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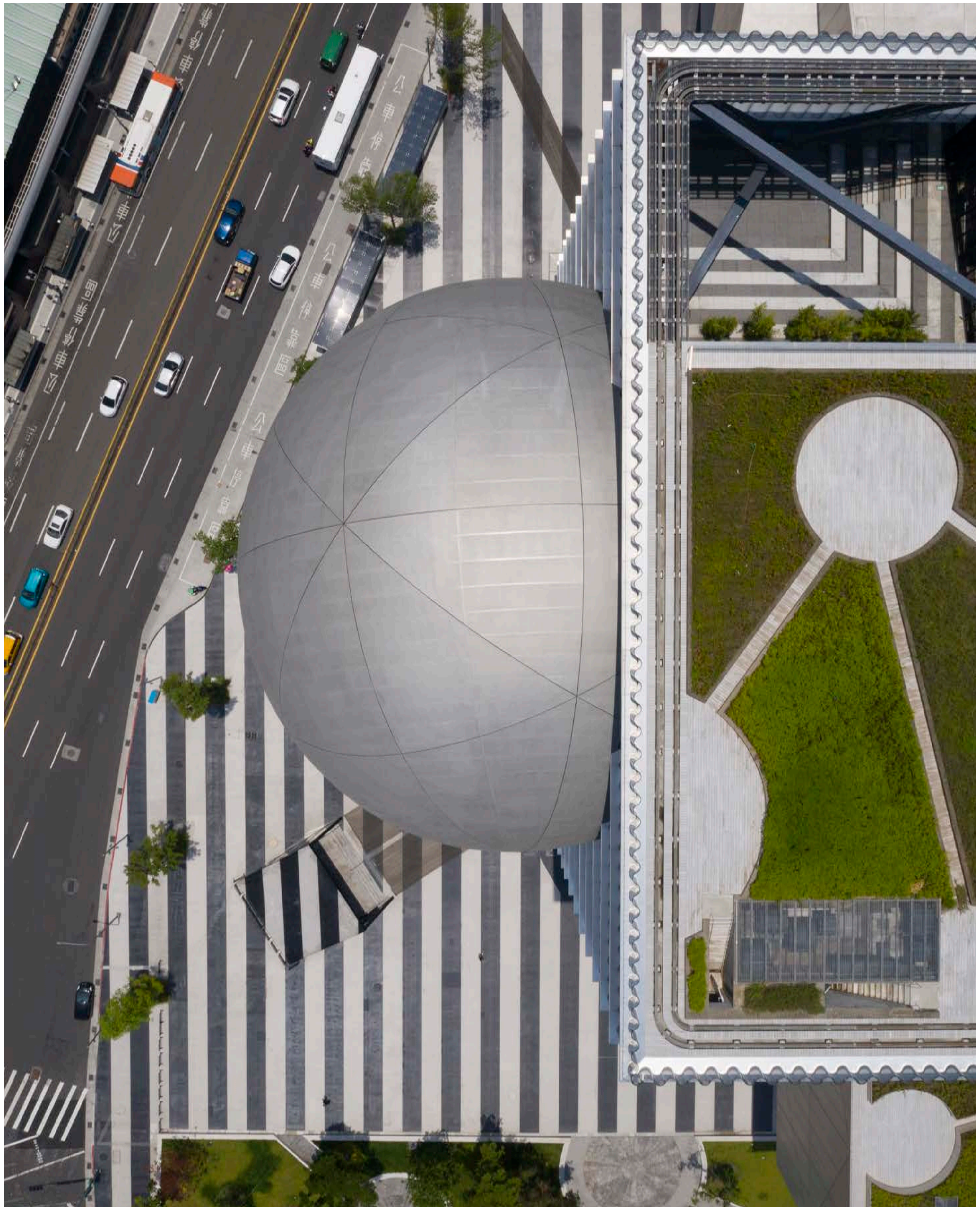
ARUP

The Arup Journal



Contents

Taipei Performing Arts Centre, Taipei City:
Shephotoerd Co. Photography (courtesy of OMA)

Timber regeneration

In the first mass-timber overbuild in Washington D.C., a low-carbon solution was combined with impressive aesthetics

Authors David Barber, Matt Larson, Lauren Wingo

As business centres and urban districts become denser, cities are looking at vertical expansion as a workable option, using overbuild construction for existing buildings. Located in the Navy Yard neighbourhood of Washington D.C., 80 M Street SE (80 M) is the first commercial office space in the US capital to incorporate a vertical mass timber extension. At 80 M the design team has created an innovative, sustainable and aesthetically pleasing solution to maximise the potential of the site and the original building, which was constructed two decades ago.

The design of the vertical extension, which adds an additional 9,300m^2 (100,000ft^2) floor space, was a collaboration by architects Hickok Cole with Arup. It adds two further floors to the existing seven-storey structure, as well as a penthouse level, along with 375m^2 (4,000 ft^2) of outdoor amenity space.

A number of tall timber buildings have been completed in Europe in recent years, including the 21-storey HAUT building in Amsterdam, where Arup was the multidisciplinary engineer for what is the Netherlands' tallest timber-hybrid residential building. However, high-rise mass timber projects are less prominent in the US. This is partly due to the building code requirements, with many US jurisdictions using versions of the International Building Code (IBC) where timber buildings are typically restricted to 26m (85ft), less than the height of 80 M.

Blue-sky thinking

Arup looked at this challenge by asking: what would it take to create the additional three levels at 80 M using mass timber? Together with Hickok Cole and the D.C. Department of Buildings, Arup's mass timber specialists worked to show that the proposal for the overbuild met current fire and life safety code requirements. They also ensured that the design aligned with the revised 2021 IBC, which allows mass timber buildings to go up to 12 storeys, facilitating this project being the first two-hour fire rated mass timber structure in the US.

The use of exposed timber was not only sustainable and aesthetically appealing; it also reduced costs and disruption. By using a more lightweight material than concrete or steel, it allowed for quicker construction and minimised any intervention to strengthen the existing structure. Furthermore, by minimising disruption to the lower floors, it enabled the occupants to remain in the building during the construction works. As a renewable material, timber also carries a significantly lower carbon footprint than conventional building materials such as steel and concrete.

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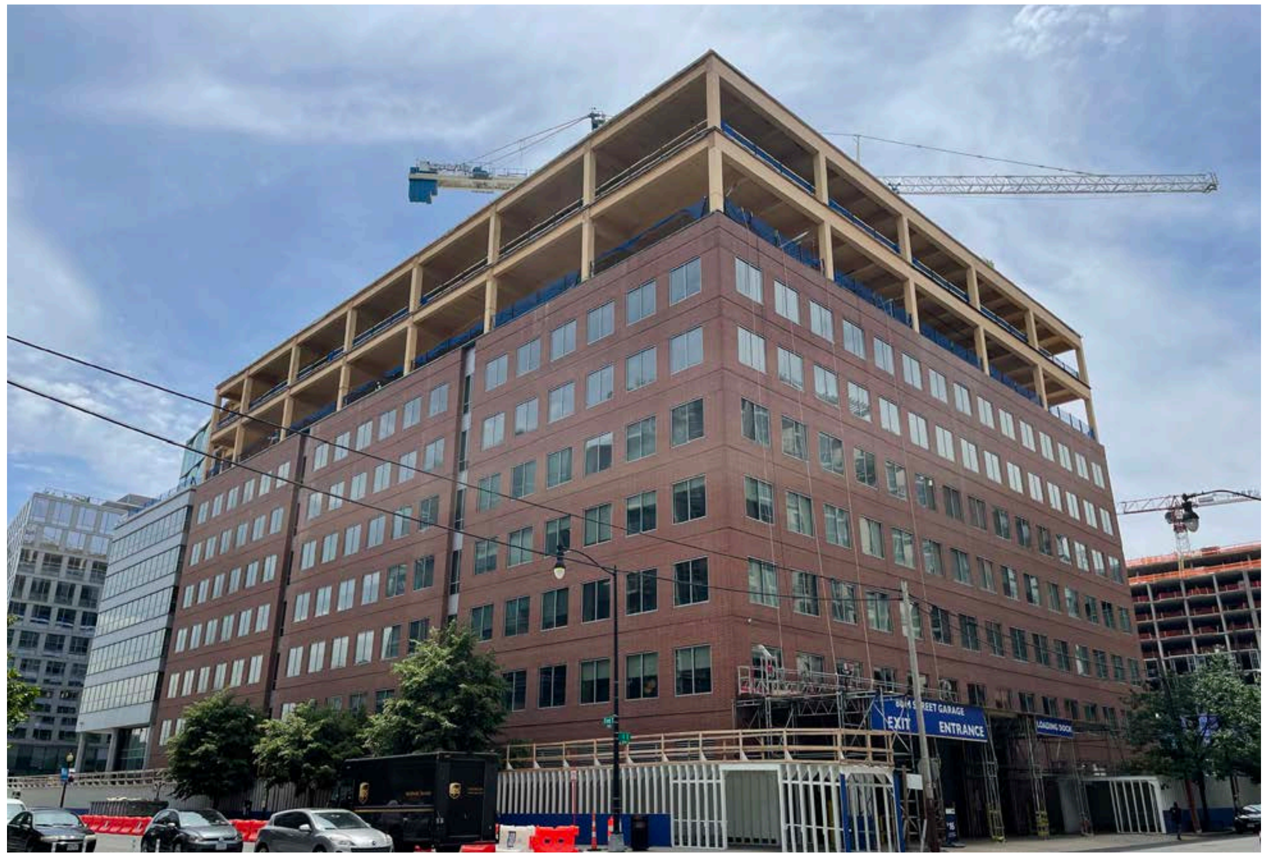
1: 80 M Street SE is the first commercial office space in Washington D.C. to incorporate a vertical mass timber extension

2: The use of timber for the vertical extension minimised disruption to the lower floors, enabling occupants to remain in the building during the construction

3 & 4: The typical 9.1m x 9.1m structural bay is supported on 475mm x 495mm glulam columns



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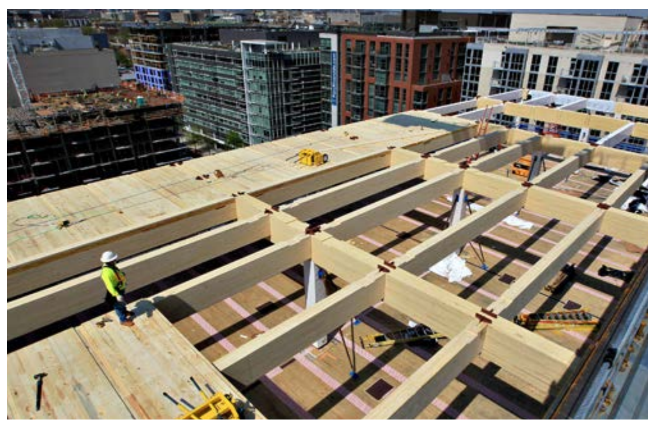
At its essence, 80 M was a developer-driven mass timber project. The developer's aim was to create something that would generate revenue, but without high capital costs. At present, projects using mass timber in the US are frequently sited at universities or owner-occupied headquarters willing to pay a premium to have an architecturally-driven space. Whereas aesthetics may play a key role in other projects, and played an important part in this one, cost was a driving factor in 80 M. With Arup's previous work with Hickok Cole on mass timber studies, the team was able to present an overbuild solution that was both visually and financially appealing to the client, Columbia Property Trust.



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The typical 9.1m x 9.1m (30ft x 30ft) structural bay is supported on 475mm x 495mm (18-3/4in x 19-1/2in) glued laminated timber (glulam) timber columns in each corner. The frame is made up of 955mm deep (37-5/8in) glulam primary beams at 9.1m centres, with 800mm deep (31-5/8in) secondary glulam beams at 3m (10ft) centres. The floor plate is a five-ply cross laminated timber (CLT) panel topped with a 75mm (3in) deep insitu concrete slab.

As demonstrated in 80 M, overbuilds can use carbon-friendly construction materials and techniques. By doing so, structures that might otherwise have been demolished or lain empty can be modernised using eco-friendly building standards. They can transform past structures and create additional income with new leasing spaces.

Arup advised on all engineering aspects of the project, including fire, mechanical and electrical engineering, public health and structural engineering. The firm also carried out the acoustic engineering for the redevelopment.

Energy savings

Thanks to Arup's building services design, energy savings of 27% were achieved for levels seven to ten. This was accomplished despite floors eight, nine and ten having a 90% window to wall ratio – over the 40% baseline. Arup carried out a feasibility study and cost benefit analysis on including a large solar photovoltaic (PV) array on the roof. The analysis found that with the savings garnered through local and federal tax incentives, the solar renewable energy credit, and utility cost savings, this brought the time horizon for return on investment down from 16 years to four years. The final electrical design incorporated a PV array that gives an annual solar production of around 85,000kWh.

During the redesign, Arup replaced natural gas as the heating source for the entire building, not just for the new floors. Based on previous usage, the power input used by the original building was sufficient and could cater to the newly added floors. This embraced the electrification of building systems without a significant increase in electrical power requirements. Arup achieved this by using a heat recovery type variable refrigerant flow system for the overbuild levels. This heating, ventilation and air conditioning system can recycle the heat generated from the building interior from the new levels all year round and transfer it to the exterior zones, where heat is lost to ambient through the façade in winter. Additional means of reducing the building's electrical load included using heat recovery ventilation technology in the ventilation system, and implementing demand control ventilation to reduce the outside air intake when the internal space is lightly occupied. The building is targeting LEED silver certification.

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5 & 6: The floor plate is a five-ply CLT panel topped by an in-situ concrete slab

7: The rooftop PV array produces around 85,000kWh of solar electricity annually

80 M is also seeking to meet WELL Certification v2 as third-party verification for health and wellness. This is an evidence-based, third-party verified certification for measuring, benchmarking and improving building performance to support human health and wellbeing. Using timber as part of the building's biophilic-inspired design forms part of the occupant's connection to nature. The reuse of the existing concrete building and improvements to its energy efficiency, coupled with the use of timber, means the redevelopment has brought about significant carbon reductions.

Successful risk mitigation

A major issue with the vertical extension was determining how to mitigate risks around the additional structural load and the perceived fire safety risk around the use of timber. The latter was the most challenging; Arup had to design new timber connections, as there were no existing connections in the market capable of achieving the project's fire rating and accommodating the structural loads.

To show the building would be fire safe, Arup carried out a comparative assessment with other buildings in the locality of the same height. The existing sprinkler system was improved by significantly enhancing its water supply and reliability. As the timber in the newly added floors was exposed, it created an additional fire load. Arup's task was to show how the building would react in the circumstance that there was a fire, and that the levels of damage would be comparative to a building constructed

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8: Testing was carried out as part of the process of demonstrating to the local authorities the fire safety resilience of the new overbuild structure

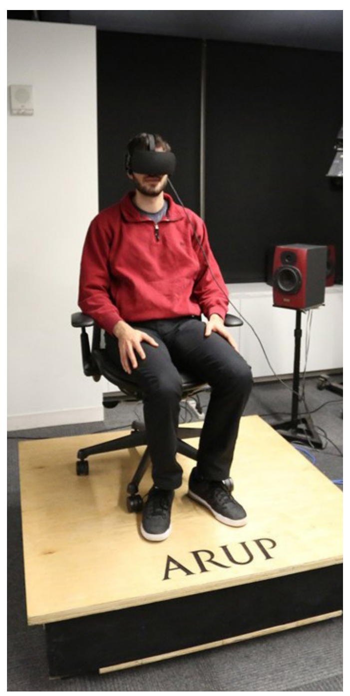
9: Arup developed new concepts for 80 M's two-hour rated exposed timber connections

using more traditional steel or concrete. The fire department were also able to access the building on four sides, allowing for external firefighting. These combined approaches for the design provided an alternative compliance path, demonstrating that the design met the intent of the code. The team worked closely with the D.C. authorities to achieve approvals for a building design which was, at the time, beyond the code requirements.

Due to the lack of fire-tested connections on the market, Arup's structural and fire engineers developed new concepts for 80 M's two-hour rated exposed timber connections. These connection concepts were further designed and tested by Katerra, the timber design-assist partner, with help from the Arup team. The unique beam-to-column connection design, using an innovative interstitial steel bracket, makes the building more efficient and fire safe. The design was groundbreaking in that it met the structural and fire safety requirements, was easy to assemble, and the exposed timber structure provides an aesthetically pleasing and sustainable design.

The budget constraints provided their own challenges. As Arup had expert knowledge of mass timber, the team was able to reduce costs by simplifying the design and working with the construction partners on the timber procurement process. While simplifying the structure as much as possible, using mass timber still has its issues – particularly because it remains an emerging industry in the US. The team was aware that it had to be conscious of the acoustics and the vibration of the building. While this is not a life safety issue, it is a factor that is key in how the occupants experience the building.

The challenge was to turn the concrete office building from the 2000s into a high-end space, ensuring the occupants would not perceive any noticeable difference between the existing floors and the new mass timber construction. With no clear industry guidance on vibration limits in the US at the time of construction, Arup carried out a detailed vibration analysis, including a demonstration within the building. A research group from the firm's New York office brought a 2m x 2m (6.6ft x 6.6ft) vibration platform to the building, so that the client could experience a simulation of the space's vibrations to help them understand what it would be like. Arup ensured that from the criteria set, the experience would be the same as for occupants in a steel-framed office building.



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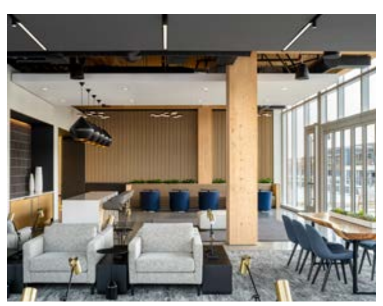

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10: A 2m x 2m vibration platform was used to simulate the typical floor vibration, giving the client an understanding of the 'feel' of the floor

11: The beam-to-column connection design, using an innovative interstitial steel layer, makes the structure more efficient and fire safe

12: The use of exposed timber is both aesthetically appealing and sustainable

For construction projects using concrete, the best practice for separating acoustic spaces is well established, but that is not the case when using mass timber. When looking at the design of the floor structure, Arup considered the vibration, acoustics and fire safety together, designing a bespoke solution for the mass timber to meet those combined requirements.

Pushing boundaries

Arup carried out analysis to ensure the new structure – a design with a low-carbon solution – met the client's cost expectations. By adding to the existing building, this was the most effective embodied carbon technique for this project. In other scenarios, the original structure might have been demolished, but Arup's team managed to reinvigorate an existing building. The use of mass timber as a construction material is a very effective way of accelerating decarbonisation, as the associated carbon footprint is much lower compared to traditional construction materials. Additionally, the timber acts as a carbon storage medium for decades to come. This will hopefully set a precedent for reusing as many existing buildings as possible and incorporating low-carbon materials when adding density.

Arup delivered the design for the first completed high-rise mass timber overbuild, including a two-hour fire rated structure with exposed mass timber, in the US. Not only did the firm manage the technical challenges, but it also advised on efficient existing structure strengthening; mass timber procurement; and testing and building in-use vibration. This resulted in the mass timber pricing being equivalent to the price of steel.

This innovative approach required careful consideration. There is a lack of familiarity with using mass timber in the US, which creates a perception of construction risks. At the time of construction, the building code did not allow timber to be built to this height. Thus, Arup was required to carry out research to demonstrate to the local authorities that the building would be safe, from a structural and fire engineering perspective.

13.

13: The overbuild adds $375m^2$ of outdoor amenity space to the development

Helping shape the policies of the future

Arup engaged early on in this project with different authorities and agencies in D.C.. Currently in the US, law-makers and developers are focused on building operating energy and have only recently begun to focus on operational carbon and embodied carbon. The policies in D.C. in particular are focused on energy use. Now, policy-makers are beginning to think about embodied carbon and the impact of materials. 80 M demonstrates that mass timber is a viable solution, with a design that uses low-carbon impact materials and is lightweight, to minimise additional load to lower storeys.

Authors

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Project credits

Client Columbia Property Trust

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Timber manufacturer and installer Katerra

Fire, mechanical, electrical and public health engineering, structural engineering, acoustic consulting Arup:
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1.

A holistic approach to risk assessment

A groundbreaking multi-hazard climate and disaster risk assessment is helping authorities in Tonga to develop long-term responses to climate change

Authors Karen Barns, Tim Mote, Ed Rowe

1: The majority of Nuku‘alofa, the capital of Tonga, rises just 2m above sea level and is highly vulnerable to pluvial flooding

On the evening of 15 January 2022, the underwater volcano Hunga Tonga-Hunga Ha‘apai in the South Pacific erupted with a force estimated by NASA to be hundreds of times more powerful than an atomic bomb. The blast sent shockwaves and tsunamis across the region, and within a few hours the Polynesian archipelago of Tonga was blanketed by a plume of ash, steam and gas.

One uninhabited atoll was completely obliterated and entire towns on the other islands, including the capital city Nuku‘alofa on the main island of Tongatapu (65km south of the volcano), were inundated by waves. This resulted in the destruction of the only fibre-optic cable connection to the rest of the world. As Tongan officials, volunteers and communities scrambled to cope with the impact, disaster managers and government decision-makers moved swiftly to assess the scope and scale of humanitarian need, and the damage to housing, workplaces and infrastructure.

The repercussions of catastrophic events of this magnitude are complex to comprehend, but officials were fortunate on this occasion to be able to draw on a comprehensive, multi-hazard disaster risk assessment of Tongatapu, completed just seven months before the eruption took place.

Commissioned by the Government of Tonga and the Asian Development Bank (ADB) and carried out by Arup, the first-of-its-kind study and associated geo-referenced database was unrivalled in its scope, covering building, water, energy and road assets in the island’s built environment. It included 50,000 buildings and infrastructure assets, and a wide range of hazards such as flooding, coastal inundation, tropical cyclones, seismic and tsunami hazards and the effects of climate change. Direct financial losses associated with each hazard scenario in the database, as well as average annualised losses by hazard and sector, were also quantified to help inform authorities’ crucial decisions and planning, both for today and for the future.

Natural disasters

Tonga is no stranger to natural disasters; the kingdom ranks third out of 181 countries in the World Risk Index 2021, after Vanuatu and the Solomon Islands. The majority of Nuku‘alofa rises just 2m above sea level and is highly vulnerable to pluvial (surface) flooding caused by heavy rainfall, and to coastal flooding from extreme sea level rise, cyclone-induced storm surge and tsunami inundation. Some agricultural, ecologically sensitive and other marginal areas are at elevations below high tide, and experience frequent inundation. Exposure is such that around 20,000 people are regularly affected by flooding on the island, a figure that is expected to increase in the future, as a result of climate change-induced sea level rise.

Keen to get a better understanding of climate and disaster risks to help inform its future planning and investment decisions, in 2020 the Government of Tonga and ADB commissioned Arup to undertake a study. The assessment was carried out by a global team of 20 Arup specialists who also collaborated with New Zealand-based firm eCoast Marine Consulting, engineering services firm Kramer Ausenco, ADB and the Government of Tonga.

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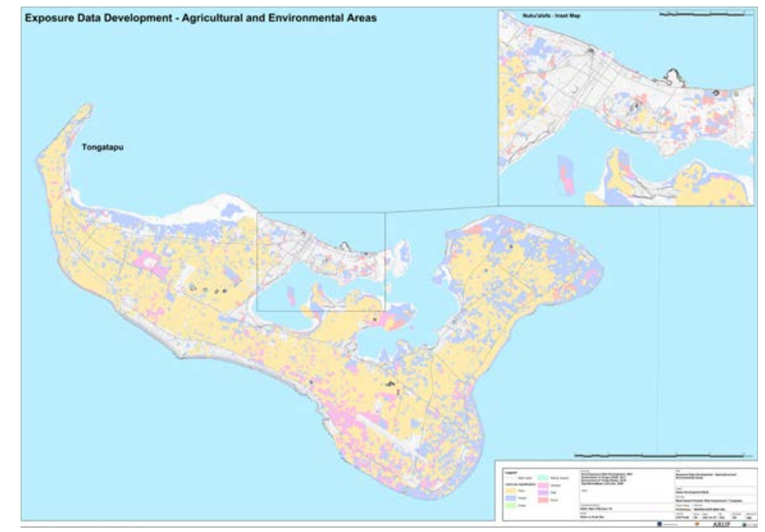
2: The geo-referenced database Arup created covers building, water, energy and road assets

3: The analysis included 200km^2 of agricultural and environmental areas on Tongatapu



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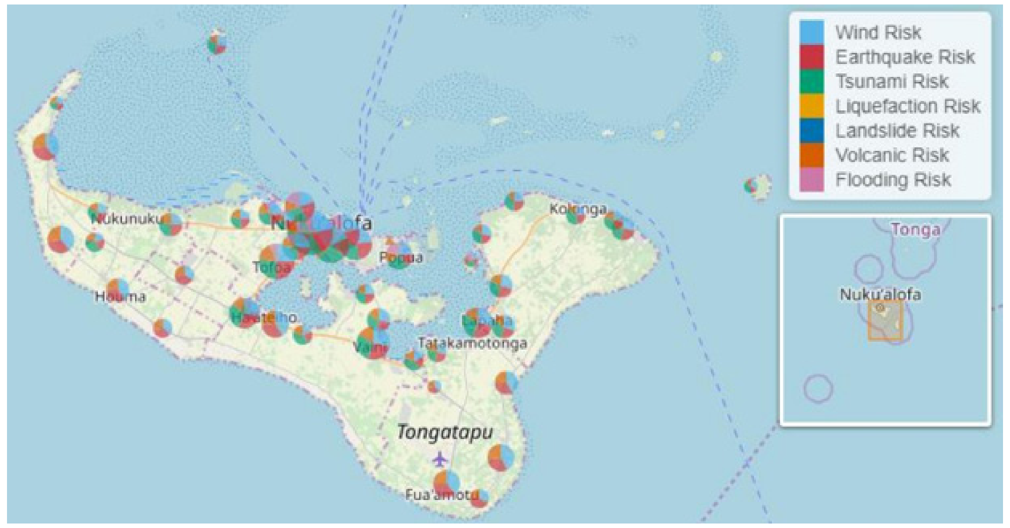
ADB and the World Bank have supported infrastructure projects in Tonga for many years, but risk assessments were typically carried out on a project-by-project basis and focused on a single asset or a particular hazard, such as flooding.

Investments in resilience measures worldwide are typically decided based on estimates of future losses, but until losses are experienced in reality, investors can be hesitant to supply funding. Arup worked closely with ADB and the government on an innovative plan aimed at circumventing this issue by taking a holistic approach, providing accurate and actionable data covering the full range of assets and hazards to ensure confidence in future investment decisions.

The project analysed in excess of 50,000 buildings, power and water assets, more than 1,000km of roads, and over 200km^2 of agricultural and environmental areas on Tongatapu to identify risks. Assets were plotted against 220 different



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4: Assets were plotted against 220 different hazard scenarios

5: The project analysed more than 50,000 buildings and power and water assets to identify risks

hazard scenarios, covering earthquakes, windstorms, tsunamis, rainfall and coastal flooding, to model the impact both with and without climate change. Climate and disaster risks to assets and population across the atoll were communicated in terms of direct financial loss, i.e. the cost to repair or replace damaged assets. This normalised approach makes it possible to directly compare the economic impact of different natural hazards and scenarios; for example, losses quantified under today's climate for tropical cyclone wind hazard can be compared with losses estimated for a future climate-influenced scenario for rainfall flooding.

Data is critical when it comes to risk assessment and the study exploited a range of international, regional and national datasets. Detailed records were available for some hazards and assets, but others were less robust and rigorous, putting an emphasis on field survey work and modelling to ensure a consistent approach.

Field surveys and machine learning

In the midst of the Covid-19 pandemic and the associated restrictions on travel, Arup remotely trained local engineers and surveyors to carry out field surveys. At the start of each phase of the project, a series of interactive training workshops were held by videoconference, instructing the recruits how to use tablet computers pre-loaded with the survey software and forms.

A subset of around 2,000 buildings and structures on the island had previously been visited and assessed, and a further 8,000 were surveyed by the Arup team. Limitations on available time and resources informed the decision to use machine learning to determine values of assets that were not visited. Notably, 50% of buildings with a plan area greater than 20m^2 had no attributes. So, a probabilistic method was developed to statistically assign and populate missing data, using estimated values through an iterative machine learning process.

Various validation exercises were applied to data sources during the project to ensure consistency, with a particular focus on buildings and roads. For example, street view software was used to validate data received from the Pacific Catastrophe Risk Assessment and Financing Initiative, and to quality-check data received from in-country surveys.

Key results

Arup's study has comprehensively quantified the potential impacts of the island's vulnerability to hazards, particularly by considering the influence of climate change for the first time. Pluvial flooding was found to be the most significant driver of risk for frequent events. However, with consideration of the rarer events, seismic hazard poses greater risk. Average annual losses for pluvial flooding were US$130m, followed by seismic at US$58m, wind at US$4m, and then coastal inundation at US$3m. Discrete rural areas and parts of the capital were found to be more susceptible to pluvial flooding, in terms of the percentage of land flooded.

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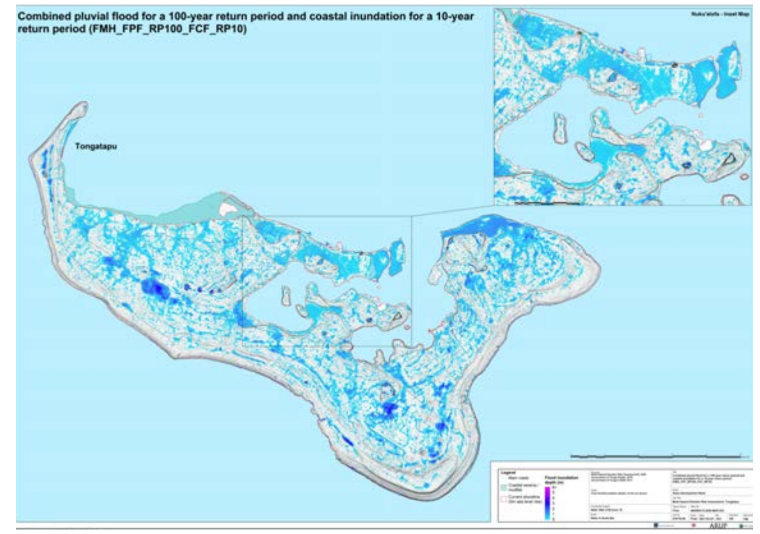

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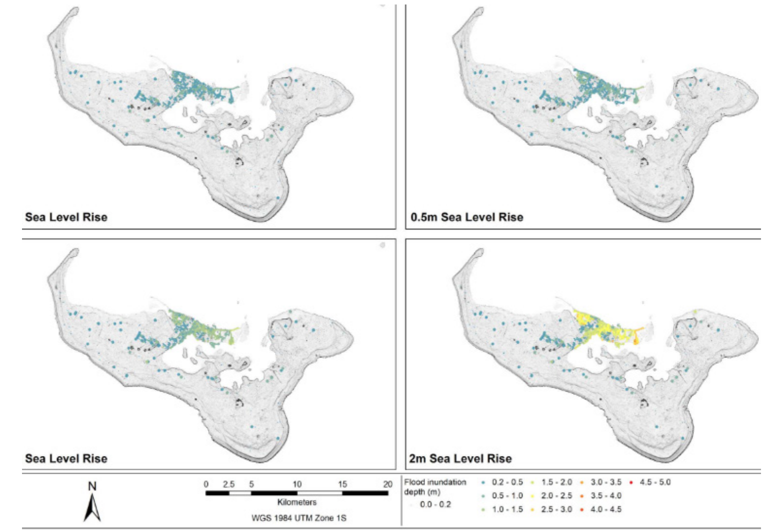

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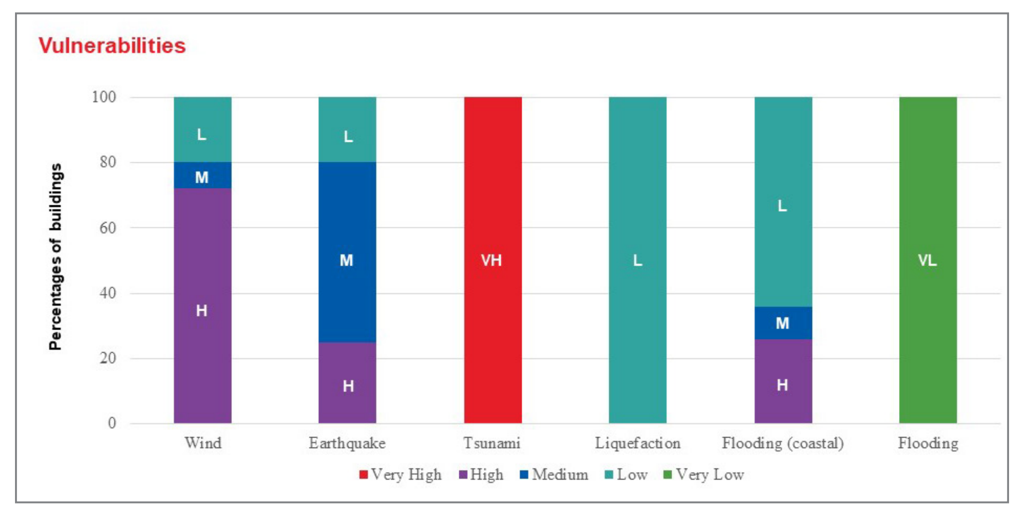
Arup's research revealed that rarer hazard events with longer return periods saw significantly larger losses than shorter, more frequent hazard events for wind and seismic activity. However, this was far less significant for pluvial flood, coastal inundation and tsunami hazards. For example, a 200-year return period seismic event resulted in a relative loss of 18.7% (financial loss as a percentage of the total asset value), which was significantly higher than the relative loss of 0.8% for a 10-year return period. A 200-year return period pluvial flood event resulted in a relative loss of 7.1%, which was only slightly higher than the relative loss of 4.0% for the 10-year return period event.

Sea levels have risen 6.4mm per year on average around Tonga in the past decade – well above the global average – and Arup's team modelled the risk of inundation for future rises of 0.5m, 1m and 2m. Increased intensity of rainfall was also considered for future climate scenarios. Permanent losses from sea level rise were significant compared with all other return period scenarios, ranging from 6% of the total asset value in a 0.5m scenario, to up to 50% in a 2m scenario. Arup found that a 1m scenario would see tidal inundation of 25% of buildings, 11% of roads, 16% of water and 29% of power infrastructure. If considered permanent losses, this would be equivalent to 10 times the losses incurred by Tropical Cyclone Gita in 2018, the most intense tropical cyclone to hit Tonga since reliable records began. However, the report found that increased urbanisation and/or new flood protection infrastructure would have a major impact on expected losses, before any of these scenarios arrive.

Informing investment decisions

The research highlights the importance of differentiating between the probabilistic occurrence of a single hazard event, and gradual impacts from projected sea level rise. For example, the predicted 19% loss of total asset value under a 200-year seismic scenario is similar to the 25% permanent losses associated with a future scenario with 1m of sea level rise. Tonga's government can use



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6: Pluvial flooding was found to be the most significant driver of risk for frequent events but, with consideration of the rarer events, seismic hazard poses a greater risk

7: Arup modelled the risk of inundation for different future sea level rises

8: The study comprehensively quantified the potential impacts of the island's vulnerability to hazards, including the influence of climate change for the first time

9.

9: Sea levels have risen 6.4mm per year on average around Tonga in the past decade – well above the global average

this information to inform investment decisions, such as upgrading buildings to resist earthquakes, which may reduce losses associated with hazard events under today's climate, or instead invest in coastal defences and management solutions over time, to address sea level inundation under a future scenario.

A number of tsunami scenarios were modelled, considering different magnitudes of earthquake source and various maximum wave amplitudes. The scenario with the highest maximum amplitude – a 9.0 magnitude earthquake with a 6.2m offshore wave amplitude – reported losses equivalent to 10% of the total asset value assessed across Tongatapu. These were concentrated in Nukuʻalofa and towns surrounding the lagoon.

The many insights revealed in Arup's assessment will help ADB and the Government of Tonga take a more upstream perspective on climate change, based around resilient development and adaptation. This should result in the gradual development of safer areas and investments in new assets outside the highest-risk areas that are also resilient to natural hazards.

Some findings have already fed into the disaster and climate risk assessment for a proposed major bridge crossing Tongatapu's central lagoon. Data on tsunami wave loading and seismic activity fed into a structural assessment of the proposed bridge design, and the anticipated impacts of climate change on local communities and road infrastructure supported due diligence on the investment in the project. The research was also presented at the United Nations Climate Change Conference (COP26), held in Glasgow in November 2021.

Immediate impact

The devastation wrought on Tongatapu by the volcanic eruption gave unexpected relevance to Arup's work, and the Government of Tonga was quick to share the data with researchers and bilateral, regional and multilateral organisations keen to help address the impacts.

Volcanologists at the University of Canterbury and the National Institute of Water and Atmospheric Research in New Zealand produced estimates of the thickness of ashfall deposits for the entire island, including detailed maps for the energy, water, road and agricultural sectors, using data from the initial assessment. This covered preliminary predictions of damage and an advisory to the government on clean-up operations. The World Bank also produced a Global Rapid Post-Disaster Damage Estimation, providing specific information on direct disaster losses in the weeks following the eruption.

It's not often that research has such an immediate impact, helping a nation to navigate its way out of catastrophe, and Arup is honoured to have been part of the process. The firm believes the same risk assessment model can be rolled out across other nations, and similar projects are already being considered for Timor-Leste and the Cook Islands.

Authors

Karen Barns is a senior risk and resilience consultant in Arup's risk and resilience group in the San Francisco office.

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Project credits

Clients Government of Tonga, Asian Development Bank

Collaborators eCoast Marine Consulting, Kramer Ausenco

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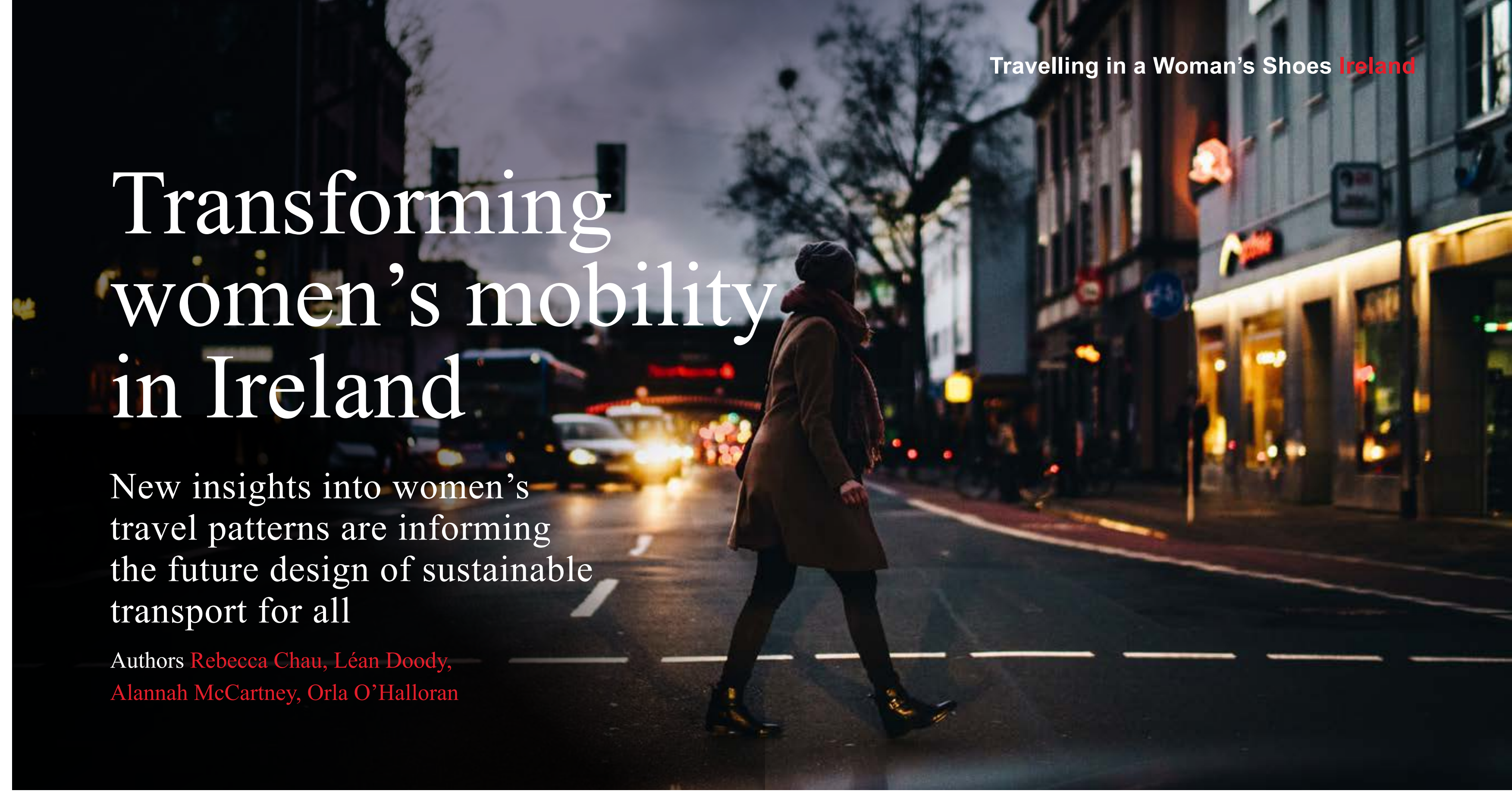

Transforming women's mobility in Ireland

New insights into women's travel patterns are informing the future design of sustainable transport for all

Authors Rebecca Chau, Léan Doody, Alannah McCartney, Orla O'Halloran

1: The research found that 55% of women avoid public transport after dark

Transport is often seen as gender-neutral, providing benefit to all equally. However, growing international research highlights that this is not the case. Today, women often have different travel needs from men, including more complex trips, heightened safety concerns and additional caring responsibilities. Yet, historically, transport has not been designed with those differing requirements in mind.

Transport Infrastructure Ireland (TII) is the agency delivering transport infrastructure and operating public transport systems in Ireland. It wanted to understand the different travel needs of women and the reasons why they rely more heavily on cars, in a bid to influence future transport policy and encourage a shift to more sustainable modes of travel.

Arup has a long-standing relationship with TII, working in partnership on a wide range of projects including tolling strategy, network operations, governance, standards, sustainability planning, decarbonisation, active travel, and infrastructure design and planning services. TII engaged the firm to carry out the first-ever study to investigate women's travel needs and behaviours in Ireland. Arup worked closely with TII, gender equality specialist Kelly Saunders and insights agency Spark, to develop a research methodology giving rich insights into women's travel experiences.

The 'Travelling in a Woman's Shoes' study highlighted the lived experiences of women in Ireland through data and real-life stories, offering a fresh perspective on discussions about equal access to public transport. Bucking global trends, women in Ireland rely more heavily on car travel, with significant caregiving responsibilities, safety issues and lack of equality of access to quality services acting as drivers of car dependency. The research found that 55% of women avoid public transport after dark (compared with 35% of men). One bad experience can fundamentally alter a woman's perception of different transport options. This can be something that happened to them or a friend, or an incident they see in the news.

The report identified opportunities for improving women's travel experiences, enabling greater use of public transport and contributing to the overall aim of decarbonising Irish transport. This study is a step towards creating a more equitable travel experience and is informing discussions about future policy and infrastructure design, to encourage more sustainable mobility for all.

Context

Equality for girls and women depends on mobility, as this gives access to quality education, higher-paying jobs, social and political life, health services and leisure. Poor access to transport significantly hinders their participation in the labour market and so having transport equality can reduce gender inequalities, including helping to close the gender pay gap.

Unsafe or traumatic travel experiences can lead to absenteeism and decreased productivity among women. When they feel empowered and safe to walk, cycle, use public transport and car-share, this reduces car dependence, accelerating the transition to net zero. A safer, more equitable transport system also improves


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transport networks for all users. Facilities that are accessible for prams are accessible for wheelchairs too, and child-friendly design helps all parents and carers.

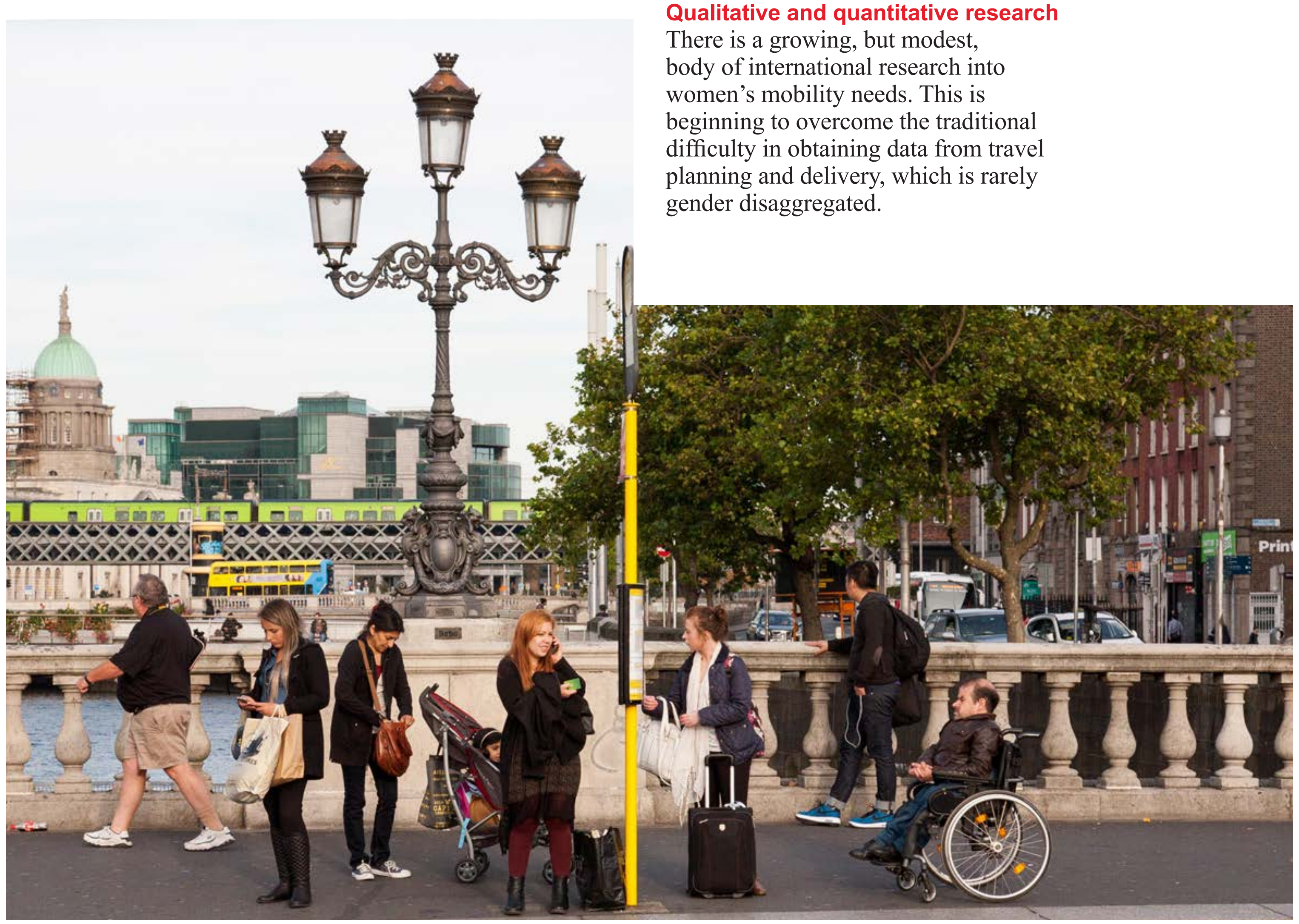
The climate crisis poses an urgent need for a fundamental reimagining of how we live and how we travel. This is a particular challenge in Ireland because of the country's historical car dependency. The decarbonisation of travel is seen as crucial in reducing Irish greenhouse gas emissions and particulate pollution. As transport networks move towards integrating shared mobility schemes and encouraging the use of public transport over the private car, the mobility needs and patterns of both men and women must be acknowledged equally to ensure a successful transition.

Qualitative and quantitative research

There is a growing, but modest, body of international research into women's mobility needs. This is beginning to overcome the traditional difficulty in obtaining data from travel planning and delivery, which is rarely gender disaggregated.

2: When people feel safe to walk or cycle, it reduces car dependence and helps to accelerate the transition to net zero

3: Public transport that is accessible for prams is accessible for wheelchairs too, and helps parents and carers alike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4: Public transport fare structures often disadvantage those who make many consecutive journeys, such as women with childcare and caring responsibilities

5: Researchers accompanied study participants on journeys to learn how they interact with existing transport services

6: Among women with children, 84% consider themselves to have the sole or lion's share of responsibility for childcare

7: Dropping off and collecting children or family members is women's primary reason for travel, while for men it is work

Arup's in-house design, research and innovation studio drew on the firm's experience in human-centred design and qualitative and quantitative research, to craft a bespoke research approach. The process began with a literature review of existing international research, including discussions with Technological University Dublin. This review looked at available data and studies from Ireland, continental Europe, Australia, the US and South America that spanned academic work, transport agency studies and research by respected agencies.

The next step was an ethnographic study. This consisted of face-to-face interviews with 21 women in Dublin and Cork. Participants represented diverse demographic and geographic backgrounds and varied travel behaviours. Through individual two-hour interviews, the participants shared their personal stories, and researchers also accompanied them on journeys to learn how they interact with existing transport services. The observations generated rich, unexpected insights into the barriers and motivations informing mobility choice in Ireland for women.

Finally, a quantitative survey, co-designed and managed by Spark, was carried out with 1,000 male and female respondents to understand their differing experiences and to validate quantitively the findings from the interviews across the population. The survey affirmed the findings and identified correlations between factors such as gender, age, location, disability and income, and different travel behaviours and motivations.

Key findings

Consistent with global trends, the research found that in Ireland, women are responsible for a large portion of society's caregiving, childcare and household responsibilities; 30% of women surveyed provide primary care to another adult, either in a professional or a personal setting. Among women with children, 84% consider themselves to have the sole or lion's share of responsibility for childcare, compared with 48% of men. These caring responsibilities require travelling with children and the elderly, and frequently entail carrying out several additional household-related journeys on top of their own work commute. Dropping off and collecting children or family members is women's primary reason for travel, while men's is work. Public transport fare structures often give preference to the traditional commuter and disadvantage those making many consecutive journeys. As women are disproportionately responsible for household and care responsibilities, they

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make a greater number of these journeys and therefore tend to pay higher prices.

Women are more likely to work in roles that rely on shift work or to engage in part-time work. Public transport is not always available or optimised during off-peak times. The lack of safe and accessible transport options can hinder women's access to employment opportunities and, as a result, they are more likely to work in lower-paid jobs that are close to their homes, or even leave the workforce altogether.

The main concerns with public transport include the lack of feeling of safety, indirect routes and long wait times, lack of reliability, and lack of support for care-giving. Safety was their top travel concern; 55% avoid public transport at night and 34% have avoided travelling because of feelings of insecurity (compared with 24% of men).

Even for many women who do use public transport to commute, the view is that having a car still remains a necessity for chores and unexpected events, such as collecting an unwell child from school; 79% of women consider the car to be a necessity, and outside of Dublin this figure rises to 95%.

Stories from the field

Embedded throughout the study's findings are the stories of the research participants (who have been given pseudonyms). Sharing their real-life experiences, the study explores the appeal of the car and compares it with cycling, walking and public transport to highlight how these modes could be improved to increase their competitiveness and how family, safety and financial position shape travel choices.

Five women's stories were focused on in detail, each representing different life stages: Alice, a 19-year-old student and part-time worker; Amanda, a 26-year-old working single mum; Josie, a 48-year-old stay-at-home mum; Karen, a married 45-year-old balancing her high-powered career with four young kids; and Gillian, a 70-year-old who helps take care of her grandkids. Each story relates the real experience of one of those interviewed. The stories showcase a moment in a woman's life and her perceptions of transport modes, family

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roles and responsibilities, safe and unsafe experiences, and privilege and disadvantage as they influence women and travel.

When 19-year-old Alice entered university, she moved into the city for the first time. Balancing her studies, her part-time work and maintaining a relationship keeps her busy. The bus is her main way of getting to university, to work or to see friends, and she aspires to have a car in the future. At times she finds it a scary place, especially given recent news stories on violent crime. Her group of friends have developed a number of tactics to help them feel safe on a night out – including wearing flat shoes in case they have to run, and staying in groups. These are tactics which many women carry with them as they get older, and they pass on their tips and advice to their own daughters.

8: The main concerns with public transport include the lack of a feeling of safety, indirect routes and long wait times, lack of reliability, and lack of support for care-giving

9: The study explores the appeal of the car and compares it with cycling, walking and public transport

10: The report includes a focus on five women's stories in detail, each representing different life stages

11: The findings of the study will help to shape all future TII infrastructure projects

11.

Design challenges and next steps

These findings and stories were derived from a rich body of qualitative and quantitative research that drew together both the soft and hard evidence to make a case for changing the way transport systems are designed. The richness and robustness of the mixed-method approach informed nuanced policy recommendations. This project presents a model for equitable and inclusive city-making, allowing insight to be gathered to address sustainable behaviour change and the climate emergency.

The study concludes by looking at how the five design challenges listed below could be tackled using lessons gleaned from the research, and highlights some global case studies that address these issues:

- *How can sustainable transport modes compete with the car?*
- *How can transport be and feel safe for women?*
- *How can an understanding of the family unit influence sustainable mobility choices?*
- *How can transport consider the diverse needs and contexts of all women?*
- *How can we accelerate sustainable behavioural change?*

Arup's local and global knowledge of the transport sector enabled the firm to interpret the findings and support TII to identify and influence realistic policy and design solutions. On publication, the study was extensively covered in the Irish media, stimulating a national conversation about the unmet mobility needs of women.

The findings will help shape all future TII infrastructure projects, including the proposed light rail system in Cork city, and the MetroLink in Dublin. TII has integrated gender assessment into national policy through its publication 'Applying a Gender Lens to TII Public Transport Projects'.

The study findings were presented by TII and Arup to the National Transport Authority and senior leadership at the Department of Transport (helping to inform national policy-making), and discussed with organisations such as the European Investment Bank, the World Bank and the Organisation for Economic Co-operation and Development.

The findings were also presented at the Oireachtas joint parliamentary committee on transport and communications in March 2022, and included as a case study in the National Sustainable Mobility Policy which was published in April 2022.

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Project credits

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11: TII

1.

A transformable theatre with unique performance spaces

This innovative new performance venue is a spectacular landmark in the heart of Taipei

Authors Jonathan Griffiths, Gigi Kam, Tony Lam, Rory McGowan, Chas Pope, Yuanyuan Song

When visitors arrive in Taipei's lively and diverse district of Shilin, their eyes are drawn to the unique form of the Taipei Performing Arts Centre (TPAC). Opened in August 2022, the building is a cube enclosed in corrugated glass and punctured by aluminium-clad boxes and spheres. It is both industrial and futuristic, but unmistakably dramatic, and its unique configuration is designed to inspire artists and directors to devise new forms of performance.

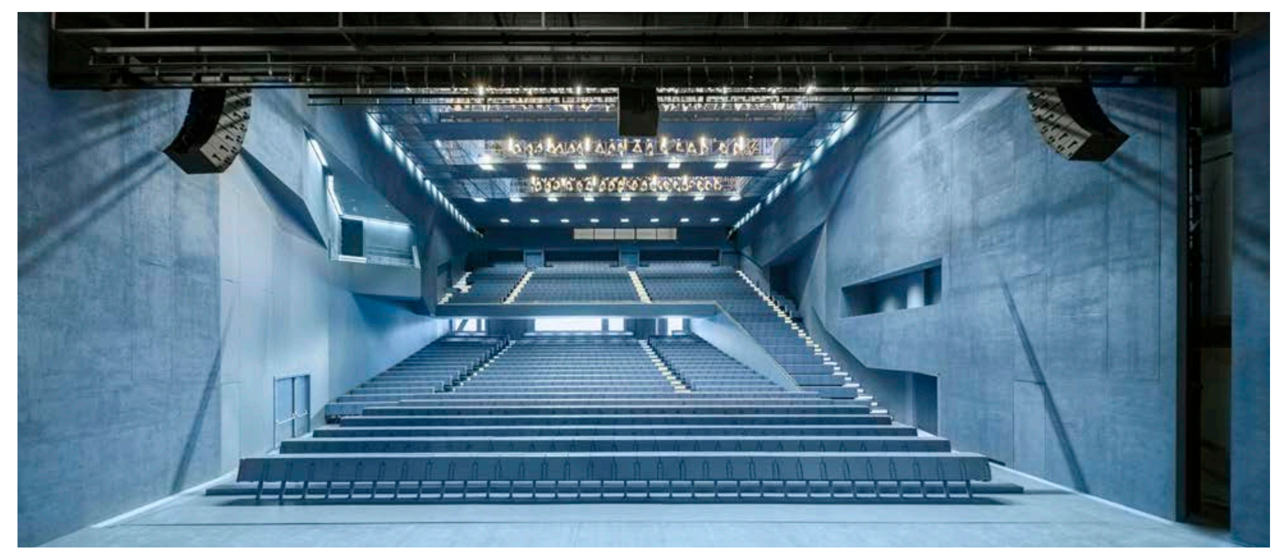
Competition

Taipei City Government's Department of Cultural Affairs launched an open design competition for a new performing arts centre in 2008, identifying a need to supplement the city's existing 30-year-old facilities to satisfy the demands of its contemporary arts scene and advance itself as an international arts capital. TPAC is designed to accommodate all genres of performing arts and aims to strengthen the Asian network of cultural facilities, enhancing the regional market for global touring productions.

The 59,000m^2 building incorporates the 1,500-seat Grand Theatre, designed to stage many different styles of performing arts, while two 800-seat theatres – the Globe Playhouse and the Blue Box Multiform Theatre – house repertory productions. For the two-stage open competition, OMA began to develop a unique architectural concept from its Beijing and Rotterdam offices, choosing to combine and consolidate elements of the three performance spaces. They looked to raise the auditoria, freeing up space at ground floor level, to

1: TPAC has become a unique landmark in the Shilin district of Taipei

2: The Grand Theatre, the largest of the three auditoriums, seats 1,500 people



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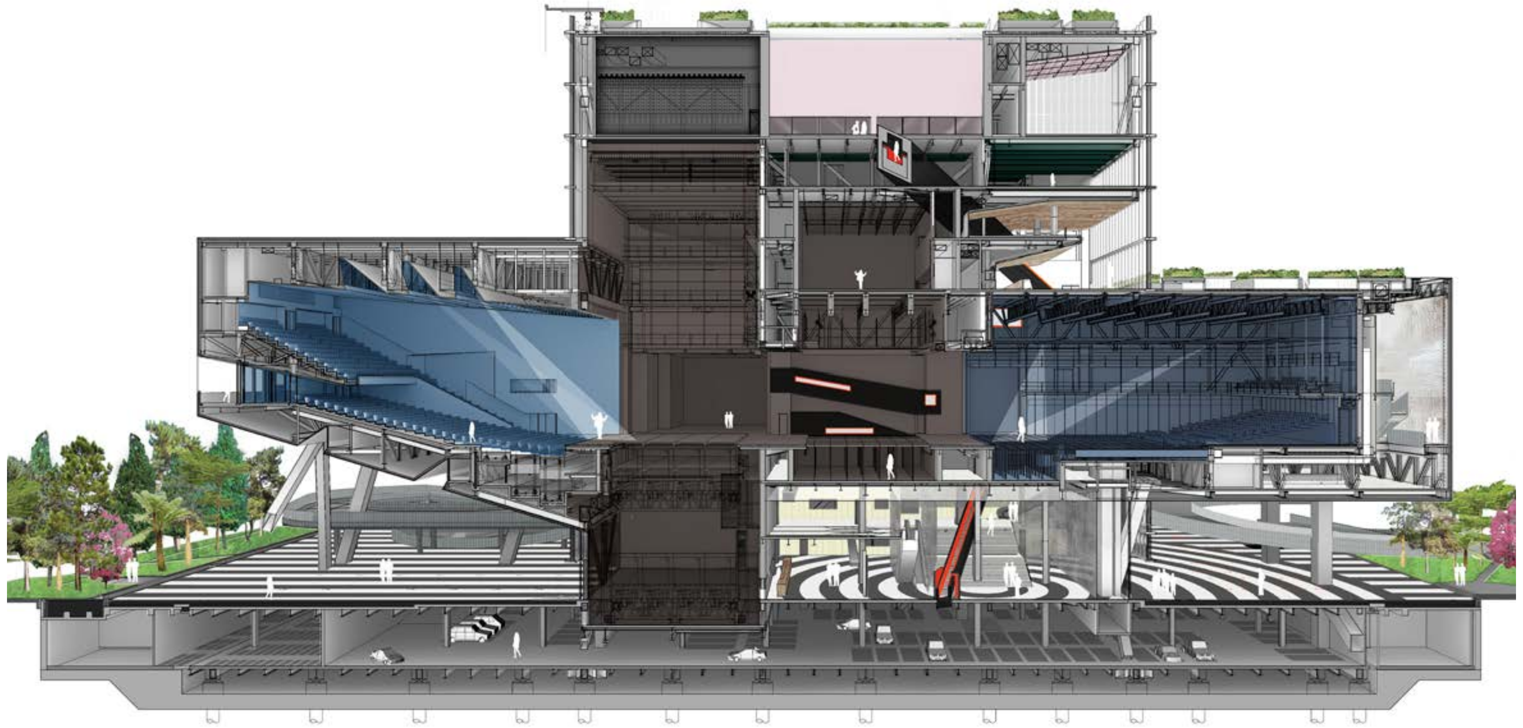

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create an external, landscaped public plaza in the busy city-centre location. For the competition, OMA turned to Arup for support, continuing a design collaboration with the same teams from the firm's offices in London and Beijing that had delivered the CCTV Headquarters in Beijing and the Shenzhen Stock Exchange.

The design is inspired by a traditional Chinese wood block puzzle. The three auditoria plug into a compact central cube that contains backstage areas, foyers, and front-of-house and support facilities. This enables the theatres to be used independently or in combination to create a 'Super Theatre'. The 'Public Loop' is a free-to-access path through the building that exposes parts of the backstage areas that would be hidden in typical theatres. The design needed to ensure the building can be fully operational even after a severe earthquake, so that it can act as a public facility post-quake.

Design team

Arup provided engineering and consultancy input for structural, building services and fire engineering and sustainability (building physics). The

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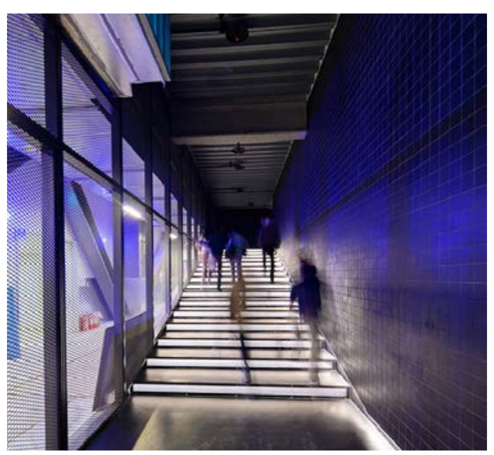
3: The three auditoria plug into a compact central cube that contains backstage areas, foyers, and front-of-house and support facilities

4: The raised auditoria create an external, landscaped public plaza in the busy city-centre location

5: The Public Loop is a free-to-access path through the building



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firm led the design for these disciplines from concept to the end of the design development phase before passing the design to consultants based in Taipei. The building services design was handed over after schematic design, once the overall strategy and systems were defined.

The team collaborated with engineers from Evergreen Consulting Engineering Inc. (structures), Heng Kai Inc. (mechanical) and I S Lin & Associates Consulting Engineers (electrical). After the competition win, the Arup design was led from the Beijing office, with support from London, Los Angeles and Hong Kong. OMA set up a Hong Kong office to support the project, later maintaining a presence on site throughout construction. It worked closely with Artech Inc. in Taipei to deliver the architectural design, bringing in a number of other specialists including dUCKS Scéno (scenography), DHV (acoustics), ABT and CDC (façade) and Inside/Outside (landscape and interiors).

Concept

Orientating the three theatres towards each other and combining many of the backstage functions results in a smaller, more compact building on the 20,000m^2 site, providing the immediate benefit of a reduced floor area and building envelope – which is hence more energy-efficient to operate. The consolidation of the stage areas enabled the creation of the 2,550-seater Super Theatre, in which the two main theatres are combined into one vast performance space with a 60m-long central stage.

The stage of the Globe Playhouse is located above that of the other two theatres. The auditorium seating configuration, developed to optimise sightlines, suggested a spherical form; the final shape is defined by two semi-ellipsoidal surfaces; an inner one marking the edge of the auditorium and an outer one forming the external shell. Between the two lies a network of circulation corridors and stairs, boxes, structure and services.

Engineering challenges

Such an ambitious concept came with significant engineering challenges, which were exacerbated by the site conditions. Key issues to be resolved were the requirement to develop a structural system that could give satisfactory performance under high seismic conditions while enabling the unique architectural concept, and meet the need for the building to be operational immediately after a severe earthquake; ensuring sustainable operation of the ventilation systems under all theatre configurations, maintaining satisfactory levels of occupant comfort without creating air flows that could disturb stage curtains and props; and securing fire engineering approval for the large spaces against a backdrop of prescriptive local design codes, particularly for the multiple stage/seating configurations of the Super Theatre.

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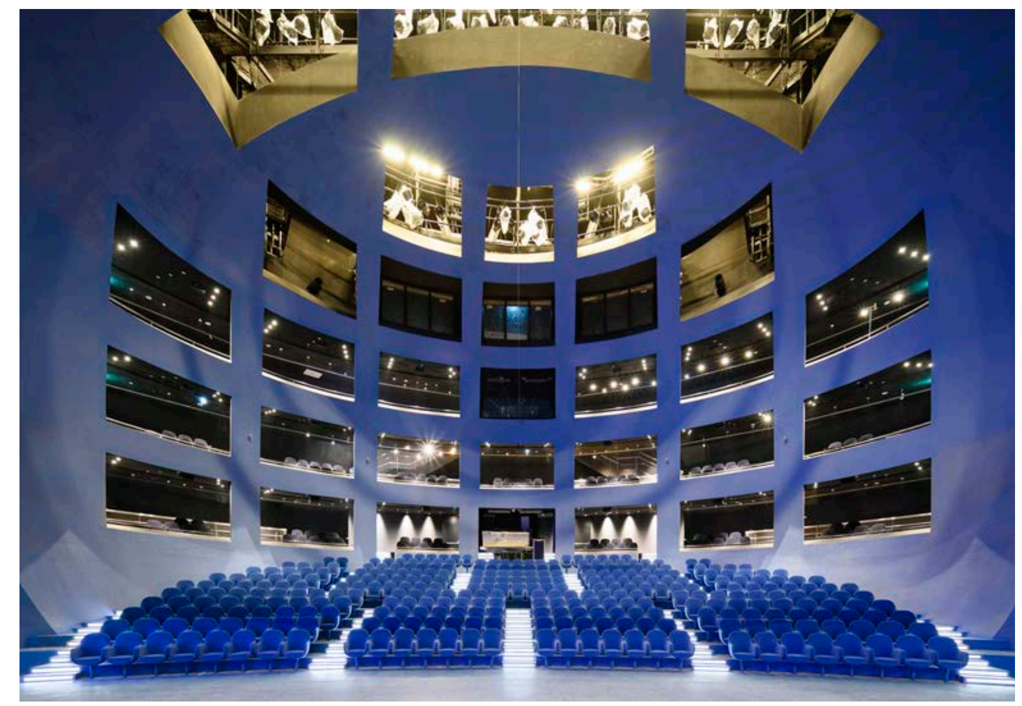

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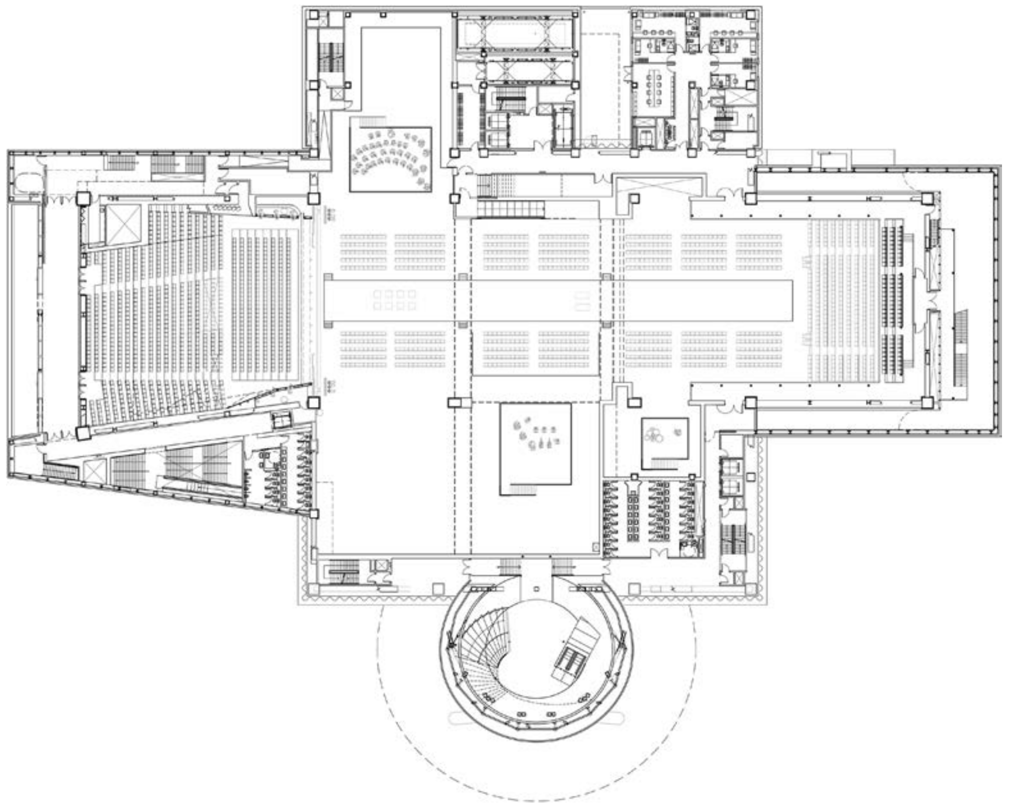
6: The stage of the Globe Playhouse is located above those of the other two theatres

7: The Globe is defined by two semi-ellipsoidal surfaces; an inner one marking the edge of the auditorium, and an outer one forming the external shell



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Resilient structure system

Faced with such complex multi-theatre planning, it was important to achieve the optimum structural system: versatile yet robust, able to give freedom for the architect to plan the large internal spaces, and with sufficient lateral and torsional strength and stiffness to resist Taipei's high seismic forces and minimise any damage to structure and finishes during a severe earthquake.

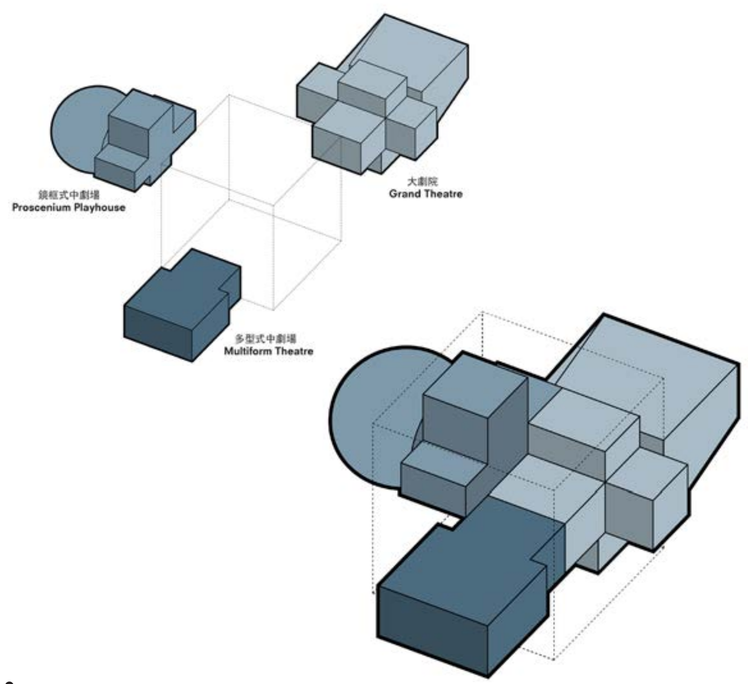
Yet the form of the building inspired a simple conceptual solution: to turn the faces of the Cube into a stiff, braced box that could resist almost all of the building's lateral loads and carry much of the gravity force. This system would free up the interior for planning of the theatres and other large, stacked spaces, and, in conjunction with columns under the auditoria, support and stabilise the three projecting volumes.

The superstructure was then base isolated in order to attenuate the seismic forces transmitted from the ground to the building, enabling element sizes to be reduced and detailing simplified. In value engineering exercises, base isolation reduced these forces by some 60%, and was demonstrated to be more economic than conventional structural solutions.

The lateral stability is provided by the braced steel perimeter frame to the Cube, which works together with the auditoria columns to provide an effective lateral and torsional resisting system for the superstructure, resisting wind as well as moderate earthquake loads and transferring the forces down to the substructure. The largest elements in the frame of the 53.5m x 53.5m Cube are 1.3m-square fabricated steel columns, which are filled with concrete to enhance their structural capacity.

The bracing arrangement was refined during the design process to achieve a balanced, symmetric arrangement with optimum lateral performance, while satisfying the architectural constraints. In particular, the braced planes were needed to accommodate the three proscenium openings for the projecting auditoria, as well as other circulation routes.

Since the auditoria project outwards from the face of the Cube, their support columns also need to provide lateral stability, either via bracing or through frame action, in order to control rotational movements at the furthest points of the cantilevers.



8: The base isolated design enables the building to be occupiable immediately after a severe earthquake

9: The theatres can be combined to create the 2,550-seater Super Theatre

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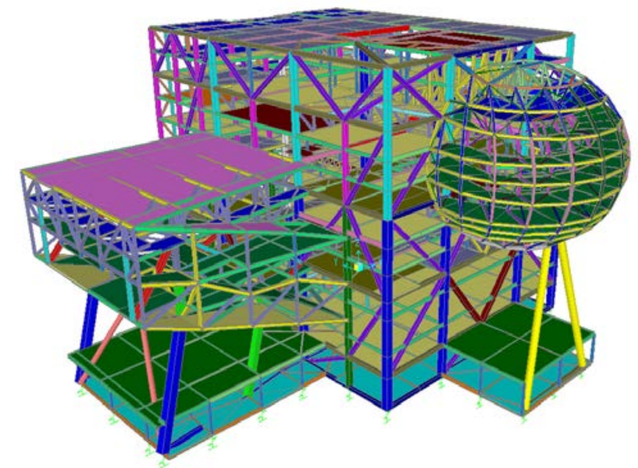
10: Linear and nonlinear analysis was carried out to assess the performance of the structure and its isolation system

11: The superstructure was base isolated to attenuate the seismic forces transmitted from the ground to the building

12: The Globe Playhouse structure is formed by a 3D steel space truss



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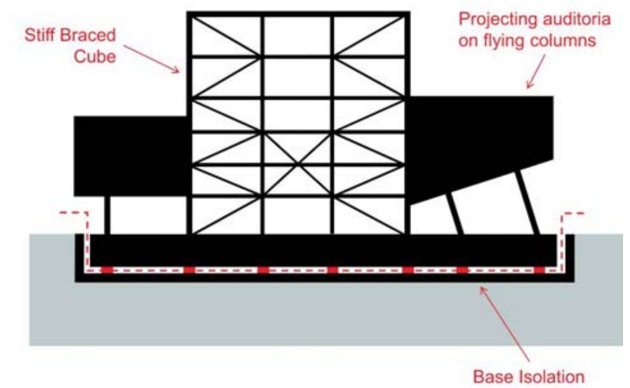

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To keep the structure rigid, steel bracing or stiff slabs are provided on all faces of the projecting auditoria, as well as on key floors where the Cube bracing nodes out with the columns. On many floors of the building, large floor voids are necessary for stage pits, fly towers, etc., so localised bracing is introduced to transfer lateral forces into the primary stability system.

Projecting auditoria

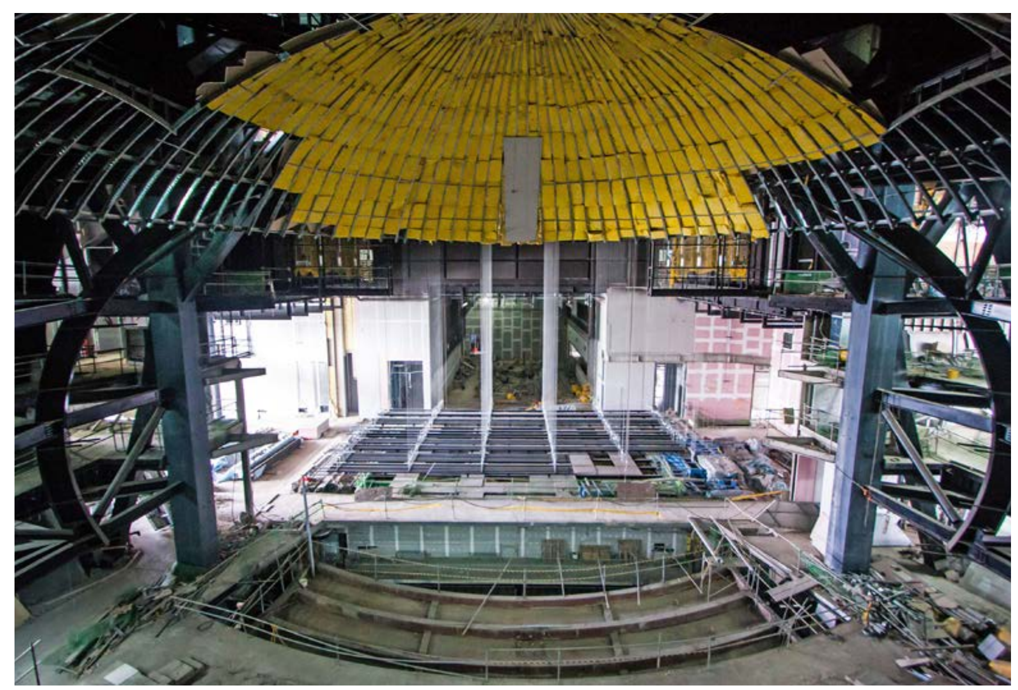
The three auditoria project up to 37m from the Cube, spanning onto and cantilevering beyond their supporting columns. Their floors are carried on trusses, which also frame around the auditorium voids, supporting balconies and lighting gantries.

The Globe Playhouse structure is formed by a 3D steel space truss, projecting 26m from the east face of the Cube between levels 5 and 12. The truss is supported by the Cube perimeter columns, as well as an external inverted-V column.

The faceted structure provides a highly resilient structural system, which enables individual elements to be removed without compromising the integrity of the system. This is essential to allow the inner shell and intra-shell zones to be 'eroded' to suit openings for balconies, circulation routes, ceiling lighting, etc. It can be broken down into the following components:

- A 'torsion truss' at the base of the Globe Playhouse, which supports the gravity loads and transfers them into the V-column and the Cube frame
- A series of trussed radial moment frames spaced evenly around the perimeter, which carry the gravity loads from each level down to the torsion truss
- Plan bracing on each balcony level, to maintain rigidity
- A fully braced outer shell
- Other elements as necessary to frame out and stabilise the structure

This theatre has an irregular shape, due to sightline and acoustic requirements. A dedicated 3D Rhino model of the structure was set up to interface between the architect's master model and the structural analysis model, enabling detailed analysis and multidisciplinary coordination to be achieved early in the design – essential for validating such a complex form.



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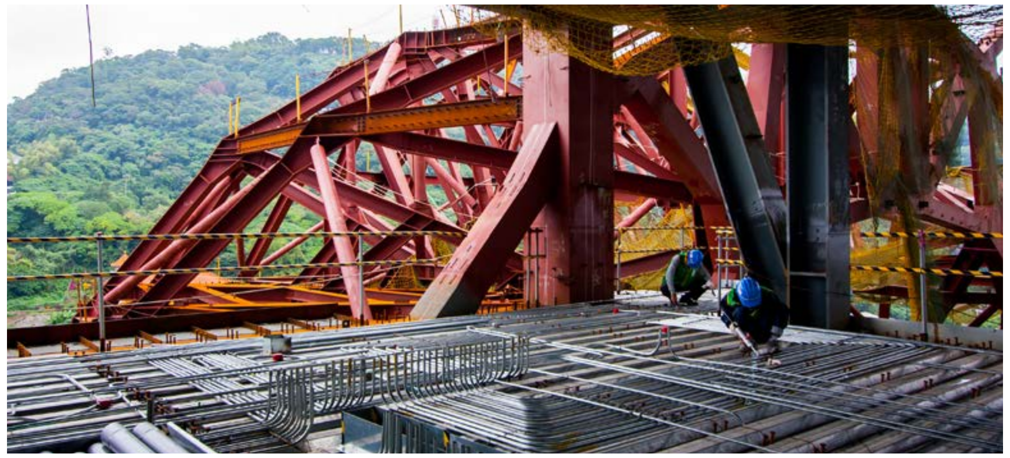
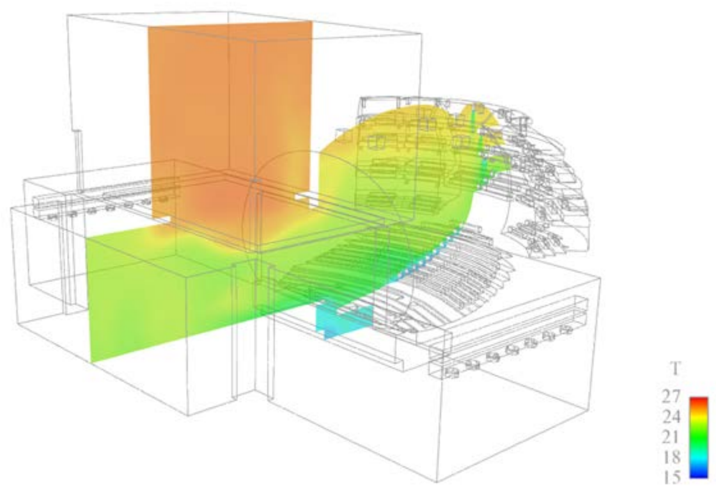


14.

13: The building uses a total of 89 isolators, in five different sizes up to 2.4m diameter

14: 175mm composite slabs were used for the floors, providing a relatively lightweight structural solution

15: The cooling system creates an efficient and ideal thermal comfortable environment in the occupant zone of the theatre



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Gravity forces throughout the building are brought down to ground by three sets of columns: those in the Cube perimeter, those supporting the auditoria, and a small number of internal columns. Due to the programmatic requirement for multiple stacked, column-free spaces within the 55m-tall building, only four internal columns are able to run the full height of the building. As a result, a network of transfer trusses was introduced to frame the large theatre spaces and support secondary columns. The trusses span up to 25m, using storey-deep trusses with elements up to 600mm x 600mm in size. The secondary columns were introduced wherever possible, to reduce floor structure depth and improve economy.

Typically, 175mm composite slabs are used for the floors, providing a relatively lightweight structural solution. The floors on which the perimeter bracing nodes out to the columns act as diaphragms to distribute lateral forces, so the thickness is increased to 200mm at these levels. The slabs are supported on trapezoidal metal decking acting as permanent formwork, spanning up to 3m between secondary composite steel beams.

Base isolation

The venue is designed as a seismically isolated building with an isolation plane between the structure and its foundation. This plane is horizontally flexible yet vertically stiff, enabling attenuation of ground-induced horizontal movements, reducing the seismic forces transferred into the building. Friction pendulum bearings, consisting of articulated metal sliders that move on a spherical bowl, were incorporated into the design, using the action of sliding as the basis for achieving low horizontal stiffness. A friction coefficient was selected such that the sliders remain stationary under small lateral loads. However, once the static friction is exceeded, the sliders start to move, with energy dissipated through the sliding friction. Because of the spherical shape there is upward as well as lateral movement, ensuring that each bearing will re-centre itself after an earthquake.

The bearings are designed not to yield (or slide) under wind loads or during ‘frequent’ (i.e. 50-year return period) earthquake events. Under severe earthquakes (475-year return period, known as a Design Basis Earthquake, or greater), the isolators attenuate the transmission of ground motions into the building, significantly reducing the forces experienced by the structure and finishes. The scheme thus provides the most efficient, economic and high-performance building possible for the challenging site location and conditions.

Such isolators are now proven technology, and have been used worldwide for over 30 years on buildings, bridges and industrial facilities. However, the construction of TPAC was the first use of friction pendulum isolators in Taiwan. To design the isolators, the team adopted a performance-based design approach, using state-of-the-art methods to set performance targets for different levels of seismic event and carrying out design checks using appropriate linear and non-linear seismic analyses to verify the structural performance for each earthquake scenario.

The building uses a total of 89 isolators, in five different sizes up to 2.4m diameter. The bearings are located in a 2.7m-high undercroft below the basement. The isolated superstructure is separated from the substructure by a 700mm-wide seismic joint. The majority of the main plant rooms are housed in the non-isolated substructure at the perimeter of the basement, such that the main utilities connections do not cross the joint; the number of servicing routes bridging it is also minimised.

Reinforced concrete is used for the basement structure beneath the isolation plane, as well as the area of basement around the perimeter of the site which is used for car parking and plant rooms. The superstructure loads are transferred via the isolators into the ground via bored reinforced concrete piles up to 1.8m in diameter, socketed 5m into the bedrock, whose level varies across the site from 15m to 40m below ground level.

Since the isolation plane is located at the basement, the ground floor slab is cut by the isolation joint and is thus unable to resist earth pressure loads around the perimeter of the basement. These loads are instead resisted by a combination of perimeter sections of the ground floor acting as a waling, and perpendicular shear walls introduced as buttresses between car parking spaces.

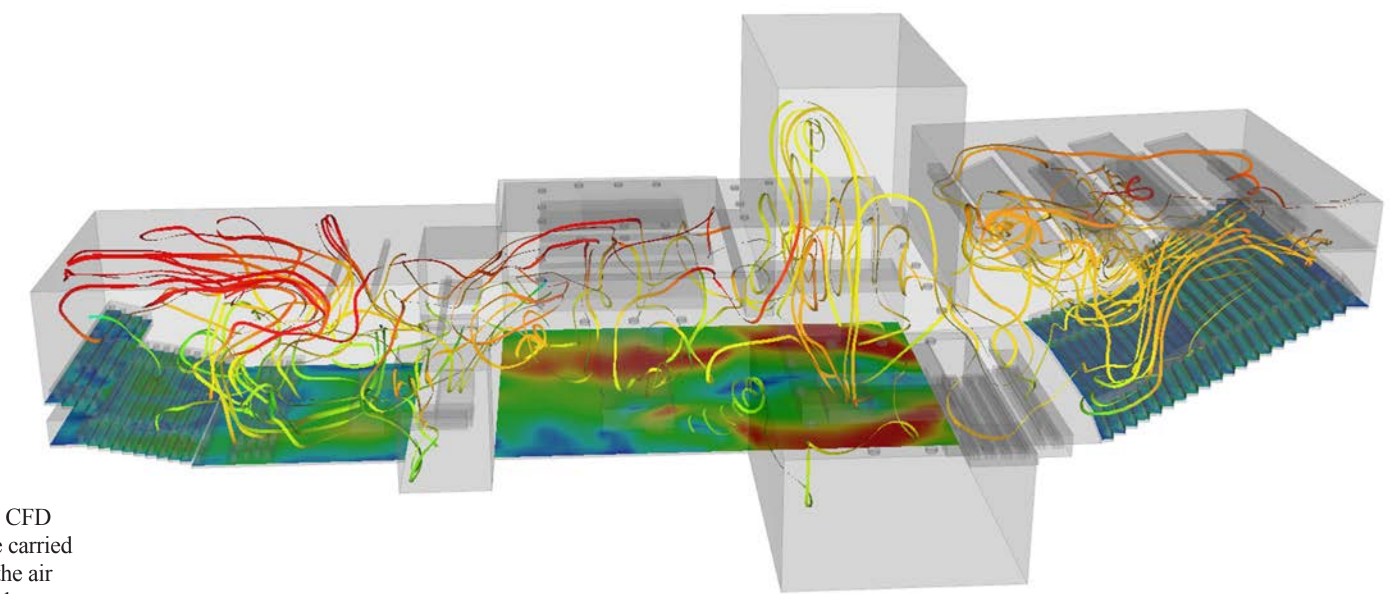
A comprehensive eight-month approval process took place after the detailed design drawings were submitted. The structural design underwent a successful special structural review, due to its complex shape. This was carried out at the National Taiwan University.

Sustainable building environment

The compact design of TPAC, with its optimised floor area, brings about a number of immediate advantages in terms of sustainable operation, such as energy efficiency, self-shading and passive design. Special attention was also paid to thermal comfort and shading design of the west-facing façade, which experiences the highest heat loads and glare issues; this side of the facility houses scenery workshops and other back-of-house spaces.

Extensive computational fluid dynamics (CFD) analyses were carried out to assess the air flow through the auditorium and stage areas in their various configurations to confirm that the ventilation strategy would achieve satisfactory levels of occupant comfort. The analysis considered the varying needs of audience and performers, as well as location and velocity of air supplies – optimising air flow and movements to ensure sufficiency of cooling while minimising the risk of movement of stage curtains, props, and even theatrical smoke effects.

Separate constant volume air conditioning systems were provided for all three theatres, foyers, retail and administration areas and rehearsal halls. The auditoria are typically ventilated through an underfloor displacement system, delivering thermal comfort with optimal acoustic and energy performance. Cooled air is supplied through under-seat swirl diffusers via an air plenum. This system supplies very low-velocity air (0.15m/s) and very low room temperature difference (supply air temperature between 17°C and 21°C), to create an efficient and ideal thermal comfortable environment in the occupant zone of the theatre. Separate



16: Extensive CFD analyses were carried out to assess the air flow through the auditorium and stage areas

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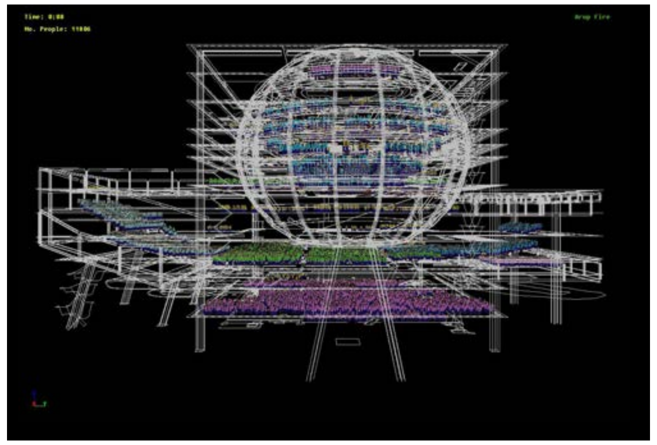

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17: A whole building evacuation model was used to review and validate the evacuation and egress strategy

18: CFD models were used to simulate the fire and smoke movement in each theatre

constant volume systems provide air to the various stages and wings, enabling them to be used separately or in combination. The dedicated constant volume system provides cool air onto diffusion plates above the stage. These plates minimise the downdraft effects caused by supplying air from a high level and at a low velocity. A supply fan variable frequency drive overcomes increasing filter pressure, while maintaining a neutral stage pressure. Local stage override controls are provided to allow the system to be temporarily deactivated, so as not to disturb theatrical smoke effects. An advanced oxidation system for air purification in the air handling units (AHUs) is used to eliminate micro-organisms, volatile organic compounds and odour, and to improve indoor air quality, because the occupancy density for the theatre is high.

Close control air conditioning units are provided for the musical instrument spaces to maintain 24-hour constant temperature and humidity. The pre-treatment fresh air unit is located in the far end of the building to minimise noise impact and reduce big shaft space. A variable air volume system was designed for the public area. Outdoor air is modulated to maintain minimum CO_2 concentrations and to minimise conditioning of outdoor air during part-occupancy. The central chiller plant room is in the basement and the cooling towers and Grand Theatre stage AHU are positioned on the top of the west side towers to minimise vibration and noise impact on the performance spaces.

The façade is a critical component of the overall environmental design of TPAC. The selected system integrates architectural features with solar protection and ventilation. An important consideration is the choice of glazing: under the local climate, appropriate glazing is essential to ensuring good thermal performance of the building. The access to natural lighting is closely related to the environmental façade design. The daylight available is tailored to the specific requirements of each space, and particular effort was made to ensure the risk of glare is minimised.

Performance-based fire safety design

The Super Theatre configuration, in which the theatres are combined to create a giant auditorium, presented significant design issues. With its multiple variations in stage and seating layout depending on the performance and auditorium arrangement, this led to particular challenges in relation to the fire design.

Arup's fire engineering team was involved in the design from the concept stage. Using performance-based fire engineering principles, the firm developed a fire safety strategy to mitigate the associated fire and life safety risks. The design was granted approval from the local expert review panel, following an extensive fire review process. The comprehensive fire strategy meets the best safety standards despite the deviations from the local code, creating a template for approving other complex buildings in Taiwan.

A qualitative risk assessment was performed to review the potential fire hazards in each performance space. Each venue was designed to form one fire compartment, as well as taking into account the requirements for the Super Theatre configuration. This fire compartment plan focused on mitigating the risk of fire spread between areas with different usage and risk profile. The final design ensures that the building occupants can be evacuated safely in the event of a fire, without enclosing the central stage area with fire curtains.

Phased evacuation is used for each performing space. The concept of a 'place of relative safety' was introduced into the design to create a fire-protected temporary queuing area outside each performing space. The rationalisation of the means of escape for the building allowed the theatre seating arrangements to be optimised, the number and width of staircases to be reduced, and the safe travel distances to be extended from the code requirements. The strategy took into account all the different building occupants, including theatre patrons who would have limited familiarity with the building and its exit layout, as well as those who are mobility-impaired.

Arup's design solution enabled a more open, integrated and flexible space in the building, as well as increasing the amount of seating in the theatres. Given the tiered seating layout, occupants in the upper seating area are more likely to be affected by smoke compared with those in the stalls located in the lower areas. Therefore, a relatively larger portion of exits are provided to the upper seating area, to enable occupants to leave the low-ceiling area quickly. A whole building evacuation model (using STEPS simulation software) was used to review and validate the evacuation and egress strategy.

To complement the egress strategy, a CFD model was used in the design to simulate the fire and smoke movement in each theatre. A performance-based smoke control system, formed by smoke or fire barriers, smoke exhaust and air makeup system, is used in each theatre space. This system removes the heat from the fire compartment and retains the smoke layer height above the egress routes, to protect occupants from being exposed to untenable conditions as they move away from the fire-affected areas.

In order to rationalise the required mechanical system, the space directly over the stage and auditorium is used as a smoke reservoir, to confine the smoke in a zone that can be extracted via mechanical exhaust points located near the ceiling level. The smoke or fire barriers are used to separate the stage and auditorium, to limit the smoke spread and improve the efficiency of the smoke exhaust system.

Dramatic building form

TPAC is a true example of total architecture, with ground-breaking design concepts in structural, fire engineering and sustainability services that were all essential in realising the building's ambitious configuration. With the focus on resilience by base-isolating the building, the design minimises any damage to the structure, enabling it to be occupiable immediately after a severe earthquake. This provides a vital post-quake facility for the local community.

19.

19: Innovative design concepts in structural, fire engineering and sustainability services were all essential in realising TPAC's dramatic form

Authors

Jonathan Griffiths led the building services schematic design. He is an Associate in the Cardiff office.

Gigi Kam led the HVAC design and was building services coordinator, liaising with the design team and local design institute. She is an Associate Director in the Hong Kong office.

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Project credits

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Landscape and interior architects Inside/Outside
Local structural engineer Evergreen Consulting Engineering Inc.
Collaborators Heng Kai Inc. (mechanical) and I S Lin & Associates Consulting Engineers (electrical), Taiwan Fire Safety Consulting Ltd. (fire), Segreene Design (sustainability)
Theatre consultant dUCKS Scéno, Creative Solution Integration Ltd.
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10, 11, 14–18: Arup
12: Chas Pope/Arup

1.

Taking the bus to an electric future

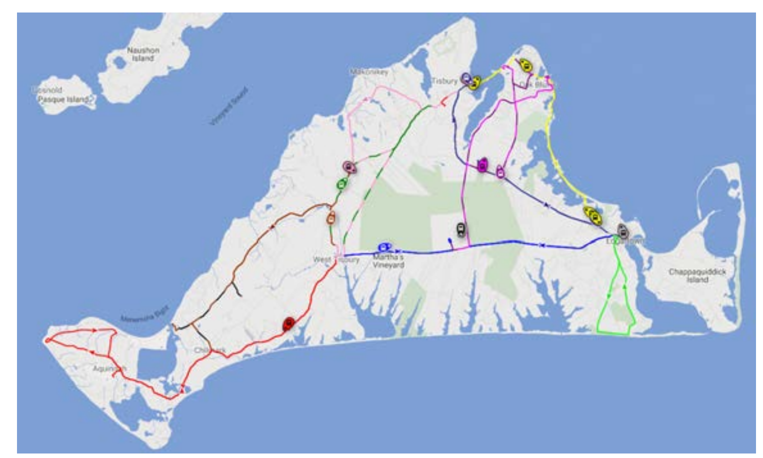
The Martha's Vineyard Transit Authority microgrid provides resilient and sustainable energy for its growing fleet of electric buses

Authors Julian Astbury, Geoff Gunn

1: The microgrid at the VTA bus depot provides a resilient, independent, zero-carbon energy source

2: The VTA provides a bus fleet to serve the island's 15 routes

3: If utility power is lost, the microgrid can use its battery energy storage, PV and back-up onsite diesel generators to charge the fleet



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Martha's Vineyard, an island of about 250km^2 (100 square miles) off the coast of Massachusetts in the USA, presents a challenge for public transportation. Accessible by boat and air only, the island traditionally depended on imported fossil fuels for electricity and to power vehicles. This not only translates into higher fuel and energy costs, but also contributes to greenhouse gas emissions and noise pollution, and leaves the island vulnerable to power outages during major adverse weather events. The limited access also makes operating and maintaining a traditional diesel bus fleet challenging, due to the complexity and number of components required in the vehicle drivetrains.

In 2018, Martha's Vineyard Transit Authority (VTA) put in place ambitious plans to transition its fleet of 32 diesel-powered buses to an electric bus system. The VTA wanted to introduce a more reliable and environmentally responsible public transportation network, connecting the six towns on the island, its 20,000 permanent residents, and the island population that grows fivefold in the summertime. The transit authority's priority was to provide a fleet to serve the island's 15 routes and 1.2 million annual passenger journeys for years to come, using reliable, emission-free and fuel-saving vehicles. In order to do this, they put the infrastructure in place to support and reflect this commitment.

However, the VTA went further than simply electrifying its transit system; it

3.

also added a microgrid, which allows on-site solar energy generation with battery storage to significantly reduce carbon emissions and energy costs. The microgrid provides a resilient, independent, zero-carbon energy source and enables the buses to be charged if the main grid goes offline, as occasionally happens. In addition to the microgrid, two on-route inductive charging sites were designed to enable the electric buses to run throughout the day, without the need to return to the depot for charging.

Arup worked closely with the VTA, Vermont Energy Investment Corporation (VEIC) and a range of vendors to help realise the VTA's goals. The project has resulted in a cleaner, more resilient and economic model for the Martha's Vineyard transport system, with 16 of the 32 buses in the fleet currently electric. An additional four electric buses will be added later in 2022.

When the all-electric bus fleet is fully in place, it will eliminate 33,000 tonnes of carbon dioxide over ten years of driving 2.25 million kilometres (1.4 million miles) annually. In the first year of use, there was a US$50,000 saving in fuel costs, with an expected US$100,000 annual saving once the full system is in place.

Electric experience

Arup's experience with working on electric bus fleet design includes a scheme with induction chargers in Milton Keynes in the UK which was launched back in 2014. Since then, the firm has worked on a wide range of projects that include bus electrification infrastructure, energy storage and renewable energy

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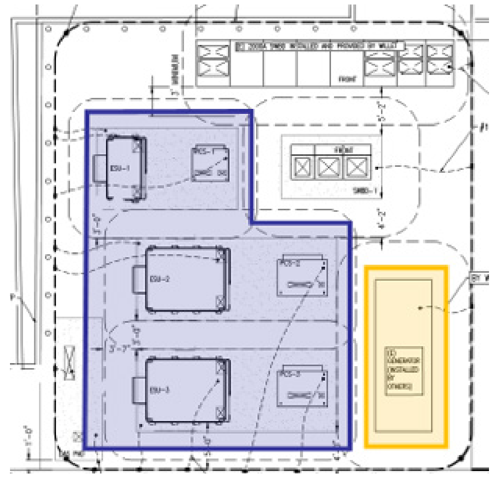
4: The 700kW DC solar PV array at the bus depot provides clean, renewable and cheap energy

5: VTA's microgrid pairs battery storage with its solar energy system



5.

systems. That experience was put to use when VEIC brought Arup on board, initially to carry out a review of the microgrid design. The role then expanded to include the electrical and civil design to support installation of the new electrical service and electrical distribution. Arup's design work also included the interconnection of the battery energy storage system and the inductive bus charging system.

Microgrid

When the VTA began transitioning to electric buses, it had to address the issue of how to reliably, sustainably and cost-effectively keep the buses charged. Options included deploying diesel or natural gas generators for when the grid is not available, or when electricity is at peak cost. However, using diesel generators to regularly charge bus batteries would defeat the VTA's cost-savings and sustainability objectives. This led to their decision to develop a large onsite photovoltaic (PV) system at its bus depot to generate its own energy.

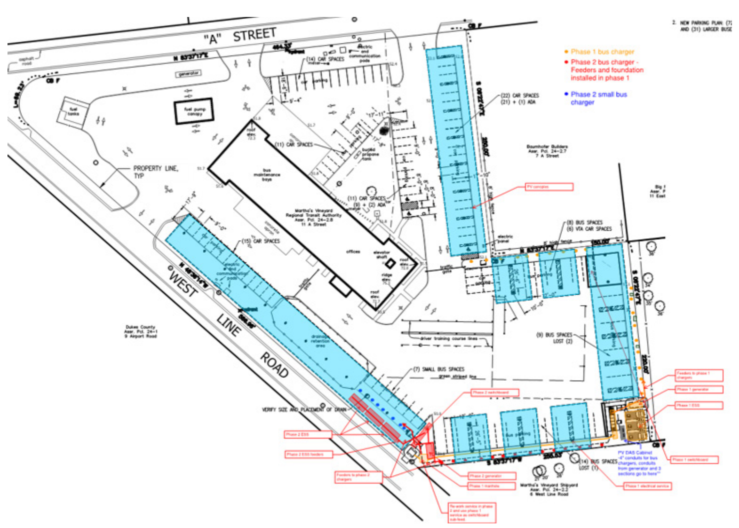
The solar array provides clean, renewable energy, at a lower price than if purchased from the utility, whose energy would also have a higher carbon content. The transit authority chose to pair battery storage with its solar energy system to manage utility costs and allow it to operate when the utility is down, thereby creating a microgrid. Surplus energy can also be sent to the grid, which further offsets costs for the VTA.

The microgrid was designed by VEIC, PXiSE and Arup. It is an energy distribution, storage and generation network that can be disconnected from the main grid during power outages to then use its own stored electricity and solar-generated power. A supplementary diesel generator is also provided to ensure that resilient power is available during nighttime hours and if the battery energy storage is depleted.

Developed at VTA's existing 11 A Street bus depot, the microgrid combines a new 700kW DC solar PV array, 1,400kWh battery energy storage and a back-up diesel generator, as well as 16 vehicle charging stations, with 20 more to be added in the coming years. This location was challenging due to limited space on site and the fact that the bus depot needed to remain fully operational during construction. Phasing of the works was also an important consideration, with construction taking place outside of the island's busy summer season. A challenge for electrifying bus fleets is the rapidly changing landscape of manufacturers, vendors and products in the market, which was further exacerbated due to supply chain interruptions caused by the Covid-19 pandemic. Arup coordinated the various manufacturers to ensure optimal interconnectivity and minimise construction disruption due to equipment delays.

Induction charging

Two on-route induction charging stations have been designed to provide mid-day top-up charging at Church Street in Edgartown and West Tisbury Town Hall. Three induction chargers, installed by Momentum Dynamics, are now in use at Church Street, with construction of the second station with two chargers due to start in late 2022 or early 2023. The induction station now enables the buses on a number of routes to recharge on route when passengers board and exit the vehicle at the charging location. This allows the buses to stay in service for their 200-300-miles-a-day circuit (320-480 kilometres), without detouring to be recharged or requiring replacement with fully charged buses from the 11 A Street depot. Arup carried out the civil and electrical engineering design, including sewer line relocations in the public way, and approvals to facilitate the installation of the wireless charging plates embedded in the ground at the bus stops.



6.

6: The 11 A Street depot was a challenging location for a microgrid, with limited space and a requirement for the depot to remain operational during construction

7.

7: The installed system leverages the microgrid's smart technology to achieve a new level of operational efficiency

Optimisation

Along with operational cost savings and reduced carbon emissions, in comparison with diesel buses the electric fleet is quieter (both inside and outside), has no adverse impact on local air quality, and typically requires less maintenance. Once a battery electric bus is on the road, its operation is much like a diesel bus, but when it returns to the depot, facility operations and recharging depart considerably from diesel procedures, upending many conventional transportation processes. Unlike a diesel vehicle that can be quickly fuelled (often conveniently drawing from large stores onsite), a battery electric bus requires longer to recharge. This is where the microgrid plays a crucial role in supporting fleet operations and costs.

The microgrid uses complex algorithms (developed by PXiSE) and forecasts to balance and optimise energy costs, carbon emissions and resilience. It also calculates the energy consumption for each bus for the next day, and plans the charging of the fleet accordingly. Similarly, in the event that utility power is lost, the microgrid can use its battery energy storage, PV and back-up onsite diesel generators to charge the fleet. This ensures that all buses are at full capacity for the scheduled start the next morning.

Electric future

The installed system supports the transit authority's requirements for reliable, regular transit while leveraging the microgrid's smart technology for a new level of operational efficiency. As an electrified fleet, combined with a microgrid, the VTA's new bus system presents a replicable framework for public transportation agencies nationwide and further afield, as transport providers look to transition to a cleaner, more resilient and economic future.

Arup is currently working on a similar but larger-scale system in Brookville in Maryland, due for completion in October 2022. The firm is the lead design and build engineer for the infrastructure for a fleet of 70 electric buses. The Brookville Smart Energy Bus Depot, with a 2MW solar PV array, will enable a 62% carbon emissions reduction and a lifetime greenhouse gas benefit of 155,000 tonnes for the bus fleet, powered by a microgrid.

Authors

Julian Astbury was the Project Director. He is an electrical engineer and a Principal in the Boston office.

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Project credits

Client Martha's Vineyard Transit Authority (owner), Vermont Energy Investment Corporation

Partners and collaborators Borrego Solar, Momentum Dynamics, PXiSE, Viriciti/ ChargePoint

Civil and electrical engineering, sustainable infrastructure design Arup: Derek Anderson, Julian Astbury, Anna Dastgheib-Beheshti, Ysabel Espinal, Emily Gill, Geoff Gunn, Aaron Manzali, Justin Palovchak, Faye Poon, Kayla Van Name.

Image credits

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4: VTA

Communicating the uncertainty of rising seas

A new digital tool to communicate the impact of sea level rise on flood risk

Authors Mike Dobson, Steven Downie

There remains a huge amount of uncertainty around how quickly, and by how much, the seas around our coasts will rise over the coming years and decades. To be able to make informed decisions on managing climate change risk, policy-makers and stakeholders must weigh up a variety of futures rather than just one. Arup's new sea-level rise insights tool explores how uncertainty over future sea level rises can be captured in the economic decision-making process to manage that risk.

The tool has been designed as a web-based portal in which users can explore different scenarios and visualise a spread of results. By creating this tool, Arup has built a new way of investigating the uncertainty in climate change predictions. The firm brought together expertise in data and climate science, coastal engineering and oceanography. It's the first time the full scope of the Intergovernmental Panel on Climate Change (IPCC) sea level rise projections can be seen in an interactive way, in an economic flood risk assessment. The tool allows decision-makers to see the economic impact of some of the more extreme climate change projections early in the assessment process, which is increasingly viewed as necessary to make better-informed decisions about how this risk is managed, in the detailed analysis that follows.

Rethinking flood risk modelling

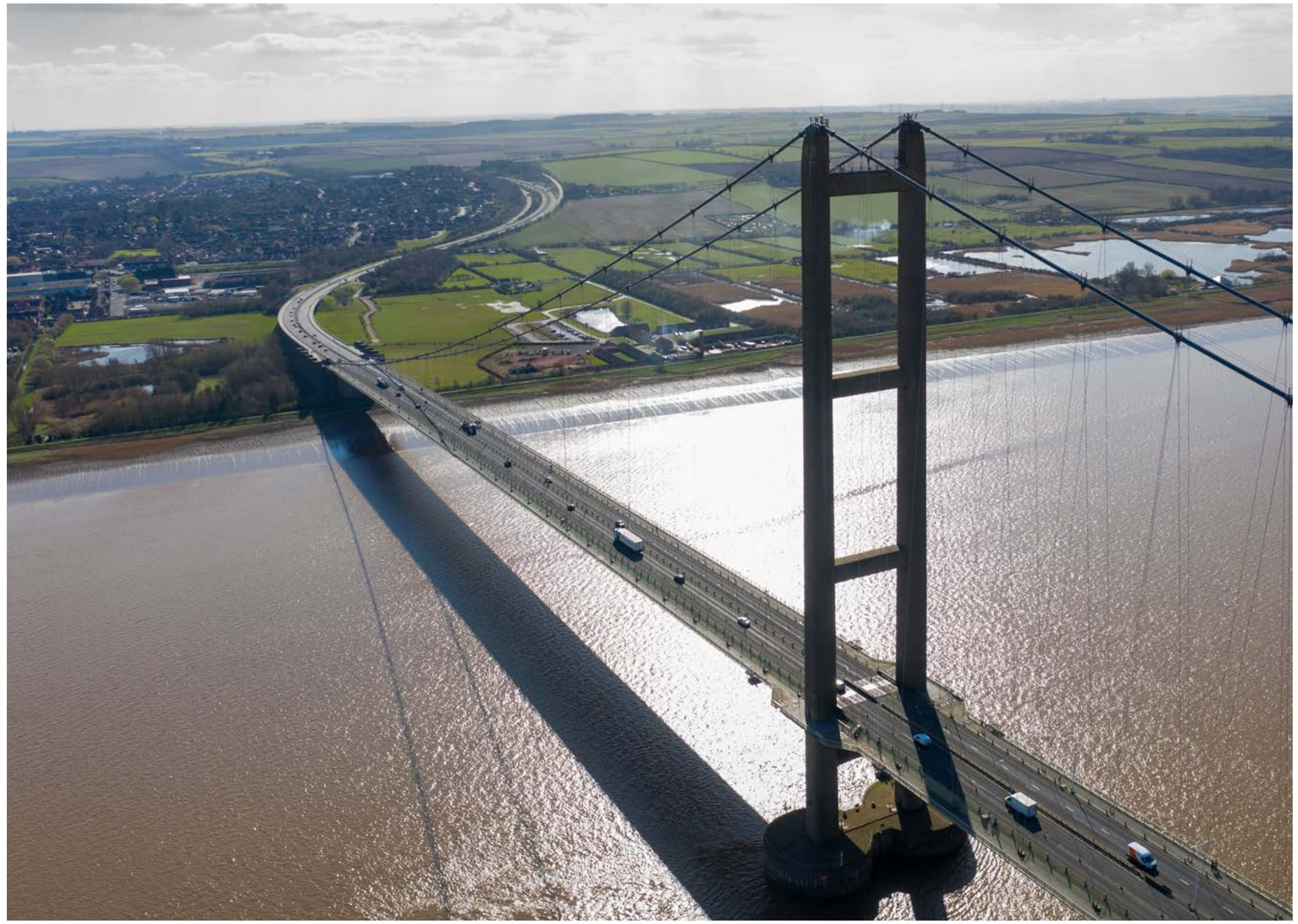
The tool was developed as part of the EuroSea project, which was jointly funded by Arup University's research programme and by the EU's Horizon research and innovation programme (under grant agreement no. 862626). EuroSea is a €13m, Europe-wide research project into ocean observing and forecasting. Arup worked in partnership with the University of Cambridge, the UK's Environment Agency and the National Oceanography Centre to develop the tool.

Typically, assessments examining flood risk only look at limited aspects of sea level rise, such as the mid-range of the IPCC projections. However, the further into the future projections are made, the greater the uncertainty of the outcome, and the more important it is to look at a range of potential futures from the IPCC. The Cambridge Coastal Research Unit (CCRU), in the Department of Geography at the University of Cambridge, led the climate change impact modelling using sea level rise prediction information from the UK Climate Projections data published in 2018. The modelling propagates the uncertainty of sea level rise through a traditional coastal flood risk assessment. It does this by incorporating the modelling of sea levels, wave overtopping, and the way flood inundation spreads inland. In this way, the uncertainty over sea level rise is communicated as a part of the calculated risk of flooding and resultant economic damage.

The CCRU ran thousands of different scenarios using simplified models. This provided Arup with a massive data set which could be translated into better insights for decision-makers, as well as being used as a conversation starter for future planning and for stakeholder engagement.

Arup's team united a wealth of expertise in climate change mitigation and adaptation, with experts who are experienced in risk management and resilience, dealing with both climate change impacts and coastal sea level rise. The team pooled its knowledge to bring together data at scale, using digital innovation to enhance strategic decision-making as we face up to an uncertain future. For the digital development of the tool, Arup worked with CADA Consulting.

The tool was developed using data from the urban coastal area of Hull which, outside of London, is the UK city with the highest number of properties at risk of flooding. The CCRU modelled 122 sea level rise increments, seven extreme water level return periods, and 25 storm conditions. This resulted in a total of



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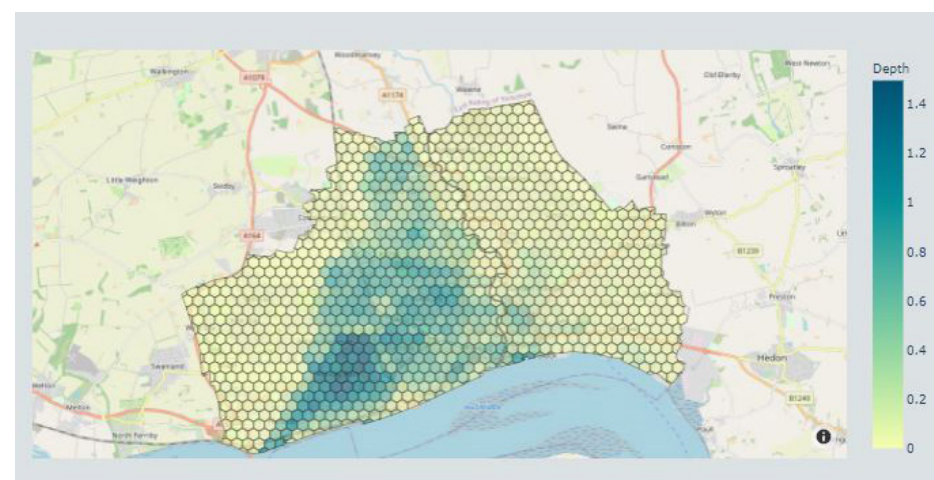

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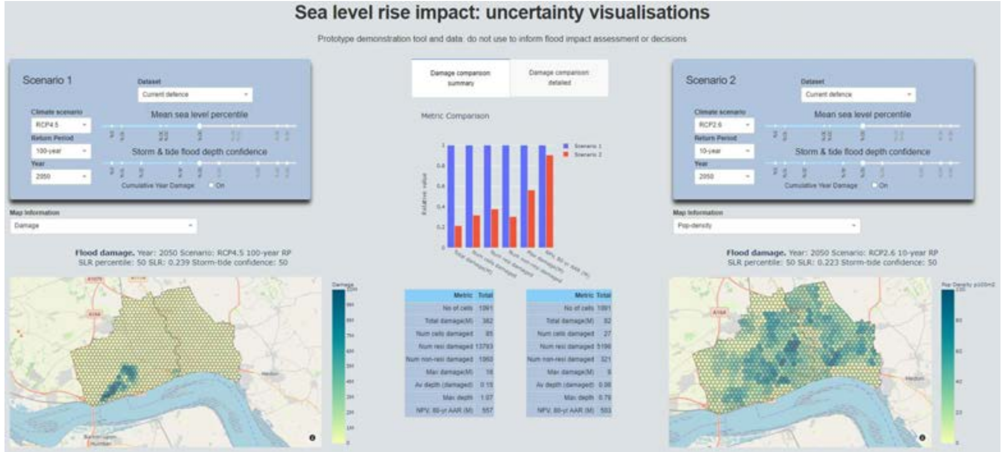
1: The Humber Bridge is the gateway to Hull, the UK city with the second-largest number of properties at risk of coastal flooding

2: The tool shows the impact of some of the more extreme climate change projections

3: While the data and test case are currently based on Hull, the scope of the project has vast potential beyond the UK



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21,350 scenarios, producing 10 million data points. Arup then worked with data scientists who mapped this data onto 100,000 properties in Hull that are potentially at risk due to the more extreme events, and added economic flood damages.

Thanks to its interactive interface, the sea level rise insights tool has given users and decision-makers the ability to explore a vast range of possible future scenarios and effects. It will allow them to develop a deeper understanding of how sea level rise may affect coastal properties, and when this may happen, to aid future planning.

Mapping out uncertainty

While a great deal of modelling science is published by the IPCC, resulting in a huge spread of scenarios, there is still a lot of uncertainty about what could happen later this century. And there are still many conversations around how we can work out what to do now, based on varying situations. Simply put, because there is so much uncertainty, at present we don't know if the rise in sea levels will be under 500mm or over 1m. There are some aspects of ice sheet dynamics that are highly uncertain and not generally included, but they could add a further 700mm to worst-case projections.

What Arup has done with the sea level rise insights tool is to bring the results to life and let users explore these for themselves. Currently, it is uncommon for funding and financial planning to delve further than the next 30 years to show what might happen. Arup's tool allows people to think about some of the more extreme potential impacts later in the century, going up to the year 2100, to show what might happen – knowing that coastal defences won't get built now, but being able to at least consider prospective needs for future defences, or even planning to live with flooding.

In the conventional approach, policy-makers and planners typically begin with the science, then look at the engineering analysis of flood damage, and then at the economics. Decision-makers consider what they will spend to stop a certain scenario from happening. However, the current approach doesn't allow more speculative questions to be asked about all possible scenarios. What level of event are we protected from in a middle-of-the-road, high emissions scenario verses a low-probability, medium emissions scenario? The tool is designed so a user can build up a wide range of scenarios, with the results being visualised through the tool interface.

Unravelling how to communicate climate change

One of the challenges the team faced before creating the tool was the initial unpicking of the problem. How can the uncertainty be communicated? How can it be broken into component parts? The answer was through modelling and data science which brought the varying scenarios to life. It's a big question that Arup is trying to answer, and it is challenging to give it shape and work out where to start.

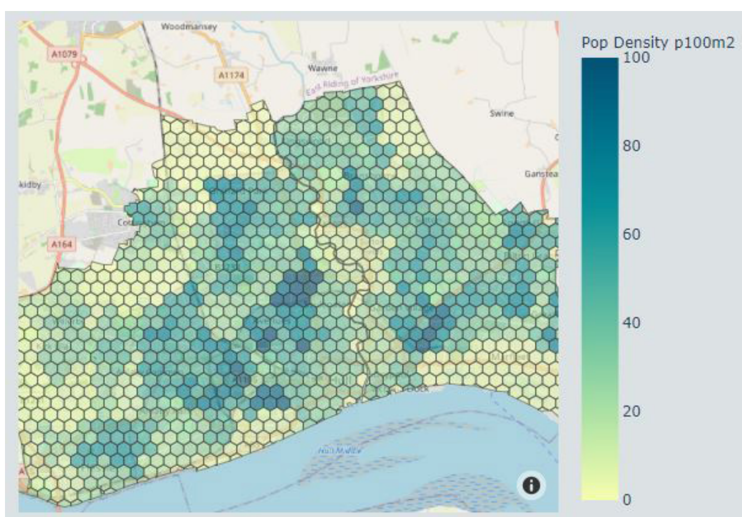
Alongside this challenge, the team also tried to communicate to people the need to question the status quo regarding climate science, and to think around it. At present, sea level rise is considered in practice, but it is done in a formulaic way. One of the concerns is that the right questions are not being asked, nor are we looking far enough into the future. The tool aims to mitigate these issues and give users the full spread of options to take into account in the early stages.

While the data and test case are currently based on Hull, the scope of the project has vast potential beyond the UK. It could probably be used globally following the same methodologies. The aim of the tool is to allow people to interact with problems at their specific location.

Sea rise levels have a temporal aspect to them. People think of the process as happening quite slowly, but if or when ice sheets melt, it can potentially progress quite quickly. There may be vast shifts in impact in a process that is currently not well understood, particularly if it begins 50 years earlier than expected. The sea rise level tool will allow users to consider these impacts.

Arup hopes that this is just the beginning of greater consideration of how rising sea levels will affect policies, future planning and the construction of cities. This project showed how a commercial organisation can successfully collaborate with third-level institutions and public bodies to influence the way fundamental science is studied and used. It's a prime example of where industry focus can help guide academic research and give a tangible outcome. The firm hopes this will be the start of further collaborations.

In the future, the tool can potentially be applied to towns, cities and regions around the world so that they can make better decisions to prepare for climate change – and, just as importantly, help explain these decisions to the public.

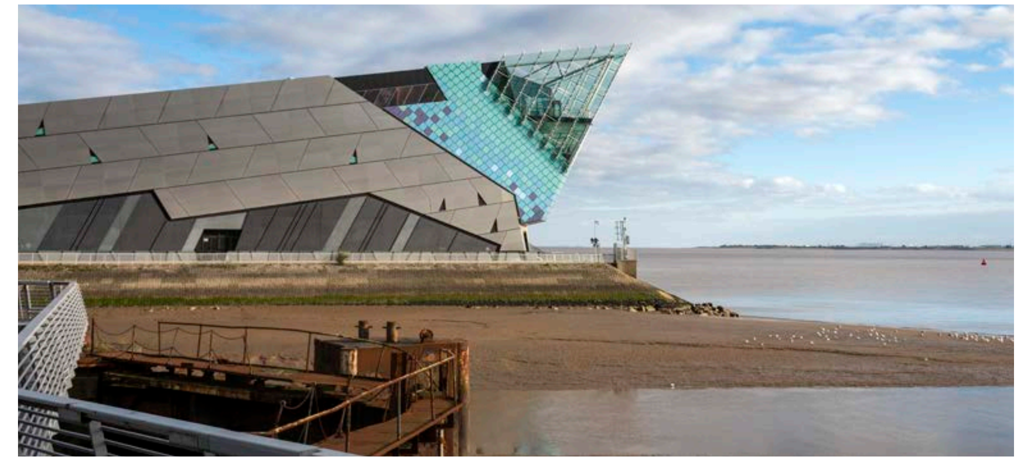


6.

4: The web-based portal allows users to explore different scenarios and visualise a spread of results

5: The modelling incorporates sea level rise, wave overtopping, and the ways in which flood inundation spreads inland

6: The tool can map a number of different metrics against sea level rise, such as population density



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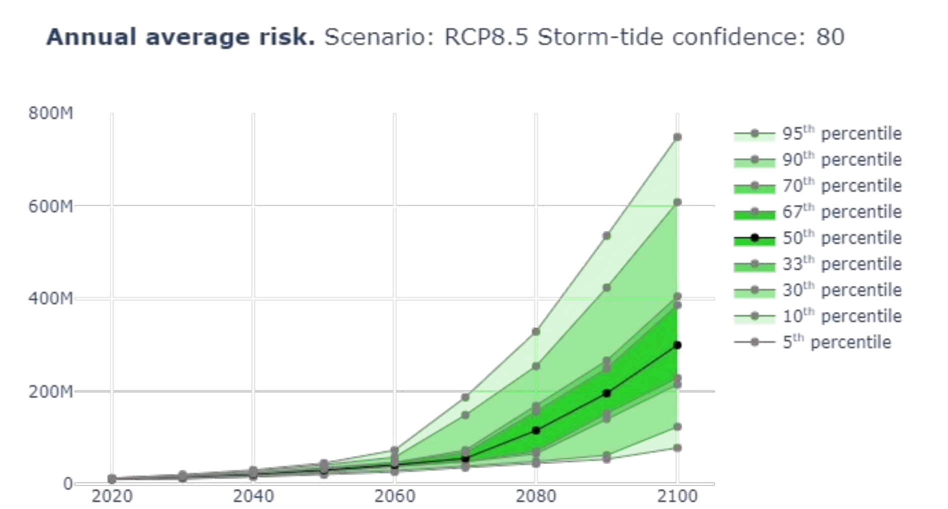

7.

7: The tool visualises the risks of different scenarios to help guide decisions about both flood risk mitigation and future urban planning

8: Arup worked with data scientists to map the modelled data onto 100,000 buildings in Hull that are potentially at risk from the more extreme events

Authors

Mike Dobson is a flood risk management specialist and was the technical lead on this project. He is an Associate in the Liverpool office.

Steven Downie is a fluid dynamics specialist. He is an Associate in Arup's specialist technology and research team in the London office.

Project credits

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Stakeholder The Environment Agency

Digital development collaborator CADA Consulting (Richard Eyres)

Flood risk management, foresight, water engineering Arup:
Dom Ainger, Mike Dobson, Steven Downie, Beccie Drake, Mark Fletcher, Louise Parry.

Image credits

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2-4, 6, 7: Arup
5: Paul White Photography
8: Paul Carstairs/Arup

The shape of sound

A dramatic performance space that emulates the irregularities of a natural rock formation

Authors Justin Fan, Xin Jin, Peng Liu, Vincent Wen

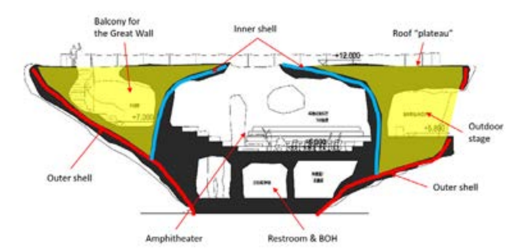
1.

Chapel of Sound is a stunning new concert venue set in a dry riverbed beneath the Great Wall of China, in the mountains north-east of Beijing. The 790m² building rises from the valley floor like a boulder from a prehistoric age. This 12m-high geological form houses two performance spaces – a semi-outdoor amphitheatre and an outdoor stage – as well as viewing platforms for taking in the majestic mountainside views. Made almost entirely from dark-grey in-situ concrete, which is exposed throughout, these are raw, elemental, almost primitive spaces. There is no decoration and, for the most part, no mechanical heating or ventilation – just several crevasse-like openings that draw in the sky and surrounding landscape, as well as the sun, wind and rain.

Until very recently, such a building would have been inconceivable. Designed by OPEN Architecture, with Arup as structural and building services engineer, its asymmetric, cantilevered structure was only made possible through the use of extensive parametric modelling. Likewise, the use of natural ventilation and passive thermal comfort, for a structure subject to direct solar radiation and heat gain from the audience, required a 3D computational fluid dynamics (CFD) model to assess airflow and internal temperatures.
The remarkable amphitheatre, which uses no acoustic materials other than concrete and air, assumed its final form only through a detailed process of collaborative simulation by the structural team and theatre consultant, led by the architect. It may appear low-tech, but the Chapel of Sound shows how cutting-edge digital design can harness the forces of nature to mesmerising effect.

Initial concept

Chapel of Sound is a new kind of regeneration project for China. The site is next to the small village of Wudaoliang in Hebei Province, two hours' drive north-east of Beijing. Like many similar communities, the local population has dramatically reduced in recent decades as inhabitants moved to the cities for employment. Developer Aranya's idea was to stem this tide with a resort of country retreats for Beijing residents, thereby generating work for villagers and revitalising the local economy. Aranya approached OPEN Architecture with an initial basic brief for a concert hall that would act as the centrepiece.



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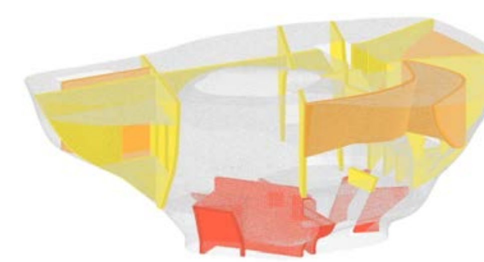

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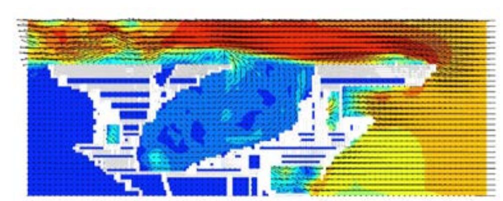


4.

1: The 790m² building rises from the valley floor like a boulder from a prehistoric age

2: The venue houses two performance spaces: a semi-outdoor amphitheatre and an outdoor stage

3: The parametric model made it possible to locate the stress points of the structure

4: A 3D CFD model was used to optimise natural ventilation performance


5.

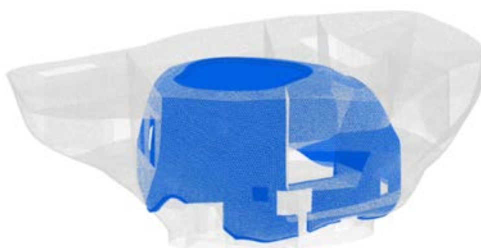
5: The Chapel of Sound is set in a dry riverbed beneath the Great Wall of China, in the mountains north-east of Beijing


6.

6: OPEN Architecture created a model of the building at concept design stage

OPEN's response was driven both by the rugged landscape and also by the way that sound behaves in nature. The architects were fascinated by the quality of reverberation in spaces such as caves, and wondered whether they could create a building with a physical form dictated by the acoustics of the interior – and, by extension, an acoustic dictated solely by the physical form of the building. They studied the contours of shells, wooden instruments and the human ear to design an organic performance chamber that would distribute sound evenly throughout the space.

Externally, the architects gave the building a similarly sculpted appearance. Wanting to keep the environmental impact on its mountainous surroundings to a minimum, they developed the boulder shape as a means of touching the valley floor as lightly as possible. Rising up and outwards from a 12m x 14m base, the chapel would grow through asymmetric curves and cantilevers to a 24m x 36m flat roof slab. In section, it looked like a ship roughly hewn from granite; in plan it was more like the body of a guitar, complete with an amorphous 'soundhole' above the amphitheatre.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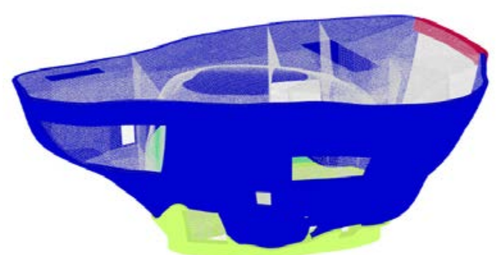
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7: The inner irregular dome houses the main amphitheatre

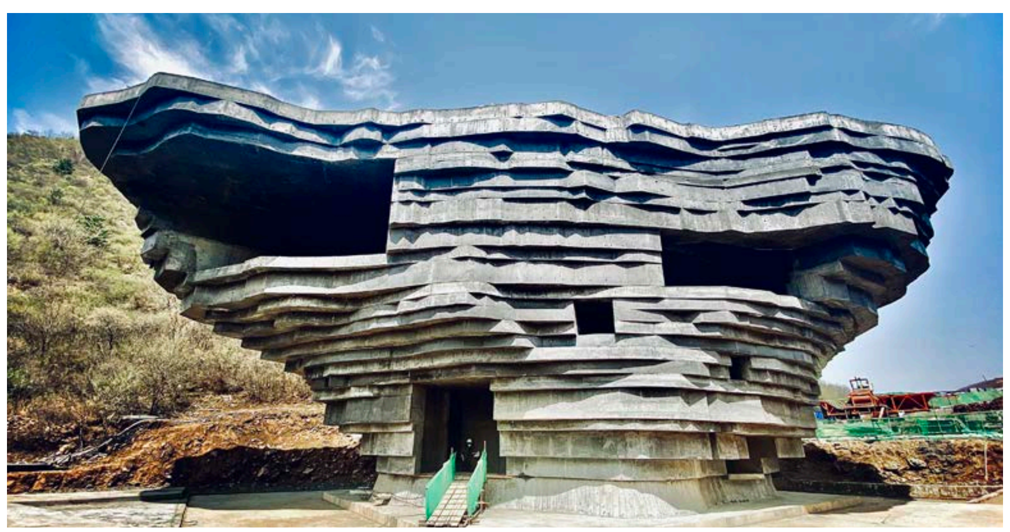
8: The cantilevering outer structure is connected by fin walls

9: The building rises up and outwards from a 12m x 14m base to the 24m x 36m flat roof slab

Refining the structure

OPEN made a handcrafted model of the building, which was 3D-scanned. Arup's structural team then imported the geometry and used Rhino with Grasshopper parametric software, as well as a structural modelling plugin developed by Arup in-house, to explore the structural forces at play. To counter the strong overturning forces of the top-heavy form, the team proposed a double shell – an inner irregular dome housing the main amphitheatre and the cantilevering outer structure – connected by fin walls.

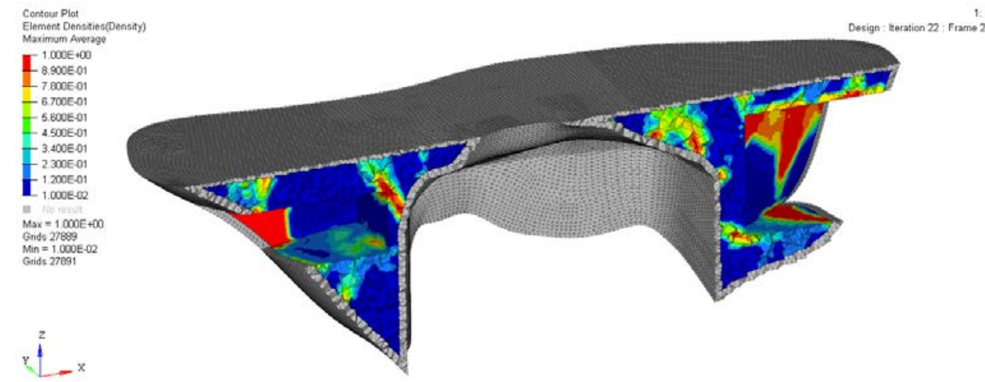
Using the parametric model, the team were able to locate the stress points of the structure, which determined the position of the fin walls. They also fine-tuned the external shape, again using an algorithm to 'form-find'. Some of the curves were rationalised and the largest cantilever, some 12m from ground to roof beneath the upper-level terrace at the south end of the building, was reduced by about 1m.


9.

The digital model was shared on a collaborative platform, which meant that the structural and architectural design could be advanced in tandem. As the structural design progressed, so too did the layout of the functional areas. The canyon-like void between the two shells provided space for two stairways: one from the south-west corner up to the amphitheatre seating, and the other from the main, south-east entrance up to the terrace, with its views over the Great Wall. At the wider, southern end of the building, an outdoor stage was carved into the outward-leaning shell, elevated 6m above the ground. The positioning of the fin walls was also refined, in order to balance structural and programmatic requirements.

To realise the sedimentary look for the external and internal surfaces, Arup articulated the walls as a series of steps attached to the structural shells. This inverted ziggurat shape worked aesthetically, as it echoed the strata of surrounding rock formations, and internally it meant that tiered seating could be incorporated into the shell, adding to the monolithic feel.


10.


11.


12.

Crucially, it also made the structure more buildable. Although different construction methods, including 3D printing, had been considered, casting the concrete shells in situ was the most viable option, due to the remote location of the project site and the available workmanship, avoiding the requirement for sophisticated machinery and minimising the cost. The rationalised curves and stepped geometry, although still highly complex and irregular in form, meant that the timber formwork could be drawn in two dimensions and constructed from straight panels. The steel reinforcement design could also be distilled into vertical and horizontal planes and was categorised as either primary rebar, following the internal shell form, or secondary rebar to support the mini cantilevers at each step.

Collaborative design

The iterative design process continued, with all digital input from architects and structural, acoustic, mechanical and electrical engineers merged into one single parametric model. This was vital, as – without any additional materials or finishes – the structure plays a large role in various other aspects of the building.

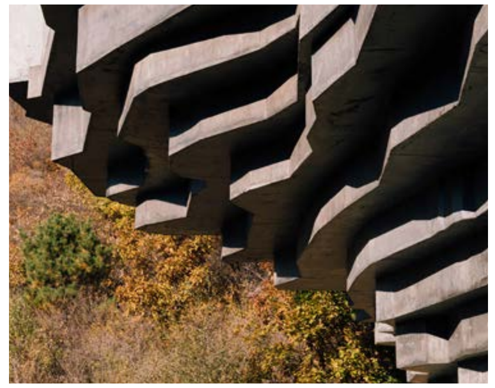
For example, acoustic simulations using a 3D digital model were integral to the design of the stepped walls. The sound quality of the amphitheatre depended entirely on just two variables: the concrete structure and the formed openings in the roof and walls. In the absence of absorption panels, these openings could counteract the reverberations off the hard, reflective surfaces. The simulations showed how slight adjustments to the angle of individual step faces or the size and shape of openings could shift the balance between reflection and absorption. By collaborating on a shared platform, OPEN, Arup and the theatre consultants could make incremental revisions to the shared model to find the optimum relationship between sound and structure. A similar approach was adopted for the outdoor stage, where the walls are precisely slanted to reflect sound onto the lawn below.

10: OPEN, Arup and the theatre consultants made incremental revisions to the shared digital model, to optimise the relationship between sound and structure

11: Using the parametric model, the team were able to determine the position of the fin walls

12: The outdoor stage was carved into the outward-leaning shell

13.



14.

13: A full-scale mock-up was made of the most challenging area of the outer shell

14: The final concrete mix incorporated local, mineral-rich crushed rocks to create the specified charcoal-grey tone

The openings in the roof and walls were also strategically positioned to provide natural ventilation to all spaces, apart from the air-conditioned toilets and back-of-house areas beneath the amphitheatre. Again, collaborative design in a virtual environment was critical to exploiting the structure to provide thermal comfort. Arup built a 3D CFD model to explore the microclimate effect of different design conditions in high summer temperatures. Various dimensions and configurations of openings were modelled and analysed, resulting in the decision to create a large cut-out on the south-west elevation, in the direction of the prevailing wind. The cloud-shaped aperture above the amphitheatre encourages cross-ventilation, expelling the air as it warms, which in turn pulls in fresh air from the south-west. The void between the inner and outer shell, which varies between 700mm and 800mm at the top of the structure, also plays a thermal role. Beneath the 200mm-deep roof slab, which is exposed to the sun, the airflow acts as an insulating layer, protecting the inner shell and the spaces within from heat gain.

Where services routes are required, they were embedded in the in-situ concrete alongside the steel reinforcement, or cabled through the void between the two shells. Circular lighting for the stage areas was cast into the exposed concrete soffits.

The semi-open structure does present the issue of shelter from the rain, particularly as summer concerts coincide with the monsoon season in this humid region (about a quarter of Hebei Province's annual rainfall can occur in July). The solution, inspired by the Pantheon in Rome, has been to drain the space through discreet holes in the gently sloping floor – another example of passive design that works with, rather than against, nature.

15.

15: The skeleton of steel reinforcement comprised 7,850 vertical and 3,500 horizontal rebar elements

Building the boulder

The concrete works commenced in May 2018 and were completed in April 2020, with work pausing for seven months during the harsh local winters. Before work could begin on site, the design team made a number of 3D-printed physical models which the local contractor could investigate and take apart, to better understand the geometry of the structure and work out the best way to build it. A full-scale mock-up was made of the most challenging area of the outer shell, to flag up any potential problems with the concrete pour.

Trials were also carried out on the concrete mix design, to make sure it echoed the surrounding terrain without simply imitating it. Many sample blocks were cast using various admixtures and aggregates, before a mix was selected that incorporated local, mineral-rich crushed rocks to create the specified charcoal-grey tone. To reduce the environmental impact of the project, the cement, aggregates and reinforcement were procured from local fabricators within 200km of the site. All concrete mixing was carried out on site.

The whole structure sits on a 1.2m-deep reinforced-concrete 13m x 20m raft, which required minimal excavation and was positioned to align with the gravitational centre of the superstructure. This provided a base from which to build the outer shell, which in turn was used as a platform to build the rest of the structure.

The first step was to build the skeleton of steel reinforcement, which comprised 7,850 vertical and 3,500 horizontal rebar elements for the inner and outer shells. Arup provided 3D shape coordinates for all the reinforcement, complemented by flat 2D drawings of each rebar. This meant that the rebar could be laid out on the ground, in plan, before being moved into position. The shell rebar was placed first, before the secondary step rebar. The position was double-checked using electronic distance measurers which calculated coordinates using the base plate as a reference point.

This steel skeleton then acted as a guide for the timber formwork, a jigsaw-like construction made from plywood sheets in widths of 400mm and 600mm. This enabled the internal shell geometry and outer steps to be cast as one monolithic element. Again, Arup provided 3D coordinates for all the formwork panels, as well as 2D drawings to ensure that the timber was cut to the correct dimensions and placed accurately. No wood was wasted: after the formwork was struck, it was recycled by a local furniture company.

16: The building has a viewing platform at roof level, for taking in the majestic mountainside views

16.

A large amount of temporary propping was needed, as the cantilevering structure was unstable until the roof slab was cast. The roof itself required an especially dense grid of reinforcement, as well as an extra 10-15mm of concrete cover, to control the risk of the slab cracking in the temperature extremes of the mountain climate. The exposed structure was finished with a jet-wash and a sprayed waterproofing layer.

The finished building is true to the spirit in which the Chapel of Sound was designed. The combination of advanced digital design and traditional construction techniques has delivered a space that is both close to nature and technically accomplished. The raw concrete interiors, accented with simple details such as brass signs and handrails, bring the craggy landscape into the human world of music. When the music stops, the lack of mechanical ventilation means that the space resounds with birdsong, the chirp of insects, wind and rain. The chapel, as its name suggests, is transformed into a place of quiet contemplation, filled only with the sounds of the mountains.

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Project credits

Client Chengde Aranya Real Estate Development Co. Ltd.
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Theatre consultant JH Theater Architecture Design Consultant Company
Lighting consultant Beijing Ning Zhi Jing Lighting Design
Contractor Heilongjiang Sanjiang Construction Group Co., Ltd
Building physics, mechanical, electrical and public health engineering, structural engineering Arup: Emo Chiou, Feng Wang, Jiao Li, Justin Fan, Joe Jiao, Peng Liu, Vincent Wen, Wendy Fan, Weng Feng Xu, Xin Jin.

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