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Contents

M+, Hong Kong: Virgile Simon Bertrand

Pushing beyond the sustainable design ridge

The building is a significant step on the road to net zero, showcasing innovative design solutions applicable in the African market and beyond

Authors Tessa Brunette, Lee-Zane Greyling, Jolyon Smith, Krzysztof Wolnicki

Given the task by the V&A Waterfront of creating a commercial property in Cape Town that pushed the boundaries of sustainable design, Arup, working with architects studioMAS, shaped a building response that accelerates the transition to net zero in South Africa. The Ridge is a low-energy building for tenants Deloitte which is designed to achieve a reduction of up to 82% in operational carbon emissions.

Conventional commercial buildings in South Africa are fully air-conditioned and sealed. Arup pushed beyond this to create a mixed-mode facility that was designed by putting human comfort first, all within a low-energy framework. This design strategy takes advantage of the city's Mediterranean climate, which is ideally suited to natural ventilation for much of the year. The goal was to maximise the periods when the building could be naturally ventilated. This was achieved by responding directly to the site location and shaping the building envelope to minimise solar load, thereby reducing energy demand.

The Ridge is located on a rectangular site that would create very deep and dark floor plates in the building without design intervention. The first step was to arrange wings on either side of a central atrium. These wings were sized to maximise natural daylight penetration into the building, which has four storeys of office space, and to allow for efficient cross-ventilation. Using extensive innovative, sustainable solutions, the design provides optimal internal conditions for the occupants in a low-energy manner. The 8,500m² building has achieved 6-star (World Leadership) Green Star design and as-built ratings from the Green Building Council South Africa.

Close collaboration between Arup and architects studioMAS was key to the building's low-energy design. The two firms had worked together previously on the scheme design for another project for

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1: The Ridge has achieved 6-star Green Star design and as-built ratings from the Green Building Council South Africa

2: Extensive excavation through soft and hard material was required to accommodate the full building extent on the site

3: The central atrium effectively converts one large deep-plan building into two connected, shallow-plan buildings that benefit from natural ventilation

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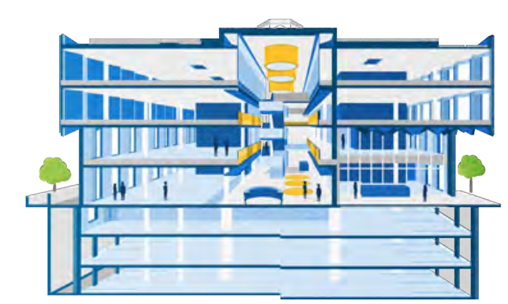

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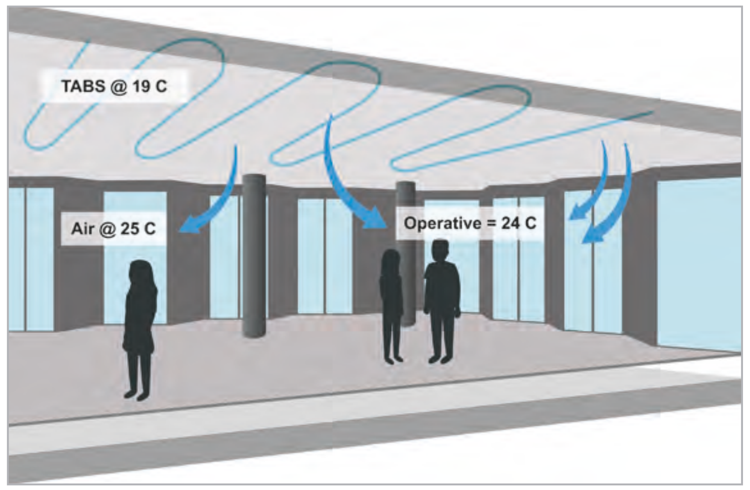

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4: Users were placed at the centre of the design of the building systems, with the aim of providing optimum comfort levels

5: The TABS reduces temperature peaks inside the building

6: The atrium pulls fresh air through from openable windows integrated into the façade, across the office spaces and out through the atrium roof lights

7–8: Manually operated windows give building occupants control over the temperature, allowing them to find their own comfort zones

the same client which also had boundary-pushing sustainability aspirations. While that project did not progress, having worked together and established a mutual understanding of what makes a comfortable and sustainable building, it enabled the team to respond quickly when the V&A Waterfront put forward this project which prioritised the sustainability agenda.

The Ridge has set a high benchmark for green building design in the African market with the use of contextually innovative design initiatives that are based on sustainable outcomes. These include energy-efficient climate control systems using natural ventilation alongside a thermally activated building structure (TABS), the use of plastic ecobricks as void formers within the structure to reduce the carbon footprint of the building, and a façade that features the first use of cross-laminated timber (CLT) at commercial scale in South Africa.

First principles climate-responsive design

The site – previously a car park – is orientated on a diagonal away from the ideal north–south orientation. While the east–west building orientation maximised the site's development area, this arrangement was not favourable from a heat gain perspective. To counteract this, Arup proposed to 'fold' the façade in a series of zigzags, a solution enthusiastically embraced by studioMAS as they developed the building's form. This allowed the orientation of individual facets to be optimised, with the glazed elements positioned facing either north or south. This minimised the heat load due to solar gains by preventing lower-angle sun from the east or west entering the building. This solution admits daylight, maintains unobstructed views of Cape Town, significantly reduces solar gain while not requiring external shading, and gives the building its characteristic zigzag façade.

Comfort-based design

Users were placed at the centre of the design of the building systems, with the aim of providing optimum comfort levels for building occupants. The overall design significantly reduced the amount of direct sunlight entering the building, which means that the internal spaces can largely rely on natural ventilation and not air conditioning to remain comfortable. This is done through a combination of passive cooling technologies and natural ventilation. When necessary – on very hot, cold or windy days – the mixed-mode ventilation system switches from natural ventilation to air conditioning to provide mechanical heating or cooling. This layered, integrated approach minimises energy consumption while prioritising occupant comfort.

The design process included extensive energy modelling of the systems being used in the building: natural ventilation, mechanical ventilation, mixed mode and the TABS. Combining these different operational systems into the energy model presented significant challenges and was a combination of firsts in South Africa with natural ventilation, mixed mode and TABS being modelled together for the first time. In addition to energy modelling, thermal comfort analysis was also applied. This enabled Arup to demonstrate that the mixed-mode operation of the building with TABS achieved year-round thermal comfort, and achieved the highest threshold of ±0.5 predicted mean vote thermal comfort for over 90% of the year.

The four-storey-high atrium is used as a chimney, pulling fresh air through from openable windows in the façade, across the office spaces and out through the atrium roof lights. Using the atrium as one of the building's systems in this manner significantly enhances the effectiveness of natural ventilation, making it possible to ventilate the full extent of the floor plates. The top floor is separated from the atrium acoustically and thermally to prevent hot air spilling back into it, both as part of the fire engineering strategy and to increase the effectiveness of natural ventilation at lower levels.

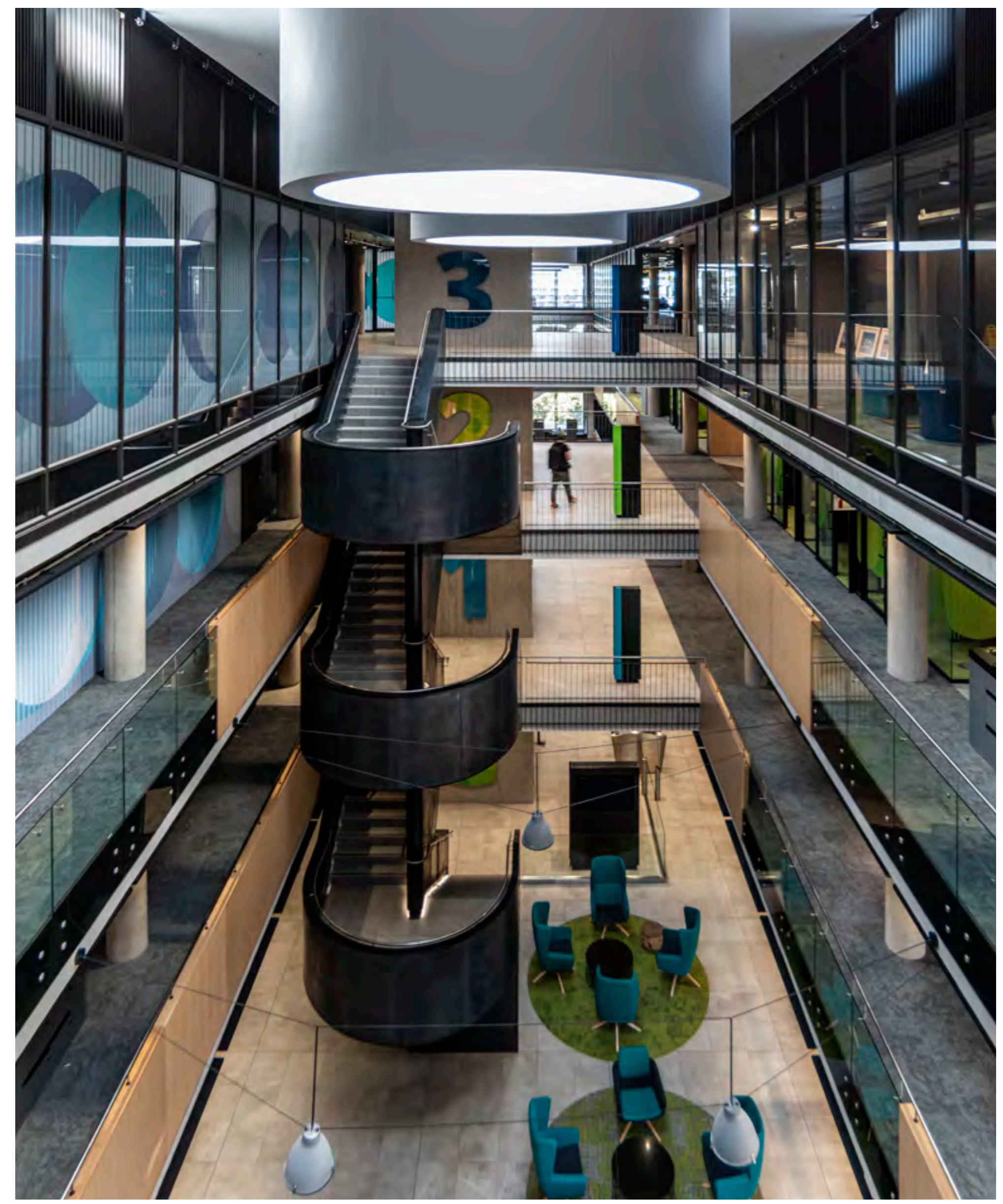
On the external façade, manually operated windows give building occupants control of the temperature, allowing them to find their own comfort zones. Compared with fully air-conditioned buildings, people are more tolerant of temperature variations when they can control window operation. The design allows occupants to let in fresh air to circulate across each floor or to close the windows to suit their own comfort levels.

A green/red light system controlled by the building management system (BMS) advises the occupants on the optimum window position based on the external temperature and wind conditions. A green light signifies that windows can be opened as the outside temperatures are suitable, with the light going off if temperatures are either too hot or too cold. A red light signifies there are excessive winds and windows should be shut.

When the weather outside is not suitable for natural ventilation and the windows are closed, the BMS activates the mechanical air-conditioning system. Users can activate a boost system at the perimeter which provides half an hour of additional cooling, giving them further local control over their environment. When the windows are opened, the mechanical ventilation system for that zone is automatically switched off by the BMS.

The floor plate arrangement around the atrium and the façade design make it possible to control the temperature of the building using only natural ventilation for up to 81% of the year. For the remaining period, when conditions are not favourable for natural ventilation, air conditioning is required to regulate the temperature.

The design of the building passively reduces the amount of air conditioning required, and when air conditioning is required on very hot, cold or windy days, it is designed to be as efficient as possible. A displacement ventilation system with motorised dampers is used, with conditioned air distributed at low level through the void below



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the raised access floor via grilles. This provides cooling at a low level, where it is most effective, before the air is exhausted at ceiling level. The benefit of displacement ventilation is that it requires lower air speed alongside less cooled supply air when compared with a typical high-level ducted ventilation system, where the cool air must drop down from a high level before it can provide comfortable cooling.

The mechanical plant is located on the roof, with the air conditioning provided through three heat pumps, one of which is a simultaneous heat pump so that it can provide both heating and cooling at the same time. The other two are reversible heat pumps that can provide heating or cooling. Local environmental conditions mean that, for most of the year, only cooling is required. There is hot water demand all year round for the kitchen area and this is provided using the simultaneous heat pump. Hot water for the bathrooms and showers, located at opposite ends of the building, is generated locally using energy-efficient heat pumps in each location. This is more energy-efficient than providing the low volume of water required from a central location.

Keeping TABS on cooling

The TABS stabilises the temperature inside the building, smoothing the peaks between hot and cold. Chilled water is circulated through pipes that are embedded into the concrete floor slabs to provide radiant cooling to the office space. This is more energy-efficient for cooling compared with a ducted air system and means the building can rely on natural ventilation and TABS when outside temperatures are as high as 23°C. Thermal comfort of the occupants is based on the benefit of the radiant effect of the TABS allowing for higher internal air temperature of 25°C.

The TABS was carefully coordinated with the steel reinforcement and post-tensioning (PT) tendons in the 270mm-thick concrete slabs. A bonded PT arrangement was used in the slabs, with the TABS located away from the live and dead ends of the post-tensioning, as strain compatibility of the multiple materials was a serviceability consideration. Prior to construction on site, a two-bay mock-up was built off site to test the PT layout with the steel reinforcement, cast-in lighting containment and TABS pipework.

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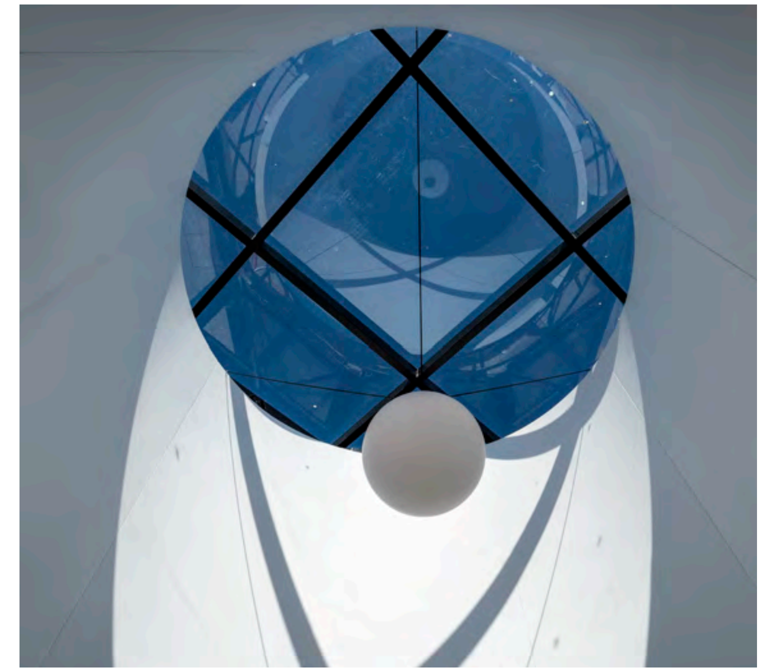
A solar photovoltaic system on the roof delivers 140KW, approximately 30% of the peak electrical consumption in the building. A standby generator provides 24-hour backup power for the building to operate the lighting, power, air-conditioning and lift systems in the building, providing a resilient power supply in the context of a constrained national power grid.



10.

9: The TABS was carefully coordinated with the steel reinforcement and post-tensioning tendons in the concrete slabs

10: Large skylights above the atrium draw generous indirect natural light into the centre of the building

Combining each of these systems and basing their design on user comfort, as opposed to just air temperature, significantly reduces energy consumption. The fully fitted-out building is expected to save 64% in energy, equivalent to 2,430,056kg of CO_2 annually, when compared with a similar building of the same size and orientation in South Africa.

Designing for daylight

The lighting was designed to provide more using less. Maximising natural daylight and access to the spectacular views, while also reducing heat load, was the key to providing a comfortable and healthy internal environment for building occupants.

Large skylights above the atrium allow generous indirect natural light into the centre of the building which then penetrates the office floorplates. Radiance-based daylighting analytical tools allowed for a complete understanding of the solar and environmental conditions on the specific site and its context. Arup carried out solar studies to determine the direct sunlight penetration, which informed the position and visual qualities of windows. Extensive thermal modelling was used to determine the most favourable glazing solution by reviewing over 20 different glazing products. The final design includes high-performance coated glass where required, to reduce heat gain while providing natural light. Lower-performance glass was used where this was possible without compromising comfort or energy efficiency, to reduce costs.

Almost all of the artificial lighting in the building is provided by low electrical demand LEDs, with occupancy sensors that control 95% of the lighting helping to reduce electrical demand even further.

Building user guide

The mixed-mode design of The Ridge is reliant on how occupants operate the building to control their comfort, and thereby reduce energy use. It is through influencing users' behaviour and empowering them to control their environment most effectively that the design intent is achieved.

In conjunction with a higher level of training and handover to the building's facilities management team than is the local industry norm, the V&A Waterfront commissioned Arup to prepare a bespoke user guide for the non-technical building users. The purpose of this guide was to encourage and enable individuals to use the building most efficiently. A team of specialists, including Arup's user-centred design and human factors teams, alongside members of the engineering design team, graphic artists, technical writers and editors, was assembled to capture all of the design elements that users can engage with and influence, to document how they can impact the performance of the building.

The guide provides information with user-friendly graphics on how to manage comfort by influencing behaviour change, ensuring the comfort of building users, but also resulting in efficient building performance.

Timber façade

The innovative unitised zigzag façade, with alternating solid timber and glazed panels, is a South African first for a commercial building. The design allows for a high level of daylight and thermal control, maximising comfort and low-energy building performance. The timber façade was designed to be robust, and comprises locally sourced, solid, self-supporting CLT panels, covered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11: The timber façade comprises locally sourced, self-supporting CLT panels

12: Approximately 14,000 'ecobricks' formed from 5.5 tonnes of non-biodegradable plastic pollution were used as void formers

13: The ecobricks – made from plastic drinks bottles filled with non-reusable plastics – were placed vertically to fill the 450mm-deep void adjacent to access floors

by timber cladding installed over a breather membrane. FSC-certified South African pine was used for the panels; this is renewable, strong and light, with low embodied carbon as well as having inherently high thermal performance. The cladding is acetylated pine 'Accoya' that can be replaced if needed at 50-year service intervals after weathering has occurred. The system has 354 tonnes less embodied carbon than more conventional alternatives.

Both the timber and glazed aluminium panels are unitised, with matching panel joints, and the aluminium subcontractor was required to be responsible for both elements. They produced a single set of coordinated shop drawings, for their own factory and for the separate timber factory. This ensured that the alternating panels fitted together on site, even though they were made in different cities, using different processes.

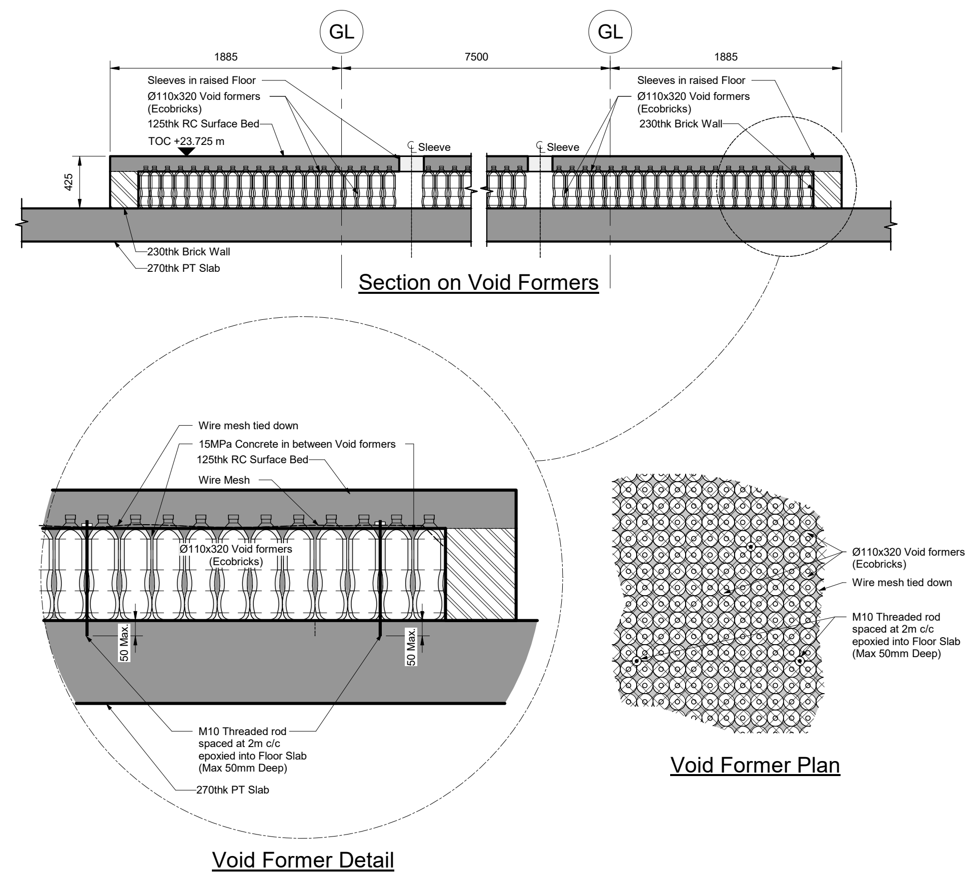
Water savings

With water a scarce resource and Cape Town having had extended periods of severe water shortages in recent years, it was vital to minimise the water consumption within the building. Grey and rain water harvesting systems were put in place. Arup conducted a study to identify the optimal storage tank size, carrying out a cost–benefit analysis on the tank size and volume of stored water and considering historical rainfall against forecast demand. The non-potable water is stored in a 100m³ tank at basement level and is used for both irrigation and toilet flushing. Low-flow water fittings are used throughout the building to help further minimise water usage.

Ecobricks

A novel sustainable solution was used to make up the floor level difference in the building. In the toilet areas, where the raised access floor (used in the office space for ventilation) was not required, rather than make up the depth difference by using typical solutions such as virgin polystyrene filler or lightweight concrete, an innovative and more sustainable option was employed.

Approximately 14,000 'ecobricks' were used as void formers. Each ecobrick is a discarded single-use two-litre plastic beverage bottle diverted from local waste streams. These are bottles that would take in excess of 450 years to biodegrade. The bottles were filled by hand with used single-use, generally non-recyclable, plastics such as sweet wrappers and clingfilm. The ecobricks were placed vertically to fill the 450mm-deep void adjacent to access floors to match the finished floor level where access floors were not desired. The bricks created a 300mm void with a 100mm concrete slab over and a 50mm screed and finishes. They were sourced from a local non-profit, non-governmental organisation, Ecobrick Exchange. Steel reinforcement mesh was placed on top of the bricks to keep them in place during concreting and to control cracking in the concrete. This construction method ensured that the ecobricks do not take any structural load. They were also used to create raised flowerbeds in the adjacent food garden.



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Overall, the ecobrick system used 5.5 tonnes of non-biodegradable plastic pollution – the equivalent of 110 people's annual use of single-use plastic in South Africa. The system not only reduced the carbon footprint of the project by avoiding the use of virgin material to create the void form, but also used material that was otherwise destined for landfill and created an income opportunity for the local community. The ecobricks were mainly sourced from schools, so this design initiative raised awareness of the issue of plastic pollution, while the plastic reuse showcased a novel example of circular economy thinking. The use of such bricks was a first for the building sector globally.

Virtual services coordination

The project team used BIM360 as their digital collaboration platform. Virtual contractor coordination sessions with the 3D model enabled contractors to pinpoint areas of concern for discussion. This virtual design and contracting team coordination resulted in the resolution of potential issues such as clashing services before they arose on site. The visual mechanism facilitated coordinated planning and programming of interfacing installations and saved time both on site and in the office.

Fire engineering

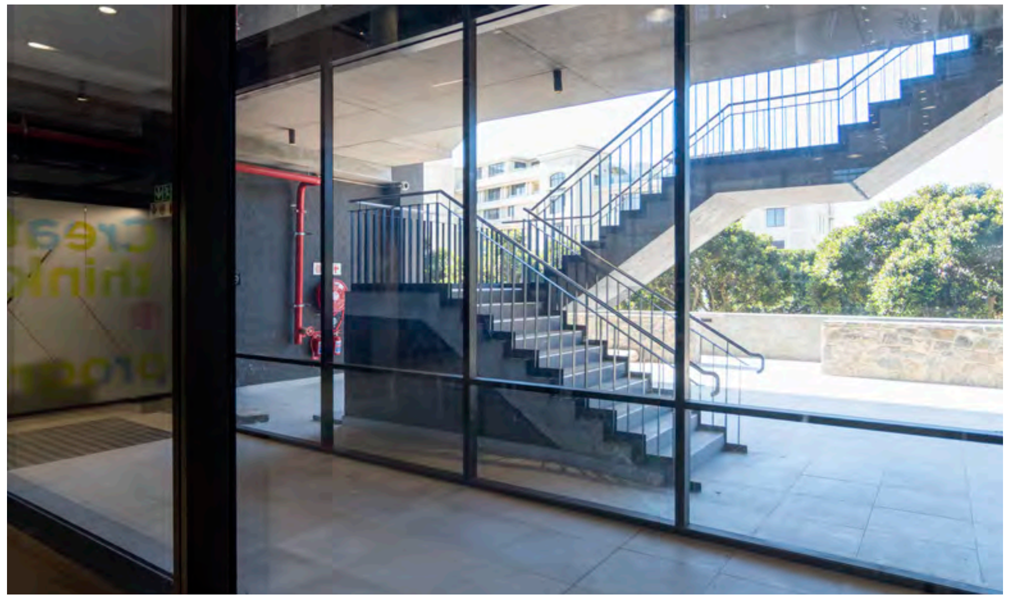
There were a number of fire safety challenges on the project that were overcome through performance-based fire engineering design. These related to the use of timber panels in the façade, fire protection of the stairs, high occupancy in the third-floor event space, and smoke venting in the atrium. The solutions put in place had to facilitate the aspiration for the open-plan nature of the building and the overall architectural aesthetic vision for the project. They needed to provide an adequate level of life safety in the building, and Arup's design solutions were discussed and agreed with the client and local fire authority before implementation on site.

A review was carried out of the façade, which is constructed on two levels (the second and third floors) with timber. The thermal mass and thickness of the panels (between 100mm and 200mm) meant the rate of fire spread is lower compared with thinner timber members commonly used for smaller structures. With the building sprinkler protected, the risk of fire spread from inside the building to the external timber panels is reduced further. As timber is provided only on the second and third floor, the fire service will be able to deal with any façade fire from outside the building.

Local fire code requirements for a building of this size were for three fire-separated stairs. However, this would not have allowed the visual connectivity desired in the architectural design, so a fire engineering solution was designed that achieves the required level of protection to the stair while preserving the visual connectivity with the rest of the building.

On the west side of the third floor, the design needed to accommodate events which are occasionally held that increase the occupancy beyond the normal day-to-day occupant load. The floor is separated from the atrium using smoke-sealed construction, with dynamic emergency signage used to display different evacuation messages depending on the location of fire in the building.

Computational fluid dynamics (CFD) modelling was used to determine the smoke venting provisions serving the above-ground levels including the atrium (except for Level 3, where smoke extraction is via dedicated automatic vents at roof level). Smoke is extracted via eight mechanical smoke extract fans; seven of these are required to meet the smoke extract duty, allowing one fan to be off-line for maintenance. Inlet air is provided via natural openings/louvres at ground-floor level, with mechanical air replacement vents at ground floor and Level 1.



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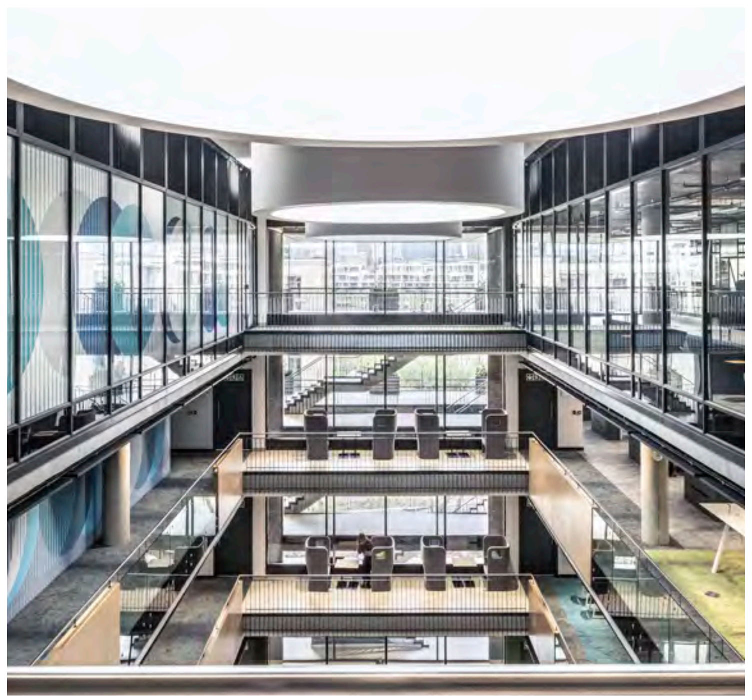

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14: A window-wetting sprinkler system on the internal side of the glazing facing the external stair reduces the risk of glass failure in the event of a fire and supports the fire strategy, which facilitates visual connectivity inside and out of the building

15: The third floor is separated from the atrium by sealed glass panels, with smoke control on this floor managed through automatic vents at roof level

16: Extensive thermal modelling was used to determine the most favourable glazing solution

MassMotion software was used to predict the behaviour of individuals and crowds during emergency escape, considering a variety of project-specific factors such as the building geometry, occupancy profile and numbers, and a variety of evacuation scenarios. This form of assessment allowed for more realistic results than the simple tabulated exit width methods upon which the prescriptive guidance is based and the results served to inform the escape stair provisions in the building.

Shaping sustainability on the waterfront

The Ridge is the latest addition to a long list of projects shaped by Arup at the V&A Waterfront. The firm developed the Resource-Efficient Design Brief for BP's local headquarters (now called Merchant House) and provided sustainability, mechanical, wet, fire and façade engineering services for the No. 1 Silo project. Arup also provided sustainability and façade engineering services, as well as other structural, mechanical and wet services engineering on each building within the wider Silo District. This includes the adaptive reuse of the redundant industrial complex to form the V&A Grain Silo Complex. No. 1 Silo and No. 5 Silo were awarded 6-star Green Star ratings (including the first 6-star as built rating in South Africa), and the precinct as a whole is recognised as an exemplar of sustainable design in South Africa.

Many of the concepts, technologies and materials used in the design and construction of The Ridge are pioneering instances of their use in South Africa, particularly at the scale of this project and in a high-end commercial space. This is an exciting new development for the V&A Waterfront, which embeds sustainable development principles through integrated design thinking wherever possible.

16.

Authors

Tessa Brunette was the Project Manager and design integrator. She is an Associate, leads Arup's climate and sustainability services in South Africa and is the leader of the Cape Town office.

Lee-Zane Greyling was the Project Director. He is a Director in the Durban office and leads Arup's property, science, industry, technology and social infrastructure business in South Africa.

Jolyon Smith led the mechanical and wet services engineering design. He is an Associate in the Cape Town office.

Krzysztof Wolnicki led the fire engineering design. He is a senior engineer based in the Dubai office.

Project credits

Client Victoria and Alfred Waterfront Holdings
Tenant Deloitte
Architect studioMAS
Project manager MACE
Quantity surveyor Smith & Co
Interior designers Paragon Interface
Acoustics engineers SRL South Africa
Independent commissioning agent PJC and Partners
Main contractor GVK-Siya Zama
Mechanical, electrical and wet services engineering, civil, façade, fire safety, structural engineering, integrated lighting design and sustainability consulting Arup:
John Abbott, Greg Bailly, Elana Benghiat, Tessa Brunette, Fiona Carr, Carin De Beer, Franz Fertig, Stephan Frantisek, Nick Gorrie, Sarge Govender, Anthony Graham-Jolly, Lee-Zane Greyling, Chandre Haber, Susan Lamont, Richard Lawson, Ryan Lloyd, Ian Marais, Usisipho Mkangelwa, Mike Munnik, Adam Ozinsky, Mishlin Pillay, Silindile Qwabe, Ridwaan Seedat, Azqa Singh, Zen Singh, Jolyon Smith, Hannah Stockley, Shikar Takurpersad, Krzysztof Wolnicki.

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2, 3, 5, 7–9, 13: Arup
4, 6, 10–12, 14: Tessa Brunette/Arup

1.

Printing the built environment

The world's first 3D-printed steel bridge showcases innovative steel printing technology

Authors Stijn Joosten, Shibo Ren, Paul van Horn, Mathew Vola

The MX3D Bridge is a remarkable structure in raw steel form that spans the Oudezijds Achterburgwal canal in Amsterdam's city centre. Working with designer Joris Laarman Lab and Dutch technology start-up MX3D, Arup was responsible for structural design of this complex 12.5m by 6.3m stainless steel bridge with curved balustrades which showcases the potential of robotic 3D construction. This new, high-precision construction technique provides opportunities and architectural freedom to designers, while potentially reducing the amount of materials used to form such structures. Such large-scale 3D printing and digital design could forever alter the shape of the built environment around us.

The process of 3D printing uses an electric arc as a heat source to generate 3D objects depositing molten metal in superimposed layers. It was patented almost 100 years ago, in 1926, but it is the use of digital processes to generate a large-scale 3D-printed structure that makes the MX3D Bridge so novel. The design gives a glimpse of what this technology can offer our cities in the near future.

With Arup as lead structural engineer, MX3D created intelligent software that transformed industrial robot arms and welding machines into 3D robotic printers to produce the world's first fully functional 3D-printed steel bridge. The

1: The MX3D Bridge, which spans the Oudezijds Achterburgwal canal in Amsterdam's city centre, is the world's first 3D-printed steel bridge


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2: As a design object for public use, the bridge was intended to be a revolutionary piece of art

curving stainless steel structure was constructed using a wire arc additive manufacturing process that marries advanced robotics with welding. Computational design and 3D printing came together to streamline both the design and production process, allowing the designers to explore greater form freedom and shrink the manufacturing timeline. With the aid of four robots with six-axis arms, the entire printing process for the bridge took just six months.

A critical part of the project was the extensive testing programme that was put in place to support the design and prove the structural capacity of the 4,500kg stainless steel bridge, whose novel manufacturing method sits outside standard design codes. In addition to developing the testing regime, Arup also provided technical advice on site, communicating with local authorities and a range of technical partners. Installed in July 2021, this fully 3D-printed stainless steel bridge provides an inspirational and structurally sound piece of public urban infrastructure that is used by pedestrians in Amsterdam's city centre.

The bridge was fitted with an innovative sensor network, with the data gathered enabling the creation of a 'digital twin' virtual model of the bridge which will be used to see how it responds to different actions occurring in its environment. The findings will support research into predicting the behaviour of the bridge and its material, with the aim of leading to better bridges in the future, and providing insight into the new techniques used in the construction of the MX3D Bridge.

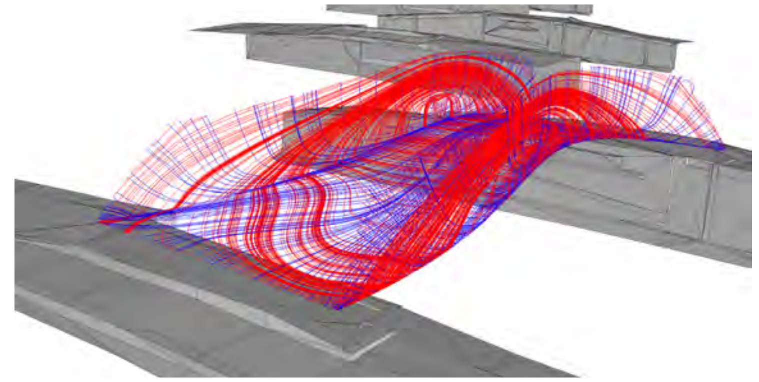
Collaborative partnerships

To bring the bridge from concept through to completion, an innovative collaboration was set up with a large group of partners marrying expertise across a wide range of disciplines including software, hardware, construction and welding. These included Autodesk, ArcelorMittal, Arup, Force Technology, Imperial College London, Air Liquide, ABB Robotics, Heijmans, Lenovo, The Alan Turing Institute and Lloyd's Register Foundation. Among the public partners were TU Delft, University of Twente, University of Bologna, AMS Institute (Amsterdam Institute for Advanced Metropolitan Studies) and the Municipality of Amsterdam. On the sponsoring side were STV, Oerlikon, FARO and Plymovent, while the visitor centre at the MX3D factory that was open during the 3D construction to showcase the printing process was supported by the VSB Fund.

Initial concept

The concept for the bridge was for a structure to span 10.3m over one of the historic city-centre canals in Amsterdam. As a design object for public use, Joris Laarman wanted the MX3D Bridge to be a revolutionary piece of art, fully exploring the rational design freedom 3D printing allows for large-scale infrastructure. The original idea was for the bridge to be built in situ over the canal, with a filigree arch structure made of trusses similar to a 3D space frame.

Arup was initially involved on the project carrying out some early material testing and scheme design exploration before helping to review the preliminary design, which was carried out by a third party. The original proposal was highly complex to analyse, making the prediction of forces, material brittleness and fatigue performance difficult to determine. The firm recommended starting the design process over to make the scheme structurally simpler, while ensuring that the goal of showcasing the architectural potential of the steel bridge using the 3D printing process remained on track.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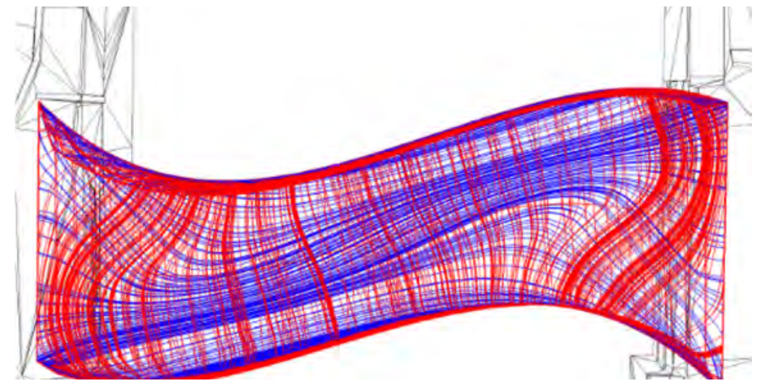
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3: The design was refined in Grasshopper, a parametric design modelling program

4: The major loadbearing elements of the bridge follow the stress flows within the bridge structure

5: Two continuous 3D-printed handrails act as the main chords for the bridge

6: The bridge was built in the factory of Dutch tech start-up MX3D

Digitally driven design

Arup developed a new structural scheme using a digitally driven design process, beginning with a U-section channel. This initial analysis determined the principal stress trajectories, showing the tensile and compressive stress flows in the structure. The firm then looked to match the major loadbearing structure of the bridge with those stress flows, determining the most efficient way to place the material. This meant the curved geometry of the bridge followed the flow forces.

Parametric design modelling was a perfect fit for this boundary-pushing design process. The team refined the design in Grasshopper, a parametric environment for designers exploring new shapes which integrates generative algorithms with finite element analysis. Under the specific loadings and support conditions, the distribution and orientation of the principal stress trajectories were generatively linked to the shape of the bridge, which further informed the shape evolution. By producing successive design iterations under a given set of parameters in quick succession, the design moved from an initial test form towards the optimal final shape.

This method provided a more efficient structure, allowing the steel material to be concentrated where it was structurally most needed. It also gave the bridge a more organic form and added redundancy to the structure, allowing redistribution of internal forces in case of local failure to provide additional safety to the bridge.

The superstructure of the MX3D Bridge was constructed with two continuous handrails that act as the main chords of the bridge. The non-printed stainless steel deck is supported by 3D-printed chords beneath the deck. The thickness of the structural elements varies, mainly


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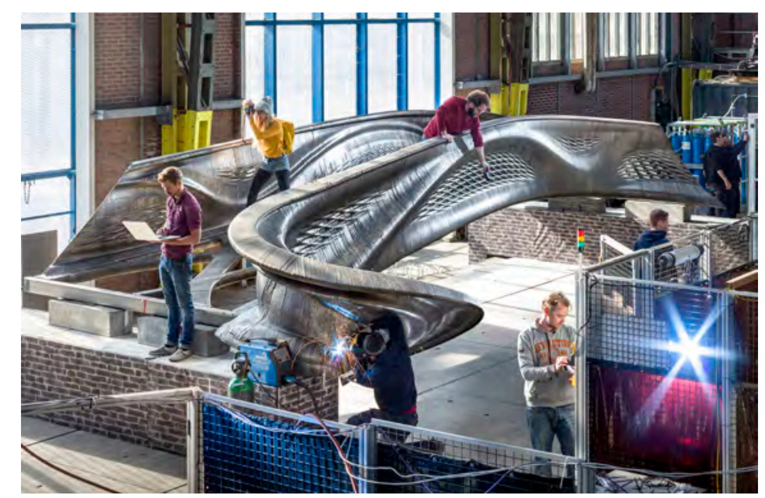
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between 3mm and 10mm. The power level and wire speed used during printing were adjusted to manufacture the different wall thicknesses.

The 3D printing process required significant computing power for scripting the design commands for robots, for the data management of sensor results and for the interaction between the design and construction processes. Extensive use of digital tools and the application of BIM helped in managing this process. Departing from the monolithic, U-shaped bridge design, by using extensive design iterations Arup was able to progress swiftly through several stages of design before delivering the final, more organic, S-shaped bridge.

Laboratory testing

Designing beyond the codified materials was made possible thanks to a significant programme of testing that was developed for the structure. This testing was done with support from the materials team in Arup's London office, Imperial College London, ArcelorMittal, TU Delft, University of Twente and University of Bologna.

The starting point was laboratory material testing of samples of printed elements, moving on to structural element testing before conducting full-scale load tests on the completed bridge. The results from each part of the testing programme informed the design, as they were fed into the structural assessment and allowed Arup to check the safety and serviceability levels of the bridge.

Understanding the performance of the material (308LSi stainless steel grade) was one of the first steps of the design process. The testing sequence had two main goals:

- Helping to refine the parameters that had an influence on the structural analysis. Arup's engineering team used the testing sequence to build and refine their structural analysis model.
- Demonstrating the structural capacity of the bridge independently from the structural analysis and determining a safe live load that the bridge could withstand.

The existing structural design codes do not have specific elements relating to the design of structures fabricated from stainless steel weld-based material using 3D printing. So the testing put in place was to provide a mechanism to prove the structural capacity of the built sections with an adequate degree of reliability. The results were then used to show that the design of the bridge was compliant with the principles laid out in Annex D of EN 1990. This is the annex of the 'Basis for structural design' Eurocode relating to design assisted by testing. This section of the code outlines the parameters for using new materials outside of the code and defines the required testing and applicable safety factors.

The initial testing was carried out on small section printed samples, including tensile and ductility tests to help understand the material's performance. The material and mechanical properties of this self-supporting 3D-printing steel differ from those of regular steel. While the welded product is less homogeneous than conventional steelwork, the testing determined that the material's characteristics are similar to standard stainless steel in terms of ductility, toughness and yield strength and the material is relatively free of in-built stresses. However, the elastic modulus is lower, making the printed sections less stiff.

Following the initial material testing phase, typical sections of the bridge were printed and then laboratory tested. This enabled calibration of Arup's numerical simulations, verifying the properties used in the calculations. Some values in the models were required to be updated according to the data obtained from the laboratory testing, ensuring documentation and calculations were in line with the reality of the material performance. As knowledge of the safety requirements, material properties and technical potential grew, a final model emerged in early 2017.

Arup and Imperial College London built finite element models in GSA and Abaqus respectively. Arup modelled the deck in 2D and the main and deck chords as beam elements, while Imperial College's Abaqus model included the entire bridge with 2D shell elements. Both models were validated and calibrated following a test of a 2.4m section of the bridge carried out in November 2017.

Full-scale testing

After arriving at a final design, the team moved into the production phase. Several tests, including load viability, were carried out to ensure that the structural behaviour of the bridge complied with code safety requirements and to confirm the performance of the new 3D-printing steel. This final design step saw validation carried out by testing of the full-scale bridge prototype. Arup worked closely with Imperial College London to perform several full-load tests to measure the bridge's integrity and verify its structural capacity. The testing carried out in the MX3D factory included a 115kN vertical load test (equivalent to a load of 5kN/m² on plan) and horizontal loading (a series of three 7.5kN point loads along the length of the bridge).

In September 2018, Arup, along with researchers from The Alan Turing Institute's Data-centric Engineering programme – a consortium of researchers from Imperial College London and the University of Cambridge – performed a successful load test of more than 10 tonnes on the

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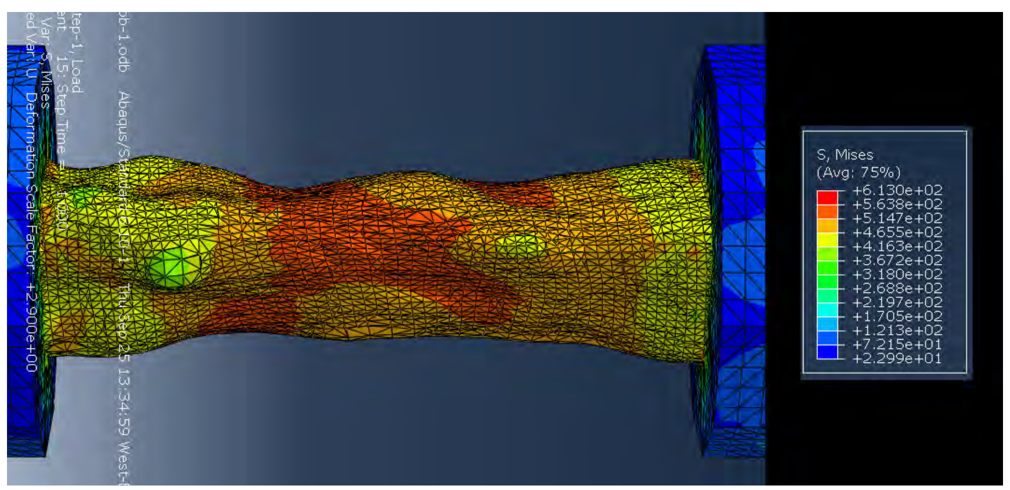

8.

7: Four robots carried out the entire printing process, which took just six months

8: The bridge design went through an exhaustive testing programme, and the results from each phase informed the iterative design process

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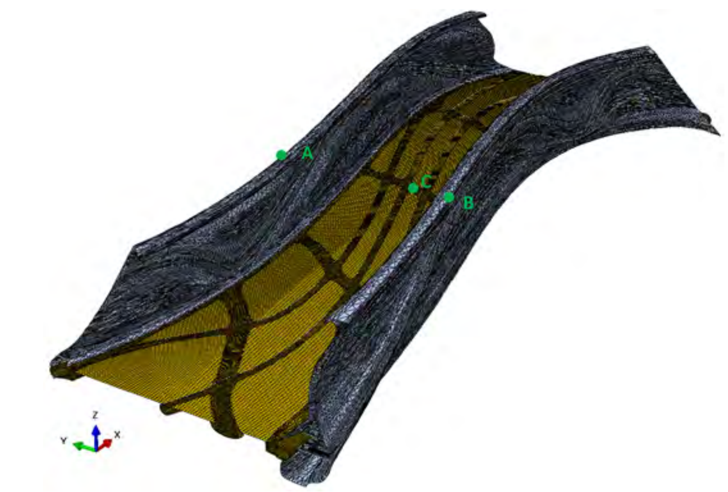

10.

11.

9: Typical sections of the bridge were printed and then tested in the laboratory

10: Imperial College used Abaqus software to model the entire bridge with 2D shell elements

11: Full-scale load testing was carried out on the bridge

12.

bridge. The following month, the completed structure was put on display in Eindhoven as part of Dutch Design Week. During the event, visitors were invited to walk over the bridge to generate the first data set. This data was used by partners such as The Alan Turing Institute, along with Autodesk, to build the digital twin model, using advanced data analysis to monitor its performance in real time. In 2019 at University of Twente, the bridge was tested for the maximum design load of 20 tonnes.

Permitting and installation

With the structure due to be placed in the public realm in Amsterdam's city centre, a building permit was required. Arup submitted the design to the local authorities and walked them through the design process. With no prescribed code for the design and no other 3D-printed bridge having been manufactured using these techniques, this involved going back to first principles and proving technically that the bridge design had an adequate safety factor. The previous pedestrian bridge over the canal was removed. Investigation excavations behind the quay wall were carried out by the local authority to determine the properties of the material being supported by the wall and to ensure there was sufficient capacity to support the load of the new bridge. The MX3D Bridge was lifted into place by crane and was officially opened in July 2021 by Queen Máxima of the Netherlands.

Digital twin

The bridge has been fitted with an innovative sensor network by Autodesk, Force Technology, Imperial College London, Lenovo and HBM to obtain data regarding cycling and pedestrian traffic and structural integrity, and to collect readings on its surroundings and environment.

The sensors measure strain, displacement and vibration, people-flow and related applied loads. They also measure the environmental conditions on the bridge including issues relating to natural corrosion and wind, thermal, light and air quality, as well as human activity. The data gathered allows the

12: The finished bridge was lifted into position using a crane

13: The MX3D Bridge demonstrates how it is possible to print safe, large-scale structures in metal

13.

creation of the digital twin, with the virtual model of the bridge monitoring its performance under different environmental conditions and changing dynamic loads. The findings will fuel additional research into machine learning, data analytics and management, and optimised design.

An award-winning project

In 2018, the bridge was awarded the European Commission's prestigious STARTS Prize, an award that champions innovative projects at the interface of science, technology and art and recognises digital transformation projects that have the potential to contribute to economic and social innovation.

The jury report noted that "this project is not only great in engineering and design but also generates discussion about the future of design and construction. The project innovates the type of materials and the techniques used and presents a new kind of open collaboration. It defines data-driven algorithmic methods for evaluating the safety of the bridge and enabling the bridge to interpret its environment."

The bridge also won the Public Award for design research at the Dutch Design Awards and a 3D Pioneers Challenge Award.

14.

14: The MX3D Bridge was a highly collaborative project that brought together diverse creative, technological and governmental organisations

Designed by humans, printed by robots

This highly collaborative project by a team of diverse creative, technological and governmental organisations shows how it is possible to print safe, large-scale structures in metal. The MX3D Bridge not only demonstrates that a 3D-printed steel bridge can be created, but also showcases how these steel printing methods can achieve shapes that cannot be formed using standard methods of steel manufacturing. The technology allows for a more optimised design that can lead to more efficient structures that use less material. As the world's first 3D-printed steel bridge, the design offers a glimpse into how computational design, together with state-of-the-art robotic construction technology, could shape our cities in the future.

Authors

Stijn Joosten led on the material testing and permitting for the bridge. He is a senior engineer in the Amsterdam office.

Shibo Ren led the digital design of the bridge. He is a senior engineer in the Amsterdam office.

Paul van Horn was the Project Manager. He is an Associate Director in the Amsterdam office.

Mathew Vola was Project Director. He is a Director and Property Business Unit Leader in the Amsterdam office.

Project credits

Clients MX3D and Joris Laarman Lab

Partners and collaborators Autodesk, ArcelorMittal, Force Technology, Imperial College London, Air Liquide, ABB Robotics, Heijmans, Lenovo, The Alan Turing Institute, Lloyd's Register Foundation, TU Delft, University of Twente, University of Bologna, AMS Institute, Municipality of Amsterdam

Structural engineering design, testing and evaluation, parametric design Arup: Stijn Joosten, Bertrand Le, Shibo Ren, Maarten Rikken, Tom Tebbens, Paul van Horn, Tania van Mens, Mathew Vola

Image credits

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7: Olivier de Gruijter
10: Imperial College London

Making island life more sustainable

Three islands in the Great Barrier Reef will benefit from the implementation of innovative solutions to reduce carbon emissions and improve resilience

Authors Kellie Charlesworth, Ian Hustwick, Sam Koci

1.

1: In the face of climate change, there is an urgent need for the islands of the Great Barrier Reef to become more self-sufficient and sustainable

The Government of Queensland in Australia is taking action to tackle climate change as it works towards a target of zero net emissions by 2050. As part of this initiative, it has implemented a programme to help support the islands of the Great Barrier Reef, home to a range of communities including Aboriginal and Torres Strait Islander Traditional and Historical Owners. The archipelago of over 900 islands is a UNESCO World Heritage Site that extends more than 2,000km from the Torres Strait in the north to Fraser Island in the south. This area of significant natural, ecological, cultural and economic value is exceedingly vulnerable to the effects of climate change, so there is an urgent need to support its communities to improve their self-sufficiency and sustainability.

In 2019 Arup was appointed to a team supporting the island communities to transition to a low-carbon future and become more resilient. We worked with the local communities to identify priority projects for reducing carbon emissions and improving island self-sufficiency. Each project proposal was developed into short business cases suitable to be used to secure grant funding from public and private sources. The community pilot programme focused on three islands – Masig Island, Magnetic Island and Palm Island – and the outcomes can be leveraged to other islands and remote communities in Queensland. The pilot programme involved engaging with the residents of each location to ensure the measures would meet their needs, taking into account the diversity of views and traditional ways of life.

In carrying out this work, Arup collaborated with the Queensland Department of Environment and Science; scientific benchmarking group EarthCheck; Regional Economic Solutions (RES), which is dedicated to bridging the economic and social gap between indigenous Australians and the rest of the population; and the Queensland Tourism Industry Council, a not-for-profit organisation that represents the interests of the state's tourism and hospitality industry.

The islands

Each island involved in the community pilot programme has different characteristics, including different sizes, climates, habitats, populations, socioeconomic contexts, land uses and connectivity, but represent the diversity of islands in the Great Barrier Reef. The islands in the programme also share some characteristics, such as their high cost of living; dependence on the mainland for goods and services; reliance on private vehicles; and a tropical climate of high rainfall, humidity and vulnerability to cyclones and severe weather which can cut islands off from the mainland for up to several weeks. They also all share a vulnerability to the effects of climate change and have a heavy reliance on carbon-intense fossil fuels for their energy and transport needs.

Magnetic Island, for example, is a 20-minute ferry ride from the mainland city of Townsville and spans 53km². Relatively affluent, it is traditionally known as Yunbenun and is the seventh largest island in the Great Barrier Reef World Heritage Area. People aged over 65 make up a quarter of the population. The island has an active community with sustainability and environmental interests. From 2007 to 2012 it was home to a landmark rooftop community solar programme – Ergon's Solar Suburb programme – and the community are keen to build on its legacy and be more self-sufficient. It has an abundance of businesses operating in the housing, food, retail and leisure sectors, and a variety of transportation options. Projections indicate that the island will experience a temperature increase of 0.82°C by 2030 and 1.55°C by 2050, and an increase in the number of hot days by 21 days per year by 2050. The island is connected to the mainland electricity and water supply and relies on the mainland for most services including waste management, healthcare and food supplies. It receives about 140,000 visitors every year, which brings economic opportunity as well as environmental impacts to be managed on the island.

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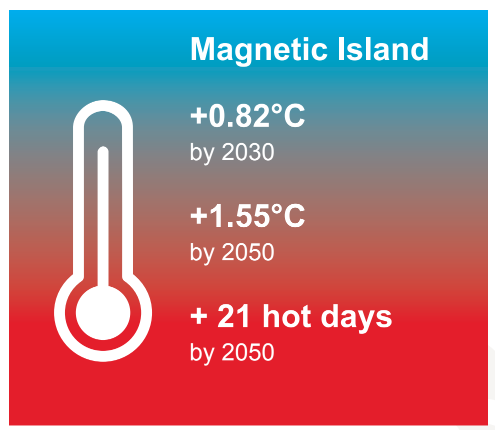

2: Magnetic Island, the seventh largest in the Great Barrier Reef, is reliant on the mainland for services and food supplies

3.

3: Palm Island is an area of social disadvantage suffering from a lack of employment, healthcare, housing, and transport

4: Masig Island in the far north, near Papua New Guinea, is particularly vulnerable to the effects of climate change

4.

Palm Island, traditionally called Bwgcolman, is located approximately 50km north-east of Magnetic Island and has a similar tropical climate. It is actually a group of 10 islands covering 70.9km², with Great Palm Island covering 55km². Many of today's Palm Island community members are descendants of Aboriginal and Torres Strait Islander people forcibly removed from across Australia and relocated to the island. Today the community is self-governed by the elected Palm Island Aboriginal Shire Council and seeks to improve the historical social disadvantage through 'Closing the Gap' social initiatives and sustainable development. Palm Island has a diesel-generated electricity microgrid and its own water and wastewater treatment plants. Housing is predominantly social housing and there are limited employment opportunities on the island. The cost of living, including electricity, groceries and transport, is of significant concern in the community. The island is self-sufficient in energy, water and wastewater and some community education and healthcare services, although security of drinking water supply has been an ongoing issue.

Masig Island, also known as Yorke Island, is located in the Torres Strait between Cape York Peninsula and Papua New Guinea. It has a total area of 1.62km² and a population of 270 people; more than half of these are aged under 24, with children under 14 the largest age group. Its main employers are the public sector, education and fishing, and its residents have a median weekly income that is almost half of the Queensland average. The island's power supply has just enough capacity for the current population, who have limitations on their energy consumption. Most people live in public housing and there is a long waiting list for homes.

Community engagement

Engagement with the island communities focused on their ideas for caring for their communities, land and sea country. Island communities typically have limited means for sustainable development initiatives, but they have a disproportionate need for sustainable self-sufficiency and resilience, particularly in the face of climate change. The potential decarbonisation and community self-sufficiency benefits were identified for each initiative. The final proposals also needed to demonstrate how the interventions would have tangible benefits and how they would be delivered in practice.

Communication was critical, both to explain the aims of the project and to gauge the priorities of local people and organisations. The project team's indigenous engagement consultants, RES, facilitated discussions through a process called 'Moon-Da-Gatta Yarning'. It included three phases designed to gain the trust and support of residents: 'Listening to Hear' aimed to understand the current situation and the community's strengths, integrating the stories of individuals and places, and local ways of living, into the technical sustainability assessment of the island's infrastructure; 'Dreaming Big' identified goals and fostered hope for the future; finally, 'Whichway Now' focused on grouping together themes and deciding which actions to take forward. Following these phases, the findings of the project were shared with the people involved, with the intent being to ensure they can continue to be involved as the final project options are progressed.

Integrating traditional knowledge was an important part of this process, as long-term residents of these islands are deeply invested in protecting their local

5.

5: Discussions with the local communities on each island took place across three phases

6: Funding for some of the proposed projects has already been released, and Arup hopes to continue working with these island communities to make them more sustainable and resilient

environments. Data and information was captured through stories and conversations with community and stakeholders, with themes of energy, water, waste, transport and resilience key parts of those discussions, helping to inform the subsequent project phases. The communities are accustomed to initiatives being instigated but not sustained, so each project was set up with a short business case to support further funding initiatives for implementation. Arup carried out three-day visits to each island for each of the three phases, speaking with people in different situations to understand their needs and making sure a wide variety of views were taken into account.

The projects

The team started by conducting a sustainability assessment for each of the islands, developing carbon emission profiles and island-wide risk assessments. They worked closely with the island communities and other stakeholders to identify opportunities. They then developed business cases for a range of projects – some suitable for all three islands, others location-specific.

Many of these focused on energy savings and power generation measures to facilitate energy cost and carbon emission reductions, as well as other co-benefits for community wellbeing. The cases included upgrading buildings to improve airflow, insulation, glazing and heat reflection; installation of photovoltaic panels; incentives for acquiring energy-efficient appliances and tools; upgrading hot water systems to use solar power; and systemic interventions such as renewable energy plants, organic waste and glass recycling, and greener fuel. Better design standards are required to improve the energy efficiency and comfort of homes, particularly the public housing that is often poorly suited to the hot climate; Arup proposed community-led, codeveloped housing design codes to ensure future homes and upgrades would suit local needs.

For Magnetic Island, Arup proposed a solar-powered electric bicycle rental scheme and a low-emission ferry service to Townsville. The firm suggested low-emission bus services for all three islands – particularly important for residents of Palm and Masig Islands, which have no public transportation. Better walking and cycling paths would allow residents to have a more active lifestyle, while Masig Island would benefit from better lighting along the roads, jetty and beach.

Instead of relying on food travelling from great distances, both Palm Island and Masig Island were keen for a market garden where they could produce fresh food and come together as a community. For Magnetic Island, a native plant nursery and an aquaculture system for local sea species could reduce dependence on the mainland.

Water security can be improved on all three islands through measures such as improved rainwater harvesting and community-led demand management initiatives. Through consultation with the Palm Island community, it was evident that strong community engagement and participation will be necessary to build the relationships and trust required to deliver better water management outcomes (in terms of both quality and quantity). Some ongoing initiatives to improve community participation and awareness were identified through the project, including school water education programmes and easier access to chilled water, to support water regaining its place as a healthier drink of choice in the community.

All three islands have the potential to boost their tourism economies. However, impacts on the environment and the communities need to be carefully managed; for example, developing plans for Magnetic Island to gain accreditation as a sustainable destination, and for Palm Island to develop community-led tourism and increase its capacity to host visitors, given the Museum of Underwater Art attraction planned for the area.

Other proposals seek to safeguard the islands' environments in the long term. For Palm Island, an expansion of the indigenous land and sea ranger programme would provide more employment and allow residents to better care for the land and sea country. For Masig Island, a new job role was identified: an on-island sustainability officer to oversee the delivery of sustainability projects, such as the conservation and restoration of seagrass and mangroves, and to oversee the start-up of the community garden. On Magnetic Island, a community-led programme of environmental education would ensure valuable knowledge is retained and shared.

The future

Arup's work on the project was carried out over the course of a year. The team calculated that, if successfully implemented, Magnetic Island's 18 project options would reduce annual carbon emissions by 22,130 tonnes, generate AU$2.9m in savings annually and create 12 jobs; Palm Island's 17 options would reduce carbon emissions by 7,260 tonnes, save AU$3.7m and create 25 jobs; and Masig Island's 18 projects would reduce emissions by 1,698 tonnes, generate AU$200,000 in savings annually and create 16 jobs.

The Queensland Government has since released funding for some of the plans. On Palm Island, the council will start a community bus service and refine plans for a waste and recycling facility. On Masig Island, a sustainability officer will trial smart solar streetlights and a market garden, lead a campaign on reducing waste and support community-led traditional knowledge-sharing and education. Magnetic Island will install a bioregen machine to turn food waste into fertiliser, host community and business workshops, and begin studies on the feasibility of establishing a microgrid for solar energy.

Arup hopes to continue to work with the communities on all three islands to make sure these projects and others are a success, now and in the future.

Authors

Kellie Charlesworth was the Project Director. She is an environment and sustainability adviser and an Associate Principal in the Brisbane office.

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Project credits

Client Queensland Government

Collaborators EarthCheck, Regional Economic Solutions, Queensland Department of Environment and Science, Queensland Tourism Industry Council

Arup:

Kellie Charlesworth, Ian Hustwick, Melanie Kempton, Sam Koci, Andrew McPherson, Susie Mills.

Image credits

1: Getty Images

2, 4–6: Arup

3: Cameron Laird

6.

A green legacy

A groundbreaking project setting new standards for infrastructure providing environmental growth on private land at scale

Authors Ben Oakman, Pippa Wood

1: The project areas emanate like green ribs from the A30 spine along the Cornish peninsula

2: The principle underlying Keyn Glas is to protect and enhance existing landscapes

2.

In 2015, England's National Highways appointed Arup to design a major road scheme: the 14km A30 dual carriageway from Chiverton Cross to Carland Cross in Cornwall. The existing route along an undulating ridge forms a spine down the middle of the Cornish peninsula; it connects people, but also severs links between landscapes and habitats and restricts north–south movement for wildlife and communities alike.

During the project, the brief was expanded; Arup was asked to look beyond the usual environmental mitigation associated with highway schemes, and instead actively regenerate the surrounding environment. The project team utilised National Highways' Environmental Designated Funds – money allocated by the Department for Transport to mitigate the impact of infrastructure projects through activities such as innovation, carbon reduction, and community and environmental enhancement. Arup worked collaboratively with National Highways to develop the design for a series of environmental regeneration projects extending up to 3km either side of the A30.

National Highways initially commissioned Arup to undertake a feasibility study. They then gave the firm approval to progress with a £3.2m commission to develop detailed designs for 15 of the proposed environmental projects – together called Keyn Glas, or 'Green Ridge' in the Cornish language.

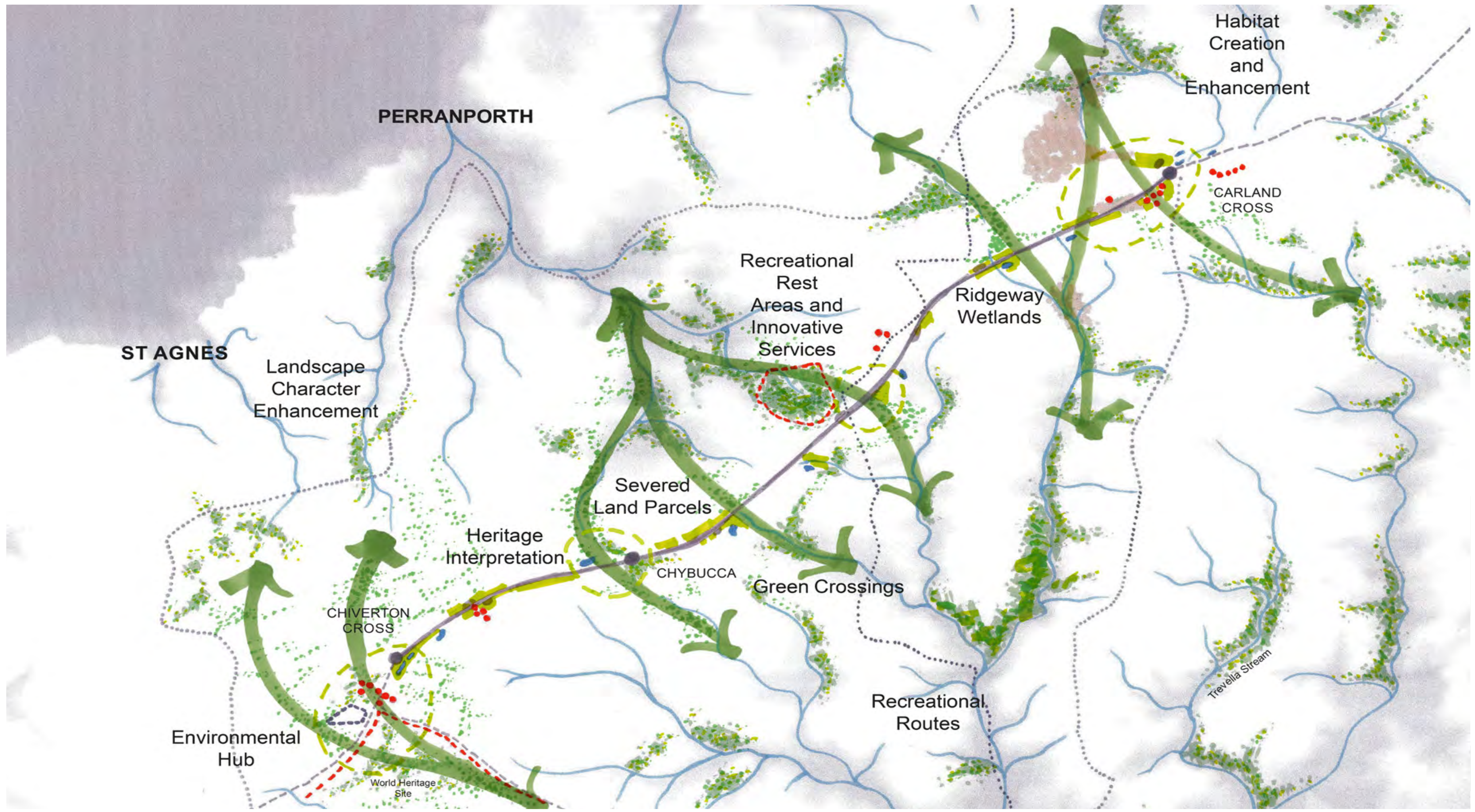
Six of these projects, known as the Green Ribs, were designed to span some $50km^2$ of central Cornwall's landscape. So far, three Green Ribs have been delivered, across nine farms, with the remaining three to be implemented as part of the second phase of the project.

Arup assembled an interdisciplinary team of landscape architects, ecologists, heritage consultants and water scientists to work with National Highways to conceive a holistic strategy to bring the vision to life. This would ensure the work would have a long-lasting positive impact on the Cornish countryside, for people and nature.

A unique project

Keyn Glas is unique in its scale and nature. The vision was to give back some of what had historically been taken from the landscape by road construction. In other words, to rebalance grey infrastructure with green infrastructure for wildlife and communities.

The area around the A30 is dominated by intensive arable farming, with occasional valleys of overgrown hedgerows and woodland. Arup assessed that improving what already existed should be the



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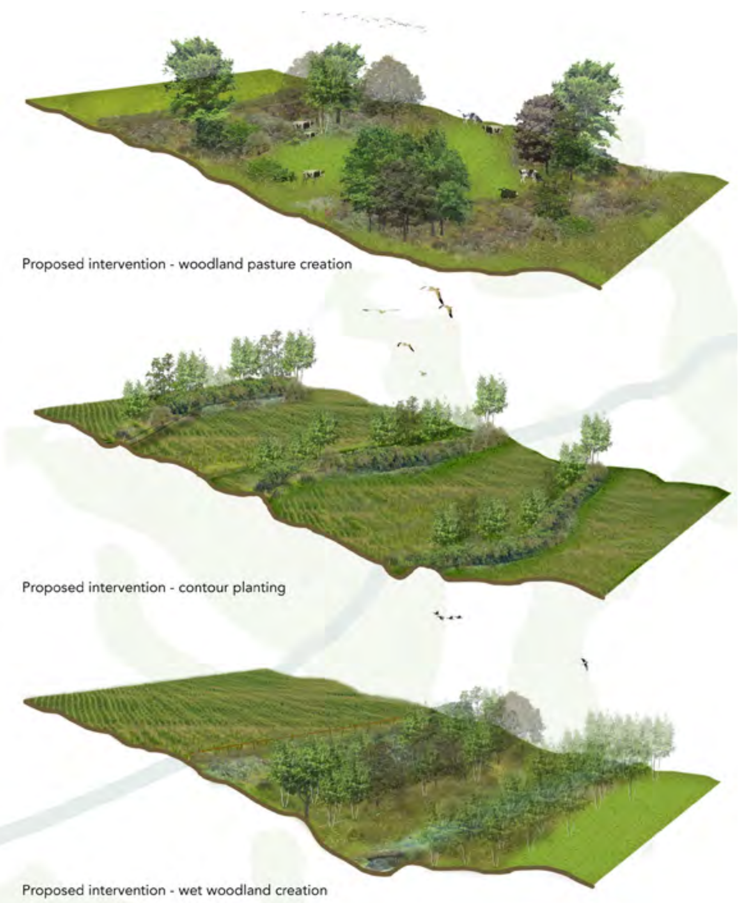

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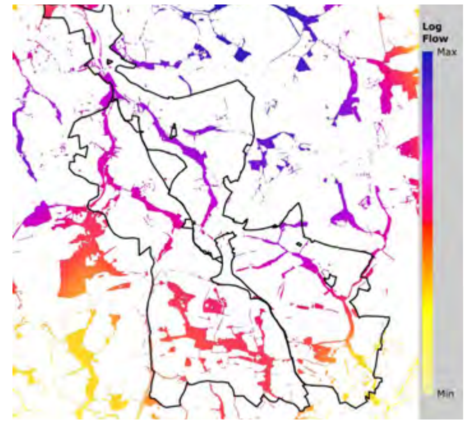

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3: Nature-based interventions include natural flood management, hedgerow and woodland planting, and the creation of wetland and flower-rich grasslands

4: Condatis was used to study local habitats and wildlife movements

5: Interventions have been delivered across nine farms so far

primary aim, as this would be more beneficial – and incur lower costs – than removing what was in place and putting in new landscape features. For example, the design focused more on habitat restoration; bringing back habitats' diversity and condition after years of degradation, habitat enhancements such as pond restoration projects, and new habitat creation through planting trees and creating Cornish hedgerows.

Arup used an innovative new GIS-based tool called Condatis, developed by the University of Liverpool, to analyse the local landscape and habitats. This helped identify the best areas to improve habitat connectivity and enhance biodiversity flow throughout the landscape. This enabled the design team to concentrate effort where it would have the greatest impact. The aim was to help National Highways move from their target of no net loss in biodiversity, towards achieving significant biodiversity net gain in projects.

The interventions reconnect and enhance the fragmented countryside on either side of the A30. Measures include natural flood management, hedgerow and woodland planting and restoration, and the creation of wetland and flower-rich grasslands. Collectively, these bespoke interventions are designed to work cumulatively. The result is environmental benefits far greater than the sum of their parts. For example, new hedgerow planting provides habitats for pollinating insects and rare and declining birds and mammals. When connected with other new and existing habitats, it links up wildlife corridors and reinforces historical field boundaries and landscape character. In addition, restoring and aligning these new features along existing contours helps hold vital water on farmland, attenuating stormwater runoff and improving water quality.

An ambitious yet manageable implementation plan, developed in close early collaboration with the contractor, meant that the project went from concept to design and then completion in just 18 months. This success has meant that this project has set the standard for the use of National Highways' Environmental Designated Funds on private land around road schemes.

Green goals

Early in the project, Arup understood what National Highways wanted to achieve with its Environmental Designated Funds. Impact targets included carbon emission reduction, biodiversity gain, landscape enhancement, water quality improvement and flood alleviation. The Arup team then calculated the cost–benefit ratio for their proposed measures using National Highways' environmental appraisal tools.

In implementing these changes, Arup made as much use as possible of materials from the site, reducing the costs and carbon emissions of transporting anything to those sites.

Over the course of the project, interventions have been delivered across nine farms, connecting 32 habitat areas and creating and restoring five traditional orchards and restoring four pond habitats. Eight woodlands are under enhanced biodiversity management, with 8km of new and enhanced field boundaries installed, including traditional, distinctive Cornish hedges, hedgerows and fencing. This has led to a net increase in biodiversity of up to 250% in some areas – a striking improvement on the 10% net gain that development is now obliged to achieve by the Environment Act.

Carbon reduction and capture

Calculating carbon benefits on even a small project is a complex process, because it involves taking into account the various stages of construction, as well as the longer-term operation and management of a scheme.

On this project, Arup made an estimation based on factors such as how much carbon would be absorbed by the greenery that was put in place. With the planting of 13,000 trees, as well as new hedgerows and scrub, and the creation of grasslands and wet habitats, the firm estimates that this will absorb approximately 10 tonnes of CO_2 every year. At the time of writing, Arup has invested in and is undertaking a detailed carbon impact calculation on this project.

Water management

The project also included natural flood management measures across three catchments. An example of these nature-based solutions is contour woodland planting, in which lines of trees were planted to slow down water runoff from high ground and redirect it into the ground. This curbed storm runoff and reduced flooding, as well as improving water quality by filtering it through the soil. Another intervention was the creation of wet grassland habitats, one of the best ways to sequester carbon and improve water quality.

The overall aim was to promote a catchment-scale approach to water management. This involves looking holistically at the water needs and demands of an area, with an emphasis on natural flood management and nature-based solutions.

Social value

The interventions proposed had and will continue to have a positive impact on local people. Social benefits range from creating jobs through work with local bodies such as Cornwall Wildlife Trust and Objective Tree Consultancy, to improving the quality of the environment for the farming community, as well as making their businesses more resilient by diversifying agriculture and reducing flood risk.

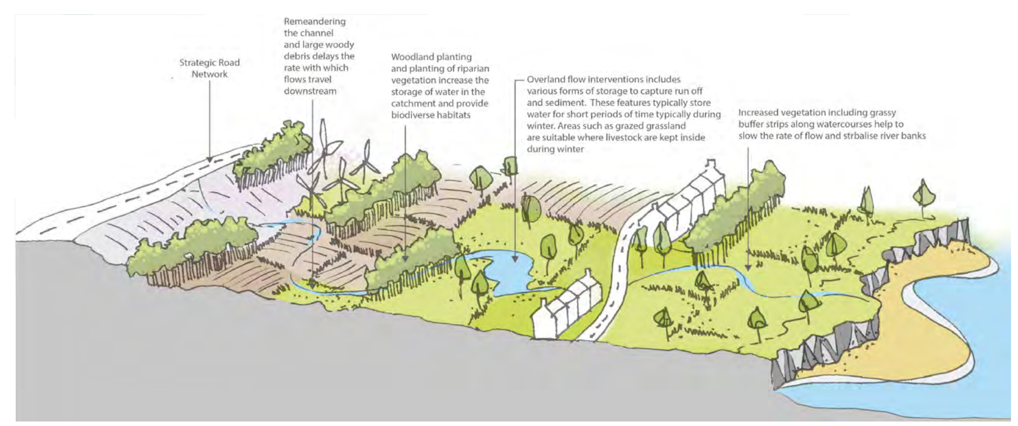
The interventions put in place were designed to fit with the local character and culture. For example, building new Cornish hedges, a feature that derives from historical precedents and makes use of local skilled craftspeople from the Guild of Cornish Hedgers. Fields, woods and other landscape features have been restored in a way that is in keeping with the existing patterns and traditions. Meanwhile, the project as a whole will provide an attractive backdrop to the cycle paths and walking routes that are being built in the area. The result is a more resilient, beautiful and productive landscape that has benefits for the wellbeing of those who spend time in it.

7.

Local engagement

The project was a collaborative effort between National Highways and the design team. As well as landscape architects and ecologists, Arup specialists ranged from civil engineers, project managers and town planners to carbon, water and heritage disciplines. This multidisciplinary team allowed the firm to deliver on its promise of a holistic total design.

From the outset, Arup was conscious that an intimate understanding of the local landscape and culture was



6.

6: The Arup team took a strategic approach to green and blue networks at a catchment scale

7: Cornish hedges are traditional boundaries that were used to reinstate the historic character of the local landscape

8.

8: Arup actively engaged with local landowners and stakeholders to help inform the design process and get their buy-in to host the interventions

9: Over time, the Keyn Glas projects will transform the countryside either side of the A30, regenerating the landscape and making it more resilient, beautiful, productive and self-sustaining

essential. Instead of the firm's design team relying on research conducted from afar, or intermittently during site visits, Arup took advantage of local expertise. Cornwall Wildlife Trust were brought in as collaborators. They are closely connected to the farming community and their local knowledge helped Arup develop a toolkit of locally appropriate and biodiversity-led landscape interventions. These were designed to complement agricultural practices, to enhance the landscape's cultural and historical characteristics and to suit the local climate. Engaging the trust also fulfilled National Highways' requirement to employ small to medium-sized enterprises in the area during the project.

The Wildlife Trust was also instrumental in highlighting the benefits of the project to local farmers and other landowners. This was essential, because they needed to opt in on a voluntary basis to host the works and care for the new features on their land for a minimum of 10 years.

The team held informal landowner engagement sessions in the locality, at which it presented the Keyn Glas vision and its advantages. The emphasis was on how the interventions would have beneficial effects on farmers' operations, with minimal extra work beyond what they already did to manage their land.

With the Wildlife Trust's input, Arup devised an easy-to-read catalogue of interventions. This was an essential tool used in landowner engagement and proved instrumental in winning over many host landowners. More broadly, dealing regularly with the familiar figures of the Wildlife Trust, such as farm liaison officers, engendered greater trust with the farming community.

To ensure that the scheme would be acceptable to landowners, Arup and National Highways adapted and simplified the standard 25-year third-party landowner legal agreement by reducing the management period to 10 years. They also worked closely with the Rural Payments Agency via Natural England, to agree an approach that did not conflict with existing Countryside Stewardship agreements that many farms are already committed to.

Building strong relationships with the community affected by this scheme is part of National Highways' wider strategy to engage local communities and improve their customer experience. It also encourages community guardianship of environmental assets, which is crucial to deliver long-term benefits from this sort of work.

It was also vital to engage with local and national stakeholders in the project.

Arup held monthly meetings, as well as regular design approval workshops, with bodies such as the Environment Agency, Cornwall Council, Cornwall Catchment Partnership, Natural England and Historic England, so that anyone with a vested interest in the project was involved from the start and throughout. Getting early buy-in from these bodies helped smooth the way through consenting, as any constraints could be addressed early in the design process. This was particularly important for the elements of the project that required planning permission, as they were less likely to face unexpected, last-minute objections.

In 2020, the project won the Best Practice Award for Stakeholder Engagement from the Chartered Institute of Ecology and Environmental Management. It was also shortlisted for the Landscape Institute's Sir David Attenborough Award for Enhancing Biodiversity and the Association for Project Management's Programme of the Year.

A groundbreaking project

National Highways is now in discussions with the Cornwall Wildlife Trust about delivering the remaining projects.

Keyn Glas is groundbreaking in several ways. It sets the standard in the infrastructure sector for investing public money to fund environmental growth. It is an example of creating a landscape that is adaptable and resilient, and working in a way that is regenerative to the environment, rather than simply repairing the damage of large-scale engineering projects.

By embracing this approach to delivering environmental infrastructure, National Highways will be better placed to achieve its targets to reduce carbon, improve biodiversity, tackle climate change and integrate its schemes into landscapes.

This is a flagship project in Arup's Regenerative Land Management proposition. It demonstrates the firm's restorative design approach and how it can be used for future infrastructure projects.

9.

Authors

Ben Oakman led the Keyn Glas element of the A30 project. He is a landscape architect and an Associate in the Bristol office.

Pippa Wood is a principal ecologist and Associate in the Bristol office.

Project credits

Client National Highways

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Image credits

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1.

1: California requires almost 1.2 million shared and public EV charging stations on its roads by 2030

2: Results from the Charge4All platform are displayed on a digital dashboard for the city, with the darkest shade of green indicating the areas most suitable for EV charging infrastructure

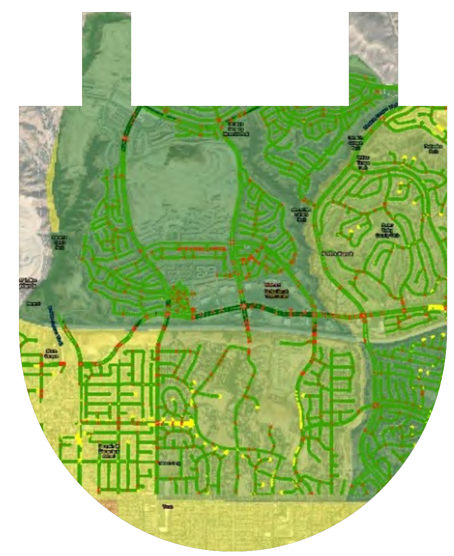
Equitable public electric vehicle charging

A major increase in electric vehicle uptake in California inspired the development of a powerful digital platform to accelerate and democratise priority charging sites

Authors Sam Lustado, Katherine Perez, Cole Roberts

Electric vehicles (EVs) will play a pivotal role in transitioning to a zero-carbon future. Among the many planned rollouts worldwide, the state of California has embarked upon one of the most aggressive switchovers to decarbonised and clean transportation. In early 2020, in a significant move to tackle climate change, the California governor signed an executive order that will effectively eliminate the sale of petrol-powered vehicles in the state by 2035.

This seismic shift has major implications for the electricity grid (an EV can consume as much electricity as three households during charging) and increases the urgency of ensuring equitable access to charging infrastructure for EVs. It highlights the massive scaling-up needed to roll out public charging stations that are accessible to all members of a community – including those without off-street parking – focusing attention on opportunity fast charging at destinations such as shopping centres and libraries, as well as longer duration charging near apartment blocks. It also raises the prospect of leveraging the extensive electrical infrastructure already in place throughout streets and parking lots.



2.

According to analysis by the California Energy Commission, the state requires almost 1.2 million shared and public EV charging stations on its roads by 2030, a huge leap from the 75,000 that have been installed to date. Their successful delivery is key to encouraging greater uptake of EVs by homes and businesses.

Arup developed a geospatial EV site suitability platform, Charge4All™, to streamline the deployment of public charging points. Charge4All offers two benefits: first, a clear picture of where best to locate and phase charging infrastructure to service the diversity of projected users; and second, a means to speed up the rollout through cloud-based digital automation and data-driven insights. The result is that city authorities, in collaboration with other stakeholders – such as transport authorities, regeneration teams and energy distribution network operators – can harness the power of data to guide their decisions.

Power partnership

To investigate the complexities of EV charging infrastructure in southern

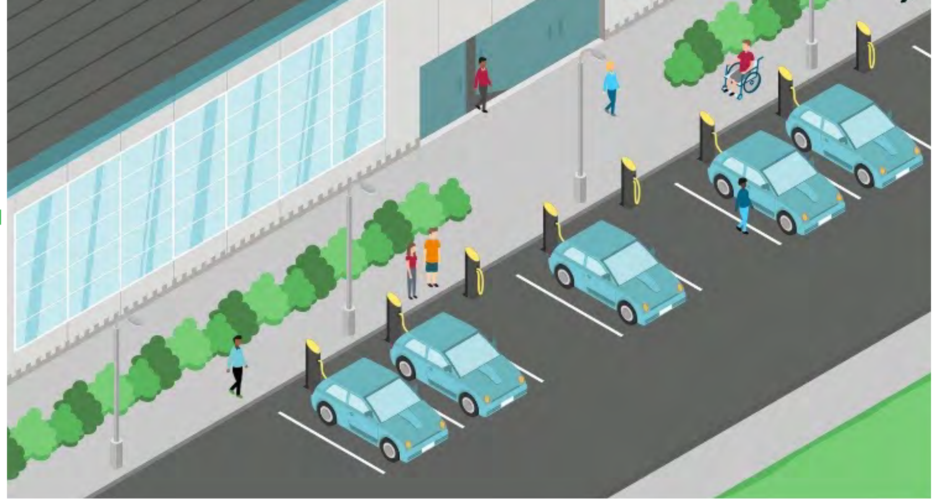
California, Arup joined forces with the Los Angeles Cleantech Incubator and three leading energy utility companies (Los Angeles Department of Water and Power, Southern California Edison, and Burbank Water and Power) to assess the kerbside charging landscape. A year-long research phase involved multiple interviews and workshops with the three utilities, as well as City of Los Angeles local government departments (including the Bureau of Street Lighting) and other important stakeholders, to identify the main opportunities and challenges.

Site selection for kerbside charging is recognised as a significant bottleneck in deploying accessible EV charging infrastructure. The expanding network will need to serve vehicle users without access to at-home charging, particularly residents of multi-unit dwellings and those in economically disadvantaged neighbourhoods. Also, grant funding programmes for charging installations are most often used by those with the knowledge and ability to access them, limiting the build out of a network that meets the needs of all segments of the community.

Speed of deployment is also a pressing priority. Arup's research revealed the lack of a coordinated and data-driven strategy for site evaluation, whereas a more standardised process would be able to identify the critical attributes that define a site as suitable or not suitable. This helps to facilitate quicker decision-making.

Examining current strategies in detail revealed that there was insufficient data in the study area, including a lack of data on existing electrical infrastructure and on restrictions related to privacy and other regulatory issues. It also highlighted the absence of a centralised, accessible data resource – something Arup considered to be vital to digitalising decision-making.

As a result, processes are typically time-intensive (even preliminary site consideration is contingent on an in-person site visit), with the potential to derail the anticipated rollout of thousands of chargers per year in the future.



3.

5.

3: The expanding EV charging network will need to serve vehicle users without access to at-home charging

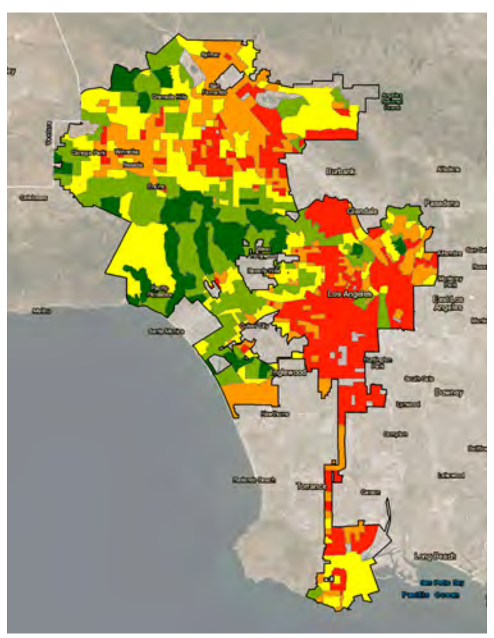
4: High-level analysis allows stakeholders to identify charging location suitability on a regional scale

5: A higher adoption of EVs will lead to better air quality

Context considered

Equipped with a new understanding of the importance of clearly defined site identification and data-enabled decision-making, Arup developed an innovative, web-based site suitability platform and approach called Charge4All.

Renewable energy companies and utilities are increasingly turning to geographic information system (GIS) technology, open city data sources, and 360-degree street condition photography in the knowledge that contextualised information supports more accurate and informed infrastructure decisions. The Charge4All platform harnesses the power of these sources to work with more than 45GB of data covering criteria such as transportation networks, energy networks and demographics (including population density, proximity to places of interest



4.

and existing EV usage) to identify the best locations for chargers as EV adoption increases.

Charge4All centralises information about neighbourhoods and their needs and enables those responsible for charger deployment (including utility companies, city agencies, private developers and NGOs) to quickly digest high-level data and identify the most suitable areas for chargers. It also helps them to visualise both at a high level and at the street level what deployment will look like.

Equity was placed at the forefront of the platform's development to ensure that new infrastructure supports EV ownership across diverse demographics. Infrastructure development programmes can fall short of meeting the needs of all communities, so the Arup team worked with geospatial consultants, software developers and data engineers to ensure that low-income and disadvantaged neighbourhoods were factored into the analysis.

As a result, Charge4All takes into account equity criteria such as socioeconomic demographics, EV ownership, lack of off-street parking and proximity to direct current fast charging and electricity infrastructure. These are overlaid onto other technical criteria (e.g. kerb restrictions) in the platform to help guide decisions in the early planning and design stages.

A higher adoption of EVs will lead to better air quality, while construction of EV infrastructure can expand access to well-paying jobs – benefits that can be quantified to help communities that disproportionately suffer from poor environmental conditions and negative health outcomes caused by particulate emissions from combustion vehicles.

Zoomed in

Efforts to scope out potential charging infrastructure sites are traditionally carried out at district or regional level and rarely acknowledge the many nuances that could make individual street locations ideal candidates for an installation.

Arup and the team turned this notion on its head by building into Charge4All the ability to assess sites at both macro and micro scale using detailed contextual geospatial data. The platform examines two levels of resolution to determine a site's suitability. High-level analysis allows stakeholders to identify suitability on a regional scale, which is useful when planning early-stage priority distribution and mass deployment. Detailed-level analysis then zooms right into the kerb to explore on-the-ground suitability, taking in factors such as nearby hydrants and electrical infrastructure, road types, and proximity to points of interest, including public buildings such as libraries and city halls. This perspective supports engineers, designers, installers and other teams responsible for the physical deployment of the EV chargers. Results are displayed on a digital dashboard for the city where site suitability is denoted by various colours, with the darkest shade of green indicating the areas most suitable for EV charging infrastructure.

Los Angeles is a huge city that is difficult and time-consuming to traverse.

6.

6: The Charge4All tool harnesses the power of GIS to work with more than 45GB of data

Charge4All's micro-level streetscape analysis and visualisation enables initial site reviews to be completed from an office computer, reducing the need for site visits and lengthy data lookup and analysis. A handy 'point to 360-degree street view' function provides the quick visualisation of the area that helps the user to understand on-the-ground challenges before going out into the field.

The platform's inherent flexibility means criteria can be configured to match stakeholders' specific deployment goals, depending on the availability of and access to relevant data. For example, it can take into account dense areas of multi-unit dwellings, utilisation data, or vehicle miles travelled.

Charging ahead

By addressing cost, stakeholder coordination and data opportunities, Charge4All bridges the gap between data analysis, community engagement, and physical implementation through an automated and streamlined process.

Decision-makers in the US have seen the benefits of this ambitious project, and further initiatives are already using Arup's Charge4All platform and approach to fuel the equitable transition to clean energy transportation. These include a recently completed EV site suitability programme for the City of Pittsburgh in Pennsylvania, a San Francisco Bay Area kerbside EV programme design, and phase two investment funded by the California Energy Commission to pilot installations of equitable kerbside public charging infrastructure, scalable throughout California. Global decarbonisation efforts hinge on the widespread adoption of zero-carbon modes of transport. Data-enabled and community aware projects like these will ensure that everyone can be on board for the journey.

Authors

Sam Lustado led the GIS elements of the project. She is a senior analyst in the Los Angeles office.

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Project credits

Collaborators Los Angeles Cleantech Incubator, Los Angeles Department of Water and Power, Southern California Edison, and Burbank Water and Power

Advisory services Arup: Kaitlin Coari, Tara Davis, Felicity Graves, Geoff Gunn, Sam Lustado, Roland Martin, Katherine Perez, Cole Roberts, Vinny Riscica.

Image credits

1: Getty Images
2–4, 6: Arup
5: Andrew Roberts/Unsplash

A big plus

Constructing an iconic new museum of visual culture while overcoming significant engineering challenges

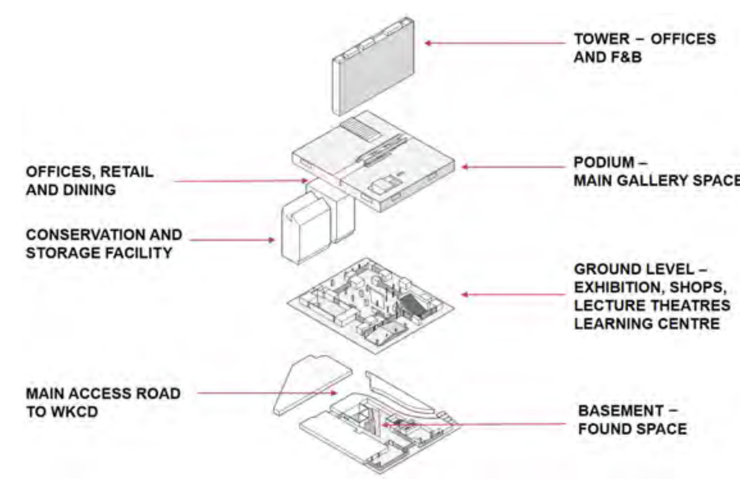
Authors Vincent Cheng, Yu-Lung Cheng, Paul Tsang, Rhodri Williams, Young Wong

1.

As the flagship project of Hong Kong's West Kowloon Cultural District, M+ occupies a prominent site on the southernmost edge of Kowloon, overlooking Victoria Harbour. Opened in 2021, the project – designed by the M+ Consultancy Joint Venture, comprising Herzog & de Meuron in partnership with TFP Farrells and Arup – is Asia's first global museum of contemporary visual culture.

The 65,000m² development includes 17,000m² of exhibition space across 33 galleries, as well as three cinemas, a Learning Hub and Research Centre and a garden on the 130m x 111m podium that is open to the public all year round. Its tower is home to offices and restaurants, while the façade features an LED media display screen that can be seen from the Kowloon waterfront and across the water on Hong Kong Island.

It is the aspiration of the Hong Kong authorities that the M+ project will support the city's development as a creative economy and global metropolis. It is a major initiative to foster the growth of local cultural and creative industries, attract and nurture talent, promote international exchange and cooperation, enhance the quality of living and make Hong Kong the cultural gateway to the Pearl River Delta and beyond.



2.

1: M+ is Asia's first global museum of contemporary visual culture

2: The 65,000m² development includes 17,000m² of exhibition space across 33 galleries

3.

Reclaimed land

Hong Kong's West Kowloon Cultural District is built on land reclaimed from the harbour between 1990 and 2003. One of the largest reclamation projects ever undertaken in the city – 40ha in total – it increased the size of Kowloon by a third and extended the waterfront by a kilometre. The original plan for the district was based around a Foster + Partners masterplan for a city park, designed to better connect Kowloon with the Victoria Harbour.

During the M+ design competition stage, to develop the conceptual design for the engineering components of the project, the Arup team in Hong Kong collaborated with the London office, who have a long-term working relationship with Herzog & de Meuron. The collaboration between the two offices proved successful – the London team drew on their years of experience of working with the Swiss architects and the local team on their extensive knowledge of complex projects in Hong Kong.

The M+ Consultancy Joint Venture began working on the project after winning the design competition in 2013. Arup provided a wide range of multidisciplinary design services including structural, geotechnical, civil, façade and building services engineering, environmental consulting, sustainability, landscape and lighting design, security and transportation consultancy.

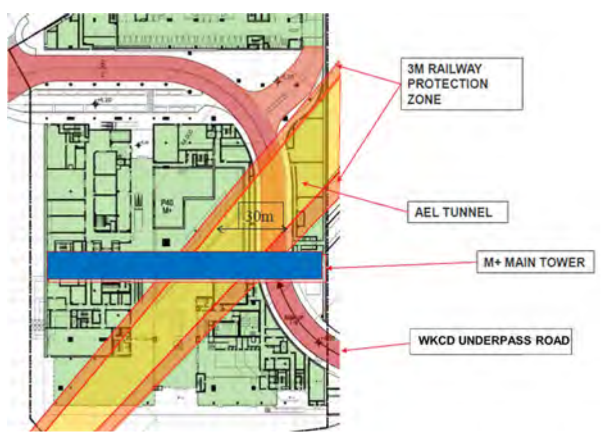
The relative simplicity of M+'s external form as an inverted T, however, hides both the complexity of the building within and of the site itself, which provided significant engineering challenges from the outset of the design.

Overcoming site constraints

Just 1.5m below the surface of the site run the Airport Express/Tung Chung MTR (Mass Transit Railway) lines, which cater to millions of residents daily and form an integral part of Hong Kong's transport infrastructure. The MTR carries passengers to the airport as well as to the western districts of Kowloon and some of Hong Kong's islands.

The Airport Express/Tung Chung lines, originally designed by Arup, diagonally bisect the site from north-east to south-west and the tunnel structure is, on average, 30m wide and essentially floating within the ground, with no piled foundations. It could not support any building loads and had strict movement limits set by Hong Kong's transit and building authorities. It was not permitted to move more than 20mm in any direction during the construction process – a limit that was strictly observed.

The architectural design embraced the tunnel, both by incorporating its stepped side profile into the design and by excavating so-called 'Found Space', which is now used as gallery space. This zone links the basement and ground floor levels with a broad diagonal opening, providing an open area that extends across multiple floors and offers multiple vantage points for viewing the works on display.



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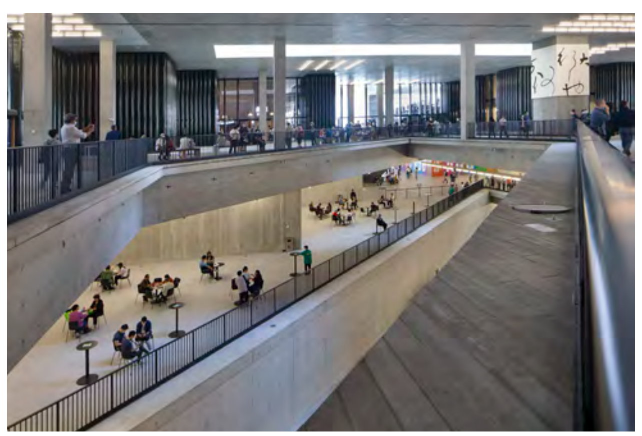


5.

3: The West Kowloon Cultural District is built on land reclaimed from the harbour

4: The Airport Express/ Tung Chung MTR tunnels run 1.5m below the surface of the site

5. The stepped side profile of the tunnels was incorporated into the design, providing an open area extending across multiple floors

Arup's solution at the conceptual design stage was to minimise basement depths adjacent to the tunnels and to use construction methodologies and sequences that mitigated possible vertical and horizontal movements. These included using non-percussive sheet piling techniques and preloading excavation strutting to control lateral tunnel movements. Low-angle soil berms were also used close to sheet pile walls adjacent to the tunnel as a means of reducing lateral movements. Moreover, specifying positive recharge of groundwater levels outside of the basement excavation zone reduced any groundwater drawdown and consequent settlement of the tunnels.

7.

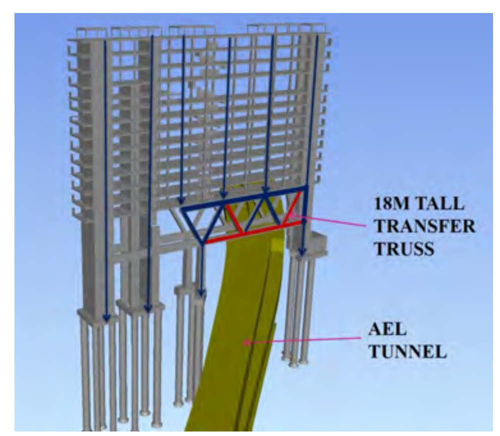
To overcome the site constraints, Arup designed large steel transfer trusses that span across the underlying tunnels. Five major steel transfer trusses were ultimately used: three trusses, each 11m tall, support the podium and another two, both 18m tall, span 55m to support the main tower. In total, the two main trusses support 17 storeys of structure and each one carries around 30,000 tonnes of load.

The podium structure was conceptualised to be steel framed at the competition stage, providing column-free spaces in the galleries. The structure was changed to conventional reinforced concrete construction during the design stage, except for the transfer trusses, for which steel-concrete composite construction was adopted. Arup developed an innovative solution for the transfer truss steel fabrication. While the conventional method is to build large box sections for the truss member using heavy steel plates, here a simple structure for the main truss elements was used. Two planes of 100mm-thick flat steel plates were spaced roughly 1m apart, then simply bolted together to minimise fabrication work. The steel plates were arranged vertically so that it would be easy to pour concrete between and around them to form the remainder of the truss member.

The design provided several benefits. First, by encasing the steelwork in concrete and making use of their composite action, steel usage was reduced by around 20%. This reduction in steel material was especially important in Hong Kong, where steel is much more expensive than concrete. An added advantage was that it immediately achieved the required four-hour fire rating for the steelwork without the need for further fire protection. Finally, encasing the steelwork in concrete meant that no painting was required.

Second, the buildability of the transfer trusses was improved. Welding was confined to in-line butt welding, minimising the risk of cracking in these large steel plates. The simpler fabrication process led to a construction cost saving of more than 30%.

Third, the trusses were exposed to enhance the aesthetics of the building (as in the case of the 18m-tall main trusses) and fulfilled the architect's desire to expose the concrete soffit of the podium structure. Indeed, like the tunnels, the trusses have become part of the visual design of the building, with aspects of



6.

6: Two 18m-tall transfer trusses span 55m over the underground tunnel to support the main tower

7: In the transfer trusses, two planes of 100mm-thick flat steel plates were spaced 1m apart and bolted together

8: Steel usage in the building was reduced by around 20%

8.

9.

10.

9: The transfer trusses are part of the visual design of the building, with aspects of them left exposed

10: The tower façade is made up of 140,000 pieces of ceramic tile

11: The façade louvres are embedded with LED light bars that transform the building into one of the world's biggest screens

them – including the chords and diagonals – left exposed throughout the museum. On the second floor, for example, the diagonals cleave the gallery section on both sides of a broad, wood-floored space that leads to a spiral staircase, while other aspects can be seen from the atrium and roof garden. Throughout the building, concrete has been left exposed in the galleries in an attempt to maintain the industrial character of the site. Combined with the visible trusses, M+ pays homage to the complexity of its design in both subtle and explicit ways, becoming an expression of art in itself.

The second major design constraint was the main West Kowloon Cultural District underpass road, which passes directly beneath the M+ building. It provides road access to the entire site and, like the MTR, is a critical piece of infrastructure for Kowloon and Hong Kong.

The underpass road significantly restricted where support structure such as columns and staircore walls could be located due to both the road alignment and the required sightlines. To overcome these constraints, Arup used the composite transfer trusses to span over the tunnel and underpass road, coupled with long-span concrete elements filling the spaces between them. Ventilation fans and dedicated plant rooms were installed to serve the road beneath the building, to alleviate concerns about the risk of vehicle fires.

Ingenious façade

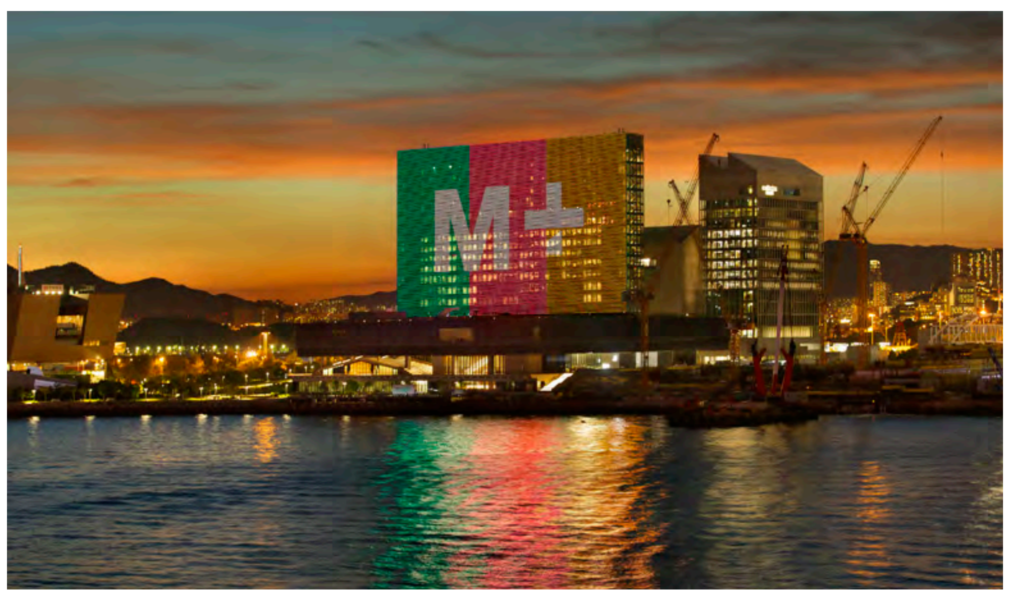
While the façade of the M+ tower looks simple from a distance, it is in fact made up of 140,000 pieces of ceramic tile laid out in a horizontal louvre structure to contribute to shading the interior. The modular terracotta cladding also extends to the podium and some sections of the ground floor and references traditional Chinese roofs. The tiles were made from clay in a ceramic factory in Chianti, Italy, assembled in precast units in Shenzhen and then shipped to Hong Kong.

There are two types of modular panels, one for the podium and one for the tower. The podium panels are semi-cylindrical tubes that partially cover the walls and columns in the main hall and the openings of the windows, vents and mechanical, electrical and plumbing (MEP) units on the façade. In the tower panels, rows of terracotta mullions and tuiles are cast in concrete as part of an aluminium frame with window glazing and serve as sun-shading louvres for the interiors.

The recesses in the louvres are embedded with LED bars that transform the building into one of the world's biggest screens, 65.8m high and 110m long, to display specially commissioned works of art.

Fire safety

Fire was not only a concern when it came to the underpass road running underneath the building; considering the planned visitor numbers and the fact that M+ is home to over 8,000 works of visual art and more than 50,000 archival objects, fire safety was paramount. Arup adopted a comprehensive performance-based fire engineering approach that enabled the spatial planning design of the large atrium, high visitor density and maximum flexibility on fire load distribution in the building.



11.

An innovative smoke control system was designed specifically for M+, alongside smoke behaviour and evacuation engineering analyses, all of which amounted to a comprehensive fire safety plan that suits the museum's unique design and function.

Security and risk

M+ will play host to some of the most valuable pieces of art in the world, and as a result the security of these pieces is vital. Our specialist consultants carried out a comprehensive risk assessment which analysed the risk exposure to all types of security threats. The resulting strategy led to the implementation of measures such as defined physical construction standards to resist forced intrusion, counter-terrorism deterrents and a comprehensive intrusion detection system. The design uses intelligent video analytics and biometrics to ensure that M+ will benefit from the very highest levels of security.

Acoustics design

Room acoustics in the gallery spaces and the auditorium with flexible mode settings are vital to achieve the design intent for the operation of M+. Seamless acoustic ceiling treatments were designed for the spaces with due consideration given to services maintenance and operational requirements. To achieve a balance with the architectural finishes and the functional needs, room acoustics analysis using speech interference levels was conducted. The auralisation approach was demonstrated in Arup's SoundLab, with the client and designers informing the design direction. Cutting-edge audio research and development, modelling and applications using ambisonic 3D audio and computer modelling were used, allowing the design to be optimised for performance and cost.

To mitigate the groundborne noise from the underground railway trains, the noise was assessed with an analysis distribution model. A bespoke raised slab isolation system was developed that integrated the structural, building services, fire and architectural requirements.

Assessment of wind-generated noise and rain impact noise on the ceramic façade fins was also conducted based on the prevailing local wind speed and rainfall conditions. Laboratory sound insulation tests and wind noise tests were conducted to verify compliance of the specific performance requirements.

Innovative plant solution

The unique nature of the site meant that accommodating plant rooms in the building was challenging. Unlike in other projects, it was not feasible to have a dedicated basement level for plant due to the presence of the MTR tunnels and the underpass road, as well as the fact that excavating a second basement level would have substantially increased the cost of the project.

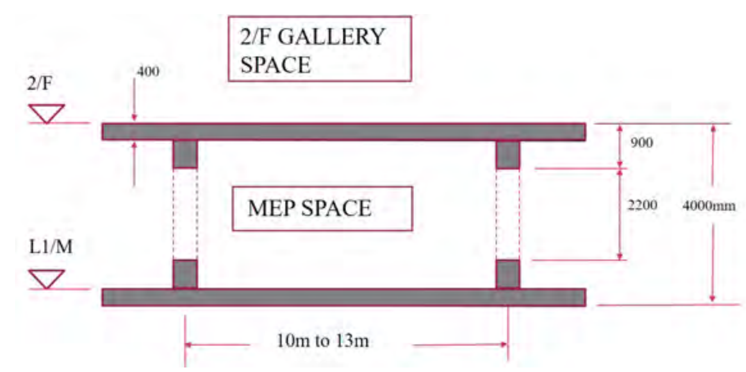
As a result, a decision was made to sandwich the plant rooms in a dedicated floor between the ground floor and second floor gallery spaces. A conventional solution to this would have been to have two separate floor levels for the MEP plant space and the gallery space, but there was a concern that this would make the podium too big in relation to the tower position of the building.

In order to use this conventional method, the total height of the separate structural concrete floors plus the MEP floor would have needed to be 6.2m deep. Instead, Arup opted to invert the lower floor structure and tie it to the floor structure above for a combined height of just 4m, allowing spans up to 30m even with the heavy plant room and gallery loading.

The two 400mm-deep concrete floors top and bottom work together, linked with a series of 4m-deep concrete walls that form the web, with the floor slabs forming the flange of concrete I-beams. The cross walls are at 10m and 5m centres throughout the MEP floor and have openings for ducts to pass through, allowing room for maintenance and for plant to be moved in and out. On the east and west faces, openings were created to allow for air intake and exhaust. The result is a structure that satisfies the architectural design and can deal structurally with the long spans of the galleries below and above.

Controlling heat and light

Where to locate the plant was only one of the building services challenges that needed to be overcome. Another was to make sure that it worked effectively to keep visitors and staff comfortable – and, importantly, to protect priceless works of art. Hong Kong has a subtropical climate and humidity levels over 60% are common in the summer months – a damaging level for artwork.



12.

12: Conventional design for the MEP floor required a 6.2m overall depth, but by inverting the lower floor structure, a depth of only 4m was needed

Arup used computational fluid dynamics (CFD) to model the movement of air from the underfloor air delivery systems to the air grilles on the ceiling of the room, under which warm air tends to pool. Four computational models were analysed to ensure that the stratified level of warm air did not descend lower than 5m below the ceiling and risk damaging the exhibits.

Meanwhile, M+ uses daylight and occupancy sensors to provide light only when it is needed, while highly efficient and high-quality fittings allowed lighting energy use to be reduced by 23% by design. Daylight was prioritised over artificial light, both in order to reduce energy consumption and to provide an alternative lighting ambience in spaces for works of art to ensure they are not damaged by light.

Indeed, curators often prefer daylight to artificial light because it provides excellent colour, rendering a subtle dynamism. It also has health benefits for both visitors and staff. Throughout the project, daylight has been harnessed away from the hottest east and west facades to illuminate galleries where less sensitive work will be exhibited. Meanwhile, in the galleries that contain more sensitive work, blinds and effective orientation strategies have been used to completely shut out daylight.

The artificial lighting system is simple and minimal to the eye, working harmoniously with the raw interior finishes and emphasising the materials and bold structural elements. A systematic linear pattern was used to keep the ceiling appearance clean and provide the flexibility for adjustment as required in the galleries and exhibition spaces. The direction in which the lights are placed works in conjunction with the architectural design to subtly allow the light in from the exterior.

Sustainability opportunities

The focus of the sustainability design of the building was to enhance the museum's microclimate and reduce both energy demand and operating costs. Both passive and active strategies were used with the aim of minimising use of energy, materials, water and land, and maximising the use of ambient energy sources such as daylight, wind and solar.

Among the major challenges of designing a sustainable museum building in a subtropical climate is the energy consumption associated with cooling and humidity control. Museums need sophisticated environmental controls to ensure that both temperature and humidity are closely monitored and maintained at a steady level. In a subtropical climate like Hong Kong's, which experiences extreme heat and humidity during the summer months, this would tend to translate into much higher energy consumption than in other types of buildings.

Both the building occupants and the artwork on display at M+ have specific environmental requirements, including temperature, temperature distribution and humidity. One of the main concerns in a subtropical climate is solar heat gain, which will drive up cooling loads and the associated capacity and energy consumption of the cooling plant. By reducing glazed areas and locating the ones that were glazed away from the east and west façades – as well as providing shading for the tower with extensive overhangs – Arup was able to reduce annual solar heat gain in the office portion of the project by more than 64%.

Cooling loads are served from a district cooling system with open-loop seawater heat rejection. The district systems make use of diversity across the site, with the seawater heat rejection providing a lower average rejection temperature compared with the ambient air.

In the archival and gallery spaces, where close humidity control is needed – to avoid any development of mould, which can happen when relative humidity exceeds 60% – desiccant dehumidification systems are used. The reheat from these systems is in part supplied by solar thermal hot water panels and heat recovery chillers; solar energy accounts for almost 1% of total building energy by design.

13: The artificial lighting system is simple and minimal to the eye, working harmoniously with the raw interior finishes and emphasising the structural elements

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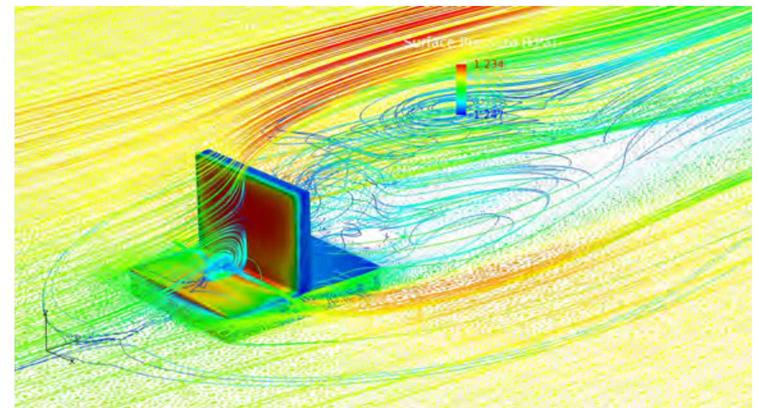


15.

14: The podium-level roof garden is planted with native species chosen to enhance biodiversity and provide habitats for insects and pollinators

15: Arup simulated the local wind speed using CFD that took into consideration the massing of buildings in the neighbourhood and the features of M+

Energy consumption, however, cannot be driven down to the lowest levels and still provide an excellent environment, and the air quality inside M+ had to be excellent. This was achieved using high-rated air filters and increased fresh air rates – with associated increased fan energy consumption – and as such, Hong Kong's indoor air quality standard of "good" has been achieved.

Toilets in the building are also flushed with seawater and sanitary fittings are low flow, saving more than 92% of potable water.

Throughout the whole development of the M+ building, the project team aimed to follow BEAM Plus standards – a comprehensive environmental assessment scheme widely adopted in Hong Kong and similar to BREEAM and LEED – at Gold or above ratings, and West Kowloon Cultural District sustainability key performance indicators as far as practicable for sustainable building design features.

Emphasis has been placed on integrated sustainable building design for the whole M+ development: integrating architectural, construction, mechanical, electrical and other technical disciplines throughout the design process, in order to minimise energy consumption and reduce greenhouse gas emissions.

Roof garden and landscaping

The landscape architecture design was carried out by Vogt Landscape Architects AG in collaboration with Herzog & de Meuron, with Arup responsible for executing the landscape design in Hong Kong.

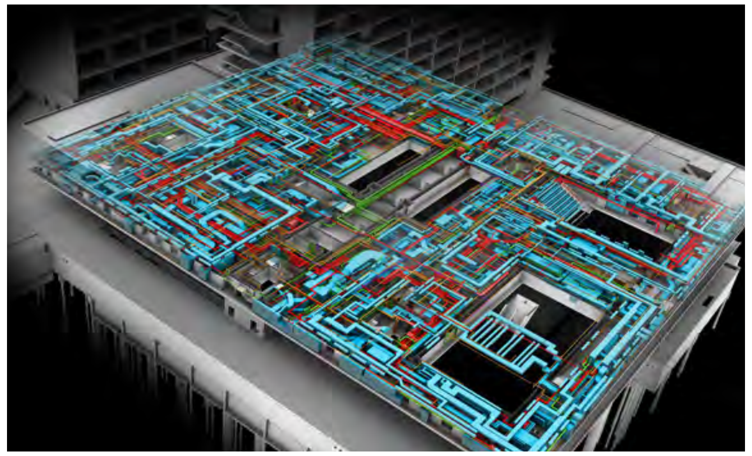
M+'s podium-level roof garden is open to the public and has been designed to be a comfortable environment all year round. Planting and shading have been used to reduce surface temperatures, while the roof garden's orientation has been designed to harness cool breezes from the harbour.

During the design, Arup simulated the local wind speed and solar radiation using CFD that took into consideration the massing of buildings in the neighbourhood and the specific features of the M+ building. As a result of the simulations, planting was concentrated towards the north-east of the garden, where it was hottest, and pedestrian walkways placed in the coolest areas.

An added benefit of planting, which covers over 50% of the entire space, was in creating both a thermal and acoustic buffer between the roof garden and the galleries below, lowering the need for artificial cooling and reducing the chances of visitors being disturbed by footfall above. Rainwater harvested from the roof is designed to provide over 10% of the water needed to irrigate the garden. The planting predominantly used species native to Hong Kong and was chosen to vary in height, to enhance biodiversity and provide habitats for insects and pollinators.

Pedestrian comfort was also paramount at the lower level, where direct sunshine in the Hong Kong summer can rapidly become unbearable. As such, the building was designed with a setback at the ground floor façade that allows the podium to provide shading to pedestrian routes and encourages a breeze to flow around the building.

The roof garden was only one element of the landscaping detailed design carried out by Arup as part of the project. Others included the landscaped area on the Avenue and the vertical



16.

16: BIM was used from initial design through to construction and facilities management

17: As one of the very first projects to be completed in the West Kowloon Cultural District, M+ has set the bar for sustainable design

green located in the Learning Hub courtyard within the building.

When the West Kowloon Cultural District is complete, M+ will be surrounded by a mixture of densely built cityscape and open, lush parkland. The landscaping of M+ sought to reflect that mix, as well as the juxtaposition of water and land, the topography of the peninsula, the heat and humidity of the climate and the skyline of the city of Hong Kong, already so iconic and recognisable.

17.

BIM

BIM was used from initial design through to construction, with the contractor using the federated clash-resolved model, and then by the facilities management team in charge of the completed building. It was invaluable in coordinating services and structure.

Arup's early concept for the podium design was to provide a dedicated space for MEP services and place them towards the edge of the building, to minimise the length of ductwork and allow easy transport of equipment for installation. But the MEP space was eventually modified extensively to incorporate a large number of escape corridors.

Using BIM, Arup was able to coordinate the space requirements across different disciplines, and the BIM model also helped ensure that the pile foundations would safely bypass the tunnels and existing utilities underneath.

Indeed, the client – a statutory body established by the Hong Kong Government – stipulated from the outset that BIM should be used and that the model should be expanded to eventually cover the entire West Kowloon Cultural District site. The ambition is to establish a large BIM facilities management model for the whole District.

As one of the very first projects to be completed in the District, M+ has set the bar for design, sustainability – and overcoming significant odds in terms of site constraints – for the rest of the area to follow.

Authors

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Project credits

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Local partnering architect TFP Farrells Limited
Engineering consultant (structural, geotechnical, civil, façade and building services engineering, environmental consulting, sustainability, landscape and lighting design, security and transportation consultancy) Arup:
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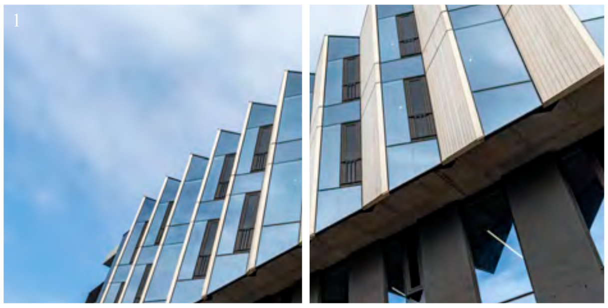

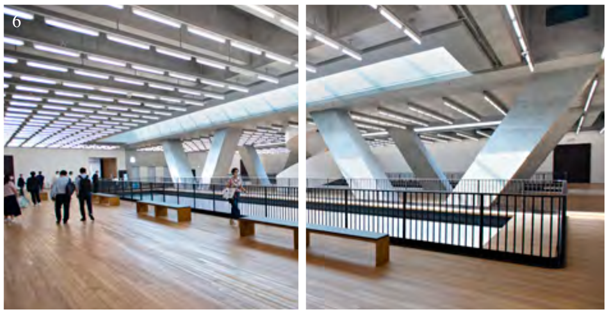

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