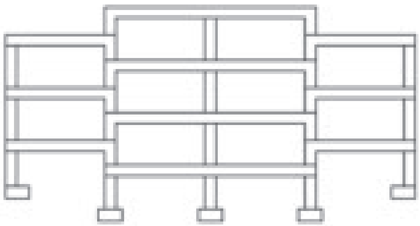

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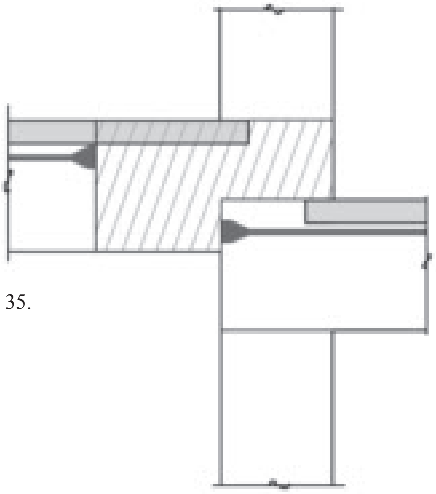

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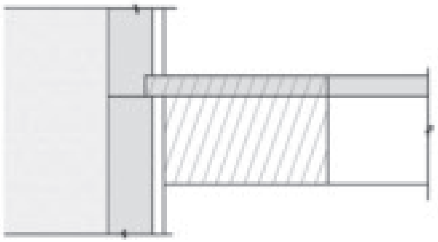

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36. Tall, slender pipe-in-pipe columns and cable-net wall contribute to the architectural effect of the atrium.

The atrium

Striking the balance

The four-storey 9000ft^2 (836m^2) atrium is at the heart of the campus, providing a daily focal point for staff as an informal meeting space and café as well as acting as a hub for large gatherings and presentations for up to 1000 people. Highly glazed and transparent, the atrium is visually and physically connected with the outdoors and the courtyard of the campus, and the desire was to "expand" it to an indoor/outdoor space in the summer months, through two walls of operable doors.

The atrium's wide variety of desired uses were significant drivers in the integrated design solution. Its typical daily use as a café and informal meeting area make it a low-occupancy, flexible, bright and lively space for staff interaction and relaxation.
Soon after seeing the initial design, however, the Foundation realised that the atrium could be more, and asked the team to explore a wider variety of uses, including large gatherings, presentations, and even musical performances.

Maintaining the architectural vision of transparency and openness while allowing the uses to shift amongst the varied desires of the Foundation was a challenge and an opportunity for the team. Adding to the challenge were the smoke control requirements of an atrium open to outdoors.

The desire for indoor/outdoor permeability led the team to consider natural ventilation as a ventilation and cooling strategy.
The Foundation did not like the idea of the atrium having a large environmental footprint supported by massive mechanical systems — especially when it would be open to the environment. However, a large design occupancy, smoke control requirements, and the desire for acoustics to support AV presentations and musical performances, formed other drivers to restrict operational freedom. Striking the balance between the drivers required all Arup's disciplines to come together with the architects to find an optimal solution.

Internal environment

Through integrated lighting, comfort, energy, AV, and acoustic design, the atrium is a multifunctional space, dynamic enough to serve a range of occupancies, from lunchtime café and informal meeting place to evening banquet venue.

With fully glazed south-east and south-west facing façades, the solar loads and daylight endemic to the design were fighting the other drivers — low-energy comfort solutions, controllable light, and absorptive surfaces for acoustics. The solution was to combine high-performance glazing in a cable net wall system with the use of a double layer shade.

This comprises two independently controlled fabric layers separated by a 12in (300mm) gap. One shade fabric is designed for solar and glare control while the other is a blackout fabric to enable AV presentations, even during the long Seattle summer evenings. The gap between the shades acts as an acoustic pocket, absorbing sound in an otherwise very live space (glass walls, stone floors). The shade system controls were integrated between the various needs, with both AV and mechanical drivers determining shade position.

Thermal comfort is maintained with a mixed-mode approach to ventilation, cooling and heating. Operable windows, controlled by the building management system, provide the fresh air inlet for ventilation and cooling throughout most of the year in Seattle's mild climate. The air is exhausted through the ceiling plenum and a roof-top exhaust that uses six fans in an array, allowing for 10:1 fan turndown to accommodate the wide occupancy range. Fans were used in lieu of upper façade vents due to concerns over maintenance access to high-level windows, as well as the desire to keep the upper façade aesthetically clean.

A radiant floor provides a base level of heating and cooling to the space. In very cold and very hot weather, trickle vents with integrated coils above the doors pre-heat and pre-cool the ventilation air; the windows are shut in such conditions and the ventilation air passes through the trickle vents before entering the space. The atrium mezzanine levels are provided with heated and cooled air via the adjacent office underfloor air distribution system, creating a micro-climate at each level despite the thermal stratification within the large volume.

A trench fin-tube heater along the south-west and south-east façades controls downdrafts from the tall glazing, augmented by the architectural shelf created at the façade; the two in combination keep drafts above occupant head level. Multiple CFD analyses of the atrium under different occupancy and climate conditions tuned the design and gave the design team and Foundation confidence in the solution — which was quickly put to the test at the opening party for the design and construction team, where nearly 1000 people gathered to celebrate the success of the project on a warm summer evening!

Fire engineering design

This was also critical to the atrium's success. Preliminary code calculations indicated the need for a 350 000ft^3/min (165 000 litre/sec) smoke exhaust system. Arup performed a performance-based fire life safety analysis that reduced the smoke control exhaust flow to 150 000ft^3/min (70 800 litre/sec) and also showed that the smoke control inlet could be achieved through operable windows and doors at the atrium base.

This analysis allowed for inlet air speed of over 300ft/min (1.5m/sec) through the operable openings, enabling around 50% reduction of inlet area compared to the prescriptive code maximum inlet speed of 200ft/min (1.0m/sec). Smoke exhaust is collected through the acoustic ceiling via slots that also accommodate lighting systems for the atrium, and expelled at the upper roof level by a dedicated smoke exhaust fan.
The design of the window and door actuators required review with the City and the City's special inspector for the smoke control system to ensure UL compliance and feedback (and over-ride) to the firefighters' control panel.

Primary atrium structure

The atrium structure is based on the façade option of a cable net, which spans vertically between the level 1 and level 5 steelwork. At level 5, the cable net connects to a box beam, which spans horizontally 20ft (6.1m) to supporting column lines. This horizontal box section is necessary to resist torsion due to offset/eccentric cable tension forces.

The atrium's south and east walls are clad with transparent butt-glazed insulated glazing supported by cast-steel clamped fittings off of vertical stainless steel strand cables, each prestressed with 50 000lbf (220kN) of tension to provide the stiffness

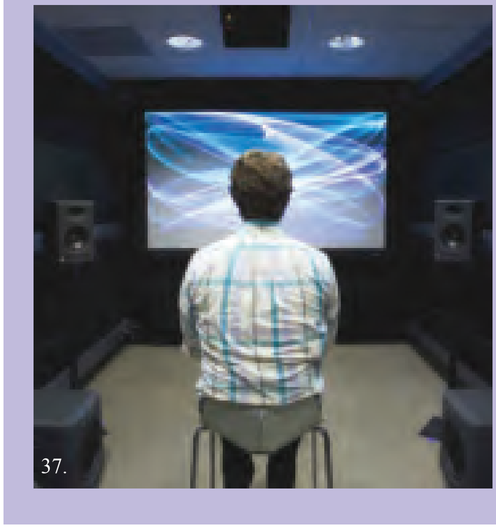
37. Arup's *SoundLab*™ in San Francisco, where the Foundation made its decision on the prototype offices.

38. The pipe-within-pipe system.

39. The data centre cabinets, with chimney extensions to duct hot exhaust.

40. Vertical circulation.

Using Arup's *SoundLab*™ as a design and decision-making tool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Early in the schematic design stage, Arup brought a portable *SoundLab*™[3] to the Foundation and NBBJ offices to demonstrate differing levels of speech privacy that could be achieved with various wall partition constructions.

Following these successful auralisation presentations, the opportunity arose to let the Foundation use the San Francisco office's permanent *SoundLab*™ to decide which particular demountable wall manufacturer to specify for the wall partitions, knowing that acoustic performance was a key consideration for enhancing speech privacy and productivity in offices.

Identical prototype offices from each manufacturer were mocked up, and the acoustics team took real sound recordings of the acoustic performance and speech privacy level that each provided. NBBJ and key Foundation stakeholders visited the permanent *SoundLab*™ to listen to the difference. The acoustics team played back various conversations and typical office activities and allowed the Foundation stakeholders to listen to the acoustic privacy achieved, just as if they were sitting in the next office.


38.


39.

to resist out-of-plane wind loads. A row of 10 slender, 60ft (18.3m) tall, architecturally exposed steel pipe-within-pipe columns, set inboard from the glazed wall, supports the large compression loads from the vertically pretensioned cables (Fig 36).

Fire-rating the columns

Code also required these columns supporting the large façade loads and roof load of the atrium to be two-hour fire-rated. Desired to be as architecturally reticent as possible, they were to have an architectural finish surface. The final column diameter of 14in (350mm) was accomplished by sleeving 10in (250mm) diameter pipes — ready-coated in the fabrication shop with a two-hour intumescent fire-rated system — within the larger pipes so that they share common end plates (Fig 38).

As the façade is a non-fire-rated enclosure, the large outer pipes can be non-rated as well, though they support most of the façade load. The inner pipes were sized for a separate dead load + snow load combination to ensure that they alone can support the floors above should the outer pipes (and façade) be compromised in a fire. This approach was verified during the design phase via a code clarification letter to the Seattle Department of Planning and Development.

Data centre

The main data centre at the Foundation houses its core IT infrastructure and is designed to be a flexible, efficient and reliable computing environment. The initial IT design load was 258kW, increasing to 340kW, with an initial move-in load of 160kW.

Space conditioning for the data centre is via a raised floor air delivery system served by two AHUs, each of which includes full outside air economiser capability for free cooling throughout the year. The units use an n+1 approach to fans within each unit for redundancy, rather than fully redundant units. This less aggressive approach is an acceptable level of risk management due to Seattle's mild climate, which allows for free cooling to provide much of the typical cooling redundancy. This approach also reduces energy consumption since cooling redundancy is normally manifested in multiple redundant coils that cause continuous parasitic fan energy consumption.

The key approach to HVAC efficiency in the data centre lies in the configuration of the room's cabinets (Fig 39). Over 60% of the room load is within fully contained cabinets with chimney extensions that duct hot exhaust from the servers to the ceiling return air plenum. The effect is to create a "cold room/hot ceiling" approach, similar to the more familiar "cold aisle/hot aisle" approach, with the benefit that the thermal zones are fully contained within physical boundaries that do not intrude on the spatial layout, now or in the future.

By using a cold room approach, the room temperature equals the rack inlet temperature, which in turn approximately equals the supply air temperature (with the exception of meeting the remaining non-cabinet loads). This allows for higher supply air temperatures and higher return air temperatures. As a result, the AHUs are in at least partial economiser operation throughout the year, and in full economiser operation for most (88%) of the year.

The lack of hot aisles also allows for improved working conditions within the data centre — some hot aisle temperatures can limit working periods due to employee heat stress risk.

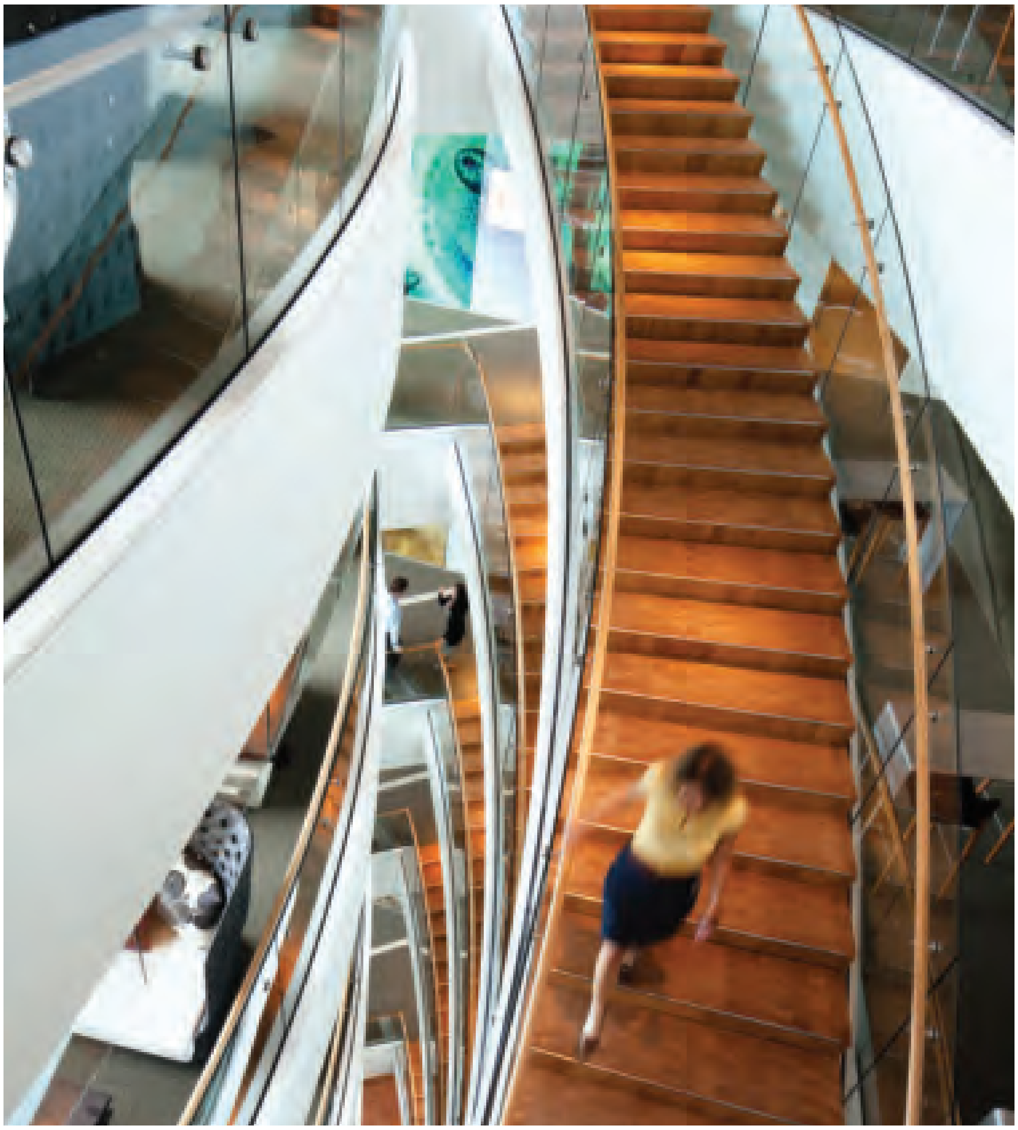
The Foundation also adopted a relaxed approach to thermal conditions in the data centre, expanding set points beyond the typically tight range. The current operating conditions are 68˚–82˚F (20˚C–29.4˚C) with relative humidity controlled to 30%–60%. These expanded operational conditions allow for increased economiser operation and reduce dehumidification and humidification energy consumption.

The data centre redundancy requirements on the electrical side are met via the central plant's generators and a full UPS system with n+1 redundancy. The generator plant supports the AHUs as well as the chilled water plant. While the latter could have relied on generator back-up to just two of the modular chillers, the team decided to connect to all four to allow for increased operational flexibility. The TES tank also serves as a key component in the data centre's resiliency, providing a source of chilled water even due to catastrophic failure of all the chillers.

Sustainable design

The project started out with the initial target of LEED Silver, in support of the city of Seattle's green building mandate for municipal buildings. But from the outset the team goal was to design the right building for the Foundation — to make smart decisions in support of the over-arching design precepts — and the approach to making smart decisions with a view towards long life solutions (the Foundation's remit was for a 100-year campus) ensured a sustainable approach to all aspects of the project, not just those within the typical remit of sustainability.

As decisions were made and designs synchronised, the LEED credits simply fell into place. Achieving LEED Platinum was thus a by-product of the design — the opposite of many where LEED point-chasing drives the design. In October 2011 the project was awarded LEED-NC (Leadership in Energy and Environmental Design for New Construction) Platinum (Version 2.2) certification, with 54 total points out of 69 available. Fewer than 8% of all projects submitted for LEED-NC certification achieve Platinum, and the Foundation headquarters has become the largest nonprofit LEED-NC Platinum building in the world.



40.

"The goal was never LEED Platinum; it was simply to design the right building for the Foundation staff and surrounding community. We had a mantra of 'do the right thing', and that's what drove the various green building decisions."

Margaret Montgomery, NBBJ Principal and lead sustainable designer.

"A sustainable Campus was a natural result of the Foundation's overall philosophy, keeping in line with values to be a good steward and positive addition to the neighborhood."

Martha Choe, BMGF chief administrative officer.

a. **Atrium** Airy central gathering space uses radiant heat and passive ventilation to conserve energy.

b. **Living roofs** 1.4 acres on the garage and over 0.5 acres on campus buildings insulate, reduce heat-island effect, limit rainwater runoff, and add bird-friendly habitat.

c. **Rainwater storage** underground tank with 1M gallon capacity stores rainwater for use in reflecting pools, irrigation and toilets.

d. **Thermal energy storage** Underground tank with 750 000 gallon capacity minimises energy used to cool buildings; it stores water chilled at night for recirculation during the day.

e. **Windows** Highly engineered windows conserve energy while admitting exceptional daylight and views.

f. **Landscape** Plantings feature native and non-invasive drought-tolerant plants and trees.

g. **Energy conservation** Energy-and water-efficient systems reduce load on local power supplies.

h. **Smart lights** Electric lights automatically dim in natural light and inactive spaces.

i. **Ventilation** Underfloor air ventilation saves energy and simplifies future space modifications.

j. **Welcoming streetscape** Wide sidewalk and large wooden benches invite a pleasant stroll or relaxing break.

k. **Digital art** The work of international artists on a digital screen.

l. **Poetry** Texts of poems run along a bench-height wall.

m. **Visitor Center** Showcases the work of Foundation grantees as well as local and global issues.

n. **Public parking garage** Serves the Seattle Center, the Foundation's staff, and its Visitor Center.

41.

Integrated and engaged design was a hallmark of the overall design/construction process, and fundamental to this achievement. The underlying currents of the Foundation's sustainability goals were to create a "superlative workplace" for its staff, and a respect for the greater environment.

For example, the design team and owner considered energy use, water use and associated carbon emissions when selecting the HVAC strategy, so as to evaluate the potential environmental impact of each option. At all times synergistic benefits were explored and leveraged to improve the performance of the campus, and simultaneously enhance its sustainability. Sustainability is not a sidebar to the story of the campus — it underwrites its entire story, woven into decisions from those as simple as paint and carpet to the more complex questions of energy supply and central plant provisions.

Many of the sustainable measures don't fall into the LEED structure but still provide benefit, an example being the use of the TES tank in the central plant. Not only does the TES tank enable the system to save water and remain energy efficient, it also:

- lowered the peak chiller installed capacity by 40%, reducing the overall refrigerant charge for the campus cooling system, and therefore its greenhouse gas impact
- eliminates not just the water consumption associated with cooling, but also the chemical usage associated with water treatment and associated sewage treatment
- enables the generator test energy to be recovered
- allows the chiller plant to run predominantly at night, minimising acoustic impact.

None of these outcomes is spelled out by LEED, but they are undeniable environmental benefits, and arose because of the holistic thinking of the entire design team making the right choices.

Conclusion

For the Arup team, there were many great things to take away from this project.
The end-product shows what the design and construction industry can achieve when it absolutely works together to achieve a common goal.

Perhaps the most inspiring aspect of the whole project was being able to help the Foundation achieve its mission.
The Foundation thanked the "best team in the world" for creating a building that "inspires them to do their best every single day." Martha Choe, chief administrative officer for the Bill & Melinda Gates Foundation, quoted John Ruskin at the opening event:
"We require from buildings, as from men, two kinds of goodness: first, the doing their practical duty well: then that they be graceful and pleasing in doing it; which last is itself another form of duty."

41. Sustainable features of the campus.

42. Informal break-out area.

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(2) http://en.wikipedia.org/wiki/Minimum_efficiency_reporting_value

(3) www.arup.com/Services/Acoustic_Consulting/SoundLab_Overview.aspx

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Project credits

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Technology consultant: *TechPM group*
Contractor: *Sellen Construction Company.*


42.

Image credits

1, 3, 6, 8, 11–12, 16, 18, 24, 29, 36, 40, 42 *Timothy Hursley*; 2 *Bill & Melinda Gates Foundation*; 4, 7, 27-30, 41 *NBBJ*; 5 *Nigel Whale*; 9, 13–15, 17, 19, 26(a), 37 *Arup*; 10, 38 *Sellen Construction Co*; 20-21, 23, 26(b), 39 *Sean Airhart, NBBJ*; 22, 25 *Bob Bowlin*; 31-35 *Nigel Whale/Arup*;

Awards

United Stated Green Building Council (USGBC): LEED-NC (Leadership in Energy and Environmental Design for New Construction) Platinum certification 2011 (Foundation campus)

United Stated Green Building Council (USGBC): LEED-NC (Leadership in Energy and Environmental Design for New Construction) Gold certification 2009 (Seattle Center garage)

National Association of Industrial and Office Properties (NAIOP) Washington State Chapter: Office Development of the Year Award 2011

American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE): Region XI Technology Awards, Commercial Facilities/New, 1st Place 2012

Interior Design Magazine Best of Year Awards: Office (Large, Corporate), Winner 2012

Associated General Contractors of America (AGC): Build Washington Awards. Private Building Over $25M, Construction Award 2012.

The Al Bahar towers:

multidisciplinary design for Middle East high-rise

Location
Abu Dhabi, United Arab Emirates

Authors
Andy Armstrong Giorgio Buffoni
David Eames Roy James Leonora Lang
John Lyle Konrad Xuereb

Background and overview

Set amidst the financial centre of Abu Dhabi, the Al Bahar towers are the latest addition to its ever-changing skyline; a project conceived by the Abu Dhabi Investment Council (ADIC) during a period of intense construction activity in the UAE that also saw a big push for sustainability.

Following an international design competition in 2007, ADIC chose the striking concept submitted by London-based architect Aedas, together with Arup as multidisciplinary engineering designer (Fig 1). Construction began in March 2009 and was substantially completed by late 2012.

The site is in Sector 25, the south-east part of the Abu Dhabi city peninsula, at the junction between Al Salam Street (8th Street) and Al Saada Street West (19th Street). The plots for the towers are zoned within the "Outer Central Business District" defined by the city's authorities.

The project comprises two near-identical, 26-storey, 145m tall towers, whose architecture embraces Islamic geometric patterning. Sharing a two-level basement, both towers are primarily for office use but also contain ancillary space that includes catering, plantrooms, auditoria, prayer rooms and a gymnasium. The basement functions predominantly as a car park and includes several large plant areas, a secure vault, and various back-of-house areas associated with catering and storage (Fig 2).

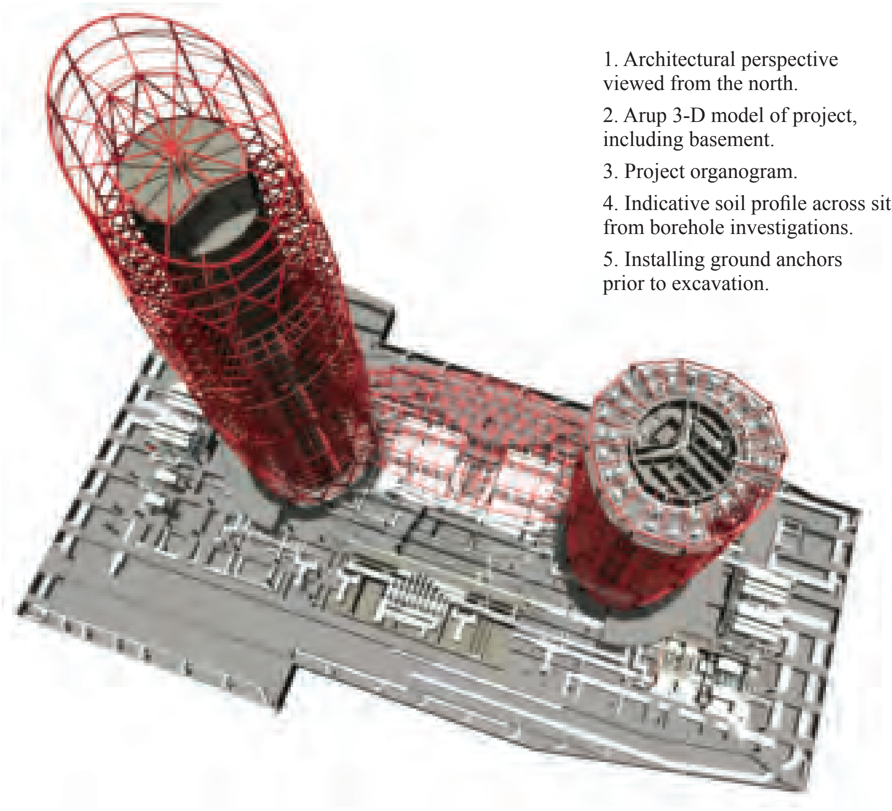

1.

Between the towers a 100m wide curved roof forms a shallow dome over the entrance podium, its front partially glazed and forming a dramatic entrance to the buildings. Arriving visitors enter this fully conditioned space and can proceed directly to either tower, to the main auditorium, or to one of the prayer rooms.

In addition to this main entrance, each tower has a dedicated VIP entrance accessed at mezzanine level from the far side of the podium. Both towers incorporate three- or four-storey skygardens over part of their perimeters, while the crown, a vaulted observation level, tops each tower and offers spectacular views of the surroundings.

A key design driver was to develop a building envelope that was both efficient and iconic, related to Islamic architecture and also embodying a novel approach to reducing the effects of the high ambient temperatures and intense solar radiation that characterise the local environment. The innovative idea was to develop an external movable shading system, the "Mashrabiya", named after the form of shading screen that had been used for centuries in Islamic architecture.

1. Architectural perspective viewed from the north.
2. Arup 3-D model of project, including basement.
3. Project organogram.
4. Indicative soil profile across site from borehole investigations.
5. Installing ground anchors prior to excavation.



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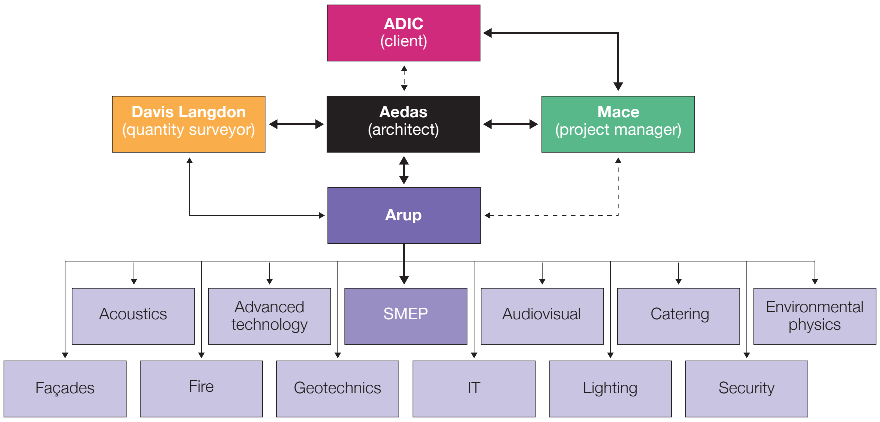

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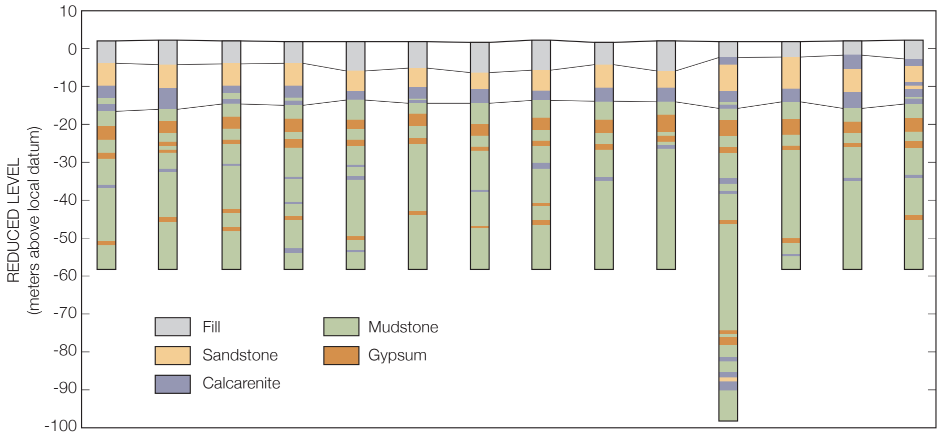


4.

5.

Project structure and Arup's role

Arup was involved from the competition through to the construction stage, providing the full range of design services and specialist advice, from the core disciplines of SMEP (structural, mechanical, electrical, public health) engineering to specialisms like environmental physics and advanced technology (Fig 3).

Integration of the disciplines concerned was one of the vital features of Arup's contribution, and all the design engineering, including all specialisms, was provided by the firm, largely from London but with contributions from offices in Vancouver, Leeds and Sydney, as well as Abu Dhabi. A total of 336 Arup people contributed in some way to the project.

Substructure and basement

The geology of the site is typical of the Abu Dhabi peninsula, consisting of 4m–8m of superficial soils overlying 8m–14m of sandstone and calcarenite, over mudstone and gypsum (Fig 4).

A key client requirement was to incorporate the two-level 200m x 100m basement to accommodate 450+ car parking spaces. Conforming to local authority requirements, the team adopted a perimeter twin-wall system, comprising an outer temporary/sacrificial secant piled wall and an inner reinforced concrete wall integral with the substructure. The temporary piled wall is connected by a reinforced concrete capping beam and is tied at the top by a row of ground anchors (Fig 5).

6. Substructure during construction.

7. Installation of plant at the basement levels.

The towers are deliberately separated from the substructure by means of movement joints at the first basement, ground floor and podium levels, to allow them to behave independently from the substructure and from each other. This simplified the structural analysis, in particular regarding any out-of-phase oscillation under seismic effects, which would have induced large in-plane forces in the basement slabs. It also facilitated the construction, as the towers — on the critical path — were now independent of the basement structure.

The towers' reinforced concrete cores, for stability, rest on piled rafts, each with 61 large-diameter (up to 1.5m) piles bored approximately 30m into the mudstone layer. The basement structure outside the towers' perimeters consists of a hybrid reinforced concrete flat slab and slab/beam construction supported on columns set out on 11.4m x 9m grids, supported on single piles (Fig 6). The permanent inner concrete wall at the perimeter and the 500mm thick reinforced concrete lower basement slab do not have any movement joints, and were designed to withstand shrinkage and creep stresses.

The site is less than 200m from the sea, and this close proximity naturally results in a high water table, approximately 2m below ground level. During construction this necessitated dewatering ,which commenced once excavation reached formation level and was cut off on completion of the substructure box. The substructure is protected from surrounding corrosive environment by a continuous membrane. To ensure stability at all phases of construction, the piles were designed to withstand a maximum tension equivalent to uplift less the self-weight of the substructure. Intermediate tension piles were introduced between column grids to alleviate the stresses arising on the slab at the lower basement level.

6.

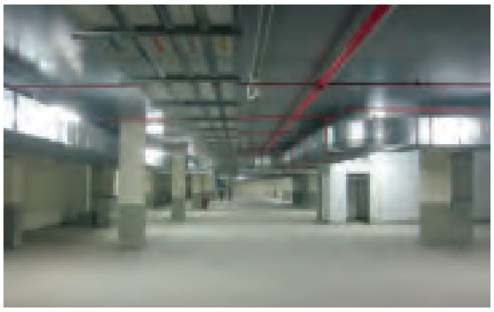
Central services installation

The basement, ground floor and podium levels accommodate the central plant, which house the central water storage, primary chilled water equipment, ventilation equipment, main incoming electrical transformers, backup generators, heat rejection equipment (cooling towers), and a secondary chilled water system (Fig 7).

The dedicated ventilation and smoke extract system is fully ducted, with extract fans at ground floor level. Make-up air supply is provided via the car park access ramps and two dedicated risers.

A series of strategically located carbon monoxide monitors linked to the building management system (BMS) control the extract rate from the car park, and should a fire occur there, a secondary fire mode increases the ventilation, so as to extract smoke at an NFPA-compliant rate (US National Fire Protection Association) on the fire-affected level.

The basement back-of-house areas are served by high-efficiency air handling units (AHUs) providing tempered outside air to the various accommodation areas. Each unit incorporates a thermal heat recovery wheel to reduce cooling load and ultimately energy consumption.



7.

Cooling systems

The peak cooling load for the entire building is approximately 10.5MW, which is met by a series of four water-cooled chillers at basement level. Each incorporates two variable-speed compressors with the aim of maximising performance and efficiency.

The BMS controls the sequencing of the chillers and their associated primary circulation pumps, depending on the varying cooling load in the building. Under normal daily operation the chillers activate sequentially in response to increasing cooling load. At peak daily conditions, all four chillers run at an optimal partial load. Should a single chiller require maintenance, the remaining three are capable of meeting a typical daily cooling load. At peak load, excess cooling is shed to the secondary cooling system.

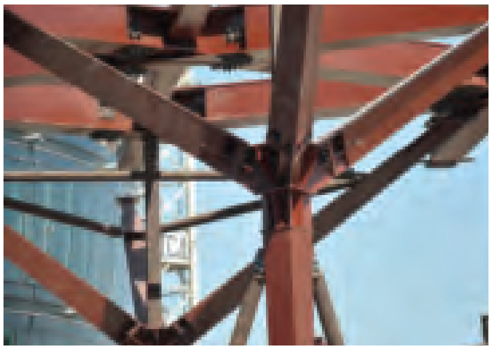
8. Architectural perspective of podium and mezzanine between towers.

9. Tree-like steel columns supporting podium roof.

10. Podium structure, with reinforced concrete shear walls providing stability.

11. Podium roof during construction, viewed from crown level.


8.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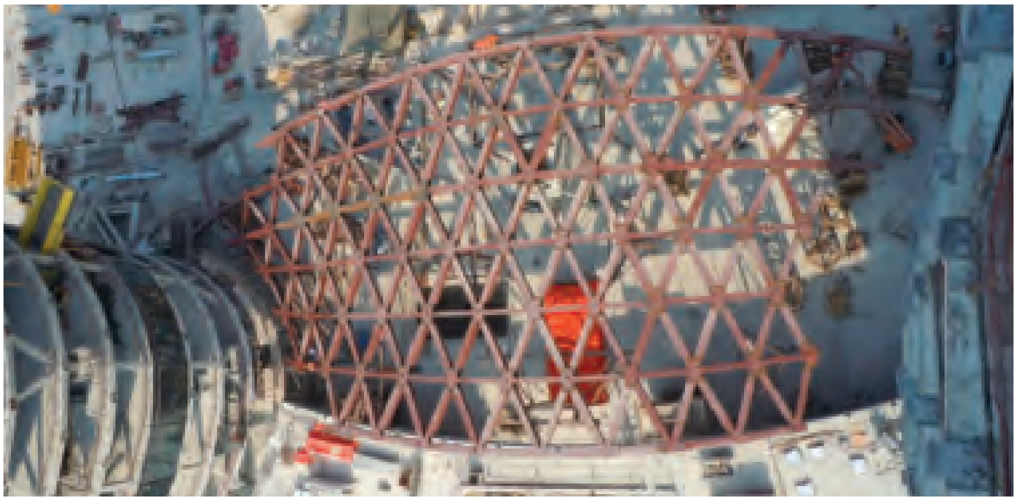
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Heat rejection is accommodated at podium roof level, where two banks of cooling towers are carefully integrated into the raking podium roof structure and concealed by an architectural aluminium mesh overcladding. A condenser water storage tank sufficient to maintain the buildings' cooling load for two operational days at full duty has been provided for added resilience.

An independent secondary chilled water system acts as a resilient back-up cooling supply for business-critical equipment and selected executive office areas. Under normal conditions this secondary system shares the cooling duty in these areas with the primary system, but should the latter fail, the electrically-driven and generator-backed secondary system increases its output to meet the additional cooling load.

Podium/foyer

The podium area between the towers incorporates the grand entrance lobby (Fig 8), central auditorium, male and female prayer rooms, back-of-house areas, two restaurants with associated kitchens, mezzanine level café, and plant.

The structural shell roof enclosing this dramatic space is formed of a series of ribbed elements spanning between springing points at ground and podium level, and supported on tree-like columns positioned within the foyer space (Fig 9). The roof surface is singly curved, its form derived from a section through a cylinder, and obtains rigidity through a combination of triangulated action and lateral arching to the thrust points at ground and podium level. The podium roof is independent of the towers, and stabilised by raked reinforced concrete walls and a central reinforced concrete lift core (Figs 10–11).

The diagrid typology, accommodating triangular soffit architectural inserts, defines the inner space and also enabled an efficient structural system, especially towards the front which carries large loads from a mezzanine hung beneath. The structure was also conceived to facilitate the construction process, whereby it could be erected in only four parts.

The steel mezzanine, with its composite deck, is suspended from the front edge of the overlying foyer roof. This space forms the cafeteria area and is directly above the heavily glazed main entrance. A "g-value" lower than that specified for the towers and a variable amout of additional fritting were incorporated in the glazing specification to reduce solar radiation ingress to manageable levels. Argon-filled double-glazed units were specified both on the podium and the towers to minimise heat gains due to conduction.

Fan coil units integrated into the bespoke geometric pattern of the foyer ceiling provide cooling for comfort.

The foyer space incorporates a large raised floor void which is used as a supply air plenum for a displacement-based HVAC system. Dedicated supply units pressurise the plenum with tempered air, and bespoke grilles integrated in the marble floors supply this air at very low velocity into the space, generating a cooling effect. Warm air rises and stratifies above the occupied zone at high level within the foyer's vaulted envelope. Here it is extracted back to the dedicated AHUs.

Towers

The towers are elliptical on plan and cylindrical in section. Stability is provided by the central 20.3m diameter cores, with their 450mm thick perimeter walls, and each core accommodates passenger and goods lifts, together with ancillary rooms, storage and plant (Fig 12), and thus freeing the floor plates for office use. Rigorous co-ordination during the early design stages allowed a constant core arrangement from the basement up to the crown at level 26 to be achieved.

This repetitive core layout allowed the contractor to slip-form the concrete, resulting in the efficient construction rate of a floor every three to four days. The core steps in above level 26 to suit the architectural form, and traditional construction was adopted above crown level to achieve this desired change in geometry.

The perimeter structure is of steel columns following a honeycomb geometry to fit the architectural concept. The trussed nature of the perimeter structure attracts the forces when the building is subject to lateral stress, contributing approximately 10% of the superstructure's overall lateral stiffness. The relative low stiffness ratio to that of the core, however, necessitated that the factored gravity load combinations should dictate the design of the perimeter structure. The geometry of the perimeter structure also adds resilience under accidental loading by providing alternate load paths to adjacent perimeter columns (Fig 13).

Primary radial beams span between the concrete core and the perimeter steel columns, and edge beams connect into the perimeter columns. Secondary radial beams span between the core and the edge beams to form trapezoidal floor plates closed by 160mm deep composite decks.

Steel beams cantilever beyond the edge beams to define the structural edge, and form connecting positions for the supporting arms of the Mashrabiya (Figs 14–15). At alternate floors, the Mashrabiya struts do not align with the radial beams and a system of backspan beams was introduced to support the shading devices.


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13.


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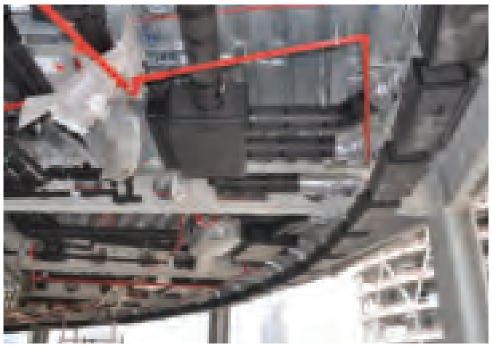
15.


16.

12. Slipforming of tower core.

13. Perimeter structure of steel columns.

14. Mashrabiyas installed onto cantilever brackets.

15. Stub connections for Mashrabiya bolted to ends of radial beams to house cantilever brackets.

16. Integrated services concealed in the suspended ceiling.

The tower floor plates outside the cores accommodate open-plan office space, cellular offices and meeting rooms. These areas are provided with ventilation and cooling from a concealed fan coil unit system distributing tempered air to the occupied zone. Detailed co-ordination of the services integrated in the suspended ceiling, including grilles, lighting, sprinkler heads, smoke detectors and occupancy sensors, resulted in an elegant system that both allowed straightforward installation and enables adaptability to future layout changes (Fig 16).

Level 17 was designated as a plant floor and contains ventilation plant for tower accommodation, additional water storage, intermediate chilled water pumps and associated electrical switching and life safety equipment. Additional ventilation plant levels 27 and 28 serve the crown and executive areas.

Two central AHUs at level 17 provide tempered outside air to individual fan coil units at each level; the AHUs incorporate heat recovery devices to reduce the duty associated with cooling warm humid outside air to suitable supply conditions. Heat is effectively recovered from both general accommodation extract and WC extract.

Due to the towers' complex cylindrical shape, steel construction (Fig 17), and the extreme external ambient conditions, the team employed a co-ordinated approach using 3-D modelling (Fig 18) to check both the spatial co-ordination of services in plant areas and that of services plant with structural elements at key "pinch points".

Skygardens

A key architectural feature of the towers is their skygardens, which are formed by the removal of the floors across two structural bays over four levels to create dramatic outward-facing environments (Fig 20). The perimeter columns are restrained at these levels by curved trapezoidal sections that follow the perimeter geometry and support the Mashrabiya elements (Fig 19).

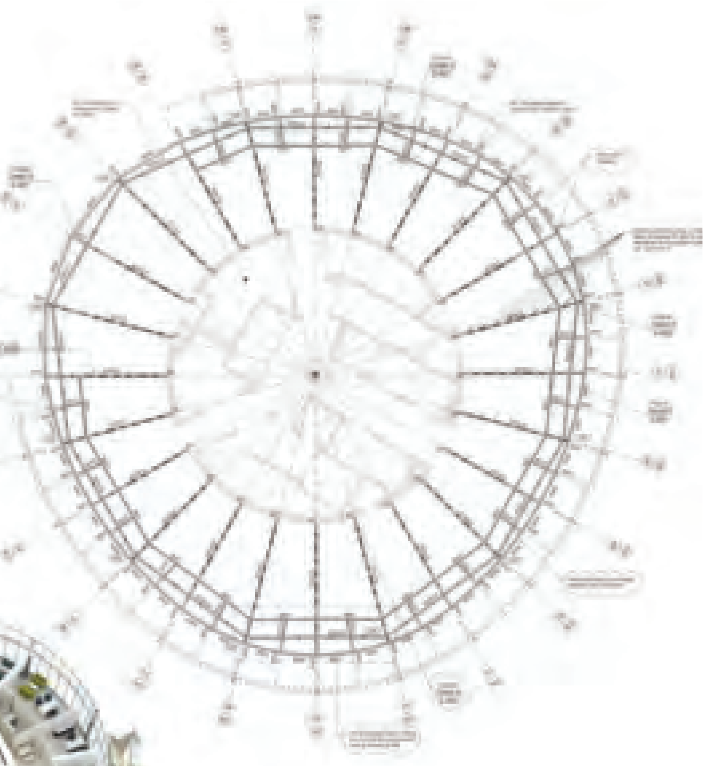
The honeycomb nature of the perimeter geometry means that the floor plates bounding the skygardens do not align with structural bays at alternate skygarden zones. Here the radial floor beams defining the skygarden edges are hung by ties supported from the perimeter nodes above.

17. Tower steel floor framing at alternate floors showing backspan beams.

18. Axonometric view of tower showing typical office floor layout at skygarden level.

19. Perimeter structure at skygarden levels prior to installation of Mashrabiya.

20. Completed skygarden from within office space.



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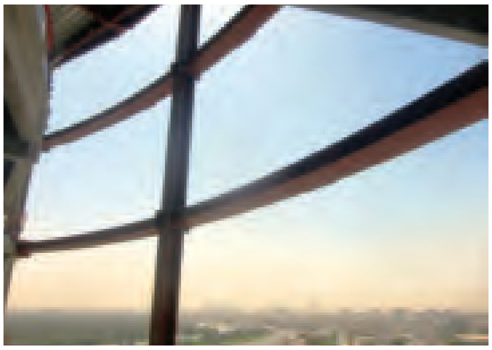


19.

20.

Nodes in the perimeter steel frame

The towers' form and perimeter structure generated geometrically complex nodes, weighing from 1 to 2 tonnes, and the team undertook numerous optioneering studies for the node typologies early in the design. The preferred option introduced horizontal and vertical dividing plates at the node level, thus simplifying a complex 3-D problem into straightforward 2-D connections, and allowing the same approach to be adopted for all 240 nodes. The radial beam and projecting cantilever stub connect directly to the node (Fig 21).

At ground floor level, the towers' perimeter steel columns meet the underlying reinforced concrete structure. This interface is resolved by adopting reinforced concrete plinths inclined at the respective angle of the incoming steel columns. Equilibrium is attained through noding out of elements at the ground floor slab mid-depth.

21.

22.

21. Fabricated nodes at steelwork fabrication plant in Abu Dhabi.

22. Unrestrained Y-shaped columns defining double-volume entrance to towers.

Unrestrained Y-shaped columns at podium level

Both towers can be accessed from the connecting foyer space at the ground floor level. The tower floor plates at the podium level are intentionally recessed (Fig 22) to allow this volume to be amalgamated with the dramatic foyer space between the towers. This floor recess, however, entailed removal of restraint to the highly loaded perimeter columns at a location where a kink in the geometry would occur. The unrestrained Y-shaped columns were therefore straightened (unkinked) and stiffened to allow sections similar in size to the other columns and aligning with the desired geometrical elegance.

Resilient services systems

As the primary business functions of the towers include financial transactions, brokering and dealing, resilience of the building services was a key consideration in the design.

Each tower incorporates a data centre at level 2 and a series of sub-equipment rooms at each level of office accommodation. In terms of cooling and power supply, these facilities were designed to be highly resilient and able to continue operating in the event of primary system failure.

This resilience is provided primarily by N+N system redundancy (ie each component has an independent back-up component) in terms of both cooling and electrical supply. Cooling is maintained by two wholly independent chilled water systems, while the electrical supply has both dedicated UPS (uninterruptable power supply) systems in each tower (in dedicated plant areas on level 1) and diesel generator back-up at ground floor level at the rear of the podium.

Vertical transportation

An innovative vertical transportation strategy was adopted for the towers. The lifts are zoned normally for peak travel times. The low-rise lifts are for general staff use, and the high-rise for executive staff. Destination dispatch is used to enable the designers to allow all the lifts to act as a single group during peak times so as to handle the increased traffic flows in the morning and afternoon. During off-peak times, the lifts work as separate groups. Proximity access control is also provided to the high-rise lifts to facilitate the restricted access requirements for executives only.

Tower façades: the Mashrabiya

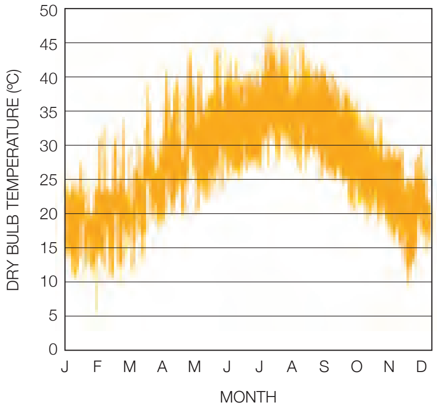
The climate in Abu Dhabi is classified as subtropical desert, having maximum temperatures of around 46˚C and very high solar radiation levels year-round (Fig 23). Reducing the energy use associated with providing internal comfort was perhaps the biggest single challenge faced by the design team. The answer was the innovative Mashrabiya shading devices with which the Al Bahar towers are wrapped; in fact the Mashrabiya became a key architectural theme in the towers' design (Fig 25).

Most recent high-rise buildings in the Middle East use highly glazed façades with dark, reflective, or body-tinted glass. This type of solution limits solar gain, but significantly reduces natural daylighting and general internal comfort. Frequent use of internal blinds is normally needed to control glare effects and this inevitably increases the lighting energy consumption, defeating the purpose of a transparent building.

The Mashrabiya is, by contrast, a novel and sustainable feature, drawing inspiration in its design from the traditional shading screens of vernacular Islamic architecture (Fig 24). The design team undertook extensive solar and thermal analysis of the effect of this unique active shading system on select areas of the towers at various times through the year (Fig 26). As built, the Mashrabiya devices clad the towers on their east, south and west façades, significantly reducing solar gain to the internal accommodation and permitting the use of floor-to-ceiling clear glazing. This was a marked departure from the heavily tinted external glazing of older buildings in the region. Different options were investigated to select the most appropriate fabric for the shading system, and PTFE-coated glassfibre mesh was identified as the most durable and best-performing solution.

In total each tower has 1049 Mashrabiya shading devices, each weighing about 1.5 tonnes. Arup built on knowledge gained in other projects with movable elements, and worked with the architect to conceive schematic parameters for these elements and their detailed performance specifications.

The shape of the building in plan and elevation led to 22 different variations in the Mashrabiya geometries, which in itself created a technical challenge for managing their manufacture and assembly. The main technical challenge, however, was to develop



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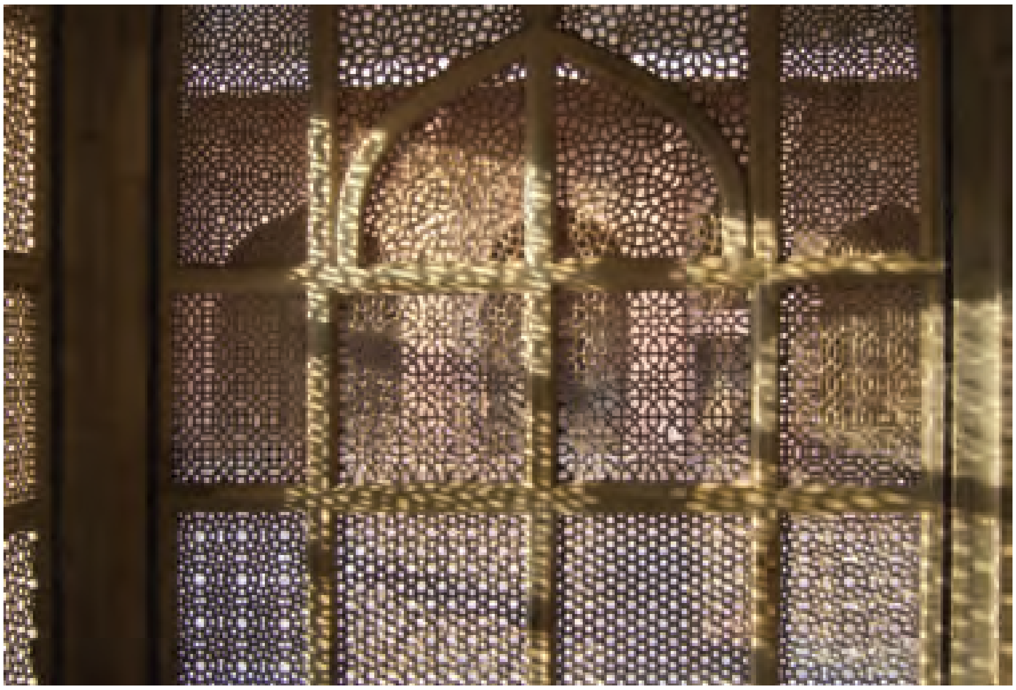

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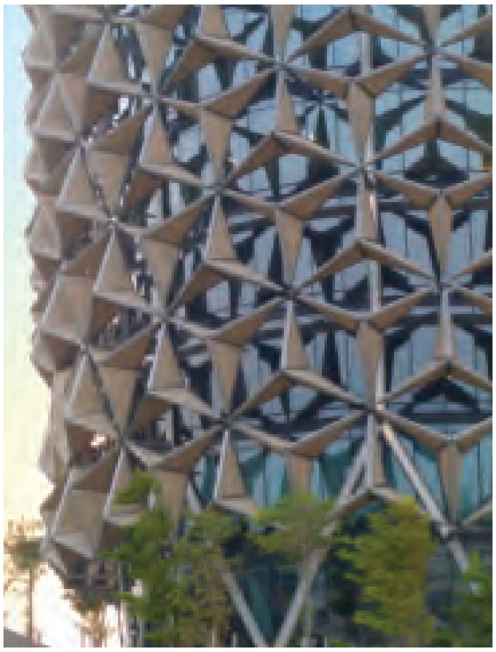

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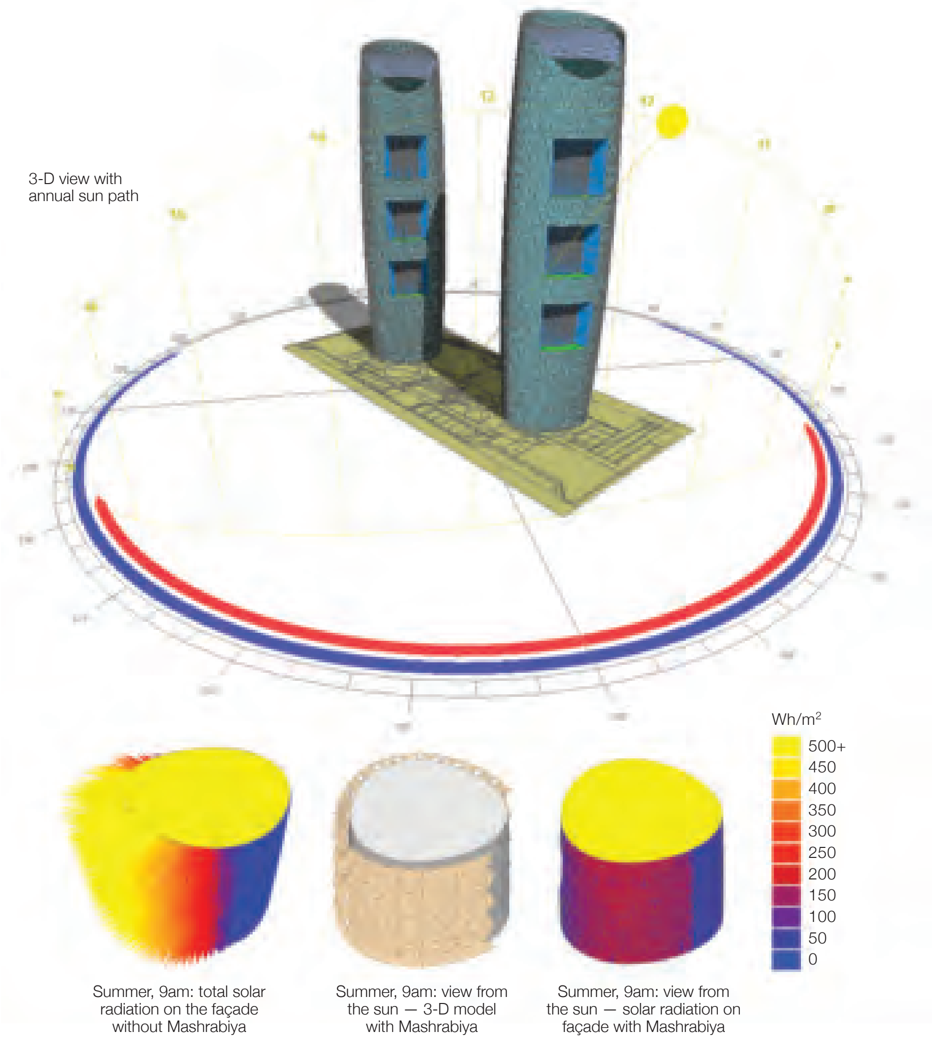


Summer, 9am: total solar radiation on the façade without Mashrabiya

Summer, 9am: view from the sun — 3-D model with Mashrabiya

Summer, 9am: view from the sun — solar radiation on façade with Mashrabiya

26.

23. Average diurnal temperature-range in Abu Dhabi.

24. Traditional shading screens used in vernacular Islamic architecture.

25. Installed Mashrabiya in open mode.

26. Solar exposure analysis.

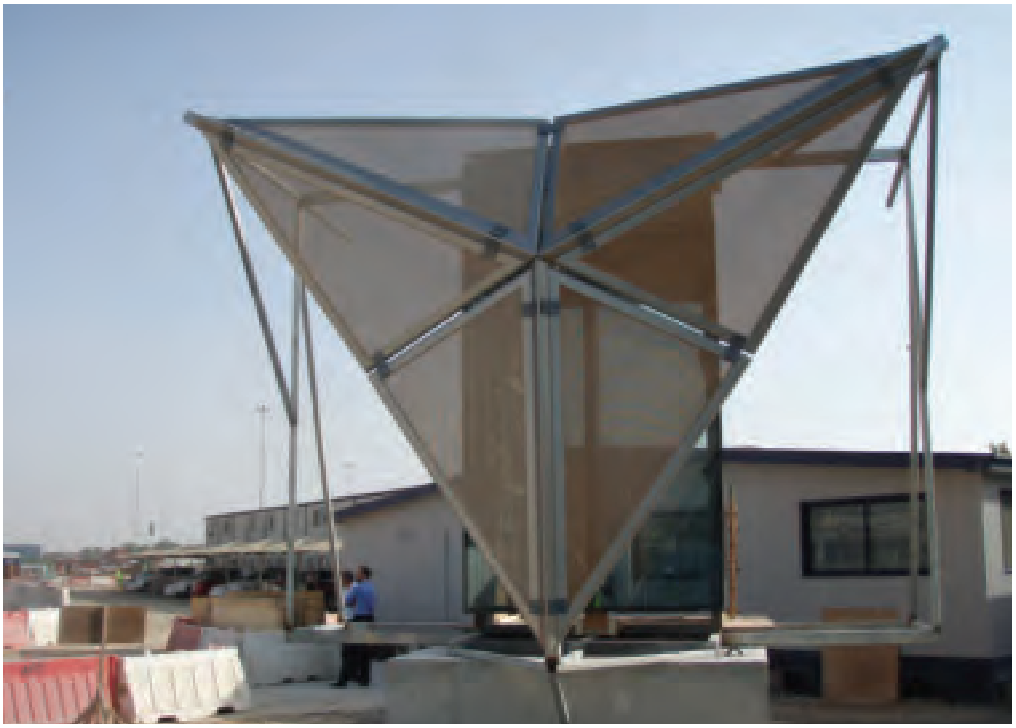
a unique and unconventional movable shading device that not only protected the buildings from the solar radiation and high external air temperature, but could also operate reliably in an aggressive environment. A series of prototype tests on a fully functional 1-to-1 scale shading panel were carried out, including wind tunnel tests and accelerated tests in a climatic chamber. More than 30 000 opening-closing cycles were simulated at different temperature conditions, applying sand and salt water on all the critical joints (Figs 28–30). This step was essential to de-risk the design process and prove the required durability life of actuators, bearings and mechanisms.

A full-scale mock up was subsequently erected on one of the towers, while the curtain wall was being installed, to allow the Mashrabiya mechanism to be tested in situ (Figs 31–33).

The result is a responsive and dynamic skin, able to react differently according to the sun's orientation and to adapt to varying external conditions throughout the year. In consequence the building's appearance itself is always changing, reflecting natural daily and seasonal rhythms.

By detailed assessment of the combined shading and glass performances, a correct balance between solar control and light penetration was achieved. The type of glass selected has a clear appearance with high visible light transmittance, enhancing the daylighting and the view through, while the external shading panels help reduce the solar radiation significantly — and only where and when needed.

The Mashrabiya elements are grouped in sectors and operate by sun tracking software that controls the opening and closing sequence according to the sun's position. The system can be overridden to control individual panels, however, from a desk in the BMS control room.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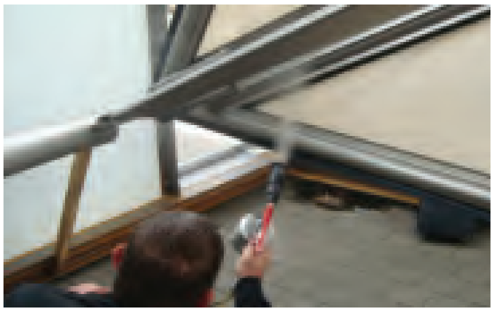
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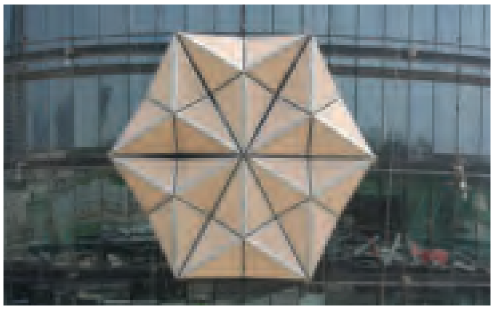
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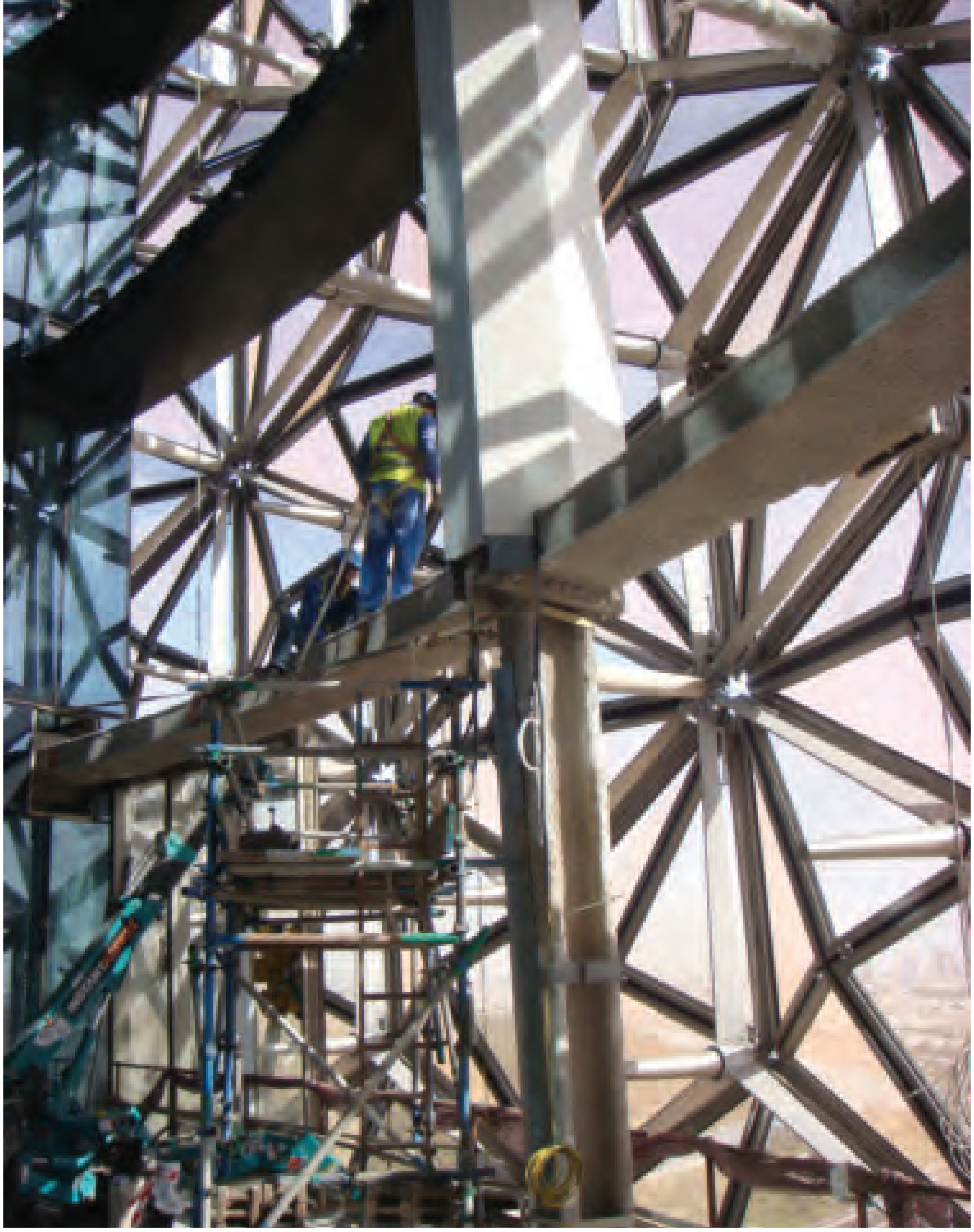
27. Part of Mashrabiya mock-up assembled on the ground.

28. Spraying salt water on panel.

29. Spraying salt on joint.

30. Spraying water on joint.

31–33. Mock-up Mashrabiya in situ, in various configurations.



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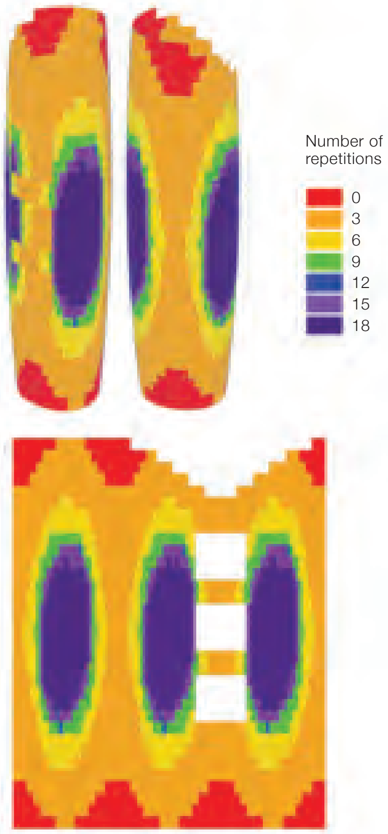


36.

The control system is linked to an anemometer at the top of the building which will automatically prevent operation of the shading, and will retract the units if the wind speed exceeds the peak operating threshold. A similar approach, using solar radiation sensors, is used to trigger the opening of the Mashrabiya panels in prolonged overcast conditions.

Various conceptual arrangements were assessed early in the design, including connecting all shading elements to one another and into the superstructure, but this led to conflicting behaviours between the Mashrabiya and the internal support structure. A more straightforward strategy was thus sought, in which each Mashrabiya was conceived as a unitised system cantilevering 2.8m from the primary structure (Fig 34). The supporting arms allow connection from the ends of six adjoining Mashrabiya, and each shading device has different releases at each of three supporting nodes.

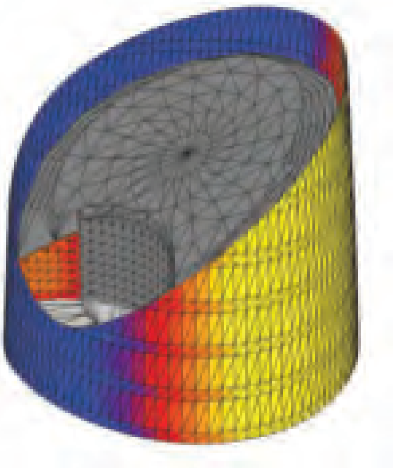
The principle for access and maintenance of the Mashrabiya and curtain wall (by others) is via a BMU basket running externally within the cavity between the two skins. The baskets are supported by cranes on top of the central reinforced concrete cores.

The curtain wall behind the shading is a standard unitised system shaped around the Mashrabiya brackets and developed to accommodate variable building geometries (Fig 35). The design and overall shape of the building were optimised to improve the panel repetitions, limiting rectangularity deviation and any warping. This helped to significantly reduce the system's complexity and ultimately the costs (Fig 36).

34. Installation of Mashrabiya from the inside.

35. Bespoke panels accommodating Mashrabiya brackets.

36. Panel repetition study allowing for a 10mm tolerance.



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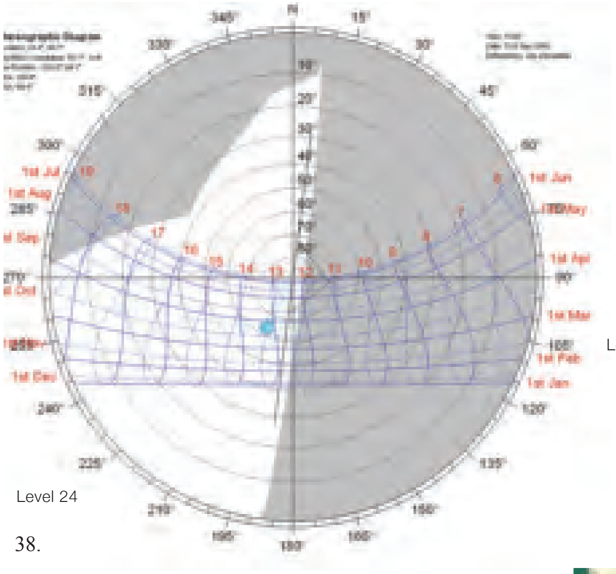

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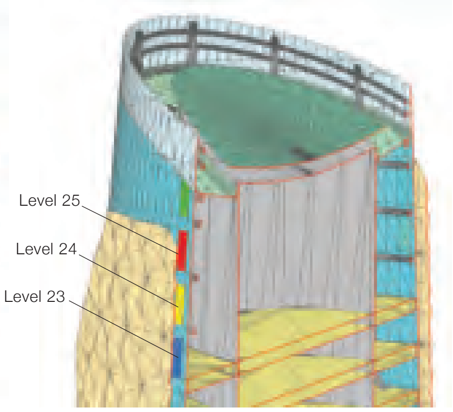

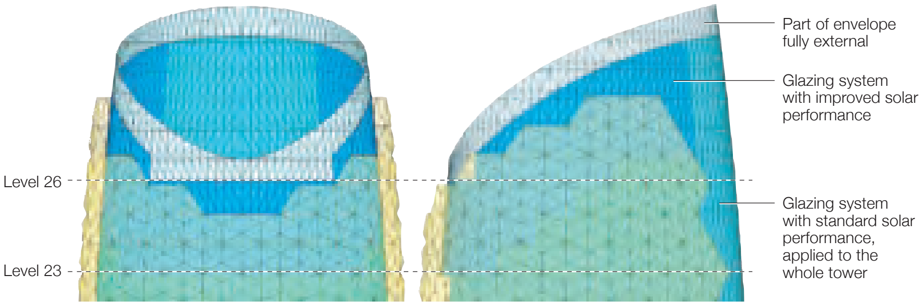

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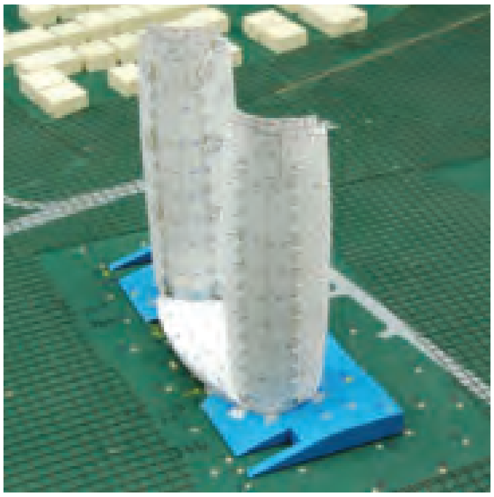

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37. Total solar radiation in summer conditions at 9am.

38. Shadow mask used to prove effectiveness of Mashrabiyas at the top of the crown, to assess whether additional measures were required.

39. Modified shading system.

40. 1:300 scale model utilised in wind tunnel tests.

The Crown

The crown was the subject of a separate solar and thermal analysis, so as to optimise the Mashrabiya extension at this level, and verify where the external shading system would be required, to provide an efficient cooling strategy.

Based on the 3-D model from the architect, Arup prepared a revised 3-D model of the tower to carry out the solar analyses. A simplified section of the top part of the tower was derived for a first solar exposure review, while a more detailed model was used for the sun path analysis.

The solar exposure study (Fig 37) suggested that at the top of the tower, the Mashrabiya system should follow the configuration already suggested for its lower portions. However, due to the architectural desire not to extend the Mashrabiya to the very top of the crown and due to the shading system's distance from the façade, additional design measures were required to ensure that solar gains through the façade from level 26 to the top were reduced below the target limit.

The glass performance in this area was improved by applying additional fritting with a variable pattern according to the level of solar control required. This reduced the g-value and contains the solar gains (Fig 39).

Dynamic behaviour

Wind loading

The elliptical/circular geometry of the buildings results in an efficient response under wind action. To determine the overall wind loads that would be acting on their superstructure, the two towers were tested at 1:300 scale in a wind tunnel at BMT Fluid Mechanics (Fig 40).

41. The towers were built in parallel, with the steel skeleton lagging six floors behind the core.

42. Completed cladding with installation of Mashrabiya in progress.

These tests showed that a peak base bending of 550MNm was experienced at the base of the towers, 15% less than preliminary wind structural loads estimated using the UK wind code *BS6399-2*[1]. Furthermore, the loads on the towers, if built in isolation, were found to be similar to or less than those when both towers were completed. The wind tunnel tests thus helped to reduce the structural steel weights required.

Seismic loading

Limited historical seismic events data exist for Abu Dhabi, so scientific opinion on the seismicity of the region varies depending on how the data from surrounding regions are extrapolated.

The team carried out seismic analysis using seismic parameters and ductility, based on the Uniform Building Code, (Edition 1997)[2], for a zone 2A seismic region as required by the Abu Dhabi Municipality. Later checks were made employing a site-specific seismic hazard assessment of the 2475-year earthquake return period, but with reduced levels of ductility (R factors). The latter checks were based on recommendations of the Council of Tall Buildings and Urban Habitat (CTBUH) seismic working group. The seismic design was generally found to be less critical than that for wind action.

Construction sequence

Introducing movement joints around the towers at substructure levels enabled them to behave independently of one another and not rely on the substructure for stability. Apart from simplifying the analysis, this methodology facilitated the construction sequence, allowing the contractor to progress with the towers, which were on the critical construction path.

They were built in parallel, with the steel skeleton lagging six floors behind the core (Fig 41), while the decks in turn were erected and concreted four floors behind steelwork. Installation of general building services such as ductwork, pipework and electrical distribution immediately followed completion of the structural works for a given area. Major plant items like water-cooled chillers and generators were ordered so that they would arrive on site at defined points in the construction sequence to coincide with structural works. This efficient construction sequence, combined with round-the-clock working, allowed the enabling works and shell structure to be completed in just over 12 months.


41.

Sustainability credentials

The Al Bahar project is being assessed under the US Green Building Council (USGBC) LEED for New Construction version 2.2 (NC v2.2)[3] and is predicted to achieve a Silver rating[4]. Under LEED the building is assessed in areas such as energy cost, land use, water use, occupant comfort and materials specification. Evidence is provided to the USGBC and points awarded when qualifying design/specification features are included or when performance exceeds a defined threshold. The final collated score determines the final LEED rating.

The architect acted as the LEED administrator for the project and provided a LEED Accredited Professional to the project design team from an early stage to determine the target rating and advise the design team on specification and documentation requirements.


42.

43.

Conclusion

The Al Bahar towers are now a notable landmark in Abu Dhabi's financial district. Their adaptable skins, the Mashrabiya, form a key feature of the project, responding to the external environment, considerably reducing heat gain, and enhancing sustainability credentials.

The project won the 2012 Council for Tall Buildings & Urban Habitat's (CTBUH) Innovation Award, and was listed amongst its "Innovative 20" tall buildings that "challenge the typology of tall buildings in the 21st Century"[5]. It also featured in the November 2012 *Time* as one of the "25 best inventions of the year"[6] — alongside NASA's *Curiosity* Mars Science Laboratory rover.

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Image credits

1, 8, 14, 19, 28–30, 35, 43–44 *Aedas*; 2, 7, 9–10, 16–19, 21–22, 24, 40 *Arup*; 3–4 *Nigel Whale*; 5–6, 15, 20, 25, 27, 31–34, 41–42 *Peter Chipchase*, 11–13 ©*DIAR*; 23, 26, 36–39 *Arup/Nigel Whale.*

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Project credits

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43. View of completed project from the north east.

44. The north façade, where the Mashrabiya are omitted.

The Fulton Center:

design of the cable net

Location
New York City, NY, USA

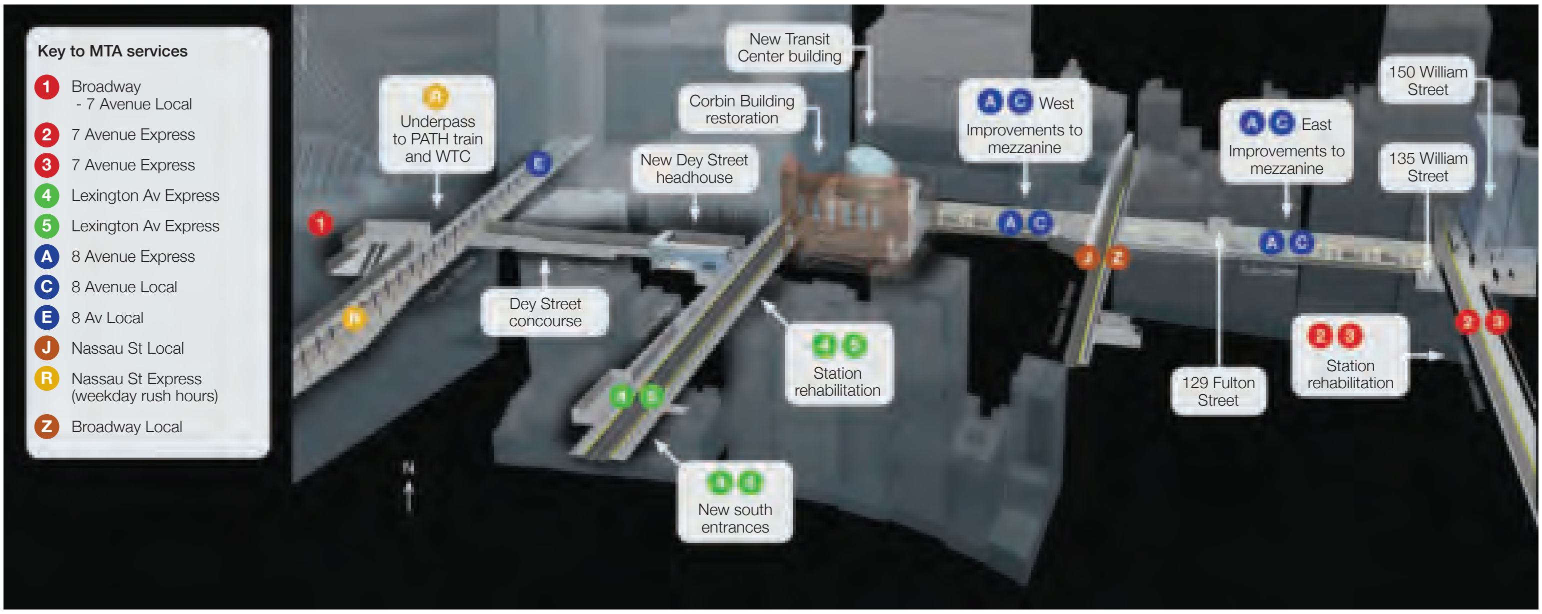
Authors
Zak Kostura Erin Morrow Ben Urick

1.

Introduction

At the corner of Fulton Street and Broadway, one block east of the World Trade Center site and two blocks south of City Hall Park, 11 New York City subway lines converge in a hub serving over 300 000 transit riders daily. With their dense tangle, these lines have evaded efficient connection for nearly a century, a legacy of disparate planning and construction practices common to the era of competitive, privatised transit operation — and despite being unified under a single state agency in 1968.

In the aftermath of September 11, 2001, the Metropolitan Transportation Authority (MTA) enacted plans to redevelop this hub into an efficient transfer point, replacing the labyrinth of corridors, retroactively constructed to link existing lines, with an efficient system of pedestrian mezzanines, concourses and underpasses, complete with elevators and escalators to comply with the provisions of the Americans With Disability Act (Fig 2). And at the corner of Broadway and Fulton, the MTA planned a spacious



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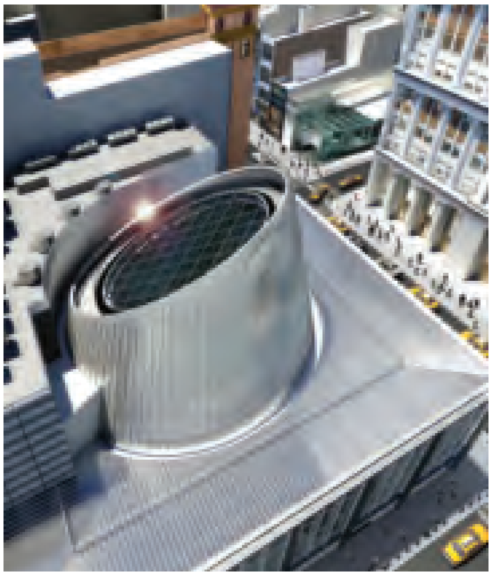
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multi-storey pavilion structure to crown the new underground pedestrian network and form an iconic gateway to Lower Manhattan.

In 2003 Arup was awarded the role of prime consultant for the Fulton Street Transit Center (now the Fulton Center), and has delivered a wide range of multidisciplinary design services since then. As architect for the Center's superstructure, Grimshaw Architects designed a three-storey glazed pavilion set around a central eight-storey dome structure (Fig 1). Topped with an inclined 53ft (16.15m) diameter circular skylight known as the oculus, this large central space serves to collect and redirect natural sunlight through the building to the exhumed sub-levels below, and forms the project's main focal point (Figs 3–4).

The central space beneath the dome and oculus offered a rare opportunity for a large-scale artistic installation to add character and extend the architectural objective of repurposing incident sunlight to illuminate subterranean spaces.

The client and design team identified artistic potential in the architectural gesture planned for the Transit Center atrium, and responded to this opportunity with a public art competition held by MTA Arts for Transit and Urban Design in 2003. This led James Carpenter Design Associates (JCDA) being selected as collaborating artist for the atrium installation. Over the next two years, an engineer/architect/artist collaboration between Arup, Grimshaw and JCDA developed and designed an independent reflective lining, offset from the dome's interior, to direct sunlight down (Fig 5). The final design involved a steel cable net structure supporting nearly 1000 coated aluminium infill panels using flexible, universal node connection assemblies.

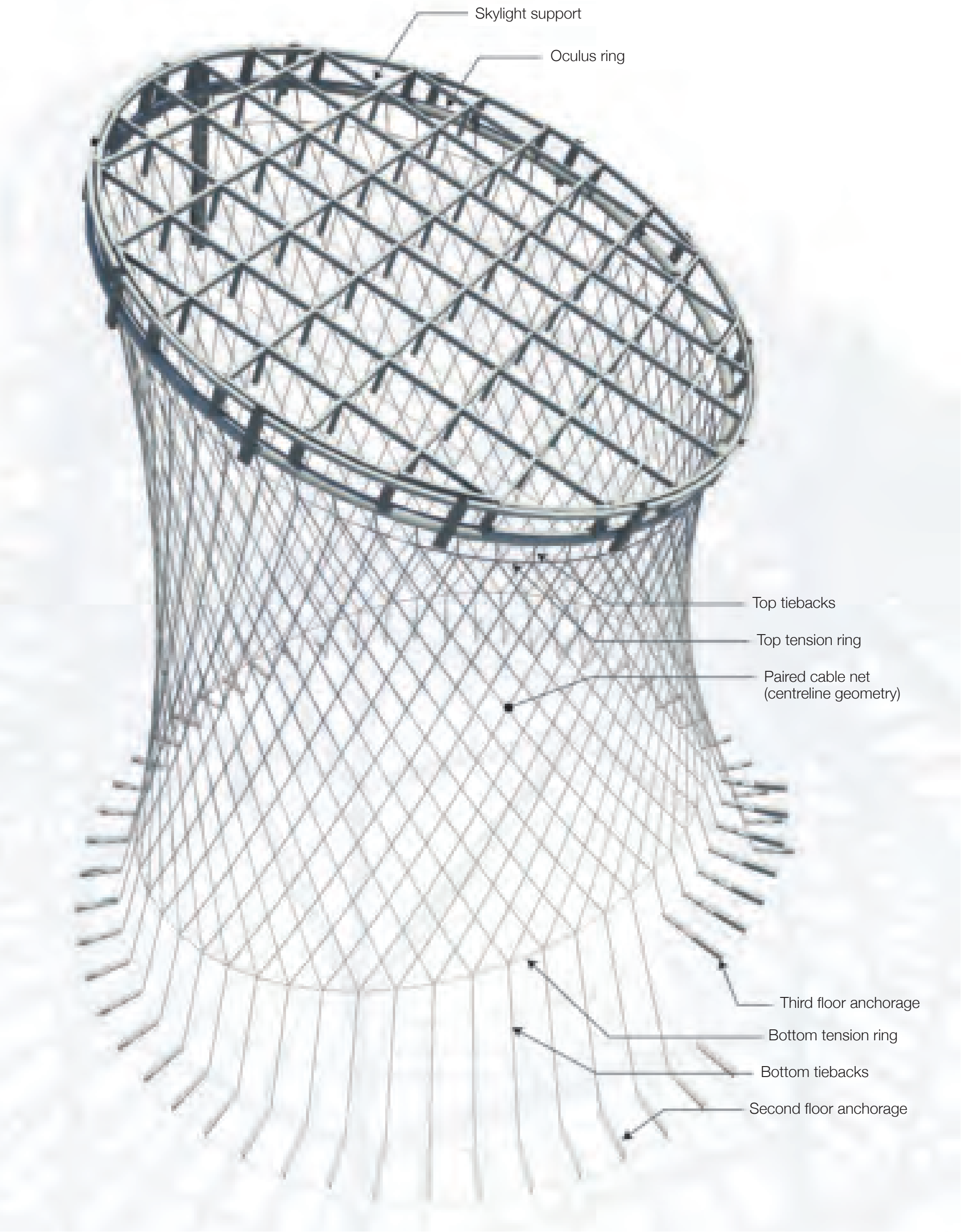
1. Architectural rendering of the Fulton Center pavilion with dome.

2. Extent of the new Fulton Center complex.

3. Rendering of the dome and oculus interior.

4. Rendering of central public space beneath the oculus.

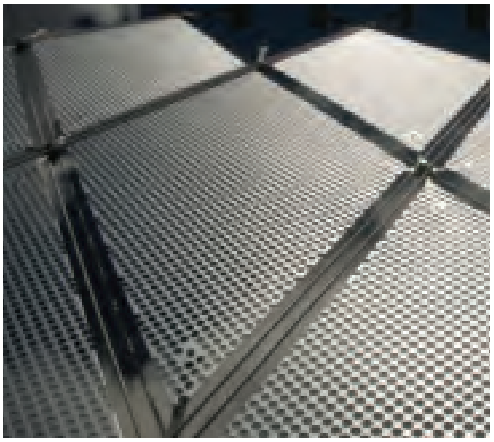
5. Rendering showing cable net and oculus.



6.

6. Cable net components and boundary support.

7. Reflective infill panels.



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Cable net design

Extending the full height of the central public space, the cable net is suspended from 56 connection points around the compression ring of the oculus and anchored to as many cantilevered beams at levels 2 and 3. It is a skewed hyperbolic paraboloid, or hypar, in form, but unlike a regular hypar, it has double curvature. Moreover, the skewed form has only one axis of symmetry, so each four-sided infill panel has a unique shape, defined by the lengths and intersecting angles of the cable segments along each side (Fig 6).

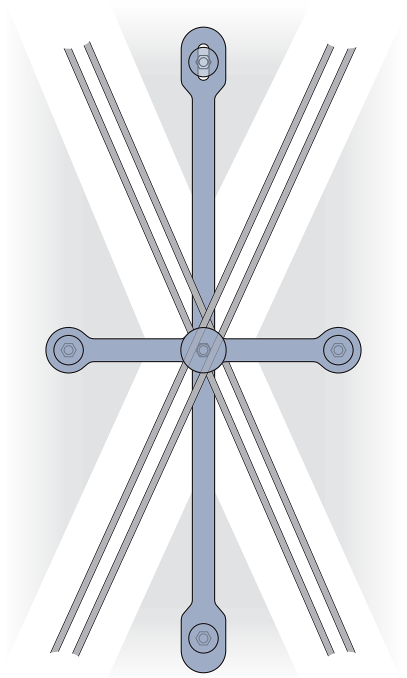
The reflective infill panels are of 0.125in (3.2mm) thick aluminium substrate with a high-performance coating on the interior faces (Fig 7). They are perforated with a regular circular pattern to control the quantity of light reflected, permit the passage of interior air currents, and reduce loading on the cable net, to which they are linked at each corner by cruciform connectors fixed to the nodes (Figs 8–9).

The strategy to secure them follows conventional cladding practice. Each panel is suspended from its top corner by a pin fed through a standard hole in the corresponding connector, and its angle and position in space are established at the bottom corner, where a pin is fed through a vertically slotted hole that allows for correct positioning with minimum restraint. Holes in connector arms at the left and right corners are oversized to allow for independent movement from changes in temperature across the whole eight-storey net, or air pressure from large air intake grills at its midpoint.

The net is made of 112 pairs of stainless steel 0.25in (6.35mm) diameter cables, mechanically swaged at each node. Swages are through-bolted with cruciform connectors arranged between the opposing cable pairs. Stainless steel rods are used for top and bottom ties as well as ring elements (Fig 10).

Form-finding

Initial assessment of the skewed hyperbolic form proposed by the artist indicated that a form-found tensile system could be developed to fit the desired geometry. This was enabled by using the swages at the nodes to grip the cables tightly, allowing each segment to carry a unique tensile force and dramatically broadening the range of geometric forms achievable using a purely tensile system.



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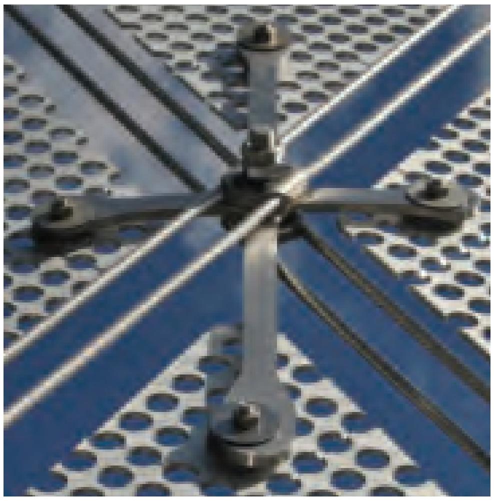

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As the desired final form was known, this "form-finding" entailed ascertaining the tensile force required in each cable segment to achieve that form. Arup developed a computational model of the desired cable net geometry, including all node positions, and initially ran it with a uniform 900lb (4.00kN) tensile force in each cable pair. The resulting found form varied significantly from the initial, desired geometry due to the generalised prestress force: where the force entered was larger than the true prestress, the segment shortened; where the force was smaller, the segment lengthened.

These geometric shifts from the initial geometry, while undesirable in principle, lead to redistribution of the generalised initial prestress, eg shortening of segments that were overstressed leads directly to a reduction in the force in the element after form-finding and prestress redistribution. Put simply, the prestress redistribution inherent in the form-finding process is self-correcting.

These redistributed forces were again applied to the desired architectural geometry. The resulting node displacements were smaller than observed in the first iteration, and the redistribution of prestress from this second form-finding routine further approached the correct prestress values for each cable segment.

Arup then developed a Microsoft *Excel* custom that automatically ran subsequent iterations, each time applying the redistributed loads to the original geometry and performing a form-finding routine. This terminated at the 113th iteration when the convergence indicators were met. The resulting prestress distribution pattern had maximum average values of 906lb (4.03kN) at the top and bottom rows, and minimum average values of 886lb (3.94kN) at mid-height. These were converted into element strains and applied to a new analytical model embodying the desired architectural geometry as well as the actual stiffness properties of the cable net elements.

Non-linear static analysis of this model demonstrated negligible movements in the nodes, confirming the validity of the strain distribution. These strains were then used to determine the unstressed length of each cable segment — data later used for fabricating the cables and swage assemblies prior to installation.

The validated architectural geometry was tabulated and presented as a set of Cartesian node co-ordinates, which in turn became the set-out geometry for the 952 infill panels. Successful execution of the installation's design thus necessitated correct distribution of tensile force throughout the net, with each node positioned so that each panel's shape matched that of the space within the net that it would occupy.

Understanding movements

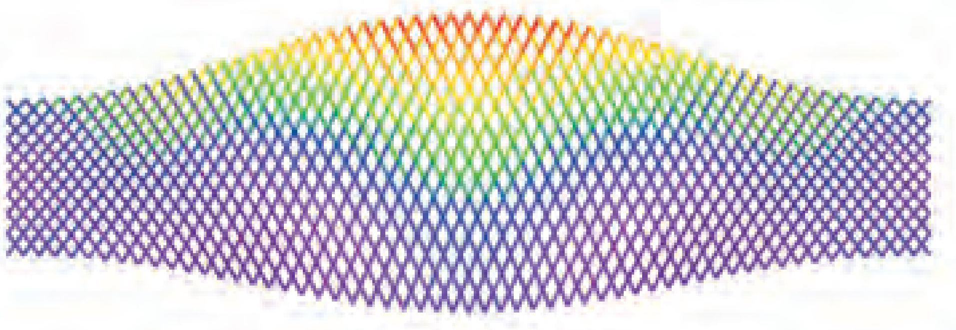
This analysis to establish a suitable strain distribution pattern was predicated on several assumptions about the net's real-world environment, including uniform ambient temperature, no loading from internal air pressure, and an exact match between the prescribed prestress distribution and what would actually be applied to the system.

In reality, the eight-storey space inevitably has thermal gradients, as warm air collects near the oculus and cool, conditioned air is diffused within the occupied space below. The ventilation strategy for the building relies on developing air currents that must pass through the panels, resulting in pressure drops across the perforated surface and generating loads that will influence the net's shape. Realistically, tensioning the net had to acknowledge errors inherent in the final values, and a review of industry standards suggested variations in applied tension loads of ±20%.

Because of its scale, the cable net must be viewed as a dynamic structure whose form constantly changes corresponding to the sum total of loads — the weight of panels, thermal strains, air pressures, and applied prestress forces — that will vary over time. Consequently the position of each node will also vary, and thus it was essential to understand and quantify the maximum conceivable movements in the nodes under all realistic environmental conditions.

8, 9. Universal node assemblies, with cruciform armatures and cable swages.

10. Stainless steel rod tie and connections to panels.



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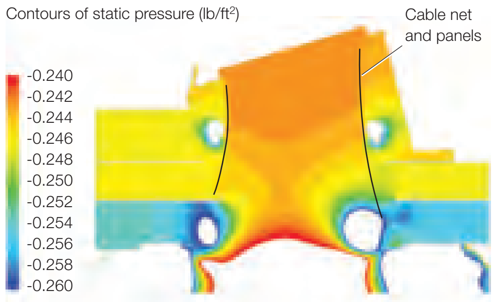

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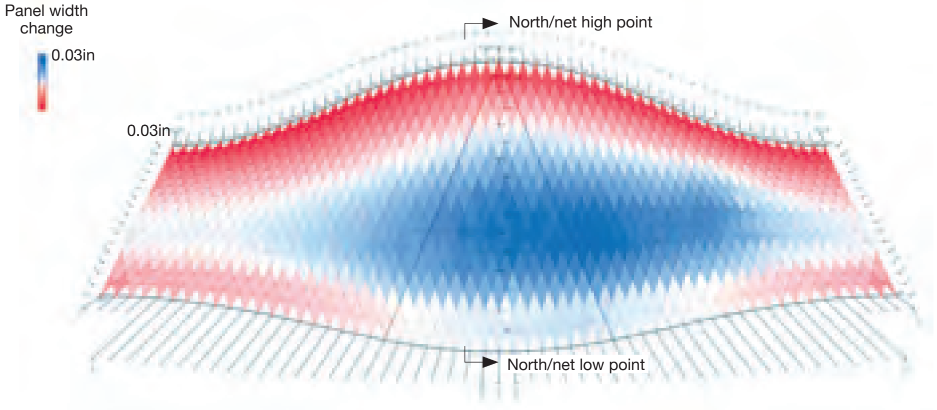

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11. Axial force in cable pairs under nominal panel loading and prestress.

12. CFD model generated to determine air pressure on each panel.

13. Assessment of individual node movements for a single load case. The component of node displacement measurement normal to the surface of the net was denoted as "node-surface deviation".

Should any of these movements transfer tensile forces to the infill panels, they would quickly overwhelm the delicate aluminium elements. The cruciform connector arms thus hold each panel in place with minimal restraint to allow for unrestrained movement of adjacent cable net nodes, enabled by the slotted and oversized holes in the arms on the left, right and bottom corners of each panel. The dimensions of these non-standard holes had to be co-ordinated with the maximum conceivable movements to provide sufficient freedom of movement and avoid transfer of force into the panels (Fig 11).

Arup studied each environmental characteristic and developed realistic scenarios to cover the range of corresponding load conditions. To determine the magnitude of pressures from interior air currents, a computational fluid dynamic (CFD) model was developed in the *ANSYS* program to identify the pressure drop across panels, given the known volumetric flow of intakes and diffusers throughout the building and the degree of permeability in each area of the cable net (Fig 12).

The scenarios for each environmental characteristic were then superimposed to generate 815 unique load combinations, each with a presumed unique cable net shape, and static non-linear analysis conducted for each combination. A custom subroutine was written to interrogate the position of each node under each load case and determine the largest changes to the support conditions of each panel. Increased distance between left and right corner supports was referred to as "panel width change" — the peak value implied the required dimensions of the oversized holes at these support points. Correspondingly, increased distance between top and bottom corner supports was "panel height change", which provided information on the necessary dimensions of the vertically slotted hole at the bottom connection point.

Analysis revealed that the largest resolved movement of any node under any perceivable load combination is around 2.06in (52.3m). Broken down, however, this maximum movement results in a change of only 0.23in (5.8mm) in panel width and 0.08in (2.0mm) in panel height. The dimensions of oversized and slotted holes were thus set to accommodate these movements in addition to acceptable construction tolerances of 0.25in (6.35mm) in either direction (Fig 13).

Modeling a universal connector

Working with the architect, Arup developed the universal cruciform connector for adequate panel support in the various configurations that result from the skewed hypar shape. Each connector comprises a horizontal and vertical armature, linked by a bolt at the midpoint and set between swaged cable pairs. All elements are free to rotate about the bolt axis, to allow the connector armatures to conform to the various required configurations. The armatures, nominally 0.25in (6.35mm) thick, taper to 0.125in (3.2mm) at their midpoints to minimise the effective thickness of the assembly, and the corresponding eccentricity between opposing cable pairs.

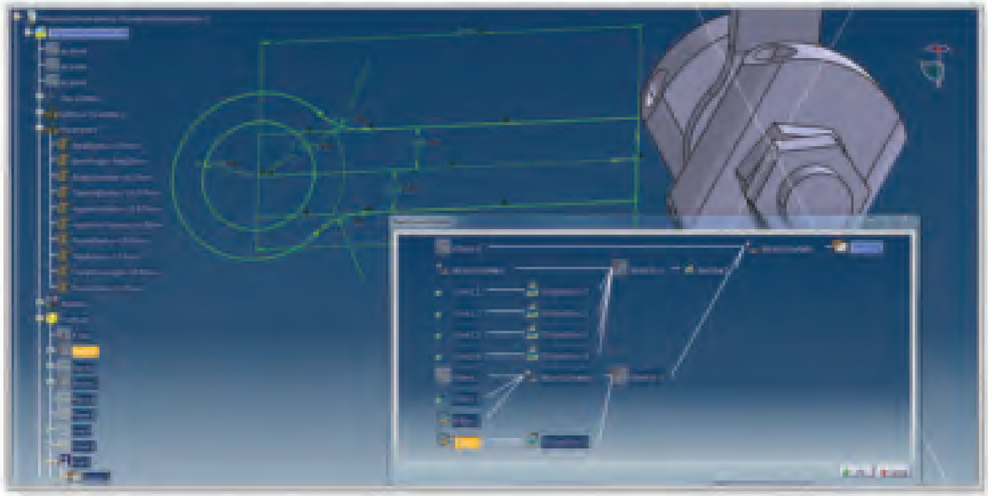
Designing the universal connector armature required geometry that incorporated the space-saving taper while facilitating the free rotation of elements to accommodate the various panel configurations, and Arup developed a parametric model in the *Digital Project* program to assess the performance of various designs. All components — armatures, bolt and swages — were individually modelled as discrete parts and then assembled into a single component. That assembly was instantiated into a global model containing the 896 cruciform connector nodes (Figs 14–15).

Set-out instructions intrinsic to each connector facilitated its rapid configuration, given the position of adjacent nodes in all directions. A separate clash detection program was then used on the solids to confirm the rotational adequacy of the universal part design.

Limitations to computing power then available led to instantiation routines that took days to complete. The design team observed that the instantiation of solid components was by far the most time-consuming; points and lines that established the location and orientation of the components were much faster to instantiate.

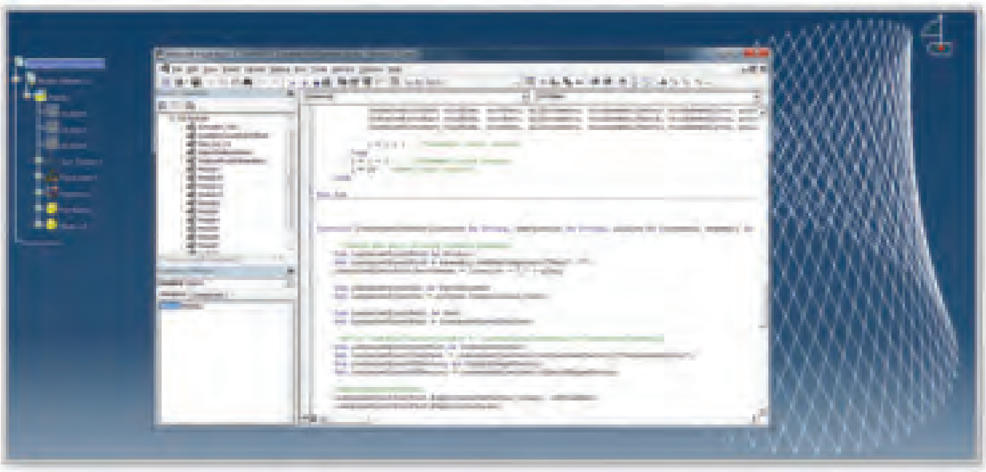
To accelerate the process of studying each armature design, solid components were removed and only set-out lines instantiated. A custom script was written to interrogate the relative angles between each armature pair, and the most severe angles were then modelled using the solid components to test their suitability. This modified approach to parametric modelling proved exceptionally fast, and instantiation of armatures on all 896 points was completed in a matter of seconds.

The geometry of the armatures for the universal connector was optimised for visual and performance criteria through the parametric model, and the final design was extracted from the individual part models and presented as simple 2-D sections and elevations in the contract drawings.



14.

14. Parametric definition of horizontal armature.



15.

15. Custom routines instantiate the connector prototype throughout the node cloud.

Documentation

Throughout the design process, the cable net system seemed to wear two masks simultaneously: one of an intricately detailed sculpture in which the architect and engineer had both laboured over the aesthetics of every pin, clevice, armature and connector; and one of a form-found system with discrete performance metrics tied to a range of building disciplines such as structure and lighting. It was thus imperative to adopt an approach to documentation that would ensure conformance to the geometric characteristics intrinsic to the sculptural piece while promoting a performance- based approach emphasising ends rather than means.

The design team therefore employed a hybrid approach to documentation, largely embracing prescriptive design but also integrating performance criteria to ensure the selection of a specialist subcontractor knowledgeable and experienced in the construction of such a system.

In addition, Arup incorporated performance requirements so as to facilitate a productive dialogue with the contractor that would allow the designer to more effectively monitor and observe the contractor's co-ordination, shop drawing preparation, fabrication, and assembly. The resulting working environment promoted open dialogue on potential construction issues and a balanced approach to risk management.

The design team's extensive form-finding analysis yielded comprehensive data on the characteristic node co-ordinates and element strains in the cable net system. Because these data remained available to the team members, who were highly confident of their validity, a prescriptive approach to documentation became the team's baseline. Nodes were given unique identifiers, tabulated and presented in the contract drawings with explicit 3-D co-ordinates.

For tensioning, the drawings conveyed to the contractor the precise force to be applied to each boundary element. Average tension forces were provided for each row of cable pair segments, as the standard deviation in any given row of the net was considered low relative to the magnitude of tension forces and the corresponding margin of error intrinsic to the tensioning process.

16.

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16. Full-scale mock-up prepared by fabricator TriPyramid at the production facility in northern Massachusetts, September 2011; a 13-panel section of the net was tensioned and assembled for design team review.

17. The mock-up tested the design configuration and revealed opportunities to enhance the system's configuration while such changes were still viable.

18. Preparing the cable net:

a) As each panel is geometrically unique, to ensure proper installation connector components were marked with serial numbers.

b) Connections throughout the net involve sophisticated assemblies of custom components. Here, a connection between the net cables and lower tension rods is packaged for transport to site.

c) Components — panels and tension rods — are geometrically unique. Where etched serial numbers were not called for, the supplier included temporary identifiers for reference during installation.

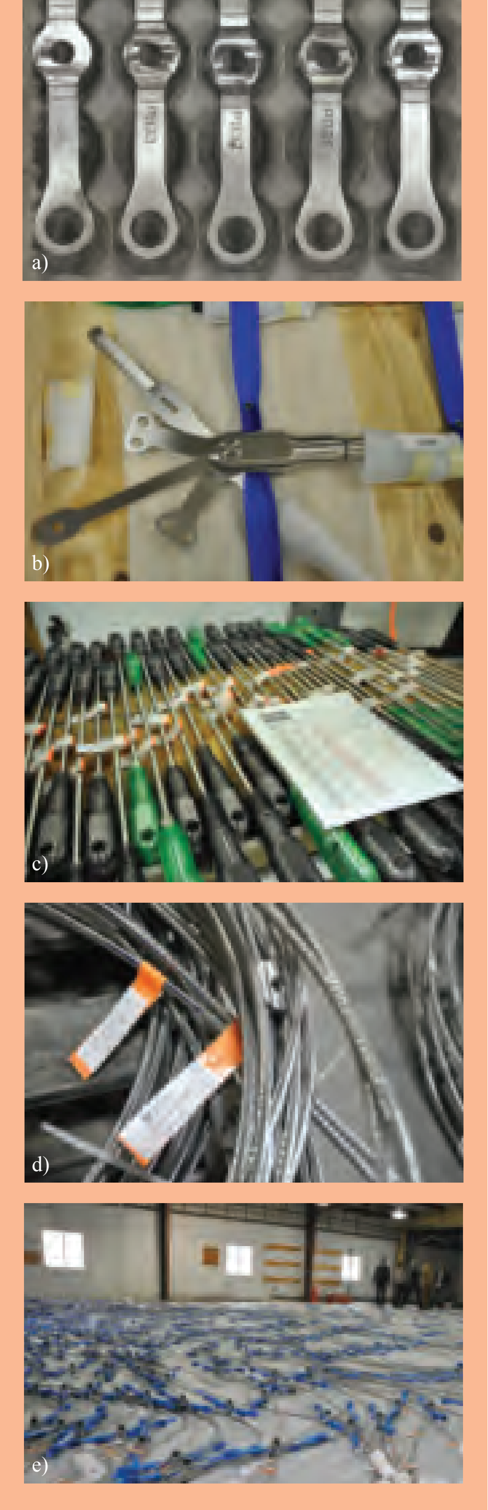
d) Close-up of cabling prior to assembly.

e) The net was assembled at a rented warehouse in a town in rural northern Massachusetts, and then lifted by crane in a field to simulate installation, before transport to site.

The provision of this prescribed set of tensioning data helped ensure that the contractor's system embodies not only an acceptable distribution of tensile forces to achieve the desired form, but also an average level necessary to ensure that movements under environmental loads are kept within acceptable limits.

Had the design team produced a performance-based design, the contractor would have needed detailed information on loading assumptions in lieu of prescribed tension forces, and would have had to perform a far more sophisticated analysis of the system to identify tension forces commensurate with permissible node movements — analysis already conducted by the design team to arrive at a component design that balanced aesthetic and performance requirements. Such duplication would have been costly and added more tasks to an already complex construction schedule.

Providing the tabulated node co-ordinates on the drawings put the onus on the contractor to ensure that the co-ordinates on the installed cable net matched those in the design drawings within specified construction tolerances. This requirement would thus incentivise the contractor to carry out analysis to ensure that all cable and rod segments were fabricated to lengths appropriate for the specified boundary tension forces outlined in the drawings.



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This analysis yielded specific tension forces in each element that were used by fabricators to prepare shop drawings illustrating cable marking lengths. These were received by the design engineers as submittals, allowing them to check the resultant shape using non-linear static analysis.

The design team was thus reassured that fabrication drawings had been developed from a suitable analytical model, owned by the contractor, that had produced results matching those produced by the designer's model. However, the prescriptive dimensional and force data from the design team eliminated the need for the contractor to undertake complex form-finding. Rather, the tabulated node co-ordinates were used to generate a non-linear static model that could be analysed with the documented tension forces to confirm that any node displacements would remain within the governing performance-based requirements.

Construction

The building's superstructure and fit-out of the area bounded by its enclosure and foundations were packaged into a single construction contract, awarded to a joint venture of Plaza and Schiavone (PSJV) in August 2010. However, the cable net's complex and unconventional nature caused PSJV to engage several specialist subcontractors to fabricate and install it. Co-ordination was managed by Enclos, the subcontractor also selected to supply façade components for the enclosure and the oculus. TriPyramid Structures provided the cables and cruciform armatures, while the anodised aluminium infill panels came from Durlum of Schopfheim, Germany.

Together with the steel fabrication and erection subcontractor STS Steel, all the construction team added skill and expertise to the value of the design through open collaboration. Performance-based provisions in the contract documents, aimed at promoting discourse among team members, generated fruitful if occasionally intense discussion over elements of the design and strategies for its execution.

Mock-up

The specifications required a full-scale mock-up of 13 panels, provided by the contractor so as to validate his means and methods and enable the design team to assess the system's performance (Fig 16).

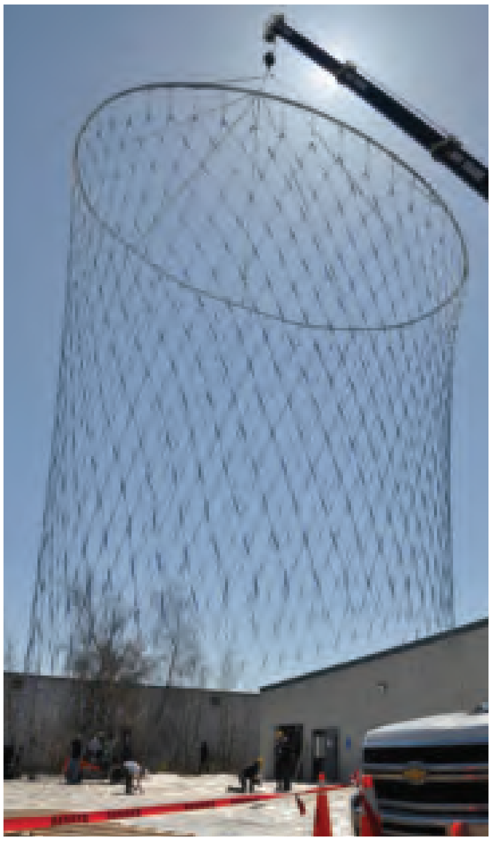
Detailed review revealed opportunities to enhance durability and longevity through minor tweaks in the geometry of perforated infill panels and hardware components such as neoprene washers, spacers and nuts (Fig17). The contractor worked with the design team to realise these enhancement opportunities, and with minimal impact to the construction cost.

The contractor used tabulated node co-ordinates and a small set of typical details to develop the geometry of each unique infill panel, and automated scripts to rapidly develop shop drawings for each. These drawings, once approved by the design team, were used by Durlum as electronic instructions in the computer numerically controlled (CNC) process used to fabricate each panel. The panels and cruciform connectors were stamped with a unique identification code to facilitate proper assembly in the field (Fig 18).

Fabrication, assembly and installation

TriPyramid Structures fabricated and assembled the net in a small rural town in northern Massachusetts. Each connector assembly was pieced together and wrapped for protection during transport. Once assembled, the net was lifted by crane in a field outside the assembly facility to simulate its actual installation on site (Fig 20). The net was then lowered and rolled immediately for transport to site by truck.

Once on site, the net was lifted into place using a temporary aluminium lifting ring raised by a set of hydraulic jacks mounted around the perimeter of the atrium at the Fulton Center's upper levels, and lifting cables that doubled back over the oculus above (Fig 21).



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19. Uday Durg, MTA-CC Program Executive, in attendance at test lift.

20. The assembled net crane lifted in a field near the facility, to both simulate installation and review its untensioned form.

21. The untensioned net following installation on site.

22. Contractors on the swing stage complete work on hardware connected to the lower portion of the net.

23. 3-D LIDAR scan of the tensioned net both before and after panel installation; the survey gave detailed information on the as-built position of the cable net nodes.

22.

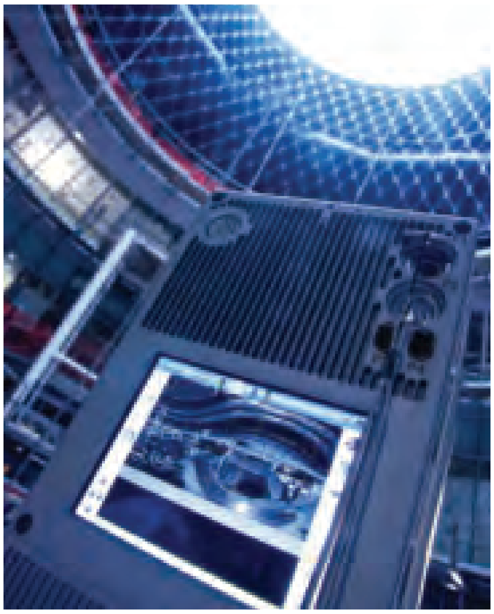
Once all boundary connections were made, the installer, Enclos, tensioned the net through a procedure that involved imposing known and unique displacements on the lower tension rods, inducing target boundary forces obtained through design team analysis and provided on contract drawings (Fig 22).

Panels were then installed with two man-lifts and a swing stage platform suspended from the oculus. Panel installation was completed in about three weeks (Figs 24–29).

Survey

The Arup design team contracted Naik Consulting Group PC to carry out a 3-D LIDAR ("light"+ "radar") survey of the cable net at critical installation milestones. Using remote sensing technology to measure distances, this generated a cloud of several hundred million points, representing the as-built surface geometry of the interior atrium space (Fig 23). The point cloud was used to identify the position of cable net nodes following installation and tensioning, both before and after panels were installed. The design team used the resulting information to assess the conformance of the constructed system to contract performance requirements, and identify regions of the completed net for in-depth, up-close review.

The survey was commissioned by the client during construction administration as an effective risk management tool. Although nothing occurred to prompt extensive use of the LIDAR survey data for corrective action, the availability of this information enabled the distribution of tension forces throughout the as-built structure to be compared to those established through design stage analysis, thereby providing information on system elements requiring adjustments to their tensioned length. The LIDAR results also serve as a permanent record of the as-built net geometry, should any panels require replacement in the future.



23.

Conclusion

This installation at the new Fulton Center combines two generally disparate structural systems: a form-found cable array prone to movement under varying loads, and rigid, delicate aluminium panels sensitive to strains caused by movement at their support points. To achieve harmony between them, detailed nonlinear analysis was performed to fully understand the magnitude of deflections under all conceivable loadcases. A linear algebraic model of the net facilitated rapid interrogation of deflection components within the plane of the panel surface.

These movements were subsequently addressed through the design of a universal, flexible connection assembly that isolates the panels from the effects of the net's dynamic behaviour, through strategically-placed slotted and oversized holes. Flexibility of the universal assembly was tested by parametric modelling, which simulated the geometric configuration of the assembly in each of the 896 intermediate node positions.

The detailed analysis enabled the use of prescriptive design documentation, which provided the contractor with clear geometric and force data. The resulting fabrication, assembly and installation occurred without major incident.

The cable net was substantially completed in June 2013 at an estimated cost of $3.8M. The Fulton Center complex is scheduled to open to the public in June 2014. A year prior to opening, the cable net was already receiving considerable attention in the press including *The New York Times*, as well as in other media.

Acknowledgments
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Erin Morrow is a senior consultant in the Toronto office. He provided 3D modelling support for the cable net design.

Ben Urick was a structural engineer in the New York office, and contributed to the cable net design.

Project credits
Client: *New York City Transit Authority* Architect: *Grimshaw Architects* Artist: *James Carpenter Design Associates* Structural engineer: *Arup — Scott Bondi, Craig Covil, Bruce Danziger, David Farnsworth, Matt Franks, Kristina Moores, Erin Morrow, Ricardo Pittella, Markus Schulte, Jason Shapiro, Tabitha Tavolaro, Ben Urick* Contractor: *PSJV* Specialist sub-contractors: *Enclos; TriPyramid Structures; Durlum; STS Steel.*

Image credits
1, 3-5 *MTA-CC/Arup/Grimshaw*; 2, 6-7, 9-29 *Arup;* 8 *Nigel Whale.*

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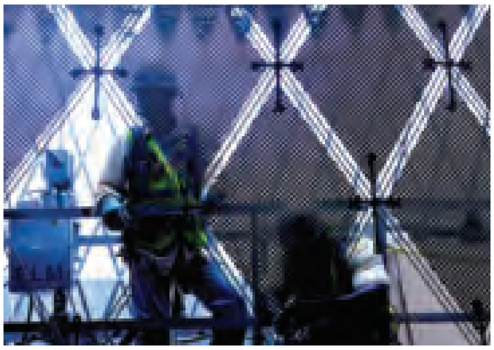

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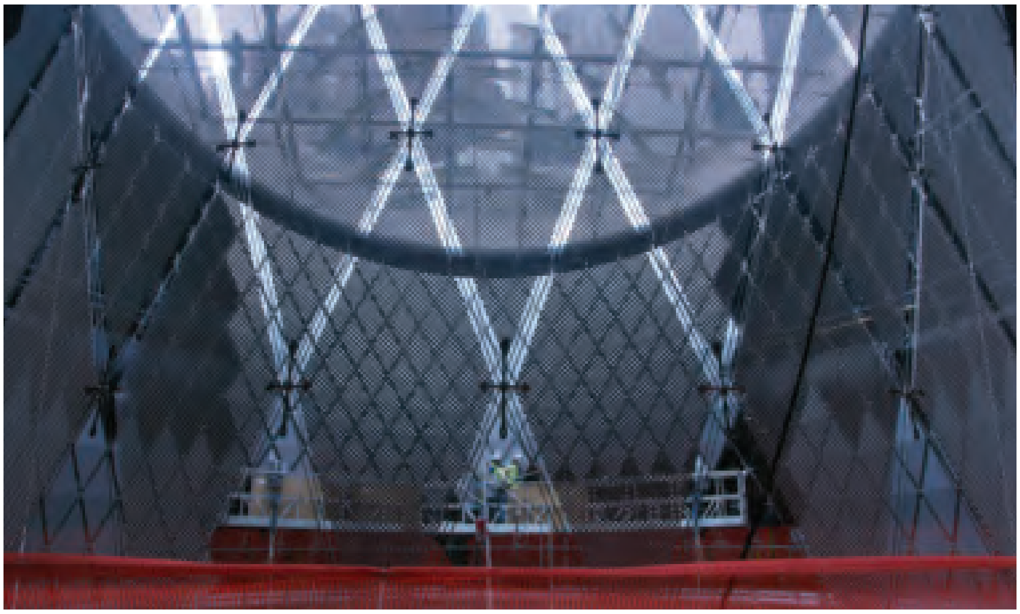

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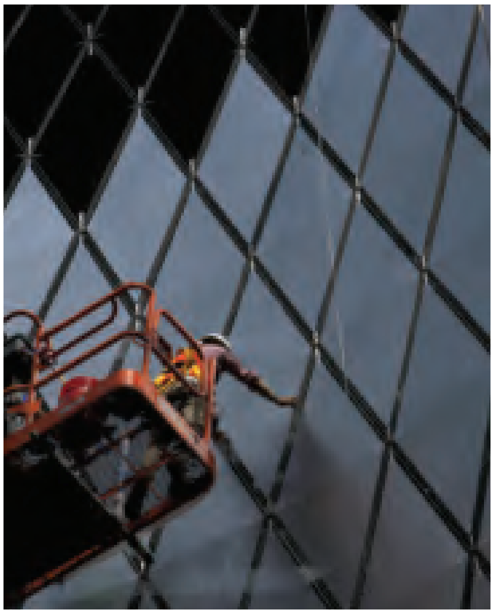

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24. Removal of the panels' protective films.

25. Three teams of contractors installed the panels, connecting each to cruciforms at the four corners.

26. The dramatic lighting effects of the cable net became apparent as panel installation progressed.

27. Panel installation took approximately three weeks.

28. Arup engineers took to the boom lifts to assess the built configuration against service requirements; as the form-found structure will behave dynamically under changing environmental loads, it was necessary to ensure the panel connections retained adequate allowance for associated movements.

29. Contractors' final check of the completed system: art integrated with architecture and engineering.

"Lloyd's Cloudless":

reglazing Lloyd's of London — a first for recycling

Authors
Mark Bowers Philip King

1.

The need for refurbishment

Designed by the then Richard Rogers & Partners, engineered by Arup, and opened by HM The Queen in November 1986, the new Lloyd's of London at 1 Lime Street (Fig 1) is a City of London icon and a key project in Arup's history.

The building had performed well for nearly a quarter of a century, but by 2010 some refurbishment was clearly needed for it to continue as a compelling, vibrant and commercially useful space. The one City of London business sector that had remained buoyant through the recession was insurance, and competitor buildings had proliferated in Lloyd's' vicinity. Lloyd's needed to act to hold the sub-tenants it already had and remain the focal point of what is still the global centre of insurance underwriting.

More natural light would brighten the interiors, and so the client implemented a glazing replacement programme. Arup was again engaged — 30 years after the original project — its materials and façades teams now working with the client and the original architect (now Rogers Stirk Harbour + Partners) to strategise the reglazing programme to meet the new requirements. Jones Lang LaSalle provided quantity surveying services, and the Stuart Brown Partnership was appointed project manager.

Project challenges

As the building's original "sparkle glass" was highly attractive and special to Lloyd's, the design team determined that as much as possible of it had to be preserved. Also, the window design meant that reglazing a total of 1182 floor-to-ceiling units had to be carried out from the inside. The team was faced with working around a live building doing business as normal, and thus involving not just the occupants, but their furniture, IT cables and server rooms, possessions, equipment, fitted kitchens, heavy safes, and many other obstacles (Fig 2).

Also needed was some external scaffolding, which had to be removed by the start date of the London Olympics. Arup reviewed scaffolders' design proposals for how they could locate its weight around the building,

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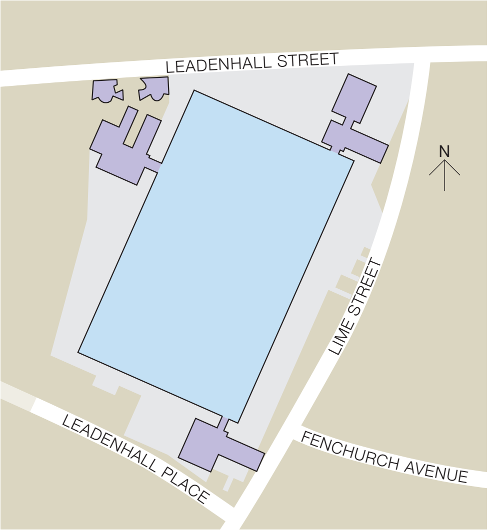

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where the paving incorporates many basement smoke vents with limited load-carrying capacity.

As the building is no longer owned by Lloyd's itself, the new owner, an overseas investor, also had to be satisfied. And finally there was the City of London, which was concerned with end appearance. The building is Grade 1 listed, so it was imperative that the exterior be not significantly altered. Progressing the project required much persuasion both from the design team and from Lord Rogers himself, who was supportive.

Background: the original design strategy
The 1977 architectural competition was won "by defining what was essentially a design strategy rather than a building"[1]. The first key point was to "allow for maximum flexibility of use", and this led to the innovative strategy of putting the building services, lifts and stairwells in satellite towers — making it an "inside out" building[2] (Fig 3). This enabled the vast open floor space that the client required, surrounded by flexible gallery space that could become offices as needed.

The original glazing comprised both clear vision glass and the "sparkle glass" (Fig 4). The casting process embodied very accurate 8mm lenses to produce the sparkle effect, unlike normal cast glass where a random or fine pattern would hamper visual performance. This effect was developed by the architect and cladding contractor, using the internal and external skins to create a crystal-like play of light, sometimes sparkling, sometimes glowing, across its surface. The glazing was very important in the building's design, as the HVAC system pulls air through the window cavity, causing the inner skin to be at a near constant temperature all year around.

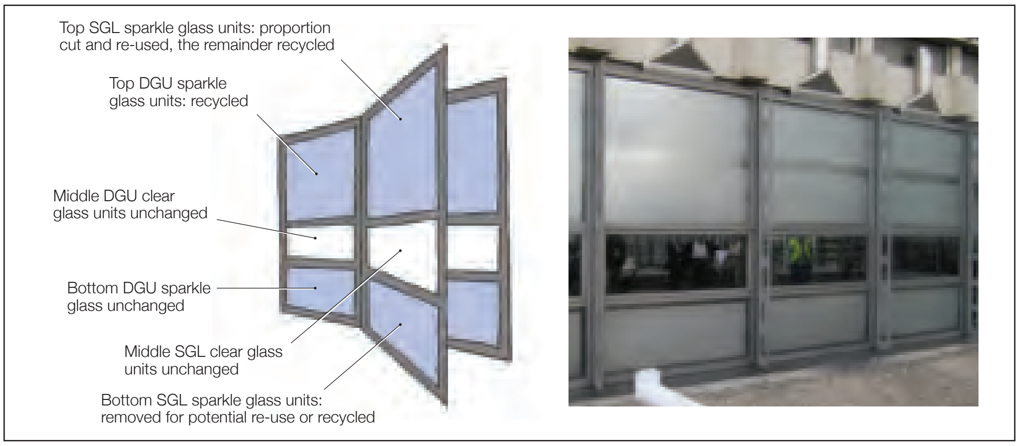
1. The new Lloyd's of London soon after completion in 1986.
2. Removal of panels from the occupied building.
3. Building plan, showing satellite towers.
4. "Sparkle glass" panel.

5. Existing glazing arrangement and reglazing strategy.

6. New glazing arrangement.

7. Completed units where bottom used to be sparkle glass.

8. Coffee table made from sparkle glass.



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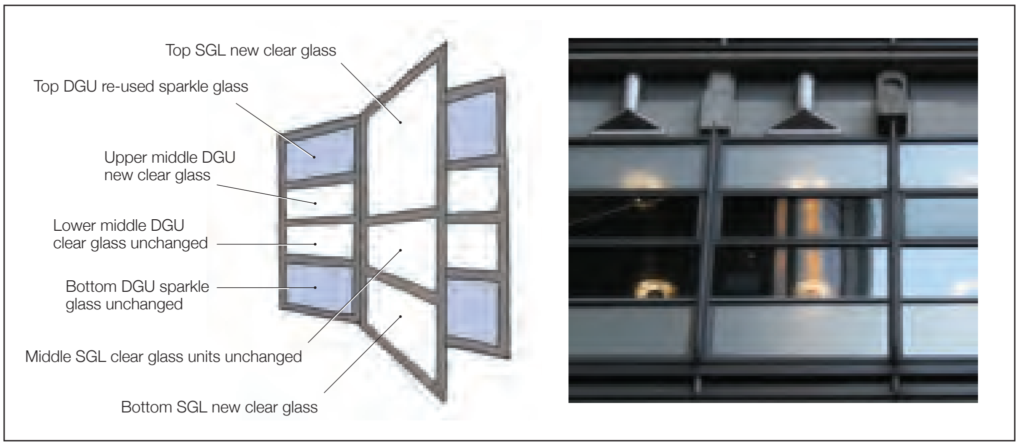

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Replacement and recycling

Each floor-to-ceiling unit has two layers of glazing — outer double glazing (DGU) and inner secondary glazing (SGL) — with bands of sparkle glass and clear glass that are arranged differently on upper and lower floors. To increase the perceived light gain, the design strategy was to replace the sparkle glass in the SGL upper pane with new clear glass throughout, and re-use some of this released sparkle glass together with new clear glass to create a new vision band for the DGU (Figs 5–6).

Some of the released sparkle glass was sent to a Belgian factory of the glazing supplier, Saint-Gobain Glass (SGG), to be cut down to the new required size, fabricated with new glass into DGUs, and then returned to the UK for reinstating into the building.
The remainder was turned into cullet (waste glass pellets) and sent to SGG in the UK for recycling — though some was set aside to make a set of bespoke coffee tables (Fig 8).

In 2001, SGG UK had instituted a strategy for recycling waste float glass from its factories and suppliers; but though more than 100 factories now feed into this process, this recycled waste had always been virgin glass. Together with SGG, the Lloyd's design team developed an innovative procedure to achieve minimal wastage (<1%), with all the removed glazing being either re-used or recycled. Such a mass recycling of "post-consumer" glass had not been attempted, and the Lloyd's project was the first to input to SGG's process. This represented a high degree of environmental responsibility, as discarding such a quantity of glass would have been very wasteful.

Over the last 10 years, SGG's process has increased in efficiency, making it the leader for recycled content in glass — one reason it was chosen for this project. SGG includes around 36% of glass cullet in its new float glass, 4.5 times that of its biggest competitor. This pioneering project was an exciting opportunity to showcase just what is possible with recycling glass, opening the door for more of the same in future.

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The recycling process

Initially the cullet is crushed in a hopper into pieces approximately 1cm^3 in size, which are then checked for contaminants by a large electromagnet and a non-ferrous metal detector. The electromagnet removes large pieces of ferrous metal like nails, while the non-ferrous detector determines which sections of the line may contain other metallic contaminants. Any that do so are removed.

The material that passes these tests is stored ready to be used in the production line, while the glass that failed is down-cycled to a paint factory to be used in road paint. As a result, the glass is almost 100% recyclable; in 2011 from a production line that produced 196 000 tonnes of glass, only 255 tonnes was waste sent to landfill.

The cullet is weighed out with other raw materials to a tolerance of 0.1%. Steam is then passed through this mixture to form a binding agent and act as a pre-heater so that the material does not enter the furnace cold. To ensure it is clean, it is again passed through the non-ferrous detector.

From here it heads to the furnace where, as with any other glass production, it is melted, floated on tin, cooled, and then cold-processed to size. Once in the cold room it is tested to the same tolerances and allowable defect limits as all SGG float glass. Any section with an unacceptable level of defects is smashed out of the line, to be collected and then put back into the process at the beginning of the line.

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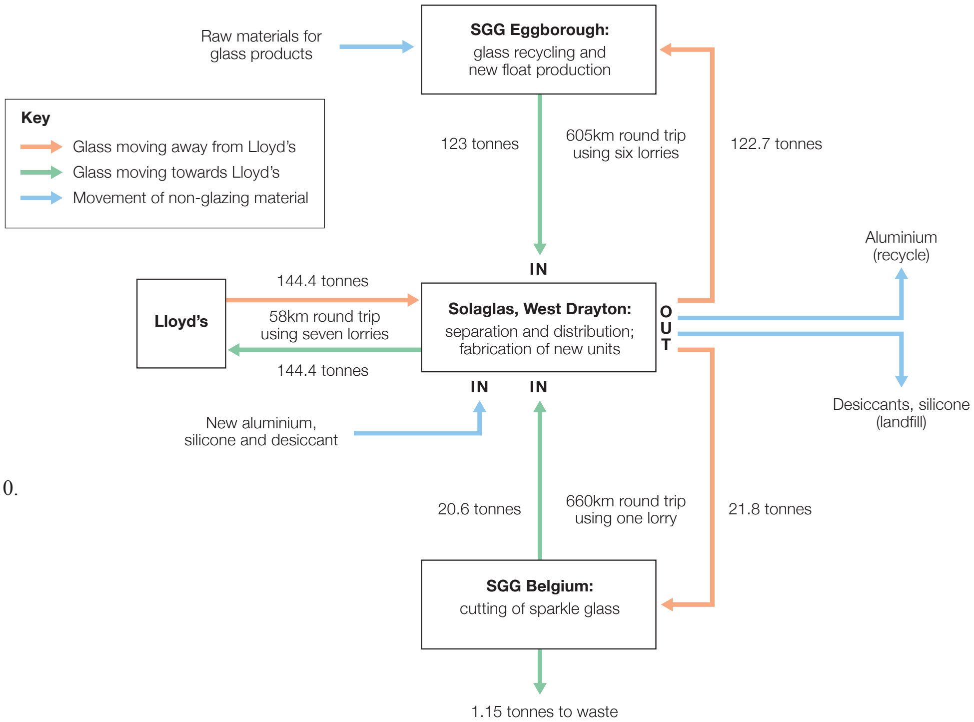

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9. Recycling process.
10. Process flowchart.
11. The refurbished façade (overleaf).

Procedure

A rolling programme was established to systematically remove and replace the glazing, and an area in the Lloyd's building was set aside for stillages to transport the removed DGUs and waste glass out and bring new DGUs in. Once a lorry-load of waste DGUs were removed, they went to the depot at Solaglas (a division of SGG) to be separated from the framing materials, and all elements were sent on for further processing (Fig 10).

The "inside out" nature of the building posed considerable challenge to the scaffolders. Also, once an area had been completed there could be no further access to it, requiring the Arup team to inspect the work as it proceeded. Internal access restrictions added to the difficulty, particularly with server rooms where there was limited space for manoeuvring the large panes of glass and only one operative allowed inside at any one time.

The process, of course, threw up some non-glass materials as waste, such as aluminium spacer bars, sealants and desiccants. Where possible, and depending on quantities, the aluminium could be recycled, but not the silicone, which had to be disposed of. The biggest risk in recycling glass is of contaminants. Where the glass is factory-new, the risk of contamination is small, but with post-consumer glass, exactly what is being recycled must be tightly controlled. Metals, desiccants and sealants are a risk to the float line as are types such as heat-resistant glass, which could cause a shut-down and consequent losses in time and money.

Two other challenges were encountered during the reglazing. Some leaks were found, as would be expected after 25 years, so the contractor replaced seals as necessary. Also after 25 years it was hard to get a colour match on the anodised finish required for the aluminium trim. To overcome this, the aluminium received a special paint coating that matched both the colour and sparkle of the original anodising.

> “We are delighted with the results of Project Cloudless. Arup’s attention to solution-focused detailed design allowed this very challenging project to make headway.”
>
> Jack Kent, Head of Property Services, Lloyd’s

Environmental benefits

When making glass from raw materials, the yield is not 100%, so that when it reaches the furnace there is ignition loss. The ratio of raw materials to final product is about 1.2:1. Cullet, conversely, does give a 100% return, there being no ignition loss. It also requires less heat to process and thus less gas, which saves the factory around £2M/month as well as reducing usage of a valuable natural resource. The SGG factory’s annual production of 196 000 tonnes of glass contains some 70 500 tonnes of cullet. That yield of glass would require 235 000 tonnes of raw materials, but with 36% recycled only 150 000 tonnes are needed, an annual saving of around 85 000 tonnes.

Also, there is a substantial reduction in CO^2 emissions from the factory. For every 1000 tonnes of cullet processed, 350 tonnes of CO^2 emissions are saved, equating to around 25 000 tonnes of CO^2 pa. In addition, empty trucks are avoided if the cullet can be collected on the return trip after delivering new glass. This transport efficiency reduces mileage and carbon embodied in transport — another reason why there is a good environmental case for recycling schemes of this kind.

Cost analysis

Some of the environmental savings gained by the programme are hard to quantify, due to commercial sensitivities over releasing precise data, but it was easy to quantify economic savings by getting waste disposal quotes, the average received by the team being £6765 for disposing of the glass, including transport.

It was then imperative to calculate the recycling cost. After investigating the effective man-hours it would take to separate the DGUs, remove the silicone from the single glazing, and load the cullet onto stillages, the labour cost estimate was £4896. The cost for fabricating a breakout table to dismantle and break the glass was estimated at £1525 and the disposal cost for residual waste at £335, giving a total recycling cost of £6756. Transport could be excluded from this as it is included with the delivery of the glass on the “cullet return scheme”.

The cost of recycling was thus very close to the disposal cost, but additionally SGG would pay for the waste cullet at about £15/tonne, yielding around £2000 that could potentially be put towards labour cost and making recycling viable financially. Recycling became a cost saving to the project, as well as being the right thing to do.

Conclusions

This project showed recycling to be a potential solution for similar projects. Until very recently, glass producers had no wish to take post-consumer glass as its source, given the possible presence of contaminants. SGG is very cautious about what it uses; even from known suppliers it does not mix glass from different sources so that, if there is an issue, it is certain which glass has caused it.

It should be noted that recycling laminated glass and heat-resistant glass is not practicable. Though delamination is now possible, the cost outweighs any potential financial benefit, and the energy required negates the energy saved in the recycled line. Also, it is a common misconception that glass coatings will be a contaminant. SGG’s testing has shown that using 100% coated cullet was not detrimental to the final product, with no impact on clarity or colour of the final float glass. The only exception is recycling mirrored glass due to its metal content.

Any project that wishes to use the glass recycling service will need to have a sample of its waste glass assessed by being ground down and run through various tests to determine any problems. Once it passes all the tests it can be accepted for recycling and a collection scheme put in place.

Questions have been raised about the quality of recycled glass, but the stringent control procedures on the float line ensure that its quality equals that of any glass product made to the same tolerances and with the same allowable levels of defect. This being the case, and with recycling potentially less expensive than new glazing, there is no reason not to consider it for a refurbishment of this scale. Although, cost analysis figures are small within the overall cost of the works, this project shows its potential for success. So far as Lloyd’s itself was concerned, the total cost of the reglazing was small compared to the benefit in maintaining sub-tenants and thus enhancing the income stream and the building’s asset value.

In a world where sustainability is increasingly important for businesses, solutions that reduce strain on natural resources and reduce carbon emissions should be embraced and encouraged. This is a true value story of helping to “shape a better world”.

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Authors

Mark Bowers is an engineer in the London office, and a member of the materials team for the Lloyd’s Cloudless project.

Philip King is an Associate Director in the London office, and was Project Director and Project Manager of the Lloyd’s Cloudless project.

Project credits

Client: *Corporation of Lloyd’s* Architect: *Rogers Stirk Harbour + Partners* Glazing designer: *Arup – Mark Bowers, Simon Cardwell, Camille Destres, Graham Dodd, Steven Downie, Philip King, John Robinson, Kristian Steele, Sian Williams*
Quantity surveyor: *Jones Lang LaSalle*
Project manager: *Stuart Brown Partnership*
Glass supplier: *Saint Gobain Glass UK*
Glazing contractor: *Osprey Contracts Ltd.*

Image credits

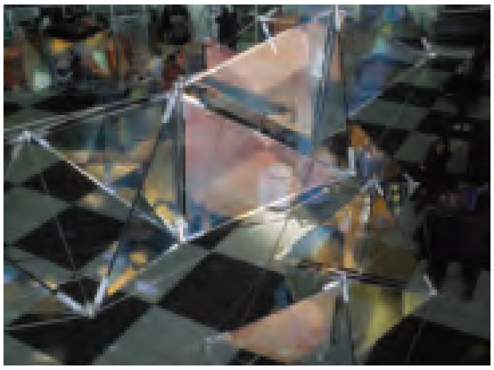
1 *Janet Gill*; 3, 10 *Nigel Whale*; 2, 4-9, 11 *Mark Bowers*.

11.

Developing bio-responsive façades:

BIQ House — the first pilot project

1.



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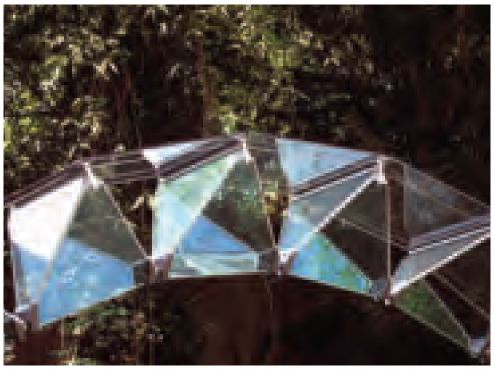


3.

1. The foliage canopy's responsiveness is a great inspiration in developing adaptive building envelopes.

2. Architect and designer James Carpenter's glass sculpture "Refractive Tensegrity Rings", Munich Airport, 1992.

3. Glass cell structures using the tetrahedron as a structural module hold the potential to use the enclosed volumes as containers for gas or fluids to enhance environmental control.[2]

Location
IBA Wilhelmsburg, Hamburg, Germany

Author
Jan Wurm

Introduction

With sustainability ever more sought after, and net-zero carbon emissions an increasingly common target for building designers, the design community is looking for ways to create highly responsive façades that are adaptive and change in response to their environment. The biological cycles of nature are a great source for inspiration. The foliage canopy, for instance (Fig 1), provides the best natural protection from the sun during the hot summer months, while at the same time it is permeable to light and cleans and moistens the air — and yields fruits and firewood.

The architect Mike Davies' concept of the "polyvalent wall" from 1981[1] is still a stimulating reference for all who are researching technical systems for smart skins: multiple coated glass panes that integrate electrically and chemically active layers, allowing the transparency to adjust to internal requirements and external conditions. At around the same time the tremendous potential of structural glass to not only promote transparency but also use the liveliness of reflecting surfaces with the presence of colourful absorbent building fabric in innovatory artwork was being explored (Figs 2–3).

This article describes the evolution of the concept of a bio-responsive façade. It combines both biological and technical systems, in which microalgae are cultivated in transparent glass containers known as flat panel photobioreactors (PBRs) to facilitate the biochemical process of photosynthesis in a controlled environment.

The concept

In 2008, Arup established its materials consulting practice in mainland Europe, and shortly afterwards the new consultancy was approached by the Austrian architectural practice SPLITTERWERK to join its design team in a competition for a smart materials house at the International Building Exhibition (IBA), to take place in Hamburg in 2013. This competition proved to be the perfect occasion to combine and develop the previous experience in this field of both firms (Fig 4).

The design featured what the architects referred to as "supernature" — a second skin enclosing stacked residential units so as to create a "mezzo-climate" between the inside and outside. Around the same time Peter Head, a Director of Arup and leader of its global planning practice, had published his vision of the "ecological age"; in his 2008 Brunel International Lecture[3] he described approaches towards a new green urban infrastructure, a key element of which vision was façade-applied microalgae systems.

Microalgae perform photosynthesis up to 10 times faster than higher plants, thus allowing the implementation of short carbon cycles. Their use in façades was also being considered by the UK Institution of Mechanical Engineers, and some architects had started to show algae systems in visual renderings. These first concepts, however, were all based on tubular glass bioreactors, in which water and algae circulate through a meandering transparent tube to absorb light and carbon — a costly and maintenance-intensive type of system, and not supported by any holistic building concept.

Working on the "supernature" skin, the Arup competition support team identified a small hydrobiology specialist company called Strategic Science Consult GmbH (SSC) in Hamburg, which was researching processes for cultivating microalgae. On an open field test site SSC had developed and tested a flat panel bioreactor that could turn daylight into biomass with an efficiency of close to 10%. This was achieved through air uplift technology, where pressurised air is injected at the bottom of the panel and the turbulences created by rising air bubbles stimulate the absorption of carbon and light, while also "washing" the panel clean from the inside (Fig 5).

As well as the increased efficiency of this system for cultivating biomass as a renewable energy resource, two further points made the major difference with respect to building integration:

- The bioreactors produce heat, similar to solar thermal collectors, that can be used for warming the building.
- The panelised geometry allows control of the algae density in the medium and consequently the transparency and total energy transmission of the façade.

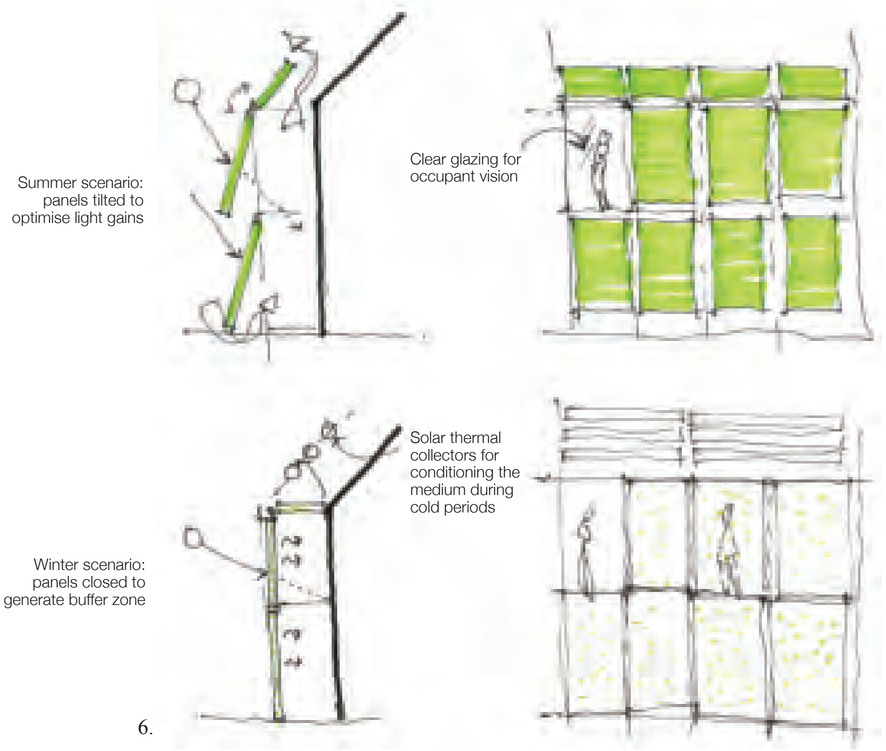
It is a tribute to the collaborative spirit between individuals in the design team's member firms, namely Mark Blaschitz of SPLITTERWERK, Karsten Peleikis of IMMOSOLAR GmbH (which also came in as a member of the team supporting the Arup concept), and Martin Kerner of SSC, that this initial idea of a bio-responsive façade for the external skin was adopted and developed further. In March 2010 the IBA announced that the project had won first prize, the bio-responsive façade being highlighted by the jury as the key innovatory component.


5.


4.

4. Visualisation of the pilot project fitted with 200m² of bio-responsive façade, for realisation at IBA 2013 in Hamburg

5. Detail of the flat panel bioreactor developed by SSC, showing the rising air bubbles to enhance turbulence in the medium.



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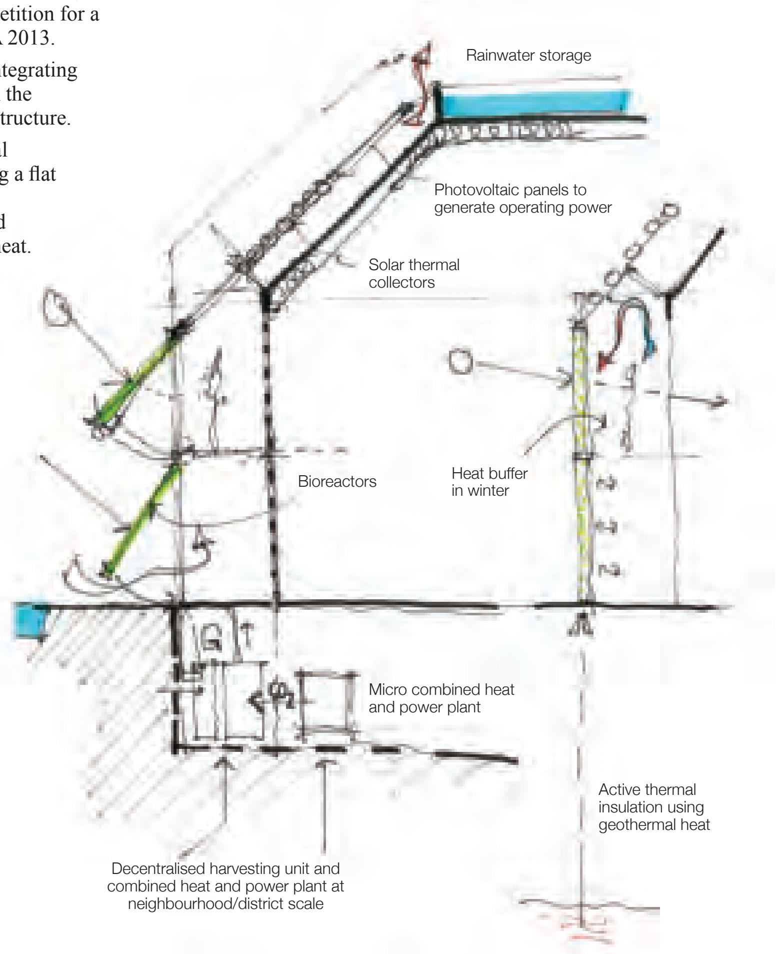


7.

6: Arup concept sketch: integrating flat panel bioreactors for team SPLITTERWERK's "supernature", international design competition for a smart material house, IBA 2013.

7. Arup concept sketch: integrating flat panel bioreactors with the building's technical infrastructure.

8. Visualisation of external shading device, integrating a flat panel photobioreactor for cultivating microalgae and generating solar thermal heat.

External collaborative research and product development

With the opening of the IBA only three years away, the team pushed ahead with the system design so as to attract private investors to buy into the scheme. Arup's Berlin office was instrumental in pulling together an industry consortium for developing and testing the system. This now also involved Colt International, a global player in façade and climate engineering components. Thanks to the commitment of Lukas Verlage, Ulrich Kremer, Manfred Starlinger and Jörg Ribbecke of the Colt team, a façade system for the building integration was jointly developed in a time frame of only just over two years.

Further funding for the product development was secured through the "Zukunft Bau" (future building) initiative of the German Federal Ministry of Transport, Building and Urban Development. Within the overall team Arup undertook the co-ordination, design management and engineering roles; SSC was responsible for the process technology, and Colt for the detail and system design as well as for the procurement.

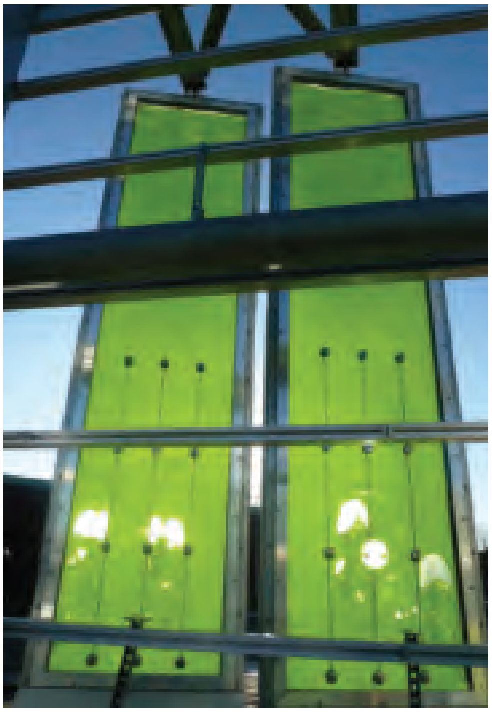
The façade component as finally developed was a storey-high glass louvre: a dynamic shading device that integrates a photobioreactor for generating biomass and solar thermal heat. The louvre is supported on its central vertical axis, allowing it to track the path of the sun. All services, such as the pressurised air supply, and inlet and outlet of the medium, are integrated in the perimeter framing (Figs 6–8).

The build-up of the glass units comprises four panes of monolithic glass. The inner pair form a central cavity of 18mm for the circulation of the medium and the outer pair enclose, on either side, 12mm wide insulating spaces. The front panel is a laminated extra-clear micro-textured safety glass to maximise solar gain. The framing is designed in such a way that different glass build-ups can be integrated to suit project-specific requirements.

The first fully operational prototypes were installed on SCC's test site in January 2011 (Fig 9), and a second generation followed in December 2012. The tests demonstrated that the flat panel glass bioreactor:

- has considerably higher production rates than tubular reactors under the climatic conditions of Northern Europe throughout the year
- has 8%–10% efficiency in transforming solar energy into biomass
- experiences no deposition of algae and successive bio-fouling, due to the high flow velocity on the inside surfaces
- does not require cleaning of the inside, and
- can be operated by a fully automated control system (eg when adding nutrient to the medium), thus keeping maintenance costs down.

10.



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The BIQ House — the first pilot project

On the basis of this product design, the IBA in Hamburg made funding available to SSC for constructing a pilot project featuring 200m² of the façade system, and including all the mechanical components to operate a closed loop system on site. The contractor Otto Wulff Bauunternehmung GmbH, also an investor in the scheme, was asked to implement the technology on a four-storey residential building on the IBA site in the Wilhelmsburg quarter of Hamburg by 2013 (Fig 10).

Arup was commissioned to develop the energy concept as well as the design of the energy control centre and the mechanical systems. By pulling together specialists from the fields of sustainability and environmental consulting, ICT (information communication technology), and building physics, as well as the more traditional mechanical, electrical and public health engineering disciplines, Arup was able to supply the unique set of skills required to design, in collaboration with SSC and Colt, the world's first bio-responsive façade.

Dubbed the BIQ (Bio Intelligent Quotient) House, the building was successfully unveiled on March 23, 2013, and this global debut of an operating algae-based bio-responsive façade system immediately triggered great interest from national and international media[4–7] and other stakeholders. Alongside the formal BIQ House opening, Arup's partner Colt rolled out the jointly developed façade system under the brand name *SolarLeaf*. This is now commercially available and will be marketed through Colt, generating successive planning commissions.

9. First prototypes of the glass bioreactors.

10. The completed BIQ House.

11.

12.

The façade is fitted as a secondary structure on the southwest and southeast elevations. Clusters of three to five panels, each 2.5m tall and 0.7m wide, are linked by a closed loop to the plantroom. The inputs and outputs of the loop system are monitored by the building energy management system, which controls the supply of nutrition and harvesting of the algae at the interface with the building services system. At this interface the algae content and the medium's temperature level are monitored.

The heat generated through the solar thermal effect needs to be dissipated to prevent the system overheating; for a stable production rate the temperature is kept below 40°C. The excess heat is harvested by a heat exchanger and either used directly for the provision of hot water or stored in geothermal boreholes. The algae biomass is continuously harvested, stored and in regular intervals transported to a nearby biogas plant where it is transformed into methane.

For this small-scale pilot plant, the biomass potential of the algae represents around 30kWh/m^{2}a and the net solar heat again is around 150kWh/m^{2}a. In comparison to fossil fuels, about 6 tonnes of CO_2 is saved and an additional 2.5 tonnes of CO_2 absorbed by the biomass every year.

Because it relies on complex, optimised systems, this technology is ideal for use on a larger scale. Fully integrated into the heat and emission flows of a site, it can play an important role in establishing surplus energy and zero carbon building clusters, and its implementation in newly built or retrofitted industry sites and local energy distribution networks is particularly promising.

With the possibilities of local and decentralised energy generation, new perspectives arise for planning on the urban scale. As the product is intended to create synergies by linking different systems, the key to implementing PBRs on a wider scale will be co-operation between stakeholders and designers. It is a technology that benefits from strong interdisciplinary collaboration, combining a range of skills from the fields of environmental design, façades, materials, simulations, services, structural engineering, and control systems.

Conclusion

It is important to emphasise that this is a pilot project, and that the team is still optimising processes and hardware components.
The key outcome so far is that the BIQ House, which contains 15 apartments, clearly demonstrates that integrating algae systems into building services is perfectly feasible. Currently the system is being fine-tuned to run at high efficiency. This technical monitoring is progressing well and the same time the team is monitoring user acceptance — critical to marketing the project successfully.
The building is almost fully occupied and the inhabitants are really positive about the façade and living in the BIQ House. This is a great relief, as none of the team had any real knowledge of how people would perceive and interact with a green bubbling façade!
The next step will be the energy monitoring, to commence at the beginning of 2014.

The team believes this to be just the beginning of using the biochemical processes of fast-growing and highly responsive micro-organisms in smart and adaptable building envelopes; a first step towards the vision of the external skin of buildings becoming fully synergetic with the otherwise disparate natural and technical cycles of human environments.

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Author

Jan Wurm is an Associate Director of Arup in the Berlin office, and was Project Manager for the bio-responsive façade project.

Project credits

Clients: *Bundesinstitut für Bau Stadt und Raumforschung/Strategic Science Consult GmbH (SCC)* Architect: *SPLITTERWERK* Materials, glass design, ICT, energy concept, building physics, façade and MEP engineer, and project co-ordinator: *Arup — Tobias Burkard, Graham Dodd, Andreas Ewert, Matthias Frechen, Yaiza Gonzales, Nicolo Guariento, Jan Jirak, Ewan McLeod, Marina Miceli, Sebastian Oehm, Martin Pauli, Dirk Regenspurger, Henning Schlechtriem, Rudi Scheuermann, Cornelius Schneider, Jan Wurm, Gertraud Zwiens* Design team collaborators: *Strategic Science Consult GmbH (SCC), Colt International* Contractor: *Otto Wulff Bauunternehmung GmbH.*

Image credits

1–3, 5–7 *Jan Wurm*; 9 SSC; 4, 8 *Arup*;
10–13 *Colt/Arup/SCC.*

13

11. Pressurised air bubbles rise upwards through the medium, keeping the inner surfaces of the panels clean.

12. The bio-responsive façade stands approximately 320mm proud of the building walls.

13. Detail of the BIQ House façade.

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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The full study of Arup's design contribution to the Montréal bypass Autoroute 30 (A30) extension, as previewed in *The Arup Journal*, 1/2013, pp62-63, will now appear in edition 1/2014.

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