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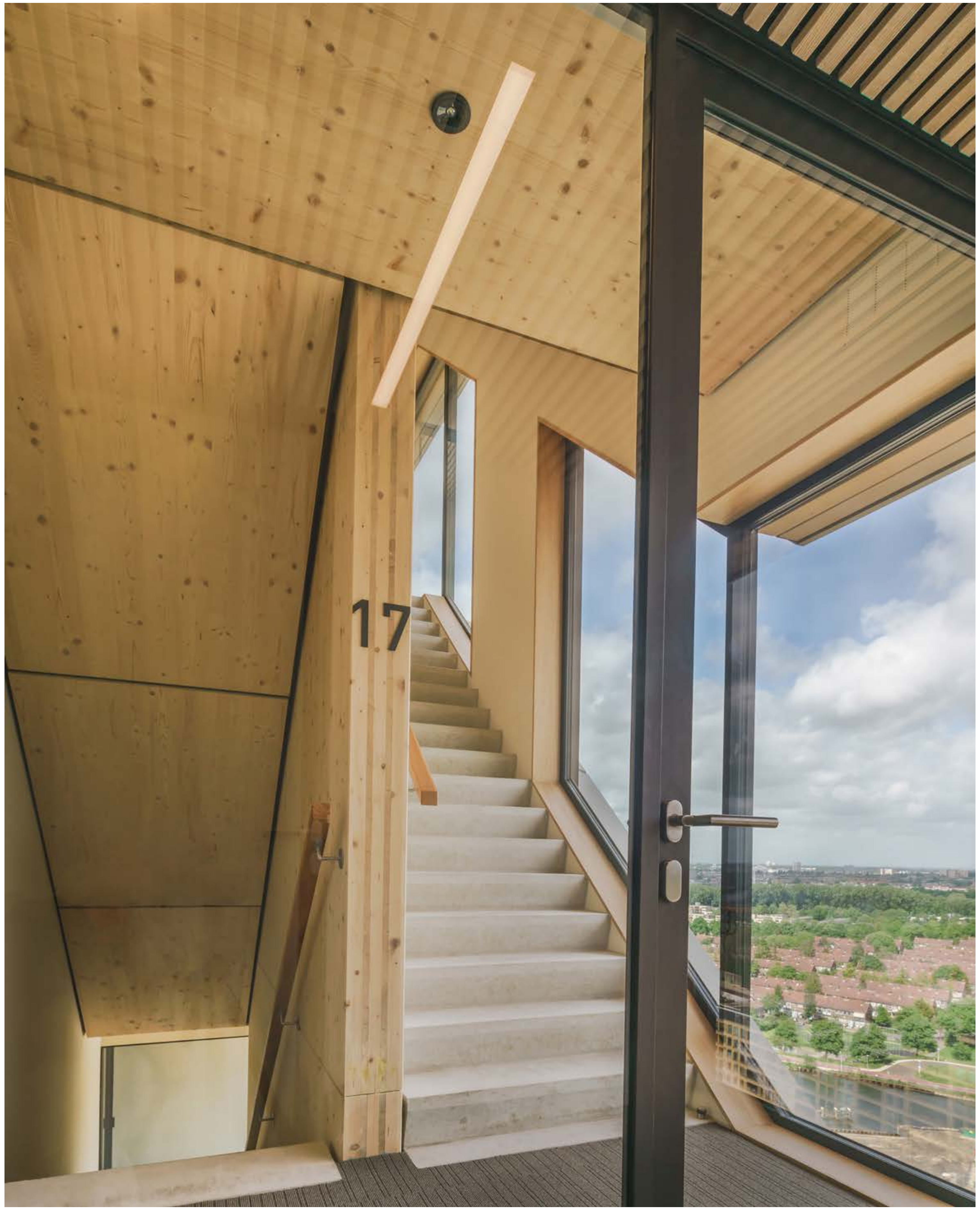
ARUP

The Arup Journal



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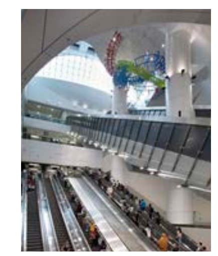

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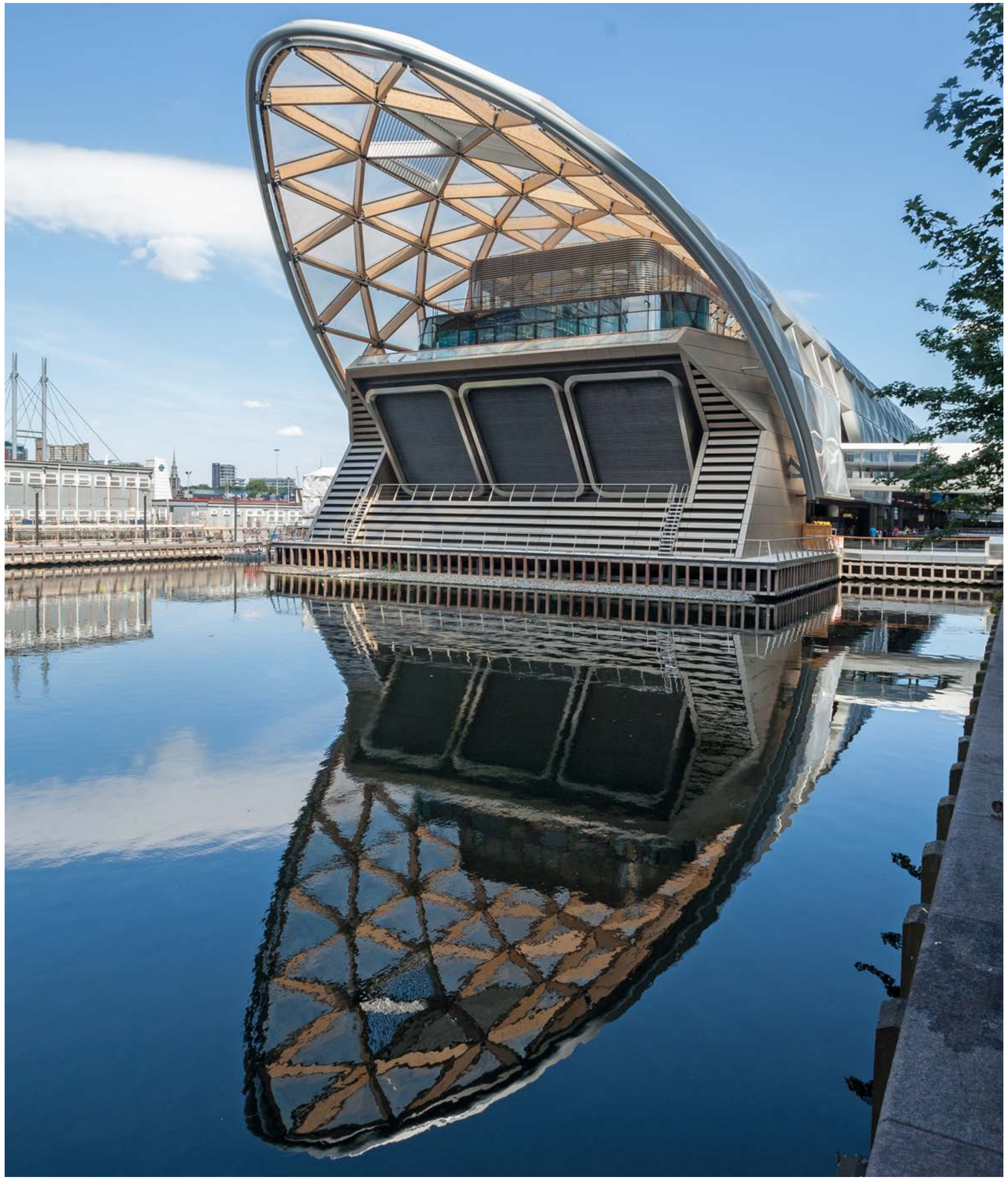

1.

Connecting generations to come

The first mass rail extension of its kind, London's Elizabeth line makes a notable contribution to supporting regeneration

Authors Tim Chapman, Alison Norrish, Graham Williams

After more than three decades of planning, excavation and construction works, the Elizabeth line (known as Crossrail during its design and construction) opened in May 2022. Providing 100km of rail services from Reading and Heathrow west of London to Shenfield and Abbey Wood in the east, it was one of Europe's largest railway construction projects. It has expanded central London's rail capacity by 10%, and directly links important locations including Heathrow Airport, the West End, the City of London and Canary Wharf. The railway is capable of transporting up to 200 million passengers annually and is already exceeding ridership forecasts. Many important lessons can be learned from the new line for other global metro projects, including on design choice and tunnelling techniques, as well as the positive impacts on the economy, society, and the environment.

From inception to completion

Arup worked on the Elizabeth line project for more than 30 years, from its inception and design, right through to its construction and operation. In the 1980s, the UK government asked Arup to assess East London's transport options, and in 1989 the firm recommended increased investment in rail infrastructure to address the city's growing capacity and connectivity issues. In line with its core values, Arup advocated for the potential of the Elizabeth line from the start, and the outcome shows the firm's dedication to inventive cooperation on even the most challenging public infrastructure projects.

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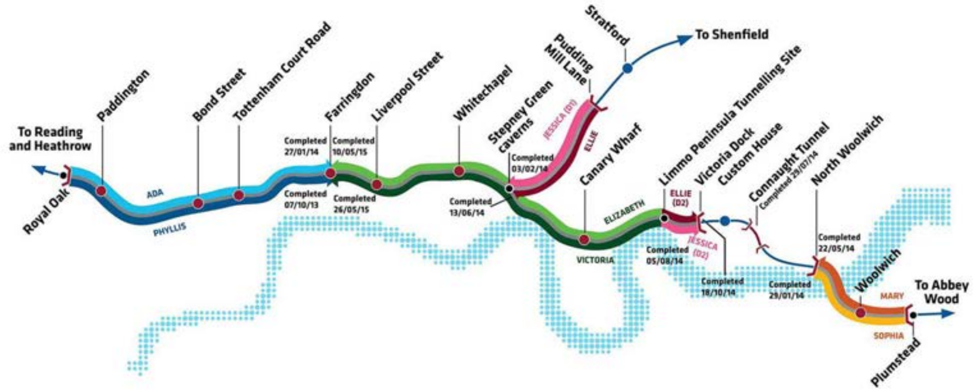
Arup's work included the geotechnical site investigation carried out in the 1990s for the central core route, concept and detailed design of tunnels, shafts and stations in central London, and the assessment and mitigation of over 4,000 buildings and existing railways, and critical utilities along the route.

In the initial phase of design, the firm updated the scheme for the section between Royal Oak, where the route enters the tunnels on the western section

1: The Canary Wharf station sits 18m below the water level, with four levels of amenities above the waterline

2: The Arup-Atkins JV designed 42km of 7.1m diameter twin-bore tunnels extending under the heart of London



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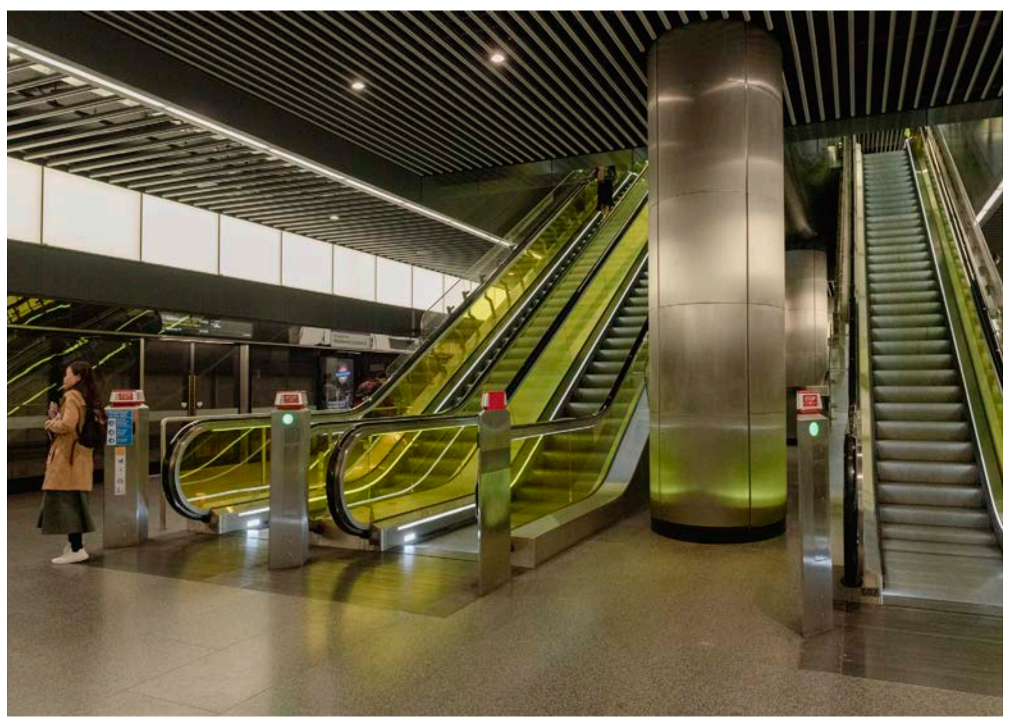
of the route, and includes Paddington, Bond Street and Tottenham Court Road stations. Arup carried out much of its work in a joint venture (JV) with Atkins on infrastructure, geotechnical engineering, station technical design, tunnelling, fire engineering, acoustics and other key elements.

In the main phase, the Arup Atkins JV won the largest of the commissions and, in just over three years, the JV found an unobstructed alignment and designed 42km of 7.1m diameter twin-bore tunnels that extend under the heart of London. In addition to working on the detailed design of the tunnels, the team assessed how the tunnelling, shaft and station excavations would impact surrounding buildings, 12 operational underground lines and other existing infrastructure, and over 12,000 critical utilities along the route. Later this commission was extended to include new sidings and a maintenance depot at Plumstead.

The JV was also successful in winning the detailed design commissions for Tottenham Court Road and Custom House stations. This commission was extended to include Woolwich station. Separately, Arup was appointed by Canary Wharf Contractors to design the new station at Canary Wharf. In the construction phase, Arup was appointed by the contractors to complete the fit-out designs for Bond Street and Liverpool Street stations. As well as station and tunnel design, the firm provided the project with numerous specialist services, including acoustic and fire engineering, technical risk and reliability, archaeology, and sustainability consultancy.

Since its inception, more than 4,000 Arup team members have worked on the project. Some of the major technical challenges faced included minimising track vibration, reducing the negative effects the line's creation would have on those living and working above it, and creating brand new tunnels less than a metre from other underground stations and escalators.

Arup also advised on the oversite development for several commercial partners, including designing mixed-use commercial developments above the stations at Tottenham Court Road (Soho Place), Bond Street (65 Davies Street), Canary Wharf, and Farringdon West and securing planning consents for Tottenham Court Road West and Woolwich. Oversite development was an important factor in the overall scheme and site disposals were required to make a substantial contribution to the funding envelope.



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3: The new line provides 100km of rail services, from Reading and Heathrow west of London to Shenfield and Abbey Wood in the east

4: Arup provided numerous specialist services for the project, including acoustic and fire engineering, technical risk and reliability, archaeology, and sustainability consultancy

5.

5: Arup designed the alignment of the route to ensure that the works minimised the construction and noise impact on existing buildings and surrounding utilities

Key statistics

The Elizabeth line is an exemplary model of how major metro projects around the world can be implemented successfully. The project involved:

- 42km of new underground tunnels under London
- 8 tunnel boring machines, weighing 1,000 tonnes each
- 17,000 structures assessed above ground

Another important aspect was that the firm also undertook research for future major rail projects. This included assessing the social and economic benefits that rail provides to communities. The firm's research has established that thousands of new homes have been built within one kilometre of Elizabeth line stations, with populations growing and employment opportunities increasing within 500m of the Elizabeth line stations in some of the city's most deprived areas. The new line shows how mass transport schemes that are inclusive, accessible and well-designed can play a key role in shaping a city's character. The project has encompassed multiple challenges, and many success stories have emerged from it, highlighting the tenacity and capabilities of everyone involved.

Modelling the underworld

Creating a new network of tunnels under one of the most congested cities in the world, with some of the most tightly packed existing underground tunnel networks, was a significant task. Arup had to design the alignment of the tunnels and stations and ensure that the works minimised the construction impact on thousands of buildings (and their occupants) and hundreds of thousands of critical utilities. The main challenge was in finding a physical route for the new line that would avoid any obstructions, as London's subterranean world is so densely filled with remnants of centuries of development. The firm had to prove to itself, the client, and all of the asset owners that this could be undertaken safely.

The Arup-Atkins JV team, with help from Crossrail Ltd's geographic information systems (GIS) team, employed innovative geospatial technology and mapped all of the data so that the route could be checked for obstructions so far as possible. The firm designed a project-wide GIS model to store both the underground and overground data. The information came from the results of surveys, building reports, site investigations and utilities data. Arup then used a risk-based approach based on the height, age and construction materials of the buildings. It adeptly identified, recorded and gave access to details on any structures or buildings affected. The firm's early recognition of the need for a GIS platform to manage the land, site and geotechnical data that would be involved also delivered time savings.

The model was a crucial part of the project, and was adopted by the client as the backbone of its data management. Thanks to the GIS specialists, the information was readily available to all project staff, and was consistent and applicable to the issues facing the wider project team. A web-based GIS map tool was created to display up-to-date spatial information in an accessible way, and augmented with aerial photography and other data from third-party mapping and surveying providers.

At the time this was a novel approach, but it has now become common practice in similar construction schemes. Crossrail developed the platform further into a Building Information Modelling (BIM) model of the whole line. The BIM model incorporates data – physical, environmental, commercial – on every element designed for the Elizabeth line.

The database Arup created included:

- 100 attribute fields
- 17,386 assets, including:
  - 13,384 utilities
  - 3,284 buildings
  - 669 heritage structures
  - 370 underground stations
  - 249 overground structures

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6: Arup's work on HS1 informed the tunnelling strategy and helped to minimise the number of boring machines needed

7: Arup's design work included mitigating ground movement caused by tunnel and station excavations

Another core part of Arup's work was mitigating ground movement caused by tunnel and station excavations. More than 17,000 buildings, utilities, railways and listed buildings were assessed. The team designed mitigation measures for buildings which they assessed would be impacted by the ground movement, comprising changes to tunnelling construction methods. These included compensation grouting, to stabilise soil conditions beneath some structures, and underpinning to stabilise and/or re-level building foundations where required.

At Whitechapel, the firm showed that the 150m long boring machines could excavate platform tunnels safely below a residential and school building, without costly mitigation measures that would have involved disruption to residents, pupils and teachers. The team also avoided the need for an underground junction at Stepney Green by changing the boring direction along the route. This helped save £20m and reduced health and safety risks for construction teams needing to work in a limited space.

The JV team managed to reduce costs significantly by streamlining the underground connections and refining the scope of three stations: Paddington, Bond Street and Tottenham Court Road. Arup leaned on its work from HS1 (the Channel Tunnel rail link, the final stage of which opened in 2007) to develop the tunnelling strategy, reduce ground settlement, and minimise the number of boring machines needed.

Futuristic station design

One of the reasons for adding rail connections to Canary Wharf was a desire to draw in tenants and the public to the area, as well as commuters. The fully submerged Canary Wharf station is in the 9m deep North Dock, and acts as a link between the Canary Wharf Estate and Poplar, to its north. This presented a challenge, as the station had to be designed to sit 18m below the water level; accommodate the load from the Crossrail Place development above; and be robust enough to withstand ship impact.

The challenges thrown up by designing Canary Wharf station were plentiful, and required innovative engineering solutions. The station was constructed surrounded by water, with the majority of it fully underwater, and only the four levels of shopping, restaurants and other amenities above the waterline. The original plan was to drain the whole of the 200-year-old North Dock, but due to potential environmental damage, the high financial cost, and the risk of failure of the heritage protected dock walls, a lower-risk solution was developed.

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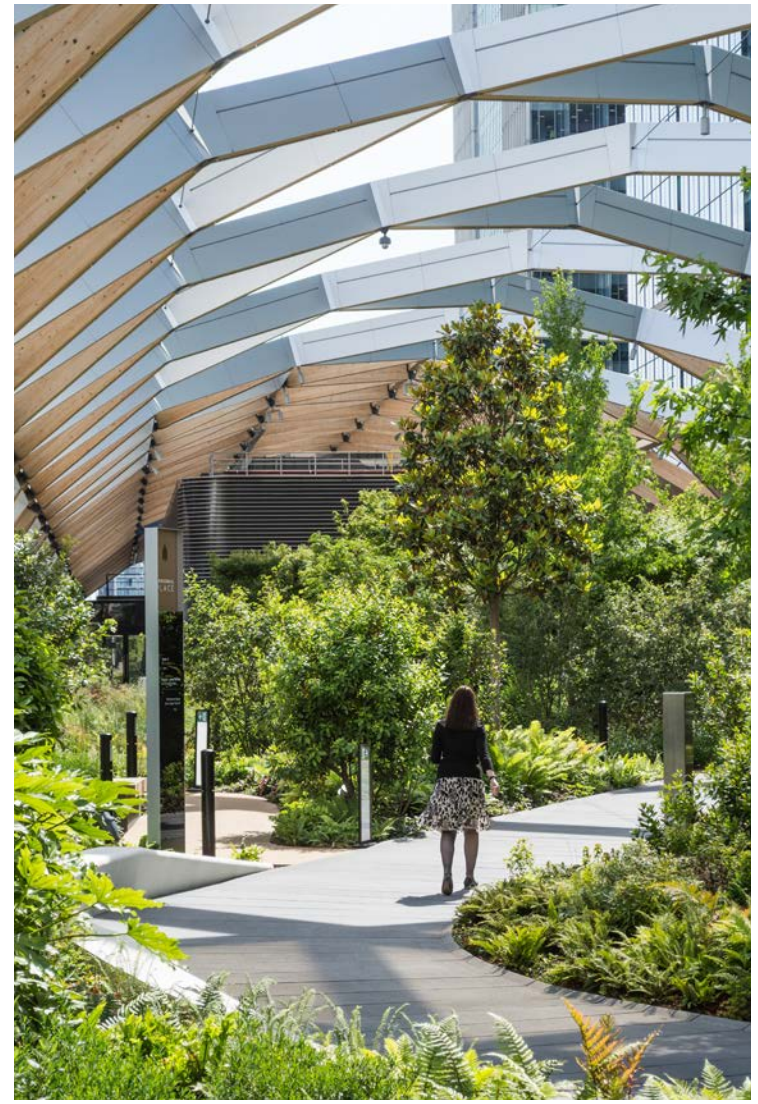

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8: The 310m long roof at Crossrail Place in Canary Wharf is one of the world's biggest continuous timber roofs

9: The roof garden at Crossrail Place is an example of how the new stations encompass new developments as well as public spaces

In a UK first, Arup used the Japanese Giken piling system for such a challenging situation. This method uses hydraulic pressure (rather than impact) to drive the piles so that it produces no vibration and minimises noise. Reducing both construction vibration and noise was critical as the station is set next to the headquarters of several major financial institutions. The piling system's interlocking joints allowed for a single line of 1.2m diameter steel piles to be constructed, rather than a double row of sheet piles acting together, creating a watertight perimeter wall forming the 260m long x 35m wide cofferdam. Over a five-week period, 98 million litres of water (the equivalent of around 40 Olympic-sized swimming pools) were drained, allowing the station to be built safely inside the cofferdam.

Arup's hydrogeologists were responsible for designing the groundwater control and monitoring. During construction, ground movement and water pressures were closely monitored and reviewed to ensure the safe emptying of the dock water, reducing risk to construction personnel, the site works, and the neighbouring buildings and their occupants.

Another standout aspect of this station was the flexibility of the design itself, important because Crossrail Place above was completed several years before the opening of the station below. The building services for Crossrail Place and the station are entirely independent of one another, allowing them to be operated entirely independently by different end users. The 10,500m^2 development is built in such a way that all the units – retail and otherwise – are changeable. They can encompass mezzanine floors, lifts and stairs, and double-height spaces, giving them an appeal to a broad range of tenants. This means that in the future, should the needs or function of the building change, they can easily be altered without too much disruption.

The timber roof at Crossrail Place was, when constructed, the UK's largest timber project, and at 310m it is one of the world's biggest continuous timber roofs. The development is designed to look like a ship, echoing Canary Wharf's original function as a dock. It is now a destination in its own right, thanks to the new public roof garden, restaurants and shops.

The team decided that the design would benefit from reorientating the tunnel ventilation fans at the station, each of which is the size of a jet engine. They were moved into a vertical position at each end of the station to optimise the area and allow more space for station operations and retail. Thanks to the team's use of innovative design methods, costs were reduced from £860m to £500m, and the programme was shortened by 12 months.

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10: At Liverpool Street station, Arup designed the ventilation system to be passive; 75% of the annual cooling is done via natural air

11: Tottenham Court Road features London Underground's third-longest escalator

12: As an existing major underground station, Tottenham Court Road proved to be one of the most complex undertakings of the entire project

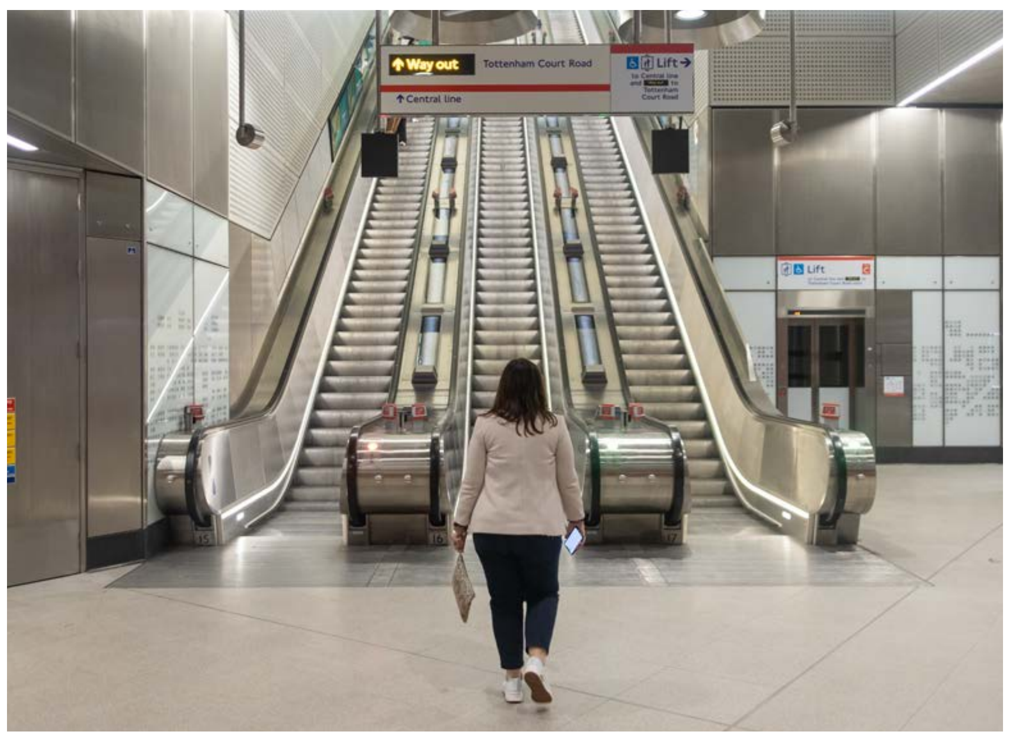
A close fit

Tottenham Court Road station proved to be one of the most complex undertakings of the entire project. As an existing major underground station with multi-line interchanges, adding a new line was not straightforward. A significant challenge was building the declines to be able to fit in the escalators. The top of the tunnels would have come very close to listed buildings set within water-bearing gravel. Typically, the adjacent area would have been stabilised using ground freezing to carry out the works.

However, when Transport for London agreed to remove the requirement for a direct link from the Dean Street ticket hall to the tube's Central line, this avoided the need for high-risk tunnelling. It meant that a single flight of escalators (the underground network's third-longest) could be designed to fit into the station's footprint.

Building a brand-new rail station within Soho and on Oxford Street was no small feat. Arup advised that the entrance should be on Dean Street, which was subsequently pedestrianised, rather than directly on to the much busier, traffic-heavy Oxford Street. This meant there was no need to remove high-value retail shopfronts, and unnecessary congestion on a major shopping street was avoided. Nevertheless, creating a new station entrance in Soho required studying the safe movement and flow of people across the service's daily operations. Westminster City Council agreed to the final proposal.

An added complication was the lack of space between the underground tunnels and the new ones. The only option was for the tunnels to be directly over the Northern line and below the underground station's escalators. The design managed to meet this requirement, leaving just 700mm between the tube tunnel and the new Elizabeth line.



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Another key aspect of the works was mitigating the noise and vibration effects on Soho's many theatres and recording studios above ground. The team did this by creating a special 'floating slab' track structure which rests on elastomeric bearings for a 3km stretch. The slabs limit the transmission of noise and vibration from the train wheels to the surrounding ground where its impact on the buildings above may be unacceptable. These slabs were used in other critical locations including under the Barbican estate and its performing arts centre.

A custom design

Custom House station is the only new above-ground station on the Elizabeth line and acts as an interchange with the Docklands Light Railway (DLR). The challenges for this station were the interface with the DLR, maintaining both full operation of the station and the important access to the adjacent exhibition centre ExCeL London. The constrained 20m wide worksite was sandwiched between the DLR and the adjacent main road, and partially overhung by 400kV power lines. To accommodate these constraints, the JV design enabled the station to be constructed from prefabricated elements using just-in-time delivery to site.

Energy efficiency

At Tottenham Court Road, Liverpool Street and Canary Wharf stations, Arup designed the ventilation system to be passive, meaning that 75% of the annual cooling is done via natural air. Electrical chillers are only needed when temperatures reach a certain point. By using less powered ventilation, the stations are operated

13: Design constraints at Custom House station included working adjacent to the DLR and below overhead 400kV power lines

14: Special 'floating slab' track structures on elastomeric bearings were used to limit the transmission of noise and vibration to the surrounding ground

15: Each train on the Elizabeth line can carry 1,500 passengers

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more sustainably and at lower cost. LED lighting with an advanced digital addressable lighting control system was adopted throughout to further minimise electrical demand.

Recognising that the developments planned above the stations were going to require a sustainable source of heating and cooling, it was agreed with the Crossrail property team to incorporate a network of pipes in the perimeter diaphragm walls of the station boxes. These were collected together into a header and made available to the developers to use in conjunction with heat pumps to heat or cool their buildings.

Design safety

Arup's team of specialist risk engineers assessed, identified, and managed more than 1,300 operational hazards for six of the new Elizabeth line stations. By carrying out specialist studies such as hazard identification and explicit risk assessments, the firm was able to assess, analyse and evaluate the level of safety risk.

The firm's reliability, availability and maintainability team advised on the final systems design to ensure it could reliably deliver in the coming years. The team detected areas of potential critical failure and were able to provide alternative designs, to ensure high operational performance targets would be met throughout.

Operational readiness

Using Arup's operational readiness activation and transition (ORAT) methodology, the firm helped plan and prepare the mobilisation of the new line, building confidence for a successful first day and for operations beyond. Through extensive stakeholder engagement with contractors appointed to build the railway and stations, the ORAT team developed a comprehensive training programme, to familiarise and upskill the Transport for London staff who would operate and maintain the new line. More than 100 real-life scenarios were identified that needed to be trialled. In a series of workshops with network control, operations, maintenance, and trial operations teams, Arup mapped out the scenarios, rating the risks and prioritising them.

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16: Arup's operational readiness activation and transition team helped plan and prepare the mobilisation of the new line

17: The new line makes travelling into and through London easier, quicker and less crowded

18: An additional 1.5 million people are now just 45 minutes travel away from the West End and the City

18.

In total, 278 training packages were developed, with 508 training sessions delivered across a 14-month period ahead of the opening. The programme consisted of approximately 150 trials, followed by five major mass-volume volunteer exercises ranging from 300 to 2,000 people. The ORAT methodology not only provided a platform for the stakeholders to prepare for the opening of the new line, but also identified operational opportunities for improvement and corrective actions.

A world class railway system

The new Elizabeth line is a high capacity, high frequency rail system service, serving 41 stations from west London, passing through central London, and to the east and south-east. By providing additional capacity to the rail network, the new line has significantly reduced travel times, increased journey opportunities, and relieved overcrowding on some of London's most heavily used tube and rail lines. Each 200m long train, with nine walk-through carriages, can carry 1,500 passengers.

Arup succeeded in designing large underground stations which were built from very small sites at the surface level using the construction equivalent of keyhole surgery. Together, the new stations encompass new developments as well as public spaces, such as the roof garden at Crossrail Place in Canary Wharf. They add to the fabric of the city and positively affect the way people experience London.

The line has also played a small but significant role in supporting regeneration in the city. The scheme has already provided a huge economic stimulus to deprived areas like Thamesmead, Woolwich and Abbey Wood, and by offering radically faster access to the city, it has connected their populations to new opportunities for work, education and leisure. New developments at Abbey Wood in east London include a new library, public square and supermarket. There are now an added 1.5 million people who are just 45 minutes away from major employment opportunities in the West End, the City and Canary Wharf, as well as leisure and entertainment choices.

The opening of the line is a milestone for London. The Elizabeth line provides people with an alternative public transport option, and a further reason for people to leave their cars at home. Passenger journeys over the coming years will tell the story of how Arup has contributed to working towards net zero carbon targets.

Authors

Tim Chapman was the Bid Director who helped win the tunnelling design contract and carried out several other roles on the project during the design phase. He is a Director in the London office.

Alison Norrish was the Project Director. She is an Arup Fellow in the London office.

Graham Williams was the Project Director for the Tottenham Court Road station and Project Manager for the construction phase services station work. He is a Director in the London office.

Project Credits

Clients Crossrail Ltd., Canary Wharf Contractors Ltd., Laing O'Rourke (Liverpool Street), Costain Skanksa JV (Bond Street), Transport for London. Joint Venture partner for Crossrail works Atkins Architecture partners and collaborators Hawkins\Brown, Weston Williamson, Adamson Associates Infrastructure and station technical design, tunnelling, geotechnical engineering, fire engineering, technical risk and reliability, archaeology, sustainability consultancy, acoustics services, operational readiness activation and transition Arup

Image credits

1, 8-11, 15-18: Paul Carstairs/Arup
2: Arup
3, 5, 6, 14: Crossrail
4, 13: Ada Ihebom/Arup
7: Daniel Imade/Arup
12: Thomas Graham/Arup

1.

Vision of the future

Using circular economy principles to sensitively refurbish a heritage listed building

Authors Russell Cole, Graeme DeBrincat

The Burrell Collection comprises a vast array of precious art from around the world. First opened to the public in 1983, the museum in Pollok Country Park in Glasgow was granted Grade A listing by Historic Environment Scotland in 2013. It is one of the country's few Category-A heritage listed post-Second World War buildings. Unfortunately, a steady deterioration of the building fabric over recent years gave rise to a host of environmental issues that were detrimental to the museum's operations. Water ingress and façade performance issues meant that essential intervention was required to bring the building up to contemporary museum standards and guarantee its future.

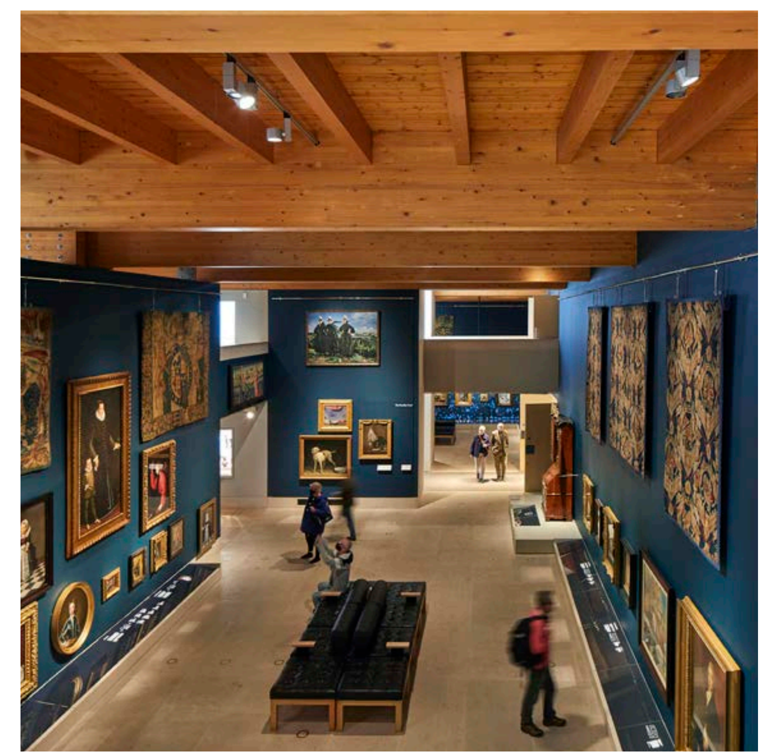
The original double-glazed façade system was typical for its time, with a monolithic outer glass pane and a clear internal laminated glass pane with no solar control coatings, making it less than suitable for 21st century needs. Much of the building's glazing was south facing, exposing visitors and artworks to high levels of sunlight. This was detrimental to the art, and also created significant overheating and occupant comfort issues, which put considerable strain on the building's cooling systems in the summer and heating in the winter, resulting in high energy costs. The water ingress was detrimental to the museum's ability to fully display the collection and limited the use of some parts of the building: resulting in the forced closure of the mezzanine level for example.

Arup was part of the design team on the five-year regeneration of the museum that resolved these issues, safeguarding the future of the building and its highly prized contents. The firm designed the upgraded sustainable façade, a crucial part of the works that has enabled the redisplay of the collection, which includes more than 9,000 objects spanning 6,000 years – all donated to the City of Glasgow by Sir William and Lady Burrell in 1944.

Circular economy principles were placed at the very heart of this refurbishment project, with as much original building material reused, recovered or recycled as possible. The redesign looked to maintain the building's history while

1: 80 tonnes of glass was repurposed as part of the project, with 16 tonnes recycled into architectural glass

2: The Burrell Collection houses more than 9,000 objects from across six millennia



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adding to its sustainability credentials. The upgrades provided the opportunity to significantly improve the building envelope's thermal performance, reduce energy consumption, and provide carbon emission savings.

The refurbishment resulted in the repurposing of over 80 tonnes of glass, with 16 tonnes recycled back into architectural glass. No glass material removed from the museum was sent to landfill; body-tinted, laminated and large-scale glass units which could not be readily recycled were processed into other building products.

Building inspection

The initial client brief required considerable upgrading of the building fabric, with key drivers including improved thermal performance, clarity of glass and natural light balanced against maximum solar control, full ultraviolet light spectrum filtering for collection preservation, and specific security requirements.

From the very early stages of the project Arup's façade team worked closely with architects John McAslan + Partners and building services and environmental designers Atelier Ten. The firm inspected and investigated the façade systems resulting in a pre-disassembly audit. Those initial inspections enabled the retention of as much material as possible for refurbishment and reuse in the upgraded façades. The reuse of the existing glazing framing was a key conservation criterion for the design team, who defined and validated a performance criterion that could be met by the contractor team within the bounds of the existing building and its listed heritage status. Each intervention was carefully considered, designed, refined and measured to understand its impact on the building's overall performance. This approach allowed the most suitable and practical interventions to be included in the design at the time of tender to the contractor team.

Glazing framework

Arup designed and detailed subtle façade interventions, implementing new performance elements. The opportunity to reuse the glazing bar was unlocked by the design of a new silicone cloaking gasket and thermal break system overlaid on the existing glazing bars. Development of this design resulted in a new watertight and airtight façade system, adapted with a new thermal break element to accept new modern double-glazed units within the constraints of the original glazing bar profiles.

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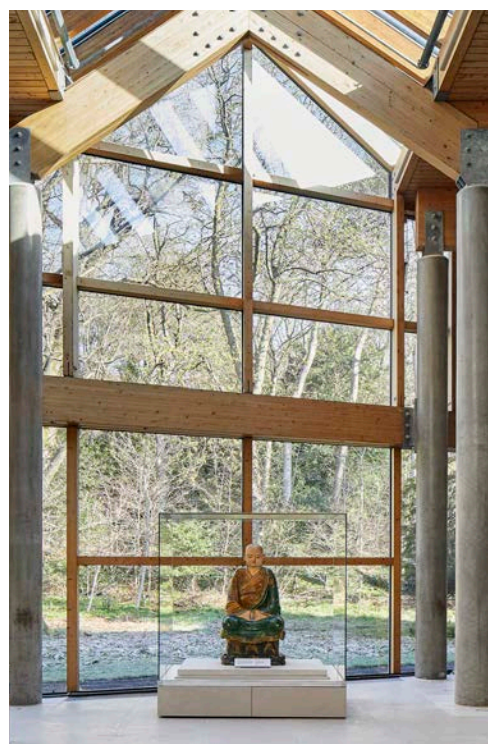

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3: None of the original glass removed from the museum was sent to landfill

4: The original architectural team dubbed the glazed wall looking out onto adjacent woodland as the 'walk in the woods'

5: The façade's northerly orientation meant the team could select neutral low-e coatings, improving thermal performance without compromising on visual clarity

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6: Circular economy principles were placed at the heart of the five-year refurbishment project

7: Reusing the existing elements and upcycling glass saved more than 100 tonnes of embodied carbon

A painstaking process of detailed inspection, structural analysis, cleaning, repair and strengthening of fixings to support the new high-performance glazing units enabled over 4.5km of glazing framework to be reused. The reuse of the existing framework generated a saving of 8.5 tonnes of aluminium when compared against a new system. Reusing the existing elements and upcycling glass from the refurbishment provided an exemplar of circularity in the façade industry, saving more than 100 tonnes of embodied carbon.

Solar control

High-performance solar control coatings were specified for targeted areas of the building's glazed envelope. This helped overcome the previous overheating issues caused by the lack of solar control and shading, which had a particular impact on the heavily glazed south-facing façade. The new system balanced visual clarity, glazing appearance and colour rendering.

A triple silver coating, using the latest industrial coating technology, was selected to balance the performance and visual criteria. While the glass colour neutrality was not able to match the existing uncoated glass, significant energy performance savings were realised: the coating excludes more than 70% of the sun's energy while allowing more than 60% of visible light through the glass into the building, as well as improved UV filtering. The upgrading of the glazing's thermal performance contributed a saving of 36 tonnes of operational carbon per annum.

Walk in the woods

The north façade of the Burrell Collection building is a key component in the experience of the museum. Dubbed the 'walk in the woods' by the original architectural team, the glazed wall in this location looks out onto the adjacent woodland. The link between the internal museum space and the woods required careful consideration in glass selection. Without the demands on solar control performance due to the façade's northerly orientation, the glass selection drivers allowed for neutral low-e coatings to be selected, providing thermal performance improvements without compromising visual neutrality and clarity. Minimising any colour rendering of the natural north light was of utmost importance to create the woodland link and provide optimal viewing conditions in this important museum space.

Awards

Project of the Year and Cultural & Religious Project of the Year - British Construction Industry Awards (BCIA) 2022

Refurbishment Project of the Year – Society of Façade Engineering Awards 2022

Cultural Award and Heritage Award - AJ Architecture Awards 2022

Cultural & Religious Building - AJ Retrofit Awards 2023

Café area

In the early 2000s, in an attempt to regulate excessive solar gains in the café, the facade of the south-east corner of the building was fully replaced with a proprietary glazed framing system and new body-tinted glass. This replacement removed a key feature of the original design: that identical framing elements were used for vertical glazed screens as well as the glass roof, providing glass to glass joints at the junctions. This replacement system's setting out was also inconsistent with the original building envelope.


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Arup's revised approach was to return this element back to an arrangement that reinstated the original building design at the time of the museum's opening. A new system was designed to match the regular glazing grid across the rest of the building, using identical framing system throughout. The design team standardised the external glass appearance matching the rest of the adjacent south-facing elevations. A full-scale wind and water test was carried out off site on the new system prior to installation.

Roof

The standing seam stainless steel cladding to all vertical elements and the pitched roof zones was fully replaced with a new system to improve weathertightness and insulation. The pitched roof utilises cellular glass insulation consisting of 60% recycled content, providing an airtight and vapour-impermeable layer below the membrane waterproofing and stainless steel finish. The grade and finish were carefully selected to replicate the building's existing materials. The non-visible roof systems were replaced with modern alternatives, and high-performance glazing was installed into the existing system. This upgrade provides significant improvements to the drainage of the roof spaces and its thermal performance. The greatly improved U-value of the new roof insulation contributes a saving of more than 220 tonnes of CO_2 per year in operational energy savings. The installation of new photovoltaic solar panels on these roof spaces provides a further 200 tonnes of CO_2 emission savings through the electricity generated.

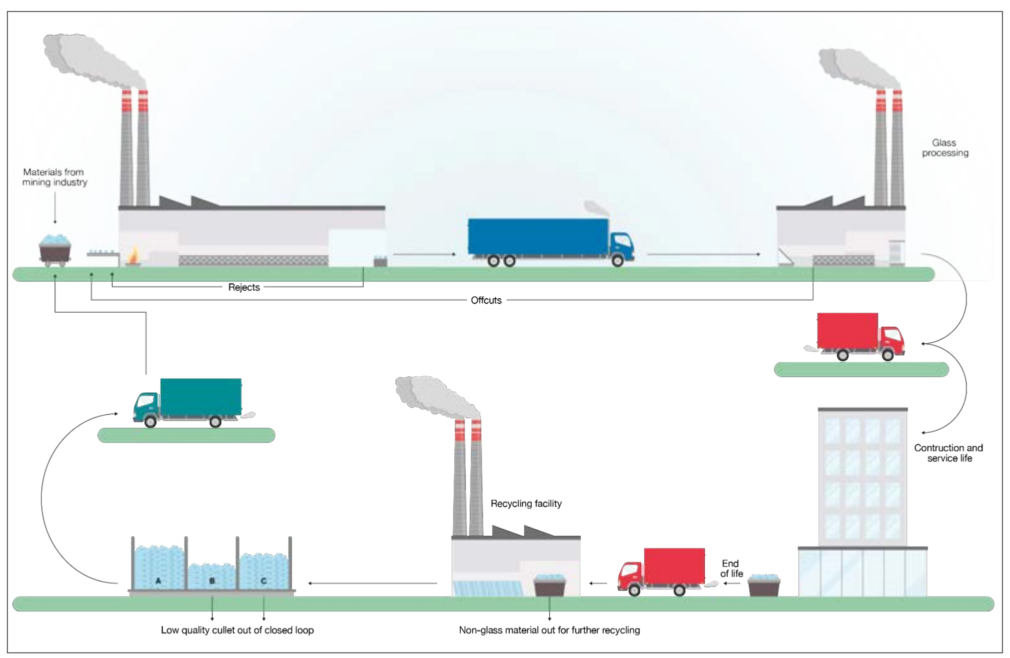
Fabric first approach

The fabric first approach adopted by the design team emphasised finding solutions that would significantly improve the building's performance, while respecting and revitalising the original architecture. This enabled the building to move from operational CO_2 emissions of around 126kg/CO_2/m^2 per annum pre-refurbishment to 39kg/CO_2/m^2 per annum. The building envelope improvements contribute 51% of these carbon emission savings, equivalent to a reduction of 626 tonnes of CO_2 emissions every year. The improved glazing solar control and thermal performance across the building saves 70 tonnes of operational carbon per annum, while thermal and airtightness improvements contribute a further 136 tonnes of carbon reduction per annum.

The refurbished building has achieved a BREEAM rating of Excellent, putting it in the top 10% of energy-efficient buildings in the UK, a significant achievement for the refurbishment and conservation of a Category A listed building. It is the first refurbished museum in the UK to attain a BREEAM Excellent rating.

Glass recovery

The Burrell Collection project was a catalyst for research by Arup into architectural glass recovery. During the research, the firm further developed an understanding of the current economic, technical, environmental and logistical structure of closed-loop construction glass recycling in the UK, as well as the typical refurbishment construction process and supply chain.



10.

8: A full scale wind and water test was carried out off-site on the new café glazing system

9: Improved glazing solar control and thermal performance across the building saves 70 tonnes of CO_2 per annum

10: 16 tonnes of recycled glass was recovered and used as feedstock for the manufacture of new architectural glass

11. The Burrell Collection is the first refurbished museum in the UK to attain a BREEAM Excellent rating


11.

Arup explored the limitations, barriers and viability of a circular approach to propose a strategy for implementing an operational system for glass recycling. The extensive research reviewed how the removed glazing could be diverted from landfill and ideally recycled back into architectural glass. With the findings and newly formed connections in the glass and glass recycling industry, Arup was able to specify that all the glazing (3,120m^2) was to be recycled, and played a key role in ensuring the specification was met.

Body-tinted, laminated and large-scale glass units that could not be recycled into flat glass were processed into other building products, such as glass fibre insulation and fines for use in concrete block production. The firm calculated potential carbon emissions from the process required to recycle the glass back into the furnace, including emissions from transportation. From the building, 16 tonnes of recycled glass was recovered and used as a feedstock for the manufacture of new architectural glass, eliminating five tonnes of CO_2 emissions from future glass manufacturing. Despite its endless recyclability, flat glass from buildings, up until now, was almost never recycled in this way. The museum redevelopment provided a successful pilot project for this glazing recycling approach, one that can be readily applied on future refurbishment projects.

In the UK, almost 200,000 tonnes of post-consumer glass waste is generated each year, with the majority not recycled back into glass. Most is downcycled into aggregate or deposited in landfill.

Expanding recycling glass would make a significant contribution to reducing carbon emissions and resource consumption, as every tonne of cullet used in glass manufacturing results in savings of 1.2t of virgin raw materials, saving more than 0.3t of CO_2 in future glass manufacturing. Arup is looking to build on the knowledge gained from this project, and is expanding the firm's research to include the challenges around effective disassembly of insulated glass units and glass delamination.

Authors

Russell Cole was the Project Director. He is Arup's UKIMEA region building envelopes skills leader and is a Director in the London office.

Graeme DeBrincat was the Project Manager. He specialises in developing Arup's approach to recovering glass and other materials from existing buildings for reuse and recycling and is an Associate in the Glasgow office.

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Building services Atelier Ten
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Contractor Kier
Façade and building envelope engineering Arup: Eva Babic, Matthew Burton, Russell Cole, Graeme DeBrincat, Robbie Fogarty, Alistair Frost, Justina Jakubkaite, Gavin Kerr, Laura McInnes, Alan McIntosh, Laura Zemella.

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1, 2, 5-7, 9, 11: Hufton + Crow
3, 4, 8, 10: Arup

1.

Wastewater infrastructure for the next century

Embracing collaboration to deliver a vital sewer upgrade, capable of withstanding earthquakes and extreme weather

Authors Sheba Hafiz, Eric Sekulski, Nik Sokol, Pete Wilkie

The Silicon Valley Clean Water Gravity Pipeline project is a 4.1m (13.5ft) internal diameter tunnel and pipeline that offers a valuable template to water authorities across the US and beyond, as they grapple with the twin threats of climate change and deteriorating 20th century infrastructure. The 5.3km (3.3 mile) tunnel, which is being delivered by a joint venture (JV) team including Arup as multidisciplinary designer, had to address numerous environmental and technical constraints. These included difficult ground conditions and the challenges of building large-scale infrastructure next to residential areas, an airport and a nature reserve. At the same time, innovative construction techniques were needed to ensure a 100-year design life, particularly in the face of climate-related extreme weather, the aggressive chemical environment predicted in the tunnel, and potential earthquakes – the San Andreas fault lies just four miles away.

The $253m tunnel was the first tunnelling project in North America to be delivered using the progressive-design-build (PDB) procurement method which utilises collaborative working between the owner, contractor and designer to maximise innovation and design efficiency while minimising construction schedule and whole life costs. As with conventional design-build, this involves the owner selecting a team at a very early stage of the project to develop the initial design. The difference is that the main construction contract price isn't fixed upfront but at the 60% level of design, before the final design and construction phase. Arup co-located its team with JV partners Barnard Construction and Bessac (BBJV) for two-and-a-half years. This interdependent working relationship was instrumental to fostering innovation and facilitating evaluation of project alternatives, such as the corrosion resistance of the installed pipeline. This led to the decision to use a large-diameter fibreglass-reinforced plastic mortar (FRPM) pipe within the tunnel – believed to be the largest such installation in North America. It also enabled the construction to start six months ahead of schedule.

Developing the concept design

The two-phase process of PDB took the project from 10% to 60% design in phase one, and then through to design completion and construction in phase two. Before that, however, the owner had to complete a concept design, approximately a 10% design level – which was a long and complex operation in itself. The project is part of the wider Regional Environmental Sewer Conveyance Upgrade (RESCU) programme run by the owner, Silicon Valley Clean Water (SVCW). The programme aims to effectively modernise their wastewater systems, building resilience and durable infrastructure for the local communities. This included replacing aged infrastructure, and upgrading pumping stations and sewage treatment works across the cities of Belmont, Redwood City and San Carlos, as well as the West Bay Sanitary District.

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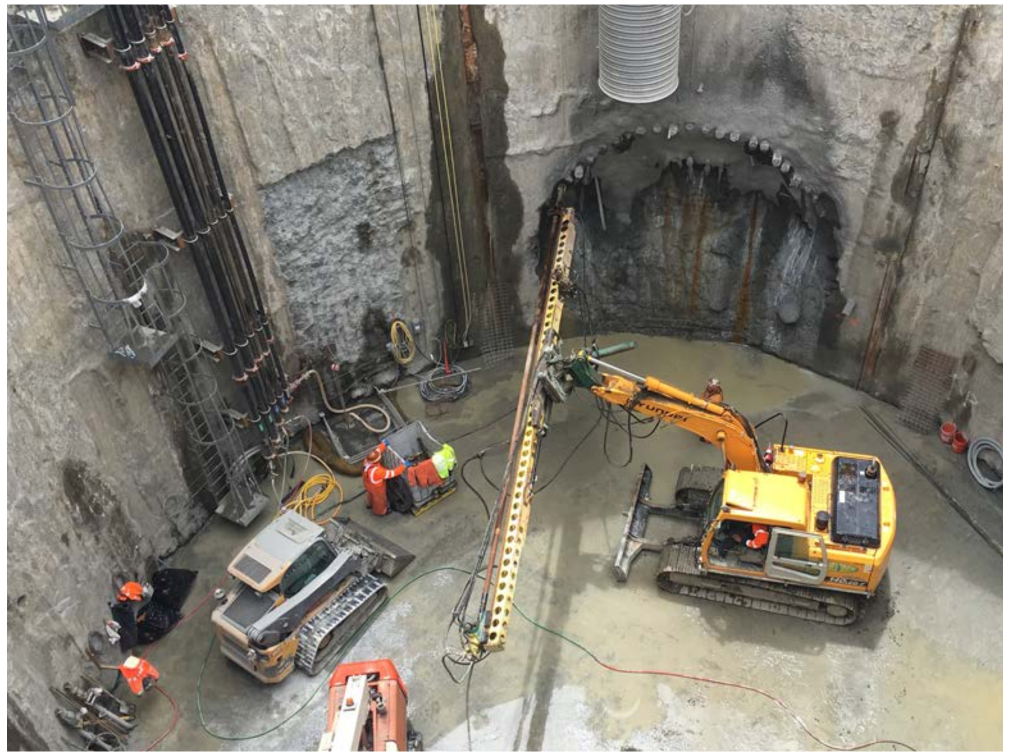
3.

1: The project offers a template to water authorities in the US and beyond, as they grapple with the twin threats of climate change and deteriorating 20th century infrastructure

2, 3: A FRPM lining was used for the tunnel to ensure long-term durability



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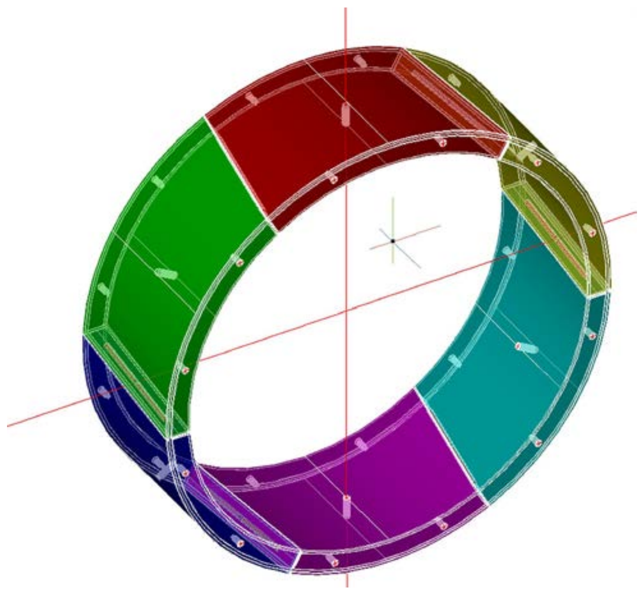


5.

4: The large excavation for the TBM launch shaft was 18.3m in diameter and depth

5: The tunnel lining is constructed from 1.5m long precast concrete rings with an internal diameter of 4.1m

The section leading to the main sewage treatment plant at Redwood Shores was one of the most urgent elements of the programme. Spills and leakages from the existing 1.4m (4.5ft) diameter forcemain were becoming commonplace, posing an environmental threat to the delicate ecology of the Bair Island Wildlife Refuge, as well as the local population. The concrete pipes, some of which were more than 80 years old, were deteriorating, and their capacity was proving inadequate. With SVCW identifying the need to manage increases in wastewater peak design flows of up to 390,000m^3 (103 million gallons) per day during wet weather, the risk of catastrophic failure was looming large.

SVCW considered 140 alternative schemes, evaluating capital and life cycle costs, reviewing risk and success factors, with five schemes evaluated in detail. Rather than a pressurised forcemain, which requires power to pump the effluent and carries the risk of both explosive leaks and expensive maintenance, the decision was made to design a tunnel system that would operate by gravity flow. This avoided an open-cut approach, either to repair or replace the existing shallow pipework from the surface level, which would have been disruptive to wildlife, transport, and local communities and businesses. The vertical alignment of the tunnel has a slight gradient to allow gravity flow conveyance of wastewater to the Redwood Shores plant.

The tunnel was sized to accept and equalise a broad range of flows from inlets connected to the existing network, as well as to store stormwater during peak wet weather events – this provided resilience to the system for both usage fluctuations and increased flows due to climate change. It also allows for flexibility of operation – saving costs by pumping wastewater during off-peak hours, for example, or pumping at a constant rate to prolong the lifespan of equipment. At concept stage, SVCW identified the notional diameter of the pipe to convey and store the flows as 3.4m (11ft). To install a pipe of this diameter at depth, a tunnel boring machine (TBM) had to be used to construct a tunnel large enough to allow pipe segments to be transported through it and connected.

The selected alignment for the tunnel was plotted along the estuary and generally followed the route of the existing forcemain. Starting at Inner Bair Island, the tunnel heads northwest towards San Carlos Airport, linking up with the Belmont and San Carlos pipelines before curving north-east to Redwood Shores. The depth was selected to ensure the tunnel would remain below a challenging geotechnical layer – the Young Bay Mud (YBM) – for the entirety of the alignment, eliminating the complexity of tunnel construction in a known difficult and sensitive ground condition. SVCW carried out an extensive geotechnical investigation for the whole route, conducting borings or cone penetrometer testing approximately every 75m (250ft). This identified the depth of the YBM and indicated a geological layer unit suitable for a TBM excavation along the tunnel alignment, through medium-stiff clays and sand, called the Upper Layered Sediments.

Building the team

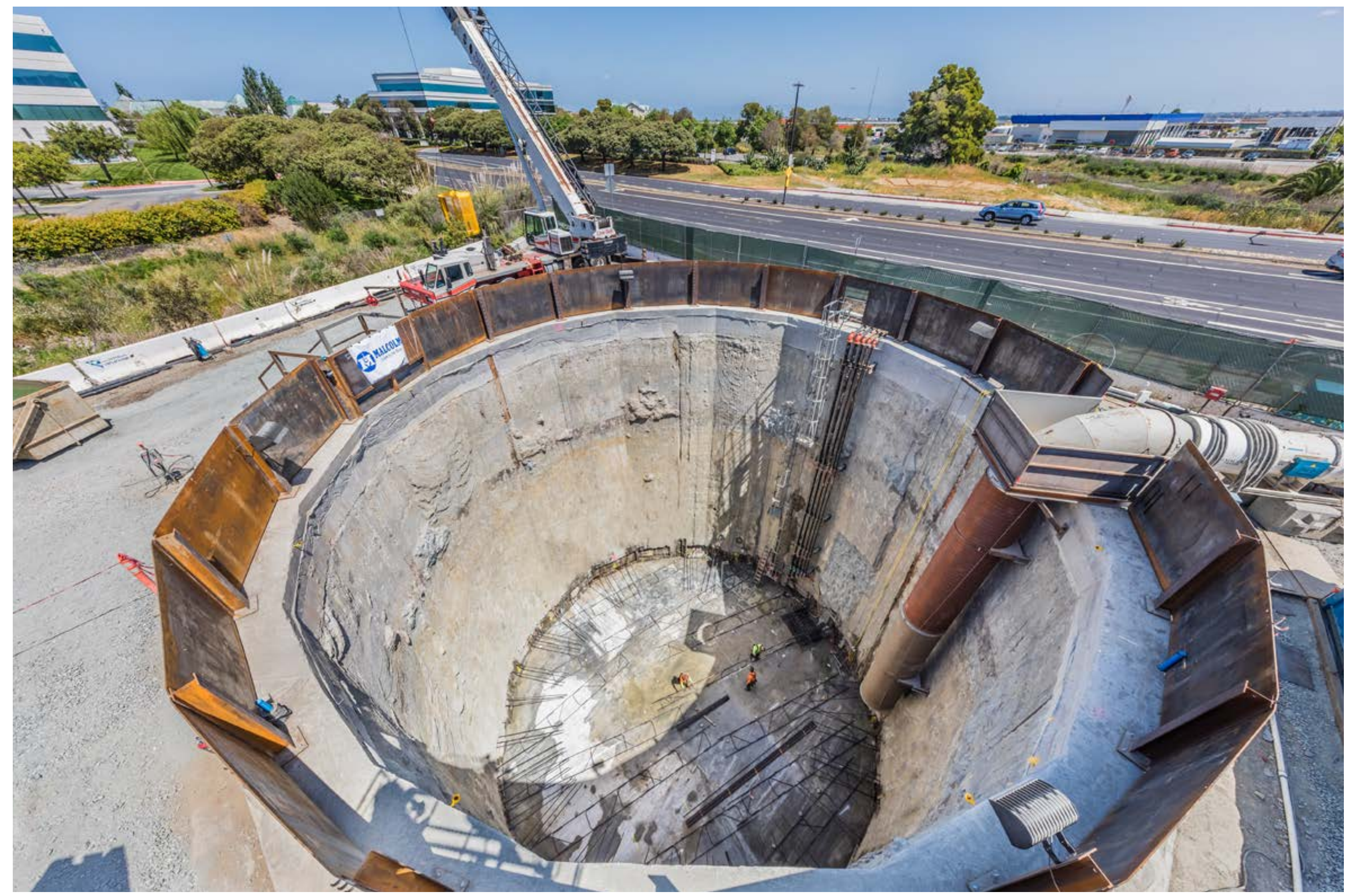
Once the concept design was completed and the project had achieved environmental clearance, SVCW invited bids for the PDB contract. As a knowledgeable owner with decades of sector experience, it made sense for SVCW to choose an approach that didn't involve a fixed budget and agreed requirements from the outset, but instead relied on flexibility, mutual trust and close collaboration with the builder and designer. An initial pool of six bidders was shortlisted to three teams. Over the course of three months, SVCW then conducted confidential meetings with each shortlisted team, evaluated their proposals and held interviews.

The winning consortium, BBJV, comprised Montana-based heavy civil construction experts Barnard Construction, which had recently completed the San Francisco Central Subway tunnels; French tunnel boring specialist Bessac; and Arup, whose multidisciplinary design role included everything from hydraulic and tunnel design to additional geotechnical investigation and analysis, and all other aspects of civil, structural, mechanical, electrical and seismic engineering.

The first phase of the contract, up to the 60% design milestone, included all aspects of the permanent works, such as the tunnel and shaft design. The design of the temporary TBM launch shaft, which needed to be big enough to assemble, accommodate and disassemble an 815-tonne (900-ton) machine, was also undertaken.

The flexibility of PDB meant that key project elements could be advanced to a higher level of design in phase one,

6: The project was the first tunnelling project in North America to be delivered using the PDB procurement method



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allowing the construction work to progress quickly after final costs had been agreed. These elements included the enabling works for the TBM launch shaft, the 100% design of the precast-concrete tunnel lining, and the specification of the TBM, which relied on BBJV's expert knowledge of closed-face tunnelling in the local ground conditions.

Tunnel design

The TBM launch shaft was placed near the airport, about a third of the way along the route. This ensured that the sizeable launch construction activities were located away from the ecologically sensitive Bair Island at one end of the tunnel and the residential areas at the north end. From there, the TBM would drive two tunnels, each to the retrieval shafts on opposite ends of the alignment, where the TBM was extracted.

The $18.2m machine, 200m (650ft) in length with all support elements, was manufactured by Herrenknecht in Germany. It operates using earth pressure balance (EPB), a system that works well with cohesive soils such as clay. EPB involves turning excavated material into a paste and using it as a support medium behind the cutterhead, balancing the water and ground pressure and thereby controlling the stability of the tunnel face during excavation.

The tunnel has a diameter of 4.9m (16.2ft) and was bored at a 0.5% gradient, dropping from 6.1m to 10.7m (20ft to 30ft) below ground level on the first tunnel drive, and then to 18.3m (60ft) on its way to the new SVCW headworks facility. The lining is constructed from 1.5m (5ft) long precast concrete rings with an internal diameter of 4.1m (13.5ft), with each ring composed of six segments. Dowels provide connections from segment to segment and from ring to ring – bolts being deemed more likely to corrode, and requiring more manual work around the TBM.

A high-density concrete mix was specified for the tunnel lining segments to minimise the risk of chloride-induced corrosion in the brackish ground conditions in the vicinity of the tidal estuary. Likewise, fibre reinforcement was preferred to traditional steel rebar. This had the added benefit of increasing the flexural strength of the tunnel and being less likely to crack – an important aspect of the seismic design. The segments were cast by Traylor Precast in Stockton, California to sub-millimetre tolerances using precision moulds made by CBE Group in France. Each of the six segments is slightly different in form, which gives the completed ring a tapered edge. This allows the tunnel to curve, simply by rotating the point of connection between one ring and the next.

Specifying the pipe

The other critical consideration for the tunnel designers was the threat of microbially induced corrosion (MIC). Microorganisms thrive in the aerated zone of a sewer, feeding on the sulphur naturally present in the wastewater and excreting sulphuric acid, which then reacts with the calcium carbonate in the concrete. This can result in up to 100mm (four inches) of corrosion over a 100-year life.

The team explored a number of options to combat this, including using a high density polyethylene (HDPE) lining integrally cast with the concrete segments and changing the concrete mix design to resist MIC. With long-term reliability at the forefront of their thinking, the team opted for the most durable option: a 3.4m (11ft) diameter lining of FRPM. Full-scale testing of the FRPM was carried out to demonstrate the adequacy of the lining installation and performance in service.

7.

7: The 815-tonne TBM was named 'Salus' for the Roman goddess of health and wellbeing

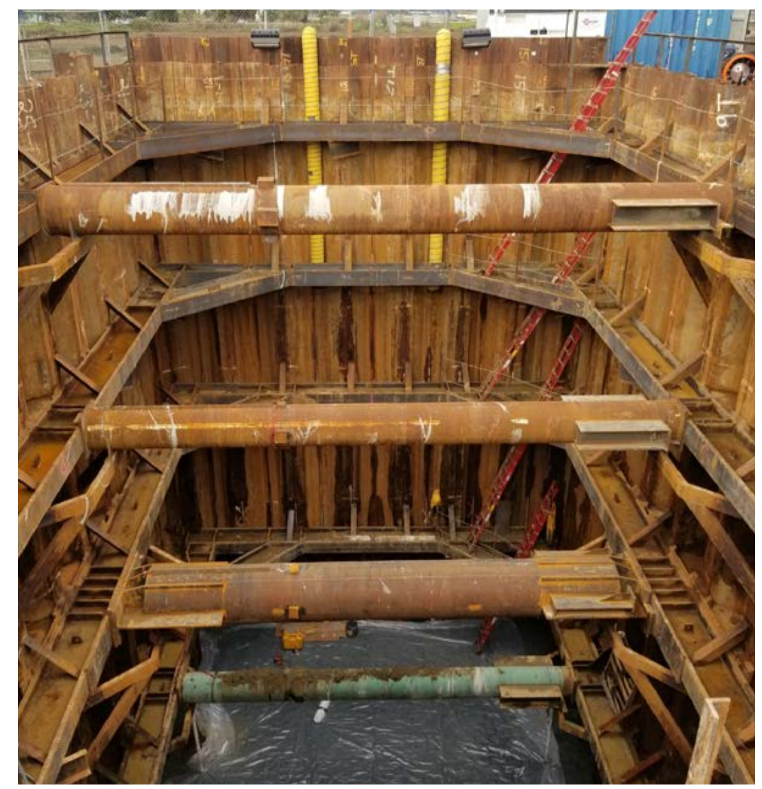
8.

An additional challenge was that FRPM at this scale was uncommon for a pipeline in the US, and there were very limited options for facilities capable of fabricating such large-diameter sections. The best available option was to import it from Future Pipe Industries, who had a facility capable of producing the pipe in Jakarta, Indonesia. Here, the team came up with a design modification that essentially halved the transport costs and related carbon emissions. For the first tunnel drive, the pipe diameter was reduced to 3.05m (10ft) – hydraulic modelling indicated that this would not affect the flow equalisation. This meant that the 6.1m (20ft) long pipeline segments could be nested and transported with one pipe inside the other.

Launch and retrieval shafts

The TBM launch shaft, known as the Airport Access Shaft (AAS), was 18.3m (60ft) in diameter and depth, with 900mm (3ft) thick reinforced-concrete slurry walls. Starter tunnels for the TBM were excavated through these linings, using conventional mining techniques, 12.8m (42ft) in either direction. As the tunnelling involved removing more than 85,000m^3 (3 million ft^3) of soil, a separate 55m (180ft) long, 3m (10ft) diameter tunnel was designed and installed to convey this material from the shaft base to the surface.

The retrieval shafts were smaller, as the modular TBM could be disassembled before being hoisted to the surface. At the Inner Bair Island end of the line, the rectangular steel-lined shaft was 7.2m



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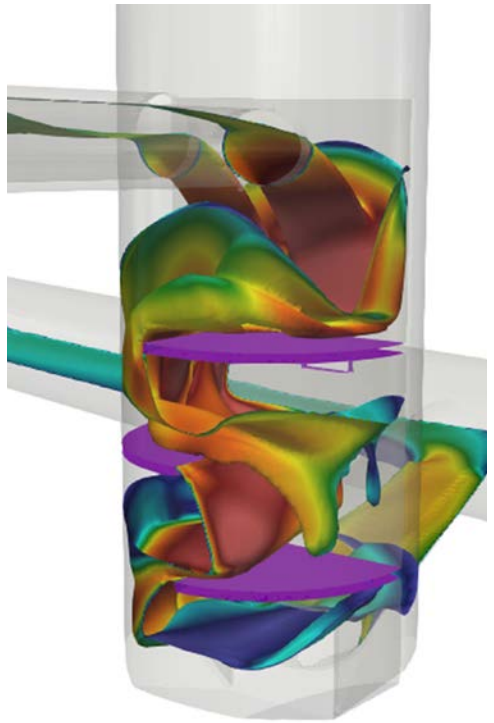
8: The FRPM liners, shown being shipped into the Bay Area, were designed with two differing diameters, so they could be transported with one pipe inside the other

9: A 7.2m by 18.3m steel-lined TBM retrieval shaft was constructed at Inner Bair Island



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by 18.3m (25ft by 60ft). At the other end, in front of the existing treatment plant, the retrieval shaft was 11m (36ft) in diameter, and also has a permanent use as a surge and flow splitter for a new headworks facility.

Drop shafts

Inflows of wastewater from the existing SVCW networks discharge into the tunnel at two locations. The flows are conveyed from the shallow inflow pipes to the deeper tunnel via two drop shafts. These structures were located at Inner Bair Island, at the eastern end of the pipeline where it connects to the Menlo Park forcemain, and at the existing San Carlos pump station, linking to the Belmont and San Carlos systems. To determine the flows, sediment travel and capacity, extensive hydraulic modelling was carried out. InfoWorks ICM was used to generate hourly and daily design flow scenarios based on average and peak rainfall derived from climate projections.

At Inner Bair Island, Arup designed a vortex drop shaft. As the influent drops from the pressurised pipe, the funnel-like shaft causes it to spiral, dissipating energy before reaching the base of the shaft and entering the gravity flow pipeline. Computational fluid dynamic (CFD) modelling was used to examine the influent and air flow, and ensure that there was no need for odour control facilities, which would have added operational and maintenance requirements to an otherwise sustainable, simple, low-energy system. The San Carlos shaft is slightly more complicated, as it connects to two separate inlets, each with different flow rates. Wastewater enters a hydraulic baffle drop structure, where it cascades down a series of ledges, before the combined flow is conveyed into the gravity pipeline via an adit, or connecting tunnel.

Arup worked closely with SVCW's and the JV's preferred suppliers to develop shop drawings for the unique drop shafts to accurately convey the design intent.

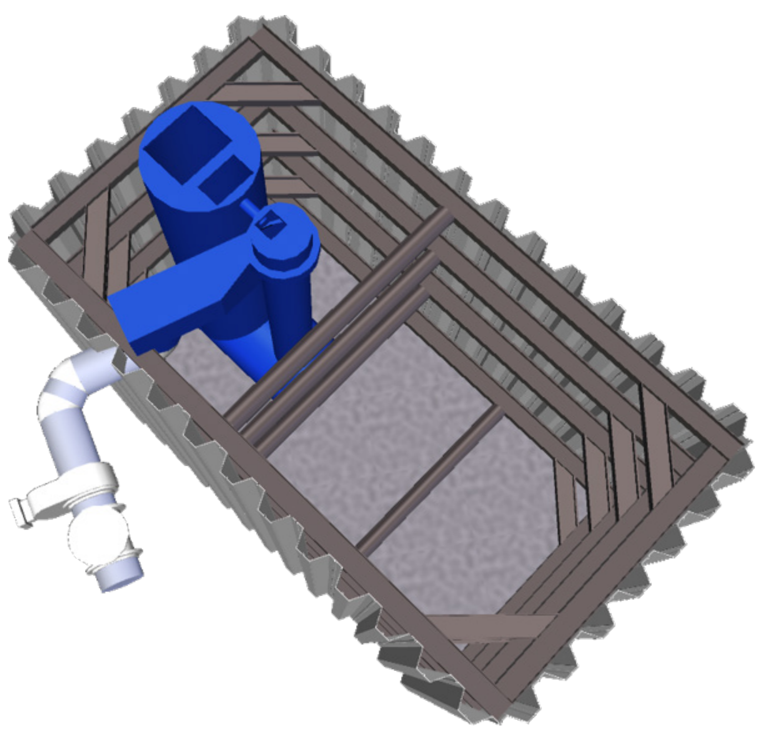
Construction

Work on the first tunnel drive began in July 2019, with the TBM (named 'Salus' for the Roman goddess of health and wellbeing) boring approximately a mile upstream from the AAS to Inner Bair Island. As much of the process as possible was automated. As the TBM progressed at the tunnel face, rails were laid behind it to deliver the precast tunnel segments and remove the excavated soil. The tunnel segments were transported on the tail section of the TBM and positioned using an erector, controlled remotely by the TBM operator. Once each ring was completed, it became the support for the TBM's thrust cylinders, pushing the cutterhead forwards into the tunnel face. The average excavation rate was approximately 30.5m (100ft) a day.

The first tunnel bore successfully reached the AAS in March 2020, at which point the main parts of the TBM were hoisted out of the shaft and transported back to the AAS to begin the second drive. Smaller components were taken back through the tunnel. The second drive, 4km (2.5 miles) to the headworks facility in Redwood Shores, began in June 2020.

As the second drive was under way, work began on installing the FRPM pipe in the first tunnel. This used a robotic pipe carrier, designed specifically for the project. The carrier could place the pipe precisely, rotating it and pushing it into the previous section, where it would be connected. The second drive reached the retrieval shaft on schedule in June 2021. The pipe carrier, which had been adapted for the larger 3.4m (11ft) diameter section, could then complete the lining of the pipeline. After the pipeline was installed into each tunnel drive, the space between the concrete tunnel and the FRPM liner pipe was filled with cellular grout to fix the pipeline in place.

SVCW and the JV partners are now working with the other RESCU project teams to coordinate the commissioning and start-up activities for the entire SVCW system. These activities are set to be complete by the end of 2023.



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10: CFD modelling was used to examine the influent and air flow of the pipeline

11: At Inner Bair Island, Arup designed a vortex drop shaft

12.

12: As the TBM progressed at the tunnel face, rails were laid behind it to deliver precast tunnel segments and remove excavated soil

Authors

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Project credits

Owner Silicon Valley Clean Water
Contractor Barnard-Bessac Joint Venture
Advanced technology and research, assets and operations, civil, electrical, geotechnical, mechanical, seismic and structural engineering, hydrogeology, infrastructure and tunnel design
Arup: Brian Albin, Eden Almog-Goldreich, Bernard Bodin, Jodi Borghesi, Stephen Burges, Kevin Clinch, Michan Condra, Tom Doyle, Steven Downie, John Eddy, Kirk Ellison, Chihurumanya Felly-Njoku, Nuno Ferreira, Audrey Fremier, Abraham Gebrezgiabhier, Mark Gilman, Alexej Goehring, Sheba Hafiz, Yuli Huang, Jon Hurt, David Knight, Guneet Kohli, Christopher Krechowiecki-Shaw, Pawan Kumar, Christopher Lim, Qiyu Liu, Dee Dee Maggi, James McCay, Mark Milkis, Angeliki Mitsika, Guillermo Munoz-Cobo Cique, Ryan Nordvik, Andrew Page, Luis Piek, Rubina Ramponi, Gayla Reeves, Sarah Sausville, Eric Sekulski, Keith Seymour, Surur Sheikh, Nik Sokol, Darren Sri-Tharan, Kevin Stanton, Emily Steinkamp, Eron Sudhausen, Anusan Sugumaar, Aihua Tang, Laura Thring, Alessandra Vecchiarelli, Julia Villanueva, Frederik Vind Jensen, Martin Walker, Pete Wilkie, Lazarus Zambezi.

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1, 4, 5, 9-12: Arup
2, 3, 6, 7: Barnard Construction
8: Infrastructure Solutions Australia

Sustainable provisions for the future

Working on a new approach to local food production to help with a sustainable future

Author Chintan Raveshia

More than half of the world's habitable land and over 70% of our fresh water is used for food production. How can we rethink the way we produce our food, how we consume it and how we deliver it, minimising the resources needed for production and reducing the impact on the environment?

These are the questions Arup examined while creating the Urban Food Production Masterplan Framework for Singapore, developed as part of the firm's own research programme. The framework considers how we can produce food in urban areas in the future, while achieving circularity and reducing global greenhouse gas emissions.

The Ellen MacArthur Foundation notes that by 2050, 80% of all food will be eaten in cities, so we have to examine how we grow, consume and dispose of food in urban areas. Circular economy principles will be critical in reducing waste and pollution, keeping products and materials in use, and regenerating natural resources that allow for food growth.

Currently, Singapore imports 90% of its food, including 98% of its fresh produce, making it particularly vulnerable to stressors like global supply chain issues, climate change and pandemics. However, the challenges facing the city-state are not unique. By 2050, more than 68% of the global population will live in urban areas. Population growth, combined with rapid urbanisation, resource scarcity, the climate emergency and technological advancements, is making people radically rethink the food cycle in cities. Urban

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1, 2: Singapore's small footprint and dense population made it an excellent testbed location for Arup to explore new approaches to urban food production

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farm benefits include employment, neighbourhood regeneration, and providing city dwellers with direct access to fresh produce that has travelled far fewer food miles.

In 2018, the Singapore Food Agency announced its ambition to increase food production from the current 10% of its need up to 30% by 2030. It aims to do this without impacting its climate pledge for carbon emissions to peak by 2030. This goal, along with Singapore's small footprint and dense population, made the location an excellent testbed for Arup to explore new approaches to urban food production.

4.

A world-first in food production research

Arup's Urban Food Production Masterplan Framework was launched in Singapore in 2019. The framework seeks to develop a methodology that will help advance high tech urban food production in cities without adding stresses on nature and resources, using circularity and systems thinking. Arup worked with stakeholders such as Singapore's Centre for Liveable Cities and the Singapore Food Agency to understand what changes are needed. Throughout the study, Arup engaged four key groups – food producers, distributors, financiers, and government and academia – to understand their processes and gain a wide perspective of the processes involved in food production.

The framework is a world-first in research that lays out Singapore's current food ecosystem and looks at potential future scenarios. It addresses the problem from a country-wide perspective, examining food supply across the board, from large-scale food production to areas with high community engagement.

In the framework, Arup focused on developing a systems-thinking approach. The team collectively brought together experts in food production, including those with expertise in planning, engineering, circularity and environmental skills to create a framework for key stakeholders in urban food.

With a globally expanding population, the way we currently produce food is untenable and limiting in developing a regenerative future. The aims of the framework include transforming the urban food production ecosystem, connecting supply chains, and reducing worldwide emissions.

Subsequently, in 2020 Arup deployed the framework on a pre-planning study for the Singapore Food Agency where the firm's all-encompassing approach examined the entire food ecosystem, covering energy, waste, circularity, water, transport and climate adaptation. Arup drew on 45 of its own experts globally, including from within Arup University, the firm's applied research and innovation programme, as well as strategy and management consultants, urban designers, and experts in energy and hydrogen grids. Outside of the firm, a dozen local partners were consulted.

Stakeholder and ecosystem mapping

Arup initially carried out a process through which the various stakeholders within Singapore's food ecosystem were mapped out, including each of the four key groups – food producers, distributors, financiers and government.

This mapping helped analyse the relationship between the different stakeholders and highlighted the difficulties faced by each in terms of design requirements and policies. It also highlighted how these groups are dependent on one another.

3.

3: Singapore imports 90% of its food, leaving it particularly vulnerable to stressors like global supply chain issues, climate change, and pandemics

4: By 2050, 80% of food will be eaten in cities, so examining how we grow, consume and dispose of it in urban areas is important

5.

6.

Next, an ecosystem mapping process divided the process into two: stakeholders and policies. The producers and distributors informed the design requirements, including those around energy needs, water supply, waste issues and space needs. These requirements were reviewed through a circular design lens e.g. where waste is eliminated from the cycle by being used as feedstock for another cycle. The understanding of these design requirements informed the policy stage, which is influenced by the government and finance stakeholders. This area addressed planning, social and economic policies.

Food production systems

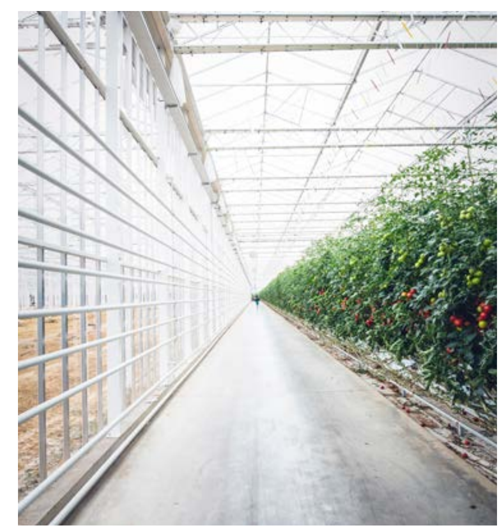
The next stage of the framework looked at the different systems of food production that exist within the city fabric. The four systems identified were high intensity farming, conventional farming, built environment and community farming – these range from high production systems to those with high community engagement such as allotments and market gardens.

5: The framework's aim is to develop a methodology that will help advance high tech urban food production

6, 7: Urban farm benefits include providing city dwellers with direct access to fresh produce that has travelled far fewer food miles

Each of the four systems identified has its own set of design requirements, and they do not just respond to each other within a system, but also interact between the four systems. The framework incorporated circular design into each system, looking at planning, energy, logistics, water, waste and the built environment.

Looking to the future, the Arup team considered how it could help local governments and city planners make changes to improve resilience and food security. In the framework, the firm considered requirements around space, electricity, water and transport in cities, and highlighted planning guidelines, design interventions and policy advice that would work environmentally, socially and economically.



7.

One key aspect is making effective use of the many tools already available, such as increasing local food production by using vertical farming. This method is driven by hydroponic crop production, which produces higher yields and reduces transportation costs. Hydroponic vertical farming is done under controlled conditions, lessening the effects of unfavourable weather and reducing water needs by 70% compared with traditional farming. This method also needs less space, with an acre of indoor vertical farming offering equivalent production to at least four acres of outdoor capacity.

Matching food requirements with education

The framework considered the importance of cultivating citizens' direct relationship with food production. For example, teaching children to plant, water and cultivate an urban garden with their family helps deepen their understanding of food production, as well as fostering social connections and community spirit.

Demand for meat has tripled in the developing world over the last 40 years, and egg consumption has increased sevenfold. This has driven a huge expansion of large-scale animal operations. Substituting meat with plant-based alternatives would significantly reduce emissions.

Educating people about better food production and consumption will also

8.

be crucial to ensure better sustainability and circularity. Currently, many still foster reservations regarding new sources of protein or fibre. But once people understand what resources are needed to grow food, they can more readily accept change. While many currently take year-round access to seasonal fruits for granted, a better understanding of the wider context could help people consider how sustainable this really is.

Food hub

As part of the Singapore Food Agency's aim to increase local food production and improve food security in a sustainable manner, it has plans to develop an agri-food production hub in the Lim Chu Kang region. Building on the masterplan framework created by Arup, the firm provided consultancy services for the preparation of the pre-planning masterplan for the hub, including urban design, architecture, transport and logistics, energy, agri-food production, water, waste, infrastructure planning, circularity and sustainability services.

The aim of the hub is to develop a high tech, high production and resource efficient agri-food precinct for Singapore. This would be provided in an attractive habitat with a vibrant and sustainable live-work-play environment, with climate resilient farms in an area well served by active mobility infrastructure and clean energy public transport. The concept includes three production hubs connected by a food and people loop, which supply the hub with water, energy and goods.

Arup reviewed the concept of food growing facilities for the hub with infrastructure ranging from those built at grade, a simple stack system (with several floors of the same food managed by one operator) to a hybrid stack (with different food types on different floors and several operators in one building). These options range from low to high across capital expenditure, complexity and land use efficiency criteria.

Thinking differently about food

Reconsidering how we think about food has become more pressing in recent years, with global supply chain issues since the pandemic, as well as regional wars affecting food supplies. By acting now, we can improve and enable urban food production, as well as the related social perspectives and policies necessary to get there. By working collectively, new ways can be found to improve food security, thereby increasing resilience, and integrating a more circular approach to the way we manage water, transport and electricity.

This framework highlights that to reconsider our food production, all stakeholders need to be involved in the conversation. These range from the government to those working in academia and financing, as well as in areas such as community farming and distribution.

Arup showed, in this unique undertaking, that there are vast opportunities in all of these areas and that collaborating with partners across all industries and spheres means we can find actionable ways to move forward. The firm has presented the framework at global food conferences, as well as to funding agencies, farming organisations, venture capital firms and others, and more recently has gone on to apply the framework to the city of Milan.

Authors

Chintan Raveshia was the Project Director. He is an Associate Principal in the Singapore office and is Arup's cities business leader in Southeast Asia.

Project credits

Economic planning, energy, environmental consulting, infrastructure design, masterplanning, transport

Arup: Fawwaz Azhar, Melwin Azwar, Michael Chadney, Ming Yew Chua, Vinicius Gaio de Siqueira, Fan Fan, Tom Gwyn, Ryan Koh, Lily Kuik, Anthony Leversedge, Ashvin Mahenthiran, Jian Kai Ng, Sarah Nurrachman, Reza Pardana, Khit Phyo, Chintan Raveshia, Ankit Sati, Shruti Shah, Kaitlin Shilling, Eike Sindlinger, Peter Stones, Bhavna Thyagarajan, Elisa Tiaras, Joyce Wan, Yichao Wang, Hans Zhou.

Image credits

1: Mike Enerio
2: Andy Gardner/Arup
3, 4, 7: Unsplash
5. Pixabay
6, 9: Singapore Food Agency
8: iStock

8: Hydroponic vertical farming is done under controlled conditions, reducing water needs by 70% compared to traditional farming

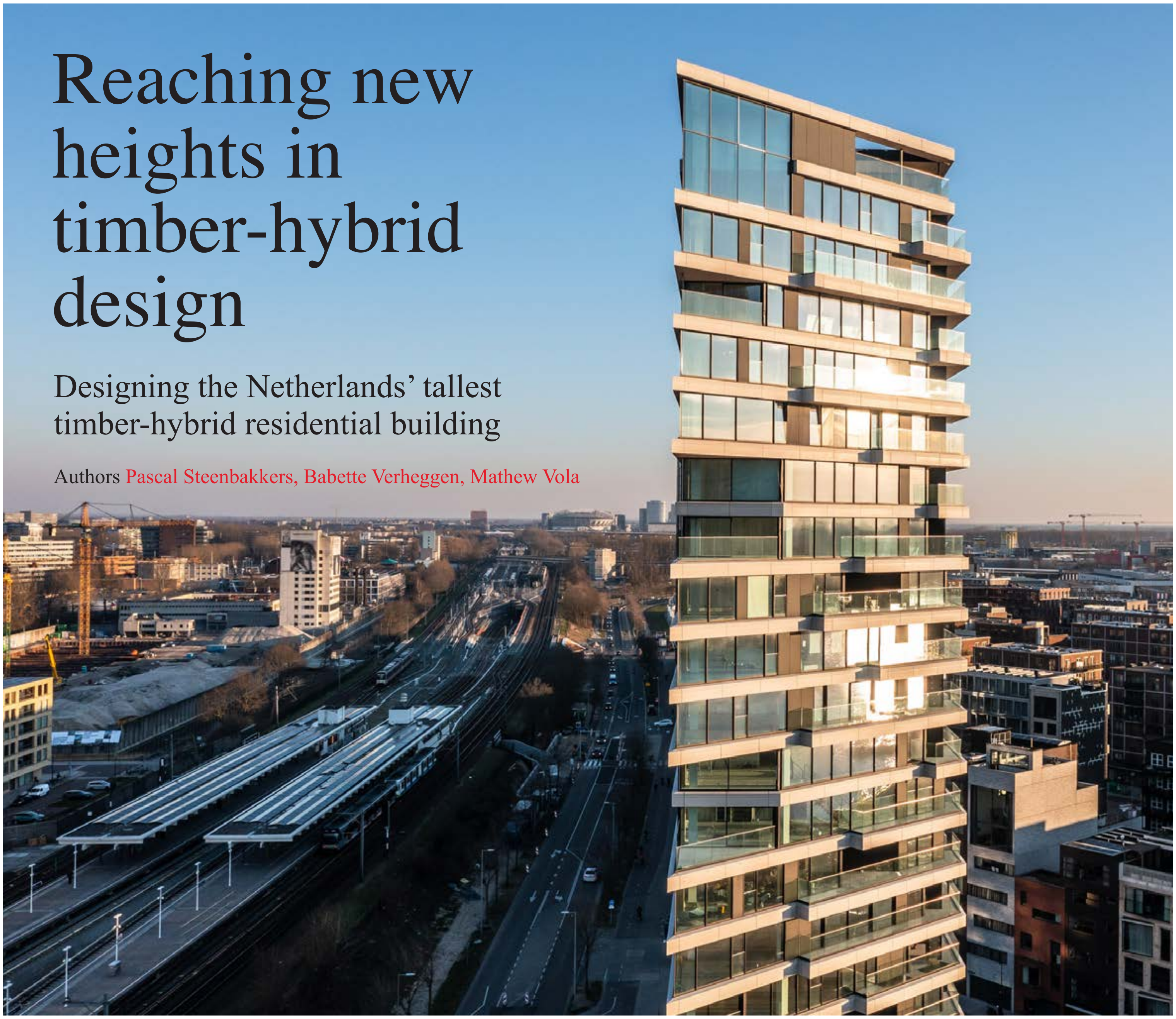
9: The plan is for the Lim Chu Kang agri-food hub to foster a vibrant and sustainable live-work-play environment

9.

Reaching new heights in timber-hybrid design

Designing the Netherlands' tallest timber-hybrid residential building

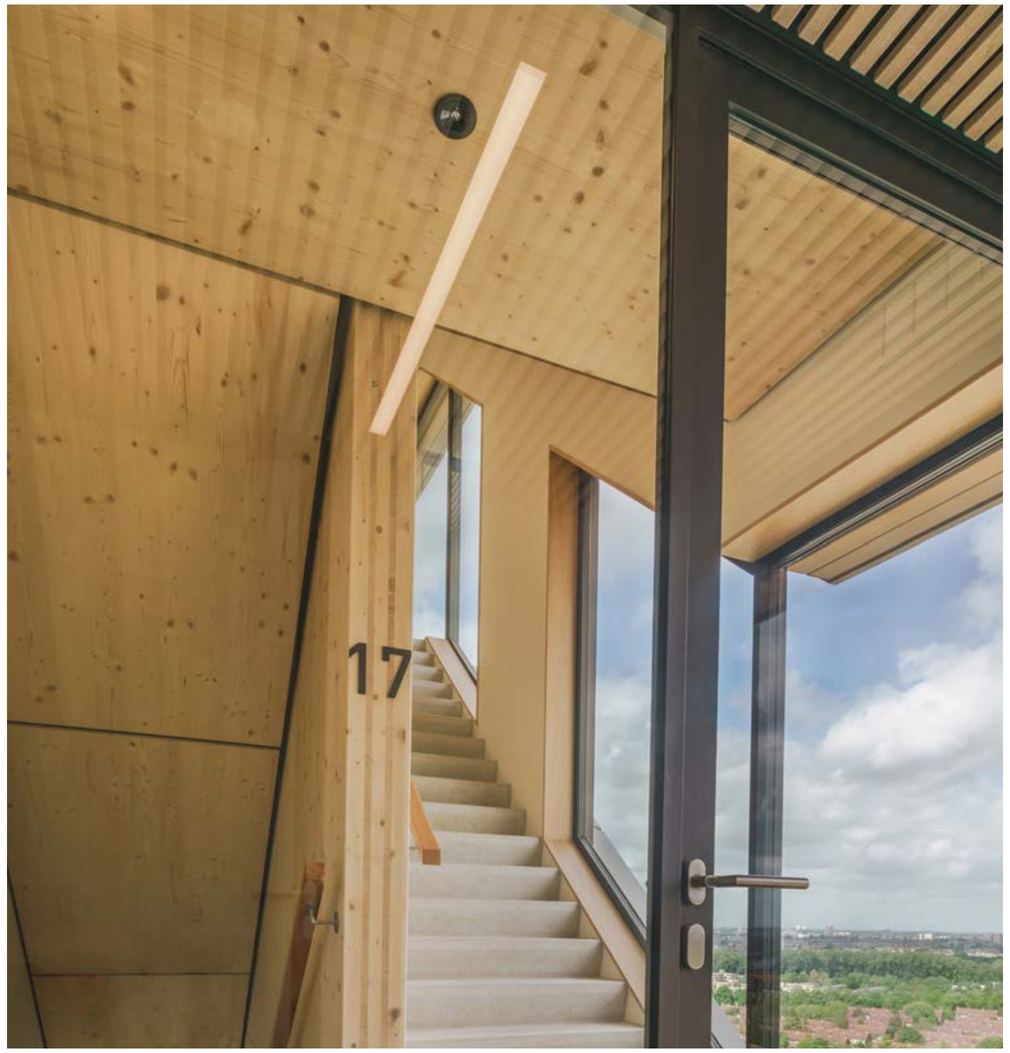
Authors Pascal Steenbakkers, Babette Verheggen, Mathew Vola



1.

1: HAUT pushes the boundaries of what is possible with high-rise timber design

Standing 21 floors tall, HAUT is one of the tallest timber-hybrid buildings in the world. The name of the building is a play on the Dutch words for timber (hout), on the French word for high (haute), and on 'haute couture', befitting this 'high end' building in Amstelkwartier – a new district on the edge of Amsterdam's city centre. When the city's municipality launched a design competition in 2016 for the building plot adjacent to the Amstel river, they emphasised the importance of the design being both sustainable and of high architectural quality. Together with developer Lingotto and Team V architecture, Arup's multi-disciplined approach has delivered on that intent with a revolutionary timber-hybrid residential tower, reaching an impressive 73m above the river. To engineer this bio-based high rise 14,500m^2 residential building, the firm's team of specialists delivered the sustainable, structural and technical design, including building physics, building services, acoustics and fire safety engineering.



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3.

2: More than 2,800m^3 of timber is used in the structure

3: HAUT is a certified BREEAM Outstanding building

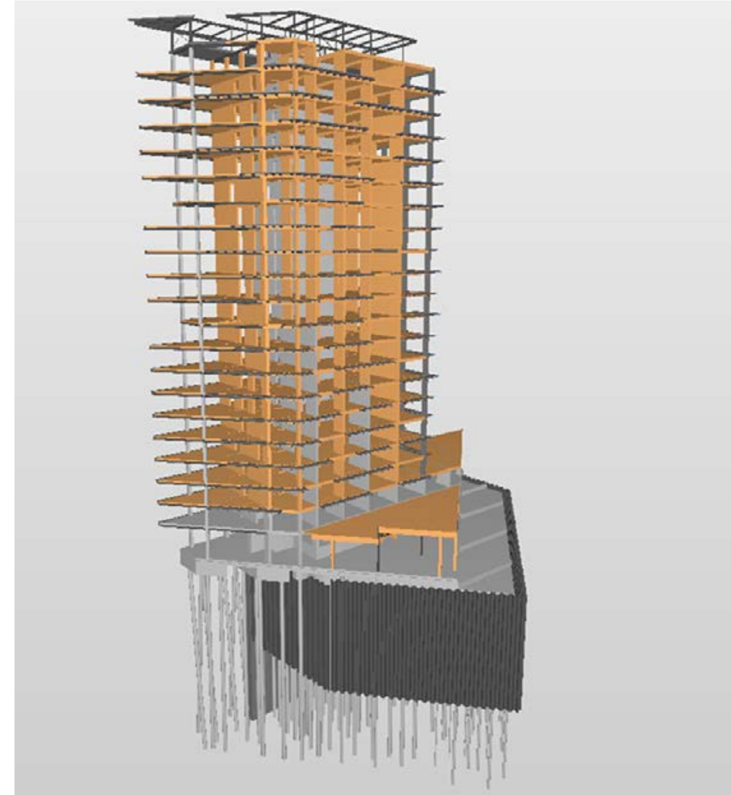
Carbon reduction

To achieve its climate goals, the Netherlands has committed to becoming carbon neutral by 2050. Using timber as a building material is one of the most effective ways of accelerating decarbonisation, as the associated carbon footprint is much lower compared to construction with concrete or steel. In addition, the timber acts as carbon storage for decades to come and is a regenerative material. In 2021, more than 80 Dutch companies signed a Green Deal covenant, ‘Houtbouw of the Metropoolregio Amsterdam’. With this covenant, Amsterdam is committing to the goal of building at least one in five residential buildings using timber as the main structural material, from 2025 onwards.

Bio-based building is gaining momentum all over the world, as more and more people embrace the natural qualities of timber. While the natural material’s enhanced atmospheric, acoustic and health qualities are a factor, the most important driver for the growing use of timber is the potential to significantly reduce carbon emissions. In HAUT, more than 2,800m^3 of timber was used in the structure alone, bringing the total reduction in embodied carbon to half of a conventional high-rise structure. When including sequestration, some 1,800 tonnes of CO_2 is stored in the structure.

Sustainable and innovative

In recent years, Arup has designed and delivered a number of timber and concrete/timber hybrid framed buildings, including the seven-storey H7 timber-hybrid building in Münster in Germany, Sydney’s Macquarie University Incubator and adjacent four-storey Ainsworth Building, and 80 M, the first mass-timber overbuild in Washington DC. The firm was able to tap into its global experience for HAUT, in particular on the fire engineering aspects, where integrated fire safety provisions played a key part in enabling the overall sustainable timber design.



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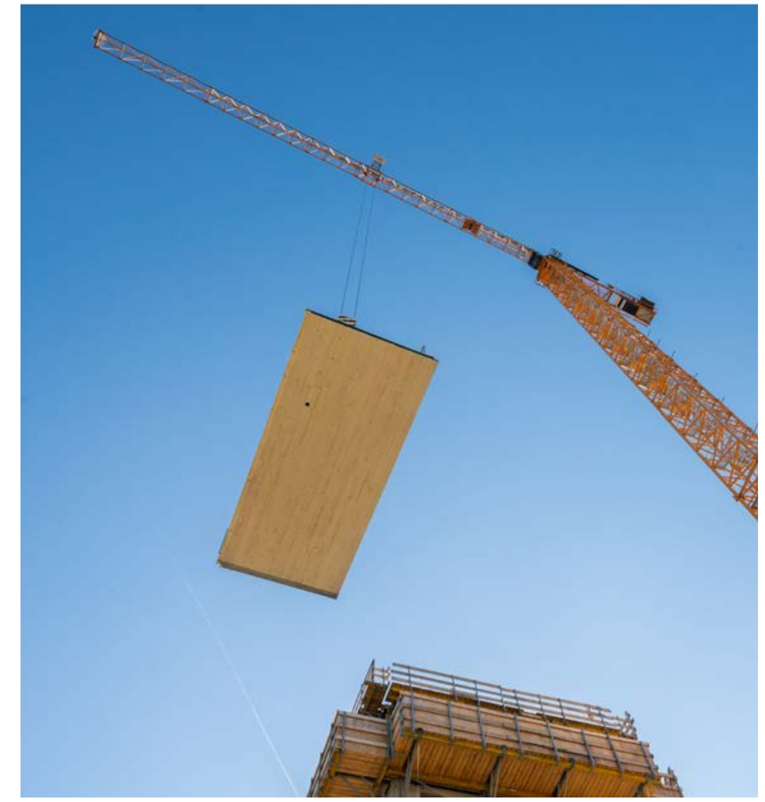


5.

4: The design principle for HAUT was to use timber where possible, and concrete and steel only where necessary

5: The timber hybrid floors are supported on CLT load-bearing walls and glulam timber columns

The architectural aim was for the tower to have a transparent appearance, with lots of sunlight supplying the building with natural heating and optimal lighting conditions. The team designed a façade that consists largely of (triple) glass, with custom photovoltaics (PV) panels that were fully integrated into the façade attached to non-combustible panels and with fire stops at floor levels.

Combined with the rooftop panels, the 1,250m^2 of PV provides an energy-positive exterior that generates a large portion of the building’s electricity. The tower features an aquifer thermal energy storage system, sensor-controlled installations and low temperature underfloor heating, making it one of the most climate-friendly high-rise residential buildings in Europe. A rooftop garden and nest boxes for birds and bats add to the biodiversity on site, with the rainwater collected at roof level used to irrigate the garden.

Structural scheme

With 21 levels, HAUT needed to be easily constructed while satisfying structural, acoustic and fire safety requirements. The design had to consider various site constraints, including the plot orientation, proximity to the river embankment, railway and existing buried data cabling, and the soft soil conditions. The foundations included 104 ground-displacing steel screw grout injection (‘Tubex’) piles and 54 tension anchors. In addition, a load-bearing diaphragm wall was utilised along the edge of the building plot.

The design principle for HAUT was to use timber where possible, and concrete and steel only when necessary. While the foundations, two-level basement, core, and ground and first floor were constructed in concrete, for the 20 levels above that, timber was predominantly used. Looking for ways to maximise the use of timber as much as technically possible, Arup developed an innovative and affordable technical solution for the upper levels. The result was a custom-designed precast timber-concrete composite floor plate developed in close collaboration with Lingotto, Team V architecture, contractor J.P. van Eesteren and the German timber specialist Brüninghoff.

Hybrid construction

The floor build-up consists of a 160mm deep cross-laminated timber (CLT) plate with an 80mm concrete top layer, supported on CLT load-bearing walls and glued laminated (glulam) timber columns. In this floor build-up, the two horizontal layers act as a hybrid system, in which the timber takes tension forces and the concrete takes the compression. In certain areas, where the floor edges are not supported by a load-bearing wall, glulam downstand beams were introduced. These beams transfer façade and balcony loads, and provide additional stiffness to the floor. They also double as a tension ring around the perimeter of the floor, transferring diaphragm forces and acting as a structural tie.

The choice of a hybrid floor plate had big advantages for footfall performance (reducing vibration), acoustic performance, construction sequence and detailing. Due to the low self-weight of the floor plates, delivery vehicles could also be loaded more efficiently, resulting in fewer deliveries to the building site.

Stability system

A concrete-timber lateral stability system was used, consisting of a concrete core and two full-height CLT shear walls. The eccentric positioning of the core (for architectural reasons) introduced torsional effects under wind loads, increasing lateral deflections and wind-induced vibrations. To determine the expected maximum lateral deflections and perform sensitivity studies, two finite element models were created. The first was a 3D model of the entire lateral load-bearing system, including the concrete ground floor, basement and foundations elements. This was predominantly used as a means of assessing total deflections and the sensitivity to stiffness of individual structural elements, including the foundations.

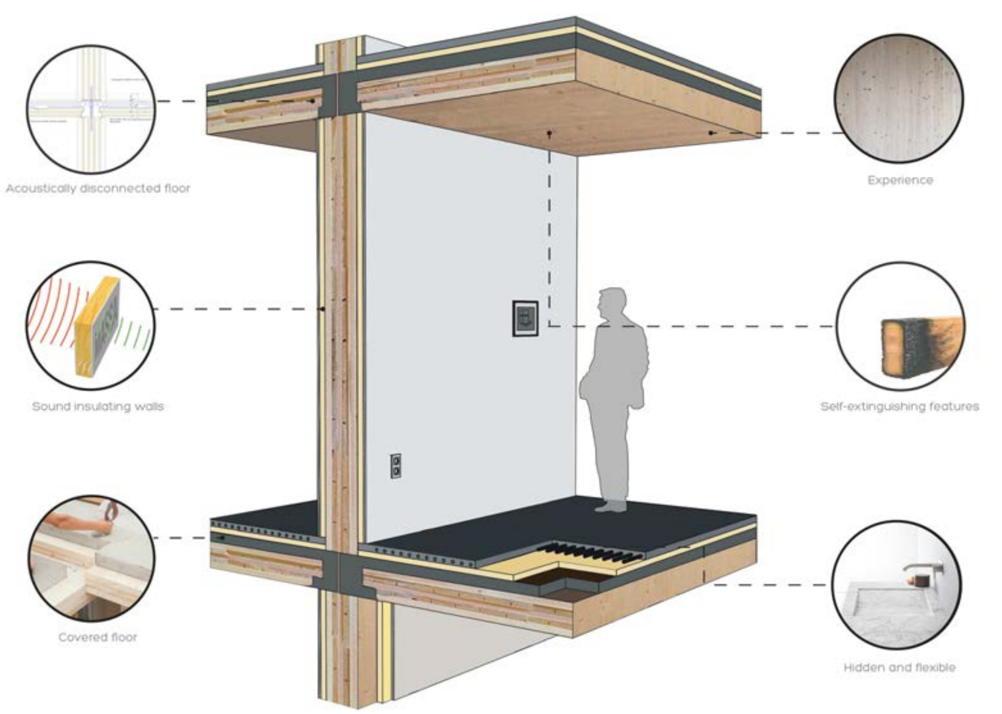
The second model consisted of a 2D model of the CLT wall, including specific wall openings, orthotropic material behaviour and locally reduced stiffness to allow for acoustical decoupling and connection details. The model was subjected to gravity loads and lateral loads taken from the 3D model. Subsequently, the resulting deflection in the 2D model was compared to the deflection in the 3D one, allowing for a check of the initially assumed stiffness.

The concrete core is also used as a fire brigade entrance and provides the fire escape routes. Risers were used for the building services, which were then distributed horizontally at a high level into each apartment. The distribution of the services required careful coordination to meet the structural, acoustic and fire safety requirements. In the apartments, the air ducting system was distributed in the ceiling zone in the non-living spaces, e.g. corridor, kitchen and bathroom zones.

Vibration control

As HAUT's hybrid structure is a lot lighter than an equivalent concrete building, wind-induced vibrations were considered a risk, and were investigated in detail to ensure compliance with the code. To calculate the expected maximum accelerations, a modal analysis was performed on the previously developed 3D model of the structure. The calculated vibrations were sensitive to the mass of the building. This was one of the most important motivations for choosing the specific floor build-up that is used in HAUT.

The additional mass of timber-hybrid floor (compared with a full CLT plate) provides additional benefits, improving acoustic performance, reducing footfall-induced vibrations, and increasing performance against wind-induced vibrations. Several floor elements are supported by the concrete core wall on one side, and a timber wall or beam on the other. The difference in mechanical properties between these supporting elements will cause differential movements between the two, and careful design considerations were given to ensure this would not create architectural or functional issues. To take into account creep and shrinkage effects, the concrete core was constructed using in situ concrete, rather than assembled from prefabricated concrete elements.

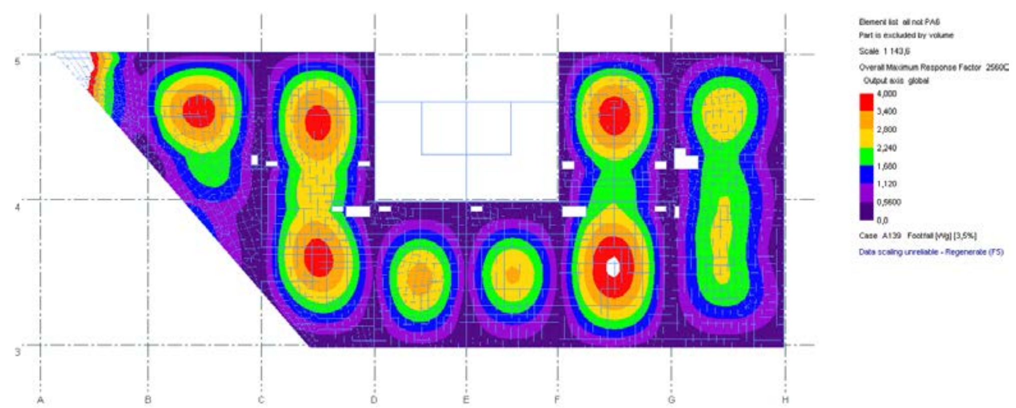


6.

6: To determine acoustic performance, a section of the floor build-up was tested for both airborne and impact sound isolation

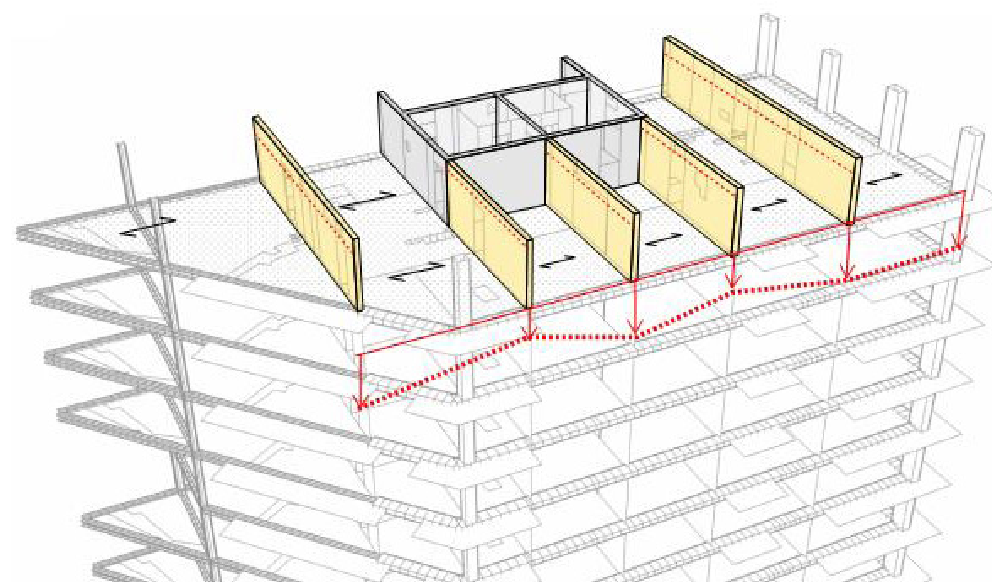
7.

7: The floor build-up consists of a 160mm-deep CLT plate with an 80mm concrete top layer



8.

8: The choice of a hybrid floor plate had big advantages for footfall performance by reducing vibration



9.

9: The difference in mechanical properties between the supporting concrete and timber elements causes differential movements, and careful design was needed to ensure this would not create functional issues

A wind tunnel test of a physical model of the building was carried out, along with on-site testing during construction with building-mounted sensors. The analysis and results from the sensors on site compared favourably.

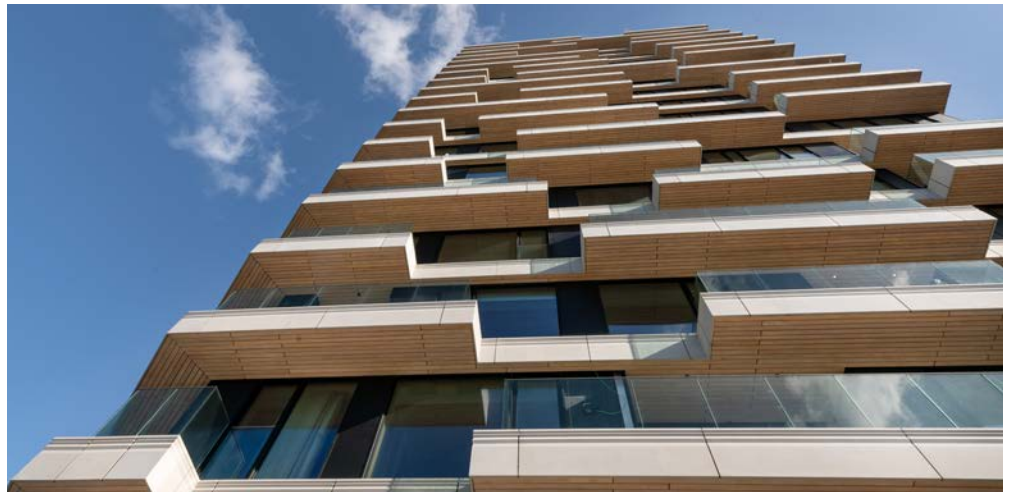
Acoustic design

Laboratory and on-site testing was completed to ensure that the acoustic design limited any crossover of sound between the apartments. This is an elevated risk for this type of project because of the extensive exposed timber elements – particularly in the living spaces, where there are no ceilings. Arup went beyond the existing acoustic requirements for residential projects in the Netherlands, which are some of the most stringent in Europe. To determine acoustic performance in those high-risk areas, a section of the floor build-up was tested for both airborne and impact sound isolation. With the lower mass of the hybrid floor system, low frequency sound isolation was the determining factor in overall acoustic performance. During construction, further tests were carried out on site to provide additional reassurance on the acoustic performance of the system.

Fire safety

HAUT pushes the boundaries of what is possible with high-rise timber design. Local building codes do not address the additional fire risks inherent in tall timber buildings. The bespoke fire engineering design needed to address those fire risks, ensuring adequate means of escape and structural stability in fire situations, and mitigating the risk of fire spread. Arup called on its global expertise to carry out a rigorous review of the project, developing solutions that brought the design in line with international best practice. This led to additional fire safety measures being implemented in the building.

The fire risks that needed to be addressed in the bespoke fire safety design revolved around the height of the building, and the use of load-bearing CLT walls and exposed timber ceilings in the apartments. As timber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is a combustible material and the architectural intent was to expose the timber at the ceiling, this fire hazard had to be addressed. The fire safety engineering assessed the likelihood and consequences of an extended fire duration and fire spreading beyond the compartment of origin. The performance-based fire strategy identified and managed those risks.

The Dutch building code does not require sprinkler protection in residential buildings of this height, but to contribute to a robust design, sprinklers were included. Also, to reduce the volume of exposed timber, a double layer of fire-resistant panels were installed to protect the CLT walls. The panels also improved the acoustic performances and are an example of an integrated design approach which enhanced the building redundancy and its quality. Laboratory fire testing was carried out in Belgium on the fire-resistant wall panels, with furnace tests providing both data and giving a practical demonstration of the compliance. Additional fire tests were carried out in Vienna to demonstrate the charring rate of the exposed CLT floor system. The tests determined the extent to which CLT panels burn over time, and helped determine the type of adhesive used. The choice of adhesive was critical to reduce the risk of CLT adhesive bond line failure in fire (so called char delamination) and to control the charring rate of the timber. Excessive charring could result in an unpredictable fire outcome and additional fire load.

10: Arup's fire team is supporting the development of additional guidelines to aid with amendments to local building codes

11: Distribution of the building's services required careful coordination to meet the structural, acoustic and fire safety requirements

12: A performance-based fire engineering approach was adopted to manage the fire risk of the exposed timber ceilings

13: HAUT is the tallest timber-hybrid residential building in the Netherlands


13.

By engaging Arup's international global fire safety engineering network and its extensive global research, the firm used the project to develop and formulate design solutions that can now also be used to enable the sustainable design of other mass timber high-rise projects. As a result of this global knowledge sharing, Arup has now been asked to support the development of additional guidelines to aid with amendments to local building codes. The firm is also influencing changes to regulations around the use of timber in construction in the Netherlands, particularly for large scale and mid-rise to tall timber buildings.

Groundbreaking

With its focus on reducing carbon footprint even before it was built, HAUT won the International BREEAM Award 2018, and following its opening, it won the Het Houtblad Timber Building of the Year 2022 award, which recognises the best timber building in the Netherlands. In addition, it was certified BREEAM Outstanding – an acknowledgement awarded to only a handful of high-rise residential buildings globally, and the first residential project in the Netherlands to achieve this sustainability certification.

Authors

Pascal Steenbakkers was the fire safety discipline lead. He is an Associate Director in the Amsterdam office.

Babette Verheggen was the acoustics and building physics discipline lead. She is an Associate and leads the acoustic team in the Amsterdam office.

Mathew Vola was the Project Director and is Arup's global computational design skill leader. He leads the structures team in the Amsterdam office, where he is a Director.

Project credits

Developer Lingotto
Architect Team V architecture
Timber engineering Assmann beraten + planen and RWT Plus
Contractor J.P. van Eesteren
Timber sub-contractor Brüninghoff
Acoustic consulting, building physics, building services, fire safety, structural engineering, sustainable buildings design Arup: Ishan Abeysekera, David Barber, Sander Boogers, Enny Breure, Jorn De Jong, Daan Duppen, Bettine Gommer, Michiel Hagenouw, Cameron Heggie, Carsten Hein, Arno Hoogendoorn, Wahit Karamali, Mark Koks, Bart Kramer-Segers, Susan Lamont, Andrew Lawrence, Mike Magnier, Hassan Moharram, Filique Nijenmanting, Warner Post, Shibo Ren, Pascal Steenbakkers, Lachie Stewart, Kevin Truijens, Wesley Van Der Bent, Layla Van Ellen, Rogier Van Reen, Miriam Van Rooij, Luke Van Velzen, Emilie Van Wijnbergen, Raymon Velthuis, Rob Verhagh, Babette Verheggen, Mathew Vola, Pieter Wackers, Tom Warger, Therese Worley.

Image credits

1-3, 5, 10-13: Jannes Linders
4, 7-9: Arup
6: Team V architecture

Lou Reed's sonic legacy

A unique multimedia installation for the first large-scale exhibition of Lou Reed's archive

Authors Gideon D'Arcangelo, Joseph Digerness, Raj Patel, Xena Petkanas, Léonard Roussel

The Lou Reed Listening Room, which formed part of the recent exhibition *Lou Reed: Caught Between the Twisted Stars*, was designed to put the listener at the heart of the music. The exhibition at the New York Public Library for the Performing Arts goes a long way towards preserving the legacy of Lou Reed, an artist who continues to influence a wide range of musicians and writers today. The Listening Room is a multimedia immersive experience that showcases key materials from the Lou Reed archive, presented in a way never experienced by the public before.

Having worked with Reed previously, Arup was well placed to design the multimedia experience portion of an exhibition that is in many ways the late artist's New York homecoming. The genesis of this project came when Arup's Raj Patel and Mike Skinner were introduced to Lou Reed in November 2008. They set about realising Reed's ambition of recording a performance so that people could hear it in the way he had experienced it on stage. Having listened to a range of material in Arup's SoundLab the following April, Reed invited Arup to record two of his gigs in 3D sound.

The SoundLab is used to reproduce (from measurements) or simulate (through computer models) the sound in any room, building, or space, past, present, existing, imagined, or those that no longer exist. It was developed to change the process of communicating acoustics to clients, allowing them to hear for themselves rather than using words, numbers or visualisations.

For the recordings, a specialised microphone and techniques are used to capture sound in 3D. Measurements are carefully calibrated so that all the parameters, such as exact sound levels at each frequency, are accurately recorded. The sound is then processed using software for the playback environment, and then reproduced through loudspeakers set up in a cube or sphere arrangement on a three-dimensional frame, providing the experience originally heard at the time of the recording.

The initial intention was to release the live recordings of Reed's performances of *Metal Machine Trio: The Creation of the Universe* at New York's Gramercy Theatre in binaural format, enabling 3D listening with headphones. When Reed heard the results in full spatial surround sound without headphones in the SoundLab, he described it as "the best live recording I've ever heard!" Rather than dilute the experience with headphones, he wanted his audiences to experience it in a similar installation setting, as this was the best representation of how he had heard the show on stage. He especially liked the approach to reproducing the experience at the same volume levels it was originally played at, experiencing the sound viscerally as well as aurally.

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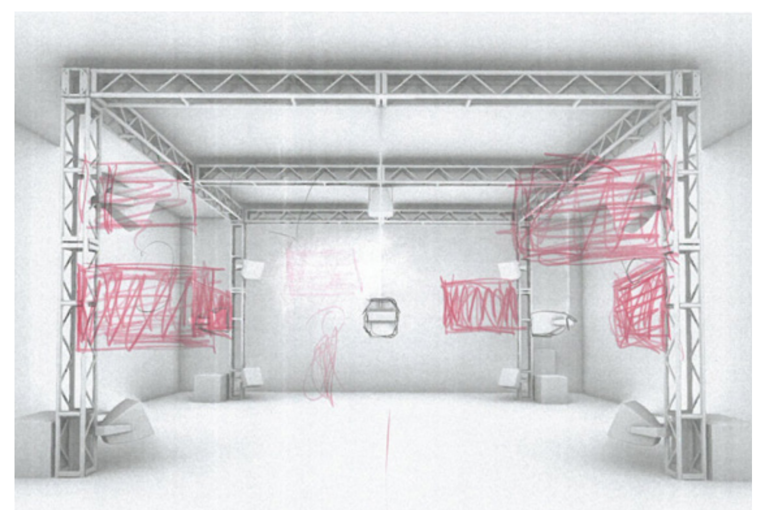

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1: Lou Reed at the Gramercy Theatre on 24 April 2009. Arup captured a live recording of this performance

2, 3: The design revealed the listening machine and the truss supporting the speakers as part of the installation's visual language aligned with the concept of being on stage

A concept was developed with Reed's input and approval, with the first installation staged at the California State Long Beach University Art Museum in 2012. Reed attended the exhibition, spending time in the installation, listening, and talking to attendees, and expressed his desire for the experience to be continued to be delivered in this format. In 2015, two years after Reed's death, the recordings were re-presented again at the Cranbrook Academy of Art in Detroit. The idea for the Listening Room stemmed from those installations, with Arup playing a critical part in the storytelling experience that the team brought to the public in the exhibition.

Caught Between the Twisted Stars

The Listening Room was installed in mid-2022 as part of the New York Public Library's retrospective of Reed's work *Lou Reed: Caught Between the Twisted Stars*. The exhibition title is a lyric from *Romeo Had Juliette*, the opening track of Reed's solo album *New York*. This was the first large-scale retrospective of the musician's archive, displaying the life and work of the icon.

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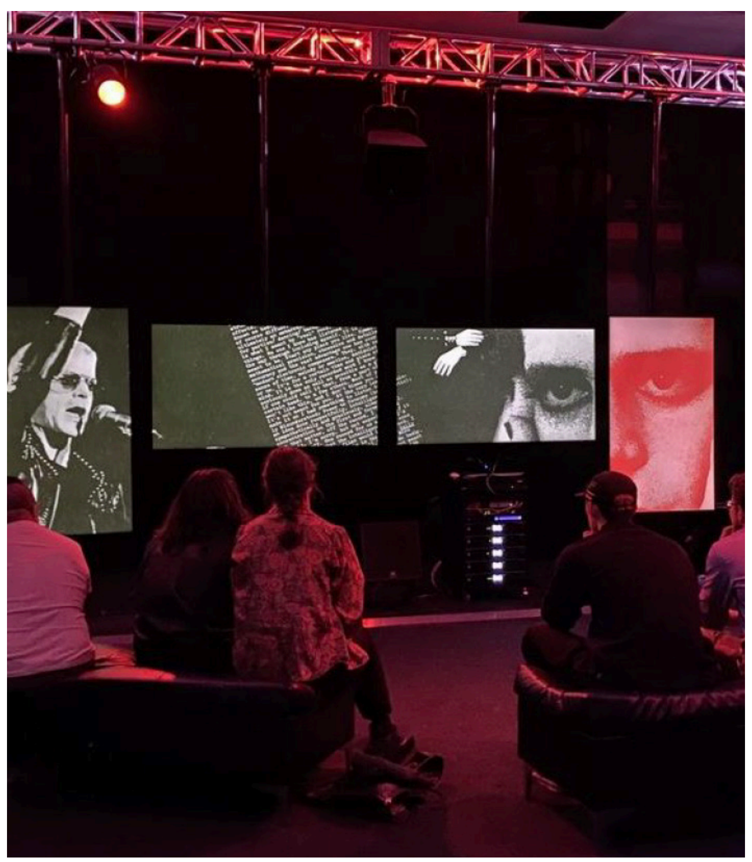


5.

4: The exhibition was the first large-scale retrospective of Lou Reed's archive, displaying the life and work of the icon.

5: Arup seamlessly blended the video and lighting design, creating washes of light when a particular video was shown

6: Using the cover of *Metal Machine Music* as inspiration, the Listening Room was created with a colour palette of black and red

For the nine-month exhibition, Arup created an immersive experience designed to seamlessly blend architecture and physical space, technology, software, and content. The Listening Room installation allowed people to hear Reed's April 2009 performances as he would have, from his position on stage. Visitors also experienced a range of Reed's discography in its original format, as he intended for it to be heard – in mono, stereo, quadraphonic, and full-3D ambisonic spatial audio. The Listening Room was designed and programmed by Arup, in close collaboration with the exhibition curators Don Fleming and Jason Stern.

Arup built the immersive cultural project from scratch. What began as an empty room, requiring exhibit and experience design, turned into an immersive space showcasing *Metal Machine Trio* for the first time in Reed's home city of New York. The team, in addition to acting as technicians, also became storytellers, working to showcase Reed's works in the way he wanted. Thanks to both the firm's and curators' longstanding relationships with the artist, the team was able to craft the content in the way they felt he would have wanted it to be experienced.

Blending audio and visual content

While Arup had worked with Reed in the past, the previous projects primarily focused on the auditory aspect of his works, with minimal lighting. The latest installation was part of much wider exhibition that drew from the artist's extensive archive and so the firm's work moved beyond the previous focus. Consolidating acoustics, lighting, visuals and experience design in a single cultural project, Arup brought together multiple disciplines to create compelling experiences. The team designed the physical aspect of the space, adding the lighting and video components, and then blending it all with the core audio content.

They chose to reveal the listening machine and the truss that supported the speakers, which became a big part of the installation's visual language and also aligned with the visual concept of being on stage. Using the cover of Reed's 1975 album *Metal Machine Music* as inspiration, where he stands bathed in red light, the Listening Room was created with a colour palette of black and red, so visitors felt like they were walking into the album cover. The firm designed the lighting so it reflected what the viewers in the space were listening to, with subtle pulses and changes that were responsive to the music being played.

Catering to the most loyal fans

One of the biggest challenges was creating something for Lou Reed fans who would want to visit the exhibit multiple times. With this in mind, the team created a programme of content to play on the platform, as opposed to a fixed set that viewers would see once. They considered not only what would be showcased at the start of the exhibition's run, but also what would happen when there was a changeover of content later.

Three chapters of the programme were curated and developed, each spanning approximately two months. They all shared one central piece, the ambisonic recording of *Metal Machine Trio*, which played twice a day. The first chapter, 'Metal Machine', was focused on Lou Reed's experimental work and featured a previously unreleased quadraphonic mix of *Metal Machine Music*, to listen in conjunction with the ambisonic mix. The second chapter was focused on Reed's 'The Velvet Underground' era, with a series of unreleased mixes of some of the band's famous tracks, alongside archive photos of the band in their youth, which drew a large number of fans to the gallery. The final chapter, 'Lou Live', featured live performance videos from various periods of his career, and some exclusive backstage content.

Using both a visual programming language called TouchDesigner and the theatrical cuing software QLab, Arup created a real-time dynamic multimedia experience that orchestrated video, sound, and lighting simultaneously. The lighting followed a sequence informed by the music. The team managed to seamlessly blend the video and lighting design, creating washes of light when a particular video was shown. The result was an immersive experience that began from the moment visitors entered the room. The media wasn't shown on a flat screen, but instead in a space and environment which changed around the viewer. The exhibit was designed in such a way that there was no strong beginning, middle and end, meaning visitors would be enticed to sit down and spend time immersing themselves.

The Listening Room is evidence of the practice Arup cultivates, and its ability to bring together a range of design disciplines to create experiences that are compelling. One of the biggest achievements was capturing the experience of the artist's work through varying means, including the technology, the physical set design, the software and content. Ultimately, though, these were just a means to let visitors live in Lou Reed's world for a while – exactly as he would have wanted.

6.

Authors

Gideon D'Arcangelo is an Associate Principal in the New York office. He is Arup's digital services portfolio leader in the Americas region and the firm's global experience design leader.

Joseph Digerness is an acoustics and audiovisual consultant. He is an Associate in the New York office.

Raj Patel was the creative director of the project. He is an Arup Fellow for Acoustics, Audio-Visual and Theatre, based in the New York office.

Xena Petkanas is a lighting designer in the New York office.

Léonard Roussel is a senior creative technologist in the New York office.

Project Credits

Client The New York Public Library for the Performing Arts
Exhibition curators Don Fleming, Jason Stern, Laurie Anderson
Acoustic, lighting and venue consulting Arup: Ed Arenius, Gideon D'Arcangelo, Joseph Digerness, Raj Patel, Xena Petkanas, Léonard Roussel, Brendan Smith, Brian Stacy, Travis Martinez.
Original 2009 recording and 2012 installation: Alban Bassuet, Ryan Biziorek, Dave Rife, Mike Skinner.

Image credits

1, 2, 5: Arup
3: Jonathan Blanc
4: Max Touhey
6: Mick Rock

1.

The making of a mega-interchange railway station

Transforming an existing underground railway station into Hong Kong's busiest four-line interchange

Authors Alice Chan, Vincent Kwok, Timothy Suen, Fiona Sykes, Ian Taylor, Matthew Tsang, Colin Wade, Jason Wong, Young Wong, Jack Yiu

The transformation of Admiralty Station into a mega-interchange serving four of Hong Kong's railway lines formed a critical part of the newly opened cross-harbour extension of the East Rail Line (EAL). Located in the central business district, the station allows passengers to reach Hong Kong Island's commercial, retail and residential areas on the extended EAL without changing lines.

The expansion of the station was one of the most challenging projects ever undertaken by Hong Kong's rail operator, the MTR Corporation. It involved construction of a highly complex and very deep station, accommodating new platform levels for two new rail lines – the South Island Line (East) (SIL(E)), and the EAL extension. These were constructed partly beneath the existing station that serves as the interchange for the Tsuen Wan Line (TWL) and Island Line (ISL). To accommodate the station becoming Hong Kong's first four-way underground railway interchange, the existing station size increased from four to eight platforms and from three to eight levels, with the number of escalators increased from eight to 42.

1: The station is Hong Kong's first four-way underground railway interchange

It is now the busiest station on the MTR network, accommodating over 100,000 passengers per peak hour.

Arup's involvement in Admiralty Station dates back to 1976, when the firm carried out detailed civil, structural and geotechnical engineering design for the joint venture contracting consortium on the original station construction. The work continued in the 1980s to include the design to accommodate the ISL. In 2009, for this latest element of work, the firm was appointed as the lead consultant for the multi-disciplinary detailed design of the station expansion. Arup's design and support for this project spanned a period of 13 years, with the SIL(E) part of the station opening for passenger services in December 2016, connecting Admiralty Station with the south side of Hong Kong Island, followed by the EAL service in May 2022.

The station arrangement, heavily constrained by the existing railway facilities for the operating TWL and ISL, required significant areas of underpinning, breakthroughs of existing structure, and phased sequencing of works. The expansion was carried out under the existing station structures, including the platforms that tens of thousands of passengers move through every hour to change between the existing lines. The construction did not cause any disruption to the normal operation of the station, which remained fully operational during the works, with the two existing lines continuing to function as usual throughout the station expansion.

3.

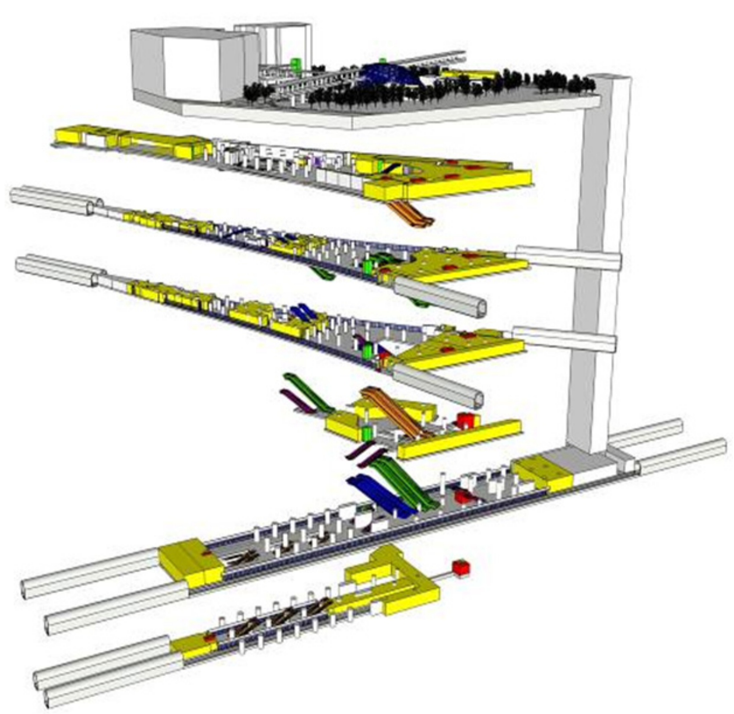
Complex underground engineering

To accommodate the SIL(E) and EAL in a configuration that would be convenient for passenger interchange, complex underground works had to be carried out at Admiralty Station beneath the existing structure. The design features three additional underground levels, reducing passenger walking distances and optimising interchange across the four railway lines.

The station extension comprises a 45m deep eight-level cut-and-cover station box and platform caverns, positioned underneath the ISL platform tunnel box, to serve the two new lines. The critical challenge in creating the interchange was to maintain the operation of the existing railway lines throughout the construction period. Additional design constraints included the requirement to underpin the CITIC Tower footbridge above the station; the maintenance of the lateral support to an adjacent underground car park; the permanent design solution for ground water uplift; the compliance with the construction noise permit; the extremely tight construction works area; and the need for the design to suit the phased opening of two new lines.

The station box is 78m long and varies in width from 45m to 70m. To cater for the long and numerous escalators, the central part of the box is hollowed out to form a large atrium void, with a varying shape on each successive floor to cater for the escalator rake. The void width is roughly 25m, with the length varying from 12m at ground level to 40m at mezzanine level. Areas around the void are taken up by circulation space, plant areas, staircases and back-of-house zones.

These new elements required the underpinning of the ISL platform tunnels while maintaining normal service on the operating railway lines. Arup designed the phased sequencing of works for the removal of 22m of solid rock beneath the existing structural box and insertion of the permanent structural framework to carry it. The underpinning system consisted of a series of beams, initially supported by temporary steel columns, constructed in a staged excavation sequence. The location of the temporary columns matched with the permanent column positions.



2.

2: The redeveloped station saw the number of escalators increased from eight to 42

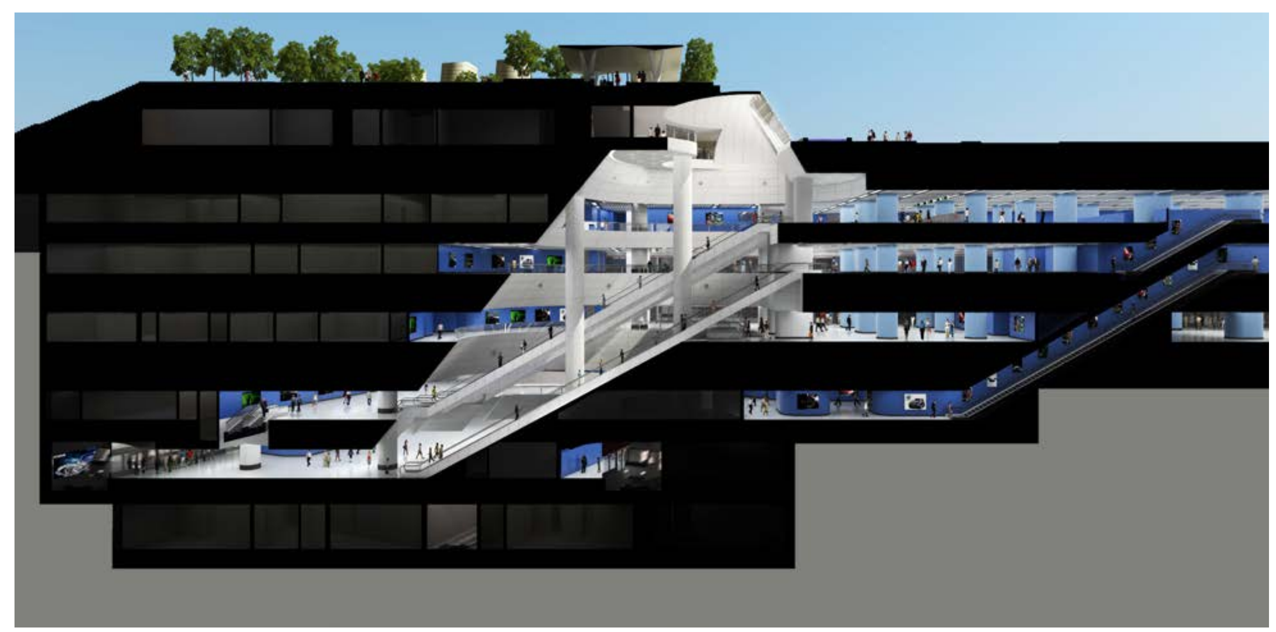
3: The SIL part of the station opened for passenger services in December 2016, followed by the EAL service in May 2022

4.

In the course of the works, the underpinning sequence was modified, with the rock excavation depth increased from 4.5m to 6.75m, and the transfer columns were re-engineered to accommodate wider slots where larger excavation equipment could operate, thus speeding up the programme. There were 19 stages of load transfer to the process. Computerised hydraulic jacks were used to control the loads, while three separate systems monitored movements to an accuracy of 0.01mm. The real-time monitoring system ensured that the ISL structure was not affected by undue movements during construction, ensuring passenger safety and the smooth operation of the running metro lines.

The underpinning works were completed towards the end of 2015. With the target completion date set for the end of 2016, the project team had barely 12 months in which to complete the permanent structure, including structural, building services and architectural builder's work, and finishing works. Achieving this target called for detailed coordination of the works, as the fast-tracking required different contractors to work side by side rather than separately.

For the EAL portion, Arup, working with the contractor, planned the complex

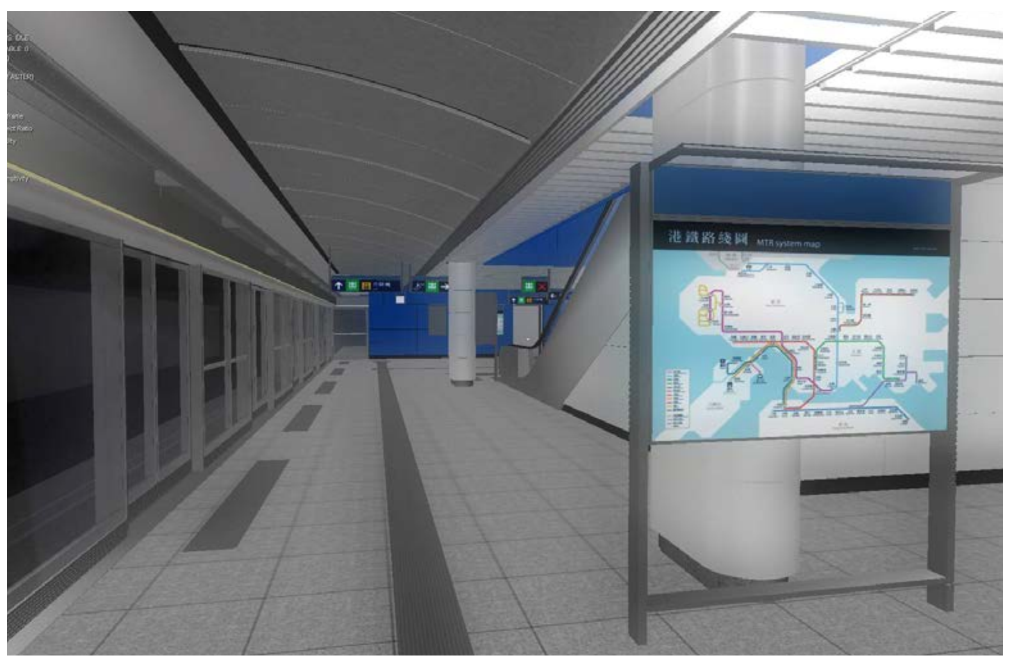


5.

4: The expansion was carried out without disrupting the normal functioning of the station, which remained fully operational during the works

5: The central part of the station box is hollowed out to form a large atrium void, with a varying shape on each successive floor to cater for the escalator rake

6.



7.

6: The project required the construction of a highly complex and very deep station

7: A real-time interactive model of the station environment helped to optimise wayfinding and signage design

8: The cut-and-cover construction was located in Harcourt Garden, which was initially the only access point for equipment and materials delivery

design and phasing of works to be integrated into the operating station. This required the removal of significant items of work that were installed in the first phase of works by the SIL(E) contractor. This included the wholesale removal of a temporary escalator, temporary public escape corridors, and a large, heavily loaded structural prop spanning the atrium. The major structural works included the underpinning and wall breakthrough works to the original Admiralty Station end wall, to the original ISL finger platform walls, and to the original TWL finger platform walls. A 110m x 25m x 15m high rock cavern was constructed for the SIL(E) platform adjoining the existing ISL finger platform box. Two 10m wide platform tunnels for the EAL flank the SIL(E) cavern, with short passenger connection tunnels between them.

The large atrium space at concourse level includes an array of long escalators, which distribute passengers to the various levels of the four-line station. To complete the interchange, 18 additional escalators were installed in the station box, supplementing the previous 10 installed under the first phase of works.

To facilitate the design check, a set of 3D models for both the existing and the new structures was analysed using SAP2000 software. The structural analysis was carried out at different stages of excavation down to rockhead level. In order to capture the appropriate soil-structure interaction during the excavation, PLAXIS geotechnical finite element analysis and Oasys FREW analysis were also used to simulate the staged excavation. Soil pressure and soil springs estimated from those analyses were then incorporated into the 3D structural model, for better estimates of structural forces and structure movements.

During the construction of the deep underground works, Arup's fire engineering team helped MTR to conduct fire risk assessments to demonstrate life safety risk met the ALARP standard (as low as reasonably practicable). They also conducted periodic on-site inspections to verify that the site fire safety conditions matched the fire risk assessment assumptions.

Permanent underslab drainage system

Due to the substantial depth of the station box and the tunnels, coupled with the high groundwater table in the station location, the structures are subjected to a high uplift buoyancy force. A permanent underslab drainage system was used to relieve the uplift pressure. The system comprises a minimum 300mm thick 20mm aggregate blanket underneath the base slab. Perforated uPVC drainage pipes wrapped with geotextile were laid within this drainage blanket, providing a preferential path for the groundwater collected to flow continuously towards large sumps, preventing the build-up of uplift water pressure. Pressure relief points are also provided at selected locations within the station box in case a blockage within the system happens, ensuring the system is fail-safe and giving the maintenance staff an indication of any blockage.

8.

Existing station alterations

The circulation in the existing station areas required modifications to provide passenger connections to the expanded station. These included the widening of a staircase while maintaining its public use, replacement of two escalators, and the forming of new passenger openings through the existing retaining walls at the rear of the TWL and ISL platforms. The escalator and wall breakthroughs involved significant structural alteration works in an operating environment.

Due to the heavy usage of two platform escalators, it was not possible to remove both escalators together, and a lengthy phased removal and replacement period was needed to carry out this work. A comprehensive set of sequencing drawings and structural modification details were developed ahead of the work being tendered. Much of the work was carried out after station operating hours, during night-time possession periods limited to four hours at most. Storage space for components inside the station was almost negligible and all public areas had to be cleared ready for each day's operation.

Wall breakthroughs

To aid passenger circulation between the existing platforms and the new station elements, two 5m wide openings were created along each platform. For the TWL, the openings were formed through the 1,200mm-thick existing diaphragm wall. This wall carries the platform levels and the roof slab of the finger platform box, which is 7m below the extremely busy Harcourt Road, and hence no load could be removed. A new capping beam was constructed to assist with underpinning works and spread loads along the wall.

The ISL openings were formed through a 900mm thick existing in situ reinforced concrete wall, which carries the original roof slab and platform slabs. The roof slab was relieved of its current soil load and replaced by the new station control room structure and redeveloped Harcourt Garden above it so new loads were similar to the previous. As the portion of wall above the new openings could not span unsupported over the void, it was necessary to insert new in situ reinforced concrete lintel beams and steel columns.

Logistics

A big challenge on the project was coordinating logistics during the extensive construction phase. The cut-and-cover construction was located in Harcourt Garden, which was initially the only access point for the delivery of materials and equipment. Two tower cranes were set up for materials handling, supplemented by a mobile crane when necessary. Logistics were planned a year ahead, with Arup acting as lead coordinator. The firm, along with the wider project team including


9.

9: The Harcourt Garden area was reinstated with a publicly accessible landscape deck, featuring an area set aside for 29 granite blocks that were originally part of a seawall constructed in the early 1900s

10: The atrium space has an array of long escalators that distribute passengers to each level of the station

the client, held weekly meetings to allocate time slots for the delivery of materials and equipment. To expedite the civil engineering works, the construction noise permit, which initially allowed the team to work until 11pm, was extended to 24 hours. Typically, the heavy mechanical and electrical equipment was delivered after 7pm, with priority given to building materials during the daytime.

To supplement the main access point, two additional access points were subsequently opened up. These were located at Wong Chuk Hang Depot – useful for delivering equipment by works trains to the lowest platform level of the station – and a ventilation shaft at Hong Kong Park. This was used to lift materials into the EAL tunnel for transport to Admiralty Station.

Harcourt Garden

Prior to the full opening of the expanded station the Harcourt Garden area was reinstated with a publicly accessible landscape deck. Prior to its use for the construction access, the original garden had at its centre two large circular ventilation structures for the ISL. In order to contain station plantrooms for the SIL(E) and EAL, the new vent shafts, and the reconfigured ISL vent shafts, a large, single-level building was constructed above the station, forming the base of an elevated landscape deck across half of the garden.

Extensive green walls and various raised and stepped planters lessen the visual bulk of the elevated deck, and the area includes a terrace for people to sit and enjoy the views. The garden also features an area set aside for 29 large granite blocks, originally used for a seawall which was completed in the early 1900s. The blocks were salvaged during the station excavation work and are set onto a stylised stone map of the locality, with outlines of the various reclamations that have taken place in the area since 1842.

Plantroom relocation

Another challenge was the design for a major plantroom relocation from the existing station to the expanded station. As entrance E is a major relocated service route for the station, early coordination was critical to set out the correct dimensional allowances and secure the main routing paths coordinated between major plantrooms. This entrance area underwent several phases under the EAL project, after opening of the SIL(E), until it reached the final phase. The relocation of services was meticulously planned and coordinated to meet the required construction phasing. Building Information Modelling (BIM) was carried out to resolve the congested services in the area to reduce the difficulties in the EAL construction stage.

Arup's large-scale BIM model integrated GIS data from multiple sources and formats, and consolidated the information with the station, tunnels, public facilities and as-built records of the adjacent buildings. The model enabled an integrated solution for the entire construction sequence to be developed. BIM enabled the production of fully coordinated construction drawings, allowing Arup designers to plan and review space arrangements for the architectural, structural and building services elements. Clash analysis greatly helped the design team to identify discrepancies between various disciplines so that issues could be resolved well in advance of construction, minimising actual conflicts and rework on site.

Atrium design

Entrance E is the signature entry to the station, with a large, glazed façade at the surface level that allows natural sunlight to brighten the 30m tall atrium void below. This effectively enhances the lighting design, reducing the internal lighting demand and allowing energy cost savings. However, the large atrium void required careful design for the smoke control strategy. The approach was adopted in collaboration with the statutory authorities to address fire safety issues. Rather than forming fire compartments according to area or volume limitations to comply with code-based fire separation requirements for general buildings, a performance-based fire engineering approach was implemented. This arranged suitable fire separation between the new and existing public circulation areas, together with smoke zoning and an innovative smoke control design for the atrium.

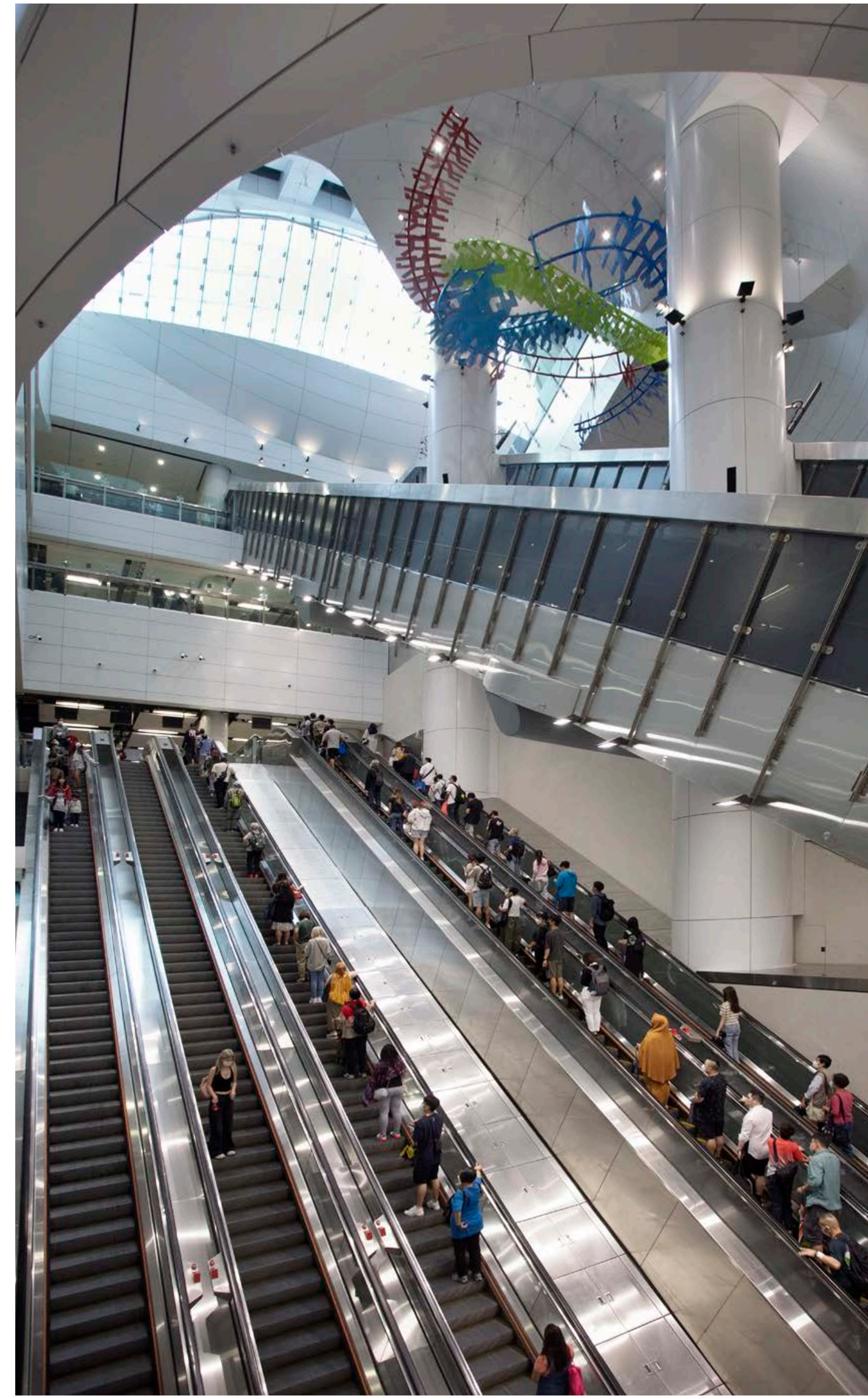
Static smoke vents were installed at the top of the atrium void in the roof of entrance E, providing an independent smoke control system serving the atrium. There are 14 separate 1.7m x 0.7m smoke vent openings through the curved skin of the atrium dome roof, with an opening mechanism triggered in the event of a fire.

The expected performance of the system was simulated with computational fluid dynamics analysis. Outside the atrium void, the smoke control system is mechanical. Arup's design had to address the challenge of a fire occurring at the boundary of the atrium, where one side of the boundary is under static smoke control while the other side is under mechanical smoke control. The back-of-house areas, including plantrooms with individual fire compartments, are separated from the public areas of the station by fire-rated walls with at least two-hour fire protection.

Emergency protocols

Fire shutters were installed at the interface of the existing and new elements of the station. These automatically close on the incident level when activated by local smoke detectors. Fire shutters at this interface located on other levels will remain open, to keep available as many escape routes as possible.

In the event of an incident at the station, emergency services will use a designated emergency entrance and a dedicated route, with a fireperson's lift and stair that provides direct access to the station control room and to all levels of the station. A secondary emergency entrance provides access to the SIL(E) tunnels and platforms


10.

11.

11: The station connects MTR lines from the north, south, east and west of Hong Kong

at the lowest level of the station. A special emergency rail vehicle is also permanently housed at track level at the south end of the SIL(E) station cavern, adjacent to the access point of the twin SIL(E) running tunnels. This vehicle will assist emergency services in responding quickly to incidents in the 3km long tunnels between Admiralty and Ocean Park stations, where there are no emergency access points.

Wayfinding

The enlarged station was significantly larger than the existing one and it was vital that appropriate measures were put in place so that passengers could readily find their way around the station.

In a conventional new station, wayfinding would be tested by installing mock signs prior to opening and checking the routing with people unfamiliar with the layout before installation of the final sign layout. This approach was not appropriate in this case given the existing station remained operating throughout the expansion and the scale of changes in the station.

Using the BIM model, Arup developed a 3D model to test the location of the signs in the form of a 'virtual walkthrough' without the need for mock signs and physical trials. The model was imported into a gaming environment, along with the initial signage design developed by the client's in-house signage design team.

The suitability and positioning of the signs were then tested in two ways. First an expert review was carried out involving professionals familiar with the design. This identified first pass issues, such as signs hidden by obstructions. Then users unfamiliar with the project were given tasks, such as navigating from the concourse to the SIL platform. This allowed Arup to identify whether there were any confusing or misleading signs.

Different user groups were modelled, including wheelchair and pram users. Quantitative data was collected to analyse the delay time for users as they tried to navigate their way virtually through the station. Qualitative data was then gathered by asking users to describe their thought process as they navigated through the model. This combination gave rich data from which to determine where modifications were required.

The testing identified 235 potential issues from the total of 970 proposed signs, with 145 sign messages or locations subsequently changed. In the implemented design, this provided clearer wayfinding for passengers and enabled MTR to avoid the cost and disruption of modifying physical signs after installation.

Award-winning design

Following the full opening of Admiralty Station, Arup's architectural and engineering design services for the extension has been recognised with a number of awards at both local and international level.

The extension received three separate architectural awards in 2022: the architecture gold prize (public and institutional) at the Hong Kong Design Awards, silver winner for architectural design (transportation) at the MUSE Design Awards and honourable mention in the architectural design/transportation category at the Architecture MasterPrize.

The firm's detailed planning and project implementation received a certificate of merit at the 2023 Hong Kong Institution of Engineers (HKIE) Grand Awards in the infrastructure category. Admiralty Station also won the Grand Award under the Project Award Infrastructure and Footbridge category at the 2023 HKIE Structural Division Excellence Awards.

Authors

Alice Chan led the pedestrian movement modelling for the station. She is a Director in the Hong Kong office.

Vincent Kwok was the design liaison engineer for the SIL(E) element. He is an Associate in the Hong Kong office.

Timothy Suen was the Project Director. He was Arup's East Asia region rail business and practice leader, and is an Arup Fellow based in the Hong Kong office.

Fiona Sykes was a project coordinator for project controls, design coordination, human factors integration and wayfinding. She is an Associate in the Hong Kong office.

Ian Taylor was the design team leader for the SIL(E) element. He is Arup's global aviation business leader and a Director in the firm's Midlands Campus in the UK (and was formerly based in Hong Kong).

Matthew Tsang led the re-engineering of the SIL(E) contractor's alternatives for the top-down construction and the ISL underpinning. He is a Director in the Hong Kong office.

Colin Wade was the deputy design team leader, and civil and structural leader. He was an Associate Director in the Hong Kong office prior to his retirement in 2022.

Jason Wong is a member of Arup's East Asia region board and leader of the region's rail business. He is a Director in the Hong Kong office.

Young Wong was the lead fire engineer. He is a member of Arup's East Asia region board and a Director in the Hong Kong office.

Jack Yiu was the senior geotechnical engineer for the SIL(E) element. He is a Director in the Hong Kong office.

Project credits

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Architect RMJM (2009 to March 2014) and Arup (March 2014 onwards)
Cavern and tunnel engineering SMEC
Quantity Surveyor Widnell (now Currie & Brown)
Landscape Architect Urbis
Main Contractor Kier Laing O'Rourke Kaden Joint Venture (SIL phase) and Build King (EAL phase)
Lead consultant, civil, structural, geotechnics, building services, fire engineering, pedestrian movement, project management, traffic, human factors, risk, safety, system assurance Arup: Eddie Ai, Lioni Alvarez, Ming Au-Yeung, Karma Barfungpa, Mathew Brown, David Bruce, Vicente Cabrera, Gerd Cachandt, Ainsley Chan, Alice Chan, Che-Cheong Chan, Chester Chan, Haydn Chan, Henry Chan, Kitty Chan, Li-San Chan, Paul Chan, Simon Chan, Tat-Ngong Chan, Dennis Cheang, Cherry Chen, Ying Chen, Cherry Cheng, Kam-Hung Cheuk, Cynthia Cheung, Gary Cheung, Ming-Fai Cheung, Simon Cheung, Justin Chiu, Thomas Chiu, Issac Choi, Erik Chow, Angus Chu, Carmen Chu, Argoon Chuang, Celsius Chung, Ming-Yiu Chung, Rene Ciolo, Laura Cox, Norbie Cruz, Jim Daly, Carmina Dela Cruz, Abs Delos Reyes, Florent Desaintpaul, Anthony Fan, Loic Fields, Siu-Man Fong, Tim Fu, Patrick Fung, Ryan Fung, Ronald Gaite, Bryan Galicinao, Sophia Gao, Alman Garzon, Reza Ghasemi, Catia Gomes Marques, Cheryl Ha, Carolina Ho, Jacky Ho, Joey Ho, Peter Ho, Stanley Ho, Eric Hong, Vincent Hong, Joseph Hui, Victor Ip, Yong-Wook Jo, Anek Kanittanon, Arthur Keung, Inho Kim, Wee Koon Chua, Iraklis Koutrouvelis, Bonnie Kwan, Gene Kwan, Justin Kwan, Philip Kwan, Henry Kwok, Roger Kwok, Eric Kwong, Millie Kwong, Nelson Kwong, Hannes Lagger, David Lai, Francis Lai, Karen Lai, Kenneth Lai, William Lai, Desmond Lam, George Lam, Ka-Fung Lam, Jerry Lam, Maggie Lam, Maurice Lam, Mai-Yin Lam, Raymond Lam, Andy Lau, Barry Lau, Clark Lau, Darren Lau, Keith Lau, Vicki Lau, Joey Law, Kin-Chung Law, Alex Lee, Andy Lee, Emily Lee, Franco Lee, Jennifer Lee, Kenneth Lee, Peter Lee, Pierre Lee, Sean Lee, Tse-Hung Lee, Eric Leong, Andy Leung, Angus Leung, Cath Leung, Chung-Lai Leung, Jacky Leung, Kevin Leung, Koon-Yu Leung, Lawrence Leung, Michelle Leung, Philip Leung, Victor Leung, Emma Li, Jonathan Li, Nicole Li, Ronald Li, Victor Li, Tim Lim, Samuel Ling, Shirley Ling, Ryan Ling, Vic Lok, Flora Luk, Terry Luk, Tsz-Ho Luk, Mingchun Luo, Ross Lyons, Mark Ma, Dylan Mak, Ka-Kit Mak, Martino Mak, Mecca Mak, Wai-Man Mak, Wendy Mak, Wilson Mak, Ciaran Mallon, Kevin Man, Tiffany Man, Roger Marechal, Armin Masroor Shalmani, Maggie Mei, Ken Mok, Polly Mok, Anne Navarro, Paul Ng, Vince Ng, Tin-Chi Ngai, Judy Ngan, Nelson Pak, Tracy Pang, Jack Pappin, Jessica Pawlowski, Simon Pearce, Simon Pickard, Phanyaporn Piyamasikkapong, Seth Pollak, Chi-Ho Poon, Phoebe Qian, Lily Qin, James Rickard, Ian Rowe, Muhammad Saif Ur Rehman, Henry Shiu, Michelle Shun, Yu-Yang Sim, Alvise Simondetti, Kenneth Sin, Peter Sin, Taurino Singson, David Smith, Duncan Smith, Candy So, Yuanyuan Song, Mark Stapley, Timothy Suen, Suravudhi Sukumganjana, Mary Sung, Fiona Sykes, James Sze, Timothy Sze, Caleb Tam, Gloria Tang, Honest Tang, Johnson Tang, Pok Tang, Wai-Shing Tang, Willis Tang, Ayako Tanno, Ian Taylor, Peter Thompson, Pui-Lam Ting, Man-Him Tong, Matthew Tsang, Raymond Tsang, Ricky Tsang, Jade Tse, Vincent Tse, Sam Tsoi, Raymund Vega, Tin Viado, Elianne Vos, Rachel Wang, Joanna Wei, William Wei, Ambrose Wong, Daniel Wong, Edward Wong, Edwin Wong, Eric Wong, Evis Wong, James Wong, Jerry Wong, Kevin Wong, Kin-Ping Wong, Louis Wong, Mandy Wong, Pauline Wong, Samuel Wong, Thomas Wong, Tim Wong, Timothy Wong, Young Wong, Victor Wong, Mike Wu, Tony Wu, Allen Yang, Joe Yang, Cheuk-On Yau, Tak-Cheong Yau, Angela Yeung, David Yeung, Elliot Yii, Fuk-Ming Yip, Jack Yiu, Kelli Yip, Robert Yip, Sunny Yip, Simon Yu, Cesar Zamora, Cherry Zhang, Vicky Zhou.

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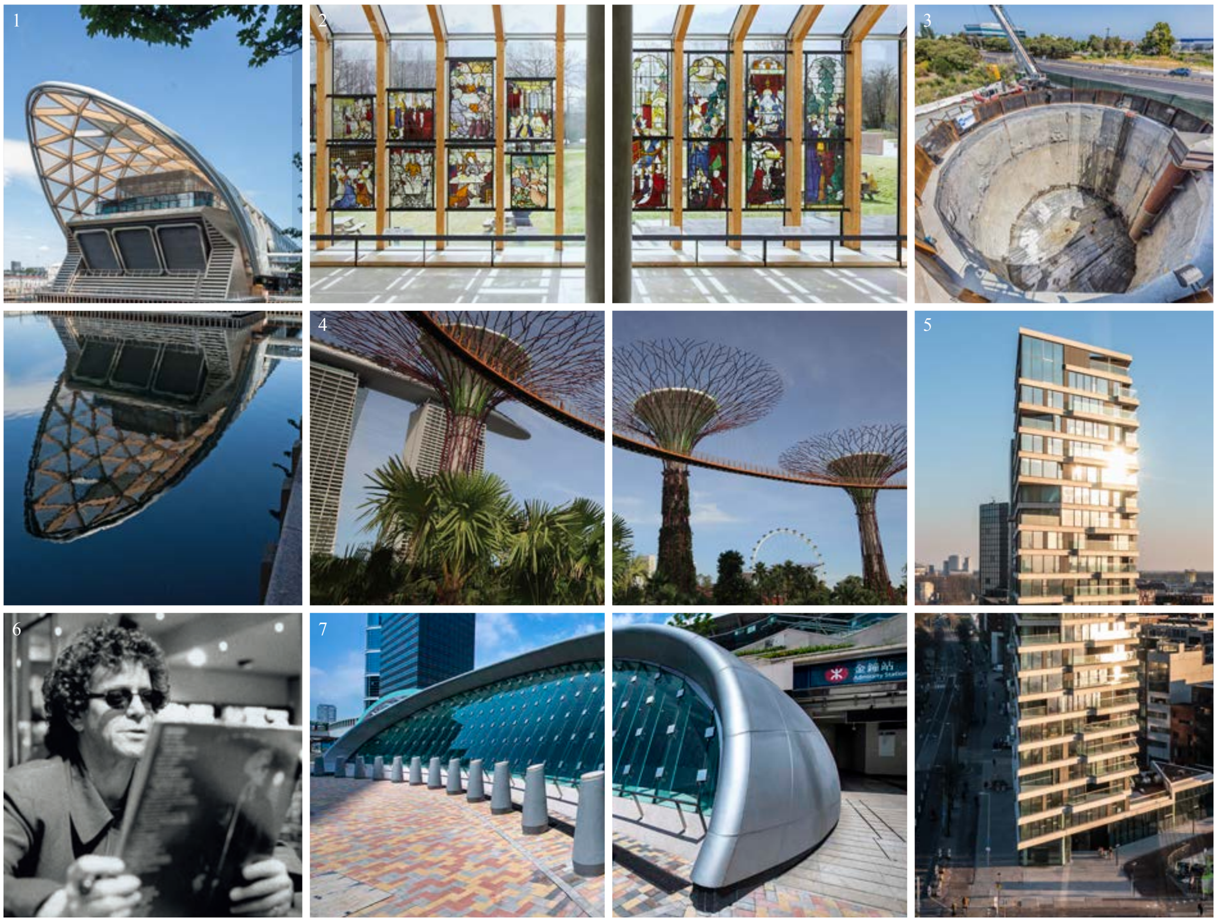

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