The Arup Journal
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On 23 October 2018, Chinese President Xi Jinping opened the world’s longest sea crossing, the 55km Hong Kong-Zhuhai-Macao Bridge. Until then, travelling between Hong Kong and Macao/Zhuhai involved either a one-hour ferry ride (sometimes through bad weather conditions) or a four-hour detour over the Humen Bridge, a crossing to the north of the Pearl River Delta. With the opening of the HZMB, it is now possible to make the journey by car in a mere 40 minutes.

Arup performed a range of roles on the project, including creating and developing the concept and preliminary design for the main bridge and tunnel, and proposing environmentally friendly reclamation solutions for artificial island construction. Arup also worked on roads, tunnels, viaducts and other associated infrastructure.

Along the way, the firm had to be mindful of the scheme’s impact on the surrounding environment and wildlife, the effect of extreme weather conditions on the programme and design, and the logistical challenges of coordinating and completing such a large and ambitious scheme – the HZMB took nine years to construct.

Developing a Greater Bay Area
The HZMB is part of a broader effort by the Chinese government to improve connections between 11 cities on the Pearl River Delta: Hong Kong, Macao, Guangzhou, Shenzhen, Zhuhai, Foshan,
Two cable-stayed bridges cross over the last three channels. The total bridge length (including the three cable-stayed bridges and the shallow and deep water viaducts) is 22.9km. The crossing then reaches the artificial island where the Zhuhai and Macao HCFs are located.

In total, the crossing is 55km long — 29.6km for the main bridge and tunnel, a 13.4km link road between the first and second sections, and a 12km link road in Zhuhai territory and a 12km link road on the Chinese mainland side. The main bridge is a dual three-lane carriageway with hard shoulders (total width 33.1m), designed for a maximum speed of 100km/h. The tunnel under the Tonggu and Lingding navigation channels is made up of 33 tunnel elements, each measuring 180m x 38m x 11m.

A project of such significance had to be aesthetically pleasing from all vantage points, as well as structurally sound in the face of frequent typhoons that occur in the region. The design and construction needed to take environmental considerations into account, in particular the impact on the Chinese white dolphins that inhabit the waters along this route.

The bridge’s alignment was designed to ensure the least possible obstruction to the water flow, avoiding various site constraints, while also enhancing the views for bridge users. To achieve the latter, horizontal curves were added.

Arup designed a seismic protection system that satisfies the local codes of the three areas the bridge runs through. The frictional pendulum bearing absorbs the seismic energy in every bearing connection, thus isolating the seismic action from the foundation. The bridge decks are supported by single column piers with wide heads, and the bases are buried deep in the seabed. Single, rather than double, piers ensure that the dolphins’ habitat and the flow of water under the bridge experience minimal disruption. In mainland China, spans between piers are typically 90m, but to help preserve water quality by minimising the number of piers that needed to be built, the spans were designed to be 95m for the composite deck in the shallow water to the west side of the crossing and 110m for the steel deck in deeper water in the middle and on the eastern sides. At the crossing between Hong Kong International Airport and Lantau Island, the span between piers is typically set at 75m, and up to 180m for crossing navigation channels and the headland between Sha Lo Wan and San Shiek Wan.

This meant fewer piers overall, and therefore less disruption during construction. Precast concrete shell construction was adopted for the pile caps to reduce the amount of temporary works construction required, and therefore lessen the impact on the environment.

The main logistical challenge of this part of the project was that all construction needed to take place in the sea. This meant that the construction materials had to be delivered to the site by marine vessels, and made working with in-situ concrete difficult.

The solution was to precast as many of the...
elements required as possible, including the pile cap structures, piers and deck segments. A floating concrete batching plant was used to supply the in-situ concrete needed to construct the foundation piles.

**Hong Kong BCF**

On the Hong Kong side, Arup’s design included using a reclaimed area of 150ha to form an artificial island – 130ha to accommodate the Hong Kong BCF and 20ha for landfill of a connection road known as Tuen Mun–Chek Lap Kok Link (TMCLKL). Arup initially began working on this element of the project in 2006 by identifying the best possible site for the BCF. This area had to include clearance and transport facilities. Ultimately, it was decided that the BCF should be placed to the north-east of Hong Kong’s Airport Island (an artificial island linked to Lantau), at a point convenient for travellers arriving into or departing from Hong Kong by air. This choice of location also avoided the need to reclaim land near the major sea channel to the north of the airport.

A particularly innovative element of the project was the development of an environmentally friendly non-dredged method of reclamation and seawall construction to create the artificial island for the Hong Kong BCF and the TMCLKL. This was the first time this method was used in Hong Kong. Typically, land reclamation projects such as this involve fully dredging the mud from the seabed and then laying down fill materials. Hong Kong’s waters are full of sediment, which traps a lot of water, and so is not easy to squeeze dry for consolidation. This full dredging method is relatively quick, but it would have required a large amount of filler materials to replace the dredged mud. Moreover, when sediment is dredged, it then has to be disposed of in sea-based mud pits, a challenge complicated by the fact that much of this sediment can be contaminated. There was no space in Hong Kong for a new mud pit, so Arup developed a method for constructing the seawall for the land reclamation without dredging.

Building on the firm’s experience in ground treatment methods and seawall building techniques, Arup developed two types of non-dredged seawall: a composite steel cell and rubble mound seawall, and a simple rubble mound seawall. For both types, the design solution required treatment using stone columns – 53,000 in total, each 1m in diameter – inserted into the soil to create a drainage path for water in the soft sediment to dissipate. These were compacted-gravel piles, installed using a vibratory method of construction.

On the composite section of the seawall, 85 circular cells, each 32m in diameter and formed by 200 straight steel sheets, were driven through the soft marine sediment layer down to the underlying alluvial layer to form cofferdams. These cofferdams were linked by two steel arcs made of similar steel sheet piles segments. These were backfilled to form a robust structure without the need for dredging. Although cellular structures on a similar scale have been used elsewhere, few have been used with the kind of deep, soft soils encountered on this project. This innovative design meant that the soft marine sediment on the seabed could be left untouched. The reduction in construction work meant there was less impact on water quality and less disruption to the marine habitat, because of reduction of marine traffic volume during construction (which was cut by half) and the reduction in suspended particles in the sea by 70%. The non-dredged process significantly reduced adverse impacts on the environment.

The completed reclamation was tested by two severe typhoons that hit the area before the BCF became operational. Both the seawall and land reclamation remained intact under these conditions.

**Hong Kong Link Road**

Arup conducted the feasibility study, preliminary and reference design, contract procurement and construction supervision for the Hong Kong Link Road. This is a dual three-lane highway connecting the HZMB with the Hong Kong BCF. It comprises a 9.4km bridge section, a 1km tunnel section through Scenic Hill and a 1.6km at-grade section on reclaimed land at the east coast of Airport Island. The alignment is curved, as the bridge had to avoid various site constraints, in particular the airport facilities, operational requirements and developments. Moreover, the airport is developing a third runway to the northern side of the island, so infringing on this space was not an option. Placing the Hong Kong Link Road on Lantau Island was also out of the question, as this is an area of forests and natural beauty and is of great ecological value. Arup designed the road to run along the narrow marine channel south of Airport Island and north of Lantau Island before reaching the BCF, with construction beginning on this phase of the project in 2012.

The bridge section is made up of more than 5,700 precast bridge deck segments, arranged in 315 spans. The viaduct features long spans crossing two navigation channels and the headland between Shu Lo Wan and San Shek Wan. This area of headland is a designated site of archaeological interest, so to avoid negative environmental impacts on this zone, no bridge pier or additional construction works were proposed in this area. A special lifting frame was used for installation of the deck segments for this span.

On the western side, where it faces open water, the viaduct spans are typically 75m. The western navigation channel has three 150m spans to allow two separate one-way navigation channels for shipping below the bridge deck. At the southern side, the viaducts run inside the channel between Airport Island and Lantau with spans in excess of 100m to minimise the number of piers and reduce hydrodynamic impact to the water channel. The span length is extended to 180m for crossing the navigation channel and the headland. These long spans were a particular challenge. The team considered various options for the design. A cable-stayed bridge was not viable because of the height restrictions imposed by the airport, and a composite steel and concrete deck was rejected for cost, maintenance and aesthetic reasons. Precast concrete segments were ultimately used – this was the longest span of this type of bridge in Hong Kong at completion.
Of the 725 piles used for this section of the project, 65 are on land (with a diameter of 2.8m) and the remaining 660 are at sea, and have diameters of 2.3m, 2.5m or 2.8m. The piles range from 7m to 107m in length.

Part of the link road is tunnelled, minimising the visual impact for local residents. It runs through Scenic Hill, under both the Airport Express railway and the Airport Road. Different construction methods were used for different sections of the tunnel. Drill and blast was utilised at Scenic Hill where the rock was particularly hard; mining techniques were used underneath Airport Road where the flow of traffic to the airport needed to be maintained during tunnelling; whole tunnel box jacking – a controlled shallow underground excavation process that causes minimal disruption – was used under the railway where there were railway tracks with stringent settlement requirements to be adhered to; and an open cut-and-cover method was used in the new reclamation area where there were fewer constraints.

When carrying out the box jacking, the team came up against extremely hard bedrock that had to be excavated manually, as blasting was not an option for the section underneath the railway. An additional smaller tunnel was excavated inside the main tunnel, using round-the-clock construction, to increase the rock excavation faces and accelerate the overall rock excavation. This was done at the same time as the box jacking on the other side, so the work could progress as efficiently as possible.

A new road was also required to accommodate the anticipated rise in traffic between Lantau Island and the North-West New Territories, a region of new towns and development in Hong Kong, which will also serve as an alternative route to the airport. The proposal was for this link road to start at the North Lantau Highway at Tai Ho, before running through the Hong Kong BCF. The road then travels northwards in tunnel form to connect to the existing Lung Mun Road in Tuen Mun and the future Tuen Mun Western Bypass.

Arup was one of the designers for the contractor of the southern section of the TMCLKL, which comprises about 9km of elevated viaducts. The southern connection between Lantau Island and the BCF artificial island travels over 2km of water. The section that travels over land passes over existing railway lines at skewed angles, requiring spans of up to 100m. The viaduct structures were designed as prestressed concrete girders, which were constructed using the precast segmental method. The southern connection viaduct was designed with a seagull theme: the supporting piers over the water are shaped like the maritime birds, with the span lengths gradually increasing from the Lantau shore towards the Hong Kong BCF to imitate seagulls flying over the sea. The longest span is 200m where the viaduct spans the Tung Chung navigation channel.

The northern section is 5km in length and includes a sub-sea twin-bore tunnel between the BCF and landfall at Tuen Mun. Typically 14m in diameter and reaching depths of up to 60m below ground level, each tunnel accommodates two lanes of traffic. They were originally designed to connect with traditional cut-and-cover launch and reception shafts at either end within the newly formed reclamation. However, to speed up construction, the contractor’s design team modified the tunnel design at the northern landfall by shifting the launch shaft 400m further north. This replaced the deepest section of cut-and-cover structure by extending the bored tunnel, significantly reducing the amount of excavation and lateral support works required at this location. The exit tunnel, which included an additional climbing lane, was formed using the world’s largest tunnel boring machine (TBM), which is 17.6m in diameter. To create a large enough shaft to launch the TBM (which required clear headroom of 20m), Arup designed a bespoke caterpillar

9: The Hong Kong Link Road was a complex part of the project, due to the geography of the area and various design constraints
10: To avoid any construction footprint in an area of archaeological interest at Sha Lo Wan Headland, a special segment lifting frame was used to install the bridge deck segments
11: At Scenic Hill, whole tunnel box jacking was used where the tunnel went under railway tracks, as there were stringent settlement requirements in this area
12: The southern section of the TMCLKL travels over 2km of water between Lantau Island and the Hong Kong BCF
HZMB | HONG KONG, ZHUHAI, MACAO, GREATER CHINA

Management
A project of this scale presented major challenges when it came to management and logistics. Arup appointed a core management team to focus on issues such as risk management, procurement, coordination, cost control, planning reviews, handling vast amounts of documents, interfaces and resources, and conducting quality assurance.

It was crucial to have a project and design review before every milestone, to make sure everything was on the right track. A review panel was set up and the budgets were assessed and refined to achieve the most cost-effective solutions. Arup’s highly collaborative approach – bringing a broad range of disciplines and stakeholders on board – created a working environment that supported shared thinking, knowledge exchange and critical review, leading to a design that was best tailored to the client and the region’s needs.

Increased connectivity
The HZMB provides the shortest link between Hong Kong, Macao and the western Pearl River Delta region. The connection between Hong Kong, Macao and Zhuhai has been greatly improved, significantly cutting the time it takes for people and cargo to travel across the bay.

With Hong Kong a well-known financial centre, Macao a major tourist destination, and abundant development opportunities in the Pearl River Delta and the Greater Bay Area, the whole area is experiencing considerable growth. The HZMB will encourage the connection of people and developments in this area. Being an impressive structure in its own right, the bridge is also a tourist attraction, providing magnificent views. It is hoped that this ambitious project will be the catalyst for further growth and integration for the area for years to come.

1. Zun Zhi Kite in Arup’s East Asia region highways business director. He is an Associate Director in the Hong Kong office.

2. Samuel Kwan was the Project Manager for the TMCLX southern viaduct section and the deputy Project Manager for the Hong Kong Link Road. He is an Associate Director in the Hong Kong office.

3. David Pegg was the Project Director for the TMCLX southern viaduct section and a Director in the Hong Kong office.

4. James Sze led the infrastructure team on the detailed design for the man-made island for the HZMB. He is a Director in the Hong Kong office.

5. Peter Thompson was the Project Manager for the twin-bore tunnel section of the TMCLX. He is a Director in the Hong Kong office.

6. Fergal Whyte was the Project Director for the HMAB main bridge and the HZMB bridge. He is a Director in the Hong Kong office and a member of the Arup Group Board.

7. Philip Wong was the Project Director for the Macao Link Road and the Project Manager for the Macao BCF. He is a Director in the Macao office.

8. Nga Yeung worked on the HZMB main bridge and is an Associate Director in the Hong Kong office.

9. Arup technical services:

Hong Kong
- Hong Kong BCF Reclamation: Feasibility Study, Overall Planning, Environmental Impact Assessment, Preliminary and Detailed Design, Construction Contract Procurement and Supervision
- Hong Kong: Feasibility Study, Overall Planning, Environmental Impact Assessment, Preliminary Design
- Hong Kong Link Road: Feasibility Study, Overall Planning, Environmental Impact Assessment, Preliminary and Detailed Design, Construction Contract Procurement and Supervision
- TMCLX: Feasibility Study, Detailed Design

Macao
- Macao BCF Infrastructure: Overall Planning, Preliminary and Detailed Design
- Macao Link Road: Detailed Design

HZMB Main Bridge Preliminary Design

Arup developed the caterpillar diaphragm wall cofferdam, creating sufficient unobstructed space to launch the world’s largest tunnel boring machine (TBM) and the world’s largest composite diaphragm wall cofferdam – the first of its kind used in Hong Kong. This cofferdam comprised a series of circular interconnected cells that formed an unobstructed strut-free excavation area by making use of hoop struts within the diaphragm walls to maintain lateral stability.

The twin-bored tunnels are connected by cross-passages at 100m intervals that serve in case of escape and allow alignment, design between the tunnels during an emergency. The original design had the mechanical and electrical (M&E) equipment required for tunnel-operation located in every alternate cross-passage. This would have resulted in two different cross-passage sizes, one with a larger diameter to facilitate the equipment rooms and the escape passageways. To avoid any construction, Arup modified the design to relocate the M&E equipment. By making use of the void space created by the circular tunnel form, the equipment was placed within a service gallery in the carriageway inside the main tunnel with M&E islands every 200m. This allowed all the cross-passage sizes to be the same smaller size, facilitating easier operation and maintenance by providing a separate corridor for maintenance purposes only.

A mini-TBM was used to construct the cross-passages, rather than mined tunnels (traditionally used for sub-sea tunnels). In Hong Kong to use a mini-TBM for cross-passage construction.

HZMB Main Bridge Preliminary Design

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HZMB Main Bridge Preliminary Design
Building BLOX

BLOX has helped reconnect a section of Copenhagen’s waterfront with the city by redeveloping a decades-old derelict site and turning it into a lively urban creative hub and public space.

Authors Michael Bradbury and Chris Carroll

Located in a prime section of Copenhagen’s harbour area, BLOX is a six-storey mixed-use building that is part of an exciting waterfront regeneration in the city. The 27,000m² venue is the new home for the Danish Architecture Center (DAC) and BLOXHUB, a new creative workspace initiative for companies, research institutions and organisations involved in sustainable urban development.

The building features an auditorium, exhibition spaces, cafés and offices, as well as 22 apartments across the top floors, and recreational indoor and outdoor areas. These differing spaces are arranged as a series of stacked cubes that form a terraced landscape, with sensitively.

Working in close collaboration with the Office for Metropolitan Architecture (OMA), Arup’s engineering expertise helped shape a complex regeneration project that overcame the constraints that challenged the viability of the site for development. BLOX spans over and under the busy Christians Brygge ring road, with the site perimeter framed on two sides by the city’s harbour wall and the Frederiksholms canal. Located close to a series of historic buildings, the ground works in particular had to be dealt with sensitively.

Arup provided structural, building services and façade engineering; sustainability consultancy services; ICT and AV; vertical transport; security; and daylighting, from inception to detailed design. The firm produced design solutions for and provided input on topics including energy efficiency, carbon neutrality, materials and embodied carbon. Arup also sought to address socioeconomic issues.

Site development

Philanthropic association Realdania invested in BLOX to help regenerate this section of the waterfront and strengthen the connection between the inner city and the harbour. Originally, the site was home to the royal brewery, Kongens Bryghus. The buildings were demolished after a fire in the 1960s.

Its location, locked in by the harbour and canal, with a busy arterial road bisecting the site, presented considerable challenges for development. Most recently, the site included a 350-space street-level car park and a small children’s playground.

Structural frame

Arup worked closely with OMA to rationalise the structural layout so that it would support the series of stacked volumes within the building. The staggered pattern that forms the building’s terraced landscape shape, the road through the building and the deep basement car park all put considerable constraints on where columns could be located and how loads could be transferred down to the foundations.

With a conventional grid structure not feasible because of the overlapping volumes and column-free spaces required, Arup developed a scheme comprising an interconnected system of transfer structures. By using a number of interventions such as downdstand beams, trusses and hangers, an initial 48 truss solution was developed. With a working scheme in place, the challenge was to reduce the number of trusses to ensure construction viability and improve efficiency.

Through further detailed design and rationalisation, the grid was re-aligned and the trusses optimised, with Arup’s final scheme an interconnected framework of 18 steel trusses that typically span 30m. They include a number of one- and two-storey deep trusses with depths varying from 2.4m to 6.4m. These create large column-free spaces within the building and also bridge over the road.

The structural frame comprises steel beams and columns with precast concrete floor planks. The structural floor plate depth is typically 480mm, with the beams located within the depth of the planks to reduce the overall floor volume. The planks in the offices were grouted together without the need for a structural screed topping.

Due to the complex interface between the trusses, Arup’s structural team devised a construction sequence in collaboration with the main contractor, Züblin. To determine the stresses that would build up in the steel frame during its assembly, Arup created a digital model of the construction sequence.

With the transfer structures and complicated load paths, it was crucial that deflections were controlled as stresses became locked in while...
8. Careful construction sequencing was required, as only very limited closures of the Christians Brygge road were allowed.

9. Ground anchors were removed. A temporary berm was placed in the water in front of the existing harbour during the construction sequence, a berm was placed as part of the construction sequence and temporary propping arrangements, with a number of trusses fabricated with pre-cambers to take into account deflections.

Arup adopted 3D design from the start. This was crucial in dealing with the complexity of the layout and building services. The design team was commissioned during construction to produce an integrated BIM model that was issued to the client and their facilities management team for use after handover.

10. Bridging over and under the road
One of the key elements to developing the site was to design a scheme that could span over and under the ring road, allowing pedestrians access to the harbour without having to cross a road that is used by more than 25,000 vehicles a day.

Traffic on Christians Brygge crosses the site supported on a section of the building’s ground floor slab. To ensure this traffic does not cause noise or vibration issues within the building, 575mm deep prestressed concrete bridge beams with a 75mm concrete topping span across isolating bearings on the supporting walls and a spine beam. Careful sequencing was required during construction, as only very limited road closures were allowed by the local authority. Prior to the trusses that span above the road being erected during overnight road closures, a crash deck was built over the road to protect vehicles.

The basement is 16m below ground at its deepest and required excavation adjacent to the harbour, canal walls and a number of historic buildings founded on timber piles. A detailed basement construction sequence and de-watering process were implemented to ensure construction did not adversely affect these buildings.

The automated car parking facility was designed to maximise the number of vehicles entering the city centre just north of BLOX. The three-storey underground parking facility can handle up to 180 cars an hour.

11. An assessment was made of footfall-induced vibrations that could occur from the exhibition floor to ensure vibration transfer did not adversely affect the other areas of the building. Arup’s footfall analysis showed the typical accelerations were within acceptable limits.

**Exhibition floor**

The main exhibition floor’s structural depth is 2m, with the floor at this level spanning almost 24m over the road. This span is achieved with a 1.6m deep plate girder, supported on steel columns. A reinforced concrete structural topping to the precast concrete floor increases the structural mass for acoustic attenuation, although it is also beneficial for the floor’s dynamic performance.

**Automated car parking**

In the basement there is a fully automated 350-space public car park. It was a local authority requirement to retain parking on the site and minimise the number of vehicles entering the city centre just north of BLOX. The three-storey underground parking facility can handle up to 180 cars an hour.

Using an automated car stacker system has significantly lessened the space requirements within the basement compared with a more traditional car park. This reduced the volume of excavation required, simplified basement construction around the road and minimised the required air handling systems. Car engines are switched off as vehicles are delivered and returned to the stacked parking bays via the horizontal and vertical stacker systems, keeping exhaust fumes to a minimum.

Ambitious sustainability targets were set to address all aspects of the design, construction and operation of the building. This included reducing energy demand by 50% compared with local regulations. BLOX achieves the Low Energy Class rating, with primary energy usage of under 40 kWh/m²/year. This meets the LE2015 energy target under Danish regulations.

The desire to create an energy-efficient building significantly influenced Arup’s building services design. The building is served by Copenhagen’s district heating system, and the city’s district cooling system was extended towards the site. The system is based on seawater cooling and the use of residual heat from electricity generation.

In addition to meeting the LE2015 energy target, other key sustainability strategies include:

- **Solar photovoltaic panels at roof level**, which produce 145,000 kWh/year;
- **use of lower emission heating, cooling and ventilation systems**;
- **a full materials assessment, screening all main materials for embodied carbon, life cycle and recylcability**;
- **Arup’s Sustainable Project Appraisal Routine (SPeAR)** was used to track the sustainability elements and help make important decisions during the design process.
BLOX is made up of a series of stacked volumes designed to provide a visually striking landmark in the Danish capital. The building draws in visitors and is a landmark publicly orientated mixed-use development promoting social integration, as well as improved local amenities and activation of public spaces.

The mechanical services required careful design to manage the variety of uses for the different spaces within the building. The layout is predominantly office space around the building’s perimeter, with the large DAC exhibition space, auditorium and conference facilities located at the centre of the building. The ground floor includes a gym, restaurant and some retail areas. Along with the basement car park, each of these areas have different drivers and requirements from a comfort and occupancy level.

Plant and building services

The mixed-use nature of the building, and the constraints of the road, meant that locating plant and developing the building services distribution strategies were critical to overall space planning and developing an efficient floor plate. Plant areas were located in various parts of the building. The basement has the main connections to the district heating and cooling, along with a ventilation plant that serves the basement and the restaurant areas. Additional plant is located under the auditorium, with smaller plant areas serving the offices and apartments.

With quite a deep plan for the building, chilled ceilings were used in the majority of areas for cooling, with fresh air provided through the floor (along with distribution for power and data). Chilled beams were used around the perimeter to provide additional cooling at the facade.

The main exhibition space uses displacement vents to distribute air, with sidewall displacement vents used in the auditorium. The restaurant and office areas have their own dedicated systems.

Detailed thermal analysis was key to achieving a naturally ventilated and highly insulated facade. The performance of the façade required careful consideration in order to achieve the correct level of light transmission into the building to meet required lighting levels under Danish regulations, while also maintaining the appropriate U-value (thermal) and G-value (solar gain). Eight façade configurations were assessed across criteria including energy, daylight, cost, maintenance and aesthetics to determine the preferred option.

Authors

Michael Bradbury was the Project Manager and lead building services engineer. He is an Associate Director in the London office.

Chris Carroll was the Project Director. He is a Director in the London office.

Project credits

Client Relations

Architect OMA

Local architect CF Møller

Traffic, environmental issues, fire, risk analyses and local engineer of record COWI

Contractor Züblin

Structural, building services and façade engineering, and sustainability consultancy services, ICT and AD, vertical transport, security, daylighting Arup

Yannic Alm, Francis Archer, Marcus Andriasso, Bita Baraj, Jonathan Ben-Ami, Daniel Bergsager, Michael Bingham, Kimberly Blackmore, Philip Bogan, Michael Bradbury, Alexa Brown, Emma Brunton-Freed, George Buffon, Chris Burgess, Tony Campbell, Stuart Carey, Chris Carroll, Andrew Charlton, Mark Chen, Anna Coppell, Dominic Coyle, James Dare, Ria Dela Cruz, Andrew Duncan, Russell Fraser, Lesley Gale, Kieran Giblin, Andrew Grant, Duncan Gray, Ning He, John Heath, Stuart Hitchcock, Ed Hoare, Christina Hisah, Dan Ingali, Craig Irvine, Ben Jones, Ben Kappara, Ani Kardous, Kevin Kwan, Amy Leitch, Ben Lewis, Roland Li, Alexander Lindsey-Behunu, Di Lu, Ian Lockwood, Georgina Lockwood, Paul Lynch, Mari Mannikunan, Adam Martin, Nina McClennon, Ben Moss, Shyota Okke, Julian Oley, Jean Peres, Dean Payne, David Peru, Stuart Pennington, Clare Perkins, Dan Poole, Tony Pulfer, Roi Quid, Milad Ragip, Vincenzo Reale, Tony Ricciolo, Amelie Rushford, Anokhi Shah, Amy Shan, Jamie Sheawan, Tanis Smith, Julian Sutherland, Mark Thomas, Multu Uncuocu, Nick Unsworth, Manja Van De Werp, John Varniers, James Whelan, Robin Wilkinson, Giovanni Zemella.

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17: Camilla Hylæsberg

Ove Arup exhibition

From October 2018 to February 2019, the Danish Architecture Center hosted an exhibition on Ove Arup that celebrated the pioneering work and ongoing legacy of the Anglo-Danish engineer and designer.

The exhibition, ‘Ove Arup and the Philosophy of Total Design’, was first shown at the Victoria and Albert (V&A) Museum, London, in 2016 and provided an overview of Ove Arup’s vision of ‘Total Design’. The exhibition revealed Arup’s collaborative approach to problem-solving in the built environment by harnessing the creativity and technical prowess of engineers, architects, urban planners, designers, consultants and technical specialists.

The exhibition featured archival materials from iconic projects such as the Sydney Opera House and the Centre Pompidou in Paris. Also displayed were digital exhibits featuring simulations and augmented reality that captured some of the most innovative infrastructure projects Arup has contributed to in recent times. They included a specially commissioned immersive installation about the Thames Bridge and a recreated Arup SoundLab® presenting a range of acoustic studies, including of the BLOX building and Copenhagen city.

15: Arup used its Sustainable Project Appraisal Routine (SPeAR) to track sustainability throughout the project
16: BLOX has helped to transform a previously neglected section of Copenhagen’s waterfront
17: ‘Ove Arup and the Philosophy of Total Design’ exhibition
Driving sustainability

Total design used to create a showcase for sustainability in a flexible highly automated manufacturing facility

Authors: Mark Bartlett, James Finestone, Philip Hives, Sean Macintosh, Timothy Snelson, David Storer

JAGUAR LAND ROVER ENGINE MANUFACTURING CENTRE / WOLVERHAMPTON, UK

By providing an appealing, environmentally controlled working environment, Arup created a facility centred around worker wellbeing. Arup designed the building so there are visual connections between the different areas, breaking down the barriers between factory floor and administration areas and making as much use as possible of natural light. The traditional factory north-light windows at roof level are complemented by 2m high windows at ground level. These bring daylight deep into the production areas and provide views of the external landscaped areas.

The focus on a low-carbon strategy meant a wide range of sustainable features were incorporated within the facility. These include the largest roof-mounted photovoltaic (PV) array in the UK; transpired solar collector cladding; solar panels for heating domestic hot water; natural ventilation; displacement ventilation to provide cooling; lighting control with daylight dimming; variable speed drives to minimise pump and fan power consumption; heat recovery on air handling units (AHUs); grey water recycling; and storm water attenuation.

The first phase of the facility was handed over just 24 months after the design team appointment. The next two phases followed in a continuous sequence from 2013 to 2017. Arup provided architecture, transport planning, environmental engineering, landscaping and access advice for the first two phases, together with civil, structural, geotechnical, fire and building services engineering for all three phases.
The Arup Journal

Layout
Arup developed the overall facility layout in conjunction with Jaguar Land Rover by mapping out the engine manufacturing process including equipment, people, materials, waste and transport movements. The first two phases of the project incorporated three linked, rectangular buildings. Efficiency in configuration coupled with future building flexibility underpinned the layout of the large factory halls (machine and assembly halls) and the connecting smaller two-storey staff support buildings.

The architectural form of the facility – with the saw-tooth roof profile commonly used on warehouses and factories around Wolverhampton – helped with the engineering solution. The north-lights allow diffused natural light into the building but limit heat gain. The south-facing elements of the roof, set at a 30° angle, are used to support the large PV array. The underside of the roof provides the primary route for distribution of services at high level, minimising the requirement for service runs in the floor slab and maximising production flexibility in the factory for future changes.

Site works and foundations
Following an enabling works package that included soil/cement ground stabilisation, Arup was able to design straightforward foundations with pad footings and ground-bearing concrete slabs. Steel-fibre-reinforced concrete slabs, ranging between 250mm and 350mm thick, are used in the factory halls and were designed to provide flexibility for equipment layout. In the staff support buildings, which have lower levels of loading, mesh-reinforced concrete slabs, ranging between 150mm and 175mm thick, are used. The site incorporates an extensive sustainable drainage system, featuring porous paving, swales and storm water attenuation ponds that control discharge to the surface water system.

Factory frame
The factory halls are based on a single-storey braced frame, supporting multi-span mono-pitched roofs, with trusses designed for multi-bay continuity. The north-lights are formed using steelwork trusses that span 30m. In the machine hall, the grid is 30m by 15m, with a 30m by 30m grid in the assembly halls. This arrangement facilitates the production areas currently required by the client, giving clear spans without compromising the quantity of services the roof can support. The bracing is kept at the perimeter, which allows for the subdivision of bays and means the assembly lines can be reconfigured if required in future. Arup developed a loading manual for Jaguar Land Rover that sets out the design load locations and magnitudes.

In designing the roof trusses, Arup took the structural analysis output and, using automated member utilisation checks, optimised all the truss members. The wind analysis carried out on the roof took into account the roof’s specific geometry and peak wind direction for the site, allowing uplift loads on the roof to be reduced by up to 70% for the majority of the surface area. These design processes resulted in significant savings, minimising the steelwork roof tonnage.

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Total design
Arup applied its total design philosophy to deliver technically creative and sustainable solutions at speed. Innovation, collaboration and worker wellbeing is at the heart of the success of this facility, which has won numerous awards.

2018
Structural Steel Design Awards: Winner, Project of the Year
World Architecture Awards: Shortlisted, Production Energy and Recycling Category

2017
CBISSE Building Performance Awards: Winner, Project of the Year
Royal Institute of British Architects Awards: Winner, West Midlands Sustainable Award and Regional Award

2014
Royal Institution of Chartered Surveyors National Awards: Regeneration Project of the Year

Renewable energy
As part of an initial energy study, Arup identified the potential for significant carbon savings by using a roof-mounted PV array and solar thermal installation on the façade. More than 21,000 PV panels were installed on the south-facing areas of the roof. These provide over 5.3MW of power – equivalent to 30% of the facility’s energy requirements – and reduce the factory’s carbon footprint by at least 2,400 tonnes per year. Further power is supplied via a ground-mounted PV array, added as part of the most recent phase of works. Solar thermal panels also provide heating for domestic hot water.

Solar cladding
The factory features a transpired solar collector cladding system, which is used to preheat the supply air to the staff changing facility. Used on the south-facing façade of the staff support building, the outer steel layer of the system is a dark perforated profiled steel sheet. It is separated from the inner insulated layer by an air cavity. Solar energy warms the perforated steel skin and the air in the cavity, and a fan at high level draws the warm air out. This preheated air feeds the AHUs in these areas, reducing energy consumption and providing significant carbon savings.

This Colourspace Renew SC cladding system, developed by Tata Steel and the University of Swansea’s Innovation Centre, heats 5m² of supply air, producing carbon savings of 1 tonne per 5m² of solar collector. The system has also been used on the third phase of the project.

Dynamometers
As part of the engine testing regime, a sample of engines produced at the factory are tested using dynamometers. Arup worked with Jaguar Land Rover to design the system that takes the energy generated during testing and feeds it back into the building’s energy distribution system.

Heating and cooling
The machine hall is heated from an all-air system with the heating diffusers located 3m above the factory floor. Six AHUs supply 85m²/s of air to the space. This volume of air is required to maintain a 20°C temperature in the machine hall, and also to provide make-up air to supplement the extract system that removes the oil mist created during the engine manufacturing process. Fresh air, with 0.25 air changes per hour, is also fed into the machine hall for staff comfort levels. During the winter months, the manufacturing equipment in the machine hall provides heat to the space, with gas-fired AHUs providing top-up heat as required. In the summer, vents in the north-light windows can be opened to expel hot air, helping to reduce extract energy.

The assembly halls are heated and cooled using a displacement ventilation system, with five AHUs supplying 71m³/s of air. To maximise the facility’s future flexibility and adaptability in relocating process plant and layouts, the displacement terminals are located 3m above floor level. To reduce airborne contamination within the machine and assembly halls, the supply air is filtered through class F9 filters – the level below a cleanroom environment.

A gas-fired heating system, rather than a more traditional water-based system, was used to serve the production halls. A water-based system would have had the potential for significant heat and pumping losses due to the length of the pipe runs required for a facility of this size. The gas heating system overcame this issue, particularly as the gas distribution system was already required to serve process equipment.

Where possible, high-level services were supplied using modular technology. Arup’s detailed design allowed for modules to be manufactured off-site to facilitate a quick and safe installation on-site. This method allowed for factory inspections prior to delivery on-site, and also reduced the amount of work required to be carried out at height.

Energy monitoring
Arup developed an energy management system in conjunction with Jaguar Land Rover to allow the client to monitor building energy consumption and energy used in each process of engine production. The system design included the communication infrastructure for the process equipment to support Industry 4.0 implementation, as well as the metering and monitoring mechanisms for all the building utilizes. Arup’s Building Performance and Systems team were commissioned after handover to carry out monitoring of the energy performance in the operational building and collate feedback from users. This work identified opportunities to reduce further electricity and gas consumption.

Digital design
The structural steel frame design was highly automated. Optimisation of design input to
Arup’s design of the staff support areas provides a working environment that brings people together through highlighting visual transparency and social spaces. Drawing on decades of experience in the design of industrial buildings, Arup reinterpreted the traditional factory form to deliver a functional, flexible and sustainable facility.


Authors
Mark Bartlett was the lead electrical engineer and the Project Manager for the third phase of the development. He is an Associate Director in Arup’s Midlands Campus in the UK.

James Finestone was the Project Director for the first phase of the development. He is Arup’s Europe region leader for architecture and is based in the Milan office.

Philip Hines was the lead mechanical engineer and Project Manager for the second phase of the development. He is an Associate Director in Arup’s Midlands Campus in the UK.

Sean Macintosh is a Senior Architect in the London office.

Timothy Smoilen was the lead structural engineer and Project Manager for the first phase of the development. He is an Associate Director in the London office.

David Storer was the Project Director for the second and third phases of the development. He is a Director based in Arup’s Midlands Campus in the UK.

Project credits
Client Jaguar Land Rover Ltd
Project manager Scafe
Quantity surveyor [KCCM – formerly Davis Langdon]
Main contractor Interserve Construction Ltd (Phase 1 and 2); Vinci (Phase 3)

Duration
The project was delivered over a period of 5 years from procurement to completion.

Scope
The project involved the design and construction of a new factory facility for Jaguar Land Rover (JLR Lichfield). The facility includes a sustainable factory expansion that is reinterpreted to deliver a functional, flexible and sustainable facility.

Architectural and Engineering Services
- Architecture: transport planning, environmental landscaping, and access advice (Phase 1 and 2)
- Civil, structural, geotechnical, security, sustainability, fire and building services engineering (for all three phases)

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the analysis models was driven from spreadsheets, to minimise the risk of manual input errors. Subsequent results from the analysis were post-processed through spreadsheets for utilisation checks. Designing in this digital environment allowed changes to be incorporated into the design as the client updated their manufacturing requirements during the design process. The structural model was produced directly from the analysis model and exported to Tekla software for production of the fabrication drawings, thereby saving the steelwork fabricator significant modelling time.

The complete building was modelled in BIM. At construction stage, Arup carried out BIM management services on behalf of the main contractor, Interserve. The subcontractors’ work was coordinated throughout the delivery of the project, and also with the fit-out requirements of the highly specialised robotics used for engine manufacturing (which were designed by PowerTrain for Jaguar Land Rover). The design model was integrated with the process and equipment model. This allowed coordination of process machinery and services, along with the building services and structural frame. The fully integrated model was issued as part of the completed project’s operation and maintenance manual and included specification and data tagging of equipment and services for post-occupancy. This ensured the client’s facilities management team could utilise all the design information embedded within the model.

As the manufacturing process changed during the design phase, the digital design elements were used to take in those changes to minimise the potential of any delay. For example, when another 30m bay was added to the building, the automated work flow enabled the design checks to be carried out quickly. The models were updated to reuse already manufactured steel, and the new bay was inserted as the penultimate bay.
A dramatic refresh of Seattle’s Space Needle

The use of cutting-edge techniques in the renovation of Seattle’s most iconic structure has readied it for the next 50 years of its life, and means that the original concept for the Space Needle has finally been achieved.

Authors Peter Alsopach, Clayton Binkley, David Okada, Kristen Strobel, Cress Wakefield

The Space Needle was built for the 1962 World’s Fair and stands 605ft (184m) above the city. It is the globally recognised symbol of Seattle and attracts more than 1.2 million visitors per year. The Space Needle Corporation engaged architectural firm Olson Kundig to help them create a new vision that would preserve the building’s historic exterior while revolutionising the guest experience and clarifying the original conceptual design vision. Arup collaborated closely with the architects on the renovation, designing a seismic retrofit, accessibility upgrade and modernisation of building services. The firm provided structural, mechanical, electrical and plumbing engineering, as well as building physics and fire consulting.

A landmark on the Seattle skyline, the Space Needle was an important part of the 1962 World’s Fair. It is the globally recognised symbol of Seattle and attracts more than 1.2 million visitors per year. The Space Needle Corporation engaged architectural firm Olson Kundig to help them create a new vision that would preserve the building’s historic exterior while revolutionising the guest experience and clarifying the original conceptual design vision. Arup collaborated closely with the architects on the renovation, designing a seismic retrofit, accessibility upgrade and modernisation of building services. The firm provided structural, mechanical, electrical and plumbing engineering, as well as building physics and fire consulting.

The Space Needle structure consists of three main components – the Pavilion Level at its base, the Skyline Level at 100ft, and the iconic ‘Atmos’ 500ft above the Seattle streetscape. Within the Atmos, the guest experience is focused on two main areas: the 520ft level that includes the exterior observation deck and the 500ft level featuring ‘The Loupe’ – the world’s first and only open sky observation deck. The top chord of 15 of the 48 radial trusses supporting the exterior skin – Olson Kundig wanted an open plan with as few obstructions as possible between guests’ first steps from the elevator and the expansive skyline view. This inside-out transparency was a major driver for the building services modifications throughout the Atmos. One of the most impactful components was a tightly coordinated reroute of the kitchen exhaust ducts from their vertical path through the observation level space to a more hidden vertical course near the core.

At the exterior, the knee-high wall and wire caging at the edge of the observation deck were replaced with new glazed barriers and integrated bench seating. The modifications required retrofit work at each of the 48 existing radial trusses that support the observation deck. The top chord of 15 of the existing trusses was removed and lowered to allow for the new staircases and lift pit. Arup designed the retrofits to be installed without the need for shoring. This allowed the contractor to modify the trusses, while thegeneral contractor, Hoffman Construction, worked around the clock on a tight schedule that avoided the peak tourist season. The Atmos stayed open to the public throughout. This 11-month period required constant communication and collaboration between the owner, contractor and design team. Arup provided on-call support to the contractor that at times included three-shift support for the 24-hour construction period.

The Space Needle renovation facts

<table>
<thead>
<tr>
<th>Space Needle renovation facts</th>
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<tr>
<td>605 Height of the Space Needle, in feet</td>
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<tr>
<td>1,300,000 Visitors to the Space Needle each year</td>
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<tr>
<td>176 US tons of glass used in the renovation</td>
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<td>196 Percent increase in the amount of glass installed at the Space Needle</td>
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<td>360 Degrees of uninterrupted views of the Puget Sound region</td>
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<td>50 Experts from around the world to advise on the renovation</td>
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<td>500 Workers involved in the renovation</td>
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<td>100,000,000 Dollars spent on the first phase of the renovation</td>
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520ft level

The work at the 520ft level included installing new stairs, an accessible lift and increased interior glazing, as well as the replacement of the exterior safety barriers at the external deck with glass vertical barriers featuring integrated glass ‘Skyriser’ benches. One of the primary goals of this work was to restore the transparency envisioned in the conceptual sketches for the original design, while making all public areas step-free and fully accessible for the first time.

The quest for transparency extended beyond the exterior skin – Olson Kundig wanted an open plan with as few obstructions as possible between guests’ first steps from the elevator and the expansive skyline view. This inside-out transparency was a major driver for the building services modifications throughout the Atmos. One of the most impactful components was a tightly coordinated reroute of the kitchen exhaust ducts from their vertical path through the observation level space to a more hidden vertical course near the core.

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The Space Needle was built for the 1962 World’s Fair. At 605ft, it is a highlight of the Seattle skyline.

1. Completed Truss
2. Build Retrofits
3. Demolish Existing
4. Completed Truss

1: The iconic Space Needle was built for the 1962 World’s Fair. At 605ft, it is a highlight of the Seattle skyline.
2: 3D section of the Atmos, showing new Oculus Stairs and increased glazing.
3: Some 176 US tons of glass was installed during the renovation.
4: Sequence showing modifications made to 15 of the 48 radial trusses supporting the observation deck.
The existing strap bracing diaphragm below the rotating floor was replaced with stainless steel tension rods. As these rods are visible below the glass floor, it was architecturally important that they be cleanly detailed and as small as possible, to minimise any visual obstruction.

Providing thermal comfort across the range of possible operating conditions was the focus of Arup’s mechanical design in this space and required careful consideration due to the increase in the glazed surface area at this level. The original heating, ventilation and air conditioning system provided heating at window sills from fan coil units located in the cavity below the rotating floor and cooling via large round ceiling diffusers. Underfloor services were no longer an option, as the cavity below the rotating floor was now visible.

The air distribution approach was refined to incorporate separate linear supply diffusers for heating at the perimeter windows, cooling supply diffusers toward the interior and a return airflow path at the centre of the structure. All air distribution elements are coordinated with the sculpted ceiling contour. Arup’s building physics team used computational fluid dynamic (CFD) analysis to optimise the design and ensure a comfortable guest experience.

The structure of the building at this level consists of a 668mm diameter box-section ring beam that rests on top of the main tower legs. Inboard of the ring beam, six radial box beams connect the ring beam and legs to the central core of the tower. Outboard of the ring beam, 48 tapered radial built-up beams, dubbed ‘canoe beams’ for their shape, cantilever out to support the rotating floor.

The original building design used the area under the rotating floor to house building services and relied on a combination of flat-strap bracing and metal deck to brace the canoe beams against buckling. As the new rotating floor was to be completely transparent, all services needed to be moved out of this area and the existing structure renovated to accommodate the view.
The creation of the rotating glass floor means there is a fully glazed cavity between this floor and the lower glazing that wraps under the building structure. Dust build-up and cleanliness of this cavity was a major concern and led Arup to incorporate a dust control fan system that circulates and cleans the cavity air. The design of the system used CFD to determine the airflow rates and design of the nozzle providing dust control, as well as to help understand thermal comfort due to the glass floor.

Oculus Stairs

The Oculus Stairs are a set of two new curved feature staircases that connect the main public 520ft and 500ft levels, along with the intermediate service level. The stair encircles a central opening of 6ft x 12ft (1.8m x 3.6m) through each floor that culminates in the glass floor oculus that allows visitors a view to ground level 500ft below. The Oculus also gives visitors views of the structure, and the elevator and counterweight operations.

These stairs are highly trafficked, as most visitors arrive on the 520ft level and walk down the staircase to exit via the elevator lobby on the 500ft level. With the staircase such an important circulation path, Arup paid particular attention to its dynamic response across a range of loading conditions. The finished stair looks light but feels solid underfoot.

The structural frame of the stair is made up of steel tube columns with a plated, curved rectangular tube stringer beam, all of which is hidden behind an architectural wood slat wall. Each stair tread is fabricated out of folded 0.75in (20mm) thick plate that cantilevers out from the stringer beam, creating the appearance that the stair floats within the oculus opening.

The opening itself was created by cutting out one-sixth of the existing floor framing at each level. Because this framing stabilised a storey-deep ring girder between the service and observation levels, the sequencing of this work was important in order to maintain stability throughout. The framing for the opening was designed such that new primary edge beams could be installed adjacent to the existing girders prior to the existing members being cut away. The new beam connections to the central core rely on the remaining portion of the existing girders in order that all the work points remain unchanged.

The connection of the stair to the surrounding primary structure was carefully considered under both normal and seismic loads. Under normal conditions, the stair columns are connected to the floors above and below, providing the necessary stiffness to control vibration and deflection of the treads. Under seismic loading, the stair itself can resist the applied loads; however, the floor framing that it connects to cannot resist the resulting forces from the stair frame while the two floors are linked together but trying to move separately. The challenge was to make a structure that was stiff during normal conditions to control the footfall response, but flexible under a seismic load. To achieve this, Arup designed the top connection of the stair columns to incorporate a shear pin that is calibrated to break away during a large seismic event. The stair remains stable, albeit more flexible, without this top connection intact, and is free to move without significantly damaging the floor framing above and below.

Services upgrade

A comprehensive building services upgrade was required due to the age of the building as well as the extent of interventions across all the levels in the Atkins. The main service level is between the 520ft and 500ft levels, with plant located between the radial trusses supported off the storey-deep ring girder.

In a more conventional building of this size, a single air handling unit (AHU) would serve the floors above and below. Due to space constraints, eight smaller AHUs are located between the radial trusses to serve this function. This space outboard of the ring girder also accommodates ducts, variable-air-volume boxes, piping, electrical distribution equipment and lighting power supplies.

Arup carried out detailed coordination to incorporate all this equipment in the truss space while improving maintenance access. New access doors at the service level upgrade the previous floor hatches (which had meant that access was previously only available from the level above). With the redesign, a clear walking path was established, eliminating the need to step over truss chords at each bay. AHU access doors were located between truss chords, greatly improving accessibility.
In addition to increased maintainability, the services upgrades brought the Atmos up to current code requirements across all disciplines. This was no small feat from an energy perspective, with the redevelopment having a glazing increase of almost 200%. There was no special energy code concession for the iconic status or unusual nature of the building. To show compliance, the renovation was compared not just to the existing condition but requirements for new construction, including the prescriptive 30% window-wall ratio and fully insulated floors.

A performance-based compliance path was selected, trading off energy-efficiency measures for the shortcomings of the historical envelope and expanded glazing. Arup performed detailed analysis of thermal bridging in the building structure, de-rating the building envelope for all the locations where steel elements penetrated the building insulation, including the service level trusses, girders and beams below the 500ft level, and within the roof. Generally, as much insulation as possible was added to the opaque areas of the building, and points of thermal bridging were addressed where possible to improve the envelope performance despite the increase in glazing.

Energy-efficiency measures included installing efficient domestic hot water and space heating plant, varying kitchen exhaust volumes based on real-time cooking needs and implementing 100% free cooling with outside air at all levels.

**Century Project**
The redevelopment was dubbed the ‘Century Project’ and was just that – a comprehensive renovation that looks back to the structure’s historic vision and first half century of operations to set the stage for the next 50 years and beyond. Final phases of the project will include updating the elevators, repainting and a roll out of a new dining experience at the 500ft level on The Loupe.
A heavyweight lift

It took just ten seconds to lift the topside of Shell’s Brent Delta oil and gas platform clear from its concrete base, yet this was the culmination of years of planning, design and structural works to the platform, and a record-breaking event. This was the first major decommissioning project in the North Sea using Allseas’ single lift technology to remove the entire topside of a large offshore platform in one piece. The topside housed the accommodation block for staff, a helipad, processing facilities, power generation, compression, flare and the drilling and operational areas, along with associated equipment. Its safe removal enabled dismantling onshore, significantly reducing offshore risk exposures.

The size of the task was reflected in the use of the world’s largest construction vessel, Allseas’ Pioneering Spirit, undertaking what was at the time the world’s heaviest offshore lift.

1: Allseas’ Pioneering Spirit carried out the world’s heaviest offshore lift when it removed the Brent Delta platform topside

Author David Gration
Arup supported the decommissioning of the Brent Delta platform by designing the strengthening required to enable cutting the three supporting concrete legs to allow the separation of the topside from its supporting base. Arup determined that strengthening works were required at the cut locations and designed the shear restraint system that provided this necessary strengthening.

This design made it possible for the platform to be de-manned several months before the topside removal. Arup also designed the concrete caps for the legs – which were put in place after the topside was removed – and worked on the strengthening of the infrastructure in the receiving harbour to ensure it could accommodate the massive topside structure for dismantling.

Brent oil and gas field platforms

The Brent oil and gas field, 186km north-east of the Shetland Islands, is one of the largest fields in the North Sea. The field has four platforms – Alpha, Bravo, Charlie and Delta – situated in 140m deep water. The topside of the Delta platform was made up of a plate girder deck structure connected via 5.5m deep steel transition sections to a concrete ring beam at the top of each of the three concrete legs. These legs were in turn connected to a concrete gravity base structure (GBS) on the seabed. The Brent Delta topside had a footprint of 72m by 47m, with a 44m height to the heli-pad and an overall weight of approximately 24,200 tonnes.

Decommissioning

Traditionally, platforms have been dismantled offshore on a module by module basis, but with Brent Delta, Shell took the decision to remove the topside in one single operation. This allowed the de-construction work to take place onshore in a more controlled environment, where detailed inspection and dismantling could be undertaken efficiently, and reduced personnel exposure due to the significantly smaller workforce required.

Arup was commissioned by the offshore contractor Allisys to develop, from concept through to detailed stage, the design for the strengthening works required post-cut, prior to the removal of the topside of the platform from its supporting structure.

Topside removal design development

Arup began the project with a workshop, which resulted in over 30 design proposals. Using a qualitative assessment, these were then rationalised down to the five most viable solutions. Following scoping calculations and after agreeing relevant selection criteria with the client, Arup used a trade-off matrix to select the preferred option for detailed design.

Using a variety of skills, including first principles structural design, non-linear analysis, laser scanning and wave simulation, Arup designed a system that was both structurally effective and reduced installation complexity. The scheme involved cutting the legs just below the topside to facilitate its removal. Non-linear analysis was used to simulate the post-cut situation, with a 3D non-linear finite element model developed for the concrete legs, associated steel transitions sections and proposed remedial works to facilitate the lift.

This cutting work had to take place ahead of the removal of the topside due to the limited weather window available for the topside lift and the availability of the Pioneering Spirit, the only lifting vessel that could accommodate such a significant load. Arup's analysis found that the shear forces that needed to be transferred across the cutline between the legs and the topside exceeded the justifiable frictional capacity of the cutline. To resolve this issue, Arup designed a shear restraint system that allowed the topside to safely remain in place after the cut.

Shear restraint system

There were several complex design requirements for the shear restraints. The system had to be installed in a simple manner offshore, the topside needed to be kept in place after cutting, and it had to disengage during the lifting process without manual intervention.

Arup designed the restraint to carry the circa 20MN shear force per leg across the cutline from the topside transition piece into the concrete leg and down into the GBS. A steel ring beam (circa 40 tonnes of steel per leg) was connected to the concrete ring beam at the top of the leg just below the 160mm-deep flange of the 5.5m tall steel transition piece (TP). Made up of eight steel fabricated angle sections that follow the internal shape of the concrete ring, the steel beams formed a continuous compression ring. Twin loading plates were shop welded to the ring beam in each of the eight corners.

To create the required load bearing connection between the TP and the compression ring, a corner plate was positioned between the loading plates. These elements were machined in the shop but put in position offshore. A trial assembly was built in the shop to check the accuracy of the manufactured elements.

In the installed condition under shear load, the TP flange contacted the corner plates, which in turn contacted the loading plates. In this way the load was transferred from the TP flange into the steel ring beam. This load was transferred around the steel ring beam in compression and then
been de-manned. Lift was carried out by Allseas’ Pioneering Spirit in April 2017. Specifically designed for the single lift installation and removal of oil and gas platforms, the twin-hulled vessel is 382m long by 124m wide and can accommodate 1060 of up to 45,000 tonnes. A 122m long and 59m wide slot in the bow of the vessel was used to position around the platform, with the lift using eight sets of horizontal lifting beams.

Over a 12-hour period the vessel was positioned under the topside, with each lifting beam aligned to touch the designated lifting points. Hydraulics enabled positive contact to be kept with the topside, all the while taking into account the movement of the vessel. The ballast was removed from the vessel before the operation, which meant that virtually all of the topside weight could be taken before the short lift – which lasted just ten seconds – took the topside clear of the legs.

The topside platform was transported 388 nautical miles to within five miles of the shore and the decommissioning yard. As the water depth at the Able UK Seaton Port in Teesside was insufficient to accommodate the Pioneering Spirit, the topside was transferred via the 200m by 57m wide cargo barge Iron Lady. The platform is currently being dismantled and recycled with the aim of re-using over 97% of the material in the platform.

Concrete leg caps
Following the topside lift, with the legs sitting close to 20m above the sea, concrete leg caps designed by Arup, each weighing approximately 100 tonnes, were placed on top of the legs. Each cap has three installation guides. These helped to position the caps when lowered from a crane on a moving vessel. As well as closing off the top of the legs, the caps provide a foundation for the navigation aid used to alert passing ships of the presence of the concrete legs and GBS below.

Concrete leg caps being lowered into place on top of the legs. 13. The Pioneering Spirit moves clear of the concrete legs following its successful lift of the platform topside.

Cutting the legs
After Shell decommissioned the pipework and equipment within the legs and installed the steel shear restraint system, the shaft cutting could proceed well in advance of the topside lift. Cut UK had conducted all the onshore cutting trials in preparation for executing the diamond wire cutting offshore on the Delta platform.

The cut was made just below the TP flange plate, cutting through the grout and the post-tensioned tendons anchored within the concrete ring beam at the top of the legs. Diamond wire cutting was deployed inside the 14m wide legs, which are approximately 1m thick. The cutting sequence was determined based on a review of the expected weather window during the cutting operation. Holes were drilled at specified centres through the concrete ring beam. A diamond wire was then threaded through two adjacent holes before the cutting process began.

Lift
The lift was carried out by Allseas’ Pioneering Spirit in April 2017. Specifically designed for the single lift installation and removal of oil and gas platforms, the twin-hulled vessel is 382m long by 124m wide and can accommodate 1060 of up to 45,000 tonnes. A 122m long and 59m wide slot in the bow of the vessel was used to position around the platform, with the lift using eight sets of horizontal lifting beams.

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Concrete leg caps being lowered into place on top of the legs. 13. The Pioneering Spirit moves clear of the concrete legs following its successful lift of the platform topside.
Preserving Malaysia’s natural heritage

An elegant solution to traffic congestion ensured minimal environmental impact on a world-renowned heritage site

Author Wan Arruz bin Wan Endut

Malaysia has undergone rapid economic growth in recent decades, with a rising population and increased vehicle ownership placing escalating pressure on its road infrastructure.

Rawang, a former mining town founded in the 19th century that has become a base for commuters to Kuala Lumpur, was particularly affected by road congestion. Located 23km north of the capital on Federal Route 1 – the oldest national highway in Malaysia – its position on this major thoroughfare made it a traffic bottleneck.

The journey to Kuala Lumpur could take over two hours at rush hour. Vehicles using the road travelled through the centre of Rawang, a route lined with shops, roadside parking and eight traffic signal junctions.

Alleviating this problem was identified as a priority as far back as 1997 by the government’s highways planning division. The Asian financial crisis around this time meant the project was put on hold, before the plan to construct the 19km Rawang Bypass was revived in the early 2000s.

The project was tendered as a design and build contract and was awarded in 2003 to a partnership between Arup and local company Panzana Enterprise Sdn Bhd. Arup provided full engineering services, and was the full-time site supervision consultant for the project.

**Bypass route**

The project was divided into three sections. The first comprised upgrading the existing federal road, transforming the single lane carriageway (starting at Selayang Interchange just outside Kuala Lumpur and ending at the Templer Park area just outside Rawang) into a new dual carriageway with 2m-wide paved shoulders. The second element was the construction of a completely new section of road – a bypass to divert the traffic north around Rawang town centre. The final section of the project was building a trumpet interchange and upgrading the 2km federal road on the north side of Rawang leading to Serendah, a popular tourist spot.

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**Kanching Forest Reserve**

The team started on the detailed design in 2004. Sections 1 and 3 were relatively straightforward and progressed smoothly, but Section 2 was far more challenging. This part of the project entailed building a bypass around Rawang that, under the government’s original plan, cut through Kanching Forest Reserve. This hilly forest is an area of outstanding natural beauty and ecological value. Referred to locally as Taman Warisan (‘heritage forest’), it is a rich reserve of waterfalls, flora and fauna, and attracts eco-tourists from around the globe. It teems with wildlife, including rare and protected plant species such as the Giam Kanching tree, of which only 400 are left in the world.

An elegant solution to traffic congestion ensured minimal environmental impact on a world-renowned heritage site.
In 2005, the state government designated the forest as an official heritage site, meaning no major development that could affect the reserve’s ecology was allowed.

**Finding a solution**

Although the road was an essential part of improving Malaysia’s transport infrastructure, the risk was that any construction work would require extensive deforestation, resulting in an unacceptable impact on the natural environment. The Malaysian Public Works Department, which commissioned the project, requested Arup to revisit the concept design and review the road alignment. For Arup, the challenge was to redesign this vital bypass to minimise deforestation, ensuring little impact on the environment during the construction phase and after handover.

Finalising the design took almost a year and involved an intense process of engaging with the Malaysian central government and other interested parties. Through meetings, presentations and public hearings, Arup gathered input from public representatives, local authorities, the country’s Forestry Department and NGOs such as the World Wildlife Fund (WWF).

Arup devised an elegant solution to the problem: an elevated bridge structure over the outer fringes of the forest, moving the road route initially suggested by the Public Works Department down to the footpath of the forest. This ensured that the bypass would be located at the edge of the heritage area, reducing the need for forest clearance.

This amended route required the road structure to be raised significantly above the ground to match the vertical alignment of the other sections of the road. The final design included a 2.7km elevated structure supported by piers that are up to 58m tall. This makes it the longest and highest bridge in Malaysia, with vehicles on this section of the road almost level with the treetops of the surrounding forest.

**Foundation and pier construction**

Having determined a more sustainable route for the bridge, it was important that the construction process also had a minimal impact on the area by avoiding extensive earthworks and deforestation. For the construction of the pier foundations, Arup devised a method that avoided using heavy machinery on site, reducing disturbance to the forest’s ecosystem. With the mountainous terrain, it would have been difficult to manoeuvre large machinery on site. This would have required removing trees and levelling the ground, with this latter activity having the potential to cause soil erosion.

Rather than using piled foundations, which require large drilling equipment, light machinery was used to dig caisson foundations. The construction works could therefore be spread over a smaller area, something that would otherwise be necessary. This method required only a narrow 50m corridor for the construction of the foundations and bridge piers. The foundations range between 1.7m and 6m in diameter, and were dug using jack hammers and hydraulic rock breakers. The piers were built using slipform construction, allowing each pier to be constructed quickly, safely and accurately.

**Movable scaffolding system**

With the need to avoid extensive earthworks and deforestation fundamental to the choice of construction method, a movable scaffolding system (MSS) was adopted to construct the high-level bridge deck. The MSS provided a quick, reliable and economical solution for construction of the elevated bridge. This was the first time this method was used in Malaysia.

With an MSS, a hydraulically operated giant steel gantry, formwork and platform slides from pier to pier, enabling the beams and concrete slabs to be constructed from the top of the piers. Once each section is completed, the formwork is released and pushed to the next pier, meaning that workers, equipment and materials have minimal impact at ground level. Instead, 50 sections of 40m span were constructed using this method. Two 600-tonne gantries were used for the installation.

**Safeguarding Malaysia’s natural heritage**

The Rawang Bypass opened to great acclaim in November 2017. For its breathtaking views over the forest, the bridge has received racing public approval and the award of organisations concerned with protecting wildlife and preserving the environment. Arup’s strategy for the construction meant that deforestation and earthworks were minimised. Passing high amid the treetops, the elevated bridge respects the ecosystem below, as well as easing congestion in the adjacent town, cutting peak journey time through this area by 90 minutes.

In completing the project, Arup has designed a piece of infrastructure suitable for the needs of Malaysia’s ambitious, fast-growing economy, without causing damage to the country’s ancient natural heritage.

**Project credits**

Wan Anuar bin Wan Endut was the Project Director and in Malaysia. Project Director for Arup in Malaysia.

**Client**

Malaysian Public Works Department (Jakatan Kerja Raya). Thanks to Haji Abd. Rahman bin A. Azi as Supervising Officer’s Representative

**Bridge engineering, infrastructure and geotechnical design, electrical engineering and construction supervision**

Wan Anuar bin Wan Endut, Wong Chee Thong, Ng Say Gim, Mohd Khaulil Aysa bin Abd Fari, Mohd Naizir bin Mat Daud, Adi bin Md Ali, Mohd Baizul bin Omar, Azizi bin Ahmad.

**Image credits**

All images: Arup
Lowering Leeds city centre flood risk

The Leeds Flood Alleviation Scheme is one of the largest flood defence projects in the UK and the first in the country to use movable weirs

Authors Michael Nichols and David Wilkes

The first phase of the Leeds Flood Alleviation Scheme was completed at the end of 2017. The works have significantly reduced the risk of floods that have the potential to cause devastating physical and economic damage to the heart of the city.

Previously, 3,500 residences and 500 commercial city centre properties were at high risk, as were key access routes to the train station area, data and telecommunications infrastructure, utility substations and more than 300 acres of developable land.

In 2015, Storm Eva hit the city, with the resulting flooding causing an estimated £37 million worth of damage. This highlighted the importance of completing the flood alleviation measures as quickly as possible. The first phase of the scheme provides protection to the city without compromising the character of the waterfront, with careful interventions maintaining the important connection between the city and the River Aire.

Scheme development

In 2011, the UK government’s Department for the Environment, Food and Rural Affairs, and the Treasury, rejected a proposal from a different firm for a £190 million flood scheme due to the excessive cost. That scheme advocated the construction of 3m high walls and embankments. While these would have provided flood protection, they would have also severed the physical connection between the city and the waterfront. Such high walls would have had a negative effect on the café and bar culture along the river, and a pleasant waterfront walking and cycling route would have been lost.

With the rejection of this original scheme, there was a risk that the flood alleviation initiative would be removed completely from the list of national infrastructure spending priorities. For Arup, whose Leeds office is located on the River Aire, getting involved in developing a new scheme was an opportunity to propose a more sustainable solution. The firm, working together with Leeds City Council, developed an alternative proposal more in keeping with the city’s character and landscape. Arup focused on reducing obstructions that were causing water levels to rise, meaning the length, visual impact and cost of the riverside defences could be significantly reduced.

By identifying which flood defence measures would provide the most immediate benefits and developing the project in stages, Arup believed it could make substantial improvements on a smaller budget, adding more sophisticated measures when further funding was secured – an attractive proposal during a time of economic recession.

The design comprised three main elements: the removal of the river’s two main navigation weirs, replacing them with moving mechanical weirs that allow the water level to be better controlled; installing 10km of linear defences in the form of walls along 5km of the city centre waterfront, embankments and landscape improvements; and the removal of a 600m-long man-made island that separated the river and canal, thus eliminating a bottleneck for water flow.

In November 2011, the Environment Agency commissioned Arup to develop the scheme further and the project subsequently secured funding. With Leeds due to connect

1: Completed Crown Point replacement weir – part of the Leeds Flood Alleviation Scheme, which provides 100-year storm flood protection
2: Arup developed a web-accessible BIM model for the scheme
with the High Speed 2 (HS2) rail link, and with the city’s South Bank being one of Europe’s largest city centre regeneration initiatives, the flood alleviation scheme was identified by the UK government as an important strategic project.

Digital construction and collaboration
Arup developed a web-accessible interactive Building Information Modelling (BIM) model for the scheme. Through this virtual environment, the project team could digitally navigate the complete scheme, including the flood defence walls, proposed weirs, and new and existing bridges. They could call up project data that was linked to the model, such as drawings and photographs.

The aim was to ensure that everyone involved in the project had a sound understanding of the scheme’s fundamentals and access to all the technical information whenever needed. Working from this common data environment ensured that the project team, including the client, the design and build contractor and other stakeholders, had access at all times to the most up to date project information. This helped to manage workflows and speed up the approval process. It enabled better coordination and collaboration, allowed the early mitigation of any critical issues before site works commenced and reduced risk overall. The model also helped provide greater certainty regarding the construction costs. Following completion of the works, all this information was made available to the client and their team who were responsible for maintaining the flood alleviation infrastructure after completion.

The design team of Arup, Leeds City Council and the Environment Agency was based in the same building. Following the contract appointment, the contractor and their designer joined the project team on site. This structure ensured there was good collaboration across the complete project team.

Replacing the weirs
The existing masonry weirs on the river dated from the Victorian era, when the River Aire valley was home to industries such as carpet and cloth making, and coal mining. These fixed weirs made the river navigable for large barges carrying industrial cargo to navigate the waterway. However, when the water level increased during flood conditions, the weirs hindered the flow, significantly increasing flood risk.

The previous scheme did not seek to change the existing masonry weirs. These would remain in place in normal conditions, but could be lowered in advance of extreme weather conditions, thereby reducing the flood risk. The mechanical gates control the water level using bottom-hinged steel plates supported on inflatable bladders. These movable weirs can be lowered in advance of extreme weather conditions, thereby reducing flood risk.

The firm proposed replacing the existing weirs at Knostrop and Crown Point with movable mechanical weirs. These would maintain the river at a navigable level in normal conditions, but could be lowered in advance of extreme weather conditions. The mechanical weir at Knostrop can be raised and lowered during construction.

The previous weirs were fixed, which made the river navigable. These fixed weirs made the river navigable.
In normal conditions, the gates are at a 45° angle, which maintains the high river level and allows for navigation. However, as the waters rise, the gates can be progressively lowered towards the riverbed over a two-hour period, removing the barrier to flows and greatly improving water conveyance. This reduces high-flow water levels by 2m at the weir locations and by approximately 1m in the city centre.

Mechanical weirs are used in other countries – in the US and Canada, for example – but typically to control the flow of water into hydroelectric plants. Arup’s scheme in Leeds, using weirs developed by Dryhoff, is the first time movable weirs have been used as part of a flood alleviation scheme in the UK.

Configuring the system’s layout and installation correctly was crucial. As part of the design process, Arup used both digital and physical models of the weirs to test the various flow patterns ahead of construction. In addition, the 3D digital model helped plan the weir construction sequence. The model was also used to create a video that showed how the weirs worked, illustrating the process to the wider public.

Arup worked with the design and build contractor to design the system, which had to meet strict requirements for control of flood risk and needed to maintain navigation during construction. For example, a temporary weir was installed upstream at Knaustrope, which allowed construction work to be undertaken in a safer manner in shallower water, and ensured the flood risk to surrounding properties was not increased during construction.

### Linear defences in the city centre

The second element of the scheme was to build flood defences on each river bank to protect a 5km section of the city centre, as the water level could still rise above the original riverbank during a flood event.

**10.** In order to ensure the connection between the city and the River Aire was maintained, flood-proof glazed units were installed along a stretch of the riverbank most used by the public.

**11.** Natural flood alleviation methods were also used, such as planting trees.

**12.** The Trans Pennine Trail was relocated so that it now crosses the river on a 70m span bridge installed to connect the trail and the north bank of the Aire.

There are many high-quality public areas along the River Aire, so a priority was to preserve these and the relationship between people and the water. As the movable weirs reduce the flood water level in the city centre, this means that the walls could be much lower than the previously proposed 3m height. Arup’s design ensured the majority of the walls were less than 1.2m high and were clad in stone and brickwork to match their surroundings. In the areas most used by the public and near residential areas, flood-proof glazed units were installed to make sure that views of the river could be maintained. A testament to the project’s success was that a very active residents’ committee with properties along the river was satisfied by the result.

### Eliminating another barrier

The final element of this phase of the flood alleviation scheme was the removal and relocation of a man-made island at Knaustrope, which separated the river and the Calder and Hebble canal along a 600m stretch. This eliminated a water flow bottleneck. Its removal was another element in Arup’s strategy to prevent flooding by eliminating blockages rather than relying on excessively high flood protection walls. To facilitate the removal of the island, Arup designed the diversion of the Trans Pennine Trail (used by walkers, cyclists and horse riders across the Pennines). The trail was relocated by creating a new 1km walkway on the left bank of the river that included measures to encourage wildlife and plantation and improved public wayfinding and interpretation of the environment.

The trail needed to cross the Aire, so a locally manufactured bridge was installed at the weir location connecting the diverted trail with the north bank of the river. Weighing approximately 150 tonnes and spanning approximately 70m, the bridge was designed by Arup, Knight Architects and the BAM Nuttall/Mott MacDonald joint venture.

Some 180,000 tonnes of material was excavated during the re-shaping and re-grading of the river. This was reused on the local development site and also for the diversion of the Trans Pennine Trail, resulting in a saving of £1.6m.

### Integrated urban drainage model

In addition to minimising flood risk from the river, Arup created a digital model to identify the risk of residual surface water flooding issues, looking at the combination of heavy rainfall and high river levels. The 275km² model – one of the biggest of its kind in Europe – brought together all the elements of local and highway drainage and both the current and historical water company records. It created a detailed picture of Leeds and its flooding hotspots. This means that measures can be designed in the future to tackle spot surface water flooding in Leeds, which has a high river flow and intense local rainfall (1,025mm per year over 152 days).

The cutting edge

The implementation of this £50 million scheme puts Leeds at the cutting edge of national flood defence schemes. The moveable weirs allow a significant reduction in the height of the walls and embankments within the city compared with the previously proposed scheme. Together with terracing and landscaping, this maintains physical and visual connectivity with the waterfront.

The scheme’s success has protected the city centre from flooding – providing a 100-year storm standard of protection up to 2069, taking into account climate change – and ensured that the development of Leeds South Bank can progress with confidence. This project has the potential to create 35,000 jobs and 4,000 homes, and will house the terminus of HS2.

Arup’s scheme has enhanced the area’s natural habitat, encouraging local wildlife to flourish. The new weirs include fish and eel passes that allow baby salmon to come down the river and for mature adult fish to swim back up. It also provides a habitat for mammals such as otters and beavers. For the first time in about 200 years, there is now a small otter population living in Leeds city centre. In addition, as part of the natural flood management techniques used by Arup, over 700 trees have been planted.

By improving river accessibility and securing the future of local leisure and business establishments, Arup’s flood alleviation scheme has added to local employment in the city. It has created 150 direct jobs and will safeguard 22,000 more over the next ten years, supporting further growth and regeneration of the Leeds regional economy.

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**Authors**

Michael Nicholls was the Project Manager and is an Associate Director in the Leeds office.

David Wilkes was the Project Director. He is an Associate Director in the Leeds office and is Arup’s Global Flood Resilience Leader.

**Project credits**

Client Leeds City Council

Contractor BAM Nuttall

Civil, water, geotechnical, mechanical, electrical, structural engineering services in addition to hydraulic design, commercial management, environmental impact assessment Arup: Daniel Aspden, Chris Baker, Luke Ballantyne, Matt Bourke, Adam Birdsworth, Eric Buffo, Olye Carlton, Oliver Clarke, Paul Daves, Richard Deakin, Alan Dean, Paul Dickers, Mike Dobson, Stephanie Dye, Mike Farmer, Nic Ferno, Paige Garnett, Libby Gibson, Arlene Goode, Liske Hancock, David Hardy, Mishia Hayne, Dean Hopp, James Hollway, Sophie Hornsby, Jen Homcock, Lan Huang, Andrea John, Michael Jones, Sian Christian, Jungie Filipk, Jenny Lightfoot, Jou Lin Ng, Amy Martin, Mark Matthews, Will McIlhan, Michael Nicholls, Alex Nicholson, Daniel Patten, Matthew Peacock, Miguel Pineda Lara, Nasir Pitter, Ruairi Reay, Fabrizio Rhodes, Victoria Robinson, Marcus Shepherd, Paul Simkins, Paul Smith, Hannah Smith, Alex Smith, Veronika Shvydova, Martin Tattersall, Trevor Taylor, Law Wallace, Jen Whelan, David Wynn and Sam Wright.

**Image credits**

All images: Arup
Founded in 1945, Amorepacific is the largest beauty and cosmetics company in South Korea and one of the biggest in Asia. Towards the end of 2017, the company moved into its new headquarters in the centre of Seoul, on a site that has been occupied by the cosmetics giant for over 60 years. The new building is an elegant 110m tall cube centred around a courtyard, part of which is glazed to provide natural light into the atrium below. With its striking outer façade of vertical fins, the building is a distinctive and innovative take on office accommodation.

Inspired by references to traditional Korean courtyard architecture and with energy efficiency and wellbeing at the centre of its design, the building is punctuated by three large openings on the 5th, 11th and 17th floors. These are landscaped with gardens and terraces, and open onto an inner central courtyard that features a reflecting pool. The openings allow natural light and ventilation to enter the heart of the building, and frame dramatic views across Seoul.

The architectural design was led by David Chipperfield Architects (DCA), with Arup collaborating with DCA on the design of the building, supported by a team of Korean consultants on the project delivery. Arup’s London and Berlin offices provided all technical engineering services, including structural engineering, building services, geotechnical,

1. The Amorepacific headquarters, which combine traditional Korean architecture and technological innovation, are based in the centre of Seoul
2 & 3. There are three openings at different levels of the structure
4. Daylight analysis of the 17th floor

Beautification and innovation

A sustainable modern building that draws on traditional Korean design to provide a headquarters for one of Asia’s largest cosmetics companies

Authors Francesca Coppa, Eva Hinkers, Julian Olley, Alexander Rotsch, Nigel Tonks, Frank Walter

Technical issues

The façade system has been developed to improve occupants’ experience by enabling clear views to the outside and achieving high daylight quality while carefully controlling solar gain and energy efficiency.

This façade is designed to achieve three primary goals:
– Optimize the quality of daylight, views to outside, and the connection to the outdoor environment using full height clear glazing and natural ventilation
– Provide external shading to reduce internal solar heat gains
– Facilitate ease of glass cleaning and maintenance

Extensive thermal and daylighting analysis was undertaken to optimize these three primary goals.

Daylight

The introduction of a courtyard and the large facade openings generate a sculptural interaction between the form of the building and sunlight, allowing daylight to penetrate into the internal perimeter offices. The careful placement of the large windows admits seasonal direct solar radiation into even the lower levels and the foyer glass roof. This results in dynamic daylight effects throughout the courtyard volume, which improves the occupants’ seasonal experience and connection with outside.

External shading for the control of heat gain (see below) in the internal facades is preferred to the alternatives of using dark glass or partial height glass. This shading system allows the adoption of full height clear glazing which gives the optimal quality of daylight and views to outside in the inner office perimeter.

The effectiveness of this particular configuration of vertical external fins and horizontal walk ways also means that the occupants will be less reliant on the internal glare control blinds. The blinds will be operated less frequently, which means the occupants will benefit from unobstructed views for longer periods.

Image of the daylight model (plan of 17th floor)
AMOREPACIFIC HEADQUARTERS / SEOUL, SOUTH KOREA

Inception

Amorepacific’s brief was clear in its aspiration to create a headquarters with presence and character that evoked the brand values of the company, which seek to celebrate Asian beauty by blending traditional wisdom, fine ingredients and technological innovation. The headquarters were to comprise 80,000m² of office space, with numerous amenities for staff and the public, including a museum (located in the basement), an archive, tea room, restaurants, retail spaces, product testing spaces and a 450-seat auditorium.

DCA invited Arup to team up for the design competition in 2010, during which many of the key massing, shape and design principles were established. Collaboration was so close during this phase that the completed project bears a significant resemblance to the competition entry, despite a further three years of continuous design refinement and value engineering leading up to the start of construction in 2014.

The winning submission proposed a sustainable and technologically advanced building influenced by tradition. The design allowed for abundant natural daylight and natural ventilation – something not common in Seoul high-rise office buildings, which tend to rely on artificial lighting and air conditioning.

Layout

To mediate between the adjacent Yongsan Park and surrounding high-rise developments, the team developed a 22-storey (above ground), medium-rise building. While the site was generous enough to accommodate large floor-plates, a novel design was required to avoid deep plan spaces that place occupants unacceptably far from windows, natural light and ventilation.

In a significant adaptation of the traditional form, large horizontal openings were inserted into three façades. This was necessary to provide a greater connection between the inner courtyard and the outside of the building. These openings bring light, ventilation, exterior views and an enhanced sense of openness to the inner courtyard. They also create space for landscaped elements in the upper reaches of the building. The introduction of nature at an elevation high above the Seoul streetscape provides pleasant recreational spaces for staff and visitors. Voted by staff as their favourite areas of the building, they contribute to a greater sense of wellbeing, as well as enhancing the biodiversity of the development.

As sunlight strikes the courtyard floor in all seasons, during design development a glazed floor was introduced to admit daylight into the spacious atrium below. A 70mm deep reflecting pool in the courtyard covers the atrium glazing, adding to the calming atmosphere and enhancing the aesthetics of the space. Motorised ventilation louvres at high and low level vent the perimeter spaces in spring and autumn. Underfloor mechanical ventilation serves the central floor zone and provides mixed-mode ventilation.

Wind

Arup optimised the locations of the large horizontal façade openings, modelling for the impact of the prevailing wind direction, wind movements down the façade onto the entrances and traffic noise. For example, the largest horizontal opening, which faces south-east towards Yongsan Park, was strategically placed in relation to the prevailing wind direction to reduce the effect of downdrafts above the main entrance. The mid-level opening is located on the Hangang-downdraft highway. The opening's elevation shields the courtyard from traffic noise. The uppermost opening is placed on the north-east façade, where prevailing wind and down-wash effects are less critical. In this orientation, the elevated opening also overlooks the city, giving views towards Namsan Mountain.

Facade

The orientation of the building is such that elevations stand at an angle towards the cardinal points. The 52° north-south orientation results in all sides of the building being exposed to direct solar gains, with the south-east and south-west façades receiving more solar exposure than the north-east and north-west façades.

Responding to this challenge led the design team to customise an engineered response to reduce energy consumption that also became a signature feature of the building: vertical fins that form a brise-soleil, which is connected to the building by accessible walkways, wrapping all elevations. As well as adding to the building’s...
reduces solar gains and, consequently, reduce the energy consumed by the building’s cooling systems.

There was little codified guidance for designing such large elements. Typically, wind loads are anticipated to be greatest at the corners and edges of a building, where wind speed accelerates. However, the configuration of the brise-soleil affects these predictions: the presence of the fins provides resistance to the wind and the repeating pattern of fins could provide sheltering effects near the corners. Surrounding buildings create additional turbulence, which can result in significantly increased wind loads at the building’s corners.

In order to optimise the fins’ design, Arup conducted a series of wind tunnel tests of the brise-soleil at different scales to determine the response to wind effects.

The fins’ size meant they could not be modelled at normal wind tunnel testing scales of 1:400–1:300. Arup’s wind specialists developed a customised approach to testing. Preliminary small-scale, whole-building testing in South Korea was followed up by 1:70 scale tests in Europe’s largest atmospheric boundary layer wind tunnel in Milan, Italy. The design of the fin section was further refined to an aerofoil shape with varying edges, with additional testing carried out at this stage of the design.

This combination of tests enabled Arup to predict the behaviour of wind at the edges of the large façade openings, the downwash impact at entrances and, crucially, to be able to refine the structural robustness of the exposed parts of the fins. The fins have piniostrap surface protrusions along their vertical axis that become visible only when near the building. While these make a strong visual contribution—purely rounded shapes can be difficult to process visually—Arup introduced the 3mm linear protrusions to encourage vortex shedding. Micro turbulence created by wind passing over the stripes reduces deflection and vibration effects as well as improving robustness.

Arup integrated the structural and the shading performance needs in determining the fin patterns, recommending appropriate sizes and weights of fins for different locations around the building. For example, shallow fins were dominant in locations with lower wind pressure and deeper fins were prioritised at the corners of the building.

Walkways
A typical challenge for external shading, which is exposed to the elements, can be the difficulty of maintenance and cleaning. For Amorepacific’s headquarters, the layer of vertical fins is separated from the building’s glazing by a series of grillages at each floor level that serve the triple function of horizontal shading, fin support and access walkways. These allow the outside of the windows to be cleaned easily and give access to the fins and motorised ventilation louvers for inspection and maintenance. The external shading has no external moving parts, greatly simplifying its maintenance requirements.

Vertical transport
The latest advances in lift technology have been used in order to provide a high level of service and reduce waiting times, thereby facilitating rapid mobility around the building while minimising the lift core sizes. Waiting times are nine seconds in normal service and 15 seconds at peak times. This is highly advantageous in a culture where work arrival and departure times and lunch times are commonly punctual, often leading to lengthy waiting times.

The central courtyard arrangement precludes the use of a central lift and staircore. Instead, cores are positioned at the four corners of the floor plates and comprise five passenger lift shafts, and one service and one firefighting lift. Each passenger lift shaft contains two lift cars operating independently. The advantage of this “twin lift” system, with half-call control, over a conventional ‘double deck’ system is an increase in capacity and reduction in waiting time, as well as a reduction in energy consumption. This application is the largest of its kind in the region.

Courtyard, atrium and glazed floor
By locating the stair and lift cores in the corners of the building, it became possible to create a large ground floor atrium below the courtyard. The importance of this space for Amorepacific goes beyond the functional brief, which was to provide secure access for staff and visitors. It is also the setting for the public entrance hall used by people visiting the building’s amenity spaces. These include the art museum, tea room, auditorium, childcare centre, product testing areas, retail spaces, restaurants and cafés. The atrium also creates a pedestrian link to the adjacent Yonggan Park.

The early design envisaged an artificially lit space. Arup worked with the architect to bring natural light into the expansive space. This...
was achieved by creating a glazed ceiling for the atrium, with a deep clear-span structure supporting the courtyard floor and the reflecting pool. The solution provides daylight to the ground floor and, looking up, below, provides a view of the sky, giving a connection with the outside.

A precise integration of structure and services defines the character of the atrium. Lighting, diffusers and sound absorption are integrated with the structure so that the exposed concrete soffit requires no additional ceiling treatment. Despite its busy public nature and hard surfaces – with natural stone floors and concrete columns, walls and ceilings – Arup’s acoustic designers created a controlled environment while maintaining its live nature.

Acoustic panels are discretely integrated with the raw finish of the space to create an effective system that is also aesthetically pleasing. The panels are located in areas where people congregate and have conversations. Corridor ceilings are treated with sound-absorbing panels comprising a 3mm mineral wool core covered with a 70% perforated metal sheet, recessed as within the concrete coffers of the exposed structural soffit. The outcome minimises high noise levels and disturbance, and so facilitates comfortable conversation among small groups.

In the auditorium adjacent to the atrium, Arup designed a variable acoustic system to allow the venue to be used for amplified and unamplified scenarios (i.e. music and speech) by deploying two layers of acoustic curtains and diffusers on the auditorium side walls.

Lighting

Amoropacific currently operates 28 brands under one roof, creating the need for various light atmospheres and a high level of future adaptability.

Taking a conscious low material wastage, high recyclability approach, DCA and Arup created a modular, re-usable and adaptable luminaire system that provides a huge variety of lighting performances. The system uses a single luminaire body shape with interchangeable optical lenses for different applications throughout the building. This is an innovative and sustainable departure from the conventional approach to lighting flexibility, which relies on different luminaire products and manufacturers for different settings. The emitting surface of the optical lenses is covered with micro lenses of different shape, producing wide, medium, oval or narrow light distributions. The unique optical system combines refraction inside the lens with refraction at the underside of the lens, and offers 12 different light distribution performances in up to 50 possible combinations. Available as recessed, surface-mounted, adjustable and pendant versions, the system provides the optimal light for any desired lighting atmosphere and room use, and forms a decorative element that complements the architecture.

Every component is replaceable and the lights can be modified for any changes in the building’s use without compromising the appearance of the ceiling. Patented by the design team, the lighting system, manufactured by Italian company Viabizzuno, is commercially available.

Museum

Designed to international museum standards, the Amoropacific Museum includes various applications could be adapted for any changes in the building’s use without compromising the appearance of the ceiling. Patented by the design team, the lighting system, manufactured by Italian company Viabizzuno, is commercially available.

The courtyard provides a natural link between the inner building and the outer environment.

Future adaptability.

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Front cover image: Hong Kong-Zhuhai-Macao Bridge, Greater China: Marcel Lam Photography.