Issue 1 2013

The Arup Journal

Front cover: The artwork *Monument to Change*, by Peter Wegner, visually and audibly engages with passers-by through its ever-changing wall of 2048 “flip digit” modules. It is one of many art installations incorporated throughout the Knight Management Center, Stanford University, CA. *Photo: Tim Griffith.*

Left: The Bill & Melinda Gates Foundation Campus was designed to respond to and integrate with its city-centre site in Seattle, WA. *Photo: Timothy Hursley.*

The Bill & Melinda Gates Foundation Campus: an introduction

Location
Seattle, WA, USA

The Bill & Melinda Gates Foundation Campus is a global centre for innovation, learning and problem solving. It consolidates five offices, bringing the Foundation's staff together for the first time in 10 years, and with the fundamental aim of enabling the staff to do their best work. The Foundation also wanted a campus that would reflect commitment to its local roots as well as to its global mission; it had to be a good neighbour, providing an enduring public amenity to the city, and conserving local natural resources.

In 2005, a team from the Seattle architectural firm NBBJ met with Melinda Gates to discuss design and planning for the new headquarters in the city's downtown. Later that year Arup joined the NBBJ-led design team to provide SMEP (structural, mechanical, electrical, and plumbing) engineering services, and subsequently added acoustics, audiovisual (AV), information and communications technology (ICT), façades, and materials consulting.

Melinda Gates took the lead in planning the US$500M campus, and for inspiration she toured a host of notable buildings around the world. She envisioned the new headquarters as a model of durability, green design, and workplace efficiency: *"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 masterplan comprised four main above-ground structures and was split over three phases: the garage, incorporating the Visitor Center; the seven-storey North (A) and South (B) Buildings connected by a basement; and the East Building. The latter is currently in design, and will add a further 400 000ft^2 (37 000m^2).

1.

Completed in spring 2011, the Foundation's new home occupies 12 acres (4.9ha), replacing an asphalt parking lot with a Campus that includes 2 acres (0.8ha) of living roofs and native plantings.
The museum-style Visitor Center opened in May 2012 and includes hands-on exhibits about the Foundation's mission.

The Campus embodies connections between global mission and 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. 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.

At 900 000ft^2 (83 600m^2) gross area, the project incorporates offices, an atrium, a data centre, a commercial kitchen, service spaces, loading docks and below-grade parking. Throughout, the Campus demonstrates how high-level sustainability can be delivered in architecture on the largest scale.

In October 2011 it 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.

The next edition of *The Arup Journal* will contain a full study of Arup's design contribution to the successful completion of the Bill & Melinda Gates Foundation Campus.

1. High-level graphic showing the Campus against the city of Seattle.

2. Graphic of masterplan design looking west, with the as-yet-unbuilt East Building in the foreground.

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

4. View of the Campus looking south towards the city centre.

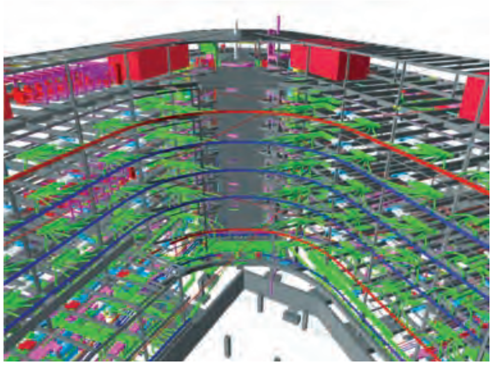
2.

Reference

(1) http://seattletimes.com/html/localnews/2015116661_gatescampus22.html

Image credits

1, 2 *NBBJ*; 3 *Arup*; 4 *Timothy Hursley.*



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Penn Park

Location
University of Pennsylvania, Philadelphia, PA, USA

Authors
Derek Anderson Jack Aroush John Hand
Tom Kennedy Tim McCaul

Introduction

Over the last 15 years, the University of Pennsylvania (Penn) has grown increasingly proactive in the social, economic and educational revitalisation of West Philadelphia, long a severely distressed inner-city neighbourhood. The success of Penn's initiatives has garnered national attention in the USA as a model of "town and gown" partnership. An important element in these initiatives, the Penn Connects campus development plan[1] strives to link city and school through redevelopment with pathways, open green spaces and athletic fields. The 24 acre (9.7ha) Penn Park, an integral piece of the plan and one of the main campus features, delivers on these goals (Fig 1).

The land where it sits was not always what Dr Amy Gutmann, Penn President, refers to as the "beautiful, sustainable, green oasis" now available to UPenn students and Philadelphia residents. Just 18 months before the September 15 2011 grand opening, asphalt parking lots, dead-end roads and aging industrial buildings overlaid soils too poor for planting trees or even grass (Fig 2). The entire park also sits 30ft (9m) below the adjacent streets, and is further cut off from the surrounding neighbourhood by a freeway and high-speed rail corridor to the east and a commuter train line to the west (Fig 3).

2.

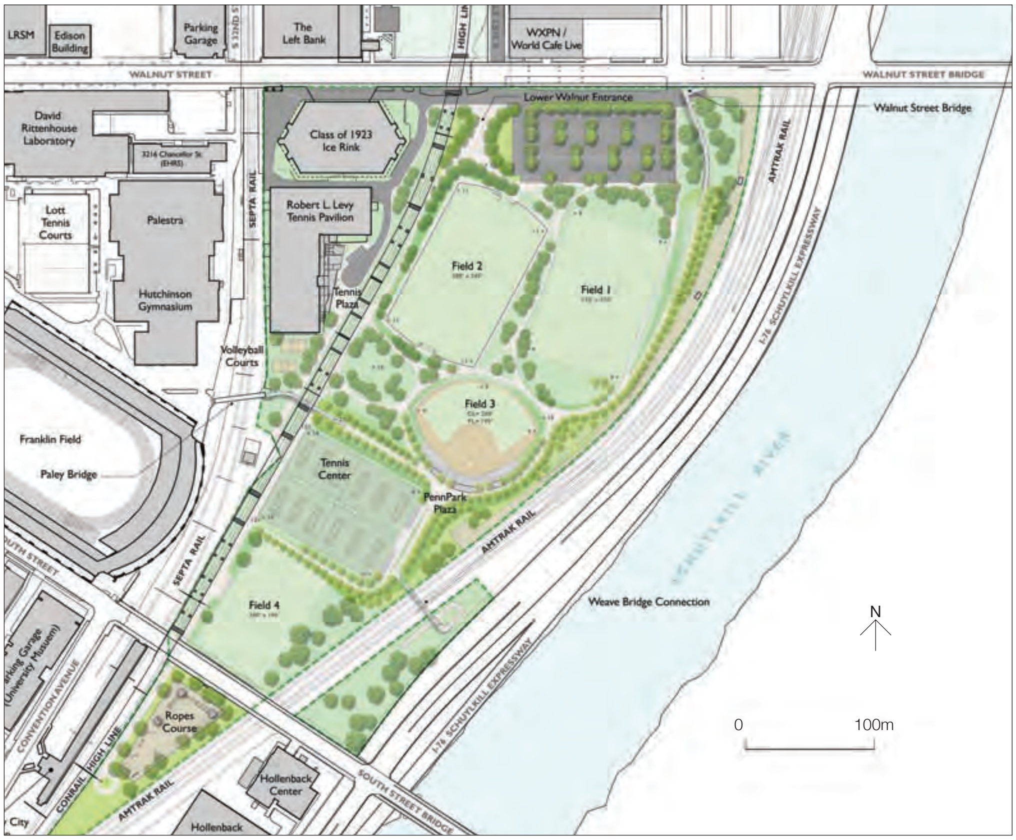
1. Penn Park in its urban location.
2. The site before development.
3. Site plan.
4. Architects’ impression.

Now three bridges connect Penn Park to adjacent roads north, east and west of the site, inviting city pedestrians onto a series of large landscaped landforms that facilitate through foot traffic while offering impressive views both of the park and the city skyline. People sit on the many benches or lay on the grass, enjoying shade from the 530 newly-planted native trees by day and the glow of the energy-efficient lighting system at night — or watch sporting events below at two new multi-purpose NCAA regulation athletic fields, a natural grass hockey field, a women’s softball stadium and 12 tennis courts. Hidden under the fields, a cistern quietly collects rainwater from the surface for reuse as irrigation water to help maintain the trees and grass.

The team

Looking to establish a strong team to develop this unique urban park (Fig 4), landscape architects Michael Van Valkenburgh Associates (MVVA) brought Arup on board for multidisciplinary engineering design, as well as other consultants for athletic field design, architecture, geotechnical support, irrigation system design, environmental and permit consulting, planting soil and bio-remediation soil design support and site lighting.

Arup’s scope was for engineering services from schematic design through construction administration. The civil component comprised the stormwater, sanitary sewage and site utilities including gas, domestic and fire water services, while the structural engineering design included the three bridges, softball pavilions and the tennis centre team room, as well as an examination of retaining walls and footings. Arup also undertook the electrical, plumbing and mechanical design for the softball pavilions, tennis centre team room and an air dome structure to cover one of the multi-purpose fields in the winter, as well as electricity and security systems for the entire park.



3.


©Michael Van Valkenburgh Associates 2010

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5. Stormwater disposal system before installation.

6. Landscape forming.

7. Installing the system.

8. Subsurface storage system.

9. Bioretention area.

10. Bioretention features.

Stormwater disposal and rainwater harvesting

Untreated stormwater runoff from most of the pre-development site had been draining via decades-old unregulated connections to a combined sewer overflow and culvert system that discharged directly to the nearby Schuylkill River. To facilitate sustainable stormwater management, Arup designed a collection and conveyance system that disconnected 48% of this area from the combined sewer overflow and culverts directly discharging to the river, without increasing flow to the city's combined sewer system or the adjacent high-speed rail corridor (Fig 5).

This task was complicated by the highly variable (and mostly poor) permeability of the soils here, which eliminated the possibility of relying on infiltration to reduce stormwater discharges from it. Also, significant portions of the park were to be surfaced with artificial turf and landscaped landforms, which considerably limited the space available for stormwater attenuation systems (Fig 6).

These issues were resolved by maximising the use of available space between the two athletic fields with a 300 000 gallon (1.14M litre) subsurface storage system based around Brentwood *StormTank*™ high void space (97%) storage cells (Figs 7, 8). The system was then further optimised by using it for two purposes; the bottom 2ft (0.6m) of storage for rainwater collection to reuse as irrigation water on site, and the top 1ft (0.3m) dedicated to stormwater attenuation, to reduce peak flows to the city's storm sewer system.

This significantly reduced additional stormwater attenuation around the site, saving Penn money by cutting the excavation and materials needed for stormwater storage. Use of the rainwater harvesting tank will lower Penn's draw on the city's potable water supply for the park by up to 70%.


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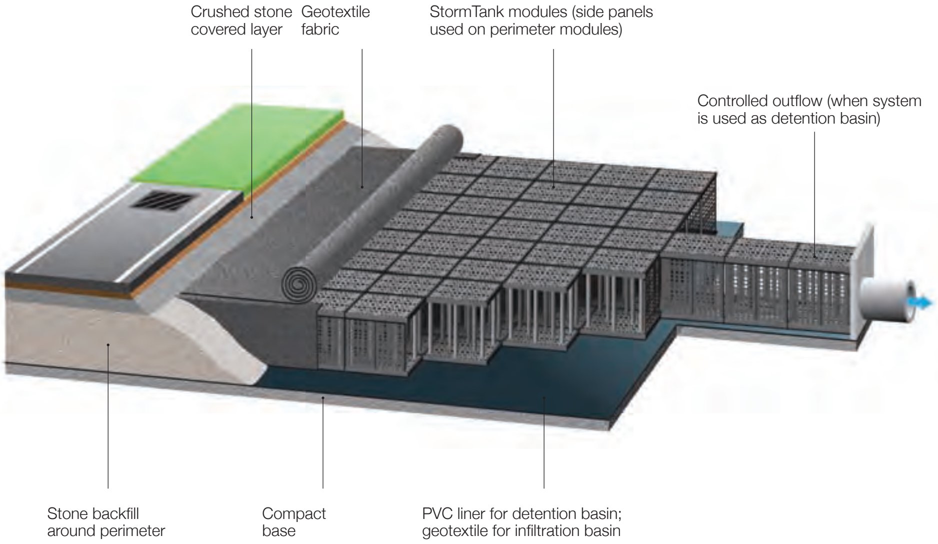

8.

Bioretention
To meet regulatory requirements and Penn's sustainability goals, Arup proposed additional treatment to remove pollutants and sediment from all stormwater discharged from the site or reused for irrigation. Runoff from the impervious areas is now routed through six bioretention areas and three bioretention swales, which adopt cutting-edge sustainability concepts by using the chemical, biological and physical properties of plants, microbes and soils to remove sediment and pollutants from stormwater runoff (Figs 9–10).

By combining such treatment with localised stormwater detention, these systems reduce stormwater storage elsewhere on the site, minimise flooding and overflows into public waterways, and decrease stormwater flow to city sewage treatment plants. These bioretention systems were situated and planted to blend into areas already containing bridges and landforms, so as to complement MVVA's vision for the landscape (Figs 13–14).

Proactive permitting process
In winter 2009/10, a design change to the landscaped landforms support system necessitated accelerating the site utilities construction start date by about six months. This significantly cut into the time allocated to obtain city construction permits for the site utilities. To meet the new schedule, Arup worked with the Philadelphia Water Department (PWD) to help it develop its own stormwater model to test the Arup design. This gained for Arup the PWD's trust, which proved invaluable to the project schedule once construction began.

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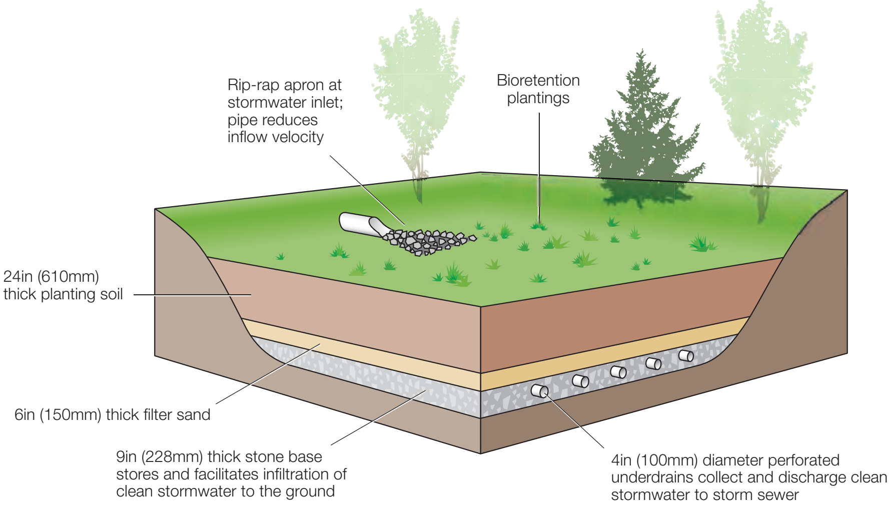


10.

Site challenges during construction
The site continued to throw challenges at the design team well into construction. During excavation, a perched water table containing unsuitable material for use in the design was discovered where the rainwater harvesting tank was to be installed.

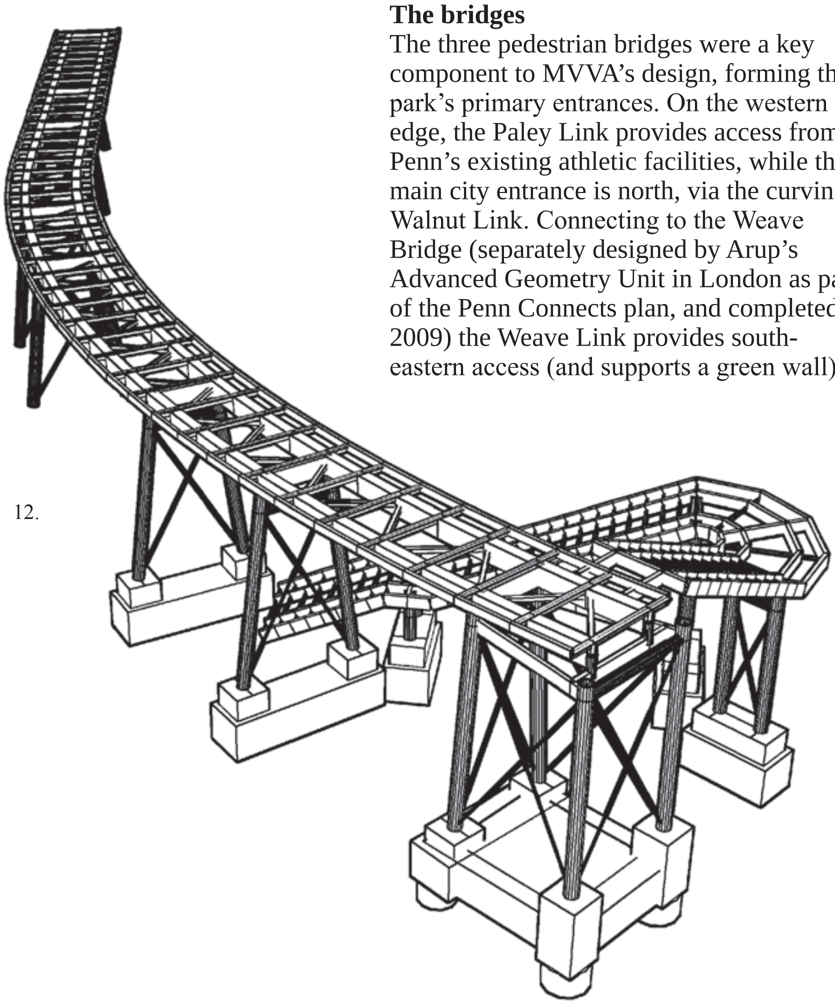
While Pennoni Associates worked to map and remove the unsuitable material, Arup redesigned the subsurface storage system to incorporate an impervious 40mil (1mm) thick geomembrane to eliminate the potential for any remaining unsuitable water or soil to infiltrate the storage tanks. To minimise cost increases and construction delays due to this redesign, Arup found a company that could manufacture, deliver and install the impervious liner, saving Penn some $75 000 against initial quotes from the contractor for multiple subcontractors to carry out these tasks.

As construction progressed, more surprises were unearthed. When the contractor, Turner Construction, began excavation for the softball field, it was found that an existing 4ft x 4ft (1.2m x 1.2m) electrical duct bank running east/west across the entire site — expected to be nearly 20ft (6m) below grade — was actually a mere 6in (150mm) below in some areas. Arup moved fast to co-ordinate directly with the contractor and MVVA's team to minimise cost increases and construction delays. Tactics included working with the permitting agencies to issue a set of "early approved" construction documents identifying what could be built immediately without impact from changes needed to avoid utility conflicts with the existing duct bank.

This allowed the contractor to continue working while Arup quickly revised the stormwater management and sanitary sewer systems, engaging permitting agencies in the redesign to ensure the changes would be accepted under the existing construction permit.

The PWD's trust in Arup's integrity and skill from the original permitting process led it to agree a "light review" only of the revised stormwater management system, thus avoiding the construction delays that a traditional permit review would have engendered.

11.



12.

The bridges

The three pedestrian bridges were a key component to MVVA's design, forming the park's primary entrances. On the western edge, the Paley Link provides access from Penn's existing athletic facilities, while the main city entrance is north, via the curving Walnut Link. Connecting to the Weave Bridge (separately designed by Arup's Advanced Geometry Unit in London as part of the Penn Connects plan, and completed in 2009) the Weave Link provides south-eastern access (and supports a green wall).

Rather than overpower key landscape features, MVVA envisioned the Paley and Walnut Link bridges as extensions of the paths, exhibiting transparency and openness compared to the massiveness of the berms. Penn wanted the bridges to be cost-effective, reasonable to maintain, and allow access to university maintenance vehicles.

The 200ft (61m) Paley Link has 20ft–30ft (6.1m–9.1m) spans and rises 20ft (6.1m) above grade (Figs 11–12). The Walnut Link reaches 300ft (91m) with 30ft–40ft (9.1m–12.2m) spans, and extends 30ft (9.1m) above grade. Both use the same structural vocabulary: helically-curved rectangular hollow structural girders with wide flange edge beams supported on circular hollow columns with high-strength steel ties. For lightness and transparency, the decking is galvanised steel grating.
To provide greater stability for the longer spans, the Walnut Link supports incline to form pairs of Vs (Figs 13–14).

Arup and MVVA spent several months refining the geometry and design of the bridges, and looking at wood, concrete and steel options. Ultimately steel was selected for its sense of lightness, as well as its presence in the *CSX* rail high line running through the site. To minimise the structural beams, Arup performed footfall analysis to verify pedestrian comfort.

13.

14.

11. Part of the Paley Link passes beneath a commuter rail bridge.

12. Rendering of the Paley Link.

13, 14. Walnut Link above a bioretention area.

15. The Weave Link (left) under construction, leading to the Weave Bridge (right).

16. Elevation of approaches to Weave Bridge.

17. Rendering of the Weave Link.

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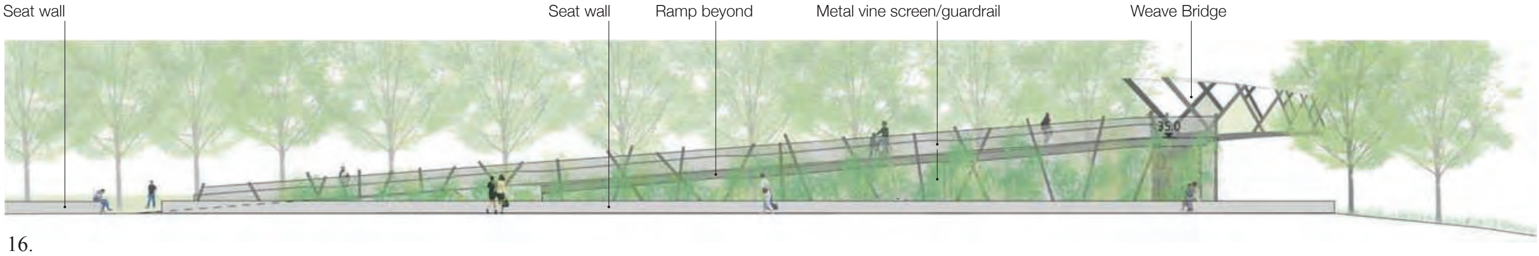
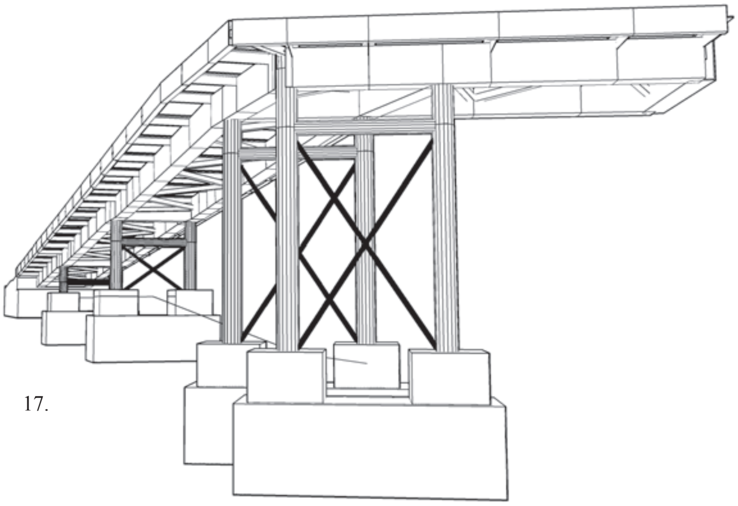


16.

The exposed steel connection details required specific attention to emphasise the line of the beams and hence the continuity of the paths. To simplify construction, the bridges were shop-fabricated, shop-painted, and transported to site in 30ft–40ft (9.1m–12.2m) segments. Only the splices had to be field-welded; all other welding was performed in the shop.

By contrast, the Weave Link acts as an extension of the berm (Figs 15–16). The bridge comprises steel framing and concrete and bituminous decking, with the green wall on either side populated with vines so that the entire Weave Link is camouflaged by foliage. It was fabricated and painted in the shop, with no additional site welding required. The steel bolted connection details were carefully designed for minimal visual impact (Fig 17).



17.

18. The tennis centre.

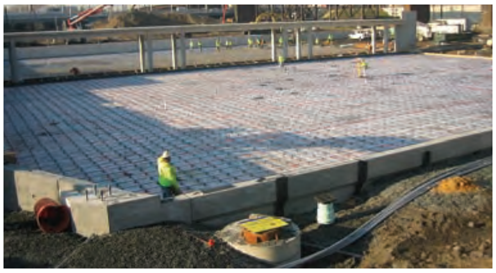
19. Placing concrete for the tennis centre.

20. View from the north, showing lighting towers.

21. Opening firework celebration.

22. Penn Park in relation to the riverfront and the Philadelphia skyline.


18.


19.


21.

Tennis centre

Penn Park now boasts one of the finest tennis centres in the US (Fig 18), with 12 courts spread across four 200ft x 150ft (61m x 46m) concrete slabs on grade, post-tensioned to control cracking rather than with expansion joints that would cut through the courts. As the concrete slabs are so large, special care had to be taken to minimise friction between them and the subgrade, using a layer of sand with two layers of polyethylene sheeting.

The interface of the slabs with the posts, perimeter drains and perimeter walls was also carefully detailed to ensure the slab was not overly restrained while the strands were tensioned (Fig 19).

Electrical engineering design

Arup's electrical scope mainly consisted of integrating the energy-efficient lighting systems designed by three separate subcontractors.

The lighting controls are integrated by a common system for the buildings, park lighting, sports lighting and seasonal-use air structure, with power distribution via a separate utility building, divided to also accommodate a pumping station for the park's irrigation system. Arup's electrical systems also provide the park with special event power: 100A and 200A receptacles placed near all open fields. (Fig 20).

The air structure's electrical services had challenges that required innovative solutions, developed in close collaboration with a code consultant hired specifically for this task. A generator was added for egress lighting, and Arup also designed the electrical power distribution specifically to facilitate set-up and take-down of the air structure.

Grand opening

On September 15, 2011, the Penn President invited Philadelphia Mayor Michael Nutter to conduct procedures as guest of honour, and in their opening addresses both praised the "engineers and designers". Mayor Nutter, a Penn alum, told the assembled dignitaries that he regarded Penn Park as "one of the most incredible projects this city has seen in decades." In particular the sustainable stormwater drainage system was singled out. Both speakers expressed relief that the park, in a flood plain, had passed its first test by not being washed away by three weeks of torrential rain.


20.

The well-attended opening ceremony then merged seamlessly into a sporting and social extravaganza organised by Penn and supported by the local public who turned out in good numbers despite the blustery wet evening. The two new athletic fields were quickly filled with student-athletes practicing for the upcoming season; the softball stadium proved the flexibility of its use by transforming into a concert venue, and tennis balls littered the 12 new tennis courts. Proceedings were brought to a close with a firework display, which signified the importance of the project to Penn and the City of Philadelphia (Fig 21).

22.

Conclusion

Construction was completed on time and within the anticipated budget (approximately $47M, funded by Penn and private donations), with much praise from both University and community.

Arup was honoured to be involved with a project that turns a blighted area into an amenity, gives Penn another facility to draw potential students (and existing students more recreational space without requiring travel), eases the burden on the city's infrastructure, and demonstrates the potential for more redevelopment along Philadelphia's riverfront (Fig 22).

Specific value added was by quick response to unforeseen and unforeseeable site challenges, the co-ordination of multidisciplinary design services within the firm, and the trust and respect Arup developed with reviewers.

As David Cohen, Chair of Penn's Board of Trustees also declared at the grand opening, Penn Park is *"critical to the future of Penn, to the future of the community we live in… and how important it was for Penn as a pre-eminent educational institution to set a standard for sustainability that nobody else in this country comes close to."*

Reference

(1) www.pennconnects.upenn.edu

Authors

Derek Anderson is a senior engineer with Arup in the Toronto office, and was Project Manager and lead civil engineer for Penn Park.

Jack Aroush is a senior engineer with Arup in the Boston office, and was lead electrical engineer for Penn Park.

John Hand is an engineer with Arup in the Boston office, and was structural project engineer for Penn Park.

Tom Kennedy is a Principal in the Chicago office, and leads the Americas Civil Engineering Practice. He was Project Director for Penn Park.

Tim McCaul is a Principal and leads the Boston office. He was Assistant Project Manager for Penn Park.

Project credits

Owner: *University of Pennsylvania* Client: *MVVA*
Civil and SMEP engineering design: *Arup — Derek Anderson, Jack Aroush, Julian Astbury, Malcolm Barr, Louis Curatolo, James DeMarco, Matt Dodge, Margaret Garcia, Ken Guertin, John Hand, William Jimenez, Carey Jones, Tom Kennedy, Anne Killough, Elena King, Michelle Lazaro, Vincent Lee, Patrick McCafferty, Tim McCaul, Anna Murray, Jim Nadeau, Andrew Neviackas, Joe Noonan, Kathy Noonan, Marie Ostrowski, Michael Pang, Phillip Podlasek, Ashok Raiji, Christian Saad, Jing Song, Ivana Sturm, Jimmy Su, Saeed Syed, Sasha Velic, Craig Webster, Saara Young, Jing Zhuang*
Athletic field design: *Geller Sport/Stantec Consulting*
Architecture: *Leers Weinzapfel Associates*
Geotechnical support: *Haley and Aldrich*
Irrigation system design: *Irrigation Consulting*
Environmental and permit consulting: *Pennoni Associates* Planting soil and bio-remediation soil design support: *Craul Land Scientists*
Site lighting: *LAM Partners.*

Image credits

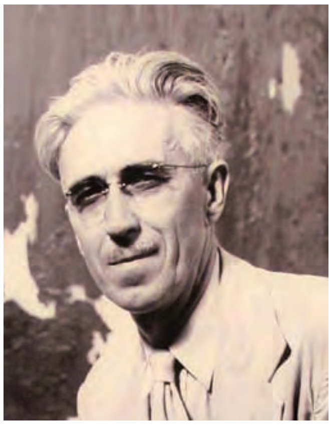
1, 21 *Scott Spitzer*; 2 *Jack Aroush*; 3–4, 6, 9, 16 *MVVA*; 5, 7, 13–15, 18 *Derek Anderson*; 8 *VARI-TECH LLC;* 10 *Derek Anderson/Nigel Whale*; 11, 20, 22 *Greg Benson*; 12, 17 *Arup*; 19 *John Hand*.

The Clyfford Still Museum

Location
Denver, CO, USA

Authors
Erin McConahey Christopher Rush Brian Stacy

1.Clyfford Still in the 1950s.
2. Upper floor plan.
3. Museum entrance.



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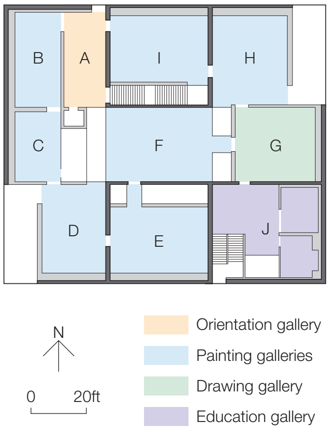

2.

Introduction

A pioneer of the abstract expressionist movement[1] in post-World War II American art, Clyfford Still (1904–1980) abandoned the New York art world in the early 1950s, just as he was beginning to achieve critical and commercial success. Settling in rural Maryland, he spent the next three decades producing hundreds of giant canvases that he refused to sell, storing them instead throughout his family's property. His stark, dramatic paintings became highly sought after, despite (or perhaps because of) their scarcity on the open market, and in 1979 the Metropolitan Museum of Art gave him a major exhibition, the largest then ever devoted to a living artist.

Still's handwritten will specified that his estate, containing the overwhelming majority of his life's work, be given to any American city that would dedicate a museum solely to it. In 2004 his widow, Patricia, agreed to Denver as the host city. Portland-based Allied Works Architecture (AWA) was selected to design the new building, with Arup as lighting designer and mechanical, electrical and plumbing (MEP) engineer.

Lighting design

To honor the spirit of Still and his work, AWA created a sparse, stripped-down design that uses light and texture for atmosphere in the two-storey, 28 000ft^2 (2600m^2) museum. The ground floor contains the lobby, offices, conservation and research areas, art storage and mechanical plant, while the upper floor includes five large daylit galleries and five smaller non-daylit galleries (these include some light-sensitive art). In AWA's own words: *"It's... an unfolded plane that's folding back on itself. It's solid from the outside, but the space writhes and weaves together on the inside. It's like a nine-square cube; some planes are subtracted, and some planes are moved around, with the goal of making a space that feels continuous."*[2]

3.

Responding to this, Arup's lighting strategy aimed to harness changes in the weather to produce different viewing conditions in the space — letting visitors literally see the work in a new light each time they pass through the museum and thus help to encourage repeat trips.

At the beginning of the project, the team and the architect visited existing galleries and other spaces to gather ideas about the kind of atmosphere they wanted to create. This clarified the unique nature of a solo art museum and how to create a very specific feel and mood for the project. leaving behind the standard "white box" gallery approach in favour of an experience congruous to the style of Clyfford Still himself. It also became clear that creative design and engineering would be required to infuse the design and visual aspirations, and manage the challenges of strict energy codes and conservation of the art itself.

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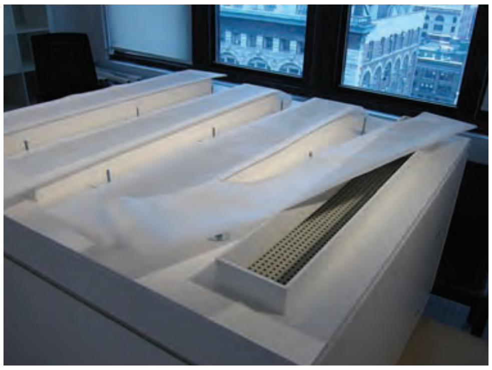
4. *[l–r]* Paintings *PH-150* (1958), *PH-972* (1959) and *1957-J-No2* (*PH-401*: 1957) in Gallery H, looking north. (Still moved away from formal titles to avoid influencing viewers' perceptions of his paintings; with his wife and daughter, he developed instead a serialised numbering system to catalogue his works.)

5. Paintings *PP-40* (1959) and *PP-54* (1959) in Gallery G, looking north towards Gallery H.



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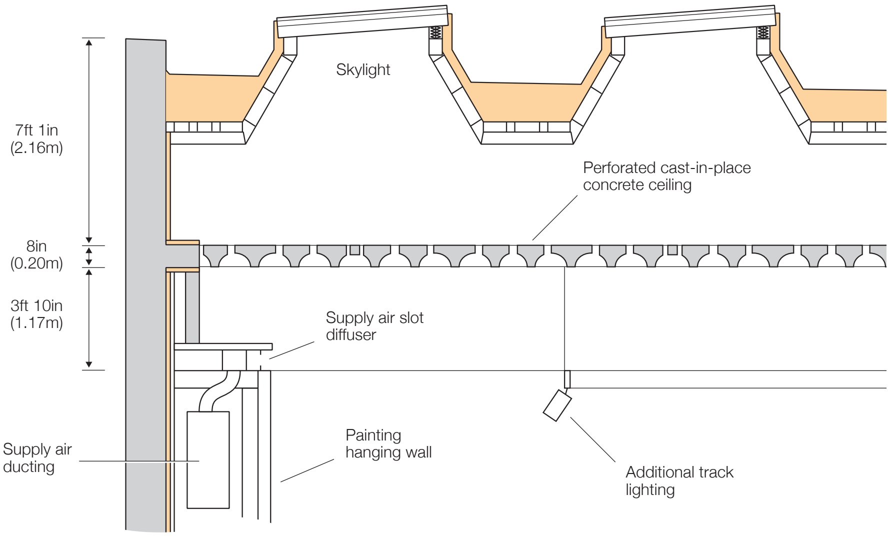
6. Initial architectural model with roof partially removed to show perforated ceiling concept.

7. Close-up of perforated ceiling mock-up.

8. Interior of part of initial architectural model.

9. Cross-section showing part of ceiling/roof geometry.



9.

Changing energy codes prevented a fully-glazed ceiling, adding to the difficulty of providing the quality of light and colour rendering that the museum desired. In addition, the floor area and building height were reduced after the first design development, to reduce costs while keeping a similar gallery layout and programme. Prior to the budget reduction, the daylight design was based on skylights around gallery perimeters and reflected onto a solid ceiling, but with the reduction in building size, the architect proposed to reassess the daylight solution for the luminous ceiling. The architect/lighting engineer team thus evolved the idea of a perforated cast-in-place concrete ceiling. and this became one of the most recognizable elements of the museum's design. Fenestration in the roof above spreads and filters natural light evenly down through the ceiling.

Arup's design also took into account the museum staff's need to fine-tune the lighting, developing a single-layer shading system that can be deployed in summer to create daylight conditions similar to those in winter. In addition, it enables the exhibition of sensitive works that require reduced light exposure, and can balance the contribution of artificial and natural light to artworks for dramatic effect.

Inevitably there are times when daylight alone is insufficient to light the spaces, and Arup's electrical team worked closely with the lighting designers to select and place fixtures for additional light. Track lighting was installed and circuited, so as to give curators and exhibition designers flexibility in spotlight placement, tailored to the museum's collection.

To help meet the client's desire for energy conservation, Arup created a daylight-responsive electrical lighting system. A rooftop sensor monitors the daylight levels and dims the electric light as needed to provide a consistent 20 footcandle (200lux) illumination of the artwork. Quantitative testing, using a combination of mock-ups, scale models and computer analysis, determined appropriate light levels for both art conservation and reduced energy use.

Mechanical, electrical and plumbing engineering

The lighting design required close co-ordination with the MEP engineers, and the multidisciplinary team worked together to select high-performance glazing capable of preventing unwanted heat transfer while still maintaining the desired light quality.

Thanks to its high altitude, Denver enjoys one of the country's highest percentages of sunny days, but for a daylit gallery this can be a curse as much as a blessing. To capture as much light as possible, both for energy conservation and to enhance patrons' experience of the art, the design team decided to include a substantial amount of almost-horizontal glazing for the skylights which enabled the daylighting. The disciplines then co-ordinated to achieve three conflicting goals:

- maximise roof glazing transparency for light transmission, *but...*
- prevent excessive solar radiation from overheating the closely controlled interior environment, *while...*
- containing the heat inside the building in winter for energy conservation.

10.

10. Painting *PH-554* (1942) in Gallery D looking north.

11 *(overleaf)*. Gallery A looking east into Gallery I, which contains painting *PH-960* (1960).

The team was concerned that Denver's cold winters and heavy snow build-up on roofs might cause the internal surface temperature of the glass to drop below the dew point of the humidified art spaces. In most building types, winter window condensation doesn't adversely affect human comfort, so few mitigation measures are taken. But in a space designed to house valuable art, horizontal or near-horizontal overhead glazing makes surface-based condensation a serious concern.

Despite the team's explorations of best-in-class glass technologies and the museum's willingness to allow relative humidities to drop into the 40% range (compared to the usual gallery setpoint of 50% rh), it soon became clear that a mechanical means of preventing condensation was needed.

At the waterproofing and façade consultant's recommendation, the mechanical team designed an auxiliary glass-heating system to ensure that the inner surfaces of the roof construction would remain above dew point under the most extreme conceivable conditions. Arup led the team and managed technical conversations with the architect and other consultants to select the quantity and characteristics of the high-performance glazing and its special heating system to meet all of these challenges.

Overhead water presented issues as well. Due to the roof's physical configuration, storm drainpipes (to collect rain and potentially near-freezing snowmelt from the valleys created by the skylight configuration) had to be co-ordinated through the void above the concrete ceiling. The design therefore features heat trace elements at key locations on the roof to prevent snow buildup from clogging the drains.

In addition, drainpipe insulation reduces the risk of condensation on pipe surfaces inside the building. The plumbing engineers and lighting designers worked together to carefully route the storm drainage piping, ensuring that it would avoid the anticipated angles of daylight dispersion through the ceiling void, so as to prevent shadows on the artwork below.

The MEP team also helped the client reconcile sustainability and budgetary concerns. Early design studies showed that connecting the new museum to municipal utilities would not be cost-efficient.
In searching for an alternative, the team developed the idea of sharing building systems with the next-door Hamilton Wing of the Denver Art Museum, for which Arup had also provided mechanical engineering services.

This existing relationship facilitated approaching that institution about absorbing some of its excess chilled water and heating hot water capacity. This idea, put into practice, allowed steam-to-hot water heat exchangers and miscellaneous steam accessories to be eliminated from the design, further cutting costs.

The design also included demand-control ventilation, using sensors in the building to track the amount of CO_2 present and thus gauge the quantity of visitors.
The system automatically raises or lowers the amount of fresh air entering, reducing the volume of air requiring treatment for humidity and temperature. Thanks to Denver's climate, the result is a substantial drop in energy requirements.

This energy-reducing effect is furthered by the use of an independent part of the air handler to precondition outside air. This eliminates outdoor-influenced fluctuations, reduces use of the main air-handler coil for dehumidification, cuts the amount of reheating necessary, and helps ensure stability of temperature and relative humidity in rooms containing artwork.

Preserving a lifetime's work

Because the museum holds 94% of Still's total output, failure to properly design the building systems could result in the loss of a complete body of work. Art conservation was therefore a particularly critical concern.

A prime consideration in developing the conservation plan was humidity control. Fluctuations in moisture damage canvas fibres, so museum environments need to ensure stable relative humidity. Denver's arid climate made this a particular challenge. Together with the museum staff, Arup examined several humidity control strategies, looking carefully at functionality, price and environmental friendliness. Ultimately, the team selected an energy-efficient ultrasonic humidifier that eliminates the first costs associated with steam generators and steam pipe connections to the Hamilton Wing, and provides significant long-term cost benefits.

Experience with the Denver Art Museum led to design solutions tailored to the context. Tests conducted during that project had shown that a systems failure during a hot Colorado summer day would lead to unacceptably low humidity levels in less than an hour. The Hamilton Wing had experienced power and service failures since its opening, so this was a real concern.

These factors led to the unusual suggestion of creating a separate backup system for the Clyfford Still Museum's archive space. Despite the high cost — particularly given the added financial pressures of the economic downturn — the client decided that it was a worthwhile investment.

In the finished building, the archives normally rely on the standard building systems, but all incoming services (electrical, chilled water, heating hot water) are monitored, and if any begin to fluctuate out of range, the backup system kicks in.

11.

In the event of a prolonged power outage, the curatorial staff can relocate artworks on display into the archive space for protection, since the backup system is powered by an emergency generator.

As for the art conservation requirements of the lighting design, the team worked closely with the Museum director to understand the long-term needs and then tailor the design accordingly to control light transmission and penetration. Arup's approach was based on cumulative exposure on the art for a typical year instead of maximum illuminance at any one time. The Museum agreed with this, enabling the daylight systems to be designed for appropriate annual exposure, rather than the single brightest hour of the year.

Conclusion

The Clyfford Still Museum opened in November, 2011, and has garnered critical acclaim. The *Los Angeles Times*[3] described it as *"nothing less than a marvelous model for what a single-artist museum can be,"* noting also that the *"visually unobtrusive perforated-concrete screen, which filters overhead natural gallery illumination from skylights, is surprisingly buoyant."* Subsequently the Museum won the Honor Award in the American Institute of Architects (AIA) New York 2012 Design Awards Program.

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(3) http://latimesblogs.latimes.com/culturemonster/2011/11/art-review-denvers-clyfford-still-museum.html

Authors

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Brian Stacy is an Associate Principal in the New York office, and leads the Americas Lighting Design Practice. He was Project Director and Project Manager for the lighting design.

Project credits

Owner: *City & County of Denver/Clyfford Still Museum* Client/Architect: *Allied Works Architecture Inc* MEP engineer and lighting designer: *Arup — Nick Antonio, Nathan Blum, Yen Chong, Vivian Enriquez, Tony Freitas, Justin Kimura, Rick Lasser, Erin McConahey, Bruce McKinlay, Morad Pajouhan, Christopher Rush, Tina Sack, Brian Stacy, Bruno Sum, Stacy Sumners, Michelle Torres, Richard Tregaskes, Chris Wells, Michael Yasuo, Randy Yoshimura, Thura Zin* Structural engineer: *KPFF Consulting Engineers.*

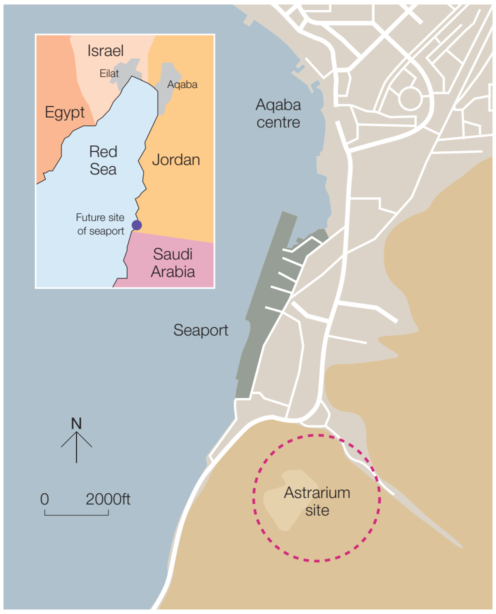
Image credits

1 *Courtesy of the Clyfford Still Museum*; 2, 9 *Nigel Whale*; 3–5, 10–11 *Jeremy Bitterman*; 6–8 *Arup*.

The Red Sea Astrarium

Location
Aqaba, Jordan

Authors
Chris Brosz Nancy Choi Said Gharbieh Tony Kirby Alex Mitchell



1.

2.

Introduction

The strategically important city of Aqaba, in the south of Jordan on the Red Sea, is the country's only seaport. Aqaba's economy is bolstered by a mixture of industry, logistics and tourism; the locale is renowned for its scuba diving and windsurfing, and people travel from around the globe to experience the warm, clear waters and world-class diving.

However, for all its rich underwater diversity, heritage, and proximity to the Dead Sea, Petra and Wadi Rum, Aqaba does not possess a vibrant, mixed-use core, and this could stifle future economic development. Beyond the luxury hotels that line its shores there is little else in the city to stimulate modern tourists. As one of Aqaba's two economic drivers, tourism needs to grow, and new ways of attracting people are needed for longer-term success.

In 2001, Aqaba was established as Jordan's Special Economic Zone. Since then, over US$20bn has been invested in its tourist and port logistics industries, boosting Aqaba's status as a transport and logistics hub in this part of the Middle East, and exploiting its seaport status to the maximum. The seaport is planned to be moved to the southernmost part of the province on the border with Saudi Arabia to increase its capacity and facilitate future mixed-use development (Fig 1).

The Red Sea Astrarium

The Red Sea Astrarium (Astrarium) is a planned 184 acre (75ha), $1bn entertainment resort and virtual reality theme park (Fig 2) that will showcase the rich cultural history and future of Jordan and the Middle East. Situated 200m above the Gulf of Aqaba on a plateau south of the city centre, the Astrarium will include four hotels, an entertainment district, a constructed saltwater lagoon, and two waterfront areas, one of them anchored by a *Star Trek*-themed attraction.

Importantly, the Astrarium also represents Jordan's opportunity to demonstrate its commitment to innovation and sustainable development, contributing to the country's strategic renewable aspirations identified for 2007–2020. Themed resorts, particularly those with global audiences, are increasingly shifting toward resource efficiency, and implementing Arup's engineering strategies will place the Astrarium at the forefront of themed-resort development.

1. Location plan.

2. Artist's impression of the Red Sea Astrarium.

3. Site access.

4. Site access topography (freight access road).

5. Entry portal concept.

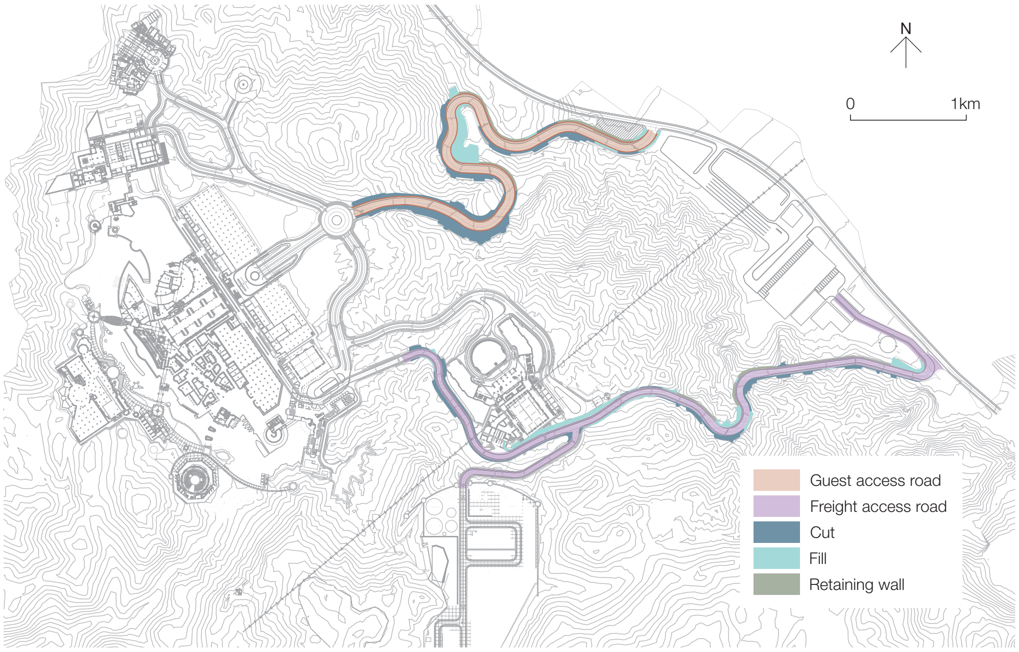
The team

Rubicon Group Holding (RGH) is the Middle Eastern digital content and immersive entertainment company tasked with transforming the site into a world-class themed resort. To achieve this, RGH (represented in Amman and Los Angeles) assembled a world-class team with Arup in a central role as lead engineer. The lead architect is Callison and other contributors include Paramount (designer for the *Star Trek*-themed experience) and local A/E firms including maisam architects | engineers, Universal Consultancy Services (UCS), and Dar Al Omran (DAO) Infrastructure.

The roles of the project team developed and changed as the design work has progressed. Arup and Callison took the Astrarium through concept to schematic design (SD) using staff based in their West Coast US offices. Arup's good relationship with Callison was critical to driving the SD phase through in five months, with the civil engineering package accelerated and delivered in just three months.

After the completion of the SD stage in November 2011, the project was handed over to maisam as the lead A/E firm to develop the design into contract documents (CD) for bidding on behalf of RGH. The project is currently at the detailed design (DD) stage with documentation being prepared for bidding the work to contractors. Bid packages are expected to be released to contractors in early 2013, with a soft completion date in early 2015.

> *"Arup's team for the Astrarium project has been a delight. They have provided context sensitive solutions and worked as informed team members to solve complex site and infrastructure issues."*
>
> Amber Richane (Director, Callison)



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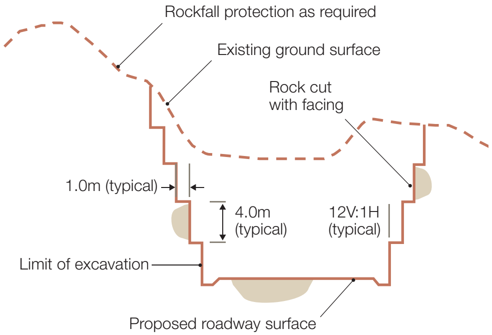


5.

Arup scope

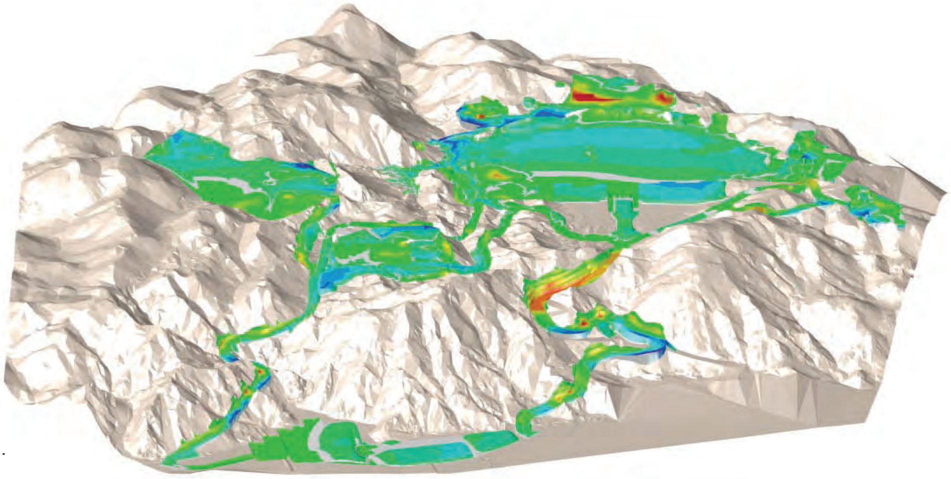
Arup assembled an international team to take on this challenging project. Directed from the Los Angeles office and project-managed from San Francisco, the Arup scope for the SD stage included:

- civil engineering and geotechnics (Los Angeles)
- water management, including design of a salt water lagoon, and desalination and wastewater treatment plants (San Francisco, Manchester, Hong Kong and New York offices)
- energy consulting, including renewables feasibility assessment (Los Angeles)
- site mechanical and electrical design (Los Angeles)
- freight and solid waste logistics (London, Melbourne and San Francisco)
- solid waste treatment (San Francisco and London)
- fire consulting and acoustics advice (San Francisco and Los Angeles).

Following the SD stage, Arup remained in a peer review role from November 2011 to May 2012, participating in weekly co-ordination calls with the entire team to drive the project through the DD stage and ensure that the intent of the SD documents was being executed by the local teams.

As part of this role, Arup attended and co-led a workshop with Callison for RGH in Amman in December 2011 to begin the DD stage and facilitate the formal design handover. A second workshop followed in June 2012 to help finalise packages for bid and move the project forward towards the construction stage.

6. Retaining wall concepts.
7. Guest access road.
8. 3-D site cut-and-fill model.



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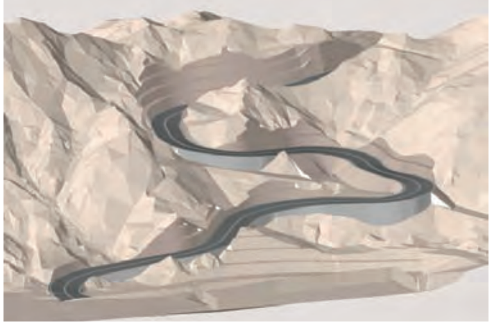
Civil engineering: creating site access
The civil engineering SD package was accelerated to release the site earthworks scheme to the local infrastructure designer at the end of September 2011. The primary focus was to establish two access roads, one for guests and the other for freight (Fig 3), but the existing terrain (Fig 4) made the design particularly challenging.

Arup's Los Angeles team worked closely with Callison to develop the schemes for the two roads, the key tasks being to:

- maintain comfortable grades for guest traffic (10% preferred), while incorporating architectural requirements for road width and the entry portal, whose side walls are tightly stepped to enclose the area (Fig 5)
- determine routes to minimise the height and extent of cut-and-fill retaining structures and requirements for them, taking account of the likely swell factor for any excavated rock and its subsequent placement elsewhere on the site as fill
- establish retaining wall finishes and geometric requirements

6.



7.

- include links to the planned Al Jashieya Road at the base of the site's western slopes and the adjacent Marsa Zayed development
- co-ordinate with the proposed consolidated freight distribution centre (DC) and guest screening areas at the base of both the site access roads and understand how these would need to operate.

To aid the design work and allow rapid testing of alignment options, the team used *AutoCAD Civil 3D* software. Once the site topographical survey file was processed, design began by setting the required parameters within the software to generate alignment options. Arup worked closely with Callison to ensure that the alignments suited their architectural requirements and the entry portal cutting was as dramatic as their vision for it was. During the SD design, more than 15 alignments were tested for both roads.

This process would have taken significant effort and time using standard *AutoCAD* software and design practices, but once the terrain model was created within *Civil 3D*, new alignments (or adjustments to them) could be tested quickly and cut-and-fill quantities rapidly generated for assessment. Retaining wall requirements could also be assessed quickly and the information within the model used to form the basis of the conceptual retaining structures design (Fig 6).

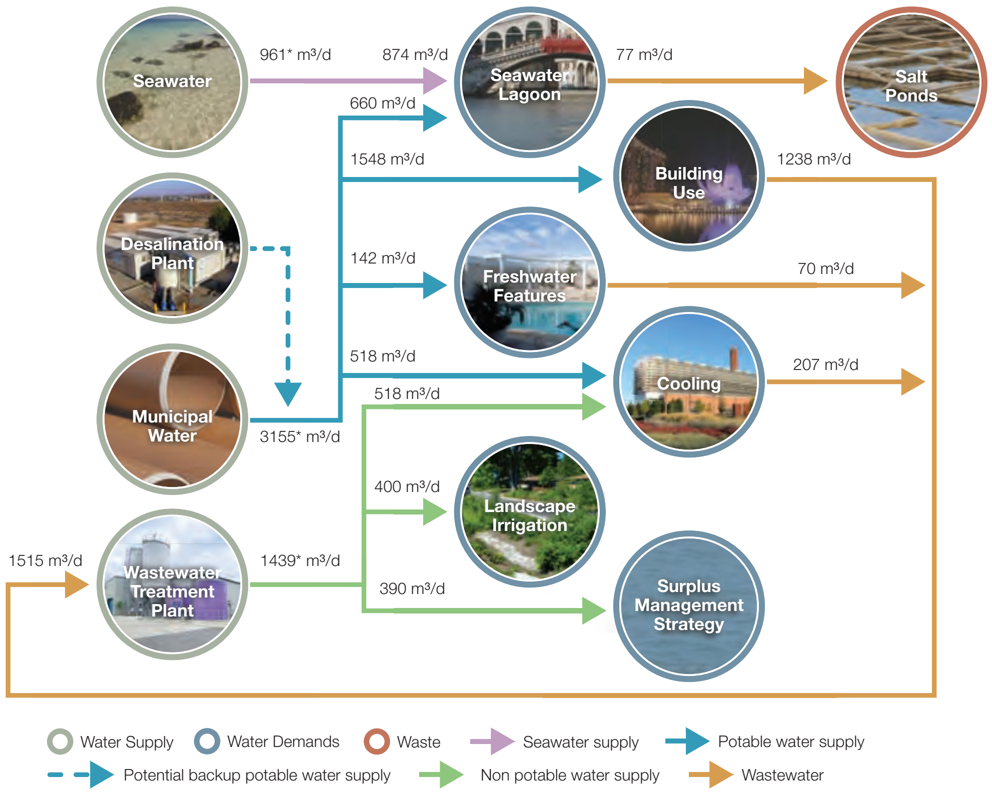
The finished model allowed for simple and effective presentation to RGH (Fig 7) as well as generating the required 2-D plan and profile engineering drawings and outputting earthwork quantities.

Mass earthworks modelling
The challenging topography would have made conventional 2-D grading design methods difficult and time-consuming for the main site development platforms upon which the buildings will stand. Also, the complex form of the buildings and their relationships to the site topography, together with constantly evolving architectural concepts, meant that grading options had to be regularly revisited and earthworks analyses (cut-and-fill calculations) generated for evolving design options.

Creating a site-wide 3-D grading model using the *Civil 3D* software allowed the Arup team to rapidly test options put forward by Callison, and output the associated cut-and-fill quantities for different options to help the design team in its decisions.

The Arup team's ability to quickly translate engineering concepts into 3-D images to clarify the design intent with Callison and RGH became a very useful tool for sharing ideas during the weekly team co-ordination meetings. Graphical presentation of the mass grading scheme to the local design team was an additional benefit of this process, allowing simplified 3-D images to be produced showing the form of the proposed site grading and identifying cut-and-fill areas in different colours (Fig 8).

Earthwork quantities could also be quickly computed for different areas of the sites and used to inform decisions relating to phasing and where material would have to be moved to and from.



* Supply includes additional 10% of demands to account for future distribution losses

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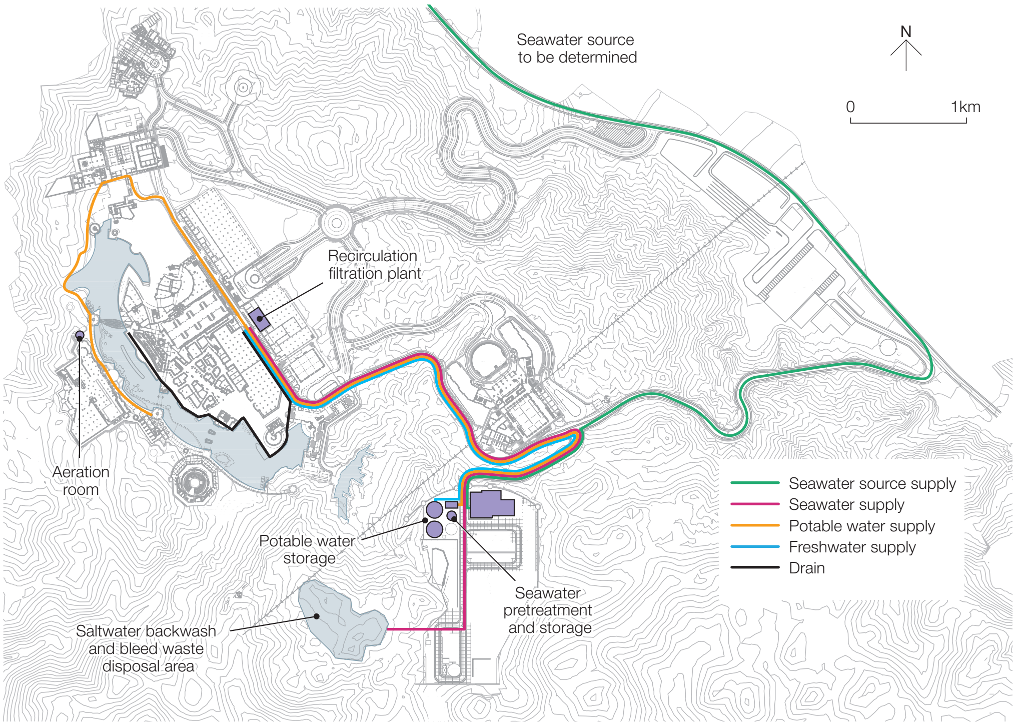

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Water management: a closed cycle approach

A global Arup water team (San Francisco, Los Angeles, Manchester, Hong Kong and New York) developed the schemes for water management throughout the site. Here, the key tasks were to:

- determine proper stormwater collection and management within the site constraints and topography
- identify the right mix of water sources, given the intended demands (potable, non-potable, seawater) at the site
- enable sustainable demand management while maintaining sensitivity to client demands
- manage wastewater and reuse
- manage the quality and quantity of water for the seawater lagoon proposed as a key feature of the Astrarium.

Jordan's extreme water scarcity presents a complex design challenge. The Arup team developed a model to estimate the Astrarium's water demand, and a supply strategy to meet this demand through a combination of municipal water, recycled water and raw seawater (Fig 9).

A baseline business-as-usual potable water demand was built from all non-saltwater needs on site (building, cooling, irrigation, water features), based on analysing water use demands commonly assumed in Jordan and around the world. The model then incorporated reductions on the baseline from water-efficient building design and wastewater recycling for irrigation and cooling. These reductions resulted in a potable water demand 35% less than the estimated demand for similar developments.

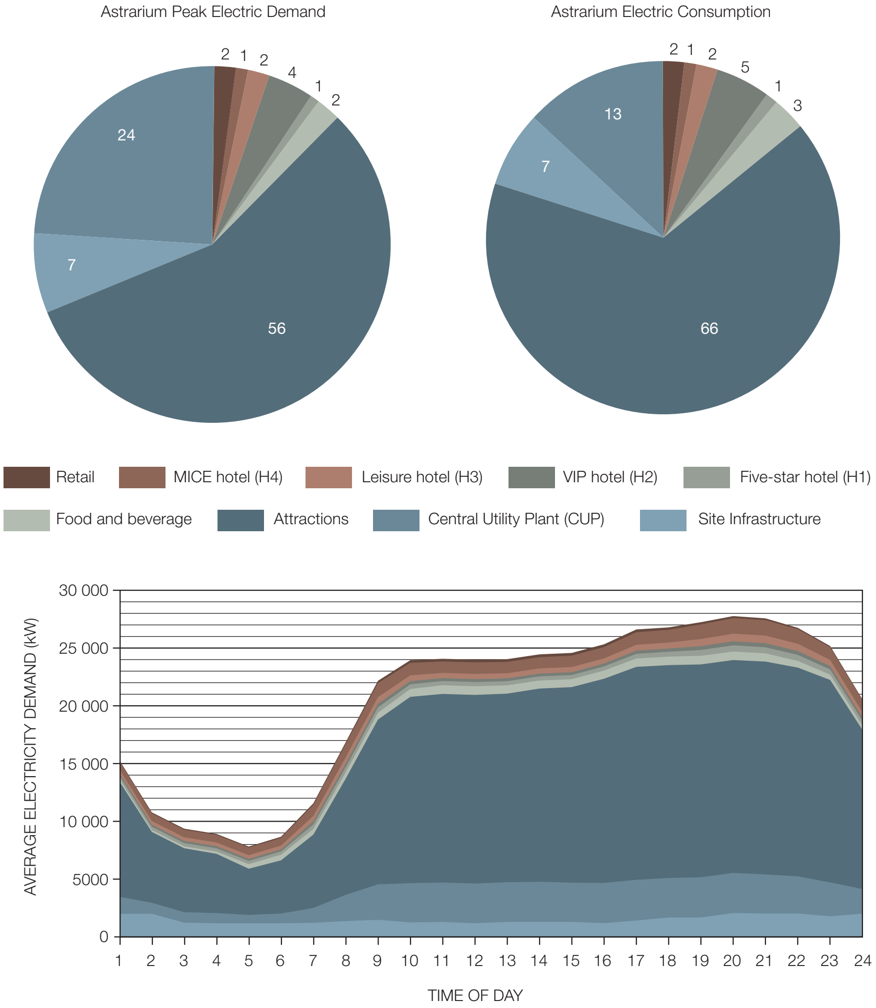
The constructed seawater lagoon will be approximately 485 000ft^2 (45 000m^2) in area and will hold around 2.5Mft^3 (70 000m^3) of treated seawater (Fig 10). It is not anticipated that the lagoon will be used for direct human contact but it will have to accommodate electric, low-speed boats on the surface and so must be designed with this in mind. A large fountain show is also planned as one of the attractions.

9. Site water balance.

10. Seawater lagoon water network.

11.

11. Arid conditions at the site.



12.

12. Summary of Astrarium power demands.

Given Jordan's extreme water scarcity (Fig 11), using seawater as the main source of supply and minimising the amount of fresh water used are the main drivers for the lagoon design, which aims to:

- maintain an approximately constant water level
- maintain consistent salinity within a set range
- maintain the water at a temperature range and sediment load so as not to adversely affect lagoon operation and quality to a significant degree
- control and reduce the risk of algal blooms from occurring on the water surface.

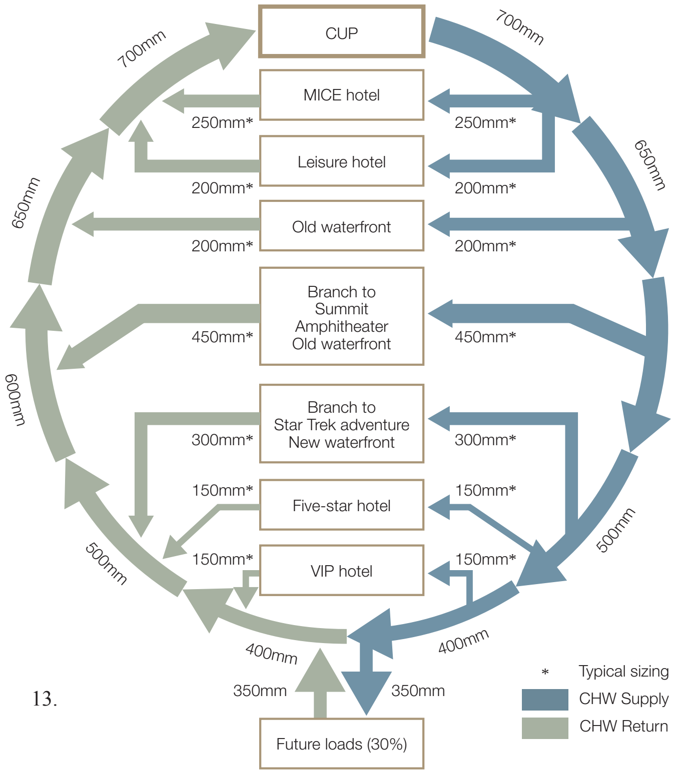
To achieve these aims, a 10-day water recirculation cycle with filtration and aeration is recommended. The amount of water treatment has been minimised by adopting an ecological approach to the lagoon's operation, with natural biological processes augmented by recirculation and filtration to prevent water stagnation. Several other options were considered but, based on experience with other constructed water projects elsewhere in the world, the more ecological approach was chosen rather than a chemically-treated swimming pool-type system.

Energy: raising the bar for themed development

Arup's scope also included several aspects of the Astrarium's energy demand and supply, as follows.

Site energy and cooling demands

Energy and cooling demands were estimated using building energy modelling for the hotels, retail spaces and restaurants. The calculated energy demands of the facilities' attractions were supplied by the client. The expected total peak demand is 32MW electrical and 6750 tons of cooling (Fig 12), of which the attraction loads represent approximately half. To ensure the most stringent energy performance throughout the later design phases, Arup produced design guidelines that adopt energy performance requirements from *ASHRAE 189.1*, the standard for the design of high-performance, green buildings[1].



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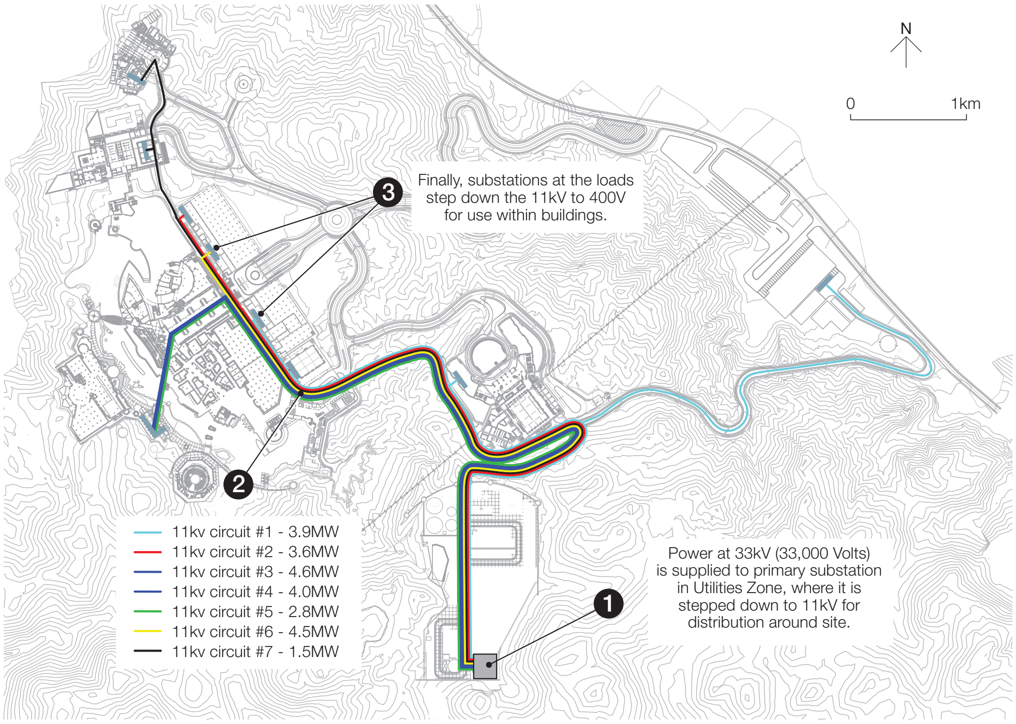


Finally, substations at the loads step down the 11kV to 400V for use within buildings.

Power at 33kV (33,000 Volts) is supplied to primary substation in Utilities Zone, where it is stepped down to 11kV for distribution around site.

14.

13. Chilled water supply and return system.

14. Electrical distribution system..

Schematic design of central utility plant and CHW distribution

A centralised approach to cooling was preferred to a decentralised unitary approach so as to take advantage of site-wide diversity and optimise energy efficiency (Fig 13). High-efficiency electric chillers will generate chilled water (CHW) for circulation to the buildings on-site. A 2M gallon (7.6M litre) CHW storage tank will also be implemented to both reduce peak electrical demand and provide additional redundancy.

Schematic design of electrical distribution

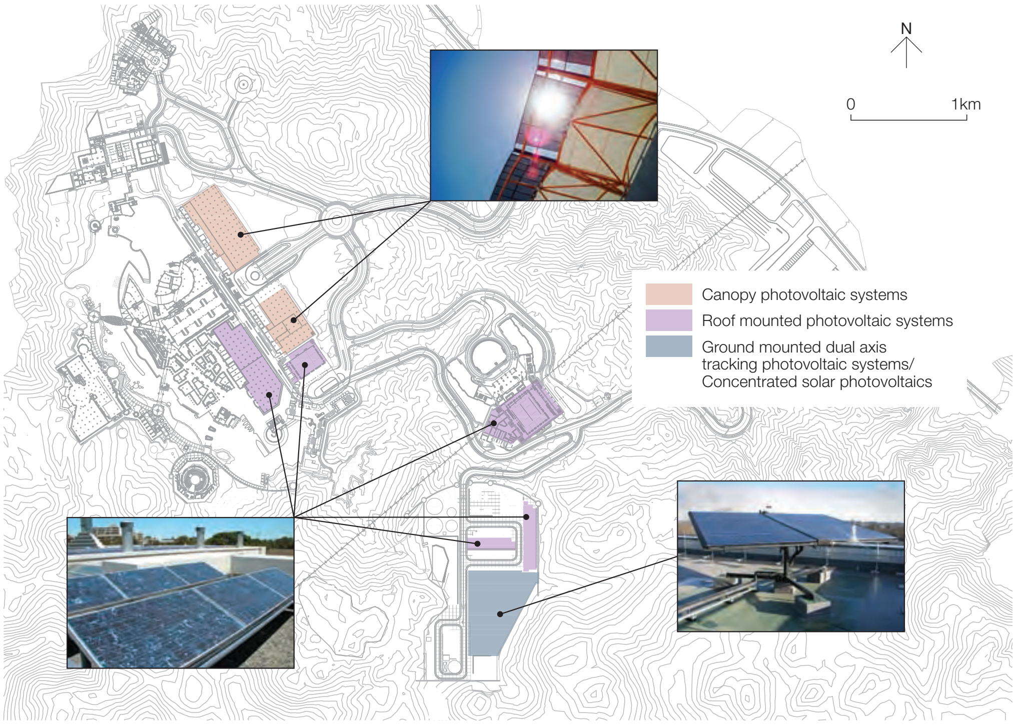
Most of the Astrarium's electrical load will be met by connecting the site to the regional network (Fig 14). Power will be distributed from an on-site utility substation at 11kV to the loads around the site, where it will be stepped down to 400V at the buildings. Arup designed the distribution network to ensure that each circuit can not only accommodate the site electrical loads, but will also have additional capacity for future growth — a key client requirement.

Solar and wind energy feasibility

A supply of clean, renewable energy is paramount for a development to be truly sustainable, so Arup investigated the feasibility of both solar and wind energy for aggressive on-site implementation at the Astrarium. The team determined that photovoltaic (PV) modules installed on selected roofs and parking canopies (Fig 15), and in a 2.7 acre (1.1ha) solar farm at the utilities zone plateau, would satisfy approximately 4% of site energy demand.

Several sizes of wind turbines were investigated, with large utility-scale turbines identified as the most attractive option, not only because the energy output is maximised, but also because their visibility would further communicate the Astrarium's commitment to sustainable development (Fig 16). With current wind resource estimates, and assuming land immediately adjacent to the site can be used for the turbines, wind energy could satisfy some 16% of site energy demand. The client is installing a 200ft (60m) meteorological tower equipped with sensors to measure wind conditions at the site.

With such an aggressive build-out of wind and solar energy, the Astrarium could generate carbon-free, renewable energy that would satisfy around 20% of the energy-intensive development's needs.



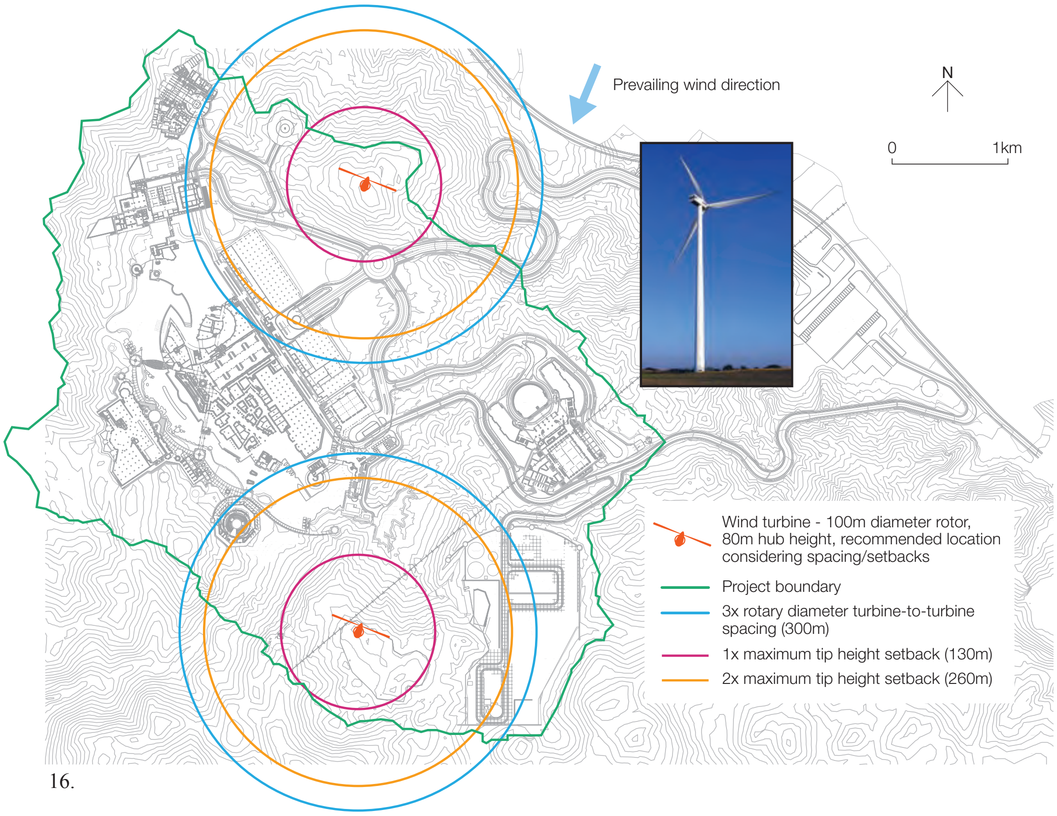
15.

Microclimate analysis

Due to Aqaba's hot climate, and because much of the Astrarium consists of outdoor plazas and walkways, outdoor thermal comfort is of critical importance to the visitor experience. Arup conducted a microclimate analysis of the site using CFD (Computational fluid dynamics) to identify particular areas of concern, informed the architect and remainder of the design team of the results, and then suggested mitigation strategies to improve thermal comfort conditions (Fig 17).

Green accreditation

As part of the developer's desire for sustainable development, Arup investigated the following green accreditation schemes to evaluate their applicability to the development: Estidama's Pearl rating[2], USGBC's LEED[3], and the Living Building Challenge[4]. LEED certification for selected buildings within the Astrarium was ultimately recommended.



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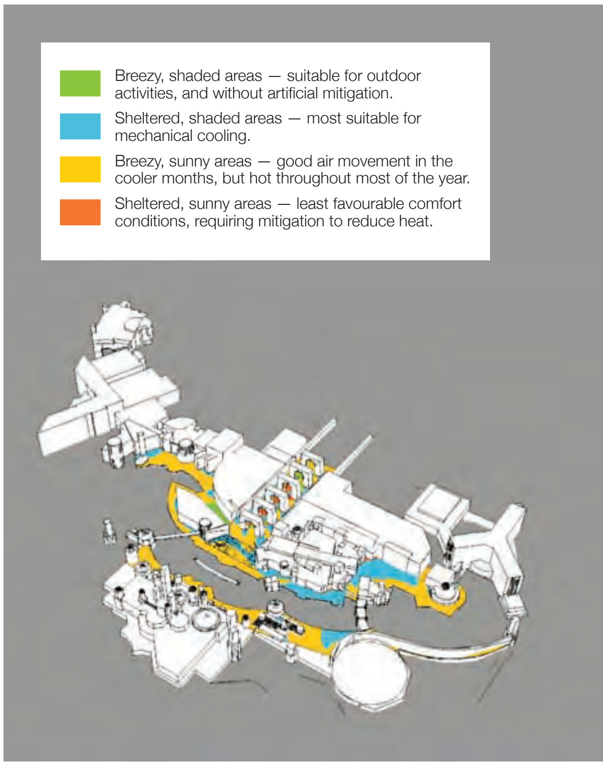
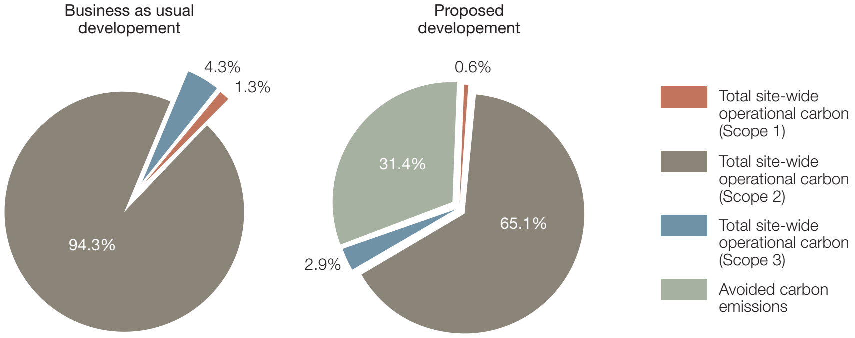


17.

15. Proposed locations for photovoltaic systems.

16. Proposed locations for wind turbines.

17. Microclimate assessment output.



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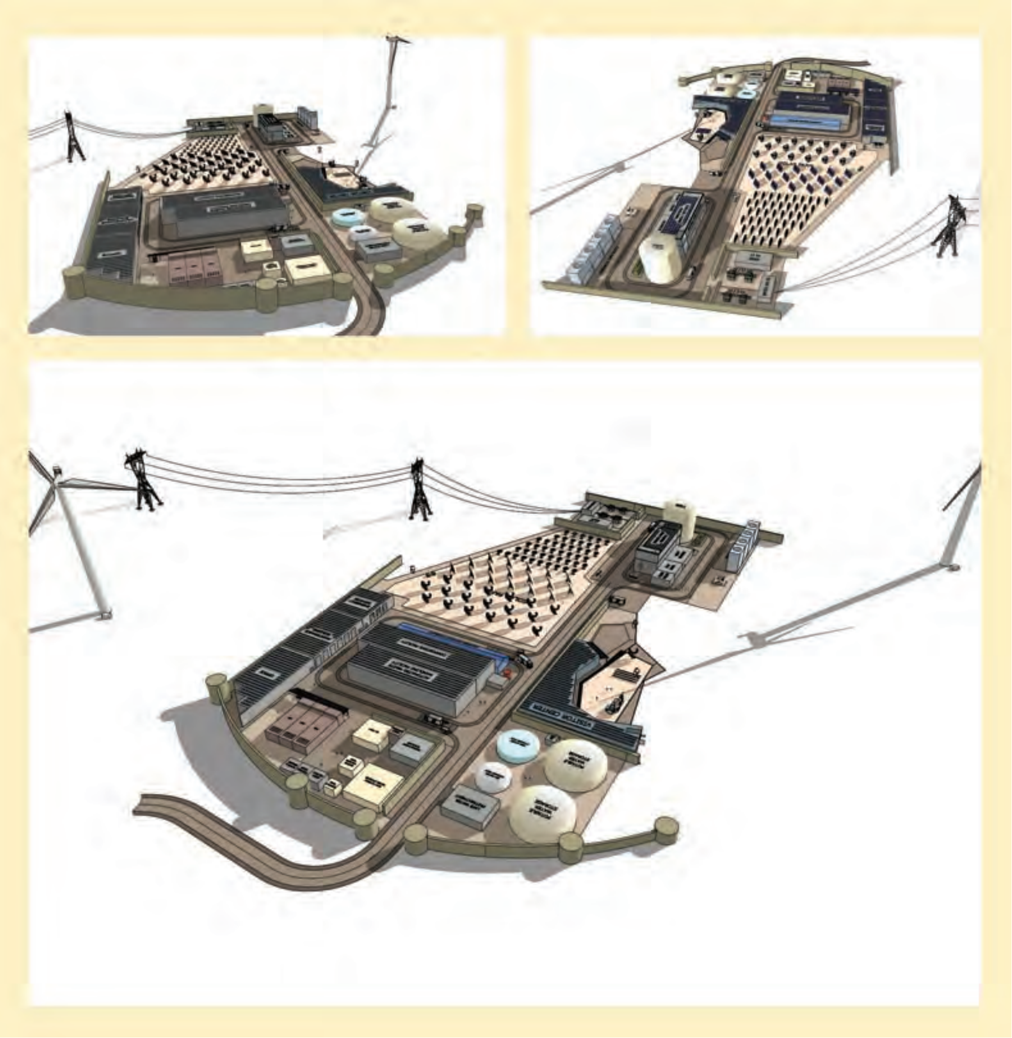


19.

Carbon assessment

Carbon emissions were quantified for both a "business-as-usual" development and for Arup's proposed efficiency and renewable energy generation schemes. All emission stages were included, and with efficient energy, water and transport planning, the Astrarium could achieve nearly a 40% reduction in greenhouse gas emissions over a business-as-usual development (Fig 18).

Utilities zone 3-D model

Finally, Arup was also responsible for the preliminary design of the utilities zone, the area where much of the development's infrastructure will be located including the wastewater treatment plant, the various water storage tanks, the automatic waste collection facility, the central plant, the solar farm, and much more (Fig 19).

The team used the *SketchUp* program both as a design tool and to effectively communicate ideas and designs. As systems changed during the project's design, a new revision of the utilities zone *SketchUp* model was created and used as the foundation for the subsequent round of discussions. Having an interactive model at its fingertips not only helped the Arup team visualise and present its utilities zone layouts internally to other disciplines, to create a more cohesive and efficient design, but it was also extremely helpful in communicating ideas and designs to the architect and the developer in a clear and visual way.

Solid waste management: rubbish in/resource out

Resource and waste management (RWM) is an important component of sustainability. As societies consume more, they generate more waste, increasing the pressure on management infrastructure and systems, the environment and human health. An inefficient system creates waste, and many of today's systems are inefficient.

The goal of RWM at the Astrarium is to support the movement from waste management to resource management. Arup proposes to achieve this by the development of three core on-site solid waste management systems, an organic waste composting facility, an automated waste collection system, and a sewage sludge drying facility (Fig 20).

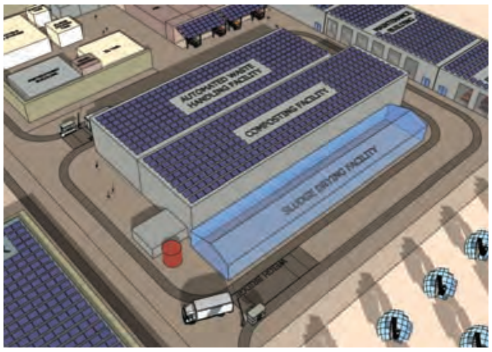
Freight logistics

To control all freight deliveries and staff movement, as well as some bulky waste flow, Arup proposed a distribution centre (DC) located between the entrances of the guest and freight access roads to the north-east of the site (Fig 21). The DC will manage in a warehouse environment all goods, deliveries, and staff entering (and exiting) the Astrarium. This process will be efficient and increase quality assurance, security and control management. The DC will enable consolidation of large freight shipments into smaller, more efficient units, thus reducing the number of delivery vehicles entering the Astrarium by 50-70% and ensuring that they are all controlled and scheduled.

Conclusion

A company is currently being set up by RGH to deliver the Astrarium project. Arup is still actively involved and is proud to have developed an integrated design that takes themed development to a new level. The design tools used on this project allowed the civil engineering SD stage to be completed very rapidly, but with solutions that were still fully optimised.

The whole team's integrated and proactive approach to energy, water, waste and transportation has given RGH a potentially stand-out project in the region, and the key relationships developed so far will put Arup at the centre of procurement for much of the site works.



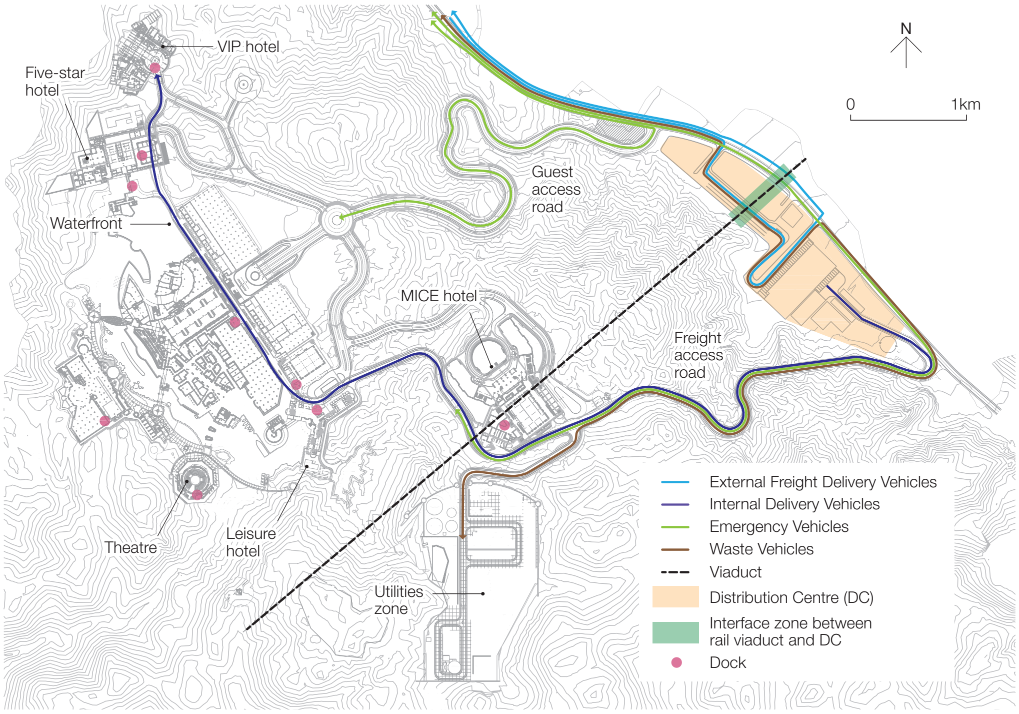
20.

18: Carbon reduction strategy.

19. Utility zone 3-D model.

20. On-site solid waste management treatment centre.

21. Freight logistics strategy.



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(2) www.estidama.org

(3) www.usgbc.org

(4) http://living-future.org/lbc

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Tony Kirby is an Associate and leads the civil engineering group in the Los Angeles office. He is the infrastructure lead for the Red Sea Astrarium.

Image credits

1. *Nigel Whale*; 2 *Rubicon Group Holding*; 3–21 *Arup*.

Project credits

Client: *Rubicon Group Holding* Lead engineer (civil, water management, energy consulting, M&E, logistics, waste treatment, fire and acoustics consulting): *Arup — Nick Antonio, Bernard Bodin, Darren Briggs, Chris Brosz, David Burgess, Stephen Burgess, Eric Caquias, Rich Chamley, Nancy Choi, Josh Cushner, Vahik Davoudi, Perry DeCuir, Andy Dodds, Steve Done, Andrew Dunwoody, Nick Elton, Enrique Farfan, Adam Finkin, Russell Fortmeyer, Jessica Fosbrook, Hugh Gardner, Said Gharbieh, Alexej Goehring, Brian Hornstein, Martin Howell, Bob Hudson, Andrew James, Murat Karakas, Tony Kelava, Tony Kirby, Brandon Knechtle, Harry Lee, Clare Leech, Steven Lesser, Bill Maddex, Roland Martin, Karla Martinez, Brian McLaughlin, Trevor Mino, Alex Mitchell, Jon Morgan, Jamison Ng, Nick O'Riordan, Derek Oriza, Yolanda Owens, Keith Padbury, Morad Pajouhan, James Reilly, Nigel Ridgway, Kevin Rietze, Max Rooksby, Steve Saunders, Tom Saville, Lynn Smith, Erik Tanaka, Jason Trenchfield, Vinh Tran, Colm Tully, Matthew Willis, Corey Wong, Robert Young, Rainer Zimmann* Architect: *Callison*
Local infrastructure designer: *Dar Al Omran*
Local architect: *maisam architects* | *engineers*.

No 7 Line extension: engineering the excavations

Location
New York City, NY

Authors
Amirreza Ghasemi Seth Pollak Nik Sokol

Introduction

This $2.1bn Metropolitan Transportation Authority (MTA) capital construction project extends New York City Transit's No 7 Line, which runs from Main Street in Flushing, Queens, by approximately a mile and a half (2.4km) from its current terminus at Times Square to a new underground station at 34th Street and 11th Avenue, on the far West Side of Midtown Manhattan (Figs 1–2).

When fully operational, the extended No 7 Line will form a vital part of one of the most significant redevelopment schemes in the city's history. As described by New York City Mayor Michael Bloomberg: *"On the far West Side of Manhattan, we're building an extension to the Number Seven subway line — the first city-funded subway track in 25 years and it will be built on time — something that you don't hear too often about subway construction. It will do for the far West Side what the Jubilee Tube line did for Canary Wharf in London: transform an old industrial area into one of the most dynamic neighborhoods in the world"*[1].

Midtown Manhattan, however, presents one of the most challenging tunnelling environments in the world, particularly for this scale of underground megaproject construction. Specific technical challenges include low rock cover, the presence of variable surcharge conditions, sensitive iconic structures in close proximity to the excavations, and a general lack of recent mined cavern construction experience in New York City.

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1. Alignment of No 7 Line extension: Hudson Yards is a train storage facility for Penn Station serving the Long Island Rail Road.

2. West Side of Midtown Manhattan.

3. Nearing completion of 34th Street station permanent works and systems installation, September 2012.

4. Completed shell for the Site L ventilation facility, 41st Street and Dyer Avenue, September, 2012.

Deploying global design skills and local knowledge

Arup had an integral role in helping to resolve many of the rock support and construction sequencing challenges on the No 7 Line extension, the tasks including tunnel design services, construction impact assessments and multidisciplinary engineering advice to the project's contractors, led from the local New York office. These services are acknowledged to have contributed to the project's widely lauded success and the delivery ahead of schedule of major portions of the work. A key to the success was understanding the limitations and opportunities presented by the ground conditions and the proposed excavation methods, as well as the contractual arrangements.

The 34th Street station cavern

Early in 2007 the team of Arup tunnel designers was commissioned by S3 II Tunnel Constructors — a joint venture of JF Shea Construction of Walnut, CA, Schiavone Construction Co of Secaucus, NJ and Skanska USA Civil Northeast of Whitestone, NY — to provide pre-proposal services. In due course Arup delivered 43 sketches detailing initial ground support requirements and construction sequencing for the various mined tunnel sections of the project. This work was carried out as an alternative to indicative drawings included in the bid documents by the Owner's Engineer, and allowed the S3 II JV to formulate a more competitive bid.

Later that year, S3 II won the US$1.2bn contract and engaged Arup as its tunnel design engineer, responsible for the final design of the initial ground support and the construction sequence design of all drill-and-blast excavations. These included three 40ft–50ft (12.2m–15.2m) diameter rock shafts, a tunnel boring machine (TBM) assembly chamber, a pair of TBM starter and tail tunnels, a TBM reception chamber, five cross-passages, two interlocking caverns, and the approximately 1000ft (305m) long, 60ft (18.3m) tall, 70ft (21.3m) span 34th Street Station cavern, with eight penetrations for ancillary adits of various dimensions and lengths.

Excavation began in 2008, and by the middle of 2009 approximately 3.5Mft^3 (100 000m^3) of rock had been removed to fully excavate the 34th Street station cavern. By mid-2010, permanent works construction was under way and two TBMs had completed excavation of the running tunnels connecting the new station with Times Square. As of September 2012, the major elements of the final subway line system had been completed (Fig 3).

During construction, Arup provided 24-hour site coverage which included geological mapping, ground support and construction sequence inspection and field modifications to the designed support when ground conditions or site circumstances required. A structural engineering team also came on board to design contractor-proposed modifications to the permanent works. The consultant GZA GeoEnvironmental contributed to the geological interpretation, mapping and instrumentation program, while Snee Geoconsult provided geological and constructability advice.

Site L ventilation facility

In 2010, the MTA awarded a separate contract for constructing a ventilation facility for the No 7 Line extension to the joint venture of China Construction America (CCA) of Jersey City, NJ, and Halmar International LLC of Pearl River, NY. CCA/Halmar in turn selected Arup as its tunnel design engineer and tunnel engineer to oversee the implementation of the design during construction. Facilities to be created on this contract included two 40ft–50ft (12.2m–15.2m) shafts, a cross-passage and two ventilation adits excavated through rock and existing segmental concrete-lined tunnels, all of which were to be constructed from a constrained site next to a skyscraper and adjacent to traffic exiting the Lincoln Tunnel, which connects New Jersey and New York City under the Hudson River.

An aggressive construction schedule commenced with surface excavation, and by the end of 2010 CCA/Halmar had excavated the two rock shafts to depth and were preparing to mine underneath 41st Street. All the facilities were excavated by summer 2011, and by September 2012 the core and shell of the ventilation facility had been constructed (Fig 4).


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Ground support design

The design of ground support for large rock caverns in a dense urban setting like New York City is governed by many factors beyond just the quality of the rock and the size of the opening. Geological challenges at the 34th Street station cavern and Site L included sheared and faulted ground and contacts between major rock types.

Both projects, however, benefited from generally consistent rock mass quality for most of the drill-and-blast excavation. Low rock cover conditions, heavy surcharges, blasting under and adjacent to sensitive structures, and the prescribed locations of numerous cross-passages, junctions and shafts — challenges associated with tunnelling in an urban environment — had to be addressed when developing the initial ground support system for the No 7 Line excavations.

Safe, effective and efficient initial ground support designs for the geomechanically complex underground facilities were achieved using empirical, kinematic (rock block and wedge stability) and numerical methods in a collaborative approach between Arup and the contractor clients. A systematic classification carried out during excavation found a satisfactory match between the predicted and encountered ground conditions, so no alterations to the designed initial support types were required[2].

> “Arup’s support design has pretty much allowed us to deal with any challenges we have come across.”
>
> Keith Mishoe, CCA/Halmar’s
> Site L Project Manager[3]

Construction

The collaborative approach between Arup and the contractors led to great successes during excavation, where the teams employed a rapidly buildable and adaptable construction sequence and initial ground support scheme. The large-span caverns were excavated with a top heading and bench, each approximately 30ft (9.1m) high. The top heading was excavated with three staggered drifts, or faces, to ensure that no more than 1/3 of the full span was unsupported at any time (Fig 5).

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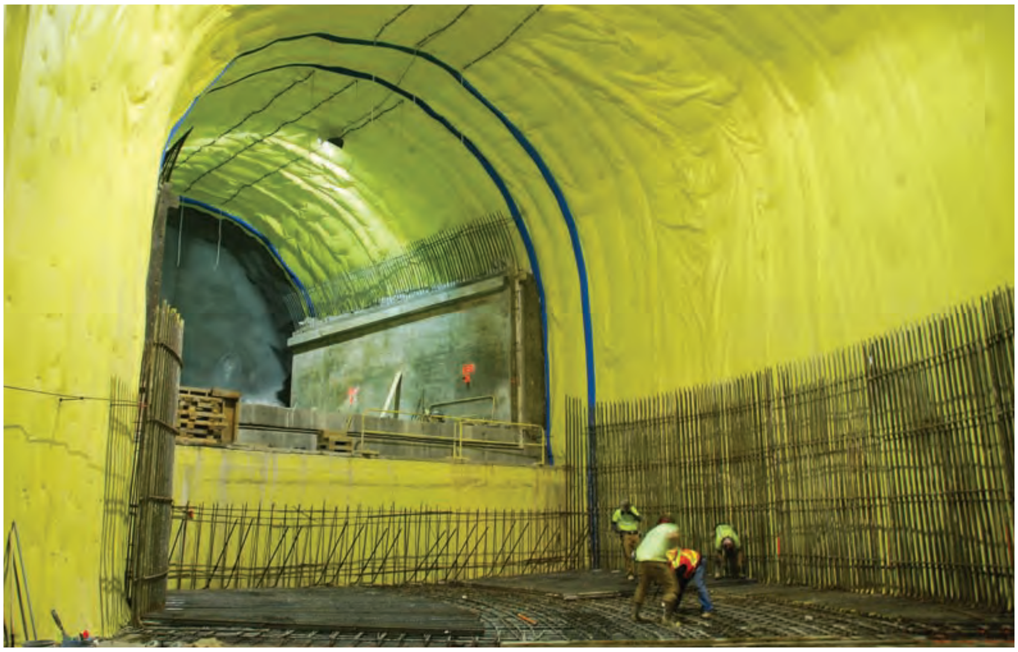

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5. Typical cavern top-heading excavation sequence with three staggered faces.

6. Typical split-face cavern benching excavation.

7. Adit excavated from cavern using full-face blasting, here seen during the waterproofing and concreting stage of construction.

8. Typical drilling for ground support installation at a cavern/adit junction.

Observation of rock mass behaviour and detailed instrumentation monitoring during top-heading excavation provided opportunities to increase round lengths and bench heights to further increase production. It was originally thought that the lower half of the cavern would be excavated with excavation levels, or benches, but when re-analysed with the geotechnical data gathered during excavation up to that point, it was possible to modify the benching sequence to a single-level split-face approach (Fig 6).

Excavation of the numerous penetrations into the caverns was initially achieved with split-face headings, similar to the cavern top heading. However, full-face adit excavations were successfully accomplished with high-quality blast hole drilling and well-sequenced blasting delays (Fig 7). Both split-face and full-face options were developed for the 30ft (9.1m) span ventilation adits at Site L, so as to allow the contractor to make the optimal selection based on blast vibration limits, mucking and localised geological features, among other considerations.

Junction design

Among the more complicated technical challenges on the No 7 Line were the numerous junctions to be constructed (Fig 8). Junctions in rock excavations can be designed in various ways, one of which employs the rock mass characterisation and empirical ground support design system known as “Q”[4]. In the Q system, the number of discontinuities in the rock mass is multiplied by a factor of 3 to account for the addition of a third dimension, formed by the intersection, along which the potential for kinematic wedge failure is increased. The “output” of the Q system comprises the spacing and length of rock bolts and thickness of shotcrete (pneumatically applied concrete) required to support the completed rock excavation.

As an alternative to the Q system, a structural beam-spring model can be employed to design the thickness of the shotcrete. This requires an estimate of rock load on the lining and does not account for any rock-structure interaction (ie no arching effects). Shotcrete capacity is usually designed to keep combinations of moment and thrust within the elastic envelope, neglecting the post-cracking benefits of steel fibres, which increase the shotcrete’s flexural strength.

Table 1: Rock mass behaviour in junction areas of 7 Line main cavern.

Adit	Span ratio [Diameter$_{adit}$/Diameter$_{cavern}$]	Rock mass classification [Q/RMR$_{89}$]		$\Delta\delta_m/\delta_{mo}$ [%]	$\Delta\delta_a/\delta_{ao}$ [%]
		Cavern	Adit		
E1	0.6	1.3/47	1.3/44	N/A	172
E2	0.6	1.0/39	2.7/49	8	280
T3	0.6	1.0/43	0.7/46	13	93

$\Delta\delta_m$ = additional roof settlement of main cavern due to excavation of adit.
δ_{mo} = roof settlement of main cavern prior to adit excavation.
$\Delta\delta_a$ = additional roof settlement over junction point due to excavation of adit.
δ_{ao} = settlement over junction point prior to adit excavation.

8.

Both methods are typically conservative, but neither resolves to what extent the area of additional reinforcement is required around the junction. Complex 3-D models can be useful, but are time-consuming to build, costly and sometimes difficult to interpret.

Constructing junctions on the No 7 Line gave the opportunity to study how the rock mass behaved by observing ground movements recorded by extensometers. In particular, the team studied three penetrations formed perpendicular to the main cavern. Direct comparison between the junctions was possible as they were all of the same size, and rock mass classification of the cavern roof revealed nearly identical rock mass quality. Table 1 summarises the results.

The adits were blasted only after the main cavern top heading had been fully excavated and supported. Consistent roof movement in the cavern of less than 15% additional strain (compared to cavern movement prior to junction excavation) was observed due to E2 and T3 junction construction, both of which were in Manhattan schist; the E1 extensometer was damaged during blasting, so no reading was possible.

The extent of the plastic zone around the junctions was smaller than assumed during design, and extensometers located 15ft (4.5m) offset from the edge of the adit showed no response during excavation, corresponding to a zone of influence of less than half the diameter of the adit either side of the penetration. In addition, extensometers located on the far side of the cavern (opposite the adit) showed no response to adit construction. The research carried out and the lessons learned here have been subsequently applied in several large-span caverns around the world, leading to a refined and rational design approach[5].

9.

Blasting over and under

Several complicated blasting challenges were encountered on the No 7 Line. Two of them are of particular interest.

A 60ft (18.3m) span interlocking cavern immediately south of the 34th Street station cavern was to be excavated under Amtrak's approximately 100-year-old, masonry-lined North River Tunnels, with only 22ft (6.7m) of rock cover at its closest point (Fig 9). In advance of this sensitive portion of excavation, Arup closely monitored the blasting. The data gathered were used to develop a project-specific ground transmission constant for the rock mass — significantly less conservative than the standard New York approach — from which the drill-and-blast excavation advance lengths were optimised to achieve maximum production with minimum disturbance to the historic structures[6]. The facility was successfully excavated without exceeding the allowed peak particle velocities.

Another blasting challenge was at Site L. Here, the contractor was faced with excavating a 30ft (9.1m) span top heading excavation immediately over the top of the recently mined, concrete segment-lined No 7 Line running tunnels. With global experience in designing segmental linings for tunnels, Arup was able to demonstrate that the existing tunnel liners did not require cumbersome propping to support the tunnelling equipment riding over the top of them during the top heading excavation. Arup also verified that the concrete liner segment rings exposed after the tunnel bench excavation would not jack into the excavation, due to expansion of the gaskets between the rings[7]. The elimination of props and additional structural connections from inside the existing tunnels greatly facilitated excavation through these sections (Fig 10).

Conclusion

The successful excavation and support of the No 7 Line extension's 34th Street station cavern, Site L ventilation facility and numerous ancillary excavations, have provided a rare opportunity to bridge a knowledge gap in the design and construction of large rock caverns in a dense urban environment. The collaborative approach implemented by the MTA, the MTA's engineers, S3II Tunnel Constructors, CCA/Halmar and Arup led to the major excavations for the station cavern being completed six months ahead of schedule, even though this was the first cavern to be excavated in Manhattan in nearly 40 years (Fig 11). The back analysis of observed rock mass behaviour has been linked with geological mapping records to deliver findings invaluable for verifying critical design assumptions, optimising construction sequences and refining shallow cavern design methodology across the globe where similar ground conditions occur.

9. The south interlocking cavern, excavated with only 22ft (6.7m) of rock cover under the existing 100-year-old masonry-lined Amtrak tunnels.

10. Tunnel excavation through existing segmental concrete-lined tunnel at Site L.

11. Southern half of the fully excavated 34th Street station cavern, at the waterproofing and concreting stages.

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11.

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Authors

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Project credits

Owner: *Metropolitan Transportation Authority/ New York City Transit* Clients and contractors: *S3 II Tunnel Constructors* (34th Street station cavern)*;* *CCA/Halmar International* (site L ventilation facility) Tunnel design engineer/tunnel engineer: Arup — *Peter Ayres, Alison Barmas, Liam Basilio, Mark Brand, Fergal Brennan, Peter Chamley, Matt Clark, Brook Ewers, David Farnsworth, Amirreza Ghasemi, Leandro Gilladoga, Amina Gueciioueur, Ivan Hee, Paul Heslop, Jon Hurt, Kenji Ishioka, Hyuk Il Jung, Hannes Lagger, Sean Lee, Kate Leitch, Steve Macklin, Chris Mee, Carlos Molina-Hutt, Robert Ou, Don Phillips, Seth Pollak, Christian Saad, Joe Saverino, Nik Sokol, Victoria Sword-Daniels, Matt Sykes, Tabitha Tavolaro, Victoria Valershteyn, Rich Vigil, Bob Couzin Wood, Therese Worley, Vito Zhang, Yelena Zolotova* Geotechnical consultants: *GZA GeoEnvironmental Inc; Snee Geoconsult Inc.*

Image credits

1 *Arup/Nigel Whale*; 2 *iStockphoto/mrtom-uk*; 3–4 *MTA Capital Construction*; 5 *Seth Pollak*; 6–8, 10 *Nik Sokol*; 9, 11 *Thomas Graham*.

High-speed rail alignment generation and optimisation using GIS

Authors
Cary Greenwood Roland Martin

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2.

1. High Speed 1: train crossing the Medway Viaduct, Kent, UK.

2. California's major population centres, and its proposed HSR network route.

Introduction

High-speed rail is increasingly relied upon across the world, with systems already in operation across Europe and Asia, and under development in numerous countries. At its most effective, HSR functions as a component within a wider transportation network, offering passengers a means to travel between cities without having to resort to private cars or navigate increasingly complex and onerous airport security systems in order to fly.

However, high speed rail (HSR) has very specific engineering requirements, such as the need for straighter routes and wider tunnels to avoid passenger discomfort without losing speed. With Arup's rail expertise, developed on the UK's High Speed 1 (Fig 1) and elsewhere, constraints like these are well understood in projects undertaken by the firm, where they are taken into account throughout the design process.

A Geographical Information System (GIS)[1] is a set of tools and techniques for collecting, managing, analysing and displaying geographical data. A GIS acts as a central data repository for incoming information throughout a project's lifespan, while allowing users to view, query and analyse data to reveal relationships, patterns and trends. GIS is particularly effective over broad geographical areas and so has proven tangible benefits for large infrastructure projects, such as rail and highways.

From the earliest planning phases through to the final detailed engineering, Arup now uses GIS to make informed engineering decisions more quickly, efficiently and cost-effectively. GIS data management allows for effective use of the project's spatial information: spatial analysis techniques enable quick understanding of the constraints, and the cartographic presentations available within GIS software allow the generation of clear and concise maps to help stakeholders understand the decisions that have been made and the reasons for them.

Suitability analysis

Optimal route distances for HSR depend on local conditions, but it typically competes best against air travel when journey times are between around two and four hours. Within such journey times, connections with other local services often allow HSR systems to offer travellers a quicker door-to-door journey than flying.

Initial suitability analysis for HSR should therefore focus on the population centres within the study area — their relative sizes and densities, and the distances and connectivity between them. Evaluating the existing populations and growth rates of potential destination cities are critical steps for establishing preliminary destinations. The vast majority of California's population centres exceeding 140 000, for example, will be directly or indirectly served by the state's proposed HSR network (Fig 2).

Much of the information required for this initial analysis is available within existing GIS datasets, typically through aggregated census data or more detailed household surveys, and additional information such as population growth rates can easily be imported from other sources if available.

Developing a comprehensive GIS database at a very early stage in a project enables subsequent stages to build on this existing information rather than needing to recreate it, and this is as true in HSR as any other type of infrastructure project.

Having identified the target destinations for the HSR network, the study then begins to focus on potential route corridors between each city pair. Typically, a good starting point is to assess existing transport links for suitability — if a new route can run alongside an existing highway or rail link, the environmental impacts will be lessened.

The potential for connectivity between locations may, however, be severely limited by regional conditions such as topography. Existing freight and passenger rail routes


3.

California HSR: Arup's role

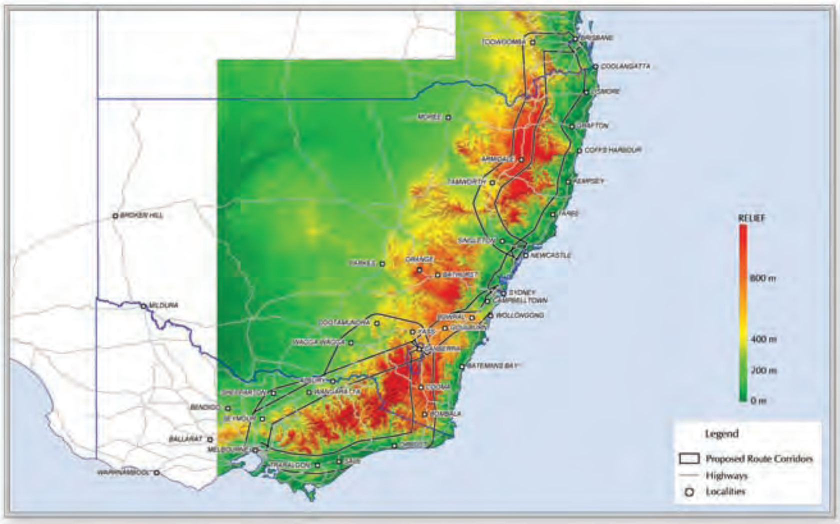
Arup, in joint venture, is providing multidisciplinary engineering services for three sections of the California HSR project: Fresno to Bakersfield (124 miles/200km), Bakersfield to Palmdale (85 miles/137km) and Palmdale to Los Angeles (63 miles/101km). These sections encompass a wide variety of terrain, land uses and environmental resources. The network will traverse farms, small communities, large floodplains, wetlands, wildlife preserves, mountains, seismic hazards, desert and dense urban environments.

The aim of the project is to provide an alternative, sustainable, means of transport between northern and southern California, with trains operating at up to 220mph (350km/h), providing origin-to-destination journey times comparable to flying. Once operational, the service will improve quality of life for Californians by reducing traffic congestion, improving air quality and providing jobs and economic growth both today and into the future.

Arup's role within the joint ventures designing the three sections of the California HSR with which the firm is involved includes structural and geotechnical engineering, rail, highways, bridges, water, utilities co-ordination, cost estimating, traffic engineering/transportation planning, acoustics, hydraulics/hydrology, project management, tunnelling and stations.

may be able to cope with this using sharp turns and switchbacks, but due to HSR's requirements for flat curve radii and relatively shallow gradients, mountainous areas can quickly increase the cost of a planned alignment. As a result, complex terrain should be bypassed wherever possible, even though this may result in longer routes. Similarly, protected areas, rivers and water bodies should generally be avoided.

Arup has conducted feasibility studies for rail corridors in various locations around the world, including HSR projects in North America, Africa, and Australasia. In the latter, the firm undertook a feasibility study for an HSR corridor in south-eastern Australia between Melbourne, Sydney and Brisbane (Fig 4), which was presented to the Australian Department of Transport and Regional Services. The team used the program *ArcGIS*^{2} to analyse population centres, soil types, terrain and environmental impacts. The initial corridor options were mapped onto this analysis, enabling consideration of the relative impacts and advantages of the different primary route corridor alternatives. The study gave a recommendation for a preferred alignment and an assessment of the commercial and financial viability of such a project.



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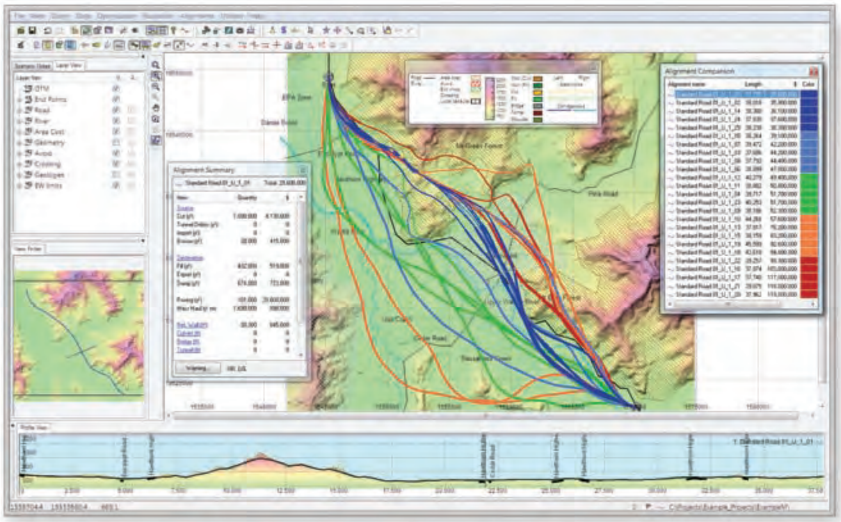
3. Artist's impressions of California HSR in operation.

4. Candidate HSR corridors with south-east Australian terrain features.



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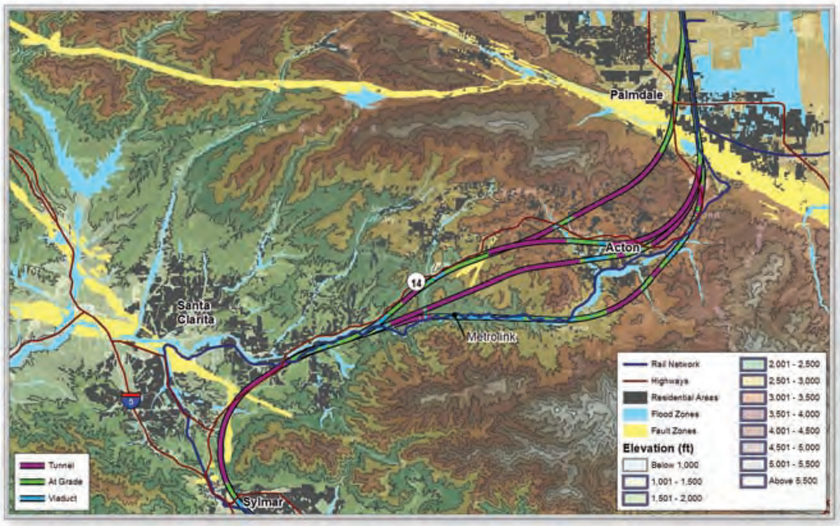

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5. Route alignments generated in *Quantm*: anticipated costs range through a spectrum from dark blue (least), via light blue, green and orange, to red (most).

6. HSR alignments crossing the Rhône near Avignon, France.

7. HSR alignments under consideration and related constraints in the San Gabriel Mountains, southern California.

8. Heavily constrained urban environment north of downtown Los Angeles, California.

8.

Such options offer good starting points to be examined in more detail as the project progresses. Once the broad corridors have been identified for a proposed HSR network, they need to be narrowed into specific routes. Certain corridors may prove impossible due to the sheer volume of constraints, while others previously thought not viable may in fact be worth considering.

In geographically complex areas, the only realistic means of assessing the possibilities of different route corridors is to generate actual alignments. For this, Arup has used Trimble's *Quantm*[3] alignment assessment software (Fig 5).

Relevant constraints are loaded in from the GIS database, and the software is then also configured with appropriate engineering constraints before being left to run. The system considers the many alignment alternatives, which are then narrowed down to a set of typical routes (50) and presented back to the user.

This process allows the engineering team quickly to generate and assess thousands of different alignment options, which can be easily developed into complex optimised routes. It is not infallible and so can only be used to guide decisions, but it is extremely useful for the route assessment stage, finding alternatives that otherwise might never have been considered or may have been unfairly discounted.

Similar results can be achieved using GIS analytical tools manually, and this can in some cases provide more appropriate answers to localised problems, since it will engage specialist knowledge and skills alongside the analytical tools.

Added to a good understanding of the typical engineering requirements of HSR, *ArcGIS 3D Analyst*[4] allows a detailed cross-examination of the local terrain and ownership or infrastructure constraints, enabling design teams to compare and optimise solutions that may not otherwise seem viable.

This makes the process of investigating potential alignment alternatives through constrained or topographically complex areas much faster and more straightforward.

Localised studies

Having identified the initial route corridors, and with some understanding of the route options within them, the next stage is to start a detailed examination of the localised constraints. Here, the focus of the project becomes less a high-level GIS study and more a detailed engineering solution, but the background information gathered for the early stages of the project still plays a fundamental role in the later stages.

As already noted, HSR has a very particular set of engineering requirements. For instance, to achieve speeds above 200mph (320km/h), alignments need long sweeping curves. Fig 6 shows an operational HSR junction in France, where the alignments are noticeably straighter than roads and other rail in the area. The requirement for straightness must, however, be balanced against the need to minimise impacts to protected areas, private properties and agricultural land, while also keeping costs as low as possible. In fact, the range of limitations is often so complex that it may be impossible to meet all of them.

In mountainous areas, the primary limitation is cost. Lengthy tunnels and high viaducts quickly make alignments extremely expensive, so a careful balance between too many of either has to be found. Conversely, unless urban stations are being included, developed areas should be avoided due to impacts on residential, commercial or industrial properties, while at the same time evading flood zones.

Seismically active areas add another dimension. Some faults are better understood than others, and so to err on the side of caution, fault zones per se may cover huge tracts of land, that would potentially require widespread redesign of rail infrastructure in the event of seismic activity. Even outside the fault zone itself, adjacent areas can be extremely susceptible to landslides, soft soils, or liquefaction. Tunnelling through gas pockets or historic oil wells should also be avoided wherever possible.

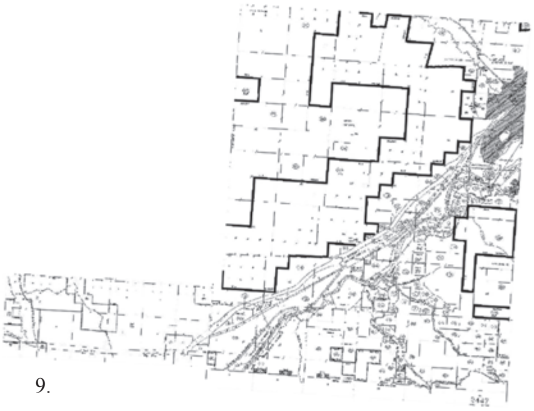
Fig 7 shows one of the mountainous sections of California's HSR system, just north of Los Angeles, but here the complexity of the terrain is only one of the variables to be considered. There are also dense urban areas close to the mountains, several major faults cross the region, and valley areas are susceptible to flooding. GIS was used to visualise and analyse the constraints side by side, enabling a better understanding of the complex relationships between them.

Flood plains and waterways often necessitate raising the alignment and adding elevated crossings, and more geographically extensive factors such as national parks, endangered animal habitats, existing infrastructure, graveyards and archaeological sites, can further constrain the design process.

In rural areas, the primary concern should be to keep close to existing rail, road, or utility corridors, but even when HSR alignments use existing transportation corridors it is often difficult to avoid deviating for some portion of the proposed alignment, so here property impacts need to be kept to an absolute minimum. This often requires local knowledge. For instance, in much of North America properties are subdivided in north-south and east-west lines, and so impacts can be minimised most effectively by planning new infrastructure to follow these lines wherever possible.

In urban environments, the constraints can be entirely different (Fig 8). The primary cost for an alignment through a city is typically for right-of-way acquisition, but cost is not the whole problem.

Commercial and industrial properties may have the major financial implications, but taking residential properties and public amenities are likely to have much greater impacts on the community. Choosing the appropriate corridor depends, however, on the availability of good quality digital land use data.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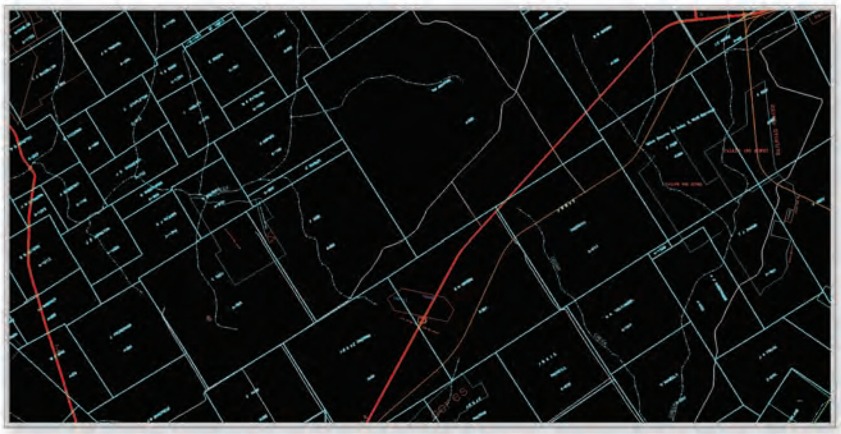
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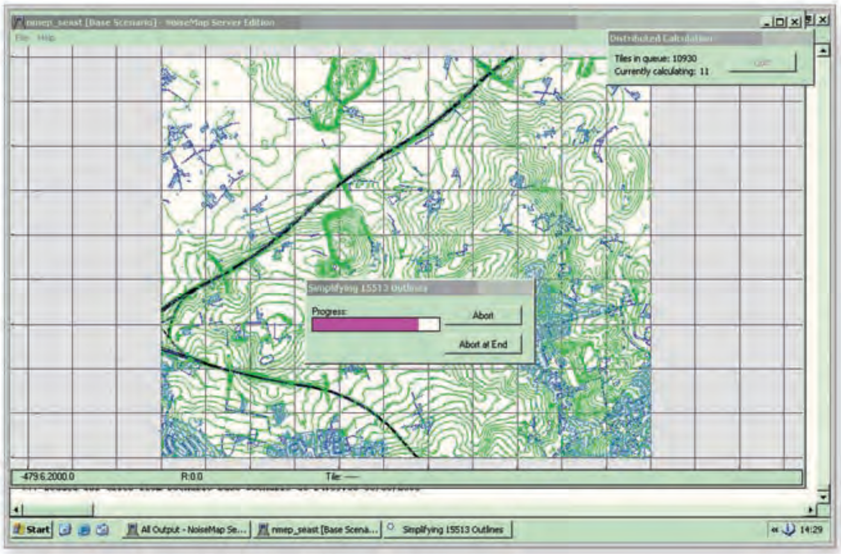
In the US, land parcel datasets are often tracked and catalogued by county, some of which are further behind in digitising land parcel records than others. On one HSR assessment carried out by Arup, the data came in three major formats depending on the county: scanned documents in pdf format (Fig 9), CAD drawings (Fig 10), and full GIS datasets.

The scanned documents needed to be accurately georeferenced by converting them to image files, recropping them to the correct extent, and then geolocating them in GIS using other base datasets such as the county boundary to help identify the correct location for the image.

Other incoming datasets may require complex processing to pick up information before they can be used for analysis, and even then the original source data may contain additional details, so that they still may be of use throughout future stages of the project.

Once the land parcels have all been collected into a usable dataset, the information can be used to inform the engineering. Any locations where the alignment under consideration deviates from existing transportation corridors can be quickly identified and the information used to understand or minimise the impacts.

Only through the use of GIS is it possible to visualise all of this information simultaneously and quickly, and thus easily understand all the relative impacts that can result from the route under development.



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Currently calculating: 11

Progress:

-479.6.2000.0 R:0.0 Tile: —

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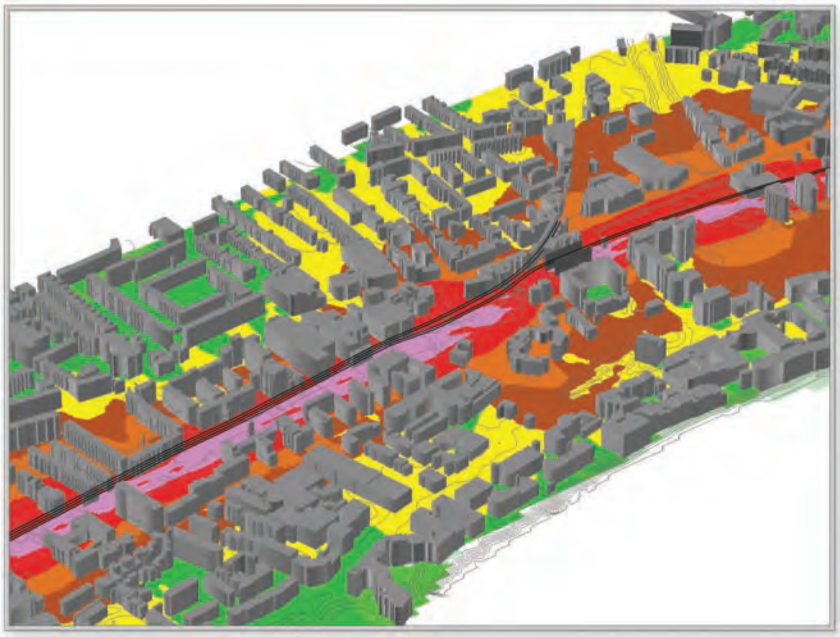
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Next steps

Informed by the preliminary alignments and the background GIS datasets gathered throughout the project, the detailed design teams can make appropriate engineering decisions more efficiently. Rail alignments can be better designed around local conditions, grade separations and utility diversions optimally located to minimise disruption, and rail structures and trenches more cost-effectively designed.

But this is far from the end of the story. The geographic information gathered from inception and during design is used throughout the project phases until construction. A right-of-way assessment, for example, uses parcel data from GIS as its basis to gather cost information for each alignment alternative.

Large engineering projects have complex environmental requirements, and visual impact assessments and ecological studies continue to generate further GIS data, which build on the information from earlier project stages. Environmental modelling information is also gathered and processed using GIS and loaded into acoustic and air quality modelling software, such as *SoundPlan*[5] and *NoiseMap*[6] (Fig 11). Using Arup's prior expertise with the packages and the experience gathered on earlier stages of the project, it is possible to convert the background and engineering data into the exact form required for the specialist modelling. The output information is then loaded back into a GIS database (Fig 12) and used to generate property counts and demographic impacts so as to quantify the relative environmental impacts of each alternative.

GIS can also be used to help stakeholders and the community better understand our projects and for us to spatially analyse information gathered by public participation processes. Arup's *Collaborative Community Map*[7], developed in the Brisbane office (Fig 13), is an e-engagement tool that uses GIS functionality to give the community information in an easy-to-access, non-technical format, and allows Arup to bring community comments into a spatial format that can be viewed and analysed against other technical data.

Conclusion

At Arup, GIS is now fundamental to developing a large infrastructure scheme. From initial conception through to detailed design, construction and project handover, environmental modelling and public participation, immense volumes of geographic data are gathered. On a HSR alignment, wherever it may be, GIS can help clients and project teams understand the interdependency of the constraints, and thereby deliver the best engineering solutions more quickly and easily.

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Authors

Cary Greenwood is a GIS analyst in the Los Angeles office. He has provided integrated GIS support and analysis for a confidential phase 1 high-speed rail alignment as well as the California HSR design.

Roland Martin is a senior consultant in the Singapore office. He was GIS consultant for the California HSR project.

Image credits

1 *Daniel Clements*; 2 *Arup/Nigel Whale*; 3 *CHSRA*; 4 *Arup/ArcGIS*; 5 *©Adrien Patane, Trimble*; 6–8 *Arup (including Microsoft product screen shots reprinted with permission from Microsoft Corporation)*; 9–10 *Arup;* 11–12 *Arup/NoiseMap (including Ordnance Survey data ©Crown copyright, all rights reserved)*; 13 *Arup (includes Google Maps data).*

13.

9: Land parcel ownership data in CAD format.

10. Georeferenced pdf parcel data.

11. Noise modelling using GIS data in *NoiseMap*.

12. Completed noise map showing proposed alignment, buildings and contours.

13. Arup's *Collaborative Map*: public participation using GIS.

"District energy optioneering" for a major mixed-use development

Location
Baltimore State Center, MD, USA

Author
Afaan Naqvi

Introduction

A new type of service is emerging in the energy planning and engineering market, whereby clients are drawn into the planning and design of ecodistricts and energy districts at an earlier stage than before. Using energy analysis tools, visualisations and indicative cost/benefit analysis, energy engineers can introduce clients to types of information previously unavailable to them, allowing them to align their district plans with a wide range of quantitative and qualitative preferences.

This process of "district energy optioneering" is developing rapidly, with increasingly positive client interactions over the last few years. This article summarises the approach, results and conclusions from its application to a mixed-use redevelopment project in Baltimore, Maryland, on the east coast of the USA.

Context

Located north of the city's downtown at the State Center BMS (Baltimore Metro Subway) station, the project as originally conceived entails redeveloping 28 acres (11.3ha) over five phases extending to 2025, eventually to include 4.5Mft^2 (420 000m^2) of retail, office, residential and civic spaces, plus associated parking (Figs 1–2). Currently the site accommodates four state-owned office buildings served by a central utility plant (CUP), together with a public assembly building (Fig 3).

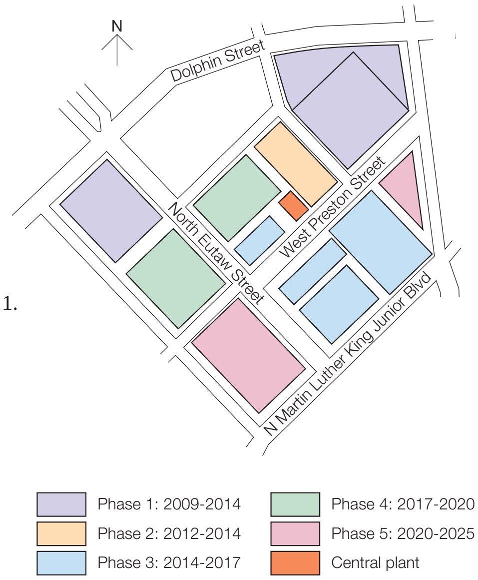
The aim is to revitalise the neighbourhood by increasing density, diversity of use and quality of space, and create a vibrant, transit-oriented, mixed-use community.

1. The original proposed development plan.

2. The existing site.

3. Existing buildings:
a) 5th Regiment Armory
b) 201 West Preston Street
c) 300 West Preston Street.

4. Artist's rendering of the proposed new development.



1.

a)

b)

c)

3.

2.

Arup's primary goals were to: (1) maximise the development's overall sustainability with a focus on energy, water, waste and carbon; (2) address the feasibility of a district system for Phase 1 and beyond, and (3) determine whether or not the existing plant could be retrofitted into a comprehensive district energy (DE) scheme.

The eco-district concept

A DE system does not define an eco-district by default. It requires design and planning moves that result in a synergy of system effects (not just an increase in efficiency). Such synergy moves include:

- increased building density, to increase system utilisation density and cost-effectiveness
- increased building mix of uses, to offer improved diversity and heat recovery potential
- optimisation over time, with new technology and add-on features unavailable to distributed systems
- integration of water recovery and reuse strategies.

The Baltimore State Center DE system accomplishes all of these and substantially helps the entire redevelopment area to work together as an eco-effective system.

Stakeholders

The site is owned by the state of Maryland and houses its largest concentration of state-owned office buildings. Ekistics LLC, a development company formed essentially for this project, and operating with several equity partners, appointed Arup for the feasibility and conceptual building design services. Funding for the sustainability and DE feasibility scope was provided by the city of Baltimore. Other consultants were Mithun (masterplanner), Design Collective (architect), Suffolk Construction (construction contractor) and Leach Wallace (mechanical, electrical and plumbing design).

4.

The tenancy agreement involved a joint venture between the state and Ekistiks. Maryland owns the land and occupies all the buildings. Ekistics enters into a 99-year lease for the land, and Maryland becomes anchor tenant for the new mixed-use complex on condition that the negotiated lease agreement is the basis for financing the entire project; the lease agreement includes specific conditions, such as energy utilisation intensity, so as to drive project sustainability.

This arrangement won support from state employees, excited at the prospect of moving from the currently aged and unattractive buildings to a high-density and vibrant mixed-use development.

Arup scope

Arup's involvement was broadly categorised into two tracks. The building level track was carried out by the Seattle office and comprised the conceptual Phase 1 building design, including sustainability performance output. Services provided included MEP conceptual design for three building performance scenarios.

The district level track was undertaken by the San Francisco office and covered DE, energy efficiency, renewable energy and water and carbon analysis. The DE optioneering upon which this paper focuses was a major part of this second track.

Options screening

The initial task was to define conceptually and assess up to 10 feasible DE options, and then select three to take forward for schematic and detailed analysis.

This stage comprised a DE workshop and brainstorming session at which the feasible options were generated communally by all the stakeholders, with simple visual tools available to communicate the spatial, operational and aesthetic implications of each idea.

Brainstorming

The entire design team, plus state and developer stakeholders, attended the two-day workshop (Fig 5). On the first day, the brainstorm session spun off a contextual presentation by Arup of the basic site conditions, constraints and load projections. As well as generating and documenting the feasible DE options, the workshop was invaluable in refining the stakeholders' objectives and uncovering some common concerns. The workshop also gave attendees a holistic view of the DE "optioneering" process, which clarified the level of analysis detail that would be possible and the kinds of assumptions necessary given the schematic nature and timing of the project.

The second day focused on considerations of ownership and procurement options. This project is ideally suited for innovative public-private partnerships that can aid financial feasibility, and the workshop explored the potential for providing tenants with affordable green energy.

Constraints

All the stakeholders understood the physical constraints of the existing infrastructure and buildings, and in addition Arup provided a summary of the loads and existing system capacities, thus keeping the brainstorming exercise specific to the project site and eliminating non-starter DE options. The existing CUP and its distribution systems were central to the discussion of constraints, as the team had identified leveraging the plant's capacity to the fullest as a primary project goal.

Physical constraints

Initial discussion of the primary physical DE scenario constraints guided the generation of ideas at the brainstorm, and these physical constraints were later assessed more thoroughly when the identified preferred options were analysed in detail. The existing buildings, naturally, form an important existing physical constraint, located as they are on parcels earmarked for redevelopment during the project. Some are scheduled to remain occupied and operational as the new buildings are constructed, and for certain DE scenarios this constrained the potential location and timing of a new central plant as well as new distribution.

The existing CUP (Fig 6) is in parcel D, earmarked to be redeveloped in Phase 4. As already mentioned, leveraging the existing CUP was highly desirable, and assessment of the brainstorming strategies included the extent to which they utilised the CUP's equipment — the capacity and remaining useful life of which were also key considerations in developing DE scenarios.

Thermal distribution from the CUP is a two-pipe, dual-temperature network in underground utility tunnels, which limits the "mode" of operation to either heating or cooling. This existing distribution system is thus unsuitable for serving the planned development, as residences require simultaneous heating and cooling due to the needs of year-round domestic water heating. A four-pipe distribution was therefore central to any DE strategy for the new buildings.

The BMS State Center station and underground tracks at the southern portion of the site impose underground crossover constraints, so the design team had to carefully evaluate buried DE services, particularly to parcels E, F and G. This in turn highlighted detailed co-ordination with the city and the Metro authority as being necessary to an investment grade study.

Ownership of electrical distribution within the site was a key consideration and a potential constraint for the DE options, which included combined heat and power (CHP) and/or tri-generation (combined cooling, heat and power). The design team clarified the co-ordination that would be needed with the utility supplier concerned, Baltimore Gas & Electric, as well as the potential Federal Energy Regulatory Commission minimum efficiency requirements that could result for these DE scenarios.

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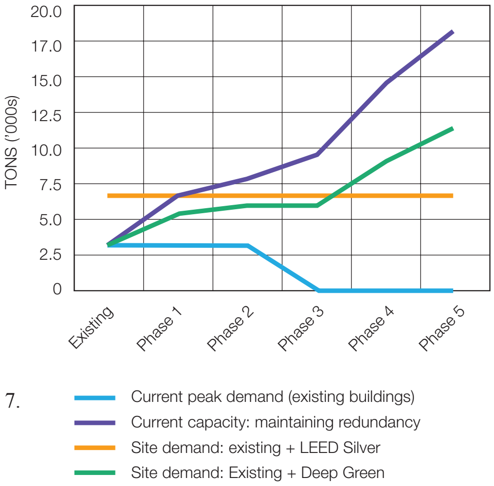


7.

5. Brainstorming with contributions from all stakeholders characterised the DE workshop.

6. Design team visit to central plant in 2010.

7. Cooling capacity vs projected load growth for the site.

8. Conceptual sketches for the design of new buildings.

9. Energy flow diagram of site-specific co-generation scheme.

Load and capacity constraints

The CUP's unused heating and cooling capacity was a key consideration. As the project grows, the CUP will face increased loading as new buildings are constructed and connected to it, as well as load reductions at other times when existing buildings come off line. The design team mapped out these load projections to communicate the timing and extent to which the existing CUP's heating and cooling equipment could potentially be leveraged (Fig 7).

The site is serviced by three primary 5MW electrical feeders. As with heating and cooling, there is spare electrical capacity and only two of the three are currently energised. The electrical constraint for DE options was therefore established as 15MW; above this, additional capacity from Baltimore Gas & Electric would be required.

Load projections for the new buildings were crucial in determining the required system capacity for all the DE options, so the conceptual design work for phase 1 included building performance criteria that could be used as inputs to the DE calculations (Fig 8). These criteria implied expectations of new building energy performance, as well as first cost and building-level system types.

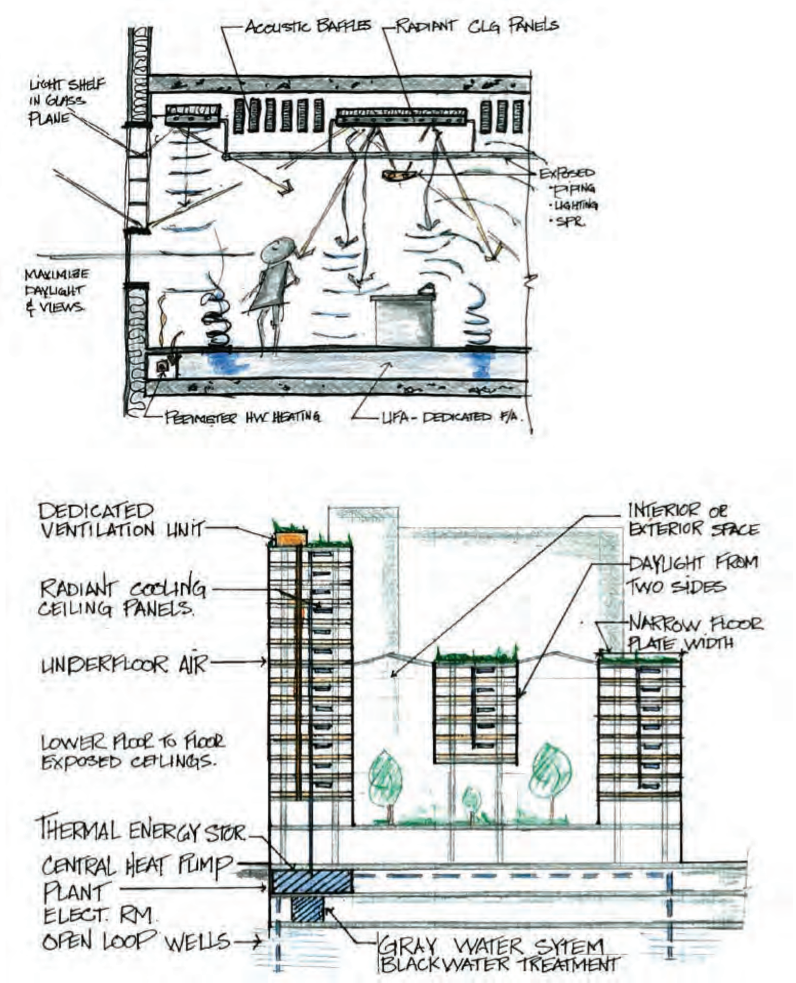
Screening tools

Some basic tools were used to communicate effectively the implications of each DE option to an audience of varying technical expertise, allowing the spatial, operational and energy flow characteristics of each option to be presented during screening. Three of these conceptual-level tools used as part of this exercise were as follows:

Energy flow diagrams

Diagrams depicting the flow of all forms of energy were created for each DE option, mapping out the flow of energy from source to end-use, and through "nodes" of energy conversion along the way (Fig 9).

The energy flow diagrams were highly successful in communicating the location, need and function of major DE equipment at the building, block and district levels.



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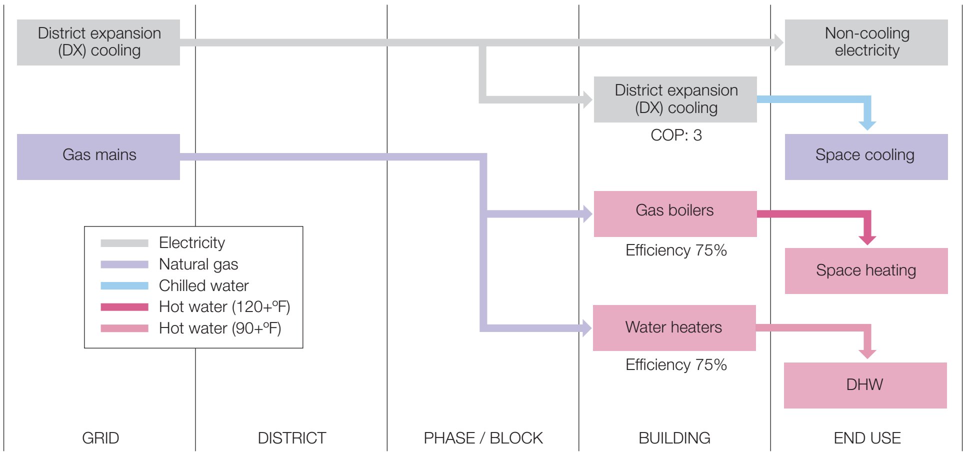

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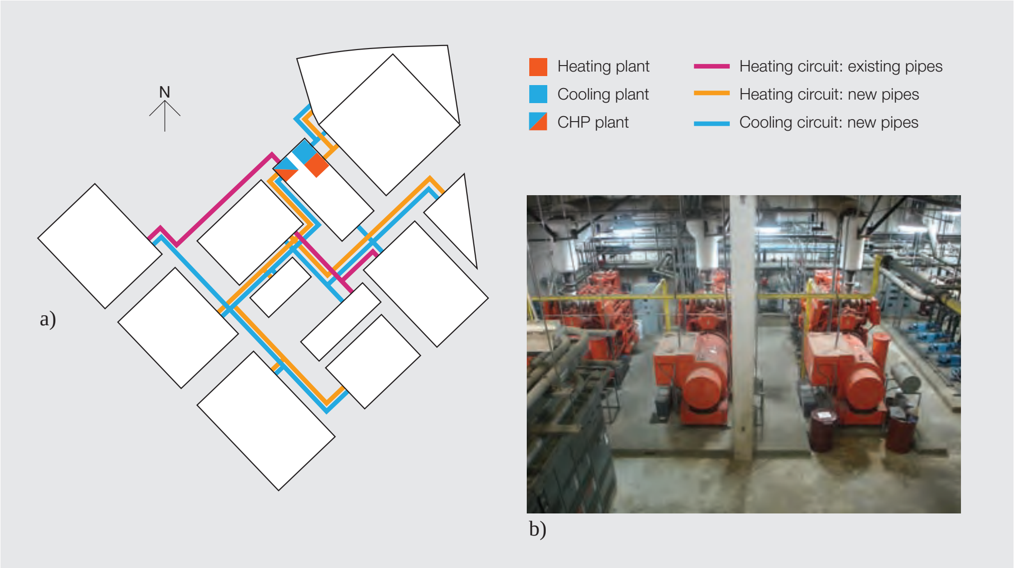
These flow diagrams quickly communicated the energy infrastructure strategy of the site for each DE option, and made the differences between the various options highly transparent. For this reason, the diagrams were particularly useful at the DE workshop and at all subsequent meetings with non-technical stakeholders. The design team also continually referred back to them later in the project to check fundamental assumptions and refine analysis methodologies.

"Pros and cons"
Simple lists of pros and cons were created for each DE option, summarising its known cost and operational, spatial, real estate and ownership characteristics. This not only helped guide discussions, but also helped stakeholders voice their support or concerns with each option and its characteristics. By enabling the understanding of each parameter's relative importance, this process catalysed the development of the weighting criteria that helped identify the preferred options.

Phased mapping
Phased maps indicating major DE equipment and distribution were used at the design workshop and subsequent meetings with city and state officials to communicate the phasing and spatial implications of each DE option. These phased maps were beneficial to screening the DE options because they:

- identified constraints associated with certain non-starter options
- illustrated the timing and need for DE elements (eg major and minor plantrooms, stacks, distribution, etc) seamlessly to the architect, state, developer and other design team members
- depicted the timing and extent to which the existing CUP was leveraged
- provided adequate detail for costing and financial analysis
- provided an overall look and feel of the site for each DE option (Fig 10).



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Options appraisal

Preferred DE options

The screening process identified those DE options to be taken forward for detailed appraisal, including energy and life-cycle cost analysis for each of the following:

Baseline
The baseline DE option comprised building-level heating and cooling plants for all new buildings, with no provision for CHP, tri-generation, or thermal storage. These plants were to be stand-alone, and sized to meet only the loads of the buildings they served.

The existing CUP and two-pipe distribution would be retained, continuing to serve the existing buildings until they were redeveloped. During redevelopment, these parcels would be built with their own stand-alone heating and cooling plants, and all the equipment in the existing energy centre decommissioned and removed.

Option 1a
This involved retaining the existing CUP and modifying and extending it to meet future site demands for heating, cooling and CHP. The existing plant and networks were to be used as far as was practicable, and capacity for future phases added as required.

The potential to supply Phase 1 from the existing CUP was central to this option, and was thought to offer economic benefits versus separate, stand-alone systems for the Phase 1 buildings.

Option 1b
In this option, the existing CUP would be retained in the short-to-medium term, serving the existing buildings until the parcel containing it was up for redevelopment.

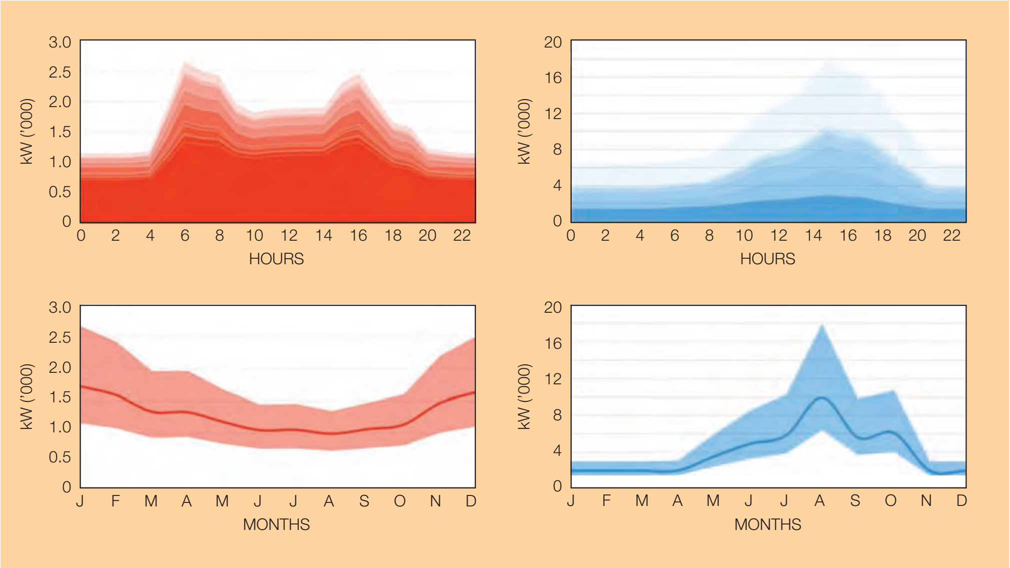
A replacement central facility would be built as part of the Phase 2 parcel redevelopment, and would serve all new buildings. Phase 1 parcels would therefore contain stand-alone facilities under this option (until Phase 4, when they would connect into the district system).

Option 2
This option involved retaining and modifying the existing CUP so that it could provide heating and cooling simultaneously, and expanding the district heating system only. In the short term the chillers at the existing plant would continue to provide summer cooling to the existing buildings via the existing dual temperature system.

In parallel, a district heating scheme would be developed to meet the site demands for heating, with cooling plants provided at the building level for new development.
The chillers and cooling towers at the central plant would ultimately be repurposed to provide cooling for Phases 4 and 5.

10. a) DE map representing option 1a at Phase 5, b) Existing central utility plant (CUP).

11. Daily and annual heating and cooling modelling.



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Managing input assumptions

A vast range of model input assumptions is inherent in feasibility studies of this size, diversity and timescale. Additionally, the team included many stakeholders, ranging across experts in the retail, development, energy, building and infrastructure design realms, each of whom had independent perspectives on suitable assumptions.
The resulting input assumptions ranged from well-defined and high-certainty values to reasonable estimates suitable to progress the study. Input variability was tested through sensitivity analysis.

With this in mind, Arup led the effort of keeping inputs transparent, up to date, and shared among the stakeholders so as to maximise consensus and achieve a joint vested interest in the results. Linking the energy and financial models was again highly valuable, as changes in results for both could be generated rapidly as inputs were refined and tested.

Detailed technical analysis of the preferred DE options

Detailed technical analysis was necessary to assess the energy performance of each preferred DE option, and involved modelling the hourly cumulative building demands and the energy consumption needed to supply those demands. In this way, the DE options could be compared on the basis of relative energy, energy cost and emissions.

Heating and cooling
For each land-use type in the project, regional building energy consumption benchmark data were calibrated to account for new building efficiencies, and then coupled with typical energy end-use splits to generate daily and annual heating and cooling demands. This was done for each phase and for each set of cumulative building programmes to be served by any given CUP at any point during the project. Subsequent energy modelling results from the parallel Phase 1 conceptual buildings work were also used to check and calibrate these benchmarks.

The demands were then used to estimate the amount of energy consumed by each scheme for heating and cooling, using the agreed assumptions for existing and new plant efficiencies. Thermal losses were accounted for in schemes containing chilled and hot water distribution (Fig 11).

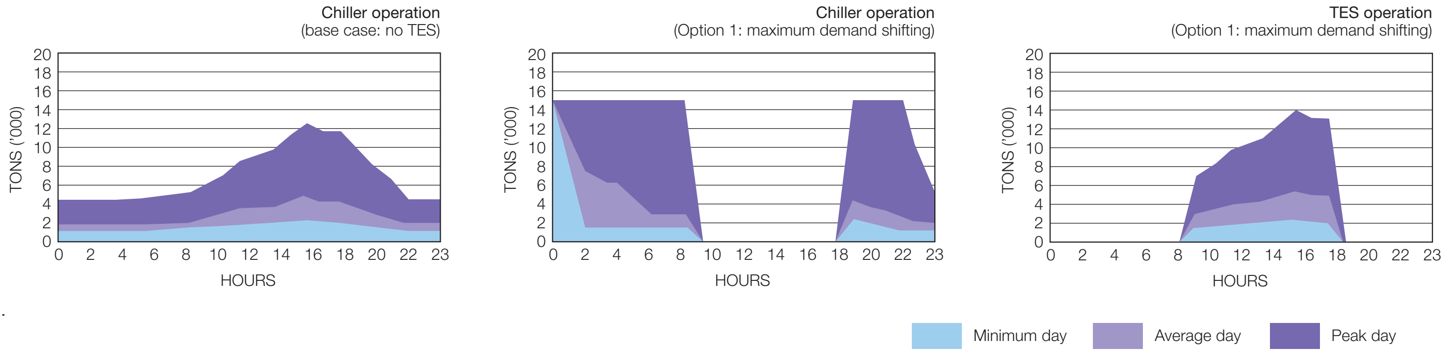
Combined heat and power (CHP)
Cumulative daily and annual electrical demands were generated similarly as for heating and cooling. Coupled with the heating demands, these were analysed hour by hour to assess the viability and energy consumption of preferred CHP options. This analysis allowed for electrical export, engine turn-down, electrical vs heat load following, maximum heat dumping and top-up boiler consumption where appropriate. Existing and new engine size, and thermal and electrical efficiency, were key inputs to this analysis and agreed-upon values were modelled for each.

Tri-generation
The heating, cooling and electrical demands were analysed, again hour by hour, to assess the viability and energy consumption of preferred tri-generation options. As well as the considerations mentioned above for CHP, the constraints of limited absorption chiller turn-down and cooling vs heating prioritisation were included in this analysis.

Appraisal tool

The Arup team used its own proprietary modelling tool, DEF (District Energy Feasibility), to carry out the technical analysis for this project. DEF had been developed as an internally-funded project through Arup's programme which encourages members of the firm to propose investment projects suitable to their interests and practice. Successful proposals are funded from global profit, and learned outcomes are disseminated within Arup.

The first version of DEF was developed in the UK Sheffield office, motivated by projects requiring district heating only. The second version was developed in San Francisco specifically for projects such as the Baltimore State Center that required feasibility-level analysis of multiple DE supply options including heating, cooling, CHP, tri-generation and other forms of energy supply not used in the present project.



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Thermal energy storage (TES)
The cooling demand profiles were analysed, one more on an hour-by-hour basis, to assess the feasibility and potential benefit of preferred TES systems (Fig 12).

The existing plant was an ice storage plant, which was also the storage form for all preferred DE options. The ultimate energy rate schedule and ratchets for the plant were speculative, and the charge and discharge hours of operation for the store were optimised based on shifting the peak four-hour chilled water plant load entirely. The cooling priority for the options analysed was as follows:

1. supplied from the absorption chiller (for options with tri-generation)
2. supplied from the TES
3. supplied from the electric chiller plant.

District pumping
District chilled water and hot water pumping energy were accounted for in each of the DE options with thermal distribution networks. Peak pumping power was calculated from peak thermal loads and pipe head (energy in the pipe flow), which were based on the agreed-upon network lengths for each option. Variable-speed secondary pumps were assumed, and the resulting energy was calculated based on the variation in load each hour.

DEF can model energy demands and supply for multiple phases and up to six land-use types. It has 10 built-in DE supply options and allows users to modify inputs and supply options, comparing results for each across a wide range of metrics.

Financial analysis

To assess the life-cycle cost of the options, the team also carried out detailed financial analyses on a Net Present Value (NPV) basis. The process was as follows:

1. Each preferred financial option was determined, so as to assess their full life-cycle costs.
2. Further detailed financial analysis assessed the project from the owner's perspective , including accounting for the energy rates that tenants would have to pay; this was carried out to analyse the project as a stand-alone investment and/or as a third party ownership arrangement.
3. Potential ownership structures and procurement methods were determined, addressing financing and risk allocation needs of the project; adjustments to the financial model made accordingly.
4. The team continues to study potential grants, incentives and the ability to sell excess electricity to the grid or to other third parties.

With engineering, sustainability and financial services under one roof, Arup was able to link the financial model(s) to the energy model outputs and the equipment and plant input assumptions of each technical analysis. This allowed for immediate and seamless updating of the financial model each time a DE assumption and/or input was changed.

Capital expenditure (CAPEX)
The CAPEX of each DE option was assessed for major new plant equipment and equipment overhaul/upgrade, plant building and distribution. The team also developed and costed equipment lists for each DE option using agreed values and/or benchmark cost data. The agreed financial analysis time horizon was 25 years, and CAPEX input was staggered to reflect true financial outlay as dictated by the phasing of each DE option.

Operating expenditure (OPEX)
The OPEX of each DE option was assessed for energy consumption and demand costs, operation and maintenance and energy export revenue. Tax incentives, including accelerated depreciation and federal tax credits for CHP projects, were accounted for as part of operational revenues, while financing costs and implications were included in OPEX as part of the more detailed models.

As noted before, the technical and financial models were linked, which meant that energy consumption and demand outputs from the technical model transferred directly into the financial model as inputs, requiring only agreed energy cost rates and inflation to be entered separately.

The goal of the financial analysis was to produce a project design, plan and financial model that would allow the project to be financed and implemented.

Spatial analysis

The footprint of the DE equipment and its required new plant floor-space was a primary concern to all stakeholders. Arup therefore calculated this for each preferred DE option at various stages of the project, as loads and equipment sizes continued to be refined. These area estimates ranged from rough order of magnitude (ROM) figures to feasibility level 3-D equipment layout, as summarised on the next page.

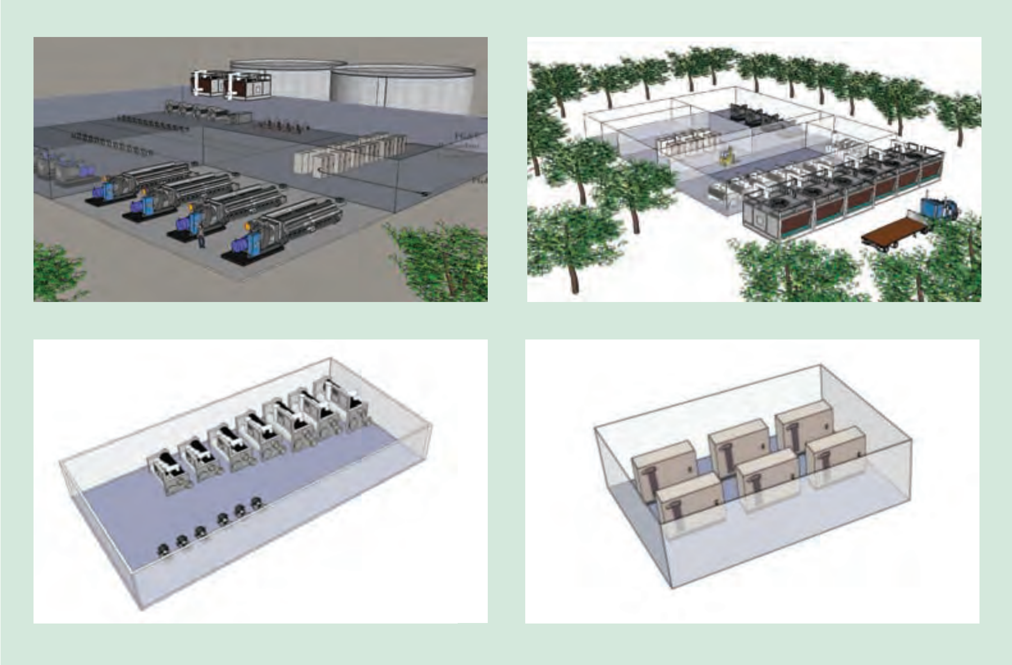
Benchmarks
Using benchmarks from previous projects, the team calculated the CUP and distributed plant floor area for each DE option. These earlier ratios of plant floor-space to full development area were examined and applied at Baltimore, enabling stakeholders to understand the ROM floor space requirement for each DE option.

The results were checked against basement and ground level floor-spaces in areas designated in the masterplan for the plant, thus enabling the design team to establish in general terms whether or not the plant for each DE option could be accommodated or whether reprogramming would be needed.

2-D and 3-D layout
Equipment lists with sufficient detail for sizing were generated for each option, including major items of the scale of chillers, boilers, cooling towers and co-generation engines, and minor equipment including pumps, heat exchangers and other balance-of-system components. Access, clearance and serviceability provisions for all systems were made in 2-D. The design team generated 3-D layouts of plantrooms for preferred options, maintaining the project theme of maximising visual representation of DE option comparison (Fig 13).

Results
The first phase of results indicated that option 1a delivers a more attractive financial solution to all stakeholders — leveraging the existing CUP essentially delays considerable capital outlay, a key factor in this overall benefit. The modular growth of CHP centrally within the dense site matches the growth of thermal and electrical loads, allowing more favourable procurement of power and heat. Perhaps more fundamentally and intuitively, the benefit of leveraging existing, under-utilised assets through the end of their useful lives strongly favours DE over and above the baseline of new, stand-alone and highly redundant building-level plant.

Conclusion
The brainstorming workshop initiated this feasibility study of DE options, and narrowed the field based on site constraints and stakeholder goals. Further refinement through qualitative comparisons and visualisations enabled informed choices by all concerned, and the preferred options were then analysed in detail to understand annual energy demand and supply.


13.

These results enabled financial modelling to generate the NPV of each preferred option, and also provide insight on different ownership and procurement methods. Spatial considerations and co-ordination with neighbours, regulatory bodies and utilities were also highlighted, giving the client a holistic comparison of three alternate DE schemes to take forward. Arup's work helped to give the client a highly efficient optioneering process, leading to an integrated and holistic feasibility study. The Baltimore redevelopment itself remains the subject of extended negotiations between state and developer.

The DE optioneering process has since been applied to other Arup projects, ranging from pharmaceutical research, development and manufacturing campuses to existing and planned Silicon Valley technology campuses. The teams on these have held regular cross-team knowledge and lesson-sharing workshops to ensure the continual improvement of tools, analysis detail and client engagement. Arup is positioned well to respond to growing client appetite for similar future work.

Author
Afaan Naqvi is a senior engineer in the San Francisco office. He was Project Manager for the Baltimore State Center district energy analysis project.

Project credits
Client: *Ekistics LCC*; District energy and conceptual building design: *Arup — Paul Anseeuw, Engin Ayaz, Manish Dalia, Giulio Farinelli, Alex Mitchell, Anne Marie Moellenberndt, Carla Morris, Afaan Naqvi, Yolanda Owens, Brian Renehan, Simon Reynolds, Anthony Riddle, Cole Roberts, Rowan Roderick-Jones, Ben Watts*; Masterplanner: *Mithun*; Architect: *Design Collective*; Construction contractor: *Suffolk Construction*; MEP design: *Leach Wallace*.

Image credits
1, 7, 9, 10a, 11–12 *Arup/Nigel Whale*; 2 *Bing Maps* & *USGS*; 3, 5–6, 8, 10b, 13 *Arup*; 4 *Mithun*.

12. Analysis to assess benefit of a demand shifting TES strategy.

13. 3-D modelling of plantrooms for spatial analysis.

Stanford Graduate School of Business Knight Management Center

Location
Stanford, CA, USA

Authors
Mathew Bamm Stan Boles Cole Roberts Jesse Vernon
John Williams John Worley

1.

1. The eight-building Knight Management Center.

2. Three decades of Arup-engineered projects on the Stanford University campus.

2.

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n Knight Management Center: SMEP and civil engineering, fire/life safety consulting, LEED co-ordination, sustainability, acoustics, A/V and lighting design, 2007-2011.

o Bioengineering and Chemical Engineering Building: analysis of impact on existing utility infrastructure; ambient noise survey, 2011–.

p SLAC National Accelerator Laboratory's Science and user support building: MEP and fire/life safety engineering, energy/sustainability consulting, 2011–.

Arup at Stanford University

One history of Arup in San Francisco can be told by walking the campus of one of the most famous educational institutions in the world. Just over 100 years after Stanford University first opened its doors, the firm started its first US office in San Francisco, and its initial project in the Bay Area was the Lucile Packard Children's Hospital, at Stanford. Over the last quarter-century, the relationship has flourished — around 50% of the university's new buildings in that period have had Arup involvement (Fig 2).

Stanford's unofficial motto is "The wind of freedom blows," and the climatic fortune that blesses this part of California has enabled delivery of some of the lowest-energy buildings on the planet. The ambition of the university, combined with the skills of architects and engineers, has delivered many notable landmarks across the campus masterplanned from 1886 onward by Frederick Law Olmsted (1822–1903).

The range of Arup services at Stanford has also grown, from building engineering to the full current suite of disciplines. The firm's contribution to the Knight Management Center[1] (Fig 1), new home for Stanford's Graduate School of Business (GSB), represents the greatest breadth of skills yet delivered to a single project on the campus, integrated to deliver three distinct, holistic sets of solutions: for the site, for the base buildings, and for their interiors. Each set was honed not only to co-ordinate and create synergies but also to respect the project's scale and ambition.

Delivering on such a promise takes trust, patience, foresight and consideration — all requiring commitment to teamwork. This project testifies to the collaboration of the team, designers and client alike.

A long history of projects between an owner and a designer builds a bond of trust and expectation — unusual in the construction industry. Trust is won over time, and is a strong bond and a powerful motivator. Arup is proud to have been trusted by Stanford University with such a large and prestigious project. That trust motivated the team and instilled a shared commitment to the success of the new Center, which educates and inspires people to deliver great business and sets new standards for a campus that is constantly searching for improvement.

From building to boundary… and beyond

In October 2006 the Philadelphia-based architectural practice Bohlin Cywinski Jackson (BCJ) invited Arup to join it in the design competition for the Knight Management Center. The university's aspirations were high and an integrated design solution seemed essential, but Arup had not provided a full multidisciplinary service for a project on the campus before. Also, time and cost were considerations: the schedule showed an opening date in late 2010, and the budget was as much a challenge as the sustainability aspirations.

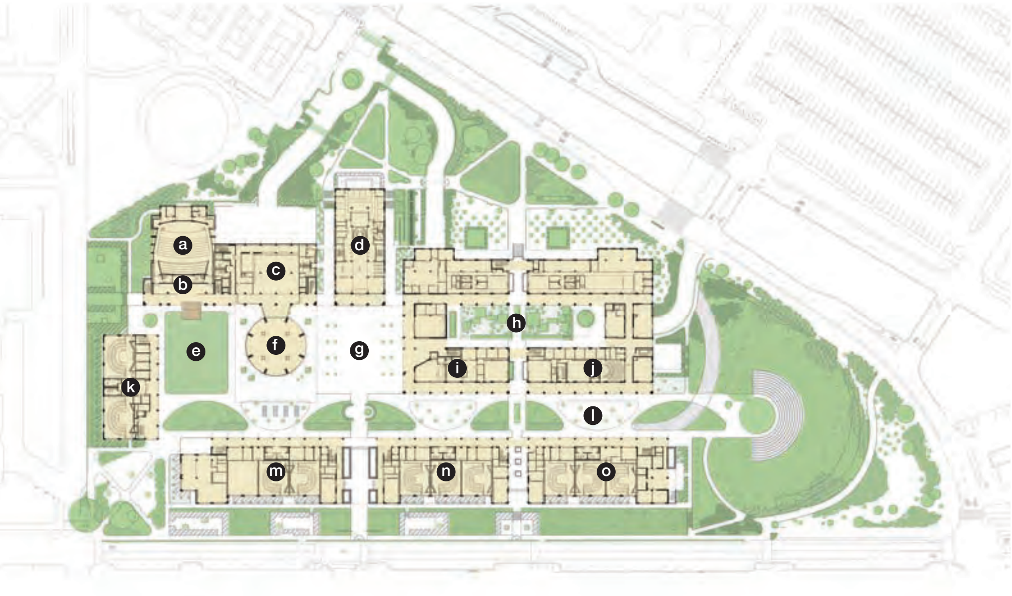
The BCJ/Arup team focused on a design solution that integrated the architecture and the engineering, making the best use of the site's scale, orientation, and relationships between uses to produce natural solutions in terms of planning, circulation, and massing, which in turn delivered performance.

In any project, the parameters of time, cost and quality generate a dynamic tension, and this competition phase was no exception. For the design of the new Center, the GSB chose to seek LEED Platinum rating, the highest green building level of certification offered by the US Green Building Council[2]. Delivering LEED Platinum solutions at a large scale within a tight budget in an educational (school schedule) context is tough, but the team's process gave direction to the design solutions.

With the competition won, the work really began, and the early collaboration of diverse project stakeholders, from donors to operational staff, highlighted the importance of design communication. Stanford's vision was to promote academic excellence through a campus that inspires its inhabitants, supports a healthy and productive teaching and learning environment, and is flexible and adaptable to future changing pedagogies and technologies.

Following the pre-design phase, Stanford transferred design responsibility for the project to the Portland, OR-based practice, Boora Architects, and the newly configured team of architect, contractor and engineer refined the concept direction, holding numerous work sessions with faculty and administration. Through a series of presentations, and listening and responding to input from lay people and experts alike, the team achieved approval from the Stanford Board of Trustees.

3.



4. a) Zambrano Hall b) CEMEX Auditorium c) North Building d) Bass Center e) Community Court f) Arbuckle Dining Pavilion g) Town Square h) McCoy Family Courtyard i) Faculty Building West j) Faculty Building East k) Gunn Building l) Knight Way m) McClelland Building n) MBA Class of 1968 Building o) Patterson Building.

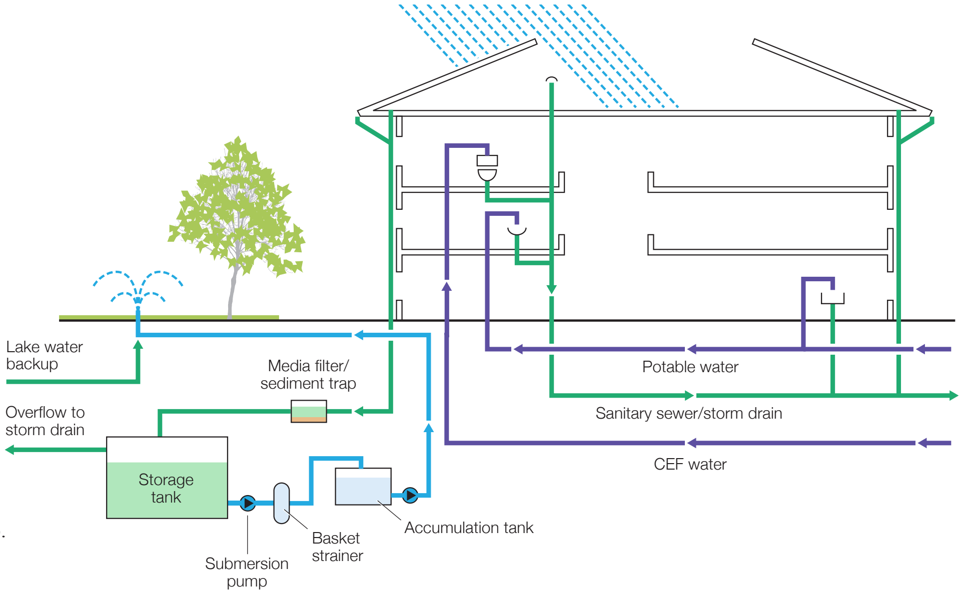
3. The benign climate enables extensive use of external spaces.

4. Knight Management Center site plan.

Balance between reduction, passive solutions, active solutions, recoverables and renewables drove the energy solutions and much of the design approach. Stanford's climate is so moderate that non-functional spaces could be external and lobby spaces could be used as thermal buffers. With this layout, structural cantilevers could then avoid columns on walkways, with backspans efficiently used to deliver simple and effective systems. The team adopted the passive approach by using volume to drive thermal systems and increase daylighting, applying active systems only when strategies to reduce and passively serve were exhausted.

The Center is not a single building but a complex of eight linked buildings within the greater Stanford campus (Figs 2, 4), taking only what it needs and returning minimum waste to the overall systems. Balancing the energy, water, and waste systems across the school, the site team produced innovations across and below the surface. Meanwhile, the buildings team organised the structural, mechanical, electrical, plumbing (SMEP) and façade systems to maximise the favourable climate and organise the massing. Finally the fire, acoustics, building systems, and lighting teams worked together to produce inspirational, safe, and fresh spaces for the users to enjoy.

5.



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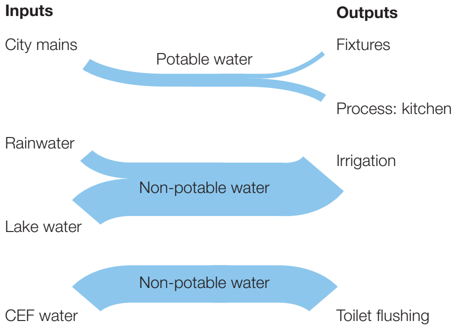

7.

5. Typical daylit classroom interior.

6. Water usage flow.

7. Overall scenario for water usage.

Integrated design

Water use

The team aimed for maximum efficiency, innovation in water reuse, and significant reduction in demand from the potable grid. Integrating significant demand-management measures with a comprehensive campus water-management strategy was critical to achieving a design solution that reduces potable water consumption by more than 80% over a “business as usual” design.

The civil engineers worked with others in the design team, including landscape architects PWP Landscape Architecture, to develop sustainable, effective approaches to managing potable water and stormwater on the campus. They studied demand-side water reductions and alternative supply strategies for cost impact and feasibility. As part of a comprehensive stormwater design approach, harvested rainwater offsets 20% of irrigation demand, while integrated low-impact treatment devices (LID) filter stormwater via low-maintenance swales and infiltration basins. This recycled water programme has earned the project a Site Design Award by the regional stormwater authority.

Potable water management

Under its General Use Permit from the Santa Clara County Board of Supervisors, Stanford is restricted from increasing potable water consumption allocated by the San Francisco Public Utilities Commission through 2020, despite its ever-increasing need to construct new facilities. To offset potable demands, the university recently began to implement a campus-wide recycled water programme that reuses wastewater blowdown from its central energy facility (CEF).

Understanding Stanford’s key long-term development drivers prompted Arup to look at the university’s campus-wide water strategy, and the team convinced the university to integrate a significant on-site rainwater harvesting system into the project, and to expand the recycled water network to the GSB.

Various water reuse scenarios were paired with the demand-side analyses to quantify treatment and storage tank sizing requirements (Fig 6). Sankey diagrams (arrow width proportional to flow quantity) visually depicted water savings: potable demands decrease as they are replaced with non-potable supplies (Fig 7).

Stanford Utilities Services agreed to extend its CEF recycled water supply 1 mile (1.5km) to the Knight Management Center, while the GSB agreed to supplement its irrigation demand by constructing a localised rain harvesting system.

The combined systems provide the GSB with a robust non-potable water portfolio: CEF water supplies 100% of the toilet flushing demand; rainwater offsets some 20% of average annual irrigation demand, with the remaining 80% supplied by the university’s lakewater irrigation network.

8.

Reducing water footprint

By recycling domestic water after initial use, the water footprint of new developments can be substantially diminished, in turn reducing the energy consumed by treating and delivering potable water. This potential is best realised through a comprehensive assessment of demand, supply, and reuse using a stepped approach, beginning with demand use reductions in buildings and landscaped areas. An alternative supply assessment is then made from low- to high-impact sources and required treatment level (Fig 9).

9.

8. Integration of water quality devices into the landscape design.

9. Arup's approach to minimising the potable water footprint for the GSB.

10. Atrium in the Bass Center.

Stormwater management

Arup and Stanford Utilities Services worked closely with PWP Landscape Architecture to integrate a series of low-impact (LID) stormwater treatment technologies seamlessly into the landscape design.

Much of the site area was converted to permeable surface. One large vegetated bioswale treats runoff from roughly 50% of the site, a scattering of infiltration basins treat another 20%, and 20% is directed to the rain harvesting tank for treatment and reuse — only 10% of the site is treated by the university's regional bioswale.

The infiltration basins blend into soft landscaped areas as small depressions, where runoff infiltrates through engineered soil layers and is drained away by perforated subdrains (Fig 8).

Stormwater-quality bioswale and infiltration devices are innovatively integrated into the landscape design (Fig 8). The shallow and almost imperceptible contouring of the infiltration basins leaves room to achieve site programming goals while effectively treating stormwater.

The harvesting system collects rainwater from building roofs, piping it through a dedicated storm network to a pretreatment filter and a 75 000 gallon (284 000 litre) underground storage tank. Rainwater is siphoned off the tank from November to May, further treated and pressurised before distribution through the irrigation network.

The LEED criteria for stormwater credits at this site required the peak discharge rate and volume to be reduced 25% from its former site condition; the rain harvesting programme reuses enough to reduce the total site runoff volume by 37%. In addition, the tank is designed to attenuate the 10-year rain event, contributing to a 35% reduction in the peak discharge rate.

This is Stanford's first such programme, and serves as a template for various project types. Early engagement with the building owner, occupants and utility is critical to ensuring that rain harvesting is appropriate for a project. While the cost of installing the system at the Knight Management Center was a significant investment, the long-term economic and environmental savings in offset toilet flushing and irrigation demands are substantial.

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11. The Knight Way thoroughfare between the Arbuckle Dining Pavilion and McClelland Building.

12. NGP Collaboration Lab (CoLab) in the McClelland Building.

Buildings

Decision-making

To design the new eight-building complex holistically on a 12.5 acre (5ha) site in a relatively short time, the buildings team had to constantly verify that design decisions met the overall project vision. This challenged the team significantly — to make informed decisions regarding architecture and building systems; to meet the aggressive design and construction schedule; and to ensure that design decisions were in line with the project objectives and goals of the stakeholders.

Many groups were invested in this project and its outcome — the GSB faculty, staff, alumni, donors, students and community; the university design and construction management; the university facilities; the design team; and the contractor. To help inform and manage decision-making, the design team needed first to understand the stakeholders' objectives, goals and values, so as to make rational decisions that supported or complemented them.

The design team agreed to work with Stanford's Center for Integrated Facility Engineering (CIFE) and use the project as part of CIFE's research to better understand and improve the decision-making process in architectural, engineering, and construction projects. CIFE introduced the design team to the decision support system it had developed — Multi-Attribute Collaborative Design Assessment and Decision Integration (MACDADI) — which is "a method of structured collaboration with social and technical elements intended to build consensus on [architectural, engineering, and construction] decisions by improving transparency, precision, and comprehensiveness of rationale."[3]

The team essentially became a test case to help CIFE understand how industry actually makes decisions, and experiment with implementing the MACDADI system in a real-world project. Though some factors prevented the method's full use, MACDADI aided the design team by providing a process to develop and define the objectives, and a loose format for evaluating and making major design decisions. After polls, meetings and summits, the following top project objectives were identified:

- a collaborative, vibrant, and engaging campus
- the highest level of sustainable design

13.

- low energy and water use
- natural lighting of spaces and connection to the outside
- configurability and future flexibility
- low operating cost
- open facility for classes in January 2011
- project cost under budget.

These aims were then used as a part of the decision-making process for selecting the major structural and mechanical systems. Arup took the MEP design through to 75% design development, then passed it over to the contractor, Therma. Through multiple meetings and discussions, the team ensured that the design intent was understood and important technical details carried forward.

Low-energy environmental control systems
To achieve the goals set forth in the MACDADI process, the Arup team worked with Boora Architects to integrate system designs that were responsive to the space programme, the occupants' needs, and the temperate "Mediterranean" climate.
Over a large campus with much variation, this required consideration of an array of system technologies, isolating the best ones for specific programme areas.

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13. CEMEX Auditorium in Zambrano Hall.

14. Aerial view of McClelland Building.

15. Communal space in Faculty Building.

Specifically, the use of traditional low-energy technologies was focused through understanding how the spaces would be used and the expectations and needs of the future occupants.

The mechanical systems approach was to:

- minimise the space loads for power, heating, and cooling
- employ passive strategies for environmental control where possible
- optimise the efficiency of required active strategies
- capture any possible waste heat
- offset this with renewable energy sources to minimise the impact of the new building on the infrastructure.

One of the first load-reduction strategies was to select a high-performance envelope of spectrally selective low-emissivity glass, which reduces solar heat gain and thereby decreases overall cooling load. The external walls and roof assemblies demonstrate a higher thermal resistance than required by code to limit heat transfer. External shades and overhangs also reduce solar heat gain.

The strategy for efficient lighting design reduced the lighting power density with high-performance lighting, combined with reduced lighting levels. High-efficiency dry-type transformers also reduce energy loss during voltage conversion.

Passive efficiency strategies included careful attention to orientation and massing, and an emphasis on natural ventilation.

Most of the façades face south and north to accommodate passive solar benefits, and the long, narrow buildings optimise natural ventilation penetration. Enclosed offices contain operable windows, interlocked to the chilled-beam cooling unit within, allowing occupants to choose to use the mechanical system or open the window.

The full benefit of natural ventilation is seen through detailed modelling for north- and east-facing offices; for these areas in two of the buildings, natural ventilation was optimised by adding openings within the floor and a roof stack to draw air through the office floor plate. To enhance the use of natural ventilation, manually controlled ceiling fans provide additional cooling airflow when necessary (Fig 17).

After maximising energy savings through minimised loads and passive strategies, the team turned to active efficiency strategies. Active chilled beams are used in cellular spaces to give occupants higher levels of local comfort control. To improve the efficiency of this system, the air supply to the beams is controlled with a variable air supply rather than the traditional constant-volume approach.

An under-floor air distribution system is used in spaces of high occupancy such as classrooms and seminar rooms, allowing for a higher supply air temperature and reduced fan pressure compared with more traditional variable-air-volume systems.

Use of the higher supply temperature also extends the number of hours the system may run in airside-economiser mode, which increases refrigeration-free cooling hours and is especially appropriate for this climate in spaces where natural ventilation could not be employed.

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18.

We are proud to have been a part of the very successful Knight Management Center project at Stanford University. Arup engineers prepared the design-development template, including a total building-energy model indicating the projected energy savings goals. As part of the design assist team, Therma worked closely with [them] to find ways to cost-effectively achieve the desired energy goals...

We are very happy to say the concepts of "professional engineered" schematic design, "design assist" design development, and contractor design-build construction worked very well throughout the project. We look forward to working with the Arup team again soon.

Mike Miller, LEED AP, Senior Project Manager, Therma Corporation.

16. The Arbuckle Dining Pavilion.

17. Mechanical systems optimised for building orientation.

18. Communal area outside the Arbuckle Dining Pavilion.

19.

Measures to achieve LEED Platinum

- Building orientation provides daylighting and natural ventilation to 75% of all interior spaces.
- 90% of rooms have a view to the exterior.
- Exterior wall design provides shaded areas of glass, reducing heat gain.
- Flexible building systems designed for future changes include the long-span steel structure, which minimises obstructions in the floor plans; added ceiling height in ground floors; and under-floor distribution of power, data and air.
- Energy-efficiency standards are exceeded by 40%.
- Photovoltaics power 12.5% of the complex's energy demand.
- Non-hazardous construction debris was recycled or salvaged at 90%.
- On-site stormwater management and treatment plus water conservation reduced potable water usage by 80%.
- Rainwater or greywater reduced potable water use for building sewage conveyance by 50%.
- Low volatility, organic compound-emitting materials provide exceptional indoor air quality.
- 50% of the site will return to natural vegetation.

A low-pressure ventilation system significantly reduces fan energy — the air-handling units are configured to allow components to be bypassed when not in use and sized for low face velocity and low duct velocity. Indirect evaporative cooling further reduces the refrigerant required for systems with a high proportion of mechanical air cooling. The radiant floor conditions the dining area and other more transient spaces that increase connectivity to the outdoors. Energy is saved by offering localised cooling through a radiant surface instead of cooling the entire air volume to provide comfort.

At pumps and air-handling unit fans, variable frequency drives reduce energy consumption at part-load operation. Demand-control ventilation decreases cooling load and improves indoor air quality by operating according to occupant densities. It also controls and maintains the level of carbon dioxide in the space. A sprayed heat pipe at approximately 60% efficacy recovers heat energy that would otherwise be wasted and uses it for indirect evaporative cooling.

After all the previous strategies had been exhausted, the team turned to on-site generation. Photovoltaic panels are mounted on rooftops to generate supplemental project electricity and provide solar-heated domestic hot water.

In October 2011, the Stanford Knight Management Center was awarded LEED Platinum for New Construction, earning a total of 60 points and becoming the highest-scoring LEED Platinum university campus in the world. It achieved a 45% energy cost savings compared to the *ASHRAE 90.1-2004* baseline building — equivalent to 10 points under the LEED v2.2 Energy and Atmosphere Credit 1: Optimize Energy Performance[4].

19. Recreational space (Town Square) in front of the Bass Center.

20. The McCoy Family Courtyard between Faculty Buildings West and East.

21 *(overleaf)*. Staircase in the Bass Center.

Seismic design

The campus is some 12 miles (19km) from the San Andreas Fault and its potential for a magnitude 8.0 earthquake (as with the Great San Francisco Earthquake of 1906). For better building performance, Stanford has developed its own seismic design guidelines that go beyond the requirements of the California Building Code and are based on the performance-based design concept. The intent is to protect life safety of the Stanford community, secure critical infrastructure and facilities, and resume core teaching and research programmes.

The university's guidelines require designers to evaluate structural seismic performance at two earthquake levels: a 475-year return period magnitude of 7.0 on San Andreas and a 2475-year return period magnitude of 7.9 on San Andreas. Structural evaluation checks include no yielding of non-ductile elements, limited plastic strain in ductile elements, and limited inter-storey drifting.

Due to the irregular geometry of three of the steel structures at the complex, the team conducted nonlinear pushover analyses to show that they met the seismic-performance objectives. The earthquake-resisting system comprises buckling-restrained braced frames (BRBF) or special steel moment-resisting frames (SMRF). The team used the BRBF system wherever possible because it has proved economical and exhibits very good seismic performance through tension and compression yielding of the brace. SMRFs were used where BRBF braces would disrupt programme space, limit future flexibility, or adversely impact the architecture.

What next?

Stanford has long been a model of sustainability among universities globally. Its earliest buildings reflected the Mediterranean-type climate. Its native oak, shrubs, and grasses stand out as a uniquely Bay Area landscape. Its academic programmes and research have progressed humanity, and educated students from around the world.

Although strong, the campus sustainability commitment in the late 20th century had major room for improvement, and the last decade has witnessed it expand aggressively to once again claim the mantle of global leadership. New building energy use has been reduced by over 60%. Renewable energy supply has increased from near zero in 2000 to almost 0.5MW today.

20.

Arup has been one of many teams to contribute to Stanford's re-emergence as a sustainability leader in the 21st century, having designed systems for over 10% of the total campus, as well as more than 50% of the new buildings in the past 25 years. The Knight Management Center is the most recently completed expansion in a period of new building totalling more than 2Mft^2 (185 000m^2) over 20 years. This also includes Arup's contributions to the four-building Science & Engineering Quad (with Boora Architects), the Li Ka Shing Center for Learning and Knowledge, the Center for Clinical Sciences Research, the Green Earth Sciences Building, and the Lucille Packard Children's Hospital (see also Fig 2).

Stanford is redirecting its focus, placing increasing emphasis on the performance of the existing buildings. Arup has been hired to update the Stanford Facilities Design Guidelines, perform post-occupancy energy modelling, plan and implement measurement and verification, and capture LEED Existing Building certification.

A post-occupancy energy model of the Jerry Yang and Akiko Yamazaki Environment and Energy Building (Y2E2)[5] showed its financial return on energy efficiency to be even better than anticipated during design. The six- to eight-year payback is now only two to three years, as a result of increased building use (and energy savings) and a sizeable incentive award.

A study of the campus's coincident heating and cooling demands has prompted the university to undertake one of the largest ecodistrict retrofits in the country.

The existing steam distribution system is being replaced with a heating hot water system that will allow for energy recovery chillers to pump rejected heat from some of the buildings to others that are demanding the heat and vice versa (rejected cooling from buildings to other buildings demanding cooling). The energy recovery strategy is expected to take 10 years, and reduce the campus greenhouse gas emissions by over 50%.

21.

Conclusion

The Knight Management Center opened on April 29, 2011. Named for Stanford alumnus and Nike founder Philip H Knight in recognition of his $105M gift to the school, the complex enables the delivery of Stanford's innovative new MBA curriculum. The Center includes advanced classrooms of various sizes and configurations, breakout and study rooms, library, a CoLab classroom (a garage-like space for an entrepreneurial problem-solving course), faculty offices, auditorium, career management centre, executive education space, and dining facilities.

The residential scale is unique within the university, responding to the GSB's "strategic smallness": a small student body, small class sizes, and an emphasis on small-group interaction. Extensive outdoor spaces exploit Stanford's beautiful climate and provide numerous opportunities to collaborate and socialise.

Business studies change rapidly due to technological advances and altered patterns of working. Finding and motivating students in business today requires a global network — the very best must come to the school either virtually or physically every day, and the school itself has to be the very best to attract and retain that global talent. This project stands as a beacon of Stanford University's graduate business programme, a vital part in its process of delivering world-class business leadership now and long into the future.

As for the team itself, people become designers to deliver projects of which they can be proud, projects that not only serve as career milestones but that may also become public milestones that enhance the built environment beyond single lifetimes, places where relationships are built and reputations enhanced, and where all learn from the experience. Stanford's Knight Management Center is such a milestone project, a product of synergy and a project of which all team members are proud.

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Awards

2010 Green Project of the Year, Private Award, by the *Silicon Valley/San Jose Business Journal*

LEED Platinum for New Construction (60 points)

Authors

Mathew Bamm is a senior engineer in the San Francisco office, and was design lead and Civil Engineer of Record for the Knight Management Center.

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Image credits

1, 3, 5, 10–16, 18–21 *Tim Griffith;* 2 *Nigel Whale;* 4 *Boora Architects/Nigel Whale;* 6–8, 17 *Arup/Nigel Whale*; 9 *Arup.*

Project credits

Owner: *Stanford University Graduate School of Business* Pre-design architect: *Boylin Cywinski Jackson* Architect: *Boora Architects* SMEP and civil engineering design; acoustic, lighting, ICT, façades, sustainability/LEED, fire and life safety consulting: *Arup — Hassan Ally, Ibbi Almufti, Tyson Alteri, Key Anderson, Gareth Ashley, Wes Ashwood, Engin Ayaz, Piotr Balas, Mathew Bamm, Paul Barnard, Sergio Barrios, Mathew Bittleston, Denis Blount, Juanito Boado, Eric Borchers, Tim Brown, Stephen Burrows, Elma Buskens, Fernando Cabrera, Ramon Catiis, Vickie Chen, Joseph Collins, Tristen Connor, Manish Dalia, Nancy Damore, Angus Deuchars, Joseph Digerness, Ian Doebber, Jason Edling, Larry Encarnacion, Fang Fang, Hamid Fatehi, Ryan Fick, Chris Field, Adam Finkin, Jessica Fosbrook, Anthony Fresquez, Alexandra Gibson, Kurt Graffy, Danielle Griego, Jian Jin Guan, Christina Hemlock, Irene Heung, Bryan Hoskins, Emma Jose, Gene Joves, Alex Kalejs, Taylor Keep, Natalia Khaldi, Dylan Kiernan, Julie Kirkpatrick, Dennis Kwan, Raymond Lai, Mike Lamagna, Susan Lamont, Jun Lautan, Chris Lautenberger, Isabelle Lavedrine, Kathryn Lee, Leanne Leflet, Toby Lewis, Yong Lim, Dee Lindsey, Anna Liu, Bill Lizotte, Matt Mahon, Siu-ting Mak, Brady Mason, Yoko Matsuyama, Lucy Mattingly, Alisdair McGregor, Grant McInnes, Rowland Minall, Kate Ming, Janice Mochizuki, Jack Mong, Carla Morris, Shane Myrbeck, Afaan Naqvi, Shruti Narayan, Thomas Natwick, Robert Netopilik, Cherie Nixon, Randy Olaes, Frank Palermo, Tim Pattinson, Stephanie Pavela, Jen Revelli, David Rich, Benedicte Riis-Duryea, Cole Roberts, Rowan Roderick-jones, Reid Senescu, Keith Seymour, Darren Sri-tharan, Eron Sudhausen, Corrine Tan, Bryce Tanner, Chris Twinn, Sherry Ung, Elizabeth Valmont, Suresh Vemula, Noel Vivar, Cassie Waddell, Jake Wayne, Joy Wei, Michael Whiteman, Nathan Will, John Williams, Matthew Williamson, Armin Wolski, Dick Wong, Will Wong, James Woods, John Worley, Frances Yang*
Masterplanner: *William Rawn Associates*
Landscape architect: *PWP Landscape Architecture*
Utility: *Stanford University Utilities Division*
Permit Agency: *County of Santa Clara*
Contractors: *Turner Construction* and *Therma Corporation*.

> Collaboration is key to a successful project, particularly a project of the size and complexity of the Knight Management Center. The Arup team was a true partner throughout the design process, continually looking for ways to optimize the solutions and offering alternates to meet Stanford's sustainability goals. As the architect, we greatly appreciated Arup's integrated multi-disciplinary approach; it was extremely beneficial to the team's ability to meet GSB's expectations for this fast-track project.
>
> Stanley G Boles, FAIA, Design Principal, Boora Architects

Autoroute 30 extension: an introduction

Location
Montréal, Québec, Canada

Québec's Autoroute 30 (A30) was begun in 1968 as a new transport artery linking the communities along just over 100 miles (161km) of the south shore of the St Lawrence. After the construction of various sections, growing road congestion in and around Montréal led to the announcement in 2006 of the plan to complete the A30 as a southern bypass to the city.

Three consortia were shortlisted to design, build, operate and finance the CA$1bn project, and in June 2008 Nouvelle Autoroute 30, a consortium of Spanish contractors including Dragados and Acciona with Arup as its designer, was selected as the preferred bidder by the Ministry of Transport Québec.

The A30 Montreal project consists of 26 miles (42km) of highway, includes 31 bridges — two of them major crossings of the St Lawrence River and the Beauharnois Ship Canal — and a tunnel. Completed in December 2012, this was globally one of Arup's largest highway projects, with design input from offices in the US, UK, Europe and East Asia, and managed and delivered through an Arup team in Montreal working interactively with the contractor client.

Design and construction was divided into five separate sections:
(1) north of the St Lawrence River
(2) the St Lawrence River bridge
(3) the A30 and A530 Autoroutes on the Île de Salaberry
(4) the Beauharnois Canal bridge
(5) the Beauharnois Canal to Chateauguay.

1.

2.

Design started in September 2008 and was substantially complete in 2010, though additional design changes were incorporated subsequently. Construction began in May 2009, and Arup provided an audit service throughout construction.

The firm's design scope included all aspects of highway and bridge design, with the Montréal project management team liaising with external sub-consultants for local design support and some specialist studies.

Notable engineering design challenges included the significant loadings imposed by ship impact, seismicity, hydraulics, wind and ice, and the team found cost-effective solutions to satisfy all of these criteria. Despite the many changes in the design introduced during the construction phase, the project was delivered on time and within budget.

The next edition of *The Arup Journal* will contain a full study of Arup's design contribution to the successful completion of the Montréal bypass A30 extension.

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1. Location map.
2. Interchange under construction at the northern termination of the A30.
3. The Beauharnois Canal bridge.
4. Typical toll area.
5. Beneath the St Lawrence bridge.
6. Typical interchange bridge.

Image credits
1 *Nigel Whale*; 2 © *NA30 CJV;*
3-6 *Anthony C Branco*.

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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