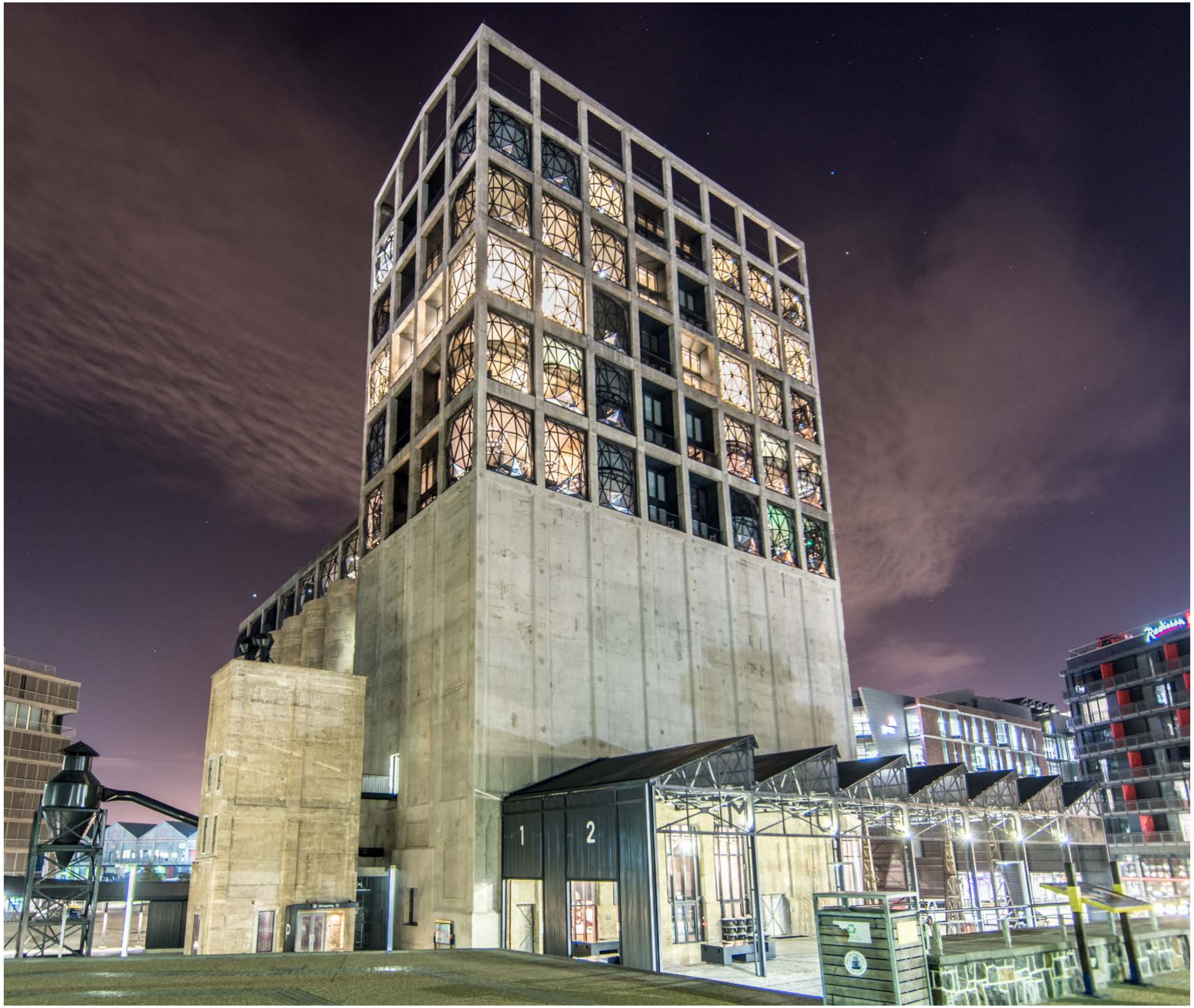
Issue 1 2018

The Arup Journal



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Sewage treatment works with a social impact

Major upgrades to the sewage treatment works serving nearly six million Hong Kong residents have modernised and future-proofed the sewerage system, and made Victoria Harbour suitable for swimming once again

Authors David Pickles and Fergal Whyte

1.

1: Stonecutters Island Sewage Treatment Works, located in Victoria Harbour

2: The annual Cross Harbour Swim was halted in 1978 owing to the poor water quality in the harbour

First held in 1906, the Cross Harbour Swim across Hong Kong's iconic Victoria Harbour was one of the city's most celebrated sports events until it was halted in 1978 because the water was deemed unfit for swimming.

At the time, up to 2 million m^3 of sewage, with only a very minimal level of treatment, was discharged straight into the harbour every day, with serious consequences for the water quality in the harbour. As well as the swimming race being stopped, nearby sandy beaches, such as Hong Kong's Gold Coast near Tuen Mun, had to be closed down to bathers.

The upgrading of the city's main sewage treatment system was required to meet both the existing and the future demands of Hong Kong. The largest environmental infrastructure project in the territory's history, the Strategic Sewage Disposal Scheme was proposed in the late 1980s. The first stage of the scheme commenced in 1994 and was completed in 2001. The second stage, renamed the Harbour Area Treatment Scheme (HATS), led by Arup, started in 2007 and was commissioned in December 2015. The quality of this stretch of water has improved to the extent that in 2011 the beaches reopened and, last year, the authorities declared the water in the harbour clean enough to resume the Cross Harbour Swim along its original route.

In October 2017, against the backdrop of the city's famous skyline, almost 3,000 people took part in the race, swimming from Tsim Sha Tsui Public Pier on the Kowloon Peninsula to Wan Chai Golden Bauhinia Square Public Pier on Hong Kong Island.

Ambition

The aim of the HATS was to collect sewage – previously discharged into the Victoria Harbour with only minimal treatment – from both sides of the harbour and channel it into a centralised sewage treatment works on nearby Stonecutters

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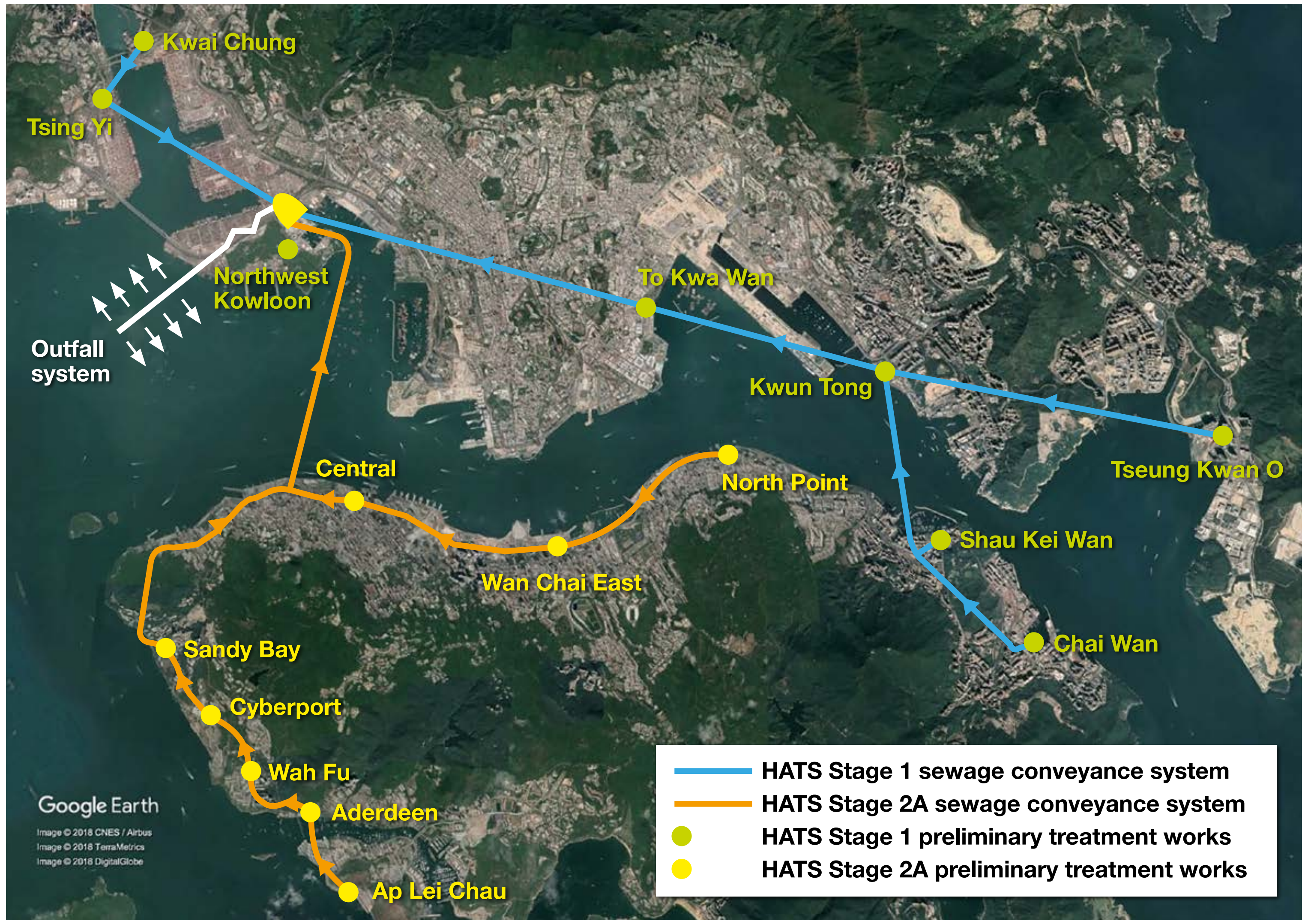

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3: As part of HATS 2A eight existing preliminary treatment works were upgraded and connected via new tunnels. The partially treated water is transferred to SCISTW via a tunnel running under the harbour

Island. There it would be processed in one of the largest treatment facilities of its kind. Stage 1 of the project provided treatment for about 75% of the sewage from urban areas around the harbour, with an average dry weather flow (ADWF) of 1.7 million m^3 per day.

Stage 2A was a commission to treat the remaining 25% of Hong Kong's sewage, bringing the treatment capacity up to a 2.45 million m^3 per day average and a 4.1 million m^3 per day peak flow. This was achieved by taking all sewage from the Victoria Harbour area to the upgraded Stonecutters Island Sewage Treatment Works (SCISTW) for chemically enhanced primary treatment (CEPT) and disinfection.

Arup tendered for Stage 2A of the project on the basis of the firm's extensive experience built up over more than 20 years designing water treatment plants in the UK.

Awarded the contract in August 2007 by the Hong Kong Government's Drainage Services Department, Arup's commission included civil, mechanical, electrical, geotechnical, tunnelling, hydraulic modelling, process, environmental, control and automation engineering, as well as programme and project management.

Arup's design included modelling the complete hydraulic system to optimise the waste water collection and conveyance across the harbour, as well as the upgrade of the treatment works on Stonecutters Island, including the design and construction of one of the world's largest underground pumping stations. As part of the project, eight of the existing Hong Kong Island preliminary treatment works that carry out initial screening of the sewage were upgraded and connected via new tunnels running along the western and northern coasts of Hong Kong Island.

The overall treatment process when finally commissioned collects sewage from around Victoria Harbour to be treated at the preliminary treatment works, removing large solids, before travelling via tunnels to SCISTW. Following CEPT, the treated sewage is disinfected by chlorination and discharges into the harbour after dechlorination. The residual sludge produced from the sewage treatment is dewatered and moved to a sludge treatment facility by ship.

The opening up of the Hong Kong Gold Coast beaches that had been closed owing to poor water quality was made an initial priority. Arup ensured this could happen in 2011 by designing the advanced disinfection package of works, showing the public the benefits of the HATS 2A project.

Challenges

In addition to designing the complex system of sewage treatment works, Arup had to ensure the construction programme allowed

4: The Stonecutters Island site (shown in 2008) is located adjacent to two other Arup projects: the Stonecutters Viaduct and Stonecutters Bridge

5: Plan of the upgraded SCISTW

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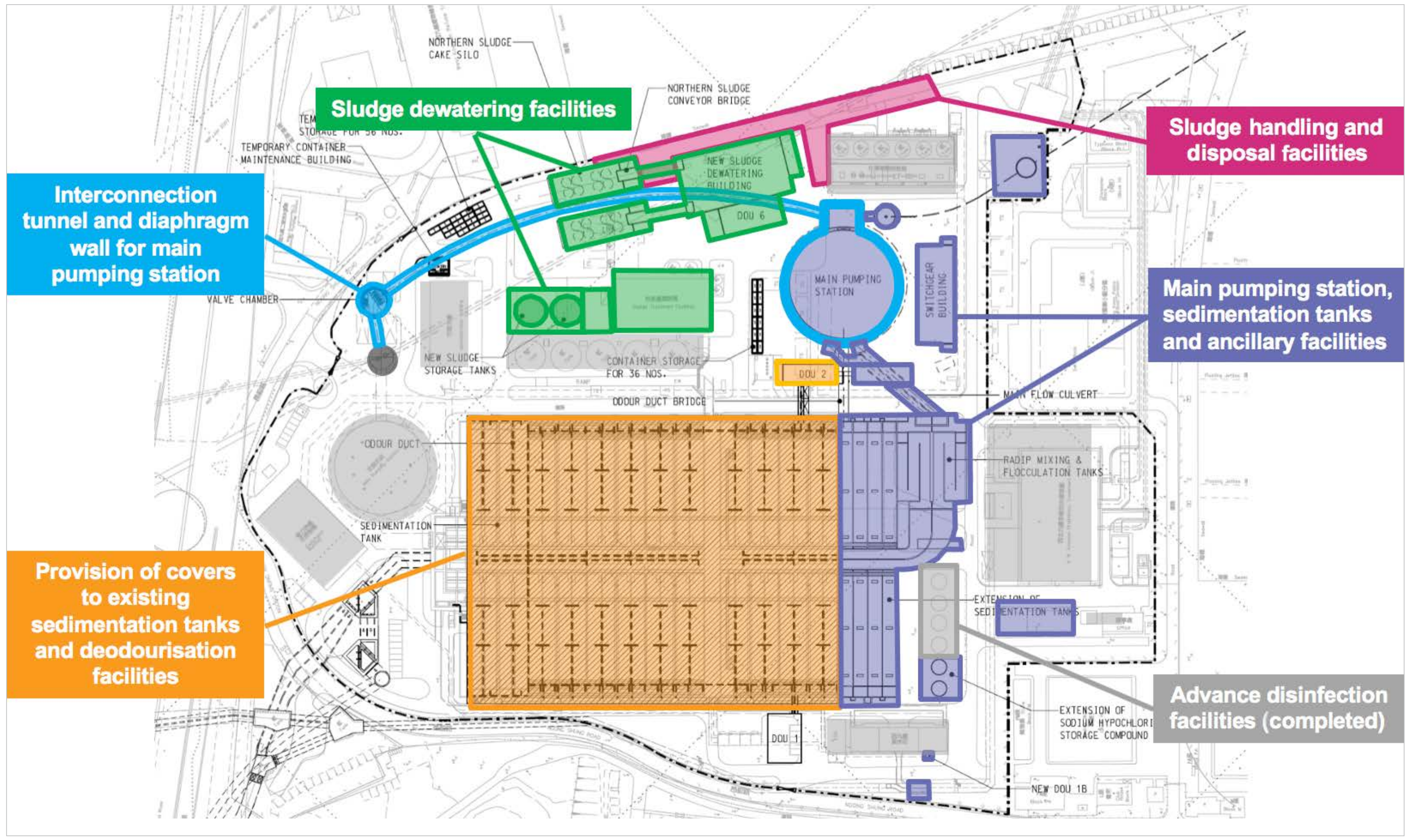

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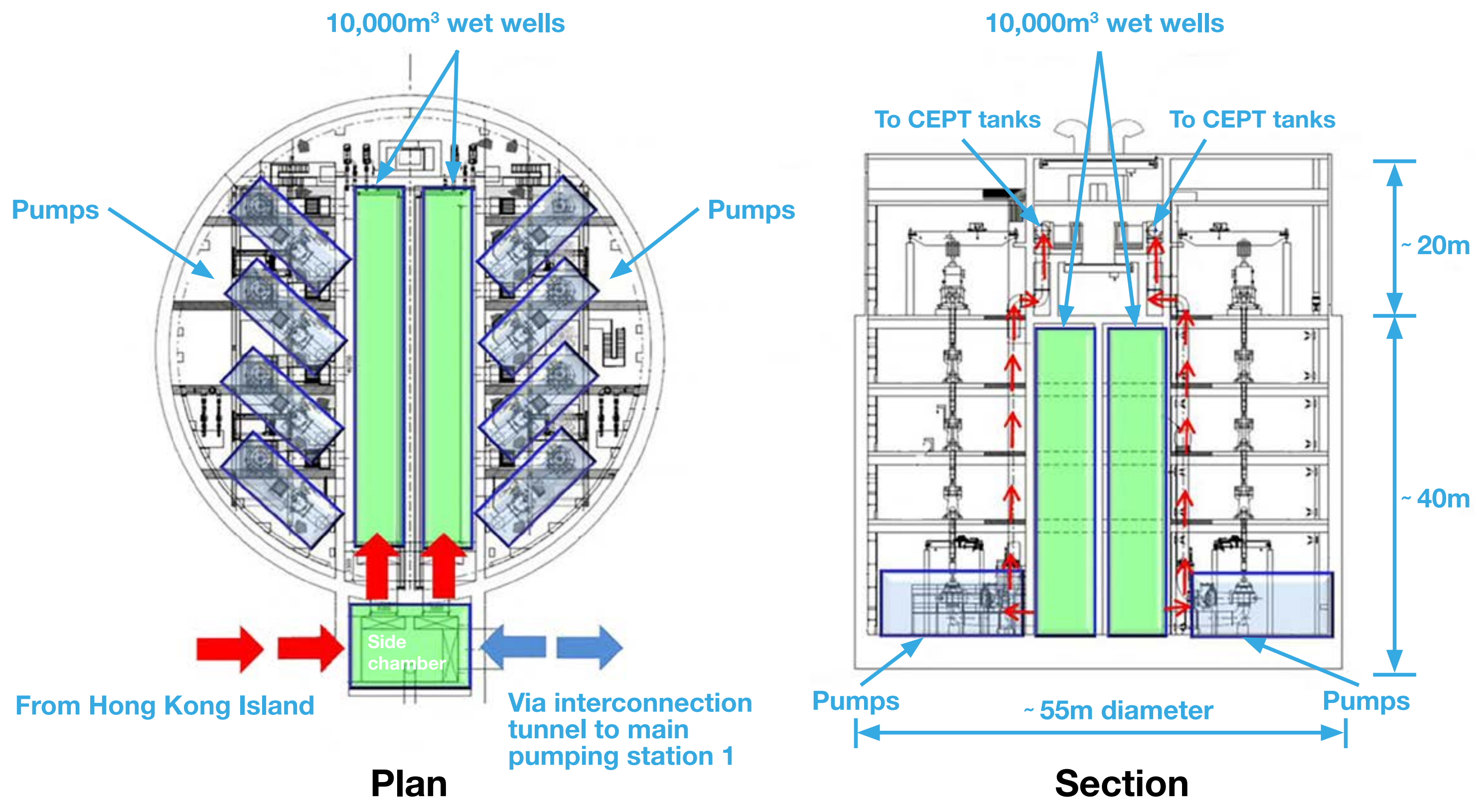

6.

6: Plan and section of the pumping station, which has a volume equivalent to 38 standard swimming pools

the project to proceed in stages to ensure the system could remain online at all times, as there could be no interruption to the operation of Hong Kong's existing sewerage systems.

Upgrading the existing extremely congested facility on Stonecutters Island also presented difficulties. In the 1990s, the island was expanded through land reclamation, connecting it to the mainland. Arup had to find a way of increasing the capacity of the sewage treatment works within the existing site boundaries.

Working closely with the client, Arup proposed a procurement strategy to suit the capabilities of both local and international design and build contractors. Detailed planning was required on the placement of various elements of the plant, designing how they would fit with the existing infrastructure and detailing how the contractors should phase the construction.

Hydraulic system

After the initial screening, the partially treated sewage drops down 120m through shafts at each treatment works, entering a tunnel that crosses below the harbour, before coming up through a riser shaft into the pumping station on Stonecutters Island for treatment prior to discharge into the harbour. Arup modelled the hydraulic system for sewage transportation from Hong Kong Island to Stonecutters Island (with the tunnel design by others).

The design challenge was to ensure the waste water could travel to Stonecutters Island through the tunnel without backing up or overflowing at the preliminary works and without solids dropping to the bottom of the tunnel floor. Typically, sewerage works use gravity to keep the flow of waste constant, with the treatment works located at a lower level than where the waste originates. In Hong Kong, however, this was not possible: the tunnels had to be deep enough to go under the harbour and below the foundations of the buildings on the shoreline of Hong Kong Island.

When designing such facilities, a tunnel of this shape (forming an inverted siphon) is generally avoided because waste can settle at the bottom. To ensure that did not happen, the tunnel was sized so that the waste water velocity was fast enough to exit from the riser shaft at the Stonecutters Island end without solids settling in the tunnel along the way. The system also needed to cope with large differences in flow rates between summer and winter months. With wet weather in the summer, resulting in high flow rates of water, and dry winters resulting in the opposite, Arup designed the system so that the velocity of flow stayed within acceptable parameters all year round, with minimal overflow. These two constraints meant the tunnel had to be narrow enough to maintain a flow of sufficient velocity to keep the tunnels clean during the drier months, taking into account the inverted siphon, but wide enough to not overflow during the wetter months. To establish the most efficient and cost-effective diameter for the tunnel, Arup developed an extensive hydraulic model of the complete system for both existing and future treatment volumes in Hong Kong. This included modelling the Stage 1 systems of 23.6km of underground tunnels, which collected sewage from Kowloon and the north-east of Hong Kong Island, as well as the proposed upgrades as part of Stage 2A.

To estimate the sewage flow through to the year 2030, Arup used data that projected Hong Kong's population and employment for the next two decades. A geographic information systems model was built and calibrated using that data and the records of historic flows. The hydraulic model assessed the velocity and head losses through the tunnel, waste water levels at various drop shafts, tunnel size and depth of the main pumping station under average and peak flow conditions.

The average flow during the dry months was calculated at 2.5 million m^3 per day for 2030. Typically, combined sewage and storm water sewerage systems are designed for peak flows equivalent to three times the dry weather flows. However, in Hong Kong, wet weather comes in the form of short flash storms rather than extensive periods of rain, with some of the storm water contained in overflows, locally known as nullahs. Arup established that to collect and treat 99.5% of the combined waste water, the peak flow would be 1.7 times that of the dry season.

This was the first time a computer-driven hydraulic model of this size had been used and it proved very successful in terms of accuracy and helping with cost efficiency. Ultimately, despite the project's complexities, the model was accurate to within centimetres. This system minimised the tunnel diameter, ensuring there was enough velocity to avoid any settlement within the tunnel and minimising any overflow.

This design balanced the land requirement, capital and operation costs against the hydraulic performance and environmental compliance requirements. A minimum capital cost saving of HK$480 million (£42.5 million) was achieved.

Pumping station

The pumping station at Stonecutters Island is one of the world's largest for sewage treatment works. It is 55m in diameter and reaches 40m below ground. Above ground, it is a 20m tall striking glass building complete with green roof. The scale of the pumping station to be constructed within the confines of the existing site presented a considerable challenge, particularly as this work was required to take place without interrupting the existing treatment works. As the overall project manager for the work, Arup developed a procurement strategy, which included space planning and a detailed construction programme. By gathering information from various contractors, Arup assessed the size of the construction equipment that might be brought to site, and determined the number and size of pumps needed to maintain the $32m^3/s$ flow, designing the space – and the surrounding diaphragm wall – accordingly.

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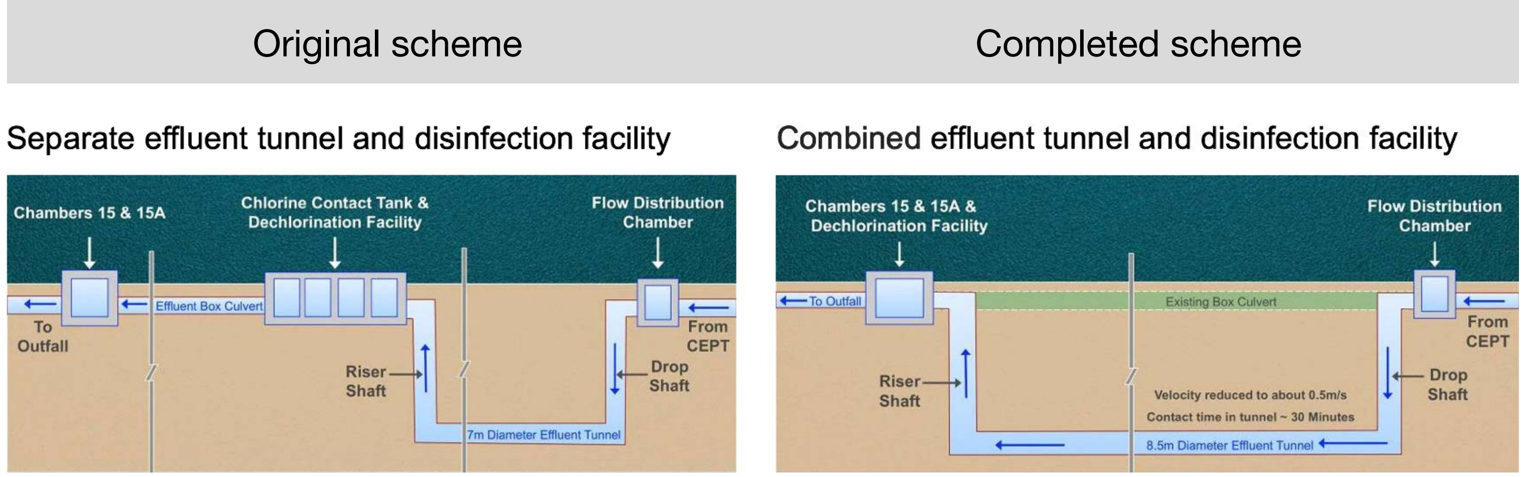
7: The Stonecutters Island main pumping station is one of the largest in the world, at 55m in diameter and 40m deep

8: There are eight main pumps in the pumping station motor hall



9.

9: Arup's solution for the effluent tunnel and disinfection facility significantly reduced excavation and construction costs

A priority was given to the efficiency of the pumps to minimise electricity consumption. The detailed design for the diaphragm walls of the underground portion of the pumping station was carried out early in the project, rather than as part of the main contract works. The pump station was sized to ensure it would be large enough to accommodate the equipment of any contractor. To prove the concept, Arup developed the design within a 3D digital model, with Hong Kong University building a 1/15th physical scale model of the final system. This allowed the excavation to commence early ahead of the awarding of the main contract, helping to speed up the overall project programme.

Effluent tunnel and disinfection facility
To minimise pollution levels in the discharged water, Arup used a computational fluid dynamic model to determine the required contact time for the treatment chemicals. Arup also designed a cost-saving solution using the outfall tunnel as the chlorine contact tank.

Originally, the proposal was for a conventional arrangement for disinfection comprising a short effluent tunnel with a large above-ground combined chlorine contact tank and dechlorination facility with connection culverts. Instead, Arup developed a more efficient solution combining the effluent tunnel and conveyance system within the same 8.5m diameter, 90m deep, 880m long tunnel, with disinfection taking place along the tunnel. It was constructed using drill and blast techniques, advancing on two faces from drop and riser shafts. By disinfecting the effluent in the tunnel, it eliminated the need to construct an above-ground chlorine contact tank (originally sized at 174m x 34m x 14m and proposed to be located close to a piled viaduct). This significantly reduced excavation and construction costs. It also released valuable space above ground for development.

The design for this aspect of the scheme achieved a saving of 40% in lifecycle costs and significantly reduced the environmental footprint.

Other works
At SCISTW, Arup designed an interconnecting tunnel between the existing and new main pumping stations. This allows flexibility to divert flows through just one of the pumping stations as and when maintenance is required on the other. The tunnel has a 3.9m internal diameter, is 250m long and is at a depth of 30m. The tunnel was constructed using a slurry type tunnel boring machine (TBM), supplemented by a state-of-the-art specialist ground freezing technique for the TBM break-in and break-out.

The treatment works are located in an area that has a very high water table and is adjacent to the sea. It was therefore essential for measures to be put in place to minimise the risk of water entering the TBM launching chamber. To minimise the potential flood risk, a series of holes were drilled from the surface to approximately 30m below ground level, with the ground chilled to -10°C for several weeks until the groundwater froze. The TBM was launched through the frozen ground, preventing any flooding of the launch chamber. This was a novel construction method for Hong Kong at the time.

As part of the project, each of the preliminary treatment works on Hong Kong Island was upgraded to increase the capacity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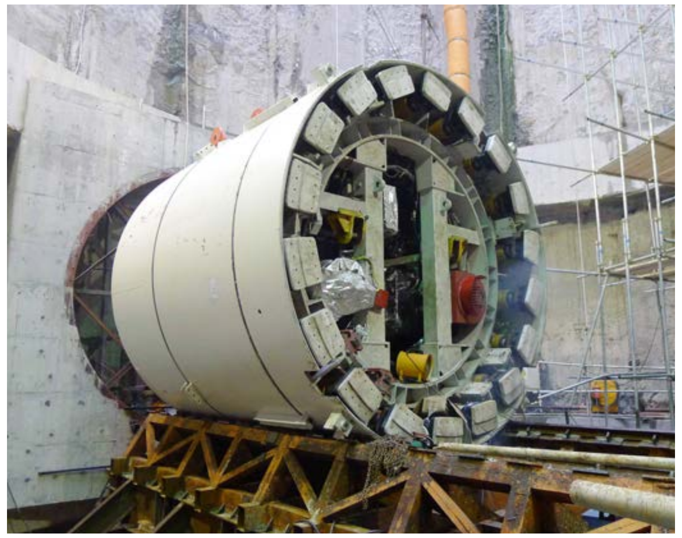
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13.

10: The TBM, dubbed 'Victoria', in the factory

11 & 12: TBM being lowered and assembled prior to launch

13: Artificial ground freezing for TBM break-in/break-out


14.


15.

14: Chemical scrubbers and activated carbon filters for the deodourisation of the sludge dewatering building

15: All the primary sedimentation tanks were covered for odour control

16.

16: The Commissioning Control Centre facilitates the management of the works, which serve 5.7 million people on both sides of Victoria Harbour, processing 900 million m^3 of sewage each year

of the pumps and initial treatment screens. Odour controls were added and, with the works located close to the roadside and some areas of housing, green roofs were added to improve aesthetics.

Deodourisation

A decentralised and compact deodourisation system was installed at SCISTW to treat the odourous gases produced from the sewage treatment works before discharge into the atmosphere. All the existing and new primary sedimentation tanks, channels and flow chambers were covered with fibreglass reinforced plastic covers. Foul air was extracted and conveyed through ducts to biotrickling filters for treatment with multistage chemical scrubbers, followed by activated carbon filters. These works all provide long-term improvements to the air quality in the vicinity of the works.

Sustainability

The new main pumping station achieved a Provisional Gold rating under BEAM Plus, the environmental assessment scheme of the Hong Kong Green Building Council, which considers energy use, indoor environmental quality, materials, water use and innovation. Arup ensured the project itself was managed in a way that minimised adverse effects on the environment. Where possible, construction materials were reduced and reused; for example, excavation material such as completely decomposed granite was sent to active landfills as a capping layer, and the excavated general fill materials were reused in other reclamation projects in the area.

Arup designed the large sludge dewatering system with large centrifuges, each handling up to 150kg/hour and capable of producing 1,200 tonnes of dry sludge cakes a day. The sludge cakes are delivered via two container vessels to a treatment facility for incineration to generate low-carbon energy. Replacing the previous transport by road, these vessels are the first diesel-electric propulsion container vessels in Hong Kong, using ultra-low-sulphur diesel to generate electricity for propulsion. They are connected to onshore power supplies when berthed, without using diesel and releasing zero emissions. The vessels collectively reduce carbon emissions by 130 tonnes each year compared with regular ships, equivalent to the carbon load absorbed by 6,000 trees in a year.

Professional excellence

To ensure the project achieved the highest of professional standards and that the works were carried out in line with contract conditions and local regulations, Arup put in place a quality site supervision plan. A system of regular inspections and audits ensured the works progressed as planned.

The team also developed an ethical code to provide guidance on acceptable business practice on the project. A training programme, in the form of an e-learning module, was developed for all staff to underline the importance attached to high standards in all business activities.

Communications

The scale and significance of the project meant that communicating its objectives, benefits and progress to the public, as well as district councils and government departments, was crucial. The project team's aim was to inform the public on the sustainability credentials of the project where the efficient use of resources and state-of-the-art technology helped improve the water quality in Victoria Harbour. This called for a comprehensive public relations strategy, including a 24-hour public hotline for the project, regular notifications to key stakeholders, public community meetings, and presentations and visits to district councillors and school communities. The team also published project brochures, newsletters and web content, and created videos and physical models. Arup designed a visitor centre in the new pumping station, to help with public outreach. The positive media coverage of the project is a testament to the success of this public relations strategy.

Also crucial to keeping the public informed was demonstrating that the project was complying with appropriate standards. As such, the performance of the new disinfection facilities and the impact of the discharged waste on the marine environment were monitored by an independent inspector, with the results made public on the project's webpage.

17.

18.

17 & 18: The quality of the water in Victoria Harbour has improved to such an extent that the beaches were reopened in 2011, and the Cross Harbour Swim resumed in 2017

Future-proofing

With demographic shifts and the impact of climate change, Hong Kong's needs for sewage treatment will change. To future-proof the project, Arup's role included predictive work on flows and loads in the treatment works. This entailed working with the Planning Department of the Government of the Hong Kong Special Administrative Region to understand its development plans for the next few decades, as well as looking at historical data, potential land use, industrial growth, projected population change and the impact of climate change with increased rainfall. This work means the system is designed to be resilient until at least 2030.

The success of the HATS project has been widely recognised, both by the government and the community in Hong Kong. It has won local and international awards, including the Global Water Awards, the British Construction Industry Awards, the Tien Yow Jeme Engineering Prize in China and the ICE Edmund Hambly award for sustainability.

The upgraded Stonecutters Island facility now has a capacity of 4.1 million m^3 per day, which makes it one of the largest CEPT plants in the world. The 10.6ha plant serves 5.7 million people on both sides of Victoria Harbour – equivalent to 70% of Hong Kong's population – processing 900 million m^3 of sewage per year.

Arup was able to draw on both local and international expertise to design and manage this large-scale, complex project, delivering it on time and within budget. Since completion, Arup has expanded its water business in East Asia, using the HATS project – and its innovative use of data and computer modelling on the project – as a reference to develop sewage treatment projects elsewhere in Hong Kong, as well as in mainland China, Singapore and the Philippines.

Authors

David Pickles was Project Manager managing the overall technical design on the project. He is a Director in the Leeds office (formerly in Hong Kong).

Fergal Whyte was Project Director. He is a Director in the Hong Kong office, a member of the Arup Group Board and is the firm's Director of Health, Safety and Wellbeing.

Project credits

Client Drainage Services Department, Hong Kong Government

Civil, Mechanical, Electrical, Geotechnical, Tunnelling, Hydraulic Modelling, Process, Environmental, Control and Automation Engineering, Programme and Project Management Arup: Gamini Ananda, Bill Au, Kitty Au, Robert Bates, Agnes Chan, Alan Chan, Albert Chan, Chris Chan, Ivan Chan, Paul Chan, Sing-Wa Chan, Siu-Yuen Chan, Andy Chee, Bernard Cheng, Anson Cheung, Eric Cheung, Carrie Chu, Daniel Chu, Corey Fan, Arlene Goode, Raymond Sy Guan, Gary Hung, Lewis Hwoi, Jeff Ip, Mark Knowles, Anil Kumar, Andrew Lai, David Lai, Gabriel Lai, King-Chak Lai, Antony Lau, Jak Lau, Michael Lau, Vicki Lau, Lawrence Lee, Donald Leung, Rex Li, Ronald Li, Yuvi Luo, Edwin Mak, Louis Mak, Wilson Mak, Nick Ng, Tin-Chi Ngai, David Pickles, Dora Shum, Franki So, Monique So, James Sowden, Jeremy Sparrow, James Sze, Stanley Sze, Lara Tang, Ted Tang, Paul Taylor, Simon Tsang, Iris Tse, Simon Tso, Shanshan Wang, Fergal Whyte, Billy Wong, Peter Wong, Jenny Yip, Simon Yu.

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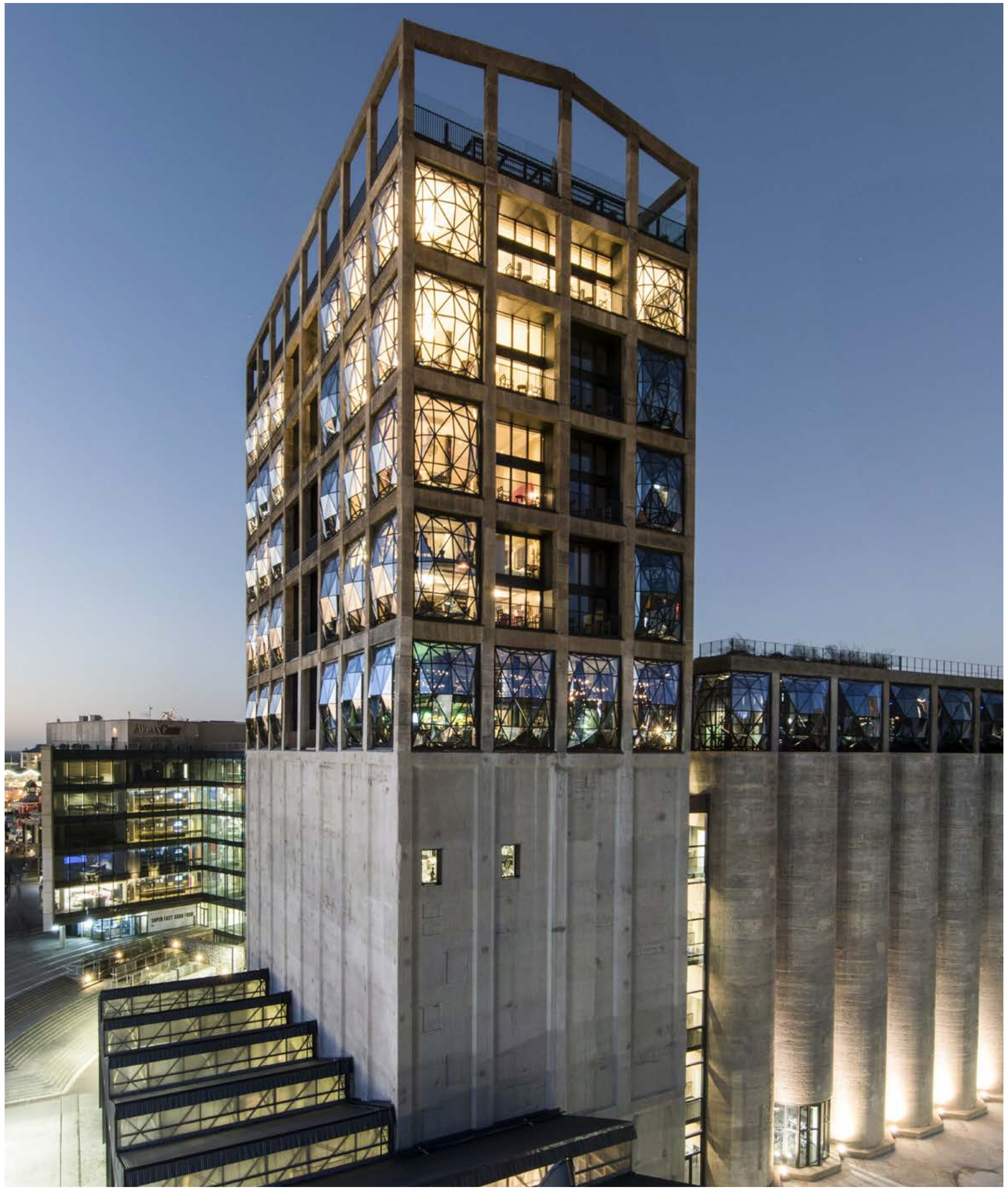


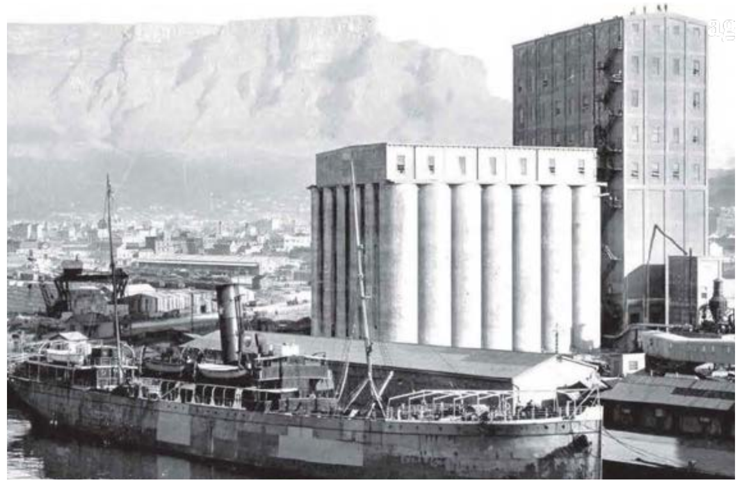
1.

A silo in form only

Advanced engineering transformed an abandoned 90-year-old grain silo complex into a cultural hub and the jewel in the crown of Cape Town's bustling V&A Waterfront district

Authors Francis Archer and Tessa Brunette

The V&A Grain Silo Complex houses The Silo Hotel and the Zeitz Museum of Contemporary Art Africa (Zeitz MOCAA). Zeitz MOCAA is a partnership between the Victoria & Alfred (V&A) Waterfront and Jochen Zeitz, whose collection of contemporary African art, on long-term loan, forms part of the museum's founding collection. Overlooking the Atlantic Ocean and Table Mountain, and adjacent to a working harbour, the Grain Silo Complex opened last year. Arup collaborated with designers Heatherwick Studio on the redevelopment, which has provided a focal point for the area's regeneration.



2.

1: The V&A Grain Silo Complex houses the Silo Hotel and Zeitz MOCAA

2: The Grain Silo in its original form, when the waterfront area was a centre for export

Spread over nine floors and 15,500m² (including the hotel), the £30m development includes 80 gallery spaces, a hotel, a rooftop sculpture garden and restaurant, and hospitality spaces. From the outside, it is a behemoth of exposed concrete. A 57m high tower punctuated with a grid of billowing faceted windows stands tall above a main, shorter block. Inside the main building, a 30m tall atrium has been carved out of the 42 tightly packed 5.5m diameter concrete tubes that previously held grain. Daylight cascades into this cathedral-like void through the skylights above. A specially commissioned artwork that is baked onto the skylights helps moderate the harsh summer sun and creates a gentle lighting transition between day and night.

Decline and revival

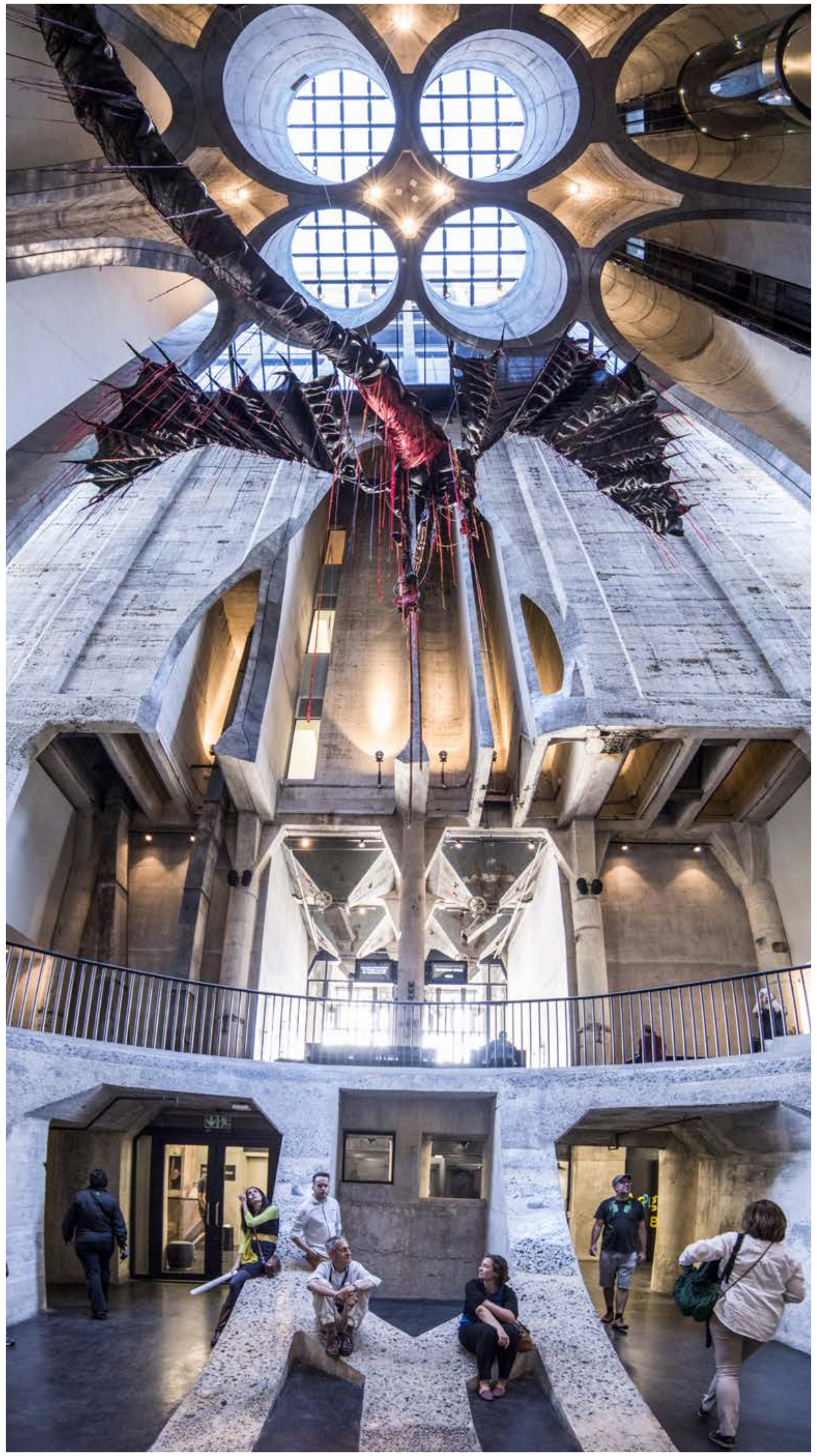
The original building was completed in the 1920s and was used for three-quarters of a century to store maize, millet, sorghum and wheat that had travelled from inland South Africa to the coast for export, mainly to Europe. It started life as the tallest structure in the country and was quite a feat of engineering for its time; for example, the concrete that formed the silos was poured in a single continuous pour in a matter of days, using an ambitious system of manual jacks to raise the formwork. By the turn of the century, South Africa's grain export market had declined and the advent of containerised shipping had made such large storage facilities redundant. The building had been left empty since 2001 and, over time, fell into disrepair. While the surrounding 123ha V&A Waterfront industrial complex was redeveloped into a vibrant mixed-use district of commercial, retail and leisure facilities, the silos sat quiet and unused, awaiting a design that would do justice to the building's historic and architectural significance. Technically, it would have been simpler and cheaper to demolish the silo complex, and if the owners had not found a way to reuse the building, this might ultimately have been its fate.

However, the client, V&A Waterfront, had an ambition for the project to instigate a cultural revival in this neglected space and, with the silo complex the closest part of the district to the city, create a stronger link and draw additional visitors to the V&A Waterfront. The original building comprises two elements: a grading tower 'working house' and a shorter 'storage annexe' block made up of 42 27m high tubular silos. Heatherwick Studio's architectural vision to create an atrium within the tightly packed silos by carving a grain-shaped void gives visitors the sense of being inside a giant honeycomb, bringing light into the building while still retaining its original features.

In 2012, Arup was brought on board as multidisciplinary consultant by the client to work closely with Heatherwick Studio to resolve the engineering challenges of the proposed refurbishment and confirm the viability of the scheme. Staff from Arup offices in South Africa, Botswana and London worked collaboratively to develop the scheme at this stage. The structural scheme was developed in London before it was handed over to local designers Sutherland Engineers for the detailed design. Meanwhile, Arup's façade team in South Africa took the window design from concept stage through to installation, providing a prescriptive design to the fabricators to ensure the buildability of the signature windows.

3 & 4: Arup's engineering solution for the carved-out concrete atrium design involved rationalising the space into a portal frame structure by tying together the silo bins above the void

3.



4.

Arup also provided mechanical and public health engineering services from concept through the detailed design stage and to project close-out, along with wind, security, and artificial and daylighting studies advice.

The storage annexe

Creating a functioning building out of a bundle of concrete tubes presented a host of design challenges. The existing structure gained its strength and stiffness by being an integral set of bundled tubes. The carved out atrium space, and the removal of all walls except the western perimeter wall, left the remaining structure with no integrity and needing new structure to hold the original concrete in place.

In the western zone where new galleries were planned, new floor slabs were to be constructed on new internal columns. However, the perimeter edge of these slabs needed new vertical support, as the original perimeter walls had no spare capacity. To avoid constructing new internal shear walls, some of this perimeter zone needed to be braced with new structure to provide lateral stability.

A variety of solutions were considered to overcome these design challenges. Initially considered was a scheme with new columns and local shear walls around the perimeter, along with new high level steelwork above the atrium to hang the original concrete. However, this solution was discarded, as these elements would be visually prominent and could be seen as 'crutches' required to hold up a 'broken' building. The design breakthrough came from studying the original slip form construction. It became apparent that by re-sleeving the retained silo walls with a new inner skin of reinforced concrete, all of the structural challenges could be solved.

A new 250mm layer was cast directly against the original concrete, which was used as a one-sided shutter. In addition to holding in place all the retained original walls, the re-sleeved perimeter walls also supply the vertical load path for the new gallery floor slabs and act as shear walls resisting lateral loads. Above the atrium the overflying re-sleeved cylinders were connected to each other via reinforced shear keys through the retained original concrete, creating a spanning portal structure.

Arup's solution allowed the architectural design to be practically realised, while still retaining the building's grandeur and authenticity, and displaying the inner workings of the original building.

Foundations

Prior to excavation there were plans to add additional short piles down to the bedrock under the new internal columns. However, during the excavation stage the original 3m deep raft structure was found to be more robust than expected. This meant new foundations did not need to be built, offering a significant cost saving.

The working house

The structural independence of the working house tower from the storage annexe was maintained in the redevelopment. With large sections of the original perimeter walls that supplied the stability for the tower removed, both at ground level and high up on the hotel floors, new stability cores were constructed containing stairs and lifts.

New floors were added in the lower rectilinear silos zone to form small gallery rooms. The floors on the upper steel portion of the building were strengthened to meet robustness criteria of modern codes. In addition, some mezzanine floors and a high level swimming pool slab were added.

Financial feasibility and construction sequence were central to this ambitious scheme and Arup worked closely on this with the contractor, WBHO, and Sutherland Engineers, who carried out the detailed structural design.

Designing the pillow glazing

While the structural issues were being resolved, Arup's façade team was working on the complex glazing design. A series of pillow-like faceted windows was proposed, bulging out of the building where existing infill masonry could be removed in between the structural grid of concrete-encased steel; both along the top rim of the storage annexe and upwards on all sides of the working house. The architectural concept was inspired by the convex glass elements of lanterns, where glass is blown out of gaps in a grid. These delicate elements would contrast against the bulk of the concrete frame and refract the light as it entered the building.

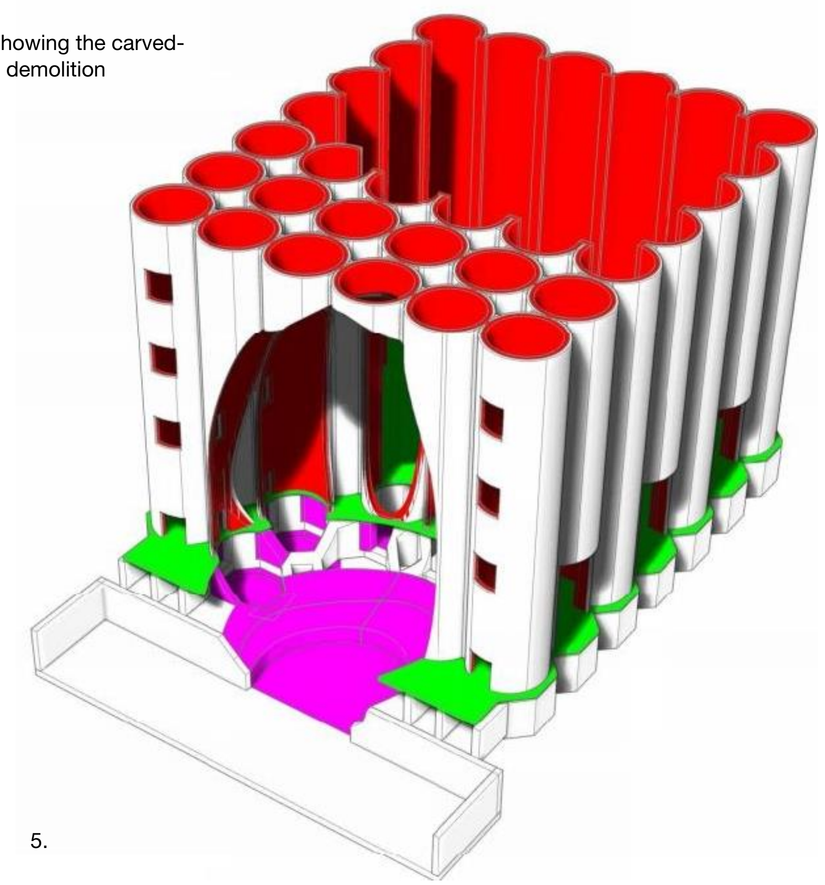
Arup had to find a way of realising these elements in a pragmatic, cost-effective and buildable manner. Working with Heatherwick Studio, this process began by determining the optimum number of facets for each 'pillow' window. The greater the number of facets, the more complicated the fabrication process. Fewer facets would overly simplify the aesthetic intent and lose the delicate yet industrial appearance that was desired. The number settled on was 56 facets as the optimum balance between appearance, cost and buildability.

A parametric solution

Arup experimented with a range of methods to conceptualise the windows. An initial attempt to project the architectural geometry onto the surface of a sphere proved unsatisfactory. Turning to a more principle-based approach, Arup established a series of geometric rules – horizontal and vertical planes meeting at the same focal point – intersected by a sphere to create the bulging pillow shape. The primary constraint was to keep the whole length of each of the main vertical and horizontal framing members in one plane so that they could be made with flat steel bars that would intersect neatly at the nodes in a way that made welding possible. Arup turned to parametric design using Grasshopper, a visual programming language for the Rhinoceros 3D computer-aided design software. By programming a script using the geometrical rules with an interface that gave the architects complete control to manipulate the projection of each node and the main joint lines, each possible solution was already pre-tested for viability. This allowed a specific geometry to be developed for each of the five different window designs, but with the same patterns and overall constraints.

This iterative parametric tool locked in the necessary structural constraints for fabrication, allowing for Heatherwick Studio to experiment with multiple iterations, each of which had effectively been pre-assessed for viability, reducing the time and cost required to

5: Isometric view showing the carved-out atrium and silo demolition



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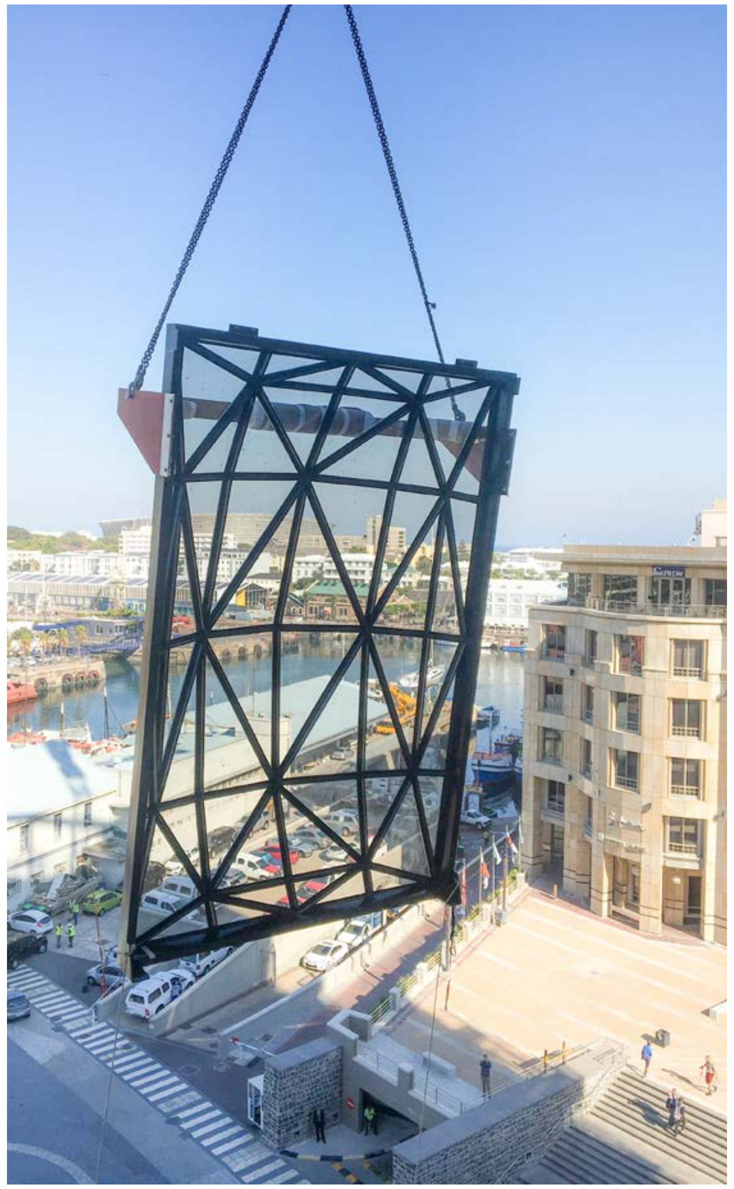

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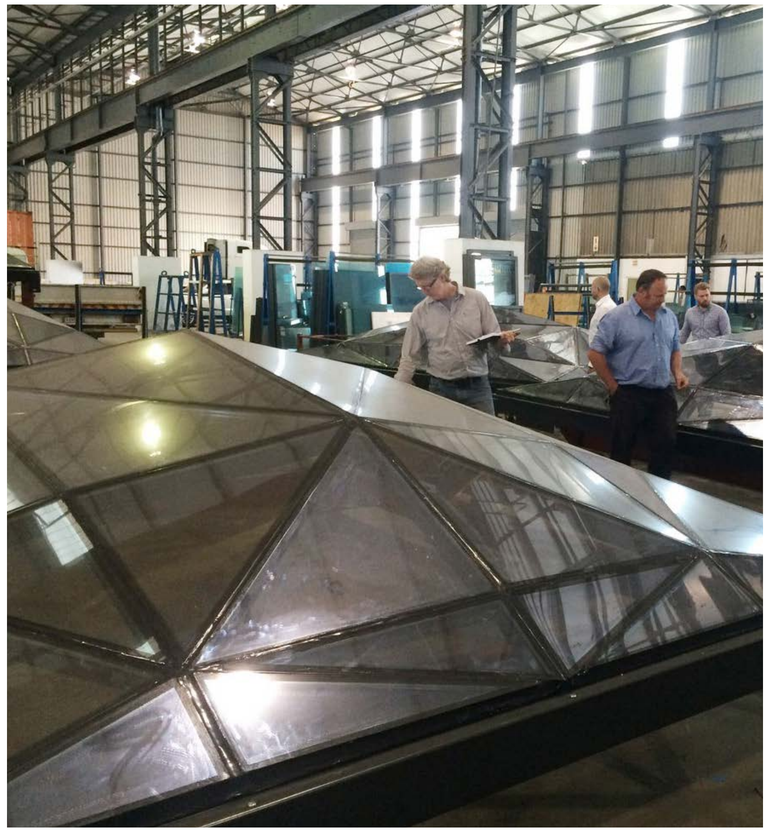

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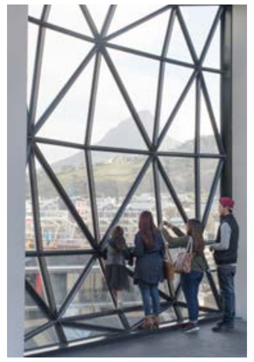


9.

6 & 7: Each pillow window was handmade in a sequence devised by Arup and the subcontractor to ensure loads were distributed evenly

8: Arup designed the window lifting bracket so each window could be fitted to a tight tolerance

9: One of the windows in situ

complete the process. This allowed the window designs to be finalised with fabrication drawings generated within a few hours. What could have been a year-long process of back and forth ended up taking just two months to design the five different types of window. Analysis methods (including Feldmeier and finite element analysis) were used to determine the glass pane flexibility of the irregular triangular shapes within each window.

Fabrication

The final window design comprised a frame made of slender flat steel 500mm by 160mm bars welded together at central nodes. Rather than aluminium, steel was chosen for the frame, allowing for very slender members to minimise the frame's visible bulk, while still maintaining strength and allowing for welded connections.

Fifty-six small triangular insulated glass units were structurally bonded to an aluminium glazing bar that was fixed to the steel frame. Double-glazing and high strength structural silicone seals provide a high level of acoustic performance, and reduce the noise entering the building from the working harbour outside. These seals were sized specifically to take account of the climatic pressure brought about by the small double-glazed triangular shapes.

The next step was to build the windows. In contrast to the digitalised design process, the manufacturing stage called for craft skills; each element was to be cut and welded together by hand. Arup communicated the design intent to a high level of detail before tender by using the 3D models produced through the parametric process. This allowed the design intent model and the shop drawing model to be reviewed and compared in a 3D virtual environment, rather than using 2D drawings. This lessened the possibility of errors. A local subcontractor, Mazor Aluminium, came on board in 2015 to deliver Arup's prescriptive design.

Making the design a reality presented numerous challenges. For one thing, each window is three-dimensional rather than flat, so locating the nodes in the right place was an exacting process, as was the sequence in which each joint was welded to ensure the loads were evenly distributed.

The steel sections were cut and welded at each node. Flat bars were cut to length and positioned on a jig, then welded together. Some of the nodes had up to eight connecting bars. Working with the subcontractor at its factory, Arup devised a welding sequence that ensured all welds could be accessed and welded after the framing was tack welded together and the jig removed. Each node was then ground smooth, before being filled out and smoothed using an automotive body filler to ensure it appeared like a continuous element rather than a joint. The subcontractor had a specialist team responsible only for dressing and shaping each of these nodes on all the windows.

Installation

Arup's design incorporated a lifting bracket that allowed the 5m by 5m window units to be installed with tight tolerances to the concrete openings. This bracket was temporarily bolted to the unit and was designed to 'correct' the eccentric centre of gravity, allowing the unit to be hoisted vertically, with the lifting cables positioned outside the concrete face. This significantly simplified the installation process, which took just 30 minutes for each panel.

Prior tests had shown that the concrete around the columns where the windows were to be attached was too weak to fix into. A number of solutions were investigated; ultimately, the team decided to strip the old structure back and install new concrete. The joints around each window were detailed to allow for large sway movements, as the windows are stiff in their own planes, and the area experiences seismic activity and intense south-east winds in the summer.

The pillow windows are the most noticeable design within Arup's façade engineering scope, but the team also designed a number of varied and complex solutions for each glazed element within the building.

Elsewhere, Arup undertook a series of qualitative desk studies to advise the design team on wind avoidance strategies in critical areas of the building, such as entrances and main pedestrian routes, and on ventilation arrangements and door types suitable for these conditions.

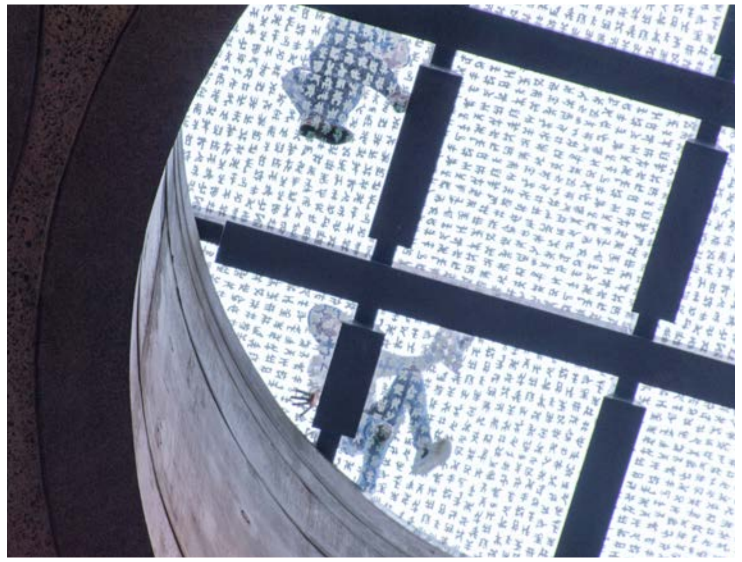
Lighting

The final element of the glazing was the skylights on top of the 5m diameter silo bins, which were an important element of the lighting control. These skylights form part of an external sculpture garden, supporting the sculptures and live pedestrian loading.

The top layer of the multiple laminated glass features artwork created specifically for this project on glazing supplied by Saint-Gobain France. The design helps control the bright, hot South African sun, ensuring there is a smooth transition between the levels of lighting during day and night, rather than a 'switch on the lights' moment. Arup conducted a 24-hour lighting analysis for the project, considering daylight conditions in the building over the period of a year, then ran simulations to help devise an ideal percentage of ceramic frits for the skylights. These were rendered on the glass in artwork

10 & 11: The silo bins were topped with skylight windows that form the floor of the rooftop sculpture garden. Bespoke artwork made of ceramic frits was printed onto the glass. The pattern controls light levels in the atrium and also acts as an anti-slip measure

10.



11.

12.

12: Zeitz MOCAA is now an internationally celebrated cultural hub that attracts visitors from around the world

created by Togo-born artist El Loko. They take the form of an anti-slip silk screen print, resulting in an element that is both beautiful and functional.

Sustainability

The cooling and heating requirements of the glazed pillow windows were collaboratively analysed between Arup's façade and mechanical teams using computational fluid dynamics. The design minimised solar heat gain and maintained natural light, while still reducing peak energy loads compared with a flat façade. This equates to lower running costs and energy use, as the mechanical systems could be designed for lower peak conditions and the plant size reduced accordingly.

Except for the solar control glass, which was imported from Europe as sheets, the materials for the façade were procured locally and local labour was used to fabricate each window, extending the project's sustainability beyond the building itself.

The mechanical engineering design allowed precise environmental control within the museum, enabling loans from international art institutions. Particular emphasis was placed on energy-efficient design to reduce power consumption and the building's demand on municipal infrastructure.

A low-velocity air displacement system conditions each gallery by means of a raised floor with grilles arranged around the perimeter. The galleries make use of the thermal inertia from the exposed concrete soffits to help regulate the temperature and humidity in the spaces, slowing the rate of change in the gallery spaces as visitors pass through the exhibitions.

The heating and cooling is fed from the precinct-wide district cooling system, which uses seawater from the adjacent harbour as a heat source or sink as needed (see 'The masterplan' story, shown right). The heating temperatures for the gallery spaces were optimised to allow the central plant designers to maximise the efficiency of the district plant heating and cooling cycles.

Cultural landmark

With the opening of Zeitz MOCAA and The Silo Hotel, the V&A Waterfront has added another destination to its existing portfolio that draws people in from the city centre, encouraging them to spend a day in the area. The museum, the largest museum of contemporary African art in the world, is an internationally significant cultural landmark and a unique platform for artists from Africa and its diaspora.

Authors

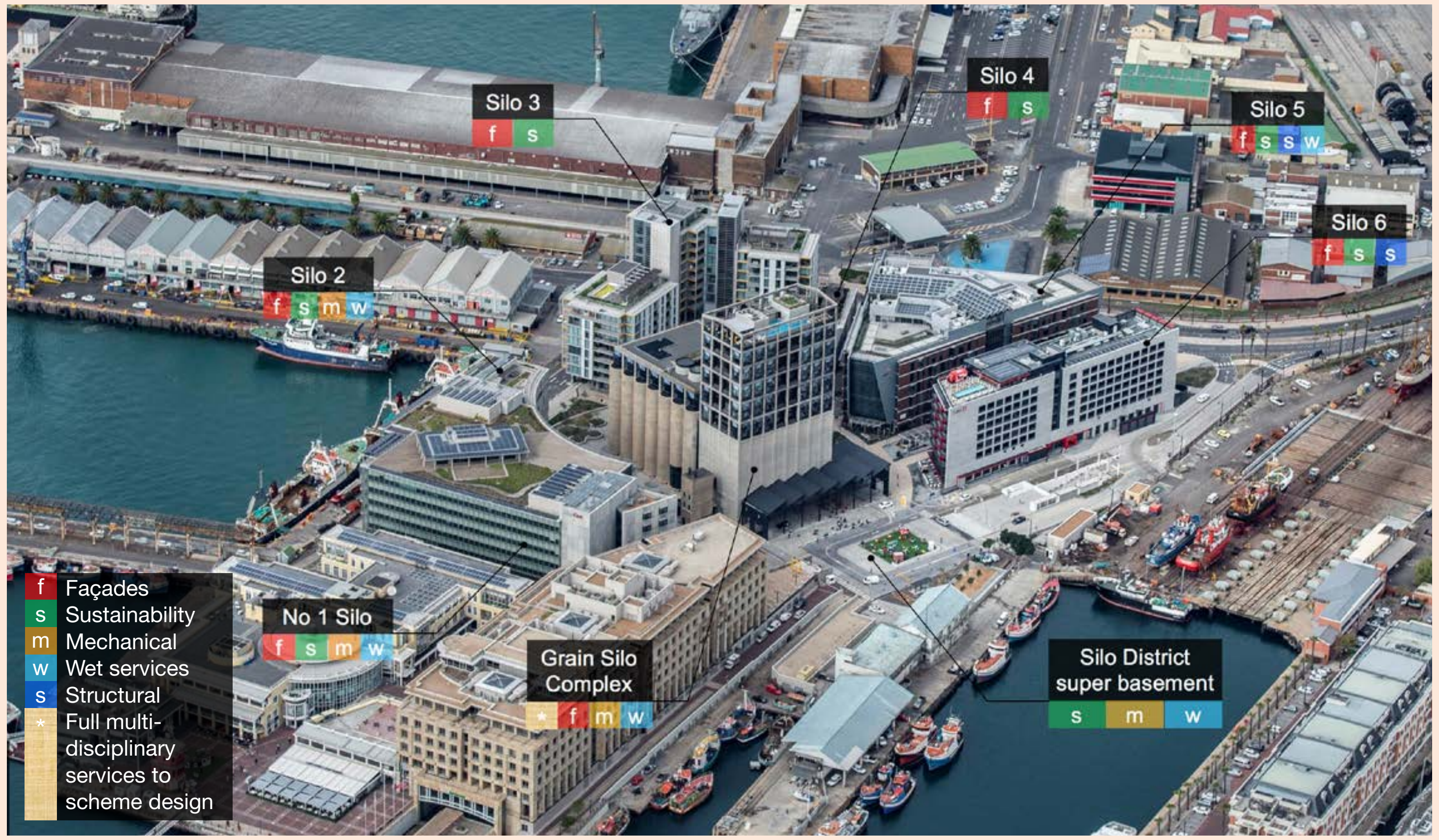
Francis Archer was Arup's lead structural engineer on the project during the scheme design phase and is an Associate Director in the London office.

Tessa Brunette was involved in the project from concept stage as the overall design manager and led the façade design during the construction stage. She is a Senior Façade Designer in the Cape Town office.

Project credits
Client V&A Waterfront, Cape Town, South Africa
Design architects Heatherwick Studio, London
Executive architects Van der Merwe Miszewski Architects, Rick Brown & Associates Architects, Jacobs Parker
Electrical engineer Solution Station
Quantity surveyor MLC Surveyors
Project manager Mace
Main contractor WBHO
Façade, mechanical and wet services engineer Arup
Structural engineer Arup and Sutherland
Arup: John Abbott, Francis Archer, Rossouw Van Der Bank, Willem Bosman, Michael Bradbury, Ian Braithwaite, Charlotte Briggs, Tessa Brunette, Ryan Collins, Gaye Dalton, Naeem Ebrahim, Simon Gill, Terence Govender, Philip Guthrie, Ed Hoare, Ben Jones, Darren Kent, Shaai-Qah Khan, Jacob Knight, Adam Lane, Adam Ozinsky, Guillermo Martinez Pajares, Pine Pienaar, Martin Radley, Gianluca Rapone, Rui Rodrigues, Rudolf Le Roux, Vanesh Seganathirajah, Jolyon Smith, Nic Smith, Con Strydom, Michael Stych, Innocent Svodziwa, Calvin Taylor, Matilde Tellier, Max Walker, Manja Van De Worp.

Image credits
1, 3, 4, 6-12, 14: Arup/Tessa Brunette
2: V&A Waterfront
5: Arup
13: InfrastructurePhotos

The masterplan



13.

The V&A Grain Silo Complex is perhaps the most significant building in the V&A Waterfront. Six new buildings were developed to form the recently completed Silo District, with the grain silo as its centrepiece. Arup's brief extended beyond the grain silo building to provide sustainability consulting to the precinct as a whole, as well as various consulting services on each of the new buildings including the underlying super-basement. This continuity, and particularly the façade and sustainability design of each building, was key to achieving the Green Star sustainability standard across the board, with two buildings achieving the highest rating possible: a six-star as-built rating.

This was primarily achieved by devising a seawater cooling system, with cold water from the ocean drawn into a cooling plant and through a heat exchanger, which is used to chill the building interior through the air-conditioning systems. This method was originally introduced on the first two buildings in the district, which were completed in 2011, and was designed with the flexibility to be rolled out right across the development. It was so successful that the plant was expanded to provide district-wide cooling, and the whole precinct is now cooled by seawater.

14.

13: The V&A Waterfront district and Arup's role in its regeneration

14: The cooling system devised by Arup uses seawater to cool the Grain Silo Complex

Collaborative science

The Francis Crick Institute is one of the largest biomedical facilities in Europe, created by bringing six of the UK's top scientific institutes together under one roof

Authors Steve Berry, Andrew Harrison, Clodagh Ryan, Richard Smith, Catherine Wells and Julie Wood

1.

1 & 2: The Francis Crick Institute is a hub for research into health and disease

The Francis Crick Institute is one of the world's leading biomedical discovery institutes. Its research focuses on why diseases develop and how they can be prevented, diagnosed and treated.

The institute has brought 1,500 scientists, researchers and support staff together into one building where new ideas can be shared and worked on in close collaboration. The vision for the building was to encourage a step change from scientists working independently and in isolation, to a spirit of collaboration across teams and disciplines.

This collaborative ethos was integral to the project management and design approach taken by Arup in the delivery of the building's design and construction, to ensure that the demanding technical requirements were met. Arup's involvement on the project began in 2003 with an appointment to assess existing facilities, and continued with the evaluation of a number of potential sites as part of the site selection process. Arup was appointed to carry out the building services engineering design; logistics; and elements of the fire and security consultancy services. Arup was additionally appointed as the client's project manager and contract administrator, from concept design through contractor procurement and appointment to post-completion.

Francis Crick Institute

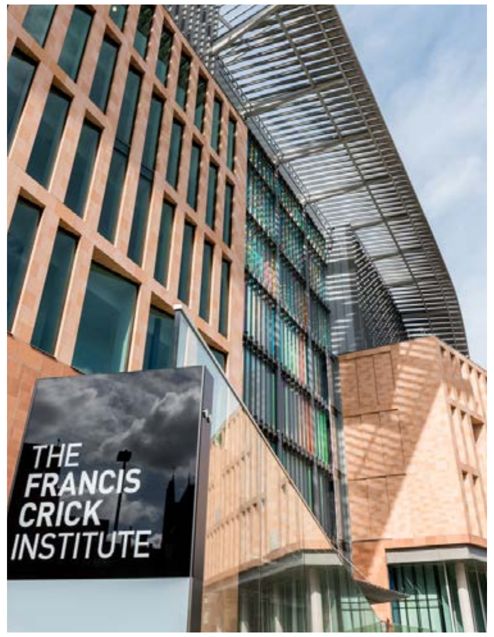
In 1953, molecular biologist Francis Crick, working with James Watson and building on research from Maurice Wilkins, identified the double-helical structure of DNA. This discovery earned the three scientists the Nobel Prize in Physiology or Medicine.

The Francis Crick Institute is dedicated to understanding the fundamental biology underlying health and disease and is a collaboration between six of the UK's top scientific institutes – the Medical Research Council, Cancer Research UK, the Wellcome Trust, University College London, Imperial College London and King's College London.

Site selection

A key requirement for the new facility was that it be attractive to leading researchers. It had to be located close to leading London hospitals, universities, existing medical institutions and transport links.

In 2008, a site beside the British Library and St Pancras Station was chosen. The location's compatibility was evaluated against a range of factors. Background acoustic levels and vibration signatures were assessed and used as the baseline for compliance and mitigation measures. Background electromagnetic levels were also scrutinised in order to minimise any potential interference with the sensitive equipment and research planned for the facility.



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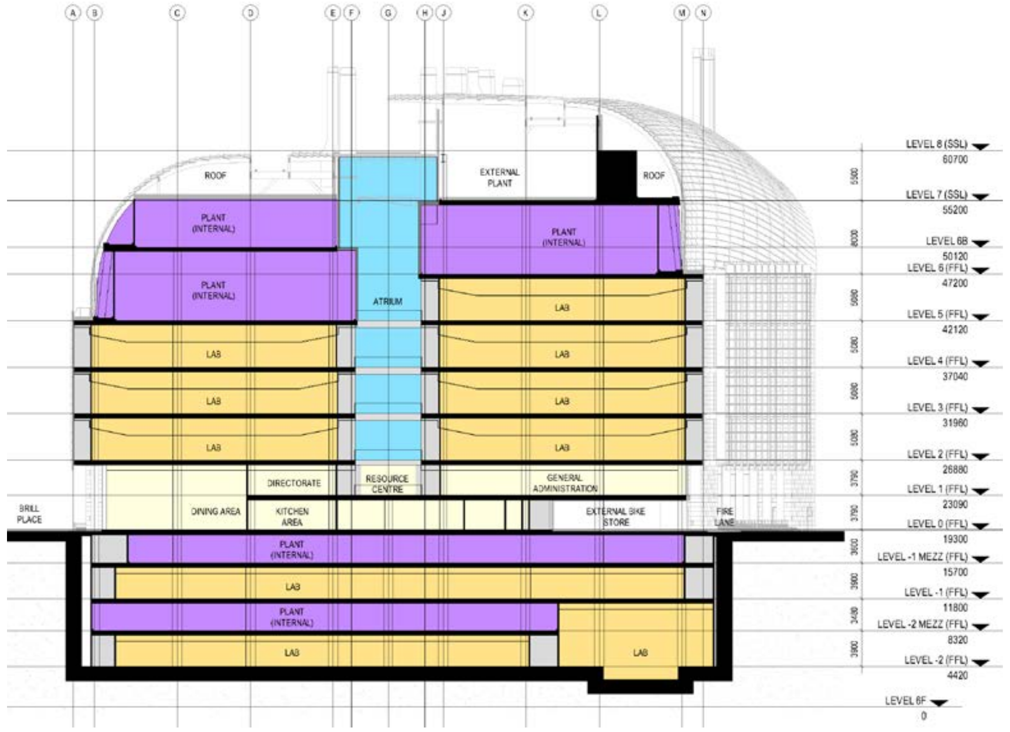
During the early stages of the project, part of the challenge was to help and support the business case feasibility. The aim of the institute was to create an establishment that would not only further cement the UK's position as a leader in the field of biomedical research, but also underpin a vision of 'collaborative science'.

Fast-track programme

Arup's Project Management team worked closely with the client to manage the delivery of planning approvals. Arup set up and led the procurement strategy that allowed the extensive basement construction – four levels below ground – to begin as soon as practically possible after receiving planning consent. The fast-track programme included a two-stage package procurement process that allowed the contractor to commence constructing the 16m deep basement as soon as planning consent was granted. A 'top-down' construction process allowed the upper levels of the building to be constructed in parallel with the basement works.

Stakeholder engagement

Arup led the strategy for engagement with building stakeholders from concept design



3.

through to handover. To achieve this a governance structure was developed for decision-making. There were 23 user groups, each with a dedicated lead who fed into a senior user group. Scientists and operational staff were drawn from across the institutes to develop the user requirements and brief. Arup managed the contractor to develop a full-scale mock-up of a typical laboratory and office area. Constructed off-site during the design stage, they were fully fitted out with equipment and user groups were able to visit the mock-ups. This gave an appreciation as to how their new work area looked and how they would work within the space, encouraging the scientists to provide feedback. It also improved success levels of achieving user sign-off at completion. Different types of laboratory furniture were tested and input from the user groups fed into the final design. This had significant benefit to the client in assurance that the final construction would meet user needs.

The mock-up also allowed the contractor to trial its construction methods. This was particularly useful for planning services coordination and construction of the high-containment laboratories.

Building services design

The building's form and function were shaped by the significant service requirements. The 82,000m² facility consists of four basement levels, including two interstitial plant floors, and eight levels above ground, which contain laboratory, plant, support, administration and amenity areas.

3: General cross-section through the building showing plant and laboratory layout

4: A full-scale laboratory mock-up created off-site for user group testing

5: A finished laboratory in use by scientists

4.

5.

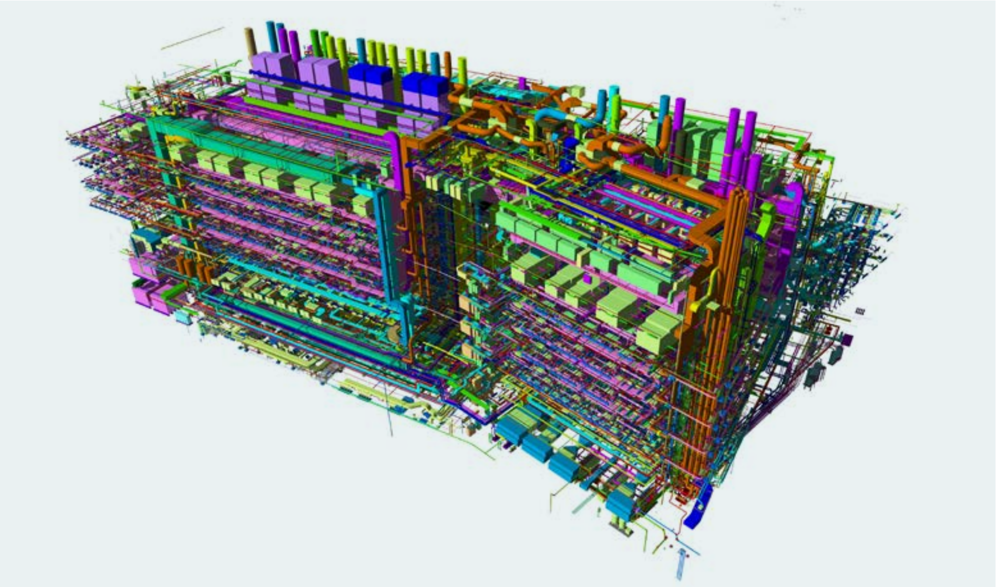
The interstitial floors accommodate the sizeable ventilation and air filtration plant, as well as other services required to support the basement laboratories. There is a main plant area in the basement, and two whole floors of plant are located at the top of the building. Large vertical distribution risers, which run the height of the building, are used to distribute services from the plant areas to occupied floors. In addition, horizontal primary routes for services connecting between risers at each floor level were created in 1.5m deep ceiling void spaces to facilitate distribution of services.

Services were set to minimise the building's energy consumption. Plant operation was optimised; a combined heat and power plant was installed to generate electricity, steam and hot water; and an extensive photovoltaic array (1,700m²) was integrated into the curved roof.

The specialist operations taking place in the building required specific consideration for building functionality and performance. Laboratories containing sensitive equipment needed to have high vibration control, and that was extended to all appropriate research spaces in order to provide greater adaptability for future use.

In addition to domestic hot and cold water, special provision was required for separate laboratory hot and cold water, reverse osmosis water, softened water for specialist equipment and water to support aquatic life. Carbon dioxide, nitrogen and compressed air are among the gases distributed from a central source.

Due to the nature of the research carried out in the building, particular attention was given to ensure resilience and redundancy within the engineering systems. There are four independent electrical feeds to the building from a primary St Pancras substation, and five substations within the institute (each of these have two associated transformers apiece). Back-up generation is provided by three 2.5MVA generation sets located in the roof plant area. These are designed to take the entire essential load of the building and are configured so that should a generator go offline, load can be shed and distributed across the remaining generators.



6.

6: Arup created a 3D building model crucial to planning such a highly complex building, which needed to accommodate specialist equipment and all the associated building services

7 & 8: Plant was housed predominantly in the basement and two interstitial floors. Two further floors of plant were located at the top of the building

7.

Laboratory areas

The general laboratory areas consist of primary, shared secondary, dedicated secondary and write-up areas, with adaptability built into the building services design to accommodate changing scientific programmes. Arup's Project Management team devised and led an adaptability strategy that recorded for the client the building services system capacity, furniture layouts and options for future change. The design for the laboratory areas was adaptable, with standardised room layouts that can be readily reconfigured as the sciences evolve. Connection points were installed above the ceilings with capacity for additional power, data, gas and water services to support future technologies.

8.

The services in the general laboratory areas were designed to operate as a Containment Level 2 area. Higher containment levels are located in dedicated areas. The write-up/office areas are located outside the laboratories.

Climate control in the general laboratories is handled by a variable air volume (VAV) system. Within secondary laboratory areas, additional fan-coil units supplement the VAV cooling.

Since the laboratories can accept only very limited, low levels of vibration transmitted within the structure, all building services plant and equipment that generate vibration were isolated using a mixture of anti-vibration mountings, spring hangers and supports. The laboratory floors are designed to Vibration Criteria-A (VC-A), with inertia slabs and local isolation tables set up in specific areas that require higher controls (VC-D and VC-E).

The drainage from the highest level containment laboratory is linked to a packaged effluent treatment plant located in the basement. This prevents any contaminants entering the drainage system.

Controls

The building has extensive controls and an energy management system with some 25,000 points, sophisticated diurnal lighting control, as well as environmental, ventilation and fire controls. Emissions from air stacks carrying exhaust from laboratories were numerically modelled. These exhausts come from fume cupboards, the biological research facilities and the high-containment laboratories – as well as the flue discharges from dual fuel boilers, combined heat and power plant and standby generators.

Discharges from the building had to be in compliance with the Clean Air Act and local authority requirements regarding contamination levels at street-level receptor points. To ensure no discharges were returned into the building through the fresh air intakes, a dispersion model was developed. The numerical analysis reviewed the stack discharge, flue dilation and concentration levels, confirming that the discharge from the 32 large extract air stacks and thermal flues was compliant with emissions requirements.

Biological research facilities

The biological research facilities are located in the basement, along with most of the high-containment laboratories. Although not high-containment, the biological research

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10.

9 & 10: The completed building enables collaboration between scientists of different disciplines by encouraging interaction in shared spaces

facilities are still subject to considerable scrutiny by the Home Office and various government agencies. These facilities have significant ventilation requirements and were designed to be capable of achieving 20 air changes per hour.

These facilities incorporate stringent odour control and ventilation regimes. Odour modelling was conducted using numerical and empirical testing of facility waste and feed materials on exhaust streams.

As the facility accommodates advanced scientific equipment, including electron microscopes, temperature control was required to within ±0.1°C over a period of one hour while maintaining airflow at low velocity. This was achieved by designing a specialist three-stage air conditioning system.

Controlling costs

Comprehensive value engineering studies were led by Arup, together with the contractor, Laing O'Rourke. These demonstrated the value of a pre-assembled modular approach to much of the building services owing to the challenging construction programme and constrained site. Arup worked with the contractor to accommodate the modular construction, factoring this into early designs and reviewing proposals.

Arup used a comprehensive 3D model, which was passed to the contractor to assist them. This was used for clash detection and routing, as well as to review how the services would be installed – critical for such a heavily serviced building. This information was tagged to assets within the building and given to the client's Facility Management team at handover.

The contractor incorporated more than 4,000 pre-assembled building services modules, along with a further 2,000+ prefabricated sections of pipework, containment and valve assemblies, within the building services systems.

Handover

The client's objective was to start moving staff in and operate the facility immediately following handover. Demonstrating correct performance of building systems and compliance of building construction with the client's requirements was essential to achieve practical completion of a project that incorporates complex environmental conditions and controls. Integration of the client's specialist equipment, which was installed outside the main contractor's scope, also needed to be completed and external approvals obtained from the Health and Safety Executive, the Home Office and the local authority, to allow occupation. Arup developed a comprehensive handover plan that set out detailed requirements to be achieved by the contractor prior to practical completion, as well as the interfaces with the client-supplied equipment and provisions for client inspections, familiarisation and training. This was incorporated in the construction contract to minimise risk and allow a successful handover.

Conclusion

Francis Crick's Nobel Prize showed how collaboration between disciplines can significantly aid scientific research. The Francis Crick Institute continues to foster this collaborative spirit, both in terms of the layout of the building, and in the way the project team worked together to project manage, design and build the institute. The project team's collaboration has also reaped rewards: the institute has secured BREEAM Excellent accreditation, a particularly notable accolade given the nature and size of this heavily serviced building.

Authors

Steve Berry was the Project Manager and the building service design team lead. He is an Associate Director in the London office.

Andrew Harrison was the Project Director for the building services element of the project. He is a Director in the London office and the firm's global science and industry business leader.

Clodagh Ryan led the project management services related to the building services. She is an Associate Director in the London office.

Richard Smith was the lead mechanical engineer and is an Associate Director in the London office.

Catherine Wells was the Project Manager for the overall project management and contract administration element. She is an Associate Director in the London office.

Julie Wood was Project Director for the overall project management and contract administration element. She is a director in the London office and the firm's global skills leader for programme and project management.

Project credits

Client Francis Crick (UK Centre for Medical Research and Innovation)
Architects HoK/PLP and BMJ
Cost Consultant Turner and Townsend
Structural Engineer AKT II
Main Contractor Laing O'Rourke
Project Manager and MEP Engineer Arup: Davar Abi-Zadeh, Michael Adams, Jim Aitken, Christian Allison, Stuart Allison, Luke Bannar-Martin, Alan Beadle, Steven Berry, Francesco Biancelli, Martyn Biss, Nicolas Bittner, Stephanie Black, Dora Boese, Miroslaw Bogusz, Bartosz Borowicz, Anita Bramfitt, Darren Briggs, Damian Bronowski, Andrew Brooks, Nathan Bryce, Kevin Burke, Kevin P Burke, Keith Butler, Lee Carter, Greg Chandler, James Connell, Shane Cooney, Anna Coppel, Marc Crompton, Tim Crow, James Davison, Grzegorz Delikat, Jennifer Dimambro, Vipul Dudhaiya, Ryan Dunne, Mike Durtnall, Sam Dust, Adam East, Mike Ebsworth, Stuart Edwards, Max Eyre, Bronwyn Field, Elizabeth Fletcher, Richard Foster, Malcolm Fullard, Rafal Gawlowski, Steve Gilchrist, Jerell Gill, Vullnet Gjakolli, Ben Glover, Artur Gorlovsky, Milan Graovac, Blair Gray, Tony Greenfield, Ross Griffiths, Amaury Guillais, Shane Haines, Kori Hamilton, Andrew Harrison, Naveed Hassan, Mike Hastings, Malcolm Heath, David Hewlett, Simon Humphreys, John Hunt, Jay Hussain, Helen Jackson, Lucas Janssen, Richard Jeffs, Rishi Jobanputra, Chris John, Ian Johnson, Andrew Jones, Mario Kaiser, Pawel Karwat, Joanna Kennedy, Peter Kinson, Simon Lee, David Lester, Mark Van Lith, Gareth Lloyd, Jenna Lobb, Michael Lorimer, Jacek Madej, Andrew Marks, Thomas Marr, Nazir Mawjee, Keith Mccall, Laura Mccann, Andrew McConachie, Ross Mills, Rayna Mistry, Kalpana Nepaul, Claudia Newsam, Pamela Nwaneri, Oliver O'Brien, Ed Oelman, Sebastian Oleksiak, Alberto Padilla-Peinado, Jessica Parsley, Steve Pennington, James Perou, Charlotte Perry, Hugh Pidduck, Mathura Ponnuthurai, Garry Porter, Anthony Proctor, Simon Rainsbury, Craig Reid, Daniel Reid, Marcin Rerak, Charles Richardson, Kat Roberts, Michael Roberts, Alice Robertshaw, Kathrine Rusling, Adam Russo, Clodagh Ryan, Stefan Sadokierski, Jodh Sahambi, Peter Samain, Demetri Serghiou, Jamie Shantonas, Celia Smith, Richard Smith, Thomas Smith, Michal Smolicki, Yeside Sogunro, Andrew Somerville, John Steele, Hannah Stevenson, David Stoker, Jon Stokes, Jiaxi Sun, Glen Swinney, Joanna Tolloczko Theodore, Mark Togher, Christopher Tolmie, Gary Towens, Mutlu Ucuncu, Mike Underhay, Gregory Visscher, Gary Walker, Ricky Watcham, Oliver Webber, Catherine Wells, Annabel West, David West, Antaeus Wheatley, Will Whitby, Gordon Wills, Marcin Wojewski, Chris Wood, Julie Wood, Jeff Yuen, Eduard Van Zyl.

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3, 4, 6: Arup
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Pushing the boundaries of 3D printing

A project that started as a design fair challenge has the potential to speed up the progress of 3D-printed buildings in Europe and beyond

Authors Guglielmo Carra and Luca Stabile

1.

Every April, the global design industry descends upon Milan for the world's best known design fair.

In the lead up to the 2018 event, the organisers of Salone del Mobile – the furniture fair at the centre of Milan Design Week – published a manifesto calling for designers to up their game when it came to tackling the global challenge of sustainability.

With this in mind, Arup worked with Italian practice CLS Architetti to create a temporary installation that went on to win the festival's Best Sustainability award, which celebrates the project that puts ethics and sustainability at the centre of design. What started as a plan to build a wall using 3D printing for an industrial building evolved into the first 3D-printed concrete house constructed in the EU, and one of the first in the world made using a portable robot manipulator.

3D Housing 05 – a 100m² structure with curved walls that enclose a living area, bedroom, kitchen and bathroom – was built on a busy square in Milan's city centre in full public view. It took just 48 hours to create the house's 35 concrete modules, each 3.2m high, which were printed in 60 to 90 minutes. The completed structure, which was assembled in two weeks, weighed about 50 tons, or 1,000kg per linear metre of printed wall.

At the end of Salone del Mobile, the entire structure was dismantled within five days, packed up and moved to a permanent location, leaving no trace of its short existence on the Piazza Cesare Beccaria as everyday life resumed in the city.

The future of construction

Over the past few years, governments and industry bodies around the world have hailed off-site manufacturing as the future of construction. The large-scale fabrication of building components in factories ahead of assembly on site has the potential to revolutionise the way our built environment is produced by speeding up the construction process and improving quality. It also has the added benefit of a more controlled and safe environment for workers than the average building site.

The technology used to 3D-print concrete buildings is still a step behind that of off-site construction, but it is arguably an even more compelling commercial proposition, as it means the advantages of industrial off-site production could be brought to the construction site itself. Greater flexibility in building shape is also possible, allowing more complex shapes and structures such as double curved walls. Digital plans could be used to print modules in situ, pushing the speed and efficiency of

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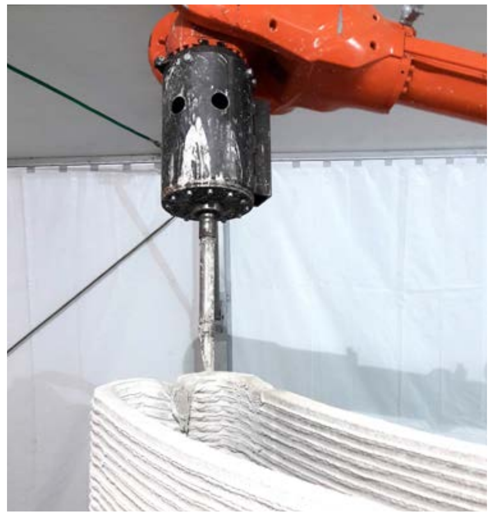
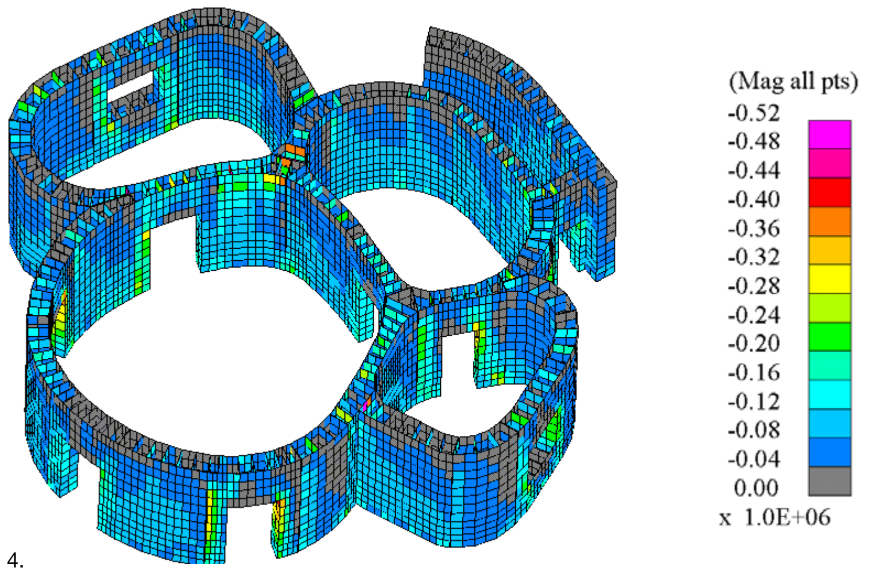


3.

1: Arup worked with CLS Architetti to create 3D Housing 05

2 & 3: The robotic manipulator can move along both horizontal and vertical planes to create shapes that are hard to achieve using traditional building methods



4.

4: Deformation analysis output under wind load from the Rhinoceros 3D software used by Arup

construction to its limits, as was the case with this project.

In such a scenario, every centimetre of material produced is used and placed exactly where needed without the requirement for formwork. This minimises materials, reduces waste and conserves energy. Using digital technology, the structure can be analysed and the design refined before it is rendered in real life and without the risk of miscommunication or human error.

Such structures, designed to the principles of the circular economy, can be dismantled with relative ease, either for use elsewhere or to recycle the basic material. Also, as artificial intelligence technology develops, several printing robots could work in combination quickly and efficiently without human intervention.

Today, there are still only a few examples of 3D-printed buildings erected directly on site. At present, China is the furthest ahead in the race to complete 3D-printed buildings of several storeys. The designs for these tend to mimic those of traditional houses, with 90° angles, rather than the complex shapes Arup helped create in Milan.

5 & 6: 3D Housing 05 was built in Milan's busy Piazza Cesare Beccaria in just two weeks, demonstrating the flexibility of this technology, which can create distinctive shapes such as curved walls with ease

5.

6.

Europe is believed to have fallen behind other parts of the world in 3D-printed construction because of its building regulations. With 3D Housing 05, the Arup team wanted to change that. More specifically, the aim was to demonstrate to the public the technology's flexibility, speed and potential to build at scale, paving the way for its use in real-world projects in the near future.

Design and fabrication

Arup, collaborating with architects CLS Architetti, provided structural engineering and materials consulting services. While Arup had previously done research into the potential of robotics in 3D concrete printing, this was the first time the firm had used the technology to create a real building. The design process commenced in January 2018, leaving just 90 days to plan and complete the scheme. With no time for test runs, the team's capability would be demonstrated for the first time live on site, with no room for error.

Conscious of the risk, the Arup team spent the months leading up to Milan Design Week conducting simulations to ensure that – at least in theory – the process was seamless. Arup used GSA, LS-DYNA® and Rhinoceros 3D software to develop the design, with the 3D model used on site during the construction process, all of which helped visualise and resolve issues in advance. Before starting on site, the team needed to consider factors such as the curing time of the concrete, the intricacies of 3D-printing unusual shapes, and the reinforcement that would allow each panel to be lifted out when the house was dismantled at the end of the design fair.

What made the project possible in a busy central Milan square was the use of a robotic manipulator, mounted on a movable base and caterpillar tracks, to fabricate the components directly on the pavement of the square. While most 3D printers are large, fixed devices supported by heavy infrastructure, Dutch company CyBe Construction's RC 3Dp is smaller and weighs just three tons.

Its flexibility and range mean it can move horizontally as well as vertically to create shapes that are difficult – and therefore expensive – to achieve with traditional techniques, at a speed of 200mm per second. The robot can extend up to 4.5m, but with some adjustment, it could go much higher, potentially allowing buildings of several storeys to be constructed.

Making it a reality

Building a temporary structure to demonstrate a technology's potential does not of course necessarily translate to the real world. The installation in Milan, as it was temporary, was not required to meet some of the regulations and codes that would apply to a permanent building. In addition, the reality is that 3D printing is currently not cheap.

The robot is priced at €349,000 and 3D Housing 05 cost about €800/m^2 to build, costing €80,000 in total, excluding fit-out and fixtures. This might be attractive to a client or an architect looking to create a customised structure with complex and unusual shapes; for example, all the modules that made up 3D Housing 05 were double-curved. However, this level of expense is not yet competitive compared with the cost of traditional methods of construction. This means it is not yet realistic to use the technology to build at scale or in contexts such as refugee camps and disaster zones, where temporary but cheap buildings need to be quickly erected.

This is partly because the process itself is complex, with the flow of concrete needing to be in sync with the robot's printing speed. The main expense is materials, which account for approximately 60% of the cost of a 3D-printed structure. For the house in Milan, CyBe Construction provided a concrete mix with performance set to meet the robot's features, therefore ensuring an optimised result. To bring the cost down substantially, different materials for 3D printing need to be investigated. Arup is exploring the possibility of reusing recycled concrete, as well as experimenting with natural materials – such as cellulose – and natural fibres, which would also mean materials could be sourced locally. The more buildings that are constructed in this way, the cheaper the technology will become.

Following the success of this project, Arup aims to build the first permanent two-storey 3D-printed building in Europe. At present, no such structures exist in Europe or the US because of the challenge of using this technology to design structures that withstand dynamic loads. Assessments are currently underway of the engineering and materials considerations, with a view to completing such a project before the end of 2019.

The widespread adoption of 3D printing in construction will require a systemic change within the industry, rather than just technology enhancements. Traditional construction sites also need to adapt if they are to become suitable and safe for rapid, factory-style production. Neither is the regulatory environment nor the supply chain currently designed to take into account the specific technologies and processes required to build in this manner. Having completed this landmark project, Arup is now leading efforts to transform the industry so that 3D-printed buildings can go from being a niche today to commonplace tomorrow.

7.

7: After the design fair, 3D Housing 05 was rapidly dismantled, leaving no trace in the piazza

Authors
Guglielmo Carra was the Project Manager. He is a Senior Engineer in the Milan office and is Arup's Europe Region Materials Skills Leader.

Luca Stabile was the Project Director. He is a Director in the Milan office and is the building practice leader for Arup in Italy.

Project credits
Architect CLS Architetti
Contractor CyBe Construction
Structural engineer Arup: Guglielmo Carra, Daniele Dozio, Eleonora Lai, Luca Stabile.

Image credits
1, 5: Arup/Luca Orlandini
2-4, 7: Arup
6: Arup/Giorgio Giunta

1.

A new phase for transport in Singapore

One of the most technically challenging underground projects ever undertaken in Singapore, the Downtown Line delivered more than just a new transport link

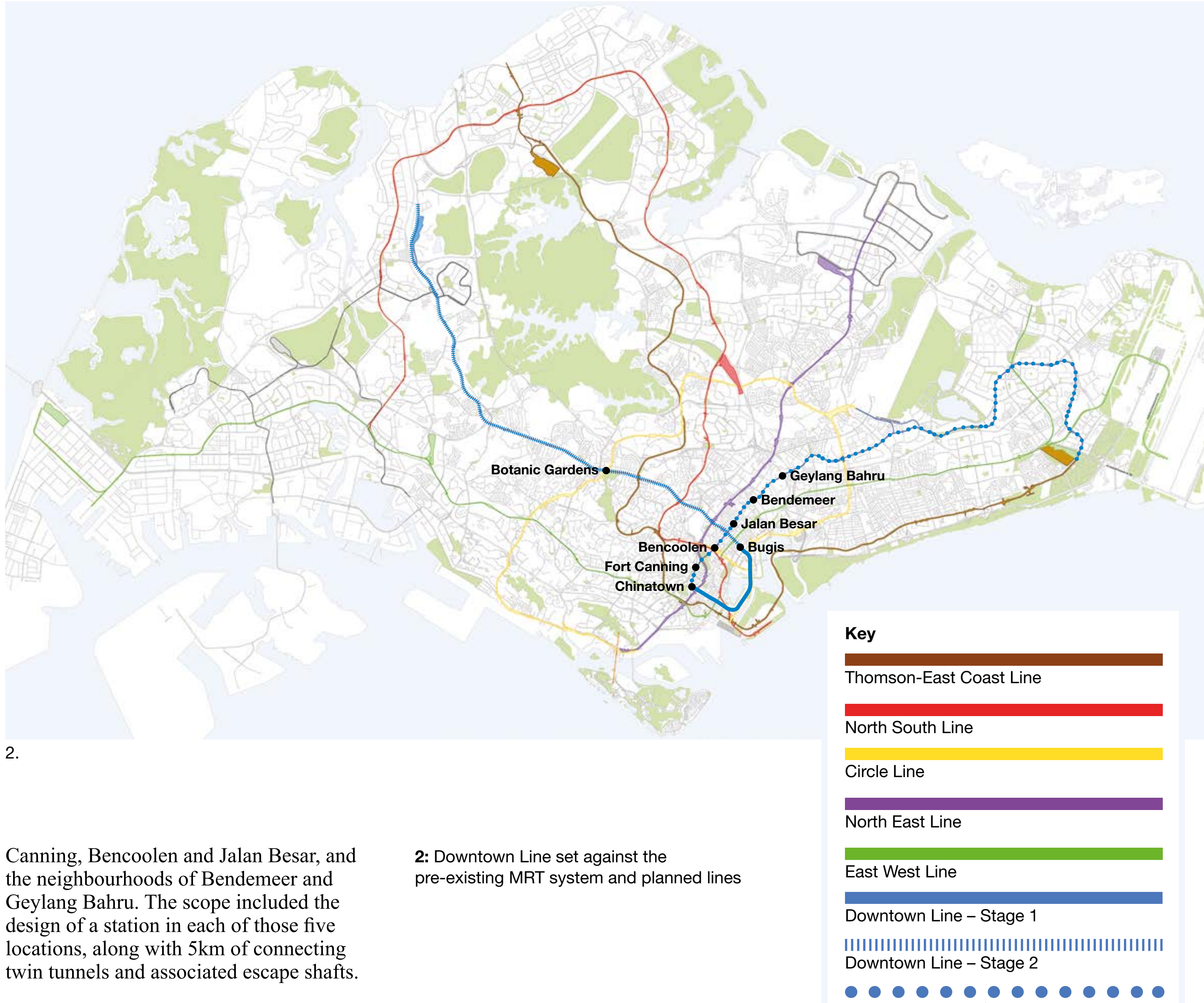
Authors Charles Im, Gordon Lee and Michael McGowan

By 2030, the Singapore government aims for 80% of households to be within a 10-minute walk of a metro station. A key part of the strategy for achieving this is a significant expansion of the city-state's Mass Rapid Transit (MRT) system, a vital part of its transport infrastructure that is used by more than three million people every day.

In October 2017, the final phase of the latest line to be added to the network was opened to the public. Downtown Line Stage 3 (DTL3) comprises 16 stations linked by 21km of tunnels. It connects the central business district with the eastern residential areas of Bedok and Tampines.

Arup's involvement in the project began in 2008, when the firm undertook alignment design for the entire length of DTL3. A year later, Arup was appointed to carry out the full engineering design for Package A of DTL3, through the historic districts of Fort

1: Bencoolen Station opened to the public after completion in October 2017



2.

2: Downtown Line set against the pre-existing MRT system and planned lines

Canning, Bencoolen and Jalan Besar, and the neighbourhoods of Bendemeer and Geylang Bahru. The scope included the design of a station in each of those five locations, along with 5km of connecting twin tunnels and associated escape shafts.

The line's central location means it runs under a dense, complex mix of modern and historic buildings, making it the city's deepest underground link. It also weaves under and over various existing subterranean infrastructure, including telecommunications, fibre optics, power, traffic and street lighting cables; water and gas pipes; and three existing MRT lines. In addition to those obstacles, the line drops below the Singapore River and skirts arterial roads and underground road tunnels. This combination of design constraints made it one of the most technically challenging underground projects ever undertaken in Singapore.

When Arup took on the project, it was conscious of the need to tackle all these challenges, while maximising ridership and the benefits of a mass transit system for commuters and businesses. Arup carried out more than 1,000 building impact assessments along the proposed route, with design solutions suggested and implemented to navigate the varied design constraints, including developing the concept for temporarily diverting the Singapore River during construction.

Arup worked with Singapore's Land Transport Authority (LTA) to develop safe, buildable designs that were not only innovative but improved the overall productivity of the construction works, while pushing the boundaries of ground engineering methods in an urbanised environment. In doing so, it has set a precedent for sustainability and innovation for future rail developments in the city-state.

Alignment

The latest addition to Singapore's MRT system, the 42km Downtown Line is the longest underground and driverless rail line in Singapore and was designed to link the downtown district with commuters in the north-western and central-eastern parts of the city. The line was developed in three stages. Stage 1 opened in 2013, Stage 2 in 2015 and Stage 3 in 2017.

3.

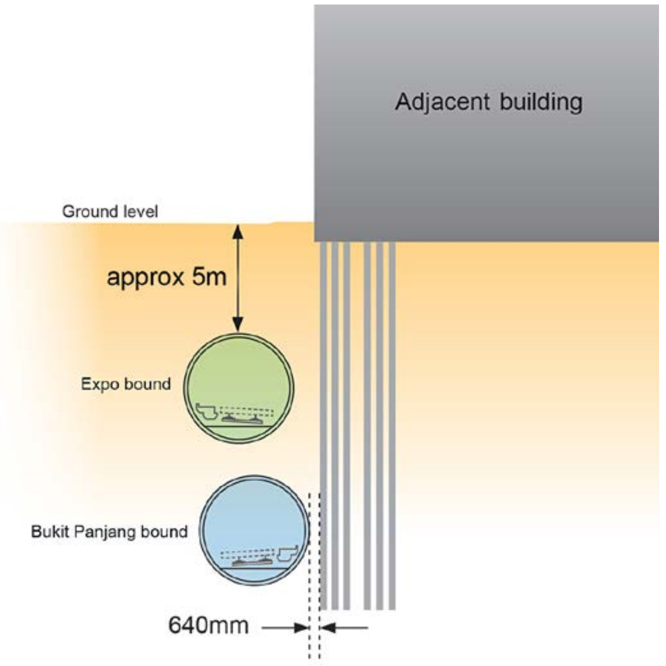
3: The tunnels between Chinatown and Fort Canning stations had to navigate a particularly narrow corridor of buildings, with cut and cover tunnel methods used for construction outside the State Courts

Arup worked on the early phases of the DTL Stage 2, carrying out the reference design for the 10km stretch of tunnels and stations from Chinatown to Botanic Gardens. Arup was subsequently appointed to develop a concept design for DTL Stage 3, including station location and alignment within all the existing under- and above-ground infrastructure. This allowed Arup to build up an in-depth understanding of the challenges involved in designing, building and operating such a mass transit system, and how these could be resolved.

For the concept alignment study, Arup developed a comprehensive horizontal and vertical alignment of the tunnels, considering buildability, operations and ease of access. This was vital because of the built-up density of the corridor. For example, the tunnels between Fort Canning and Bencoolen stations were constrained by existing MRT lines, and passed directly below a national monument, the National Museum of Singapore. The tunnels had to pass over the North East Line, with a 1.3m clearance, then under the North South and Circle Lines, with clearances of 8.7m and 3.2m respectively. The tunnels between Fort Canning and Chinatown stations had to pass through a very narrow corridor between the State Courts and a public Housing and Development Board (HDB) building, requiring the tunnels to be in a stacked configuration. At one point in this corridor, the MRT tunnels had to be constructed a mere 640mm away from the foundations of one structure.

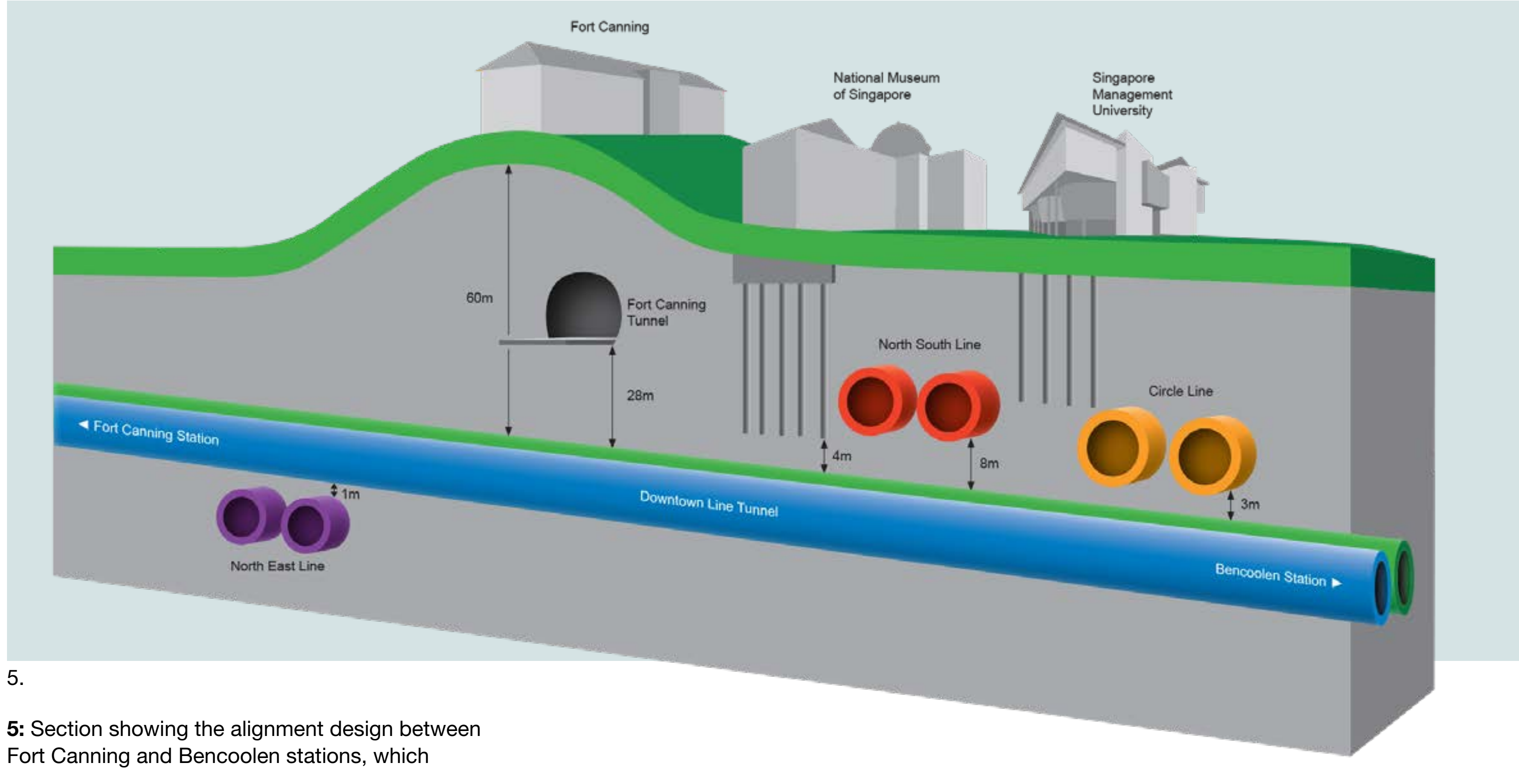
Following this alignment design, Arup was appointed, as part of a competitive tendering process, to carry out the full engineering station and tunnel design for DTL3 Package A, running from Chinatown to Geylang Bahru. The scope of design work included infrastructure, alignment, geotechnics, tunnels, civil and structural engineering, acoustics, traffic impact assessment, environmental impact assessment and geographic information systems.

During the preliminary design stage, studies were carried out to eliminate, minimise and



4.

4: The alignment is so fine between Fort Canning and Chinatown stations that at one point the tunnels pass just 640mm from the foundations of a building



5.

5: Section showing the alignment design between Fort Canning and Bencoolen stations, which efficiently navigated the existing, densely packed subterranean infrastructure

manage the impact of station and tunnelling works on existing structures. Building type, condition and heritage value were all considered when assessing the horizontal and vertical rail alignment. In addition, several investigations were carried out for key buildings and structures along the alignment to determine building foundations where as-built information was not available or the accuracy of records was in question. This helped to minimise construction risk by determining if they impeded the tunnel boring construction. Arup carried out design checks to ensure that where some piled foundations were removed during tunnelling, the buildings above would remain stable.

A key design criterion was to minimise the number of buildings requiring demolition, as acquisition and demolition would add substantially to the cost of the project. Ultimately, only one building was demolished, and Arup's work meant that a significant multi-storey building in the downtown area could be retained intact, a significant saving for the client. Arup's optimised alignment also reduced the number of buildings that DTL3 passed directly under by more than 60% from the original alignment.

The overall aim was for the underground works to be as shallow as possible, saving construction cost as well as improving public access and passenger experience when entering stations and inter-changing between lines. By challenging past practices and rail geometry design requirements without compromising operations, Arup made the design more efficient, optimising the construction process to make DTL3 safer and quicker to build, with significant financial savings for the client.

Diverting Singapore River


6.

6: As the deepest station in Singapore, Bencoolen sits below pre-existing MRT tunnel levels

Arup's role in DTL3 Package A involved not only designing a future-proofed transit system, but also managing the logistics of the project, from finding space to allow construction worksites to function, to ensuring minimal disruption to people living and working in the area. The critical challenge was the design of the tunnels under the Singapore River between Fort Canning Station, a shallow two-level underground station structure 17.5m below ground level, and the existing Chinatown Station (part of DTL Stage 1), on the other side of the river. The only feasible tunnel alignment brought construction at this location close to the Central Expressway (CTE) road tunnel and the potential that some temporary ground anchors remained in situ after its construction in the 1980s.

In addition, over the city's history, the area of the Singapore River close to the proposed Fort Canning Station had been a timber yard, which meant there was a potential risk of debris left behind in the riverbed. If the tunnelling machines encountered any remnants from these activities during construction under the river, both the DTL3 construction works and potentially the adjoining live railway lines could have been flooded.

Arup developed a concept to negate this risk: divert the river prior to the tunnelling process. This facilitated the removal of any obstructions in the riverbed, allowing for the safe construction of the twin tunnels beneath the riverbed, mitigating the possibility of a catastrophic flooding event. The diversion also allowed the river to remain fully operational and navigable by rivercraft during the three-year construction period.

To achieve this, a 42m wide, 7m deep diversion channel, approximately 100m in length, was built along the river's west bank. The river walls at either end of the diversion canal were then demolished to create the river's new temporary route. An embankment was constructed across the river's original course, allowing removal of obstructions including timber beams, cabling and reinforced concrete debris within the DTL3 tunnel corridor. To further negate soil instability during tunnelling, which would increase risk of flooding, the soils through which the tunnels passed beneath the river were stabilised and strengthened by grouting.

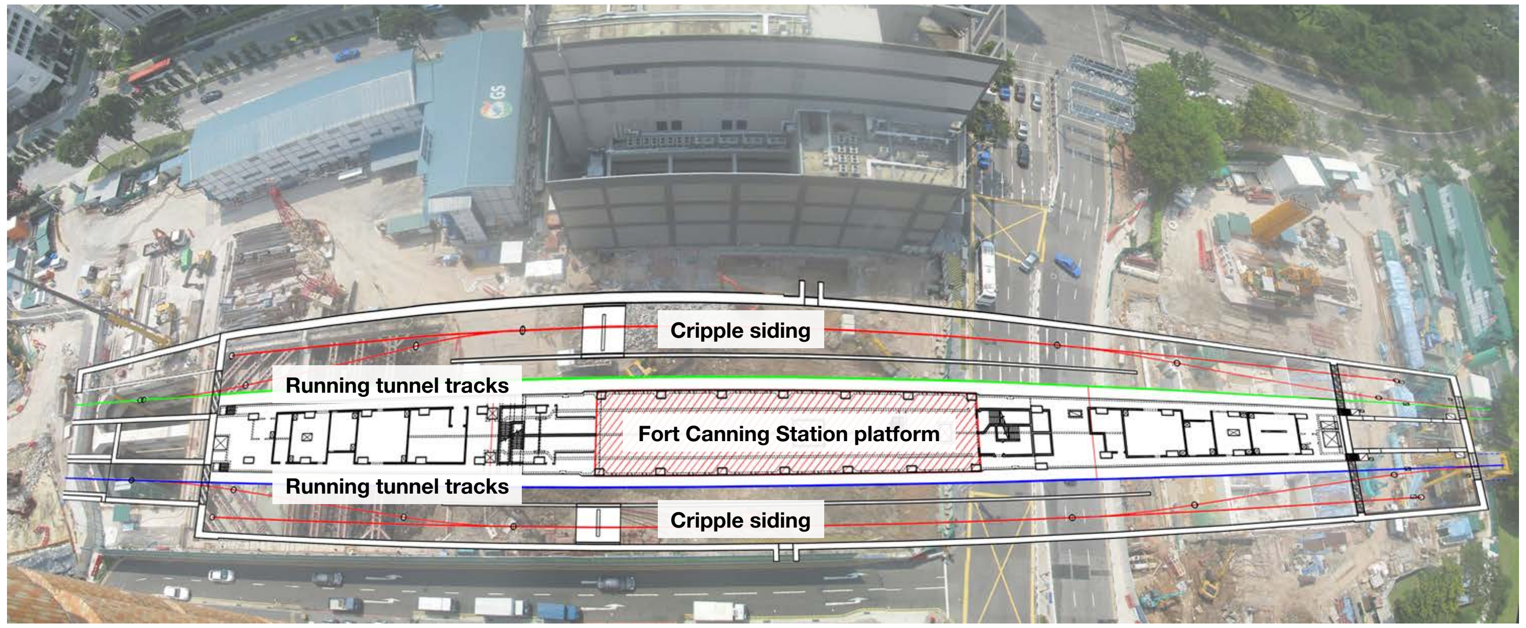
Once the debris removal, grouting and tunnelling works were complete, the


7.


8.


9.

7, 8 & 9: The Singapore River diversion works, showing the diversion channel under construction (left and centre) and the diverted river during tunnel construction (far right)



10.

10: The cripple sidings for temporary train storage were placed within Fort Canning Station rather than along the tunnels, which significantly reduced costs

11.

11: Tunnel boring machine access shaft at Fort Canning Station

embankment and the temporary bridge were removed, and the diversion canal filled in, restoring the river to its original route.

Fort Canning Station
Located within a constrained site on the north side of the Singapore River bank between Liang Court and the CTE, this station extends towards the southern end of the historical Fort Canning Hill. Station Entrance A is located next to the CTE tunnel, with a minimum clearance of approximately 5m. A robust design solution comprising propped diaphragm walls and top-down construction methods was required to control movement of the sensitive CTE. An extensive impact assessment was necessary to demonstrate that the effect of the main station excavation works on the existing CTE tunnel was acceptable.

Fort Canning cripple sidings
Arup designed the cripple siding, which is an extra track that is used to facilitate withdrawal or storage of trains, to be located within Fort Canning Station. Typically, cripple sidings are located along the tunnel length, but given the very tight site constraints along DTL3, there was no suitable site available between stations. Arup's solution to locate the cripple sidings on each side of the Fort Canning Station platforms made the station wider, but ultimately saved significant construction cost by removing the need to find additional land to construct a discrete cut and cover structure for the siding. This was a design and operations first for Singapore.

Jalan Besar Station
The construction of the four-level Jalan Besar Station was particularly challenging. The station is immediately adjacent to conservation shophouses that are founded in soft soils and required retention. The proximity to these heritage buildings posed significant space constraints for the works, as well as prompting concerns that the deep excavation (>30m) could cause damaging vibrations or movement to these buildings.

During the design stage, Arup carried out pre-construction inspections to establish the existing condition of all structures within 250m of the station excavation. This determined if there were any pre-existing building defects and what type of foundations were in place supporting the buildings. Building impact assessments were conducted to predict the potential effects of the station work and show that impacts were acceptable.

Shophouses that required precautionary protection had propping systems installed for the façade and were monitored closely during construction.

The earth retaining and stabilising system at the station comprised a combination of 1.2m and 0.8m thick diaphragm walls, crosswalls, ground improvement and concrete walers. This retaining system provided the necessary high level of wall restraint against deflections and ground movements in this critical area. The station, measuring 170m long, 23m wide and 35m deep, was constructed using top-down methods, further enhancing movement control.

12.

12: Arup demonstrated, using traffic simulations, that even with Bencoolen Street closed during DTL3 construction the surrounding roads could accommodate the temporary arrangement

13.

13: While closed for the station works, Bencoolen Street was redeveloped to be 'car-lite', creating better access for bikes and buses

The monitored ground and building movements were within acceptable limits.

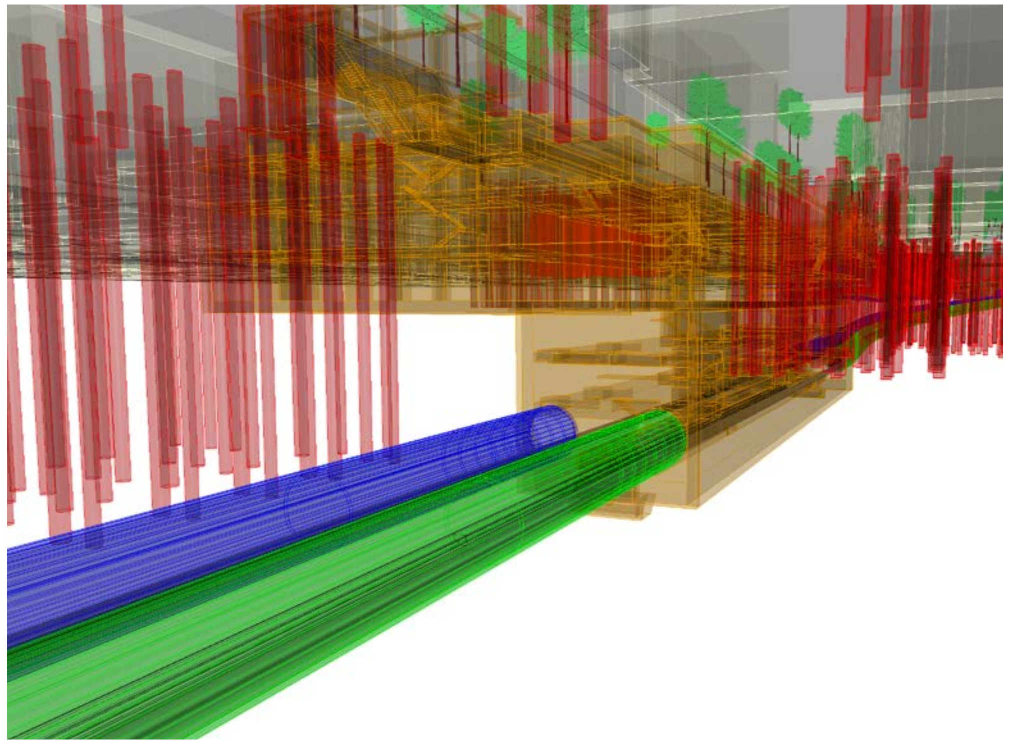
Bencoolen Station
At rail level, Bencoolen Station is 43m below ground, and is the deepest underground station in Singapore. It required the temporary closure of a nearby major street because of the complexity of construction work required within the tight construction programme. This station depth was required to avoid the existing North South Line and Circle Line tunnels immediately west of the station. The station comprises six levels and is 190m long. Critically, it is only 23m wide in order to fit within the streetscape corridor. The Arup team not only developed a system of escalators and lifts that allowed rapid and seamless vertical transportation of passengers from the concourse to platform level, but also designed the interiors to make this journey memorable.

During construction, Bencoolen Street was closed to traffic. Arup prepared a microsimulation model of the road network surrounding the site, incorporating all junctions and other relevant infrastructure such as car parks and traffic exit points. This allowed the traffic pattern to be simulated to ensure that the existing road network could carry the increase in traffic volumes with the temporary Bencoolen Street road closure.

The surrounding road network required a number of junction upgrades. In addition, roadside parking was removed at Waterloo Street, and Selegie Road, previously a one-way street, was made two-way. These adjustments ensured the extra traffic volumes along existing streets were accommodated even with the closure of Bencoolen Street.

Following completion of the works, a redesigned Bencoolen streetscape was constructed with wider pavements, an all-day bus lane, dedicated cycle paths and more bicycle parking. This 'car-lite' streetscape is one of the first in Singapore.

Steel fibre reinforced concrete
Arup proposed the use of steel fibre reinforced concrete as permanent lining for a section of the bored tunnels of DTL3, a system not previously used for tunnels in South-East Asia. The decision to use this method was made to reduce the need for labour to fix and place traditional steel reinforcement, saving time and costs during lining fabrication, resulting in increased construction productivity. The use of fibres in concrete also enhances durability and improves concrete performance under fire loads. Using less material is also more sustainable: a typical steel ratio for a tunnel in Singapore averages about 120kg/m^3, compared with a steel fibre ratio of 30-40kg/m^3. Arup developed the approach for testing the material and its performance, as well as proving the feasibility of using steel fibre concrete in underground construction in Singapore. This required Arup to engage



14.

14: BIM is now mandated on all Singapore's transit projects, a process facilitated by the standards set on DTL3

15: Journey times for the majority of people using DTL3 have been reduced by up to 10 minutes

16: At 43m below ground level, Bencoolen Station is the deepest in Singapore

17: Fort Canning Station required careful design considerations due to its location adjacent to the Central Expressway Tunnel

15.

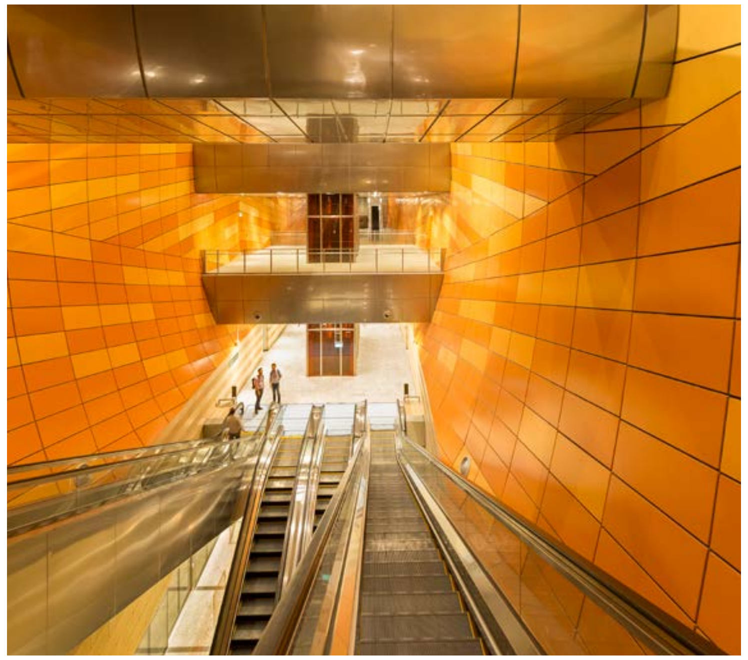
with the Building Control Authority and work collaboratively with the supply chain to ensure the new material was approved and adopted smoothly.

Digital modelling

DTL3 Package A was one of the first construction projects in Singapore to develop and use Building Information Models (BIM) for design. Arup led this drive. Using these digital methods of collaborating and coordinating, through 3D models containing every feature of each station and tunnel, meant that any clashes in the design were identified and removed prior to tender rather than during on-site construction. Designing through BIM is now mandated on all the city's transit projects. The standards of coordination and quality set by DTL3 contributed to this process.

Results

DTL3 opened towards the end of 2017, offering a swifter commute between the eastern part of Singapore and the downtown area. It is a key part of the government's transport strategy. Daily weekday ridership on the DTL has grown by more than 50%, from 300,000 to 470,000, after the opening of DTL3. About 60% of journeys involving DTL3 have been shortened by up to 10 minutes, compared with previous travel routes, while 20% of journeys are shortened by more than 10 minutes.



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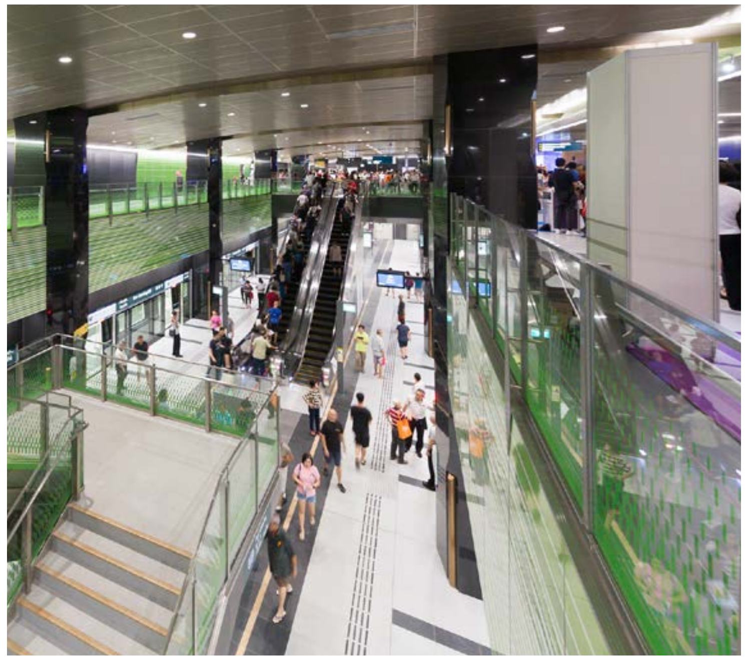

17.

The opening of DTL3 has brought people who live and work in the east closer to train stations. Today, 64% of households across Singapore are within a 10-minute walk of a station, bringing the city-state closer to achieving the goal of 80% of households being within a 10-minute walk of a train station by 2030.

Following the success of this project, Arup has secured a number of other rail projects in Singapore, including the Thomson-East Coast Line, where Arup is the designer of 14 stations and nearly 20km of tunnels. Subsequently, Arup was engaged to develop the design for the 50km long Cross Island Line. Arup will continue playing a leading role in helping the Singapore government create one of the world's best urban transport systems.

Authors

Charles Im was the Project Manager during construction. He is an Associate Principal in the Singapore office and the Geotechnical Leader in Singapore.

Gordon Lee was the Deputy Project Manager during construction. He is an Associate in the Singapore office.

Michael McGowan was the Project Director during construction and led the project management element. He is a Principal in the Singapore Office leading Arup's infrastructure business.

Project credits

Client Land Transport Authority of Singapore
Architect Aedas Pte Ltd
Contractors:
Fort Canning Station – GS Engineering & Construction Corporation
Bencoolen Station – Sato Kogyo (S) Pte Ltd
Jalan Besar Station – Leighton John Holland Joint Venture
Bendemeer Station – Penta Ocean Construction Co Ltd
Geylang Bahru Station – China State Construction Engineering Corporation Limited

Full engineering design: Arup
Roel Abubo, Nur Liyana Ahmad, Michael Alder, Lioni Alvarez, Victor Andrade, Pei Wen Ang, Serene Ang, Anton Arceo, Jhunel Arroyo, Harry Asilo, Camelia Badeo, Daniel Bali, Warren Balitcha, Jomar Baquiran, Rolando Bautista, Tim Bennett, Roger Blackwell, Tamas Bodri, Nigel Casey, Kartigayen Poutelaye Cavounder, Gary Cequena, Peggy Chan, Ricky Chan, Naimet Cheema, Andrew Cheng, Joy Cheong, Alvin Cheung, Heidi Cheung, Henry Chia, Lok Ching Choi, Fann Chong, Jin Thai Chong, Ricky Chong, Ts Choong, Shiao Teng Chow, Wai Fun Choy, Steve Colomb, Jonathan Constantinou, Argoon Chuang, James Daish, Yang Dang, Christopher Daniel, John Davies, Lauren Davis, Chris Deakin, Sheryl Demesa, David Derige, Deirdre Devery, Symur Diche, Lu Lu Din, Ronaldo Domingo, Ryan Edano, Hidayah Edward, Fendy Edy, Yu Ting Fan, Shuhong Feng, Ting Yi Foo, Vivien Foo, Arvin Francisco, Ezel Gabriana, Sacha Gebbie, Mercy Guevarra, Xinrui Guo, Hasnita Hashim, Kok Hui Heng, Andrew Henry, Ka Fui Hiew, Siaw Ling Hiew, Arge Hipolito, Kent Ho, Sai Ho, Dongmei Hu, Hangyu Huang, Sarah Huskie, Jamilah Hussain, Charles Im, Bradley Jackson, Gladys Jahja, Nur Hayati Jamalludin, Rohani Jamalludin, Henry Jeens, Jimmy Jiang, Damien Jolly, Subash Kathiresan, Zahid Khan, Rachel Khoo, Nam-Jo Kim, Yan Ru Kiu, Christofer Kristo, Siang Meng Kua, Ben Kwong, Francis Lai, Aishah Abdul Latiff, Ching Lau, Vicki Lau, Alice Laung, Phil Lazarus, Cheryl Lee, Faith Lee, Gordon Lee, Kah Peck Lee, Mandy Lee, Sazlynda Lee, Sean Lee, Sebastian Lee, Wong Lei Lei, Anthony Leversedge, Siyu Li, Yangyang Li, Hasta Lie, Keithson Liew, Daniel Lim, Deyuan Lim, Jia Yuan Lim, Lip Boon Lim, William Lim, Angie Lin, Chris Liu, Ashley Lloyd, Tom Lok, Ragavendra Lokaranjan, Annabelle Loke, Chunrong Lu, Steven Lucianto, Neville Lui, Farong Luo, Xiangyue Luo, Malcolm Lyon, Serene Mah, Noraziza Mahbob, Juan Maier, Swee Chiang Mak, Israel Maraddag, Mukunthan Manickavasakar, Noel Manuel, Haruko Masutani, Chandana Medagoda, Michael McGowan, Wing Sze Mo, Zin Soe Moe, Junaideen Sainulabdeen Mohamed, Daniel Mulyawan, Sudhakaran Nair, Andrew Nelson, Betty Ng, Jia Le Ngai, Rain Nguyen Pham, Rosella Obordo, Nurmarlia Omar, Shahnaz Omar, Khine Khine Oo, Abner Paredes, Benjamin Pascua, Michael Dela Pena, Brett Perez, Hai Pham, Alan Philp, Luis Piek, Seng Tiok Poh, Jason Poon, Chris Pynn, William Quah, Virgilio Quinones, Nizar Abdul Rahim, Hamed Rahimi, Ashish Raikwal, Pablo Romero, Ken Roxas, Ali Sadeghi, Norliah Sanusi, Wisnu Saputra, Jeyabalan Sathaiah, Dennis Seah, Sau Fong See, Kartini Shabani, Xiao Shan, Nikki Shaw, Hongwei Shi, Ming Simon, Ernesto Siochi, Sai Sivarajah, Seng Siong Soh, Jeremy Su, Lifeng Su, Leo Suhaendi, Kevin Suhartono, Arbaiyah Sulaiman, Barry Sullivan, Qian Sun, Podianko Surya, Sharifah Syed, Cheryl Tan, David Tan, Fook Aik Tan, Lawrence Tan, May Tan, Yoong Heng Tan, Yunyou Tan, Lim Mei Tang, Xin Ning Tang, Joo King Tay, Kelvin Teheri, Kim Keong Teo, Handoko Tham, Lin Than, Nagadurai Thangavel, Vivian The, Andra Thedy, Angelina Theng, Mart Umali, Henry Vong, Ekarin Wattanasanticharoen, Kenny Wen, Gary Weston, Ryan Williams, Berlina Winata, Ambrose Wong, Ling Chye Wong, Peter Wong, Eddie Woods, Nelson Xiong, Da Xu, Jingfeng Xu, Alan Yang, Kimm Ho Yap, David Yeung, Edwin You, Pippen Yung, Jie Zhang, Yimin Zhou.

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7, 8, 9: Land Transport Authority
All other images: Arup

Capturing net-zero energy design

The Emma and Georgina Bloomberg Center, part of Cornell Tech's new 12-acre campus on New York City's Roosevelt Island, combined energy demand reduction with on-site generation to achieve the potential for net-zero energy operation

Authors Fiona Cousins, Carl Mister and Tom Rice

1.

2.

1: Opened in September 2017, the Bloomberg Center was the first academic building on Cornell Tech's new campus on Roosevelt Island

2: The Bloomberg Center (left) and Tata Innovation Center (right) under construction

The Bloomberg Center was the first academic building completed on Cornell Tech's new New York City campus. The building has the aspiration of net-zero energy use as part of the campus's broader sustainability programme and has achieved the highest LEED Platinum certification.

Through close collaboration with Cornell Tech and Morphosis Architects, Arup pushed the boundaries of what could be achieved in creating such a large-scale, low-carbon energy-efficient building.

Arup provided multidisciplinary services, including: structural, mechanical, electrical, plumbing and fire protection engineering; acoustic and audio-visual consulting; communications, façade and lighting/daylighting design; security; and smart building consulting. In addition, Arup's responsibilities included key sustainability services, LEED advice and net-zero-energy goal consulting for the 160,000ft² (15,000m²) facility.

Roosevelt Island development

The new university campus is located on the two-mile-long Roosevelt Island in New York City's East River. The campus had its genesis in an initiative of the administration of then New York City Mayor Michael Bloomberg to promote the city as a hub for tech innovation. The development on Roosevelt Island represented a great opportunity for the city, as large sites such as this do not become available very often.

The city focused on a net-zero-energy development, with on-site energy production offsetting the building's consumption. Cornell Tech, a partnership between the Technion-Israel Institute of Technology and Cornell University, won a competition run by New York City to secure the site for the development of a campus.

Collaboration

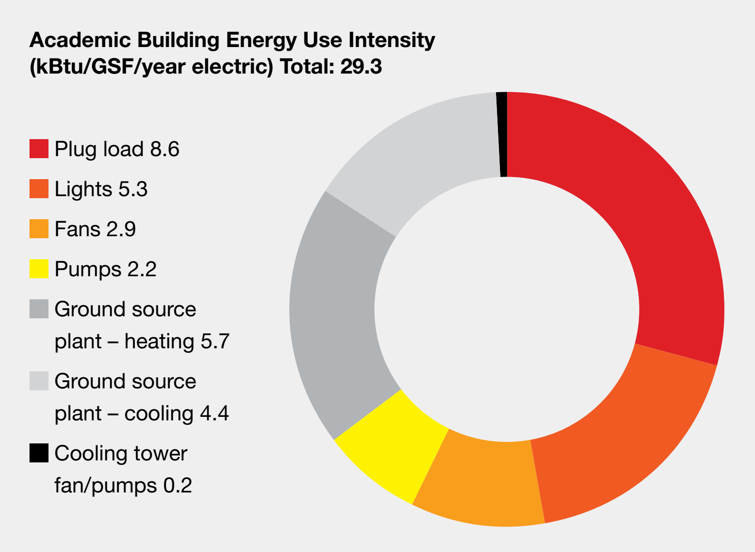
Cornell Tech was willing to change the typical form and function of an academic building to promote collaboration and innovation and set new standards in building performance and sustainability. Flexible spaces were designed to encourage collaboration, and open-plan offices were adopted.

The culture of collaboration that the finished building needed to facilitate was also to be found in the project team during the design process. Arup worked in partnership with Cornell Tech and Morphosis Architects with the aim of creating a net-zero building that would serve as a model for future development on the campus. This collaboration was essential to meet the energy efficiency goals, and Arup's multidisciplinary design philosophy helped with the delivery.

Sustainability

The aim was to create a building that is low-carbon, energy-efficient, healthy and pleasant to be in. Throughout the design, Arup evaluated opportunities for reducing energy demand through internal load reductions; for example, through the use of low-energy workstations and lighting, energy recovery systems and design for reduced solar heat gain.

To achieve this, the façade and roof canopy were used to limit solar heat gains, thereby lowering the amount of energy needed within



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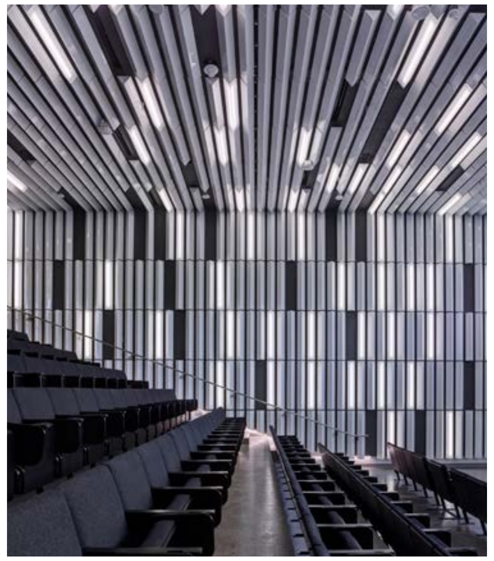
3: Arup produced a full-building energy model to track progress towards achieving LEED Platinum status

4: LED lighting was used throughout the Center

5: The rooftop canopy is made up of 1,465 PV panels



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the building for cooling. The solar photovoltaic (PV) roof canopy provides the building's primary power on-site. The building was also designed in accordance with the LEED NC 2009 rating system, and has achieved the highest LEED Platinum certification.

Arup tracked progress towards these goals by producing a full-building energy model based on an electric energy consumption rate of 30 kBtu/GSF/year, providing an improvement of 35.5% against ASHRAE Appendix G energy baseline levels.

All-electric building
New York City has the stated goal of reducing greenhouse gas emissions to 80% of the 1990 baseline by 2050. Much of these carbon emission reductions will stem from power plants as coal and oil are phased out of electricity generation in New York State and replaced by solar and wind sources.

An important characteristic for Cornell Tech was therefore to have an all-electric building ready to benefit from decarbonisation of the electricity grid. The heating and cooling are provided primarily using electrical ground-source heat pumps, and the building electricity supplied predominantly by PV panels.

PV canopy
The PV array on the Bloomberg Center's canopy provides on-site renewable energy generation, as well as shading that reduces the building's cooling load in summertime. A campus-wide array of solar panels was developed, with PV panels placed both on the Bloomberg Center and the adjacent Tata Innovation Center. The 40,000ft^2 (3,750m^2) canopy supports 1,465 PV panels. Arup worked with the client and solar project developer Distributed Sun to review preliminary energy analysis and panel layout.

The panels are laid flat, rather than placed in the more traditional tilted style. For this project, where area is limited, it is a more cost effective and energy-efficient system. More panels can be fitted on the canopy, and with flat panels there is no additional supporting structure required, nor is there any shading of adjacent panels as would be the case with a sloping strategy.

Building façade
The façade plays an important part in the building's passive energy design. It balances transparency (40%) and opaqueness (60%) to decrease energy demand. The system, developed in conjunction with the internal efficient LED lighting scheme, ensures adequate daylighting and maximises views across the East River towards Manhattan for the building's occupants. It reduces solar heat gain within the building and maximises insulation. Exterior shading systems were located on the eastern façade to help balance daylight harvesting against cooling demands, and to minimise the mechanical systems required along that perimeter.

The metal panel cladding on the east and west façades includes a series of small discs set at different angles, which form a pixelated pattern. The eastern façade image is of a gorge in Ithaca – the home of the main Cornell campus – and the western façade image shows the Manhattan skyline. The metal panels are also iridescent and appear to change colour when viewed from different angles.

5.

6.

6: The building's façade balances transparency and opaqueness to further minimise energy demand

7: The east and west façade faces are formed of small discs set at different angles, which together create an overall image

Rainwater harvesting
Initial efficiency measures for the building fixtures and operations reduced water demands and subsequent waste water discharge by 28%. A rainwater harvesting system further reduces potable water usage and discharge into the public sewer. By capturing rainfall from the Center's roof, the building supplies the bulk of all of its non-potable water demand.

This is collected and stored in a 40,000-gallon (150m^3) retention tank under the campus plaza. The stored rainwater is transferred via submersible pumps to a packaged treatment system. From there it is distributed to the building's non-potable fixtures (such as toilets), used for irrigating the campus lawn and in the cooling tower through dedicated non-potable plumbing. A back-up system is in place to deal with prolonged spells without rain.

Ground source
Ground-source heat pumps were installed to warm and cool the building, exploiting the constant ground temperature of 57°F (14°C). This ground-source system provides all the building's heating – including domestic hot water – and most of its cooling. A modular heat recovery ground-source heat pump is located in the central plant area. This provides both hot and chilled water simultaneously. A ground-coupled heat exchanger serves as the primary heat source/sink for the heat recovery chillers, with water used to transfer heat between the building and the ground.

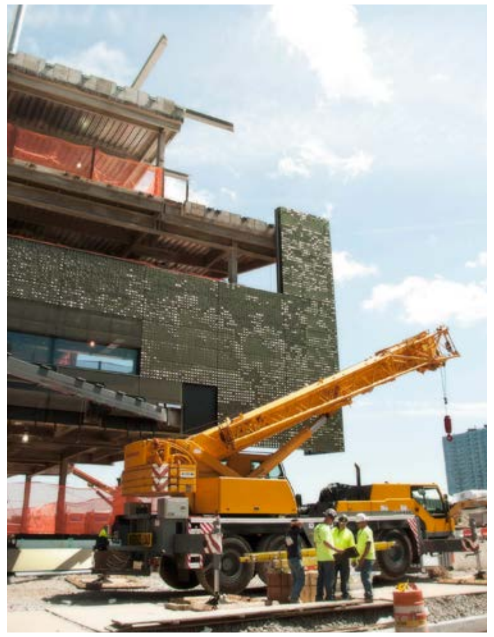
During the hotter summer months, when less heat is required in the building, the rejected heat gets pumped into the ground, while in winter this heat is drawn out and used for heating purposes. The closed-loop geothermal system consists of 80 boreholes at 6m centres drilled 120m deep. The system provides 330 tonnes of cooling to the building through an active chilled beam system. A supplementary cooling tower is used in periods when additional cooling is required. The tower supplements the heat rejection system and is also used to avoid overcharging the ground with excess heat.

Enthalpy wheels are used in the energy recovery systems, recovering warm or cool air from exhaust streams to pre-heat or pre-cool incoming air to the building as appropriate.

Building services
Building energy loads were analysed thoroughly and allowances for lighting and computers were carefully planned. The Building Automation System (BAS) is used to monitor and control the mechanical, electrical and plumbing systems, helping to conserve energy by using occupancy sensors.

The building itself is set up as an object of research and learning, with multiple data collection points throughout the building systems. Energy and hot water usage, occupancy and weather station data are all collected. Ground-source energy, the PV system, air-handling unit energy recovery, chilled water and domestic water usage and rainwater harvesting are all monitored. This data is available to Cornell Tech and other researchers, and can be used as a teaching tool for smart buildings and other applications.

The integration of the building services in the publicly accessible café needed to be carefully managed because the ceiling and tables are part of an art installation by artist Michael Riedel, who has created a striking graphic inspired by Donald Knuth's publication *The Art of Computer Programming*. Arup's design ensured the mechanical and electrical services in the café, including both the HVAC and fire protection systems (which incorporated



7.

sprinklers), satisfied code requirements and met both the architectural and artistic requirements for the space.

8.

8: Michael Riedel's black and white inkjet print graphic decorates the café ceiling and tables

Structural design

The building has a single-level basement under part of its footprint and is founded on footings bearing on rock (with rock anchors) and mini-piles socketed into rock. These act against uplift from groundwater – a key requirement, as in the event of flooding the resulting hydrostatic uplift pressure on the basement would exceed the building's permanent weight.

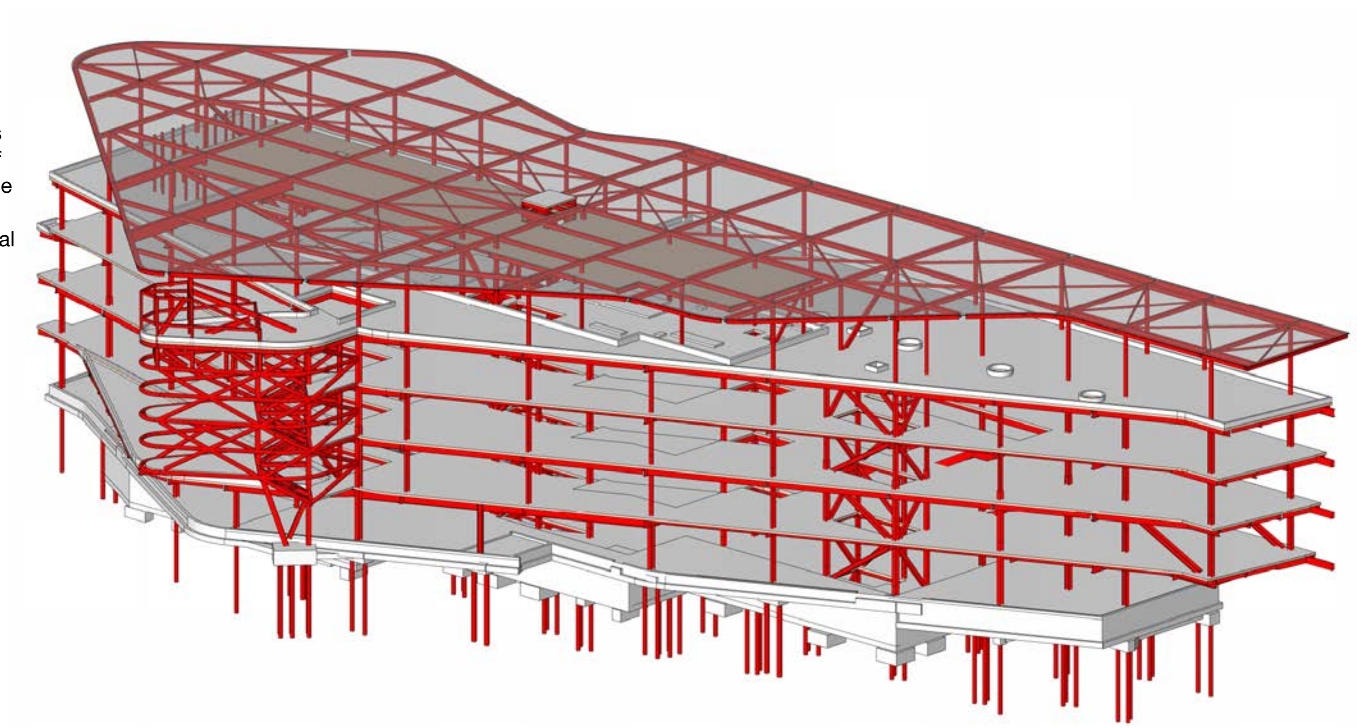
The structural grid is typically 30ft by 30ft (9.1m by 9.1m). The building's superstructure is a steel frame with a composite concrete slab on a metal deck. The thickness of floor slabs varies to suit loading requirements and the mass required for some limited acoustic and vibration control. To allow for future flexibility, a minimum live load of 100psf (4.8kN/m²) is used across the majority of the floors. This allows office spaces to be converted to classrooms without fixed seating, or to assembly spaces, without requiring any structural intervention.

The steel columns of the structure extend above roof level to support the solar panel canopy structure, above which is a grillage of steel beams in one horizontal plane supported on steel columns. A cantilever structure scheme made up of a single storey-height truss is used between levels 2 and 3 at the north end of the building. The building overhang varies from approximately 30ft at level 2 to 45ft at roof level.

Feature staircase

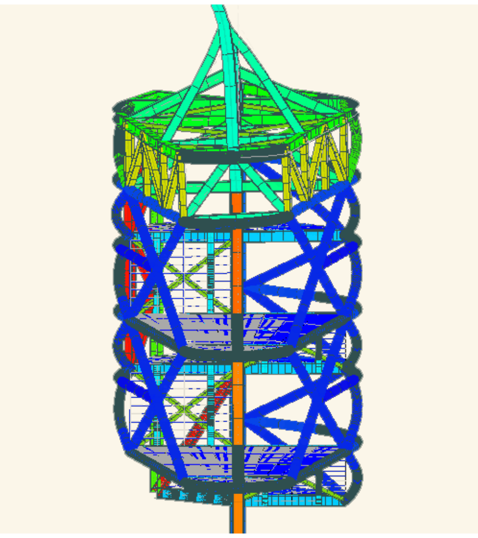
A prominent staircase is a key component of the building's eastern elevation. Located above the campus plaza and close to the main entrance, it forms the apex of the building's canopy and cantilevers out over the pedestrian route between the Bloomberg Center and the neighbouring Tata Innovation Center building.

A central spine truss oriented longitudinally along the stair axis extends up to the roof canopy, providing the main structural support. An outer, partially curved diagrid truss system supports and provides additional stiffness to the façade and structure. This system is part of the primary structural system providing gravity support to the stair edges and façade. Similar to an outrigger system used in high-rise construction, the exterior diagrid system also helps to brace the overall stair structure laterally and transfer the lateral forces back into the main building structure.



11.

11: 3D model showing the structural frame. The steel columns extend above roof level to support the PV canopy and incorporate thermal breaks to reduce cold bridging



9.

10.

9 & 10: The feature staircase is located above the campus plaza and forms the apex of the building's canopy support. Its central spine truss provides structural support to the canopy

Additional concealed trusses include transverse trusses perpendicular to the central spine truss, and an edge truss that vertically supports the perimeter diagrid system and is connected to the transverse and central spine trusses. A vertical truss on the south end laterally connects the diagrid system and central column to the main building.

Resilience

Roosevelt Island is in a vulnerable location for flooding, so resilience against flood conditions and rising sea levels was a critical design component. In October 2012, only a few months after the design process began, New York City was hit by Hurricane Sandy. The flooding caused $70bn in damage and further highlighted the resilience required by the campus.

To mitigate potential damage to equipment during a flood event, the main electrical switchroom and emergency and life safety power systems are located at roof level, along with the generator, while the basement footprint and plant equipment are minimised.

The number of electrical panels installed in the basement was kept to a minimum. Ground fault circuit interrupters were also put in place so that in the event of a flood, or if water infiltrates those circuits, they can be isolated without damaging the connected circuits or panels. Similarly, motors and critical mechanical equipment were kept above the flood line.

Continued work on campus

Arup has continued its work on Cornell Tech's Roosevelt Island campus with involvement in two further projects. Working with Weiss/Manfredi Architecture, Arup provided security, IT and AV consulting services for the interior fit out of four floors within the Tata Innovation Center. This building consists of classrooms, general and robotics laboratories, huddle rooms, studio and open office space, and several large collaborative spaces.

Currently under construction, Arup is also providing (in collaboration with Snøhetta) acoustic, AV, IT and security consulting services on the Verizon Executive Education Center, a 40,000ft² venue for executive programmes, academic conferences and workshops.

Authors

Fiona Cousins was the Project Director. She is an Arup Fellow based in the New York office.

Carl Mister was the lead electrical engineer. He is an Associate Principal in the New York office.

Tom Rice was the Project Manager and lead structural engineer. He is an Associate Principal in the New York office.

Project credits
Client Cornell Tech
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Main Contractor Barr & Barr
Cost Estimator Dharam Consulting
Geotechnical Engineer Mueser Rutledge
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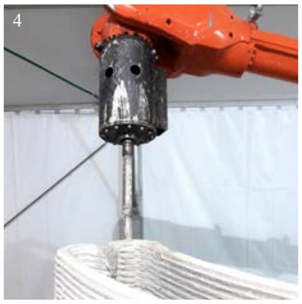

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Front cover and inside cover images: V&A Grain Silo Complex, Cape Town, South Africa: *Arup/Tessa Brunette*.

The Arup Journal
Vol.53 No.1 (1/2018)
Editor: Macdara Ferris
Designer: Wardour
Email: arup.journal@arup.com

Published by Arup
13 Fitzroy Street
London W1T 4BQ, UK.
Tel: +44 (0)20 7636 1531

Printed by Geoff Neal Group
Produced on FSC paper
and printed with vegetable-based inks.

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