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1.

> Arup's multidisciplinary design for Princeton University's new Frick Laboratory had to meet major challenges, balancing the rigorous vibration and cleanliness requirements of the laboratories themselves with the energy and resource conservation demands of the University's Sustainability Plan.

Frick Chemistry Laboratory

Location
Princeton University, New Jersey, USA

Authors
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Jeffrey Huang Sara Leitch Larry Ratz Chris Rush Andrew Smith Peter Tillson

Introduction

Founded in 1746 as the College of New Jersey, Princeton University is the fifth oldest higher education body in the USA, and one of the eight universities that form the Ivy League. The primacy of chemistry in its research agenda is equally historic.

The first undergraduate chemistry laboratory in America was established in 1795 by the physician John Maclean when he was appointed professor of chemistry at Princeton, and, as the university's website[1] states: "The discipline began its ascendancy then both in terms of its importance to science and its role at Princeton. Throughout the 19th century, chemistry was a required subject for all Princeton students."

The previous Frick Chemistry Laboratory was completed in 1929 with funds from a bequest of the 1919 will of the industrialist Henry Clay Frick. By the early 2000s it had become the oldest functioning chemistry facility in any US academic institution, with cramped spaces and ageing infrastructure, and the need for a replacement was increasingly obvious. Princeton selected Hopkins Architects to design a new building, as part of a strategy to attract leading research chemists. Hopkins collaborated with Payette Associates, a Boston architectural firm with prior experience on the Princeton campus, and Arup worked with

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both firms throughout the life of the project, providing structural, mechanical, electrical, plumbing, fire protection, façades, and telecommunications engineering, plus consulting services in acoustics and vibration, artificial lighting and daylighting, and sustainability. The old Frick Laboratory (Fig 2) is being decommissioned, and a study is under way to decide its future use.

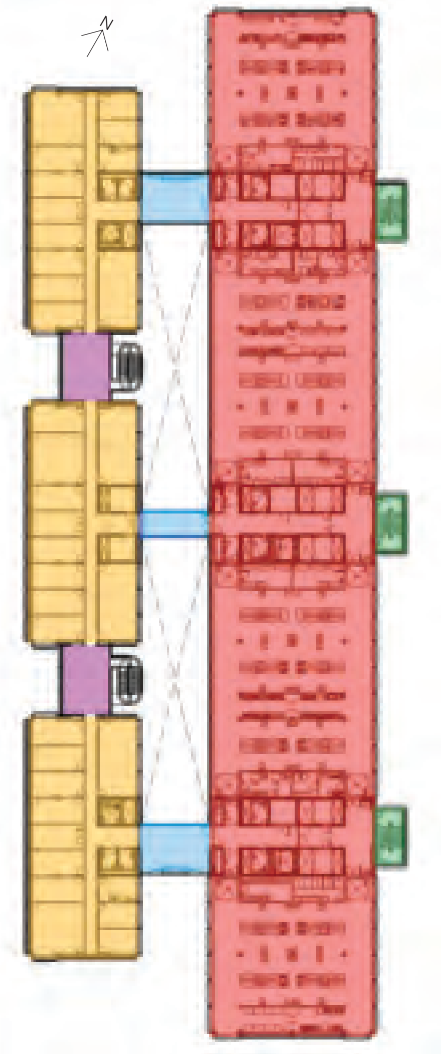
By creating a new Frick Laboratory, rather than renovating or expanding the existing, the University has made a significant investment in the Department's future.

Integrating teaching and research in one world-class facility, and locating it within the nexus of the new natural sciences neighbourhood, encourages interaction with adjacent departments including genomics, physics, and (eventually) neurosciences and psychology. One leg of the new Streicker pedestrian bridge (designed by the Swiss bridge designer Christian Menn and US infrastructure specialist HNTB) funnels visitors onto the plaza just in front of the main entrance to Frick (Fig 1). One of the other legs will connect to the new Neuroscience and Psychology Building, designed by Rafael Moneo/Davis Brody Bond and Arup.

1. (previous page) North building entrance with Streicker bridge (foreground), an important connection across Washington Road and a vital link between the neighbourhood buildings.

2. The first Frick Chemistry Laboratory, completed in 1929.

3. West/east cross-section and plan.



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Building overview

At 265 000ft^2 (24 620m^2), the $280M Frick Chemistry Laboratory is the second-largest academic building on the Princeton campus, designed to house up to 360 researchers. Overall it comprises two four-storey wings, one for laboratories and the other for offices, separated by a 27ft (8.2m) wide, 75ft (22.9m) tall glass-roofed atrium named the "Taylor Commons", running the length of the building (Fig 3).

The office wing houses 30 faculty members and 30 staff, while the larger laboratory wing can accommodate up to 300 graduate students, post-doctorate, and research staff on the upper floors, with laboratory space for hundreds of undergraduates on the ground floor. A basement level contains a 260-seat auditorium and vibration-sensitive research equipment.

There are four distinct programmatic elements: the research and teaching laboratories on the east, the offices at the west, the atrium in the centre, and the central instrumentation area in the basement.

The spaces were designed to maximise daylight and views, while allowing for easy and ample circulation between areas and floors. There are many formal and informal spaces for the varying disciplines to gather and mix, with the atrium serving as the main entrance and common focal point between laboratories and offices.

A servery at the southern end, run by the University's food service department, allows people to dine, relax, and converse in a well-furnished environment.


4.

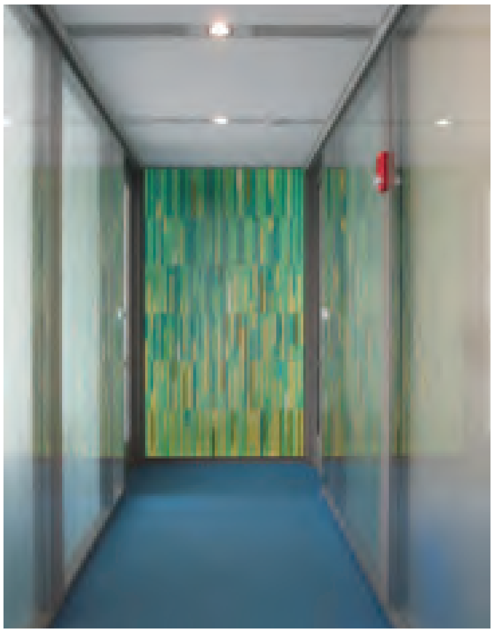
As part of Princeton's commitment to the arts, the sculptor Kendall Buster was invited to create a site-specific installation.
Her design, a large complex of hanging translucent constructions entitled *Resonance*, is intended to evoke molecular structures (Fig 4). The aim is to inspire the occupants and passers-by, while breaking up the cavernous atrium space and drawing it down to a more human scale. The artist Paul Housberg was also invited to install his characteristic coloured and fused glass at backlit end walls of the office corridors (Fig 5). This not only warms a building in which glass and metal surfaces are generally prominent, but also serves as a wayfinding cue in a visually repetitive area.

Central to the design philosophy was maintaining transparency and so putting the chemistry on display. This was achieved by exposing much of the mechanical and plumbing systems, allowing the occupants to connect with the industrial nature of their work. Ample circulation with plenty of views to both the interior and exterior were also provided, with glazing on the atrium's east wall allowing views into the laboratories and vice versa (Fig 6).

4. The atrium, looking south; the various elements of the *Resonance* artwork break up the cavernous space at different heights.

5. Glasswork by Paul Housberg.

6. Internal atrium glazing.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Building for the future

Research continually evolves, so the building was designed to support flexibility of use. Future revisions to the space will be achieved more easily, since the infrastructure was designed to be fully modular and easily accessible. The Chemistry Department was clearly looking to the future, since at the completion of construction documentation, only about half the spaces had named research occupants. The remainder of the building was to be fitted out for the specific research needs of subsequently recruited faculty members.

The complex and diverse nature of modern chemistry research required both the architects and Arup to review the existing facilities to determine specific working requirements. The intent was not to replicate the setup in the old building, but place the equipment in a completely appropriate contemporary setting. Many interviews and site visits were conducted to help define these requirements, as well as visits to the institutions of newly recruited faculty. Many collaborative meetings with researchers allowed the design team to optimise and tailor the spaces to individual needs.

Project framework and structural design

The building's structure is split into four zones, each with separate criteria:

- the ground floor and basement
- the laboratory building
- the cantilevers that support the office floors adjacent to the atrium on the upper three floors.
- the remainder of the office building.

The office wing provides faculty and administrative offices in interconnecting pods arranged by research areas. Each floor has social spaces and conference rooms, as well as senior faculty offices that include a group room, private space, and a mini-balcony accessed by a sliding glass door.

7.

The laboratory wing is a series of repeating modules, where scientists work in high-ceilinged spaces with extensive glass providing views and a sense of openness. The lighting design helps to visually unify the two wings, with a vocabulary of round fittings in public areas and linear fixtures in working spaces.

The design also creates a stimulating environment for other users of the building by putting experimental chemistry on display. Much of the lab spaces are visible across the large glazed atrium. The NMR (nuclear magnetic resonance) laboratory is visible through glass to those descending the stairway to the auditorium from the main entrance (Fig 7), as are many of the other central instrumentation rooms.

Three highly architectural bridges, with exposed fabricated steel structures and slender depths, connect the laboratory and office wings across the atrium on each of the upper floors.

Although they are thus linked, the wings are separate structures. The atrium roof is fixed to both sides, flexible enough to accommodate the movement of both buildings while being strong enough to take the forces imposed by those movements. On Arup's advice, the architect increased the roof height so that the columns would be long and flexible enough to bend and deflect. The bridges are also designed with a movement joint on the office wing side to allow them to slide and prevent axial loading (Fig 8).

Because the façades of the upper three floors of both wings sit at the ends of long cantilevers, a high concentration of primary steel was used to support them. Deep wide flange beams cantilever from the inset columns to support the floor and façade.

Two design criteria governed the cantilever beam design; firstly, control of deflections under the façade loads, and secondly, control of floor vibrations due to occupant movement. Arup liaised between the façade manufacturer and the main steel contractor, ensuring that this primary steel met façade tolerances by co-ordinating all details in 3-D and repeatedly visiting the steel contractor's workshop.

The external façades of both the office and laboratory wings are extremely heavy, with large gravity loads from their various components. The granite panels along the pedestrian colonnades (Fig 9) and the cast aluminium sunscreens elsewhere break up the mass of the building, which is also visually defined by the copious glazing. The façades were also designed to stiffen the edges of the floors to reduce vibration.

Three concrete cores designed for seismic loads stabilise each wing. This simplified the design process by eliminating the need for any special seismic treatment to the building's overall steel structure. The cores also contain elevators and service risers. All the main steel columns extend the full five-storey height of the building.

Three types of stair facilitate vertical integration of the disparate chemistry groups: the internal stairs from the ground floor to the basement (Fig 10), the social space stairs, and the egress stairs. All are architecturally expressed, with glass balustrades and highly detailed steelwork. The Arup team had to integrate the services – including pipework for the fire protection and conduit for lighting systems – into these exposed and delicate structures, incorporating them within the central support columns (Figs 11-12).

The egress stairs are integrated into and support the façade (Fig 13), which hangs from the stairwell with small connections at each level. Arup conducted extensive buckling analysis of the slim columns and asymmetrical floor plate connections to assess the viability of this design.


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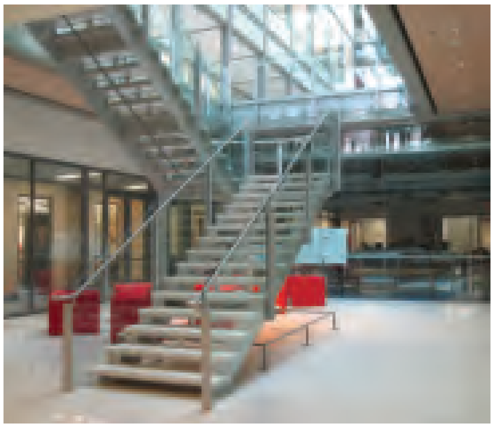
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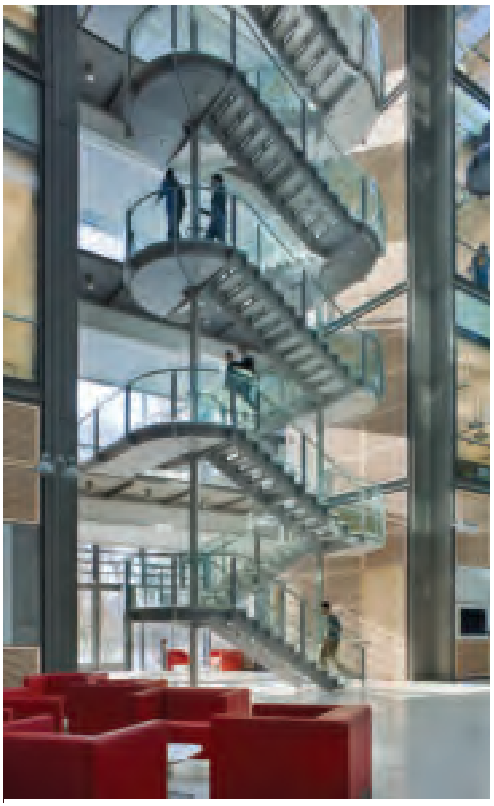
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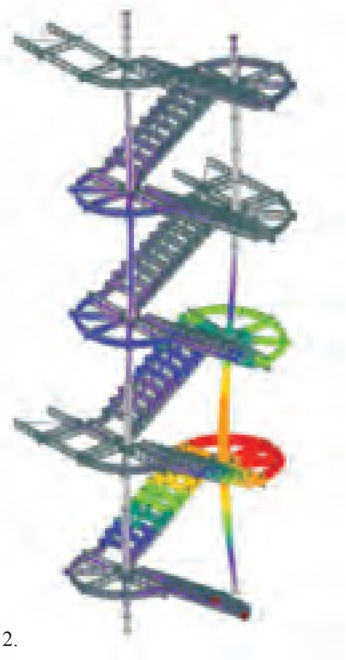
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7. The NMR laboratory.

8. Movement joint at the offices wing side of one of the three bridges across the atrium.

9. Colonnade and external shading devices.

10. Stair from atrium to basement with NMR suite behind glass.

11. Internal social space stairs.

12. Advanced analysis model of social space stairs.

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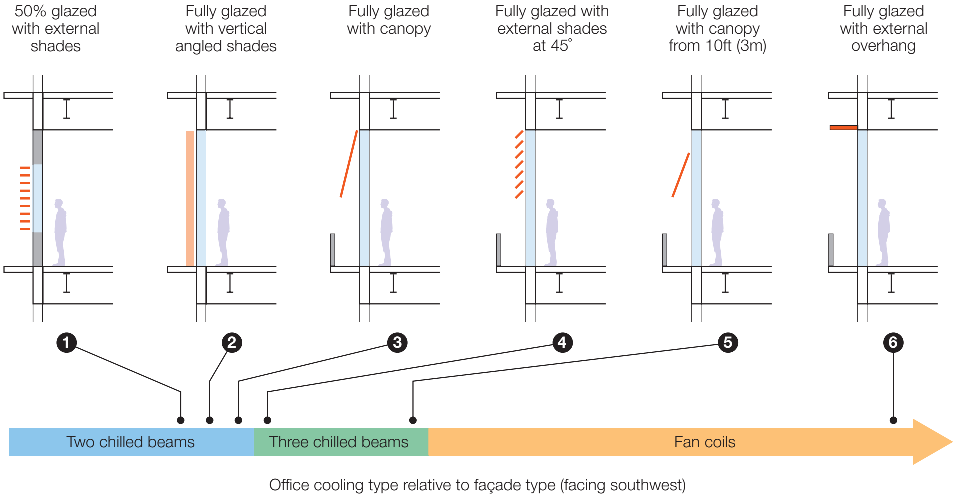
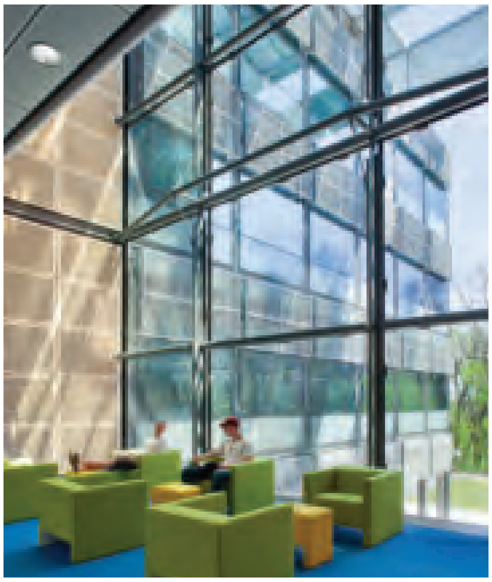


Office cooling type relative to façade type (facing southwest)

14.



15.

13. East laboratory façade with three external egress stairs.

14. Options in developing the façade design, and their energy use consequences.

15. The façade design balances concerns about heat gain with the desire for external views.

16. Rainwater reclamation.

Sustainable design

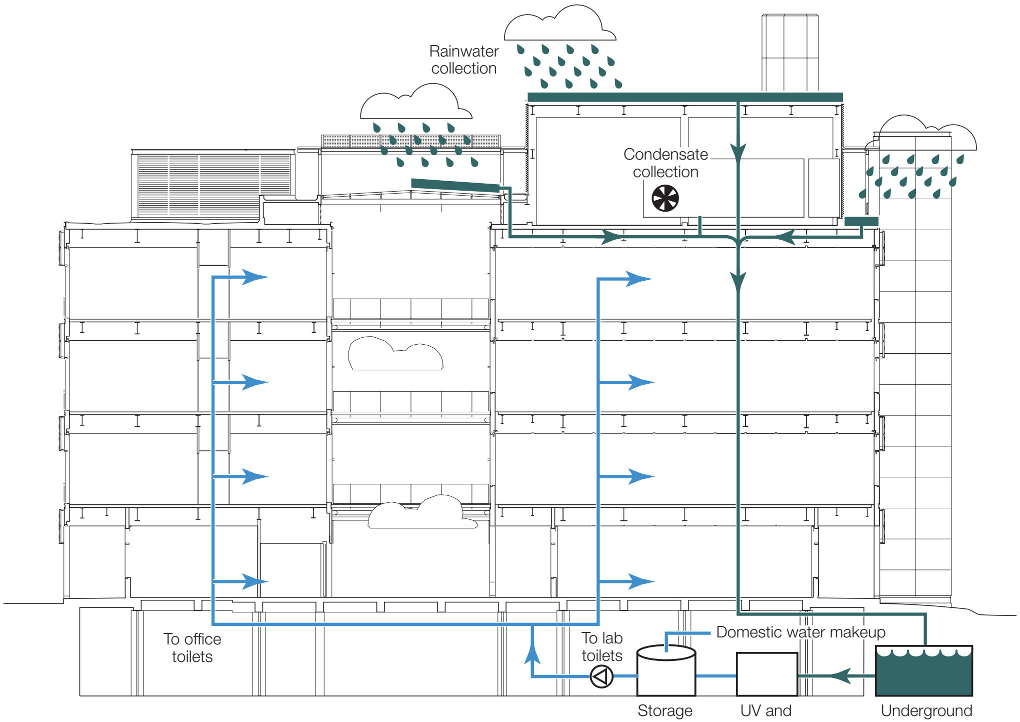
In 2008, Princeton published a Sustainability Plan highlighting three primary goals: reducing greenhouse gas emissions, resource conservation, and research, education and civic engagement. The University drew on advice from Arup in an earlier project to create these campus-wide environmental standards and guidelines.

The new Frick building is the first project to which Princeton has applied its aspirational new sustainability guidance, making sustainability a key element of Arup's work on it. The University was aware of laboratories' high energy needs, and wanted the new building to use no more energy than the smaller one it was replacing. Arup translated these principles into practice through monthly week-long workshops, developing the approach to sustainability in concert with the client's own engineering and facilities staff.

Throughout, Arup conducted lifecycle cost assessments of six components of the building, covering energy (solar thermal heating, photovoltaics, atrium ventilation schemes, and fume hood types), water (rainwater collection and reuse) and façades (laboratory perimeter heating). The analyses considered the initial cost of implementing these technologies as well as the lifecycle costs over 50 years.

Development of the façade was influenced by conflicting demands: to increase the views to the leafy exterior, and the amount and quality of daylighting in the interior spaces, but also to minimise heat gain and loss. To achieve the greatest energy saving, a fine balance had to be struck between the amount of glazing and internal and external shading. The team also conducted parametric modelling of heat loads from varying types of façade, which ultimately influenced the ceiling layout by optimising the quantity and placement of chilled beams and light fixtures (Figs 14, 15).

Daylight sensors along the façade allow fixture dimming in response to exterior conditions – a highly efficient lighting design that enables the use of natural daylight whenever possible. In addition, energy-efficient fluorescents with occupancy sensors minimise the use of electrical lighting, while internal user-operated scrim shading reduces heat loads and glare.



16.

The team also undertook multiple energy analyses, comparing the planned project with a code-compliant building of the same geometry on the same site. Through many iterations, Arup achieved a 24% site energy cost reduction over *ASHRAE 90.1*[2].

Stormwater from the laboratory portion and atrium roof, and condensate generated by the laboratory air-handling unit (AHU) cooling coils, are collected and reused for non-potable purposes, reducing the building's freshwater usage (Fig 16).

Working with the site civil engineer, plans were developed for a 12 000 gallon (54 550 litre) cistern to collect stormwater. After mechanical filtration and disinfection by UV light, the water is coloured and distributed for the entire building's toilet flushing system. During periods of low water collection (eg winter), an automatic domestic water makeup valve tops off the main collection tank.

Stormwater collected from the office side is discharged into a highly landscaped rainwater retention area, which helps to reduce the instantaneous discharge of stormwater as well as provide additional irrigation for the plantings.

To help disseminate information to both occupants and visitors, a building dashboard is installed near the front entrance of the building, displaying its sustainable and energy-saving features. Using a series of calculation algorithms based on measured data from the building management system (BMS), energy and other resource usage is tracked throughout the facility and displayed as a comparison to a conventionally designed and operated building. With it, the University intends to link all major new buildings to a campus-wide network to allow visitors to monitor and track the information across the campus.

17.

Arup project delivery and design process

This project drew on Arup's global reach, with team members in different locations providing expertise on the full range of services within the project's scope. A London-based team initially worked with Hopkins, an architect with whom the firm has enjoyed a close working relationship. Early in the design, members of the New York team went to learn about the project and work side-by-side with their London colleagues.

As the design progressed, the project moved to New York, relying on local knowledge of codes and co-ordinating with the building users as the design became increasingly focused on specific client needs. Some of the London team travelled to New York to complete the construction documentation, participate in construction administration, and oversee the early construction stages. It then became a New York-only job through construction. Overall, the project also built on past Arup expertise in laboratory design.

The services and structural engineers collaborated on 3-D design that took integration to the highest level (Fig 17). For example, a huge number of drawings were created for positioning holes in the structure, particularly the highly serviced laboratory wing. This high level of co-ordination from early in the design contributed to the completed building's ease of reconfiguration for future use, servicing, and maintenance.

The design team spent more time working with the contractors than on most projects to date, helping to co-ordinate 3-D work by all the trades. The 3-D design and co-ordination on this project has helped develop that expertise in the office. The design work began with the development of individual drawings by both Arup and the contractor, followed by intensive collaboration between the two. This New York-based process was pioneered on this project.

17. The new Frick Laboratory's structural and services systems were modelled entirely in 3-D.

18. Contour plot of laboratory floor, highlighting peak accelerations within the corridor and very low levels within the laboratory spaces.

19. Piping and ductwork at laboratory building perimeter.

The laboratory wing

A constant theme throughout the design of the laboratories is modularity, allowing for changes to the building systems to accommodate a range of research as the space requires.

Vibration was a major structural design criterion in the research laboratories, where experiments are conducted using microscopes, lasers, and other sensitive equipment. Each unique laboratory was categorised according to its tolerance to vibration, which helped to define the best locations for sensitive and ultra-sensitive equipment. Some, such as the electron microscopes and NMR imaging devices, require vibration levels many orders of magnitude below the threshold of human perception. These were segregated to the basement, where extremely low floor vibration levels could be provided.

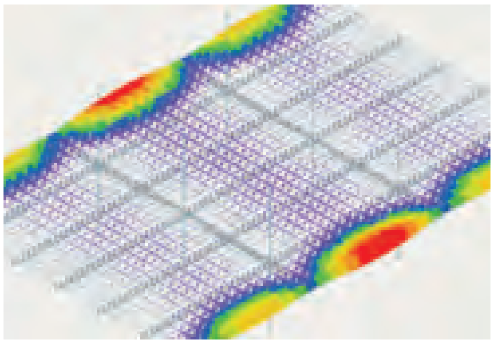
The 21ft x 31ft 6in (6.4m x 9.6m) column grid on which the building is structured allows a variety of floor loading. As this tends to be less stiff than smaller spans, the team developed a series of vibration models to calculate floor movements under various footfall inputs, leading to a cost-optimised design by identifying areas of acceptably higher and low vibration levels that met the University's criteria for the laboratories (Fig 18). The areas near columns are stiffer and can be used to support more sensitive equipment, while corridors and cantilevered areas were designated for non-critical use, where these limits could be exceeded. The increased mass of the floor sections in the middle bays of the building evened out the stiffness throughout the floor framing and created an efficient structural system for the layout and performance criteria.

Some columns were placed in-board of the façade by 10ft 6in (3.2m), with the edge zones of the floor plates devoted to non-instrumented space. Vibration up to 16 000µin/sec is permitted in these cantilevered "ghost" corridors along the building's perimeter, compared with 2000µin/sec maximum within the laboratory spaces. Cantilevered glass half-bays, 10ft 6in (3.2m) long, create the appearance of a slender colonnade, while the façade is simultaneously used to reduce vibration. This is a highly serviced area, with integration allowing the piping and ductwork to run down the corridor (Fig 19). Beam penetrations were required in these areas to allow future reorganisation of the laboratories without resorting to lowering the ceiling.

The laboratories are categorised as teaching (ground floor) and research (upper floors). In the latter are installed some 240 high-efficiency Waldner fume hoods with automatic sash closers – the first large-scale installation for Waldner in the US. To ensure that all communication protocols would be translatable between different platforms, units, and languages, many meetings took place between the University (environmental health and safety, engineering, maintenance), design team, controls provider, and hood manufacturer.

Waldner hoods are characterised by highly repeatable, low face velocity containment, and utilise airfoil surfaces on the horizontal and vertical surfaces of the hood openings. An additional internal fan boosts entrainment at the bottom horizontal and side posts to ensure laminar flow with full containment at a face velocity of 60ft (18.3m)/min, in accordance with *ASHRAE Standard 110*[3].

The teaching laboratories on the ground floor use constant-volume high-efficiency Thermo Fischer fume hoods, which also provide containment at 60ft (18.3m)/min, but are more prone to cross-draft issues than the Waldner hoods. Each teaching laboratory has 20-40 hoods, totalling around 150 on the



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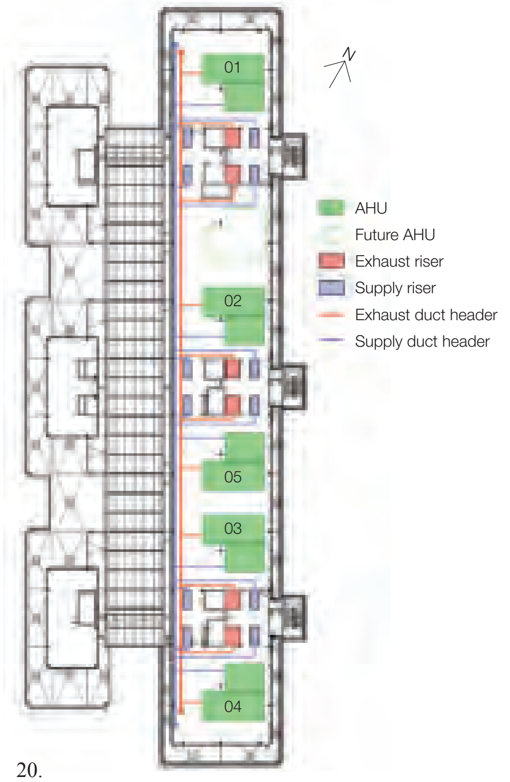
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02
05
03
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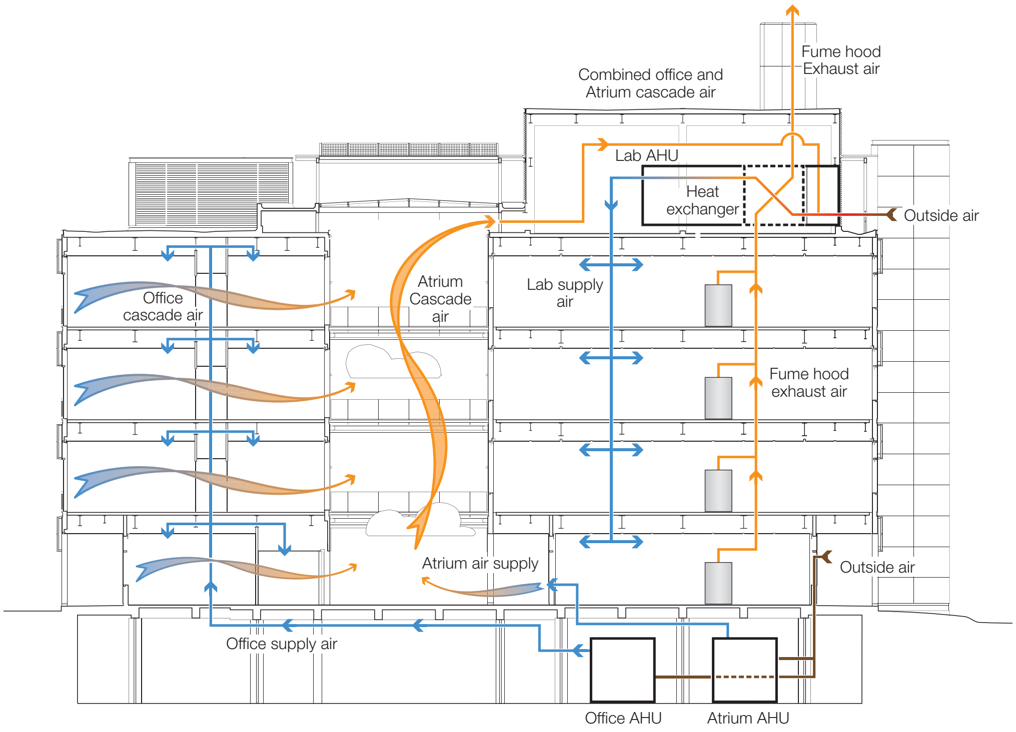
AHU
Future AHU
Exhaust riser
Supply riser
Exhaust duct header
Supply duct header

20.


Fume hood
Exhaust air
Combined office and
Atrium cascade air
Lab AHU
Heat
exchanger
Outside air
Office
cascade air
Atrium
Cascade
air
Lab supply
air
Fume hood
exhaust air
Atrium air supply
Outside air
Office supply air
Office AHU
Atrium AHU

21.

22.

ground floor. When a class is in session, all hoods in the laboratory are turned on, and sequencing them was critical to avoid air surging in the duct riser systems, and ensure a slow ramp-up of exhaust and makeup air for the spaces.

Because of the anticipated diversity of hood use, a headered duct distribution system was designed to equalise airflow across the building and allow each AHU to be run at its optimum point. With the arrangement of the penthouse, the building will accommodate one redundant standby and one future AHU in addition to the four duty units (Fig 20).

Most of the energy consumption is driven by the fume hoods in the laboratory wing. Reducing the amount of outside air thereby decreases the amount of conditioned air required by the once-through, 100% outside air laboratory AHUs. When of suitable condition, “used” conditioned air from the offices and atrium is returned to the laboratory AHUs, thus displacing outside air. This cascade air, in conjunction with high-efficiency heat recovery through refrigerant heat pipes within these AHUs, reduces the amount of energy required for the makeup air requirements of the laboratories (Fig 21).

House plumbing services to fume hoods and research benches include laboratory cold and hot water, laboratory vacuum, compressed air, nitrogen gas, natural gas, reverse osmosis and de-ionised water, laboratory waste, and venting. Special cylinder gases (eg argon, helium, oxygen, high pressure nitrogen) with pressure-reducing gas regulators are provided on an individual basis where required by the research.

All the water, gas, and vacuum distribution piping is on two sets of plumbing racks running below the ceiling and above the hoods and benches in the research laboratories, extending the entire length of the laboratory wing (Fig 22). This design approach supports flexible use and simplifies future plumbing connections to fume hoods, laboratory equipment, and research benches.

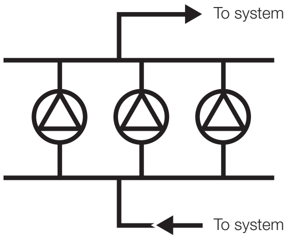
The house systems are served by the following:

- two hexaplex oil-free pump skids at each end of the building for compressed air in an N+1 compressor configuration up to 55psi (3.87kg/cm^2) at the furthest outlet
- One triplex vacuum pump skid for the teaching laboratories, and one quadraplex skid for the research laboratories, each of them in N+1 pump configuration up to 19in (480mm) of mercury at the furthest outlet.
- nitrogen from exterior bulk tanks (supplied by Praxair) at 100lb/in^2 (7000kg/m^2) at the furthest outlet
- two RODI skids at each end of the building to provide ASTM Grade III reagent water
- one triplex laboratory water booster pump.

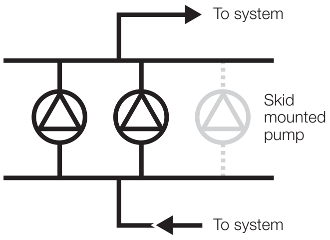
The variable speed motors as well as the multi-module skids provide energy savings for these house plumbing systems. Multiplex pumping systems allow pumps to be staged off when the building demand is reduced while increasing redundancy by staging the next pump on during a pump failure (Fig 23).

A helium recovery system was connected to an existing recovery station in an adjacent building to collect and compress spent gaseous helium to an acceptable pressure for reuse. While there are few users of liquid helium in the building, the rising costs (due to consumption) prompted the University to install the system. The interconnected piping is in solvent-welded PVC with ISO vacuum flanges and fittings.

General amenities on each laboratory floor include autoclaves and glasswashers for sterilising equipment, ice machines, and environmental rooms. Autoclaves and glasswashers require medium-pressure steam and compressed air to operate, while ice machines have water-cooled condensers. The environmental rooms are provided with remote water-cooled condensers. Experiments in these rooms tend to require long-term data acquisition, so a brief power failure can destroy months of work. Each unit is thus on optional standby power, and the condensers also have a once-through emergency city water backup system.



a) Three pumps running at high demand.



b) Two pumps running at reduced demand.

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20. Location of air-handling units.

21. Air/heat recovery.

22. Typical laboratory bay with fume hoods flanking a central bench, and overhead racked piping and ductwork.

23. Example of triplex pumping skid.

Below-grade research areas

There are special instruments with specific requirements that are better satisfied when segregated from other building and research activities. Such areas generally require very low vibration, the use of many house systems simultaneously (thus needing high unobstructed head heights), and the ability to control and block out stray light.

The basement research areas contain some specialised laboratory spaces, including those for catalysis, the protein centre, EPR/X-ray, and mass spectrometry. Various laser laboratories are also accommodated in the basement, and require art gallery-like environmental conditions. Multiple precision computer room air-conditioning units provide tight temperature and humidity control.

In addition, the large NMR facility sits just outside one of the stairways from ground to basement level (Fig 7, p6). These machines require a level of vibration as close as possible to zero, and sit on two 10ft (3m) thick concrete blocks, anchored to reinforcement embedded in the Princeton bedrock 8ft (2.4m) below ground level. The NMR pit, which is below the water table, was isolated from the rest of the building by perimeter joints to minimise vibration. It is enclosed by waterproofing that discreetly bridges the isolation joint.

Background frequencies of vibration in the bedrock and soil were evaluated to determine that none would exceed the criteria for the NMR. This affected the building and foundation design in that area, with the need also to minimise the amount of additional vibration from the surrounding building.

The systems supplying the NMR were also designed to be low-vibration through the specification of vibration isolation for rotating equipment and interconnected piping and ductwork. Many site visits carried out both during construction and later, when the equipment was in operation, ensured that the NMR facility would meet the stringent vibration requirements.

The entire laboratory also had a requirement for all materials to be non-ferrous. Nothing in a 20ft (6m) radius zone of influence was to be made of iron, including reinforcing steel; all metal had to be stainless steel, aluminium or other non-ferrous, or a non-metallic substitute. Miscellaneous structures (eg catwalks, ladders, and railings) and ductwork are of stainless steel, while all other piping in the area is copper, including the sprinkler system. All metal studs were replaced with wood – unusual in a commercial building of this scale.

Close collaboration between the acoustic, structural and mechanical engineers resulted in a design that meets the client's background airborne noise and vibration criteria for each of the building's occupied spaces. Particularly with the highly sensitive NMR laboratory, the effort was focused on achieving mechanical and structural systems performance at the desired acoustic level within the architectural framework of this complicated space.

The office wing

This wing comprises three main elements: individual private faculty offices, shared conference spaces, and social spaces for informal gathering (Fig 24). The mixing of private and public areas allows for both the research to be synthesised by the faculty, and for interdepartmental interaction.

Active chilled beams provide ventilation air and cooling for the office wing. Depending on the number of occupants and room volume, the quantity and capacity of the chilled beams were sized to match the cooling and ventilation need, as well as disperse the latent load for each room.

To provide a physical connection to the outdoors, all the private offices have operable doors to allow natural ventilation when outdoor temperature and humidity are acceptable, but to ensure that external doors are not opened while the room is being conditioned with building air, each has a link that reports to the BMS whether or not it is open. When a door is opened, the room enters a safety mode of shutting down the primary air and chilled water to each chilled beam to conserve energy and prevent condensation. Pipe surface temperature sensors are also distributed around the spaces for monitoring, and alarm when the pipe surfaces reach the space dewpoint.

24.

24. Social space with furnishings and views.

25. The café servery in the atrium.

26. Photovoltaic panels above the atrium roof.

25.

26.

The atrium

Study tables, a lounge, and seating for the catering servery (Fig 25) are accommodated in the atrium. Its glass roof maximises daylight and views, and a 216-panel 65kW rooftop photovoltaic array does double duty, generating electricity while providing shade, and ensuring that the space is not subject to excessive heat gains (Fig 26).

Arup initially indicated that installing sprinklers at the top of the atrium was not required because at this height, the smoke and heat layer would not be hot enough to set off the heads. However, the University required the sprinkler system. Later, when the Resonance artwork was designed, there was concern that it would obstruct the sprinkler discharge, covered as it is in translucent cloth-like material. A secondary system of side wall sprinklers was installed beneath the artwork to alleviate this concern.

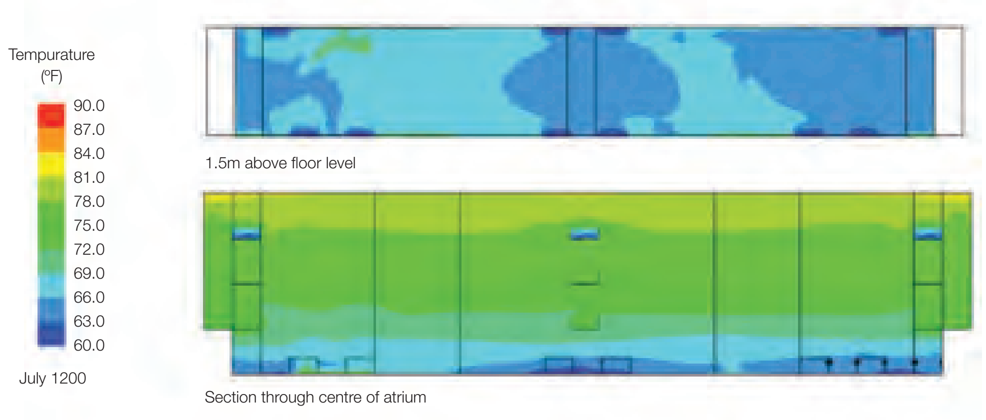
This is the first atrium on the Princeton campus to need smoke control, and a VESDA aspirating smoke detection system was installed in it to trigger the system. Due to their placement, the VESDA heads indicate a smoke condition in the atrium long before any sprinkler heat detectors are activated. Since the sprinkler system could initiate the smoke control system, and is not initiated by the VESDA system, the heat detectors provide a secondary layer of checks and balances.

At each end of the atrium, 77ft (23.5m) braced columns mark the building's entrances – graceful sentinels that also support the PV canopy structure (Fig 27 overleaf). These "bespoke" columns are 8in (200mm) diameter circular hollow steel sections braced at two points by prestressed tensioned stainless steel cables separated by bimetallic washers to prevent corrosion. Advanced buckling analysis was used to optimise the columns' slenderness.

27. South entrance with bespoke column.

28. CFD image of the atrium conditions.

29. Auditorium with slotted timber panelling.



28.

The atrium was designed with large swathes of hard surfaces, including a porcelain floor and glass on every vertical wall and roof. Numerical analyses were performed to determine the number of sound-absorbing finishes needed to achieve a level of intelligibility for the building's public address system in the space, and acoustic treatments were placed behind slotted timber panels mounted at ground level and adjacent to the bridges. This solution achieved the necessary clarity while maintaining the modular architectural design.

Knowing that the atrium would be a central gathering place for occupants to linger, each entrance zone was designed with radiant floor heating to counteract winter downdrafts from the glazing, as well as air infiltration when the entrance doors are opened.
The high mass floor helps to retain the heat, and provides a constant radiant surface temperature, even as the air temperature drops intermittently and locally.

For summer conditioning, low velocity air supply at low level creates a zone of cool air at ground level for the occupants.
To conserve energy, the temperature of the upper zones is allowed to drift higher, as there are no permanent occupants in those spaces. Air is also supplied at the bridges of level 1, to keep meeting spaces comfortable, and at level 3, because it is near the atrium roof and could otherwise get uncomfortably warm on sunny days. Multiple computational fluid dynamics (CFD) calculations were performed to determine the correct volume and temperature of supply air to maintain comfort within the occupied spaces (Fig 28).

29.

The auditorium

The acoustic design of the 260-seat below-grade auditorium optimises speech intelligibility, allowing for archival recording or distance learning, while the mechanical and acoustic design ensures a quiet system for the mechanical room adjacent to the auditorium. A concrete wall and duct sound attenuators between the auditorium and the mechanical room minimise sound transmission. The room envelope also includes a door with a perimeter seal between the laboratory preparation room and the auditorium, and a 0.375in (9.5mm) glass window for the audiovisual control room.

Following the architectural vocabulary of the public atrium, sound absorption treatment on the side and rear walls is via the same type of slotted wood panels (Fig 29).

A hard reflecting ceiling maximises speech clarity and intelligibility, and speech projection to the rear of the room.
Heating and cooling are provided through a plenum under the auditorium seating, with 1/8in (3.2mm) holes between seat posts that allow the air to diffuse at a slow rate.
To ensure that occupants do not suffer draughts from the supply air directly at their feet, numerous iterations of the seat post quantity and design were made so as to achieve the architect's design aesthetic and also meet the seat manufacturer's strength requirements.

27.

Environmental protection and occupational safety

The building's systems are designed to provide the highest level of environmental protection and occupational safety for faculty, students and maintenance personnel. Backflow preventers protect the domestic and laboratory water supplies from contamination by non-potable liquid sources, as well as any chemicals, solids or gases. The laboratory water distribution system is separated from domestic water supply by reduced pressure zone backflow preventers that completely stop domestic water contamination from the laboratory system. Each laboratory sink faucet and fume hood water outlet is protected from back-siphonage by vacuum breakers. Cold and hot water services to glassware washers and autoclaves are also protected by backflow preventers.

Apart from the more conventional standard duty/standby arrangements for the mechanical equipment, multiple system redundancies were designed into the building to ensure continuous operation of its critical components:

- manual cross-connection of two RODI skids to provide limited building service should one system fail or require maintenance
- environmental room condenser domestic water cooling connection in case of failure of chilled water supply, either from the physical plant or the building loop
- multiplex skid systems
- standby laboratory AHU, and space for a future unit
- headered duct system
- use of an array of multiple fans for the laboratory AHUs, such that the unit still has full capacity if one fan fails
- manual bypass and throttling on the incoming steam service in case of PRV (pressure reducing valve) failure
- standby CRAC (computer room air-conditioner) unit for the NMR with primary chilled water connections for cooling units
- critical laboratory equipment on optional standby power and/or UPS (uninterruptible power supply).

While power availability and reliability are very high, many experiments and instruments must be operational during these events. These mainly include the NMR, sample freezers, and the environmental rooms, but much other specific equipment is also required to be on optional standby power, provided by the 1.5MW generator.

The drainage systems are designed to minimise the quantity of wastewater discharged into site sewers and to prevent the discharge of untreated sewage or laboratory wastewater into surface, sub-surface or water streams. Wastewater from fume hoods and sinks is collected by an independent laboratory wastewater drainage system, connected by polypropylene piping.

The original design of the laboratory drainage system included active acid neutralisation, complete with sampling, storage, and mixing tanks, but it was determined that the University's policy of not dumping acids down the drains, in conjunction with documentation from the New Jersey Department of Environmental Protection, allowed the treatment system to be deleted. However, space in the basement was maintained to allow for a connection to a future treatment system.

Safety for students, faculty and personnel is one of the main priorities in the building's design, with an automatic sprinkler and fire standpipe system installed to securely protect occupants and property. Each laboratory entrance is provided with the following safety devices:

- push-button for remote master gas safety shutoff valves
- natural gas earthquake valves that disrupt distribution of the flammable gas to the building in case of a seismic event
- chemical purge button with audible and visible alarm to increase airflow to the laboratories in case of an accidental spill
- push-button electrical safety shutoff
- indicator lights to signal whether or not it is safe to enter (Fig 30).
- combination emergency shower and eyewash stations.

30.

Conclusion

Construction of the new Frick Chemistry Laboratory began in autumn 2007, and building occupation commenced in selected areas in July 2010 as soon as the building TCO (Temporary Certificate of Occupation) was granted. The dedication by Princeton University followed at the beginning of April 2011.

The multidisciplinary design contribution to the building's engineering fulfills several challenging goals. First and foremost was the University's need for a world-class chemistry research and teaching facility for the 21st century, along with the desire to exemplify the campus sustainability[4] goals. In addition, the architects' vision in response to Princeton's brief also had to be fulfilled. A safe, modular, reliable design for the future was created through close collaboration between all the design team members, and contributed to the achievement of the University's goals.

One of the recently recruited researchers proclaimed that it is "the best building for academic chemistry in the country, if not the world"[5]. As department Chair David MacMillan puts it, the building "is a dream come true".[6]

30. Laboratory entrance indicator lights.

31. Natural light penetrates the office circulation spaces.

31.

Project credits
Client: *Princeton University* Architects: *Hopkins Architects Ltd/Payette Associates Inc* SMEP, fire protection, façades, and IT engineer, and acoustics, lighting, and sustainability consultant: *Arup – Leo Argiris, Scott Bondi, Romain Buffat, Irina Bulbin, Duncan Campbell, Ashok Chawla, Katherine Coates, Adam Courtney, Fiona Cousins, Andres de Antonio Crespo, Joshua Cushner, Carmen Danescu, Arfon Davies, Therese de Guzman, Jennifer Dimambro, George Donegan, Gordon Dunlop, David Easter, Khalid Eid, Alex Engelman, Vladimir Eydelman, Neema Faryar, Vincent Fiorenza, Graham Gedge, John Giamundo, Ken Goldup, Ken Gordon, Tom Grimard, Tim Hartin, Robert Hoffmann, Jeffrey Huang, Peter Ibragimov, Carey Jones, Barney Jordan, Mike King, Jacob Koshy, Archana Kotwal, Marina Kremer, Gary Lamonica, John Lewandowski, Peter Li, Rob Livesey, Hillary Lobo, Andrew Marchesin, Neil McClelland, Tali Mejicovsky, John Miller, Chris Moore, Robert Murphy, Aidan O'Dwyer, David Orta, James Palavros, Raj Patel, Irene Pau, David Pritchard, Ashok Raiji, Nihal Rajapakse, Joel Ramos, Larry Ratz, Tom Rice, David Richards, Mayya Rudman, Chris Rush, Joe Saverino, Ruth Shilston, Anatoliy Shleyger, Martin Shouler, Andrew Smith, Valeriy Sokolov, Peter Tillson, Mutlu Ucuncu, Van Valite, James Whelan, Peter Wu, Roman Zaytsev* Civil engineer: *Van Note-Harvey Associates PC* Planning consultants: *GPRA/Jacobs Engineering Group Inc* Commissioning agent: *Dome-Tech Inc* Construction manager: *Turner Construction Company* Landscape architect: *Michael Van Valkenburg Associates* Landscape designer: *MVVA* Code consultant: *RW Sullivan.*

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Image credits
1, 5-8, 10, 12, 14, 22, 25, 27, 29, 31 *Arup/Warren Jagger Photography*; 2 *Nigel Whale*; 3-4, 15-16, 18, 21, 23, 28 *Arup/Nigel Whale*; 9, 11, 20, 26, 30 Jeffrey Huang; 13, 17, 19 *Arup*; 24 *Arup/Morley Von Sternberg*.

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(2) AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR CONDITIONING ENGINEERS. *Standard 90.1*. Energy standard for buildings except low-rise residential buildings. ASHRAE, 2007.

(3) AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR CONDITIONING ENGINEERS. *Standard 110*. Method of testing performance of laboratory fume hoods. ASHRAE, 1995.

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(5) www.princeton.edu/main/news/bulletin/docs/Bulletin-2011-02-14.pdf

(6) www.princeton.edu/main/news/archive/S28/32/85K84/

Rokko Mountain Observatory

Location
Kobe, Japan

Authors
Kazuma Goto Ryota Kidokoro
Takeshi Matsuo

1.

1. The Rokko Observatory.
2. Three-stick model.
3. First study model of the shifted frame system using chopsticks.
4. Basic parametric model.

2.

Introduction

In late 2008, a design competition was held by the project promoters Hanshin Electric & Rail Corporation for a new observation point built at an altitude of some 900m on a peak of the Rokko Mountains in Kobe, Japan. This observatory was to be a place not merely for visitors to pause and take in a spectacular view, but a destination in itself, a location specifically designed to aid and enhance a more profound experience of the natural energy and beauty of the Rokko Mountains (Fig 1). Hiroshi Sambuichi Architects' unorthodox design approach proved victorious in the competition, with Arup providing geometric and structural engineering and environmental design support from the outset.

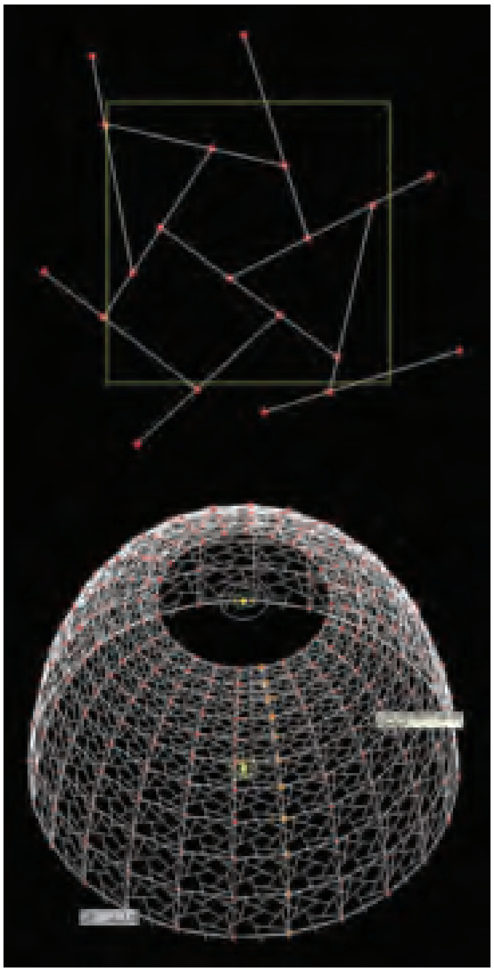
The observatory's key visual feature is its intricately meshed dome, 16m in diameter, which provides partial shelter against the weather as if by tree branches and foliage. As well as this, the environmental design has two principal aspects. Firstly, the observatory is shaped so as to passively induce air movement for natural ventilation. Secondly, winter ice that freezes in water paddies around it is stored in insulated compartments until summer for passive cooling.

Structure

The shape

The architect's first competition sketch showed a delicate network of branch-like elements forming the outer skin of the observatory space, a skin to control but not completely block sunlight, rain/snow, and wind. Arup immediately saw that the interwoven network should somehow be self-supporting – geometrically complex, but simple to construct. Constructional practicality and budget constraints were key factors.

3.



4.

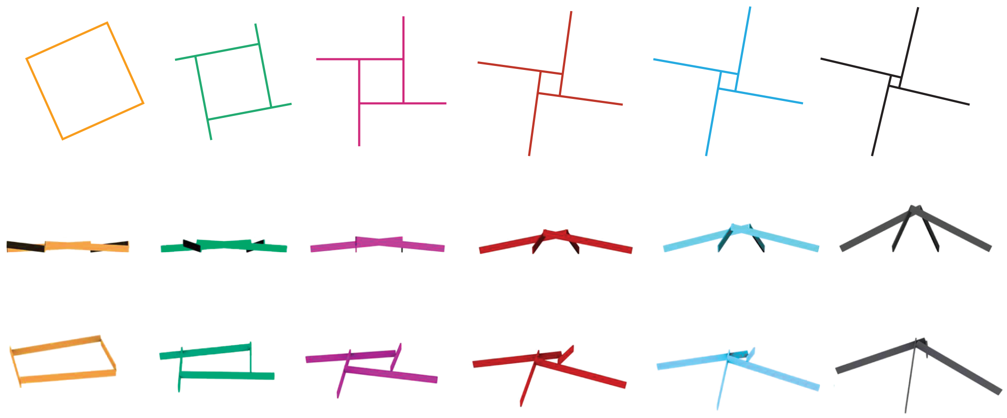
Systems of stacking and/or weaving short elements to span large spaces have existed for a long time. One example is the class of self-supporting structures called reciprocal frames[1], the simplest of which is the three-stick model (Fig 2). Another and more evolved type of layered structural system has been used for many Japanese timber temples and shrines. With such historical examples in mind, Arup developed a system that could be assembled simply by interweaving small, lightweight elements, without special connections or fabrication technologies (Fig 3).

Initial competition modelling

Based on the initial chopstick model study, a unit pattern of intersecting elements was defined in Bentley's *GenerativeComponents* program, and associated to the surface of a multi-faceted cylinder that could be manipulated parametrically (Fig 4). The elements were not at this stage interwoven, but remained flat on each facet of the surface.

The team used this parametric model to investigate the appropriate density of the elements forming the dome, in terms of structural needs and visual impact, and reached decisions that remained constant: there would be a main structural frame in 50mm diameter steel tubes, 1m-2m long, with a finer mesh of 15mm-20mm diameter wood bars (Japanese cypress) attached within.

The team was confident that this new system could work, but also understood that defining the geometry of the interwoven elements would be very complex. A completely new geometric solver would have to be developed to manipulate and accurately define the complex geometry of this shift frame system, should the Sambuichi/Arup design win the competition – which it did.



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Towards the geometry

Stacking and weaving the elements naturally shifts the entire frame out of plane, so that it becomes warped in three dimensions. The extent of the out-of-plane shifting depends directly on element thickness and the position of adjacent elements (Fig 5). As the process of stacking and weaving is repeated, the geometry becomes impossibly difficult to predict by conventional means.

But on the other hand, if the shifted geometry of the frames can be calculated and determined, this implies that the form can be manipulated to best fit any desired surface shape. To enable this, the team undertook to derive a numerical solution to solve the shifted geometry of the interwoven elements.

The first step was to define the vector and distance between adjoining cylinders in relation to the directional vectors of the cylinders themselves. It was soon realised that the vector that defines the minimum distance between the axes of two cylinders is also at right angles to those axes. Based upon this vector relationship, an extensive matrix of simultaneous equations could be formulated and then solved.

Since the geometry of the whole depends on the shift of each element, the solver program must be iterative. As the calculation becomes exponentially larger for each element introduced, even with current computational power the prototype solver would take hours for the solution converge. The method clearly had to be streamlined so as to be more parametric and more accurate, but still with less computing time so as to satisfy the project constraints.

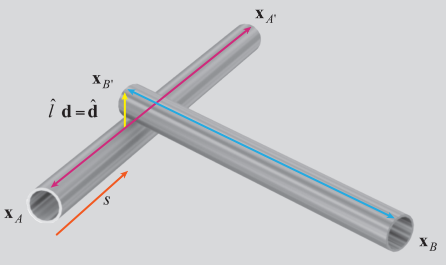
The solution

After several months of development, a program which became known as the shift frame geometry (SFG) solver was formulated (Fig 6). Simply put, the SFG solver incrementally shifts each element simultaneously towards the predefined side (over or under the element) and iterates the process until the solution converges – the solution being the actual shifted geometry.

The condition of a properly shifted joint can be expressed in two different vector equations (1) and (2), which are then equated together by the relationship in equation (3). If equation (3) is satisfied, this means the elements are properly shifted. Since combining every element assigned to be on the top, the bottom, or along the length would result in vast numbers of permutations mostly without any rationale, an optimisation condition was introduced into the solution to find a single combination that would result in the shortest total element length – the combination that results in the flattest shift frame (equation 4).

Equation (5) is the non-linear equation to locate the nearest optimal point. Finally, to solve the non-linear equation and significantly speed up the convergence (computation time), the Newton-Raphson method was employed (equation 6) – an efficient method for finding successively better approximations to the zeroes (or roots) of a real-valued function.

With the advent of the SFG solver, it suddenly became possible to convert any surface pattern of any sized elements into a desired shift frame form with complete geometric accuracy (Fig 7).



(1) Distance vector.

$$\mathbf{d} = -\left(\mathbf{x}_A + \quad \left(\mathbf{x}_{A'} - \mathbf{x}_A\right) - \mathbf{x}_B\right)$$

(2) Distance vector.

$$\hat{\mathbf{d}} = \hat{l}\ \frac{\left(\mathbf{x}_{A'} - \mathbf{x}_A\right) \times \left(\mathbf{x}_{B'} - \mathbf{x}_B\right)}{\left(\mathbf{x}_{A'} - \mathbf{x}_A\right) \times \left(\mathbf{x}_{B'} - \mathbf{x}_B\right)}$$

(3) Boundary condition.

$$\mathbf{d} - \hat{\mathbf{d}} = \mathbf{0}$$

(4) Conditional optimisation.

$$\min \pi \text{ s.t } \quad \pi = \sum_{j=1}^{n} l_i + \sum_{j=1}^{m} \boldsymbol{\lambda}_j \left(\delta\mathbf{d}_j - \delta\hat{\mathbf{d}}_j\right)$$

(5) Optimal point derived using variational method.

$$\delta\pi = \sum_{j=1}^{n} \delta l_i + \sum_{j=1}^{m} \delta\boldsymbol{\lambda}_j \left(\mathbf{d}_j - \hat{\mathbf{d}}_j\right) + \boldsymbol{\lambda}\left(\delta\mathbf{d}_j - \delta\hat{\mathbf{d}}_j\right) = \begin{pmatrix} \delta\mathbf{U} \\ \delta\boldsymbol{\Lambda} \end{pmatrix}^{\mathrm{T}} \begin{pmatrix} \mathbf{Q} \\ \mathbf{D} - \hat{\mathbf{D}} \end{pmatrix}$$

(6) Tangent matrix using the Newton-Raphson method.

$$d(\delta\pi) = \begin{pmatrix} \delta\mathbf{U} \\ \delta\boldsymbol{\Lambda} \end{pmatrix}^{\mathrm{T}} \begin{pmatrix} \mathbf{K}_e & \mathbf{K}_\lambda^{\mathrm{T}} \\ \mathbf{K}_\lambda & \mathbf{0} \end{pmatrix} \begin{pmatrix} d\mathbf{U} \\ d\boldsymbol{\Lambda} \end{pmatrix} = \begin{pmatrix} \delta\mathbf{U} \\ \delta\boldsymbol{\Lambda} \end{pmatrix}^{\mathrm{T}} (\mathbf{K}) \begin{pmatrix} d\mathbf{U} \\ d\boldsymbol{\Lambda} \end{pmatrix}$$

Key

$\mathbf{x}_i$: vector of elements $\mathbf{d}$, $\hat{\mathbf{d}}$: shift vector

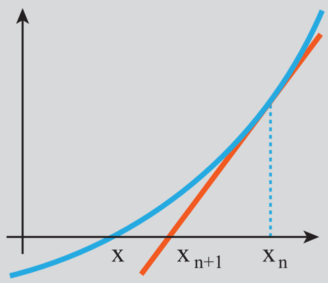
s : joint location parameter $\hat{l}$: offset amount l : element length

π : total length of vectors n : number of elements

m : number of joints $\boldsymbol{\lambda}$: Lagrange multipliers

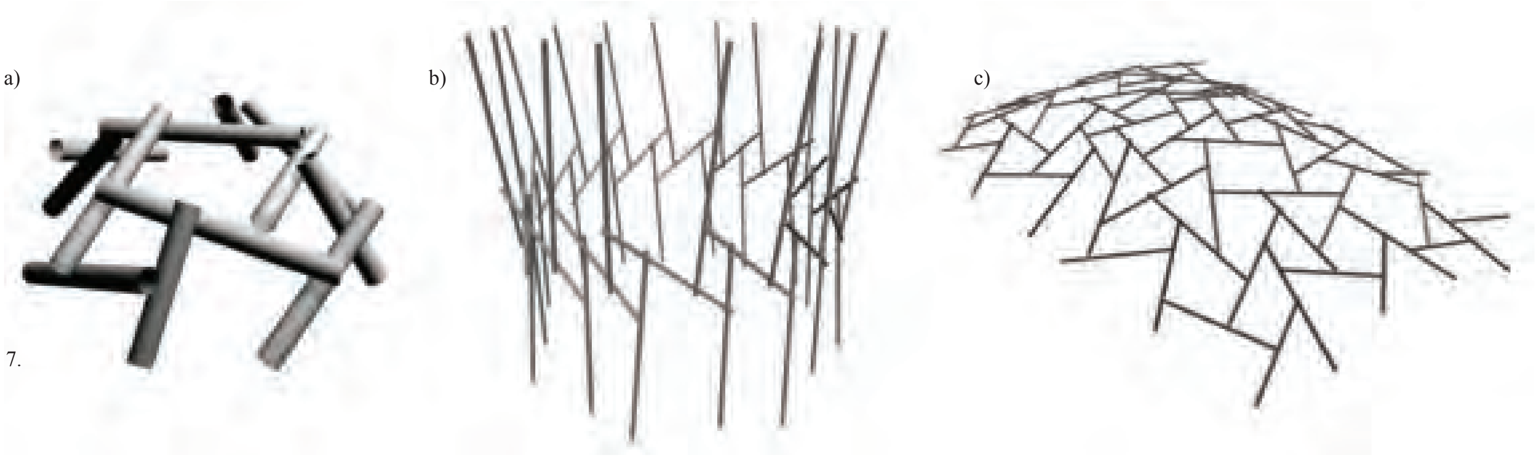
$\mathbf{K}$: tangent matrix

Newton-Raphson Method



One starts with an initial guess which is reasonably close to the true root, then the function is approximated by its tangent line (which can be computed using the tools of calculus), and one computes the x-intercept of this tangent line (easily done with elementary algebra). This x-intercept will typically be a better approximation to the function's root than the original guess, and the method can be iterated.

6.



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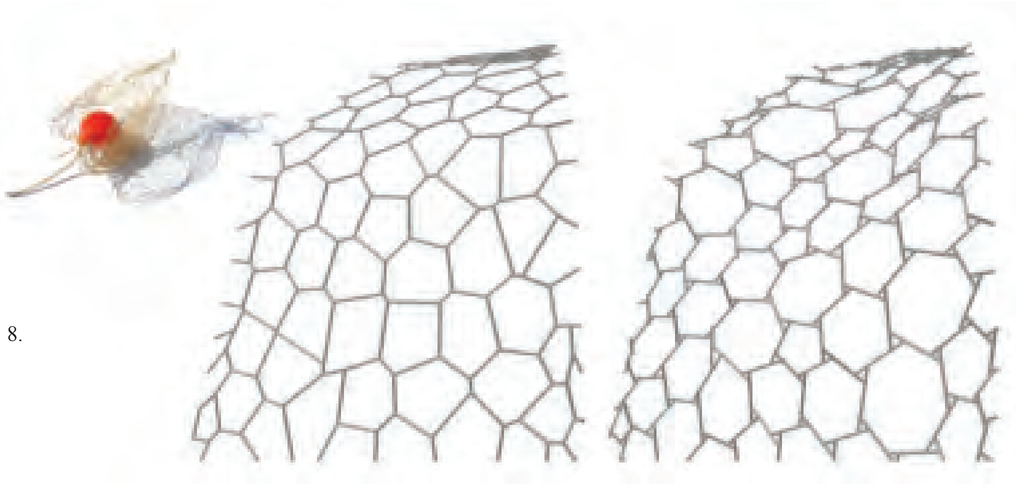


8.

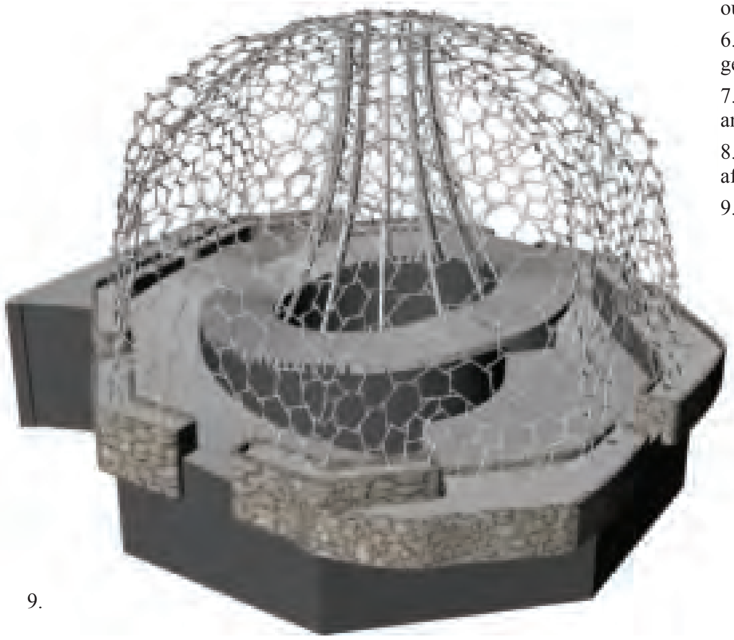
5. Differences in the extent of out-of-plane shifting.

6. Overview of the shift frame geometry (SFG) solver.

7. Variations of SFG patterns and forms.

8. Voronoi tessellation before and after running the SFG solver.

9. Final form of shift frame dome.



9.

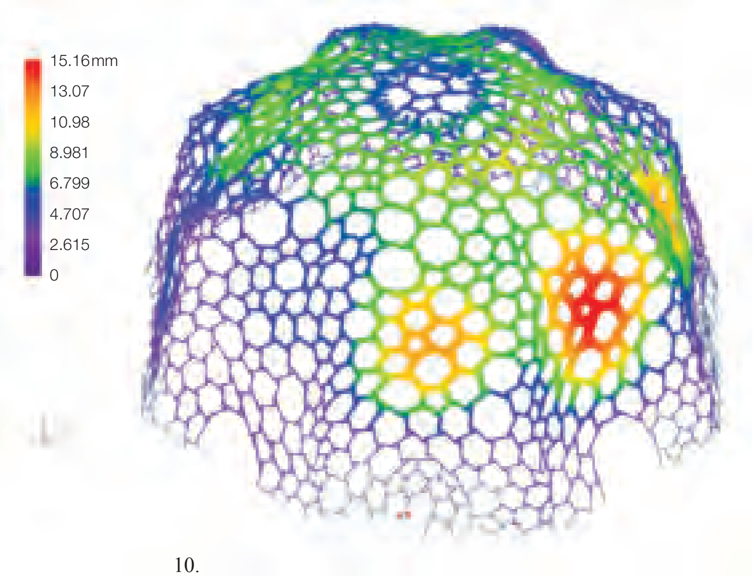
The design realised

Reverting to the design of the observatory itself, after several rounds of discussion with the architect, the pattern of the shift frame changed. Rather than it being an arbitrary formation of interwoven elements, the team agreed that patterns akin to those found in nature would be more appropriate to the overall concept, so the final pattern was based on Voronoi tessellations.

These relate to a set of points in space, the tessellation boundaries occurring midway between adjacent points. On a two-dimensional surface, the boundaries can be created by drawing perpendicular bisectors to the lines joining those points; three, or in special circumstances more, of these bisectors intersect to give the corners of the tessellations.

A separate program was quickly developed to generate Voronoi tessellations on a three-dimensional surface, and then the SFG solver was used to convert the faceted Voronoi pattern into a shift frame comprising hexagons and triangles (Fig 8). The density of the tessellations was adjusted according to the required structural capacity of the whole system.

In the final form of the shift frame dome (Fig 9), each of the straight 50mm diameter steel tubes was reciprocally shifted and the contact points welded together. The resulting interwoven network of tubes forms a stable structure that can resist heavy snow and typhoon loads.



10.

10. Structural analysis results.
11. Assembling the shift frame.
12. Full scale mock-up testing.
13. Visitors enjoy the shade.
14. Environmental design concept.
15. Winter ice crystals on the dome.
16. *Himuro* ice storage compartment.

The generated geometry of the shift frames was imported into analysis software to verify structural integrity, and the results then fed back into the Voronoi generation step and reassessed. This process was iterated so as to optimise the dome's structural and visual impact. As the shifted geometry is accurately defined in the model, additional stresses due to the eccentricity of the tube centroids are also accurately reflected (Fig 10).

Construction

Due to the complex geometry, conventional 2-D drawings were clearly inadequate for construction purposes. While in theory the process of fabricating shift frames is merely to cut, place, and weld steel tubes, it was still critical that the fabricator be technically able to comprehend fully the 3-D geometry, so from the start the team worked closely with a highly skilled fabricator. To facilitate post-processing the geometrical data, the design team prepared, in addition to the 3-D model, a table defining the geometry of each individual tube.

The position of each shift frame element is highly interdependent, so if one tube was placed incorrectly, the next (or the one after) would simply not fit. Maintaining a high level of accuracy during assembly was thus crucial in completing this spatial puzzle.

11.

12.

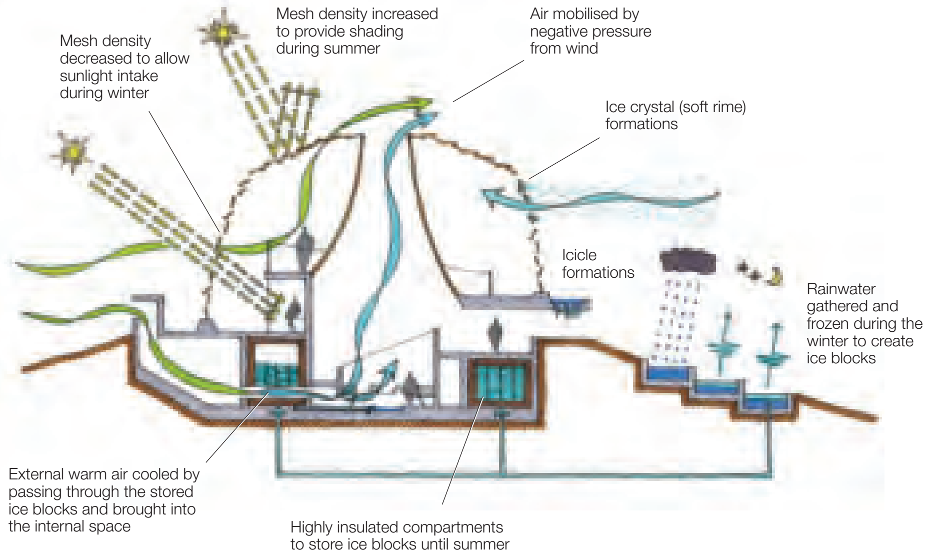
Fortunately, the fabricator proved to be exceedingly resourceful in devising new ways to measure and accurately position the tubes (Fig 11). Prior to bringing them on site, a full-scale mockup (Fig 12) was erected, which also included the smaller and more intricate wood shift frames attached to the larger steel structure.

Environmental design

Environmental function of the skin
The outer mesh has several environmental functions. First, its varying density creates a comfortable outdoor environment in the viewing space between itself and the central tower. The upper part of the south face is of high density, to reduce summer solar radiation, but the lower part is much more perforated to allow the passage of wind to keep visitors cool (Figs 13, 14). This improves visitor comfort especially here, as the observatory enjoys relatively mild summers due to its mountain-top location.

Second, in winter the mesh becomes a vehicle to exhibit the natural beauty of ice crystals (Fig 15). This ice coating, or rime, forms by water droplets in fog freezing when they touch cold surfaces. Freezing humid air and strong wind are indispensible for ice crystal formation, and Rokko is famous for this beautiful natural phenomenon.

13.



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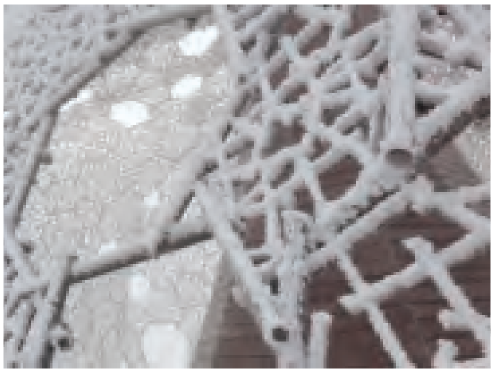


15.

16.

The architects realised that this could happen on the mesh and asked Arup to incorporate any design elements into the mesh that could encourage ice crystal formation. Low surface temperature was necessary, and thermal analysis was carried out to establish the optimum material. A mock-up was then constructed on the site to test. These results showed that thin timber with low thermal capacity was best, as it rapidly follows any external temperature drop. Roughing the timber surface also aids ice crystal formation, and in addition the northern aspect of the mesh dome was designed and constructed to be less dense than elsewhere, increasing access to the strong north winds that form the ice crystals.

Stored ice for summer cooling: the "cooled breeze experience"

Rokko Mountain is well known for its natural water supply, and the observatory allows visitors to enjoy such spectacles as winter icicle formations or summer cascades. In addition, a "cooled breeze experience" for visitors was incorporated into the plan, using the ice that freezes naturally in winter.

At other times in the year, rainwater is caught in 200m^2 paddies arranged around the observatory, this size being arrived at through knowing the volume of ice needed for the cooled breeze experience, and the anticipated number of times of freezing, amount of rainfall, and rate of evaporation.

In this district, a natural ice-making industry once prospered, and even today enough ice is frozen for storage a few times per winter season. The ice is cut into blocks and placed in highly insulated ice storage compartments called *Himuro* in traditional Japanese. At the observatory, two 16m^3 *Himuro* are provided with 500mm thickness of insulation to keep the ice blocks frozen until summer – the thickness determined by the optimum cost and performance (Fig 16). The insulation has two layers, the inner being of calcium carbonate. This has low permeability and strong vapour resistance, so as to prevent liquid water from permeating the outer layer and lowering the overall performance of the insulation.

17.

18.

17. Bench armrests, showing louvres.

18. Rokko observatory at night, and the view towards Kobe.

In summer, the ice blocks lower the temperature of incoming air, which becomes a cool breeze into the main room, the Fushitsu. At the design stage the team debated how best to introduce the cooled air for maximum visitor comfort, and a louvre in the bench armrests was determined as the most effective (Fig 17).

Taking into account climate data, the site characteristics and construction practicalities, it was determined that natural wind, shown by the data to be strong and stable at the mountain-top, would be adequate to maintain air flow over the ice. The design is focused on maintaining positive pressure at the inlet and negative pressure at the outlet. The inlet was thus located on the south side to capture the summer seasonal wind, but it was made open on all sides so as to draw air in from any direction. The outlet is at the top of the central tower ,where negative pressure is generated from any wind direction.

Air from the inlet blows down to the basement floor, and is cooled during passage through a duct at the bottom of the stored ice, designed so that liquid water drains off the edge. The length and size of duct was decided by cooling capacity and air movement resistance. The air generally cools by around 5˚C while passing through the duct at a rate of some 300m^3/hour. The volume of air moving naturally depends on the strength of the wind, and so the observatory staff control the size of the input opening to maintain the optimum air flow for cooling.

Completion

Opened to the public in July 2010, the Rokko observatory exemplifies the new possibilities for architecture in applying hi-tech analytical techniques to realising low-tech design solutions.

Nearing the first complete seasonal cycle of summer-autumn-winter-spring, well over 100 000 visitors have made the trip up the mountain to experience the changing face of the new observatory.

Authors

Kazuma Goto is an engineer with Arup in the Tokyo office. He led the geometric engineering for the Rokko observatory project.

Ryota Kidokoro is an Associate of Arup in the Tokyo office. He led the Arup project team from competition to completion.

Takeshi Matsuo is an engineer with Arup in the Tokyo office. He supported the architect in developing the observatory's environmental design aspects.

Project credits

Promoter: *Hanshin Electric and Rail Corporation*
Client and architect: *Hiroshi Sambuichi Architects*
Structural and geometric engineer and environmental designer: *Arup – Kazuma Goto, Ryota Kidokoro, Takeshi Matsuo, Yoshiyuki Mori* Steel fabricator: *Yajima Corporation.*

Image credits

1, 16-18 *Hiroshi Sambuichi Architects*; 2 *Nigel Whale*; 2-15 *Arup.*

Reference

(1) LARSEN, OP. Reciprocal frame architecture, Architectural Press, 2008.

This article is partly based on the paper "'Rokko Observatory' – Application of geometric engineering", by Ryota Kidokoro and Kazuma Goto, presented at the International Symposium on Algorithmic Design for Architecture and Urban Design, ALGODE TOKYO 2011, held on 14-16 March, 2011.

Nottingham Trent University regeneration

Location
Nottingham, UK

Author
Stephen Fernandez

Refurbishing two separate heritage buildings dating from different centuries, and joining them together to create a new heart in a university campus, was a unique challenge that brought together many of Arup's skills.

1.

Introduction

This project involved the alteration and sympathetic refurbishment of two Grade II* listed buildings to provide modern teaching and academic space for Nottingham Trent University (NTU). The redevelopment secures the long-term future of both buildings and provides a new heart to the city centre campus, using the space between the two buildings to provide a new “front door” to the University, opening onto a covered central court and link building.

Working with Hopkins Architects LLP, Arup provided full multidisciplinary engineering design: structural, geotechnical, building services, façades, fire and acoustics. Collaboration throughout between all disciplines was vital to ensure success. To successfully deliver this major refurbishment scheme with a London-based architect and existing buildings in Nottingham, the design team developed a strong collaborative approach between the two locations.

Client requirements
In 2005 NTU began a comprehensive regeneration project to upgrade much of its estate, for the benefit not only of the campus itself but also the city’s new cultural quarter, as identified in the Nottingham City Centre Masterplan. The university aspired to make its campus more accessible, inclusive, and welcoming to local people, who were under-represented in student numbers. To enable this it needed to transform the out-dated and under-utilised Arkwright and Newton buildings, both in desperate need of refurbishment and repair, into modern teaching facilities that met current requirements for user comfort and accessibility, while conserving their original fabric elegantly and economically.

Besides the need to create modern teaching environments, existing circulation and building maintenance problems had to be addressed, and areas of architectural importance retained. The engineering and architectural challenges demanded imaginative and innovative responses from the design team.

An inventive and controlled response to the constraints and opportunities of the site was thus needed. Changes had to be sensitively detailed so as to restore the original character of the older Victorian Arkwright building, which had suffered a string of unsympathetic and ad hoc alterations over the years.

Also, to give the campus its new main entrance, the change in levels between Arkwright and the 1950s Newton building had to be addressed, so as to provide convenient access between both, and improve navigation around Arkwright.


2.

The project

The Newton and Arkwright buildings are two of the best-known landmarks in central Nottingham, and have played an important role in shaping the city’s educational, cultural and social life.

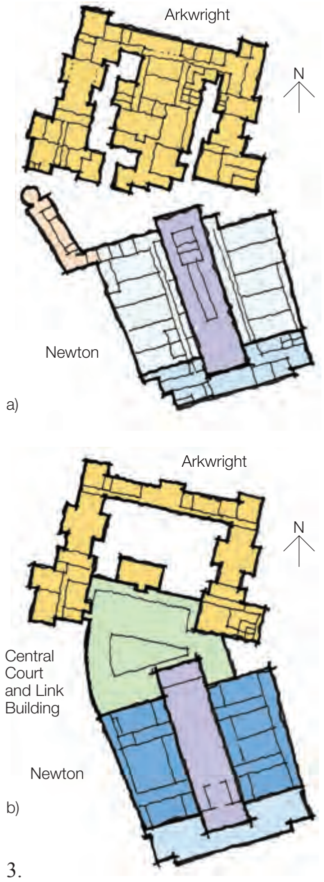
Arkwright
The foundation stone for the Arkwright building was laid in 1877. Constructed in Victorian gothic style with stone façades and masonry walls, it was originally home to University College Nottingham and the city library, as well as a natural history museum. Following its opening in 1881, the new structure was not without problems, and in the first two years several major defects became apparent. Part of the building was founded on soft fill material, and movement resulted in significant cracking. Arkwright therefore closed in 1883, and did not re-open until 1890. The building has been added to over the years, including the reconstruction of the north-west corner, which received a direct hit in the Second World War.

1. Glazed Link Building between the refurbished Newton and Arkwright buildings.

2. NTU campus prior to the regeneration project.

3. (a) Original site plan; (b) Site plan after regeneration project.

4. The completed project.



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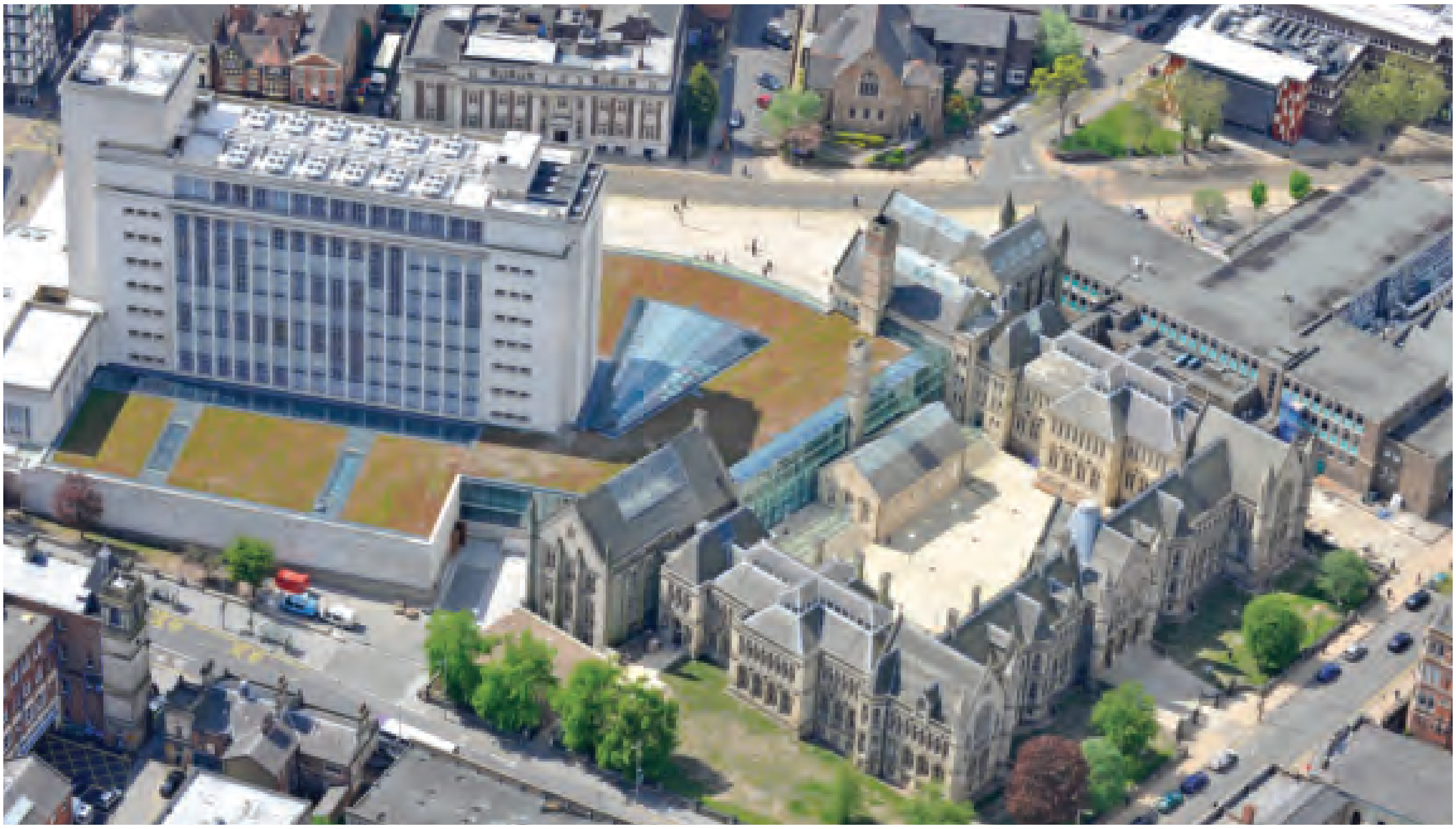


4.

The new regeneration has involved partial demolition and substantial alteration (internal and external) of the central wing to create a new space, the Quadrangle, as an area of secure semi-public open space for events and passive recreation. Its creation also unlocked some fundamental circulation problems that had existed between Arkwright and Newton. During the design stage, however, English Heritage advised that one element within Arkwright's central wing, the Chemistry building (and adjoining chimney), needed to be retained as a free-standing structure.

Another part of the central wing had accommodated a lecture theatre, and demolition of this exposed the gable wall immediately behind Arkwright's north-facing principal entrance, and thus facing south into the new Quadrangle. The gable wall had to be extensively remodelled using traditional construction techniques and incorporating reclaimed arches from the demolished buildings.

In addition to these works, non-original accretions and historical internal alterations to the front and the west and east wings were removed, with materials salvaged and re-used for elevation alterations and repairs. New staircases and lifts were installed to achieve level changes and improve access throughout what remains of the building.

As well as playing a key role in the overall development through the creation of the new Quadrangle, Arkwright was also refurbished as a new centre for NTU administration.

Newton

The neighbouring nine-storey Newton building was constructed in the 1950s to expand Nottingham and District Technical College, one of NTU's antecedents.
The building is an imposing, Portland stone-faced, example of mid-20th century architecture, with its tower at the south end rising above a two-storey podium.

The upper levels have been reconfigured and extensively refurbished and refitted to address the building's inherent environmental problems, and provide flexible spaces for teaching and academic offices. The existing basement and ground levels were also totally reconfigured. Redundant engineering workshops formerly occupied these lower levels, but these barrel vault structures have been demolished and replaced with state-of-the-art lecture theatres adjoining a new large central space, the Newton Forum. This is designed to promote informal academic interaction and study, and flows at both levels into the new Central Court and Link Building, which occupies the area between Arkwright and Newton.

Central Court and Link Building

Central Court provides NTU's new main entrance on the west side, and is the focal point for students, staff, and visitors at the heart of the campus. A vaulted glazed roof encloses the space, which provides access at two levels to Arkwright as well as to Newton. The structure is a two-storey reinforced concrete frame with slab soffit, wall, and column surfaces all exposed and expressed architecturally.

The glazed Link Building north of Central Court provides accommodation for student support service staff. It connects Arkwright's east and west wings and forms the southern elevation of the new Quadrangle.

Structural engineering

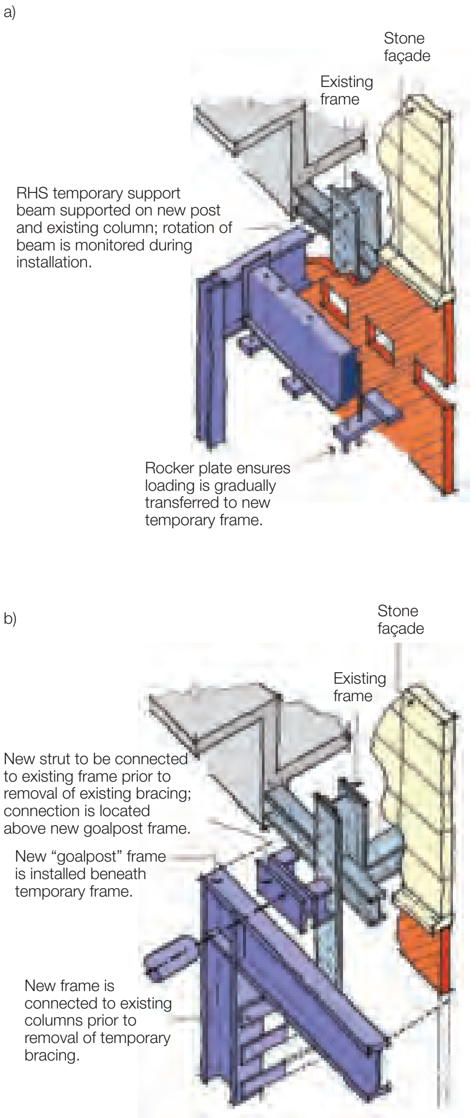
Some of the most significant structural challenges stemmed from the absence of any meaningful records of the existing buildings' construction. To understand their forms of construction, and the consequences for the significant intervention works required by the scheme, the team undertook extensive and intrusive investigation and testing.
It was essential to work closely with the contractor to sequence the construction activities, and to monitor movements that might affect sensitive building fabric.

The team was faced with not only a "Pandora's Box" of previous building works to unpick, but also significant historical settlement issues in the ground in which they were founded. Arup's painstaking investigation of building records and intrusive surveys showed the extent of work needed, enabling in turn an appropriate and sympathetic response.

Floor loadings
The basic structural design philosophy was to minimise alterations to the existing structure, and limit the repair and enhancement of the buildings to the essential minimum.

The Newton building was originally designed to accommodate lecture rooms, academic offices, laboratory spaces, etc, and over the years the structure had proved adequate to carry the floor loads associated with these uses. Demolition works to each floor involved stripping all the finishes to expose the existing structure, during which the team undertook detailed assessments of the existing superimposed dead loads. Following demolition, the existing structure could be surveyed, and no signs of deterioration or failure were discovered.

Comparison of the existing superimposed dead loads and the likely applied live loads with the proposed new loadings indicated that the latter do not differ significantly. New required floor loads were therefore matched to existing uses so as to justify there being no significant change in use. This approach was discussed and agreed with the city's Building Control Officer, and avoided the need for extensive "back justification" calculations to establish theoretical design floor capacities. This would have been particularly onerous as so little original design information was available, and rendered unnecessary any costly structural enhancements to the typical floor plates.



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Newton stability modifications
The existing stability system in one direction consisted of vertical steel cross-bracing extending the full height of the building, concealed within walls. This bracing was obviously a key component for the overall stability system. As the scheme involved opening up the entire floor plate on the north wall at the lowest two levels to link in with the new Central Court, the existing bracing here had to be totally reconfigured. The new system needed to match the stiffness of the existing bracing to avoid cracking or distortions to the stone façade, and to ensure no adverse changes in the behaviour of the existing structure. The team had to consider carefully the construction methodology and the requirement for temporary works, as the new stability system would need to be installed before the existing system was modified.

Newton "goalpost" frames
No existing longitudinal bracing was found, and investigations indicated that stability was provided by masonry walls acting as shear walls in combination with some frame action from the multiple bays. The existing walls at lower levels needed to be removed to open up the space and to provide access into new lecture theatres, and this would have significant structural consequences.

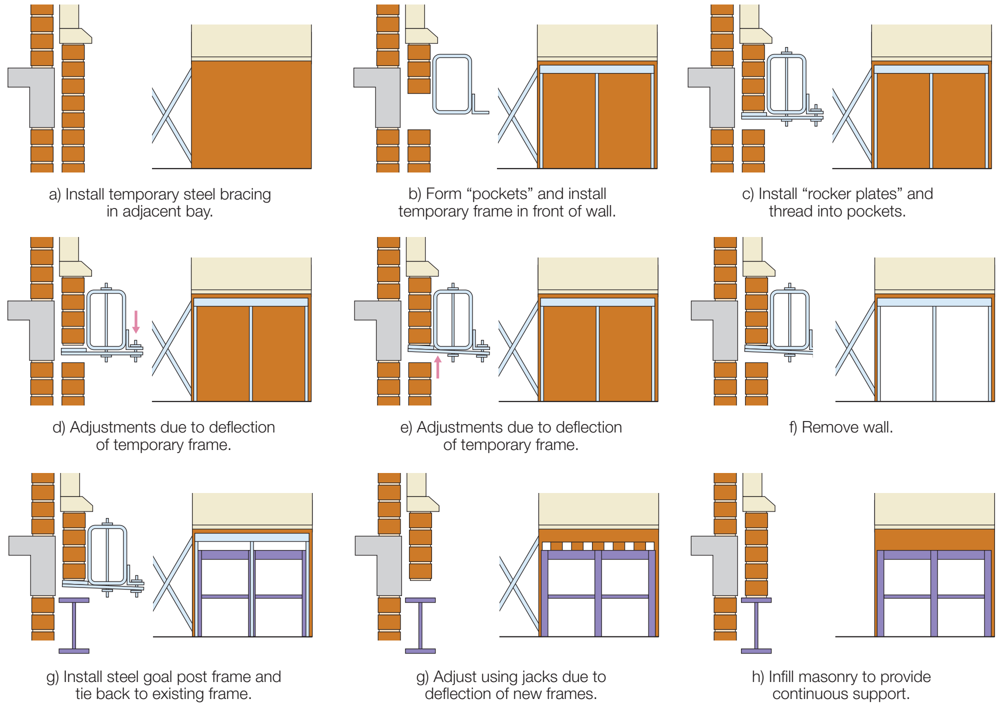
The structural strategy adopted was to replace these existing walls with a new framed stability system of equivalent strength and stiffness to resist lateral loads, while opening up the new access routes. A clear load path to transfer forces from the existing stability system into the replacement system had to be established, and new steel "goalpost" portal frames were constructed to replace the masonry walls, tied back to the existing frame (Figs 5-9).

A further complication was that the nine storeys of stone cladding were found to be loadbearing and supported on the masonry that was to be removed at the lower levels. Resolving this involved significant temporary works (carefully co-ordinated with the permanent works) to support the existing stonework and give lateral stability. The load was gradually transferred onto a temporary frame and temporary stability system. Once the original supporting brickwork was removed beneath the stone, new frames were introduced to provide permanent vertical support and stability. The entire system was monitored during the process, with adjustment measures incorporated to ensure load transfer without excessive deformation.

The Arkwright gable wall

Significant alterations to the foundation loads would exacerbate the Arkwright building's tendency to movement, so the design approach was to minimise loading changes. Where change was unavoidable, the strategy was to only locally enhance and strengthen the structure. It was not cost-effective to try to stop the building moving entirely; this would have involved underpinning most of the walls, and been time-consuming and disruptive to the other works.

To create the gable wall facing the new quadrangle, the existing previously internal wall needed to be extensively remodelled. Although the total weight of the remodelled wall on its foundations would be similar to the existing, it was felt that – given the historical settlement issues – extensive construction works might cause further settlement. The design evolved to adopt piecemeal working to form the new elevation, minimising the unload-reload cycle of the existing foundations, and limiting any potential settlement. New reinforced concrete lintel beams were introduced into the loadbearing walls using steel I-sections as stools, cast into the concrete beams.



a) Install temporary steel bracing in adjacent bay.

b) Form "pockets" and install temporary frame in front of wall.

c) Install "rocker plates" and thread into pockets.

d) Adjustments due to deflection of temporary frame.

e) Adjustments due to deflection of temporary frame.

f) Remove wall.

g) Install steel goal post frame and tie back to existing frame.

g) Adjust using jacks due to deflection of new frames.

h) Infill masonry to provide continuous support.

9.

10.

5. (a) Installation and function of temporary frame before:
(b) installation of the Newton "goalpost" frame.

6-8. "Goalpost" frame installation.

9. Newton "goalpost" frame construction sequence.

10. The new Newton Forum space in the lower levels of the building.

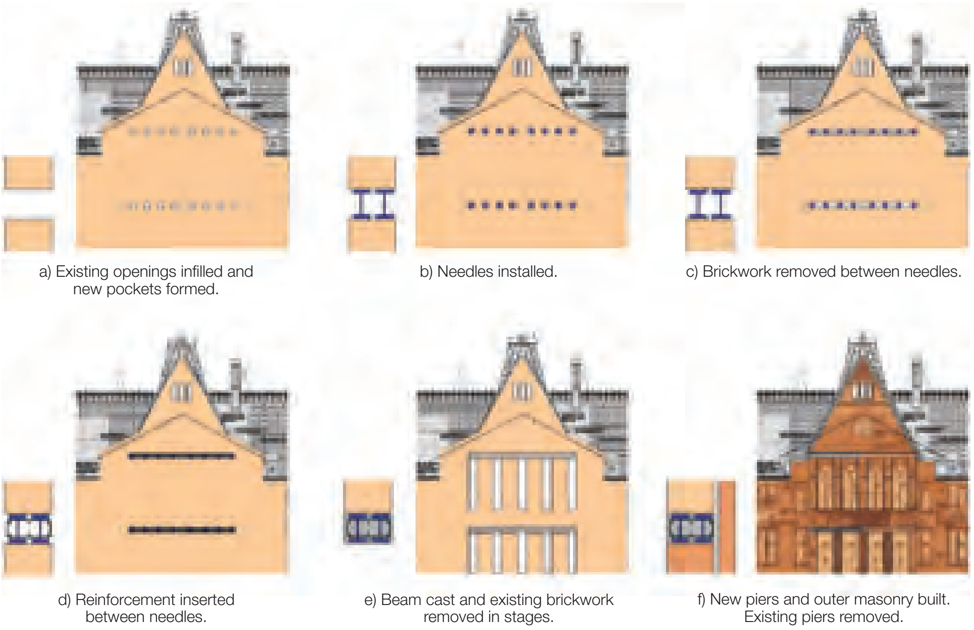
11. Forming lintels in the gable wall.

12. Gable wall construction sequence.

13. The reconstructed gable wall.

14. Gable wall reconstruction diagram.

11.



a) Existing openings infilled and new pockets formed.

b) Needles installed.

c) Brickwork removed between needles.

d) Reinforcement inserted between needles.

e) Beam cast and existing brickwork removed in stages.

f) New piers and outer masonry built. Existing piers removed.

12.

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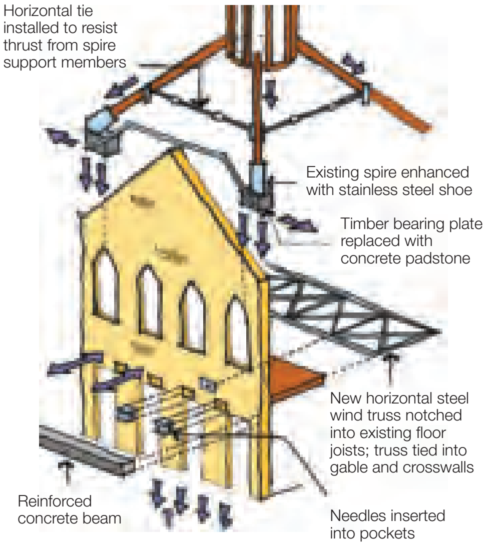


14.

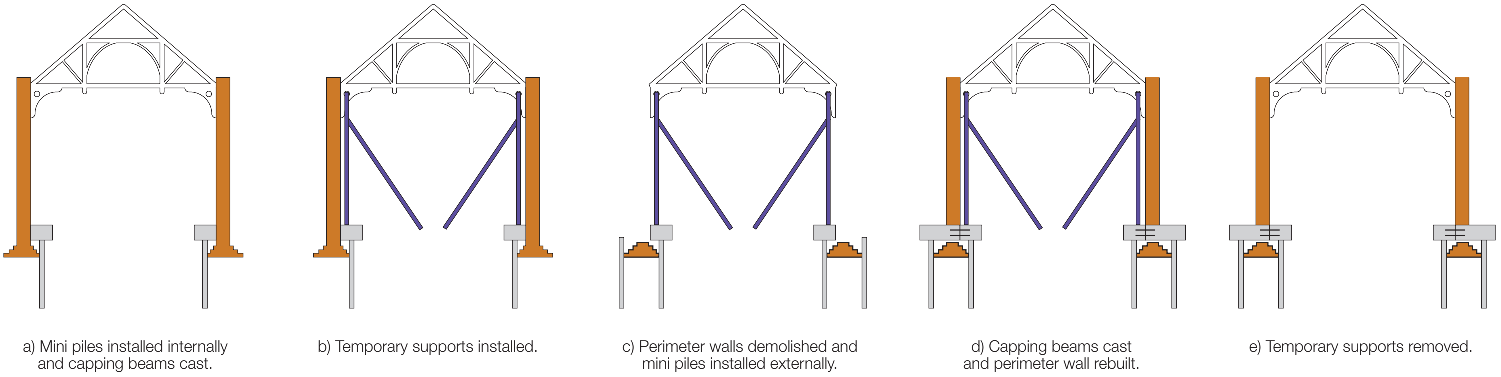
This was carefully monitored at all stages, with a remedial strategy in place should any further settlement be triggered. With several new openings being made in the brickwork, the sections of masonry that were left would be subject to higher stresses. These were replaced with an internal core of engineering bricks, surrounded by facings of reclaimed bricks from the demolition works.
The brickwork was fully cross-bonded and toothed in at interfaces with the existing brickwork, adopting traditional construction techniques including lime mortar.

The existing lecture theatre walls, floors and roof structures provided lateral support during remodelling. As the gable wall would now be external and exposed to wind loading, new lateral restraints, ties and wind-girders were designed and installed.

At the first floor there was only a balcony, consisting of timber boarding on joists. For lateral restraint, a new wind-girder was installed within the floor construction, comprising steel angle booms and cross-struts with steel plate diagonals, notched into and screwed to the existing joists with boarding relaid over. Concealed tie-rods across the width of the building were keyed into the walls and anchored with concrete padstones.

An existing spire at this location in the centre of the north wing of the Arkwright building was supported by raking timber members bearing on the walls, with the existing lecture theatre walls to the south probably acting as buttresses to resist lateral thrusts.

To ensure the spire's future stability, a new ring beam was introduced within the ceiling void, using tie-rods clamped onto the existing raking timbers. During the works, however, a further complication arose when the existing spire support members were found to be sitting on a timber bearer that clashed with the position of the new window openings to be formed. The presence of the bearer also posed a significant durability problem, given that the wall would now be exposed and was of solid construction.
The solution adopted was to support the spire internally temporarily, replace the timber bearer with new concrete padstones, modify the size of the existing timbers to allow the new facing brickwork to run past, encapsulate the timber with protective stainless steel shoes incorporating weep holes and ventilation, and rebuild the wall.


a) Mini piles installed internally and capping beams cast.

b) Temporary supports installed.

c) Perimeter walls demolished and mini piles installed externally.

d) Capping beams cast and perimeter wall rebuilt.

e) Temporary supports removed.

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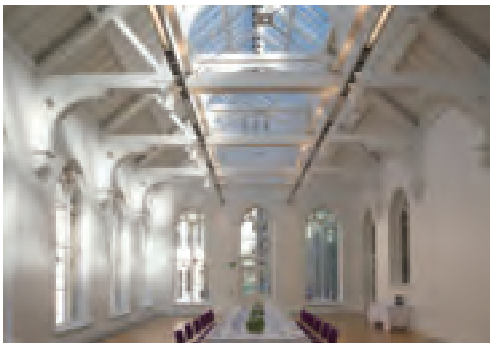
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18.

15. Chemistry building construction sequence.

16. Chemistry building temporary propping.

17. Interior of Chemistry building.

18. The completed Chemistry building adjoining the glazed Link Building.

Arkwright Chemistry building

Demolishing the existing buildings around the Chemistry building would expose it to wind loads, and so strengthening was needed to ensure stability. Due to the building's geometry, a horizontal wind-girder was introduced, located over the bottom member of the existing timber roof trusses to distribute new wind loads back to the flank walls. The wind-girder, comprising steel angles, channels and bracing rods, was carefully detailed to integrate with the existing timber trusses, being screwed to them and fixed to padstones cast into the flank walls. Timber repairs were made to ensure that each truss was effectively tied to the supporting walls, while extensive masonry works were required to thicken previously internal walls and to incorporate new window and door openings to match those elsewhere.

Here again some of the walls were discovered to be founded on fill, and so – given the change in loading, the temporary support needed for the roof structure to reconstruct the walls, and that the Chemistry building would not be physically connected to any other existing buildings – it was underpinned to avoid settlement problems. Mini-piles were bored on each side of the perimeter walls, providing temporary support to the existing timber trusses (with props built off the new piling system).

The existing walls were demolished, new ground beams installed spanning onto the mini-piles, and the perimeter walls reconstructed, incorporating the arches forming the elevations. This construction required the existing listed roof, which could not be deconstructed, to be supported on extensive temporary works. This necessitated careful monitoring for any settlement.

Central Court

The new building's high quality exposed concrete frame required careful coordination with the architect and contractor to set out expressed formwork joints, construction joints, and recessed light fittings. Generally the superstructure is a flat slab with tapered cantilever balconies around the atrium. Above is a sedum "green" roof, supported on a 550mm thick voided slab, with 125mm thick top and bottom slabs and full slab depth primary and secondary ribs. The structure for the curved glazed roof that springs from the sedum roof comprises circular glulam butterfly arches, supported on tapered concrete cantilevers forming the main frame (Fig 21).

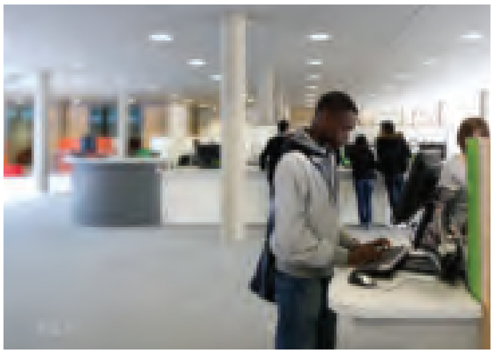
The choice of construction for the roof slab was driven by several design considerations, including the architectural requirement for a flat soffit and large perimeter cantilevers, the flat top surface necessary for the green roof system, and the need to resist the lateral thrusts developed at the springing points of the butterfly arches. The slab also incorporates cast-in lighting fittings and electrical conduit grid, and rainwater downpipes are housed within the columns.

19. Central Court in use.

20. Link Building.

21. Glazed roof to the Central Court, showing circular glulam butterfly arches.

22. GPT (general practice teaching) room in the Newton building.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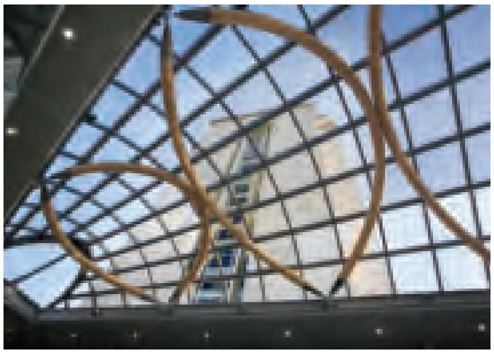
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19.

Building services

Though all three main sections of the project connect and interlink, they were treated individually, with Arkwright refurbished with replacement services on a like-for-like basis, Newton upgraded to improve the environmental conditions, and the Central Court using modern design methods (ie exposed concrete soffits).

The services systems in Newton and Arkwright were generally at the end of their useful life and no longer providing adequate environmental conditions to occupants, so the regeneration replaced the entire central plant. The building services design reflected the essence of the brief, and Arup's response consequently had four strategic aims:

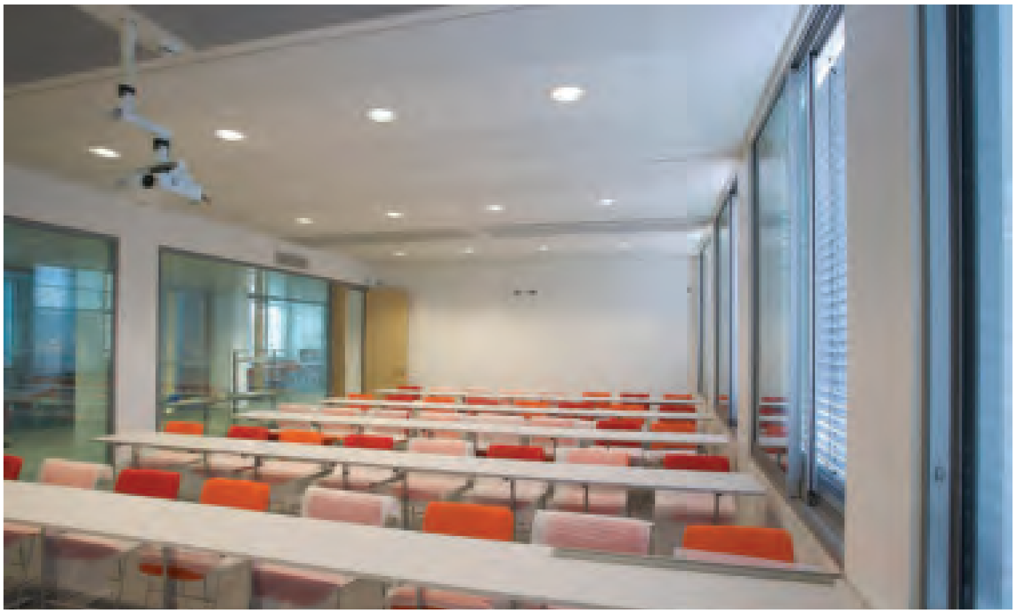
(1) to maximise occupant comfort

(2) to design energy-efficient and cost-effective systems

(3) to provide simple but robust system design solutions – easy to understand, easy to maintain, easy to modify, and long-lasting; and

(4) to make the most of the development potential by minimising services space – take in the most valuable areas and open up the University's usable floor space.

Floor-to-ceiling heights were maximised in Newton's upper floors by stripping out suspended ceilings. This provides greater daylight penetration into the teaching spaces, thus allowing lighting to be dimmed in response to the ambient light level.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Integrating modern building services into heritage buildings
Replacing the existing services and inserting new systems within the historic fabric were complicated challenges, requiring detailed investigation and close co-ordination between the structural and services team members.

The original buildings long predated information technology in the teaching environment, so the sympathetic integration of what was needed to create comfortable IT-rich teaching and learning spaces required distinct and unique solutions. However, the Newton building's previous life as the Chemistry Department yielded previously unsuspected drainage channels in the former laboratory floors, which were used to distribute all the required power, data and audiovisual connections.

Heating, ventilation and cooling to each teaching room in Newton is via bespoke active chilled beams, which also incorporate mounting connections for projectors, fire detection equipment, and lighting controls. This neat and clean solution resulted in uncluttered ceilings.

Other features of the original buildings mostly hidden from view, such as underground service tunnels and basements, were used to distribute services.

Within the Newton building, a new high-level services distribution zone runs the full length of the spine along the line of the corridor columns. Generally the existing services risers were re-used for vertical distribution, but some new risers through the existing floor slabs were also needed.

Ventilation systems
Most of the high occupancy areas are mechanically ventilated with full fresh air, which in turn maximises the possibility of "free" cooling; all air-handling units (AHUs) were fitted with heat reclaim devices to minimise heat or cooling input to the supply air. The conference areas and general teaching rooms in Newton are mechanically ventilated, using the ceiling voids for services distribution. The supply is through high-level slot diffusers, with the return air extracted through shadow gaps around the room perimeter.

The lecture theatres and conference spaces have dedicated AHUs adjacent to the space served, thus minimising distribution losses while providing large air volumes to these spaces efficiently.

The Central Court has diverse functions, and the environmental challenges for each area were addressed individually. The Link Building, reception area, and social spaces have displacement ventilation. Roof vents provide smoke extract around the Central Court rooflight and glazed elevation overlooking the Quadrangle, and also enable natural ventilation during summer. As the Central Court, reception area and Link building form one large space, the individual systems work together to condition it.

Arkwright and the Chemistry building are naturally ventilated through windows and roof lanterns with motorised openings, which have been refurbished to allow operation in summer and the seals improved for winter.

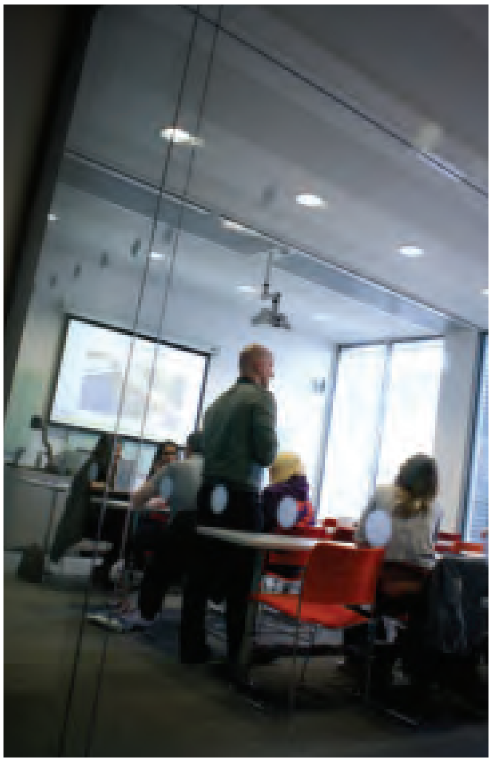
A new catering facility was incorporated in Arkwright, with the main cooking area in the existing basement, and mechanically ventilated as for a commercial kitchen. The kitchen exhaust had to be taken beyond the Central Court roof, for which purpose one of the retained chimneys was used. Once again, an integrated engineering design approach between disciplines was essential.

Access

Old buildings were not designed with disability access in mind, and numerous changes in level had to be addressed as part of the design. In total there are 15 forms of vertical transportation on the project (each appropriate for a specific need), from dumb waiters to fire-fighting/evacuation lifts.

The existing lifts serving the nine storeys of the Newton building were inadequate, and further compromised by the volume of students entering and leaving the building via the lowest level. In addressing this, Arup sought a balance between improved performance and reasonable cost.

Full use was made of the existing six passenger lift shafts, with new lifts sized to match the existing 1600kg lifts. The new lifts, however, were designed to include a destination control system, which to improve efficiency calculates the optimum travel by grouping people going to the same floor and consequentially reducing the number of intermediate stops.



23.

Environmental performance

Sustainability was embraced by the client and the entire design team from the outset, and the scheme successfully upgraded the existing environmental performance with measures such as secondary glazing and new heating and cooling systems. The key was to integrate these modifications subtly within the original fabric and structure, once again requiring careful, detailed investigation and close co-ordination between the structural and services engineers and the architect.

The first step in reducing energy consumption was through improving passive performance. Newton had long single-glazed façades, and so the internal spaces suffered from summer overheating and significant heat loss in winter. The façade was retained, but vastly improved by retrofitting secondary double-glazing with electronically operated blinds within the cavity between the existing and new glazing. This significantly reduced infiltration and solar gain.

System losses were also reduced by improving all building services insulation to meet current Part L standards. This helps to maintain a comfortable teaching environment, maximise the benefit of the available daylight, and control energy usage.

Energy use was reduced as much as possible. The active chilled beams in Newton provide efficient cooling, and facilitate a raised ceiling height to allow for good daylight penetration. Ventilation to each room has a shut-off damper linked to a presence detector to reduce fan and cooling energy for unoccupied space. All air systems have full heat recovery with the option to supply 100% fresh air to maximise use of free cooling. Also, new efficient light fittings linked to presence detectors minimise lighting energy consumption.

Nottingham's waste-fuelled district heating system provides heating to the campus, including Arkwright, Newton, and the Central Court. The system supplies hot water to the AHU heating coils and perimeter radiators in Arkwright. The heating systems are zoned to allow shut-off when heating is not required. Hot water is provided by a variable-speed pump to match supply to demand. The heating system is also weather-compensated to maximise efficiencies.

The refurbished Arkwright building was designed to be naturally ventilated where possible; creating new openable windows without affecting the architectural language was a significant undertaking. The building's thermal mass was retained to dampen the effect of peak summer and winter temperatures, and the existing glazing refurbished to improve the draft performance of the glass and hence infiltration. Efficient lighting and radiators with zoning control were installed to minimise energy use.

The team carried out detailed solar shading studies as part of the design of the Central Court glass roof, and daylighting and solar heat gains were balanced to provide maximum benefit to this space. AHUs were located as close to the lecture halls as possible to provide efficient ventilation.

In addition to these energy efficiencies, the concrete mix design – including aggregate recycled from old railway ballast – was chosen to limit negative environmental impact. Finally, at approximately 3000m², the sedum roof is one of the UK's largest; it both reduces runoff and introduces biodervisity to the project.

Façade engineering

As already described, the scheme involved opening up the lower levels of the Newton building. The existing façade above level 2 consisted of Portland stone panels on the east and west elevations, with glazing between these "solid" panels in vertical strips extending up to roof level between stone fins. Solid masonry panels also existed below level 2, but the scheme required this to be removed so as to open up the space.

To achieve this, the team carried out detailed surveys of how the Portland stone façade panels were supported, and confirmed that the nine storeys of stone cladding was loadbearing and stackbonded, and supported on the masonry below.

The stone fins between the glazing were found to be located at column positions and also centrally between columns, and made of 500mm high courses of stone projecting beyond the line of the building below. Detailed façade surveys and evaluation of historical data confirmed that the fins were base stacked, but that a structural system provided support to the stone fins at level 2. The existing masonry at the lower levels could therefore be removed with little structural remedial work.

The Portland stone-clad walls around the perimeter of the existing redundant engineering workshops of the Newton building needed to be retained. The new structure consisted of a braced steel frame providing permanent lateral support to these walls. However, it was necessary to carry out detailed façade surveys to determine the existing construction, and consideration had to be given to the construction methodology, temporary support, and possible movements.

Fire engineering

The fire strategy was developed to maximise the existing buildings' functional operation. It was pivotal to their long-term future, and has brought tangible benefits to the teaching staff, students, and the community.

Fire safety upgrades needed to be tailored and appropriate to the existing heritage nature, and the strategy was developed to accommodate sustainability aspirations, including the desire for natural ventilation as well as a smoke management system within the open-plan Central Court space.

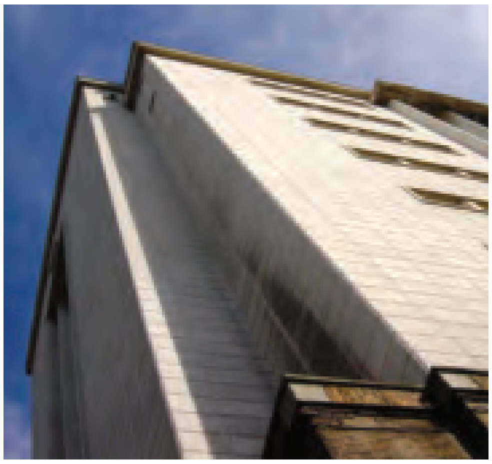
23. Teaching in the Newton building

24. Portland Stone cladding to the Newton building elevation.

25. Typical general practice teaching rooms in use in the Newton building.

26. Newton building lecture theatres.

27. The Quad in full use (next page).



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Detailed structural fire assessments established the fire performance of existing structural elements, including the "clay pot floors" in the Newton building (the floors had been originally constructed as concrete ribbed slabs with hollow ceramic void formers). The Arup team demonstrated that structural stability and compartmentation could be maintained utilising the existing fabric and without introducing substantial new measures such as fire-rated ceilings.

Fire safety upgrades included improving fire-fighting provisions through reworking the existing cores to create fire-fighting shafts, improving fire compartmentation, again by utilising and enhancing the existing fabric, and rationalising the means of escape.

The buildings were thus upgraded to meet current fire safety requirements, but subtly and discreetly because of their sensitive nature as listed buildings.

Due to the size and nature of works it was also necessary to develop an interim fire strategy to allow phased occupation of the building prior to final handover.

Acoustics

Prior to the refurbishment, Arup conducted an acoustic survey of both Arkwright and Newton. The existing acoustic environments within Arkwright were not intended to be specifically adjusted as part of the redevelopment, and external traffic noise here was assessed as being insufficiently disturbing to justify any remedial acoustic measures, which would have consequences for the historic fabric of the building.

Several areas in the Newton building did not provide adequate teaching environments, and the introduction of the new tram route adjacent to the building added a noise issue that had not been previously experienced. These issues were addressed and the acoustic performance was upgraded. After careful acoustic monitoring, the results obtained were used to adjust the acoustic properties of the existing fabric by incorporating new finishes, develop bespoke construction details to improve the acoustic properties, and introduce new measures such as secondary glazing and timber panelling, subtly integrated with the existing fabric.

27.

Conclusion

The completed refurbishment and renewal project opened to general acclaim in May 2010. NTU had the foresight to understand that radical works were necessary to deliver an inspirational learning environment for many generations of students. The scheme has now brought new life to the existing buildings as well as forming a major entrance not just to the buildings themselves but to the heart of the whole campus.

The fact that Newton and Arkwright are protected buildings was not a hindrance to giving them a new life through a range of interventions designed not to compromise the original character. A wide variety of engineering techniques and solutions were implemented to extend their life and improve their performance.

This could only have been achieved with the input of a range of specialists working closely together. Carefully considered, subtle, and discreet engineering to both listed buildings has left their public façades essentially unaltered, while radical changes have dramatically transformed and improved access and connectivity and provided new spaces, internal and external, creating a series of linked, transparent, easily comprehended, and daylit environments.

NTU now has a scheme worthy of its location in the cultural heart of Nottingham, and the entire development enhances the landmark status of the Newton and Arkwright buildings.

Ged O'Donoghue, Director of Estates & Resources at NTU commented: "The aim was to turn two rather tired Grade II* listed buildings with immense potential into proud landmarks at the heart of the city centre university quarter. When thinking about the regeneration of these two historic landmarks, the challenge has been to create imaginative and sensitive solutions that respect the buildings' history while modernising the layout and facilities. Arup's contribution was invaluable in getting the right balance between keeping the most remarkable original features of the buildings while providing the 21st century facilities required by a forward-thinking university."

Author

Stephen Fernandez is an Associate of Arup in the Nottingham office, and was intimately involved from scheme stage through to completion of the NTU refurbishment project. He acknowledges with thanks assistance in the preparation of this article from colleagues Neil Harrison, Barney Jordan, John Read, Jack Wilshaw, and Jeffrey Yuen.

Project credits

Client: *Nottingham Trent University* Architect: *Hopkins Architects LLP* SMEP and fire engineer, acoustics and façades consultant: *Arup – Sonja Abhyankar, Curro Aguirre, Mohamad Al-Dah, Julia Allison, Paul Andrew, Jenna Andrews, Graham Angus, Rozina Aslam, Ross Bailie, Trevor Baker, Keeran Balasubramaniam, Scott Bambling, Simon Bentley, Riccardo Bragoli, Steph Brewood, Chris Brown, Sara Brusoni, Jack Burvill, Howard But, Tony Campbell, Greg Chandler, Paul Coe, Judy Coleman, Ryan Coulin, Bill Coulson, Peter Court, Dominic Coyle, Chris Deverson, Jamie Donaghy, Christine Duncan, Nigel Erhardt, Iona Evans, Stephen Fernandez, Andrew Freezer, Jayne Furniss, Krzysztof Gajda, Neal Gardiner, Andy Gardner, Jonathan Gaunt, Ian Griggs, Jillian Hardie, Neil Harrison, Nathan Hattersley, Isobel Byrne Hill, Mark Hutchison, Richard Jackson, John Jones, Scott Jones, Barney Jordan, Beijhan Keenan, Charles King, Tina King, Jack Lam, Wai-Kong Lam, Aaron Lang, Robin Lee, Ben Lewis, Jan Lichocki, Tony Lovell, Rajiv Malik, Gary Marshall, Agata Marut, Michael Maylam, Gary McCarthy, Chris McKinstray, Lucy Merrony, Steve Mitchell, Jeremy Newton, Richard Nicholls, Crispin Oakman, Sheyda Okke, Dean Payne, Steve Peet, Steve Pennington, Roger Pickwick, Richard Pinder, Natwar Pithadia, Warrick Plymin, Geoff Powell, Phil Randall, John Read, David Richards, Colin Roberts, Jonathan Roberts, Mike Roberts, Christopher Shoebridge, Andrew Smith, Jolyon Smith, Chris Stanford, Nina Tabink, Con Therrios, Tim Thornton, David Toy, Tristan Toynbee, Jomel Uy, Chris Webb, Jack Wilshaw, Colin Winant, Craig Winter, James Woodcock, Toby Wright, Samantha Yeung, Jeffrey Yuen* Quantity surveyor and project manager: *Turner and Townsend* Contractor: *Bowmer and Kirkland Ltd*

Image credits

1-2, 4, 10, 13, 17-23, 25-27 © *Nottingham Trent University*; 3, 5, 14 *Stephen Fernandez*; 6-8, 11, 16, 24 *Arup*; 9, 12, 15 *Arup/Nigel Whale*.

This article is partly based on the paper "Regeneration of Newton and Arkwright buildings at Nottingham Trent University" by Stephen Fernandez, published in The Structural Engineer, *89(3), pp21-25, February 2011.*

Awards

Institution of Structural Engineers Midlands Counties Branch Awards 2010 – Heritage Category: *Winner*

Concrete Society Awards 2010 – Building Category: *Joint Winner*

Royal Institute of British Architects Awards 2011 – East Midlands: *Winner*

Civic Trust Awards 2011: *Winner.*

Sustainable design solutions for transit buildings and infrastructure

Authors Laura Frost Hilary Holden

1.

Introduction and background

Pursuing sustainability in transportation systems, as in all aspects of the built environment, has become an overriding challenge for planners worldwide. “Sustainability” can mean many different things depending upon context, but so far as transportation planning is concerned, it involves seeking mechanisms by which to encourage modal shift and cultural change in travel patterns.

However, taking sustainability into account at the planning stage, while essential, is only one factor in developing a sustainable transportation system; the system’s functioning depends overwhelmingly on the static buildings and infrastructure that support it. Only by taking a “joined-up” approach to delivering sustainability through both planning and design engineering can more sustainable systems really be achieved.

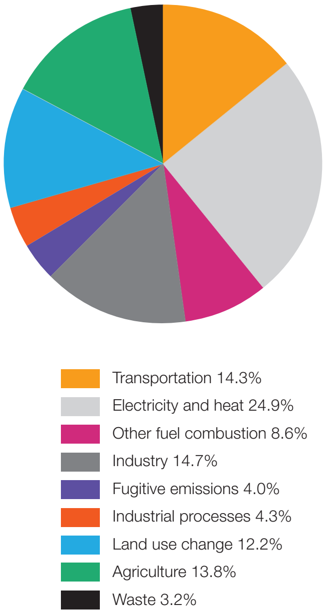
The fractious relationship between transportation and the sustainability agenda has long been recognised. Whether for leisure, commuting or freight, transportation presents discomforting questions around fuel consumption, emissions and air quality, health, equity, accessibility, and economic prosperity – all cutting across the environmental, social and economic objectives of the “triple bottom line”.

At the same time, however, transportation is fundamental to the functioning of successful and sustainable economies, enabling goods and people to be delivered from one location to another and allowing trade and transactions to take place. It is essential to quality of life, supporting social networks and enabling people to reach work and leisure facilities; the systems that facilitate these interactions are intrinsic to the functioning of socio-economic networks and human wellbeing. As demand for travel continues to grow against the context of evolving environmental constraints, there is a need to consider more carefully the way transport systems and their infrastructure are planned and developed for the future.

Solutions to this precarious balance have been widely discussed, largely with a focus on the nature and means of travel itself. Worldwide, there is a concerted effort in transportation planning towards “modal shift”, “smarter choices”, and “green travel planning”, in a bid to coax travellers out of their high-consumption private vehicles and into more sustainable alternatives. These may include walking and cycling (where practicable), low emissions vehicles, and mass transit, all of which can cut resource use and emissions, encourage healthier lifestyles, but still support the travel aspirations of the modern world.

1. Model of Vaughan Metropolitan Centre station on the Toronto-York Spadina Subway Extension project for the Toronto Transit Commission.

> As demand for travel continues to grow against the context of evolving environmental constraints, there is a need to consider more carefully the way transportation systems and their infrastructure are planned and developed for the future.



2.

Taking greenhouse gas emissions as a proxy indicator of sustainability impact, Fig 2 demonstrates why this strategy has been considered appropriate. It shows global greenhouse gas emissions by source in 2005, based on calculations by the World Resources Institute[1]. Transportation – including road, air, rail, ship and other modes – represents 14.3% of the total carbon footprint, the third largest category in the inventory. Transportation is hence a logical target for improving the emissions baseline.

But these data neglect the fact that "transportation" means more than just vehicles. Vehicles – and people – are only the moving parts within a complex system whose static infrastructure has substantial sustainability implications of its own.

Notably, Fig 2 shows that the categories of emissions having greater impact than transportation are those of electricity and heat (24.9%) and industry (14.7%). These include electricity and heat generation, gas extraction and fossil fuel production, materials manufacturing, construction, and building operations.

The buildings and infrastructure that make up the transportation system necessarily depend on these activities. Thus, the total impact attributable to the system should be viewed not only as that associated with vehicles. The static elements of the system should also be taken into account in pursuing "sustainable transportation".

3.

4.

Emerging trends

Through its work with transportation clients globally, Arup has increasingly recognised a shift in thinking by mass transit planners and operators. There is growing realisation that "sustainable transportation" requires more than just strategic planning, cultural change, and high-performance vehicles. A more systemic approach needs to be applied.

This has been exemplified through several projects where sustainable design of both the infrastructure and its buildings has been specifically requested by clients aspiring to "world class" operations.

For example, in Canada Arup is working with the Toronto Transit Commission to integrate sustainable design criteria into an underground extension to the City's subway system. As designer for two stations at the Vaughan Metropolitan Centre (Fig 1) and York University, Arup has focused on reducing the volume of structural materials early in the design process.

5.

2. Global greenhouse gas emissions by source, 2005.

3. Station entrance canopy for 2nd Avenue Subway, New York City.

4. Underground station design for Copenhagen Metro, Phase 4, showing use of natural lighting.

5. Stainless steel-clad canopy at Vauxhall Cross Interchange, London.

This will minimise construction waste on site, as well as further along the materials' supply chains. The team has also employed carbon reduction strategies to mitigate the stations' operational emissions, including the optimisation of mechanical ventilation and space conditioning, and use of high-performance insulation to minimise building heat loss. The stations meet the requirements of the Toronto Green Standard, The City of Toronto's LEED-inspired rating system, which drives a comprehensive approach to sustainable design.

Elsewhere in North America, Arup's work with the New York City Transit Authority (NYCT) on the new 2nd Avenue subway line (Fig 3) has highlighted NYCT's sustainability vision, which is framed in terms of customer safety and security; efficient movement of customers; customer satisfaction, comfort and convenience; quality design; convenient transfers and interchange; urban integration and preservation; and environmentally responsible design – a much broader array of interests than are traditionally considered as part of "green travel" planning.

The plans for 2nd Avenue subway won a "green apple" design award in 2004 from NYC Department of Environmental Protection. The Station Planning and Design Guidelines developed by Arup as part of the project reflect NYCT's sustainability goals, and are intended for rollout in all future new underground stations in New York.

Similar endorsement of infrastructure sustainability objectives has been noted in other geographical regions. The Arup team adopted an innovative approach to natural daylighting for underground stations along Copenhagen's Metro Phase 4 in Denmark (Fig 4), in this instance using skylights to link the underground interior with the external environment. In London, the Vauxhall Cross Interchange has been modernised with the addition of an iconic, lightweight stainless steel-clad canopy running the length of the Arup Associates-designed bus station[2] (Fig 5), which hosts photovoltaic panels generating 30% of the energy required to power the station area.

In Australia, Arup has worked with transport authorities on extended cost-benefit analyses, to assess the advantages that new transport infrastructure can offer to surrounding communities by improving local environmental quality, accessibility, and economic opportunity.

This new appetite for sustainable design therefore recognises the role of infrastructure in supporting a more sustainable transportation system, and the contribution that sustainable design can offer to improve the customer experience of mass transit. Only by making the travel experience more attractive will people really be encouraged to make the mode shift that green travel planners eagerly pursue.

Case study: Centro, UK

It was the ambition to "transform public transport" and "promote public transport use as a sustainable means of travel" that encouraged one Arup client in the UK to investigate more thoroughly its opportunities to "shift to sustainable public transport design".

The West Midlands Integrated Transport Authority (ITA), known as Centro, is a local government-led organisation responsible for public transport networks in the UK West Midlands. Centro has been driving a joined-up approach to delivering sustainability by building up its internal capacity for sustainable infrastructure design. As well as contributing to the sustainable performance of Centro's infrastructure portfolio, this initiative is also aimed at improving the customer experience of public transportation and influencing modal shift. Centro's exemplary approach to sustainability through the whole transportation system is one from which many organisations could learn.

ITAs are mandated in the UK's city regions to deliver local transport plans; to manage and plan local public transportation networks; and to develop, manage and maintain public transportation buildings and infrastructure. Their function joins up the constituent parts of the transportation system – vehicles, people, buildings and infrastructure – and thus encourages a holistic approach to system management. A major role of the ITAs is to promote and develop public transport options, and thereby to facilitate the shift to smarter choices. By joining the dots between its corporate responsibilities, Centro has demonstrated exemplary sustainability leadership amongst the ITA community.

Centro's corporate commitment to sustainable development is established through its Environmental Policy[3], which sets out a mission "to improve the economic, environmental and social wellbeing of the West Midlands". The Environmental Strategy 2009-2014[4] spells out additional specific actions, including a priority to incorporate sustainable design measures into future public transport infrastructure builds and major refurbishments. Strategic milestones target industry certification schemes for sustainable design, and the preparation of an internal public transport infrastructure sustainable design toolkit.

Before embarking on this agenda in 2009, Centro had adopted sustainable design initiatives on an ad hoc basis for its past projects, including the replacement of bus shelter lighting with cost-effective solar-powered fixtures and installation of a green roof at a key regional bus station. However, a more consolidated approach was needed to evaluate sustainable design on all projects, and to support Centro's own project teams with selecting and implementing appropriate solutions to maximise sustainability benefits through integrated and consistent project management. Centro recognised in turn that only by equipping its own staff with the skills and knowledge for sustainable design would real change be delivered in its built environment.

During 2009 and 2010, Arup and Centro worked together on the preparation and rollout of a design toolkit, which supports the definition and delivery of design objectives across the breadth of sustainability challenges, including energy and water management; materials and waste; biodiversity; landscape and townscape; social and community; local economy; and climate change mitigation and adaptation. It encourages Centro's officers to formulate relevant design objectives for the locality in which they are working, and to identify and evaluate suitable design solutions to be advanced through project development.

Arup's specialist engineers and sustainability planners prepared a technical evidence base that gave comprehensive information about sustainable design initiatives appropriate to each element of Centro's infrastructure portfolio: bus stops and stations, rail stations, interchanges, tram stops and depots, and park and ride sites. This evidence base served as a reference for Centro officers requiring details about performance specifications, specialist sourcing and maintenance requirements, revenue implications, funding opportunities, and case study examples, among others. The initiatives featured in the document included technical and strategic solutions to be considered in planning and designing new construction and refurbishment.

In addition, the team collated a separate advice note to describe how implementing design solutions may contribute to future certification of buildings and infrastructure through schemes like BREEAM (Building Research Establishment Environmental Assessment Method), and CEEQUAL (the Civil Engineering Environmental Quality Assessment and Award Scheme).

The two documents were aimed to lead more informed discussions between Centro's officers and its design contractors, and to stimulate greater innovation in design.

Using these raw data, Arup then worked with Centro to develop a user-friendly interface and decision-making tool. This "Design Guide" presents the entry point into sustainable design, with summary information and an evaluation process for Centro's officers to quickly identify sustainable design initiatives that may be applicable to each project. The guide is based around infographics and imagery to navigate users easily through the range of available design options, and provide a high-level understanding of the opportunities. Supported by the technical report, the Guide puts Centro officers in a strong position to deliver more integrated sustainable infrastructure design.

The toolkit has now been embedded within Centro's existing project gateway cycle, with key decision points and reporting procedures to be fulfilled at each stage of project design and delivery. By retrofitting the new process within existing corporate procedures, it is

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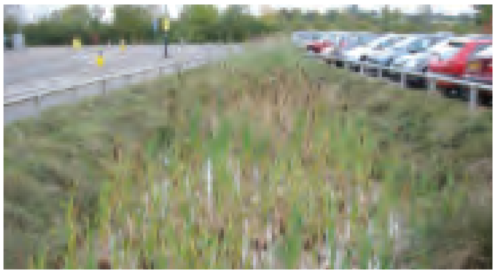

7.

8.

6. Use of durable and recycled materials in the refurbishment of a historic rail station, Birmingham Moor Street, UK.

7. Sustainable urban drainage systems, Stratford-Upon-Avon Park and Ride, Warwickshire, UK.

8. Exterior of Birmingham Moor Street station, with Selfridges, Birmingham (engineered by Arup) in the background.

intended that the new guidance will look and feel like "business as usual". The toolkit was formally launched at Centro in summer 2010, supported by capacity building workshops with multidisciplinary staff audiences, including design, procurement, commissioning and asset management. It is now being rolled out throughout the organisation and embedded more firmly within business practice.

So far, the project has been seen as a success by Centro, which envisages that it will help to drive real progress towards more sustainable infrastructure design and improved public realm transportation facilities. The next steps are to develop key performance indicators to enable sustainable design measures to be monitored in the longer term, to build up a library of "lessons learned" that will inform ongoing performance improvements.

Conclusions

The burgeoning interest in sustainability for transportation infrastructure can be observed across a wide range of project contexts and geographies, and is increasingly recognised as an influencing factor in the overall sustainability of transportation systems. Sustainability depends equally on strategic and spatial planning, and on the design and operation of a system's built assets. This approach alludes both to the physical performance of the infrastructure itself, and the potential for high quality and high performance design to encourage mode shift and cultural change for more sustainable travel choices. The symbiosis is self-evident.

Existing transportation infrastructure is ageing in cities and regions throughout the world, and refurbishments are constantly in progress. New cities and planned communities are increasingly being founded on ecological principles; new infrastructure is a fundamental requirement. There are numerous opportunities to redevelop or develop green travel networks on a foundation of sustainable infrastructure.

It is hoped that papers like this will help to open discussion between the transportation planning and infrastructure engineering communities, to build a stronger and more joined-up approach to total system design. For sustainability is inherently a question of interconnectedness and holistic thinking, which demands a systems approach for both efficiency and effectiveness.

Authors

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Project credits
Client: *Centro* Sustainability consultant: *Arup – Laura Frost, Mick Hall, Jody Harris, Bob Hudson, Ian Lanchbury, Kate Priestman, Katy Roelich, Dioni Spiliopoulou, Pete Thompson*.

Image credits
1 *Arup/Grimshaw Architects/Adamson Associates*; 2 *World Resources Institute/Nigel Whale*; 3 *DMJM*Harris+Arup (DHA)*; 4 *Arup*; 5 *Arup/Christian Richters*; 6 *Wikimedia Commons*; 7-8 *Centro*.

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Zoos SA: Gateway, Giant Panda forest, and perimeter fence project

Location
Adelaide, Australia

Authors
Sarah Allen, John Haese, Andrea Nejedlik, Rob Robson

Overview

The Royal Zoological Society of South Australia (Zoos SA) was established in 1883, making Adelaide Zoo the second oldest in Australia. Home to almost 300 species of exotic and native mammals, birds, reptiles and fish, the 8ha Zoo focuses on endangered and rare animals from the continents that derived from the prehistoric super-continent Gondwana – South America, India, Africa and Australia – as well as from South East Asia. The Zoo is in the Adelaide Park Lands between the Botanic Gardens and River Torrens, close to the city's CBD.

In 2007, Zoos SA committed to its biggest redevelopment since the original opening. A major driver for this was the 10-year loan of two Giant Pandas from the People's Republic of China (PRC), alongside the need to modernise and upgrade substantial elements of the entrance facilities and infrastructure. Sustainability and innovation formed the key foci for the redevelopment.

Arup provided complete PM (project management) services for the AUS$33M project to a brief that embraced, firstly, Zoos SA's core message of conservation; secondly, the creation of an exceptional space; and thirdly, the provision of functionality for visitors, staff and animals.

Of the Zoo's total area, the project occupies almost a third (Fig 2) and includes a complete new perimeter fence, new entrance area with visitor services, retail, a new café, a function centre and conservation centre, and the new Panda Exhibit – home to the Zoo's resident Red Pandas as well as Wang Wang and Funi, the Giant Pandas on loan.

1.

Inception and brief

October 2007
From 1984 onwards, the PRC developed a loan programme in which zoos around the world host a pair of Giant Pandas for up to 10 years and take part in scientific research. The idea of Adelaide's participation began when Melbourne Zoo and Sydney's Taronga Zoo were bidding in early 2006 for an elephant conservation programme from Thailand. Adelaide Zoo determined to bring an alternative iconic species and "Project Black and White", as it was informally named, was initiated. Negotiations across three governments – South Australian State, Australian Federal, and the PRC – were led by the Zoo and these continued for the duration of the redevelopment project.

Hassell Ltd was appointed as architect/landscape architect, planner and interior designer following the announcement of the Giant Panda loan at the 2007 Asia Pacific Economic Cooperation (APEC) summit in Australia. Hassell invited Arup to meet with the client, and Zoos SA duly engaged the firm in October 2007 – predominantly at that stage to represent the client's interests in this very significant project for the Zoo.

As well as the usual PM functions, Arup's role was clearly focused around taking the lead in key relationship management, value management, proactive risk management, contractor procurement, programming, and co-ordination advice on how the Zoo's operations would interface with the building project, plus general strategic advice.

Zoos SA embarked on this project with its core vision to the fore: "We exist to save animals from extinction." The team had to understand and respond to this simple yet powerful statement, and focus throughout on ensuring that the project's potential for achieving this aim was maximised, while maintaining strict budget and time control.

The Zoos SA message was also furthered by a sustainable and innovative design approach, enhancing this existing, much-loved South Australian facility to provide a new and significant civic space for Adelaide. The expected outcome was high quality and functional facilities for visitors, staff, and animals in a built environment that reflected not only Zoos SA's environmental and conservation ethics, but also a positive design and customer service image to local, interstate, and overseas visitors.

Arup facilitated an initial relationship workshop which, in the light of all these considerations, adopted an internal acronym. "**PEOPLE**" adumbrated the development's core elements as identified by the client and project team at inception:

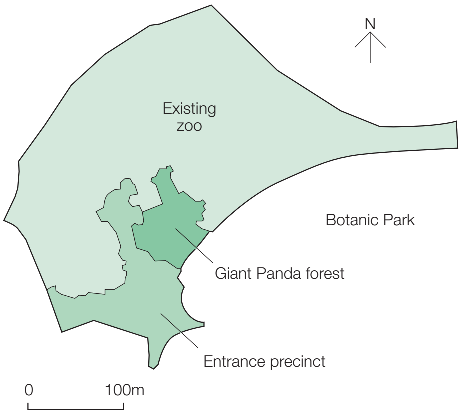
- **P**erimeter: replacement of the existing 1.7km of timber palisade fence with a new, transparent, but secure perimeter (ie meeting strict Zoo performance criteria relating to animals and people) to open up the Zoo and present it externally, unlike the previous inward focus
- **E**ntrance: a new Zoo gateway, incorporating visitor services and café covered by a green roof, with ticketing, new administration office areas, retail, conference facilities, and a Conservation Education Centre
- **O**rientation: enhanced wayfinding and entrance orientation area, and a significant public forecourt including green walls, essentially gifted to the people of Adelaide by Zoos SA
- **P**andas: new exhibition space and accommodation for the Giant Pandas and Red Pandas
- **L**earning: ensuring that the project delivered both enhanced visitor experiences as well as conveying clearly the Zoo's key messages on conservation, education, research and environment
- **E**xit: provision of new public entrance and exit to the Zoo, moved from its previous, heritage-listed Frome Road entrance.

> Arup's management of this project balanced issues of animal care, human safety, conservation, education, budgeting and scheduling, social amenity, and green building.

2.

Project timeline

• inception	October 2007
• concept design start	November 2007
• construction start	August 2008
• Giant Panda arrival	November 2009
• public opening	December 2009
• construction completion	February 2010



3.

1. Conservation Centre at the entrance.
2. Giant Panda at Adelaide Zoo.
3. Extent of the project works.

Design and documentation

November 2007-July 2008
The challenge combined very specific animal husbandry requirements, environmentally sustainable design principles, and the needs of the viewing public, all within a "fast-track" project requiring significant management, consultation and co-ordination, and driven by the Giant Pandas' arrival deadline.

The team had to rapidly embrace the implications of major construction within an operating Zoo that must maintain its quarantine status at all times, strictly control perimeters to keep vermin out, and observe specific health and safety requirements such as the procedures and policies should any animals escape to the outside. Also, an infrastructure that essentially dated back to the 19th century in many areas had to be dealt with, along with multiple issues related to animal husbandry and the potential impacts of works on the welfare of animals near the construction zone.

In response, Arup developed a detailed project plan, the core PM document that was supported by all the detailed individual plans and documents, updated as they developed through the project's many stages. This was critical for the design's success through:

- establishing and implementing project communications protocols
- managing the scope and approved change process
- establishing a complying health and safety plan (particularly ensuring that it took in the unique health and safety aspects of working within an operating Zoo)
- laying out a comprehensive stakeholder management plan.

This Zoo is a complex organisation with diverse stakeholders. Externally they include commercial sponsors, politicians, members, volunteers, visitors, schools, research organisations, commercial operators, and a key relationship with the Department of Environment and Heritage as part of the Botanic Gardens. Internally it has zoologists, keepers, veterinary staff, administrators, accountants, horticulturists, industrial and graphic designers, as well as asset and maintenance, HR, retail, media and marketing, event management and IT staff.

Relationships

Once the consultant team was fully assembled, an immediate action for Arup was to lead a detailed one-day relationship workshop. Initial discussions with the Zoo and consultants identified the need to establish rapidly a positive culture for the project and ensure the correct environment for success, with all involved understanding the project, its objectives, and what their role or roles were within the wider team.

This workshop was enormously valuable, giving very clear direction and illumination on multiple levels. It developed key outcomes in terms of team values and behaviours (Fig 4) to be incorporated into the PEOPLE project. Seventeen core values, for all project team members to apply throughout the building delivery and in their personal interactions, were identified and agreed, as well as a further set of 12 core personal behaviours.

The whole team signed this endorsed team charter, and hard copies were created and issued in an easy-to-use form. These helped ensure that behaviours and relationships were respected and appropriate, particularly through some of the more challenging aspects to which a complex project like this is subject.

The successful contractor was also inducted into the overall relationship charter, via another facilitated workshop in which Arup utilised the concept of "a day in the life" of team members to stimulate discussion and participation. Each organisation presented a storyboard, detailing its specific day in the life of the project; no other limitations or guidance were given, ensuring a diverse and interesting set of presentations. These provided useful insight into others' perceptions and views on their project roles, and were used by the Arup facilitator to guide subsequent sessions.

Key outcomes of this second workshop were the recognition and development of the team's response to issues that had arisen so far, and agreement on how to respond to them. Addressing these openly and in a workshop environment empowered individuals, enabling a non-confrontational tabling of issues that team members could not only address, but also recognise some that they may have been unaware of which could impact the overall team performance.

Following this workshop, everyone received a report documenting what required improvement and the agreed approach to adopt to ensure enhanced performance. The areas involved were based around:

- *Process*
- *One team, one goal*
- *Clarity*
- *External influences*
- *Communication.*

As well as stand-alone workshops, Arup's involvement and focus on team relationships also took in ongoing health checks and direct intervention with individuals when needed. This benefited the overall project performance, and ensured that complex, challenging discussions and decisions could be made appropriately and with the project's interests uppermost.

team behaviours**:** relationship charter

Perimeter
Entrance
Orientation
Pandas
Learning
Exit

- Good two-way communications
- Committed participation
- Clarity
- Passion
- Enthusiasm
- Responsiveness

- Honesty
- Trust
- Respect
- Equity *(proper consideration to all stakeholders)*
- Celebration
- Integrity

team values**:** relationship charter

- ✓ Convey conservation messages
- ✓ Support animal and people welfare
- ✓ Provide immersive experience for children
- ✓ Create functionality for visitors, staff and animals *(provide a guaranteed experience)*
- ✓ Provide value for members & reward membership
- ✓ Design sustainable built forms
- ✓ Create an exceptional place
- ✓ Provide a quality result through quality processes and planning
- ✓ Use resources effectively

- ✓ Create a safe environment within the Zoo
- ✓ Create a safe environment for teamwork where each team member feels safe, supported, and respected
- ✓ Practice "*no blame*" behaviour
- ✓ Do not repeat mistakes of the past through learning from our past projects
- ✓ Using all team members' experiences
- ✓ Maintain integrity and reputation
- ✓ Retain ownership of the project
- ✓ Provide transparency

4.

Engaging all these throughout the design and documentation – accessing their knowledge and encouraging ownership of design decisions – was achieved through bespoke design workshops led by the architectural team, who from the outset established three design working teams that met regularly:

- Panda: driven by the landscape architects, Zoo horticulturalists, and animal keepers
- Entrance: driven by the architects and the Zoo administration
- Fence: driven by the landscape architects, Zoo horticulturalists, and Zoo admin.

These reported to a weekly design team meeting attended by the wider consultant team, the project managers, and client representatives.

Value management and options analysis

Vigorous advice and analysis were critical to help Zoos SA make strategic, well-informed decisions at key project milestones. Arup led the process, jointly working with the cost managers, RLB, that enabled the client to make appropriate decisions in line with its established governance arrangements. This analysis began early in the design process, well before procuring a contractor. There would be no time to "re-document" if tenders exceeded the available funds.

At the outset, Arup also facilitated a value management workshop to help develop a unified set of project goals before the schematic design was complete:

- address issues within the brief
- identify and prioritise key objectives
- identify and evaluate major constraints and risks
- improve the quality of project definition and briefing
- ensure decisions were open/accountable
- develop a shared understanding of the project among key participants
- improve communication/team-working
- ensure that all aspects of the works design were effective for their purpose
- maintain a focus on the Zoo's needs during design and construction
- promote worthwhile innovation
- eliminate any unnecessary cost.

Scenario	Scope details	Scope assumptions	Budget assumptions and estimates	Estimated completion date	Development Application (DA) assumptions and risks	Delivery (construction) strategy	Documentation strategy
Baseline scope.	Maintain current design including 100% green roof and Conservation Centre.	Adopted VM savings that have not impacted brief elements being implemented; project delivered as a single, management contractor delivery with staged hand-over (separable portions).	Assumed baseline scope exceeds approved budget. This includes deletion of café and conference fitout elements.	Panda Exhibit completed by October 2009; balance of works completed by February 2010.	Minimal risk to DA due to minor alterations (no major design elements removed); assumed conditional consent provided to meet programme and full consent given for construction start-up.	Fast-track construction with managing contractor engaged at earliest opportunity, all construction activities commence as soon as possible; Panda Exhibit operational on time and balance of works delivered after opening.	Maintain current design programme, acknowledging time delay in May 2008 will impact early completion date for documentation.
Scenario A Delete green roof; delay to entrance building.	Green roof to upper level deleted; Conservation Centre delivered.	Entrance building re-scoped to budget, including rework of roof and other design impacts; project delivered as a managing contractor delivery under separable portions (staged delivery); Zoo uses alternative entry for Panda Exhibit opening.	Assumed budget met; value management savings adopted to ensure budget alignment.	Panda Exhibit completed by October 2009; balance of works completed by March 2010.	Increased risk due to potential separation of assessment; significant changes to design result in extended approval review period (assumed at six weeks delay).	Staged construction activities: Panda Exhibit commences immediately and balance of works as approvals; design completed; potential loss of scales of economy between trades (multiple site visits across project) resulting in increased cost risks.	Maintain design for Panda Exhibit as per programme; require additional design time (assume four weeks) to redesign entrance building.
Scenario B Entrance building complete on time**.**	Maintain current design including 100% green roof and Conservation Centre.	Adopted VM savings that have not impacted brief elements being implemented; project delivered as a managing contractor delivery; accelerated construction programme implemented to recover delays and deliver entire project on time.	Assumed budget met; VM savings adopted to ensure budget alignment; consideration for acceleration costs and risks to the programme; risk in achieving budget – require additional VM savings to be identified, potentially delete Conservation Centre.	Project delivered October 2009; this scenario considered high risk and potentially unachievable; investigation by a construction planner recommended to test the validity of this option further.	Minimal risk to DA due to minor alterations (no major design elements removed); assumed conditional consent provided to meet programme, and full consent given for construction start-up.	Fast-track construction with managing contractor engaged at earliest opportunity; all construction activities commence as soon as possible; ;ikely to require incentivisation and acceleration to be applied to contract.	Proceed at fast-track programme to include as much delay time as possible; risk attracting additional fees to accelerate and risk in documentation quality, resulting in cost risk in construction; contract documentation to proceed on assumption DA approval will be granted.
Scenario C Entrance building partially complete on time.	Maintain current design including 100% green roof and Conservation Centre.	Adopted VM savings that have not impacted brief elements being implemented; project delivered as a managing contractor delivery under separable portions (staged delivery).	Assumed budget met; VM savings adopted to ensure budget alignment; risk cost increases to partially open entrance (additional works, temporary works, etc).	Panda Exhibit completed by October 2009; entrance building critical works to operate complete by October 2009; balance of works complete by March 2010.	Minimal risk to DA due to minor alterations (no major design elements removed); assumed conditional consent provided to meet programme and full consent given for construction start-up.	Fast-track construction with managing contractor engaged at earliest opportunity, all construction activities commence as soon as possible.	Maintain current design programme, acknowledging time delay in May 2008 will impact early completion date for documentation.

5.

4. Outcomes of the relationship workshop.

5. An early concept visualisation.

By this time a misalignment had arisen between the order of cost estimate and the return design brief. The entrance facility comprises two storeys, with part of the ground floor (café area and visitor services) covered with the green roof. The upper floor, containing the conference facility, was to be built in concrete to support the loads associated with a green roof.

This, however, proved too costly. It was critical that a solution be found, as several of the cost-saving options, if implemented, could have seriously impacted the project design intent and the client brief. The team assessed the outcomes of the value management workshop and developed a set of options, giving due consideration to each and its risks/opportunities to the project.

Cost options considered for green roof

- Option A: Delete the uppermost portion only (above the conference facility)
- Option B: Delete from both the conference facility and long gallery sections of the entrance building, but retain the split level design concept originally been proposed
- Option C: Delete entirely to upper level and make alternative design proposal.

Time impact on delivery

- Baseline scope delivery (no change to current brief)
- Option A: Delete green roof, delay to entrance building
- Option B: Entrance building on time
- Option C: Entrance building partially complete on time.

A table (Fig 5) and programme were developed to demonstrate the impact of each option and scenario. The project required clear direction on the approach to be adopted to enable timely responses from the consultant team and to ensure maximum chance for success. The Panda Exhibit was manifestly the non-negotiable item in all considerations, as the animals' arrival date was a key driver of the whole project. Arup facilitated the client's decision to proceed with Option C. The resultant design with the adopted Value Management initiatives comfortably fell within the required budget.

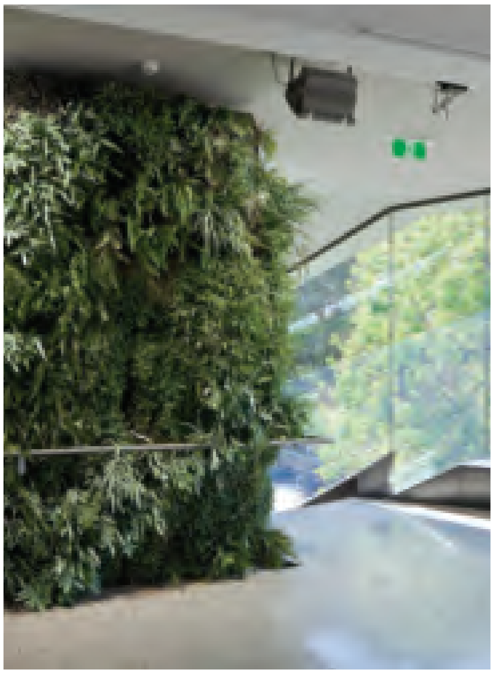
The team worked closely with the cost managers and the managing contractor through the remainder of the project to manage and monitor the costs. The managing contractor reviewed the tender documents identifying opportunities for further value management and each tender package was tightly controlled, item by item to successfully ensure the project was delivered to budget.

Procurement

May 2008-July 2008
The Arup team proceeded to develop a detailed delivery programme and procurement plan – including assessment and recommendations on contractor procurement to meet the time and cost parameters that best fitted the project and client requirements. They assessed various approaches, with a clear focus on the pros and cons of each vis-à-vis the project and its risk concerns. While there was a clear preferred option, risk remained inherent and required ongoing management and mitigation by the team. The key issues were:

- *Time: essentially driven by the Giant Pandas' arrival date and their need to acclimatise before the intense heat of a South Australian summer arrived*
- *Market pressures: driven by significant activity in the market sector (coinciding with Federal stimulus funding in response to the global financial crisis)*
- *Scope definition*
- *Aspirations versus requirements.*

In the light of all this, the recommendation was for management contracting, with a partnering charter included, in response to the project's relationship-based approach. The key considerations that directed this procurement method were that it would enable a fast-track delivery, introduce the contractor into the project team earlier (before full documentation was complete), and allow the client to maintain control over the design quality. This was further reinforced by retaining the design team contracted directly to the client, and not novating them to the managing contractor and required adherence to the relationship charter embedded in the contracts to ensure successful implementation.


6.

Collaborative approach
The value of this was demonstrated at a critical stage when, three months before opening, the Zoos SA Project Director was absent due to surgery that required several weeks for recovery. The Arup team's thorough knowledge and understanding of the project enabled it to represent the Zoo and its interests while providing direction during this period. This ensured that no momentum was lost, that the Zoo staff were able to make prompt decisions as needed, and that the consultants and managing contractor continued to receive the information they required from the Zoo to maintain project momentum.

While no one individual is bigger than a project, loss of the key role of client PD at this stage could have caused significant set-backs, or resulted in ramifications for the Zoo at a later date. During this time, the client PD wished to remain in total contact with the project, its progress and decision-making, and so regular catch-up meetings were held at his house, to enable him to receive detailed briefings and give Arup the Zoo's position when addressing current issues. It was another unique aspect of this unique project.


7.

Responsiveness
Arup's approach centred on willingness and flexibility to do whatever was required, whenever needed. One such instance was in arranging receipt and clearance from customs of a 5+ tonne marble sculpture (Fig 8) donated to the Zoo by a major Chinese sponsor for the Panda Exhibit, arriving in Adelaide only seven days before the opening.

It was imperative that the sculpture be incorporated into the exhibit, but with the team fully occupied delivering the works, this additional scope was challenging in the extreme. Arup's Project Leader stepped in to coordinate a timely resolution, arranging rapid customs' clearance, delivery to site, coordinating some quick design and documentation changes and working with the contractor's site team to modify and install this sculpture in the agreed location. It was successfully completed 24 hours before the public launch!


8.

6. Internal view of the green wall on staircase to the Conference Centre.

7. Indoor panda viewing facility under construction.

8. Marble Giant Panda sculpture.

9. The Lyrebird.

Construction

August 2008-February 2010

The managing contractor began on site in October 2008, when the one-third of the Zoo footprint that the project would occupy was to be closed off and inoperational for at least 12 months. Good communication was critical, so as to ensure that all Zoo staff were aware of what was happening.
This included understanding their obligations regarding restricted site access, occupational health and safety, and co-ordination between the Zoo's operations and the construction precinct.

Signboards about the works under way were erected, animals were relocated, temporary fencing that met the strict pest control requirements of the Zoo was erected, and demolition and salvaging of items begun.

Another relationship workshop in October 2008 brought the managing contractor on board with the project relationship charter. This identified a need to refine the processes in place to allow for greater clarity and communication with the project team, so a regular meeting schedule was established and each member of the team was tasked with the responsibility for rapid information turnaround. Registers were regularly updated and distributed at site meetings.

One risk item identified early on was the effect the works would have on underground services. An old unused well and active open sewers were discovered during demolition, and there was a continuous risk that existing infrastructure and ongoing operations would be impacted, triggering a need for upgrades and resulting in creep of the project scope.

To mitigate this, the team made an extensive survey of the underground services, and worked out a detailed programme to identify and enable works planning around ongoing operations and avoid impacting the underground services.

Further program pressures were felt due to some extreme weather conditions as Adelaide experienced prolonged periods of heat above 35°C. The site continued to work productively using tactics such as flexible working hours to avoid peak heat conditions, continuous changes on work fronts (shifting trades to internal areas when temperatures reached set levels), and providing cooling and extra drinks at all times. The managing contractor worked closely with the trades to ensure health and safety matters were successfully managed at all times.

Arup's role developed and adapted fluidly as the needs of the Zoo and the project changed. When the date for the Panda Exhibit opening was unavoidably brought forward for reasons beyond the control of the team, the already fast-track programme was ramped up to achieve this new milestone. This required detailed planning and event co-ordination as the Exhibit was within the overall construction site, as well as significant extra planning and works for a clear strategy to enable the official opening to proceed while public safety was maintained, statutory requirements met, and effective operations continued.

The foresight to include separable portions and manage these as individual design packages ensured this option was available to the project.

The managing contractor responded positively to the great pressure placed on the programme by these changes, as indeed did the entire team. The solid foundation of the relationship-based contracting enabled robust discussions that addressed core issues and led to some innovative approaches to meeting milestones.

The Panda Exhibit separable portion was agreed to be divided into a further two stages; the Giant Panda internal accommodation and the external exhibits, thus enabling the entire Exhibit to be completed on time.

It was quickly decided to base an Arup Project Manager full time at the Zoo for the final eight months of construction, to give immediate, hands-on, and accessible support to the Zoo's Project Director. In effect Arup became the Zoo PD's shadow, and a conduit for all the information, requests, and decisions that flowed between builder, superintendent, architect, consultants, Zoo staff and other stakeholders.

Life and death

Arup's close alignment with the Zoo made the Project Managers effectively part of the client team – seamlessly integrating with the organisation to not only deliver the direct project but also help address some operational matters and issues for the Zoo. While some well-publicised stories arose during construction that highlighted the unique nature of this project, some lesser-known events caused much more significant impacts, requiring detailed responses from Arup and the team.

9.

The Lyrebird can now imitate a jack-hammer perfectly[1], making some members of the public think they have accidentally walked into a construction site and not the aviary! But there was a serious side when the critically endangered orange-bellied parrots, in an aviary immediately adjacent to some essential in-ground works, laid a clutch of eggs. As only about 50 remain in the wild, this was an important event for the Zoo, and all works near the aviary had to be cancelled immediately, with no confirmed date to start again.

This was when the project had to accelerate to meet the new opening date, and resulted in the progress of the parrot young becoming a regular item on project minutes as everyone waited for the keepers to give the green light to proceed – a true test of the relationship approach! Thankfully the young (12 in all) successfully hatched, and works proceeded just in time to meet the completion date.

This was all achieved without compromise to the schedule, resulting in no delay to the remainder of the project, which was also by this stage on an accelerated path towards the official opening date. Key deadlines achieved included:

- *Panda Exhibit (internal) complete and approved by quarantine authorities for Giant Panda arrival in November 2009*
- *Panda Exhibit (external), orientation zone, and new main entrance including ticketing and new retail operations, complete for opening to the public in December 2009*
- *Entrance precinct official opening in February 2010.*

Project outcomes

Since the arrival of Wang Wang and Funi, attendance has increased significantly, delivering an excellent outcome for the Zoo and a wonderful platform to continue its core mission of conservation, education, research and environment. A sixfold recruitment rate of Zoos SA membership has also resulted, as well as wider benefits to South Australia through increased tourism and activity in and around the Zoo.

Arup responded to the client's needs with a service that aligned with the project's unique demands and challenges. Taking a leadership role and providing dedicated PM that was not confined to direct management and administration of the project fundamentals but was more broadly based as an entire client-focused service, ensured that a culture of "best for project" and stretched targets for performance were the norm. The lengthy accelerated schedule to meet the revised practical completion dates required the whole team to rise to the challenge.
Arup worked closely with the contractor and consultants to establish a clear methodology for achieving this while preserving quality and project outcomes, and the firm's Project Managers became part of the Zoo "family" – working closely with all concerned to ensure success.

Arup is proud to have contributed to an outcome that benefits the people of South Australia, the remainder of the country, and further abroad, as Zoos SA continues to advocate through its programmes and premises the core messages of conservation, education, research and environment.

Lessons learned: originality and innovation
Zoos SA supports an ambitious and innovative integration of physical, cultural and organisational strategies to focus public experience of this new facility on its core messages of conservation, education, research and environment. For this, the PEOPLE approach exposed some original aspects:

- Designing for (1) animal safety/welfare, (2) staff operations/practicality, and (3) visitor enjoyment and education was unique (eg structural engineers calculating for the impact of a 100kg arboreal mammal climbing up a frameless glass balustrade).
- The temptation to choose high-tech innovative engineering systems may not suit a zoo culture used to making do with whatever resources can be found and afforded: if something stops working and cannot be fixed easily and quickly, it may just get modified or abandoned for something more practical. The team needed to understand the realities of this.
- Investment in innovative systems and design goes on after Opening Day. Zoos SA is now a leader in managing green roof and green wall (external and internal) systems. The ongoing involvement of the design team and contractors is vital to support this.
- Zoos are 24-hour, 365-days-a-year operations, with little downtime if a key exhibit feature fails.
- Zoo fences are as much about keeping things out – feral cats, foxes, people with bad intentions – as keeping animals in.
- Planning, design and construction/operation co-ordination workshops are invaluable. The new entrance and Panda Exhibit worked like a dream after opening to the public in the peak holiday period of December 2009, even though half the entrance precinct was not completed for another two months.
- Maintaining a healthy construction and design contingency is essential to mitigate impacts from such things as latent conditions, design changes (based on new information), actual behaviour (human/animal) and accelerated costs. All these issues occurred and had to be accommodated without compromising the successful opening.
- Missing deadlines is not an option when two national governments, VIP openings, media, and sponsors are involved. The programme embodied a high risk for the reputation of the Zoo and all associated. The whole team successfully rose to this challenge.
- Zoos SA has limited people resources; with its other Zoo at Monarto, most senior staff work across both sites, juggling and prioritising commitments. Also the advent of the Giant Pandas triggered a sitewide series of upgrades to facilities, boardwalks, bridges, etc, to cope with the increased visitor numbers.
- Staged handover can damage staff morale, working in unintended conditions as they wait for builders to finish around them and systems to come on stream. Behaviours can set in that reduce the capacity to use the new facility once fully complete and operational to its full potential, as per the design intent. Acknowledgment and support from Zoo management and understanding from the project team were important to provide a sensitive day-to-day environment as the project progressed to fully operational status.

Awards
Entrance precinct
2010 Design Institute of Australia (SA) Awards: Gold Award and President's Award

2010 Australian Institute of Architects National Awards: National commendation for Urban Design

2010 Australian Institute of Architects (SA) Awards: Jack McConnell Award for Public Architecture, Robert Dickson Award for Interior Architecture, Architecture Award - Urban Design, Architecture Award - Sustainable Architecture

2010 World Architecture Festival: Shortlisted – Display

2010 BPN Sustainability Awards; Highly Commended – Public Building and Urban Design

2010 Australian Timber Design (Western Region) Awards; Winner – Best Western Region, and Winner –Public or Commercial Buildings

2010 Stormwater Excellence Awards (SA): Winner – Excellence in Infrastructure

2011 Property Council of Australia Innovation and Excellence Awards – South Australian Development of the Year

Panda Exhibit
2010 Australian Institute of Architects (SA) Awards - Commendation - Public Architecture

Entrance and Panda Exhibit
2010 National Electrical and Communications Association – Electrical Industry – Award for Excellence

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Project credits
Client: *Royal Zoological Society of South Australia*
Architect: *Hassell Ltd* Project manager: *Arup – Sarah Allen, John Haese, Andrea Nejedlik, Shirley Reeder, Rob Robson* Managing contractor: *Hindmarsh (SA)*
Other consultants: *Bestec, Wallbridge and Gilbert, Rider Levett Bucknall*

Image credits
1, 6 *Peter Bennetts*; 2 Dreamstime; 3, 5 *Arup/ Nigel Whale*; 4, 7-8 *Arup*; 9 iStockphoto; 10 *Ben Wrigley.*

Reference
(1) http://youtu.be/DyMZcqJtcKs

10. View into Giant Panda Exhibit.

10.

About Arup

Arup is a global organisation of designers, engineers, planners, and business consultants, founded in 1946 by Sir Ove Arup (1895-1988). It has a constantly evolving skills base, and works with local and international clients around the world.

Arup is owned by Trusts established for the benefit of its staff and for charitable purposes, with no external shareholders. This ownership structure, together with the core values set down by Sir Ove Arup, are fundamental to the way the firm is organised and operates.

Independence enables Arup to:

- shape its own direction and take a long-term view, unhampered by short-term pressures from external shareholders
- distribute its profits through reinvestment in learning, research and development, to staff through a global profit-sharing scheme, and by donation to charitable organisations.

Arup's core values drive a strong culture of sharing and collaboration.

All this results in:

- a dynamic working environment that inspires creativity and innovation
- a commitment to the environment and the communities where we work that defines our approach to work, to clients and collaborators, and to our own members
- robust professional and personal networks that are reinforced by positive policies on equality, fairness, staff mobility, and knowledge sharing
- the ability to grow organically by attracting and retaining the best and brightest individuals from around the world – and from a broad range of cultures – who share those core values and beliefs in social usefulness, sustainable development, and excellence in the quality of our work.

With this combination of global reach and a collaborative approach that is values-driven, Arup is uniquely positioned to fulfil its aim to shape a better world.

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