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Hong Kong's latest tourist attraction is the largest cable car system of its kind in the world.

Ngong Ping 360

John Batchelor Suresh Tank

Introduction

Ngong Ping 360, one of Hong Kong's most challenging and complex tourism projects, is a cableway linking Tung Chung and Ngong Ping *[pronounced "nong ping"]*, on Lantau Island immediately south of Hong Kong International Airport.

Tung Chung is a new town developed in conjunction with the airport, whilst Ngong Ping is home to the 34m tall Tian Tan Buddha, the world's largest outdoor seated bronze figure, completed in 1993 and weighing over 250 tonnes, and the nearby Po Lin monastery. Continuing the theme nearby is Ngong Ping Village, with attractions like "Walking with Buddha", "Monkey's Tale Theatre", and the Ngong Ping Tea House, as well as shops, restaurants, and live entertainment.

Totalling 5.7km in length, this bi-cable, circulating, detachable, cable car system is believed to be the largest of its kind in the world. Each cabin carries 17 passengers (10 seated and seven standing), and the system has the second highest transport capacity, with 3500 passengers per hour each way. It also achieves the greatest speed yet (7m/sec) in a detachable circulating system, and has the largest diameter track rope (70mm) for a bi-cable system.

The journey of 20-25 minutes from Tung Chung terminal gives panoramic views over the North Lantau Country Park, the South China Sea, Hong Kong International Airport, and surrounding areas, and culminates in a breathtaking scenic panorama as it approaches the Tian Tan Buddha and Ngong Ping.

Background

Ngong Ping is an important Hong Kong tourist attraction. It has around 1M visitors a year, despite its poor transport connections - the bus journey takes about an hour from Tung Chung on a narrow, winding road. Studies were carried out during the 1990s on the development of a cable car link between the Tung Chung new town and Ngong Ping as part of the then Hong Kong government's initiative to develop Lantau as a tourism destination.

After a competitive bid process, in July 2002 the MTR Corporation Ltd (MTRCL) and the government of Hong Kong Special Administrative Region (HK SAR) entered into a provisional agreement for the project, by then known as Tung Chung Cable Car. During this period the government enacted the Tung Chung Cable Car ordinance and the MTRCL carried out, and obtained approval of, an environmental impact assessment and a scheme design.

In November 2003, the MTRCL and the HK SAR signed a project agreement for the cable car. The franchise commenced on 24 December 2003 and will last for 30 years, after which the system will be transferred free to the government for continued operation as a tourist attraction.

Project management

Contract and procurement

With its aim a world-class but cost-effective tourism project, the MTRCL decided on a target cost contract, with pain share/gain share provisions within its standard design-and-build contract format. It adopted a two-stage tender process, and Maeda Corporation - supported by Arup - was successful in the Stage 1 tender assessment and was invited to proceed to Stage 2 as the appointed tenderer. A key part of the winning proposal was its cost-saving alternative design measures, several of which were incorporated into the subsequent target cost model.

The objective of the Stage 2 process was to develop a scheme/developed design and related working methods, with a mutually agreed and realistic target cost for the works, and this duly enabled the target cost contract to be awarded to Maeda, supported by Arup for engineering design.

4. Route alignment for the cable car system: (a) Tung Chung terminal, (b) Tower 1, (c) Tower 2A, (d) Airport Island angle station, (e) Tower 2B, (f) Tower 3, (g) Tower 4, (h) Tower 5, (i) Nei Lak Shan angle station, (j) Tower 6, (k) Tower 7, (l) Ngong Ping terminal, (m) Ngong Ping Village, (n) Tian Tan Buddha, (o) Po Lin monastery.

The Stage 2 design team, comprising the MTRCL's design consultant (Aedas Ltd supported by Mott Connell), and its own team members, was based in the MTRCL office, working closely with the appointed tenderer. They were supported by cable car operator Skyrail-ITM, from Australia, and the ropeway designer Leitner GmbH, from Austria.

The scope of the building and civil engineering works contract required Maeda and Arup to design tower foundations and pilecaps as well as provide input to the value engineering. Leitner GmbH was responsible for designing the ropeway and steel towers under a separate, interfacing contract. A target cost for the works was agreed at the end of Stage 2 and Maeda was awarded the contract to proceed with Stage 3 - the detail design and construction. Within this, Arup and Aedas, as project architect, carried out the detailed design of the works, with Arup providing civil, geotechnical, SMEP, and fire services design of the following major elements:

- Tung Chung terminal building
- two turning angle stations - Airport Island and Nei Lak Shan
- Ngong Ping terminal building
- the Ngong Ping theme village and its associated attractions
- diversion of 390m of Ngong Ping stream, constructed from gabions

5. Elevation of the cable car system (continues on subsequent pages).

- foundation design of eight towers
- slope stabilization and mitigation measures for towers and angle stations
- approximately 6km of rescue trail along the cable car alignment
- infrastructure associated with the terminal buildings, the theme village, and the angle stations.

A site team from the MTRCL and Maeda was established in shared project offices in Tung Chung and Ngong Ping, with the aim of providing effective everyday communications and quick joint decisions. At peak, the Arup team totalled around 50 engineering design staff in Hong Kong, with support from the Arup Shenzhen and Manila offices to meet multiple deadlines for design submissions.

Building approvals

All private building projects in Hong Kong are strictly controlled from design through to occupation by the Government Building Authority via its Buildings Department (BD). As Ngong Ping 360 is a private initiative operated by a non-government company, the project had to be carried out under the Buildings Ordinance.

Full structural submissions including foundations and their geotechnical input were submitted to the BD for formal approval and consent, as until consent is issued no construction may proceed for that particular element of the work. Normal approval processing is carried out within a 60 calendar day window, followed by a 28-day period for formal consent to be issued. The BD insisted that each station and tower – a total of 13 sites - be treated as a separate project from the point of view of submissions, which added significant challenges of complexity.

Responsibility for submissions, gaining approvals, consents, and subsequent safe execution within the strict controls of the Buildings Ordinance lies with professionally qualified individuals appointed by the project promoter. These individuals have a duty to see that the works are designed and constructed to the Ordinance. Overall responsibility lies with the authorized person (AP) - usually an architect - with the structural and geotechnical issues taken by a registered structural engineer (RSE) and registered geotechnical engineer (RGE). For Ngong Ping 360, these latter individuals were Arup staff, with Aedas providing the AP role. At the commencement of the project, the MTRCL initiated and chaired weekly meetings between Arup, Aedas, and Maeda to monitor a programme of BD submissions, reviewing conditions imposed by BD during the processing, and monitoring the programme tightly due to the unprecedented number of submissions (over 200) required to cover the engineering aspects of the work. Arup's work covered the building structures and tower foundations, but excluded the towers themselves and other secondary support structures covered by separate RSEs in other companies.

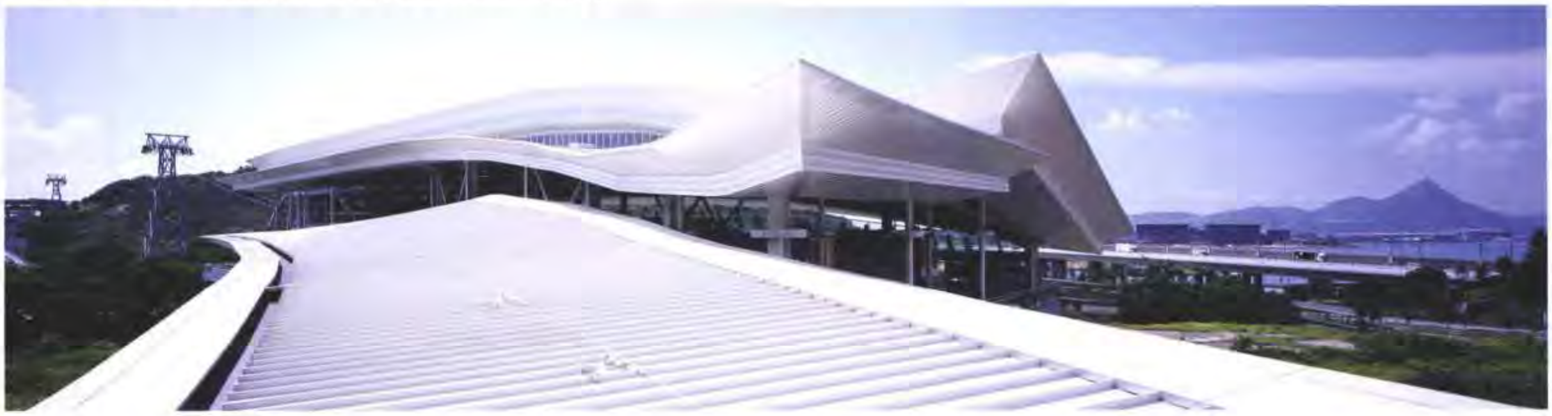
Partnering

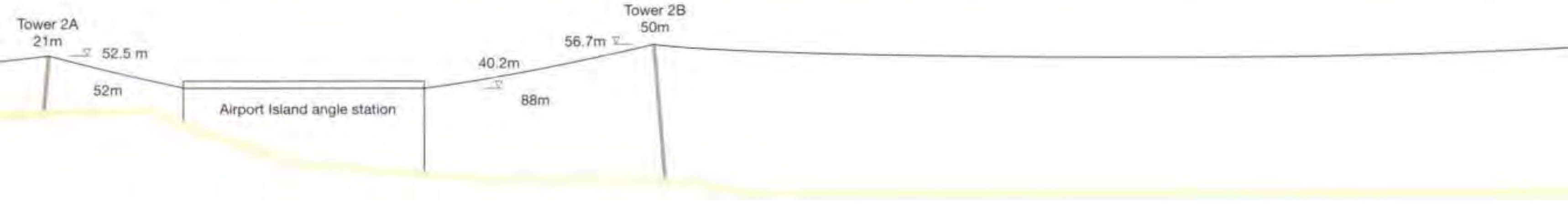
The concept of partnering was introduced at the outset. Several partnering and value management workshops, facilitated by an external consultant, were held for the project team including top management and front end site staff.

Regular monthly partnering meetings were also held on site to monitor the objectives in the project charter signed by all involved. This approach proved successful, with all parties working together to achieve common goals and creating a barrier-free and harmonious working relationship.

The cost challenges, and the complex approvals process which impacted the design costs, also tested the partnering concept, since Arup had committed to a fixed lump sum fee in advance of the BD requirements being known. However, mutual commitment to partnering by all parties enabled these challenges to be resolved without breakdown of relationships or retreat to contractual positions that would have delayed the project.

6. The dynamic roof structure of the Tung Chung terminal building.





7. Tung Chung terminal building and Tower 1.

Tung Chung terminal, elevated walkway, and footbridge

The Tung Chung terminal (Fig 7) forms the gateway to the cable car system and this is reflected in the design, with its dynamic steel roof structure (Fig 6) and its range of architectural finishes.

The main roof is split into three sections with a standing seam metal finish to the top side with concealed gutters and edge profiles. The roof structure comprises several monopitch frames with varied geometry to achieve the dynamic curved roof profile whilst keeping the fabrication and construction simple. All the steel members are straight but angled in varying directions based on geometry developed by Arup from Aedas' original design intent, working interactively with the project architects.

The upper (platform) level is mainly for the passengers to board and alight, and contains provisions for ticketing, queuing, and retail. All 112 cable car cabins are stored at night on the first floor level, below the platform level. The two track ropes supporting the system's vertical loads, one for each direction of travel, are diverted from the main vertical support through an opening in the platform slab and down to the anchorage point. The anchor drum, approximately 4.5m in diameter (Fig 8), is at this level and extends down to the pile cap. A mezzanine at first floor provides additional retail storage. Electrical and mechanical plant is mainly at the ground floor level, though it also occupies some additional first floor areas.

The main building structure is of reinforced concrete, supporting the roof above at platform level. Bored piles founded in rock carry the structure. An elevated walkway and a footbridge with stairs and escalators connect cable car passengers to Tung Chung MTR station (another Arup project[1]). Coach parking and bus and taxi interchange are also nearby.

Airport Island angle station (AIAS)

General

The AIAS site is in the lower portion of a cut slope adjacent to the junction of Chek Lap Kok South Road and Scenic Road, roughly 2.5km from the airport terminal building and some 600m from the main cable car terminal building in Tung Chung. It provides a turning point for the cable cars towards Ngong Ping, and has six levels - five of accommodation plus a platform at the top. Matching that of the Tung Chung terminal building, the roof is a monopitched standing seam metal roof supported by a slender steel frame with concealed gutters and edge profiles.

The station houses the main drive units for two sections of the system: the 600m back to the Tung Chung terminal building via Towers 2A and 1; and also the longer uphill section, with a rise in elevation of 550m and a distance of approximately 3.5km to the Nei Lak Shan angle station (NLSAS) via Towers 2B, 3, 4, and 5. The main control room for surveillance of the system is also here.

A 6m wide access road connecting to Scenic Road facilitates future maintenance access, heavy equipment and material delivery, and possible use by emergency vehicles.

8. Anchor drum and cabin storage at Tung Chung terminal.

9. Structural support at the AIAS for cable catenaries leading to Tower 3 and on to Nei Lak Shan angle station (NLSAS).

Structure

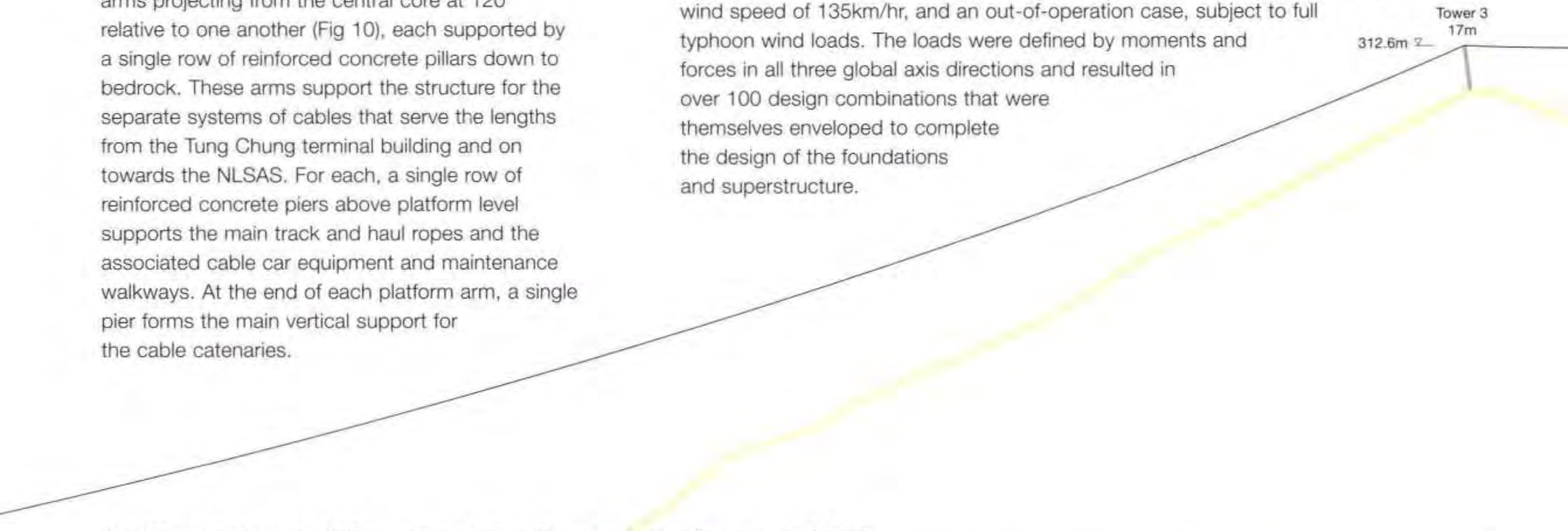
The top level of the AIAS reinforced concrete superstructure is a platform 25m above ground level (Fig 9), comprising two 40m long and 14m wide arms projecting from the central core at 120° relative to one another (Fig 10), each supported by a single row of reinforced concrete pillars down to bedrock. These arms support the structure for the separate systems of cables that serve the lengths from the Tung Chung terminal building and on towards the NLSAS. For each, a single row of reinforced concrete piers above platform level supports the main track and haul ropes and the associated cable car equipment and maintenance walkways. At the end of each platform arm, a single pier forms the main vertical support for the cable catenaries.

The foundations are a combination of pad foundations on grade II/III rock for the columns that support the AIAS structure, and a raft foundation and pre-bored rock-socketed H-piles under the central core, providing overall stability under lateral loads. Rock joint mapping, boulder surveys, and slope stability assessment were carried out to justify the proposed foundation and rock slopes.

The haul rope provides traction for the cable car system but does not support the weight of the cars themselves. It runs along either side of the central line of piers above the level 6 platform and is driven by a bull wheel on the pier closest to the central core. The bull wheel is connected by a drive shaft to a motor in the level 5 plantroom below.

Two track ropes support the system's vertical loads, one for each direction of travel. They are diverted from the main vertical support, down below the level 6 platform at an anchorage point within the level 5 plantrooms. The maximum design load on a single track rope, generated by the weight of the cable car system as well as other dynamic effects, is over 200 tonnes (2000kN of force). The combined effects of these loads from each side of the station, together with their 25m height above foundation level, generate the large overturning forces that in turn controlled the foundation design and stiffness of the superstructure. These permanent overturning forces are resisted by 500mm thick reinforced concrete core walls that spring from a stepped raft foundation, cast onto the cut rock slope and anchored by seven pre-bored rock-socketed H-piles.

The ropeway designer produced a simplified envelope of design forces for each anchorage location for the civil works design, characterized by maximum and minimum loads for each location and loadcase type. Cable loads for dead, live and wind loadcases were provided for both an operational case, with a limited design wind speed of 135km/hr, and an out-of-operation case, subject to full typhoon wind loads. The loads were defined by moments and forces in all three global axis directions and resulted in over 100 design combinations that were themselves enveloped to complete the design of the foundations and superstructure.



10. 120° angle between the AIAS arms leading to Tung Chung terminal building and to the NLSAS.

11. Nei Lak Shan angle station and Tower 4 slope reinstated after completion of stabilization works.

Nei Lak Shan angle station (NLSAS)

General

This building was sited on a rounded hilltop (Fig 11) with difficult access upslope from Tower 5 in Lantau North Country Park. It provides the turning point for the change of direction of the cable car towards Ngong Ping. As at AIAS, the cable cars detach from the rope and move at reduced speed along the station, so as to maintain riding comfort for the passengers before attaching back to the rope.

The station comprises a lower ground level (basement) and a ground (platform) level. The roof superstructure is monopitch steel frames and roof finishes similar to that of AIAS, with concealed gutters and edge profiles.

Foundations

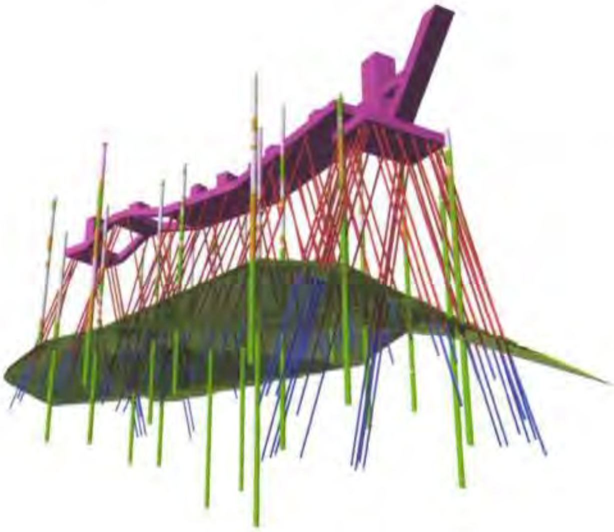
The foundations are simple pads and strip footings for the single-storey electrical and mechanical services buildings, and pilecaps and raking minipiles over the central structure supporting the cable car anchor drums and reinforced concrete columns. The minipiles were proposed due to the difficult site access (achieved by helicopters) and to minimize environmental impact. They rake in two directions (Fig 12) to resist the vertical and lateral loads - their orientation, number, and lengths being established after rigorous analysis that took into account several combinations of cable car loadings provided by the ropeway designer.

1063m

A 3-D model of the ground conditions was created to assess whether any adverse geological features were present that could affect the size and shape of the rock and soil cones assumed in the tension capacity calculation, as well as the stability of any nearby slopes. The model was based on the findings of all previous and new ground investigations, as well as geological mapping and a desk study review of geological information of the area.

The geological model did not identify any significant shearing or faulting running through the area of the foundations, and confirmed that no such adverse geological features would affect their overall stability or that of any adjacent slopes. It also confirmed the choice of socket length for each minipile under the structure.

12. Geological model showing raking piles socketed in rock (blue) together with boreholes and structure above.



Structure

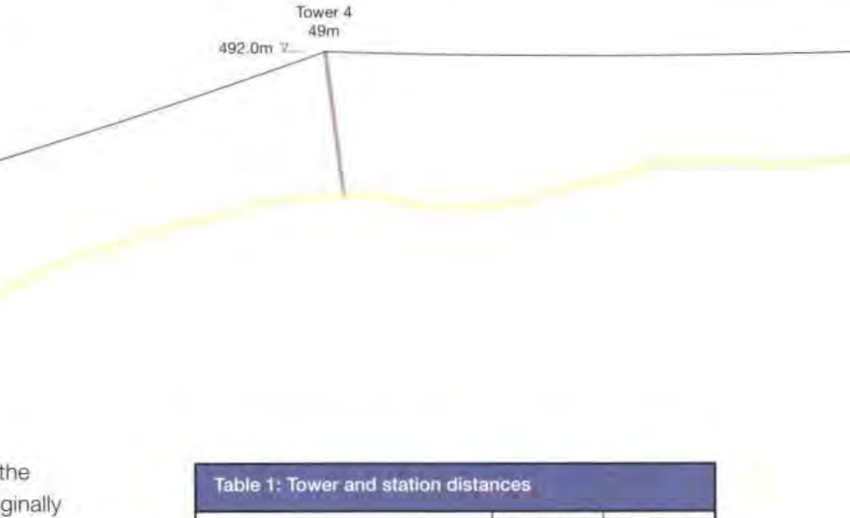
Open cut staged excavations were undertaken to enable construction of the foundations, the excavation plans being prepared after discussion with the construction team, so as to suit the preferred construction method. Due to the site's remoteness, every effort was made to minimize the volume of excavated material that had to be removed.

The foundations for the single-storey E & M services buildings were raised, both to minimize the volume of excavation and limit bearing pressures to less than 100kPa. This was to avoid regulatory requirements for plate load tests, which would have been very expensive and difficult to carry out on this remote site.

The top level of the NLSAS reinforced superstructure forms the platform. It is some 5.5m above the pilecap formation level, and comprises 40m and 35m long sections of platforms from the centre, at 160° relative to each other and supported by a single row of reinforced concrete pillars down to the pilecaps. These columns support the main track, the haul ropes, and the associated equipment for the cable car systems between the NLSAS and AIAS, and between the NLSAS and Ngong Ping terminal.

13. Roof structure at angle stations.

14. Tower 2B.



For the roof structure, three alternative schemes were compared to identify the most economic solution, as opposed to the large portal frame structures originally proposed, which formed the basis of the target cost contract during Stage 2 for both the AIAS and the NLSAS. The final scheme adopted is a trussed frame (Fig 13), which simplified connection details and only amounted to about half the steelwork weight of the Stage 2 scheme. Columns and bracing along the central gridline were limited to locations agreed with the ropeway designer.

Towers

General

There are eight towers in all, five of them in the country park (Towers 3, 4, 5, 6, and 7). The building and civil engineering contract 5201 included construction of the foundations and pilecaps within Arup's scope of works. Arup also took over all natural terrain hazard assessment and mitigation works associated with the foundation design in the country park, including identification of hazards, boulder surveys, rock joint mapping, design of mitigation measures like soil nailing and boulder stabilization, and regulatory approval processes.

Foundations

Vertical pre-bored H-piles were adopted for Towers 1 and 2B, and a combination of vertical and raking minipiles for Towers 2A and 3-7, with rock sockets to resist tension and compression. Minipiles were the preferred option for works in the country park as they could be installed with small rigs.

A typical tower foundation comprises a series of vertical and raking minipiles in two directions under a single pilecap supporting each tower leg. The ropeway designer supplied data on the most critical loads for each support, including the effects of dead load, imposed loads, wind, and earthquake loads (as required by MTRCL) from both the tower steel superstructure and the cable car system.

The maximum and minimum loads in each of the three axes, together with co-existing loads, were analyzed to give all possible load combinations from the superstructure and the cable car above. Hundreds had to be assessed so as to determine the loads in the piles and for the design of the pilecaps.

Table 1: Tower and station distances

	Horizontal distance	Inclined distance
Tung Chung terminal	116	117
Tower 1	355	355
Tower 2A	51	52
Airport Island angle station	86	88
Tower 2B	1490	1512
Tower 3	1048	1063
Tower 4	833	838
Tower 5	29	30
Nei Lak Shan angle station	161	161
Tower 6	969	974
Tower 7	386	388
Ngong Ping terminal		

Table 2: Tower heights

	Tower height in the axis	Tower width at base	Tower width at top*
Tower 1	37	12	2.5
Tower 2A	21	7	2.5
Tower 2B	50	16	2.5
Tower 3	17	7	7
Tower 4	49	16	2.5
Tower 5	44	13	2.5
Tower 6	27	9	2.5
Tower 7	46	16	4

* Below tower head

15. Tower 2A.

16. Tower 4.

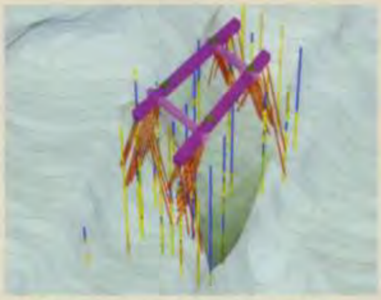
Tower 7: foundation design

The design of Tower 7 proved the greatest challenge to the project team in devising a solution, taking it through the BD approvals process, and obtaining consents for construction over a fault zone.

Based on the ground investigation provided by MTRCL (three boreholes and trial pits near the Tower 7 location), Arup's foundation design comprised vertical and raking minipiles socketed in rock a few metres below ground level. This was approved by the BD and consent was granted.

After BD approval and consent of the foundation pre-drilling, however, some of the early pre-drill holes revealed a rockhead level significantly lower than that anticipated from the original ground investigation holes. A total of 29 more holes were then drilled on a plan area of 45m x 45m to provide additional information for reviewing the ground conditions at the tower location.

A 3-D geological model for the tower was developed using data from all the boreholes and drill holes. The depth to the grade III rockhead was found to be extremely variable (7.6m to more than 60m), which was interpreted as being due to the presence of a fault zone at the tower.



17. Geological model showing transfer beams spanning across the fault with minipiles (red) founded in grade IV or better rock.

18. The completed Tower 7 showing the extent of slope stabilization, and the tower plinths.

Relocating it was not an option, as this would have had huge impact on cost and programme: the changed alignment would have meant the redesign by the ropeway designer of the towers, a requirement for additional land for the tower, further ground investigation and submission to the BD, a redesign of the tower foundations and stabilization measures, and further approvals.

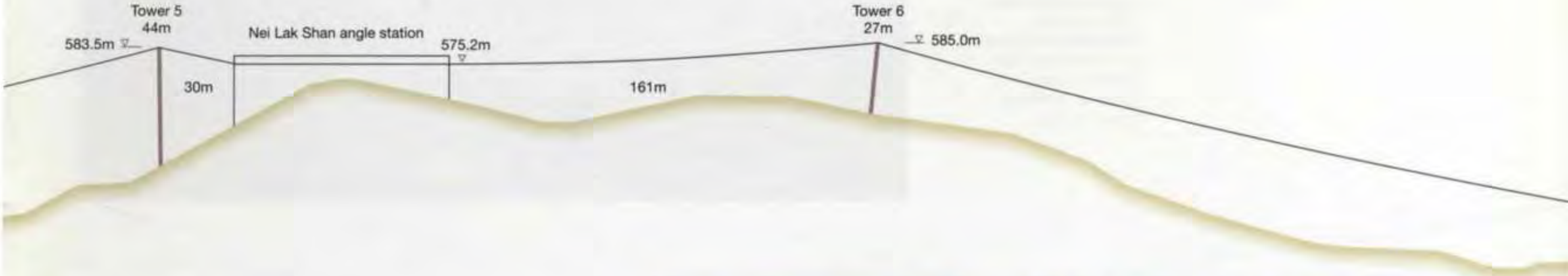
A raft spanning across the fault was also considered, with minipiles beneath it for stability. However, this option was ruled out due to the requirement for a large volume of concrete in a remote area with difficult access, the extra cost and programme implications, and impact on the stability of the existing slope due to the additional load of the raft.

The solution adopted, therefore, was a four-beam transfer structure spanning across the fault zone and supporting the four plinths of the steel tower (Fig 17). The transfer beams are supported on raking minipiles (18.4° to the vertical) and carefully located away from the fault zone in grade IV/III or better rock.

With a lot of effort from the design and construction team and the MTRCL, the geological model was agreed with the appropriate approval departments.

19. Towers, the rescue trail and Nei Lak Shan angle station.

20. Tower 3.



Ngong Ping terminal

Prior to any construction works in the Ngong Ping area, the Ngong Ping stream, which flowed directly through the site, had to be diverted to run parallel to the site's northern boundary and rejoin the existing watercourse immediately downstream of the terminal building.

Approximately 390m of banks for the diverted stream were constructed of rectangular galvanized steel mesh gabion baskets, filled with crushed rocks excavated on site (Fig 21). Gabion mattresses for the stream bed were proposed by the Stage 2 designers, but were replaced by natural crushed rocks excavated on site to enhance the environmental and ecological value of the diverted stream. Additional calculations by Arup showed that the change to the stream bed lining would have no impact on the stream's hydraulics. Detail design, government approval, and construction of the stream were all completed within five months of award of contract and before the 2004 rainy season commenced (Fig 22).

21. Stream diversion under construction, showing gabion baskets.

22. Ngong Ping stream diverted.

23. Ngong Ping Village: the terminal building is on the right, with Ngong Ping sewerage treatment works (another Arup project) in the background.

The terminal forms the start of the Ngong Ping cultural experience, and this is reflected in theming to complement the theme village itself. The superstructure of the latter's buildings are in concrete with Chinese roof tiles, except for the main terminal building roof which is of structural steel with a standing seam metal finish. The terminal building frame is in reinforced concrete with one basement level.

The terminal building accommodates the ticketing, pre-ride queuing and associated retail, covered walkway, plant, administration, and maintenance areas. Emergency vehicle access is provided around the building with the main utilities laid under footpaths.

Ngong Ping theme village

The theme village (Fig 23) has three areas of one and two-storey buildings with a traditional regional Chinese character. Maeda and Arup opted to replace the steel frames proposed by the Stage 2 designer with concrete frames to reduce cost and save time. Most of the design and drawing production for the village was carried out in Arup's Shenzhen and Manila offices and checked by the Hong Kong office before being submitted to the BD for approval.

26. A *Kamov* helicopter approaching Tower 3 (Hong Kong International Airport on Chek Lap Kok – also an Arup project - is in the background).

974m

24. One of the six mules used for transporting loads up to 120kg on narrow trails in the country park.

25. Detail of rescue trail timber construction.

Environmental considerations

The project team put great emphasis on environmental considerations. The route alignment and the type of cable car system were both selected to minimize the number of towers required in the country park. Ecological surveys were carried out by others and protected species from the tower sites were relocated.

Rather than build a haul road, helicopters and mules were used to transport materials. Six mules were specially brought from Alberta, Canada, to transport water, fuel, and construction materials on a narrow steep trail to NLSAS and Towers 6 and 7. The mules proved able to carry up to 120kg loads, and worked seven hours a day, six days a week, for 14 months (Fig 24).

Due to the nature (and weight) of Ngong Ping 360's construction materials, two types of helicopter were used, the French-built *Lama* and the Russian *Kamov*. The *Lamas* were used to transport mainly concrete and reinforcing bars to remote sites and could carry loads of up to one tonne. During peak periods, they operated up to seven and eight hours a day transporting materials to the remote tower sites in North Lantau Country Park. The *Kamov* (Fig 26) was brought to Hong Kong specifically for the Ngong Ping 360 project and to transport loads of up to 4.5 tonnes; it was used to move the bulkier construction materials, including the tower "heads", into remote sites.

The rescue trail

A rescue trail, approximately 6km in length, runs generally along the cable car alignment, for use in the event of emergency evacuation from one of the cabins. The trail is constructed in difficult terrain, using timber (Fig 25) or natural stones. Close co-ordination with Maeda enabled a design to suit the construction constraints and with minimum impact on the environment of the country park.

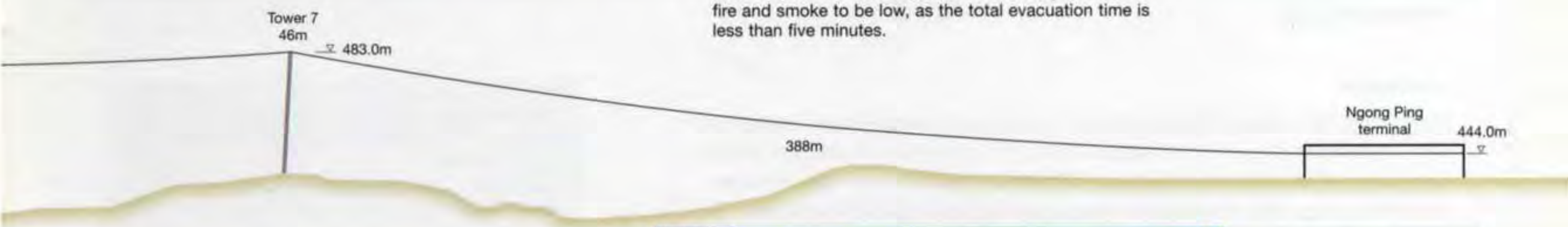
Fire engineering

A drencher system between the two levels of each terminal building would normally be necessary to divide the large single compartment into two while also permitting cable car movement between the levels through a maintenance stair opening. This, however, would have required very large water tanks, with additional cost and space requirements, and would have impacted on the operation of the cable car.

Arup provided a performance-based fire engineering approach to justify the deletion of this drencher system. A design fire was established to demonstrate whether there would be any smoke movement from level 1 to level 2 through the maintenance stair opening. The temperature and visibility of smoke spill to level 2 was also calculated. To limit the smoke spread from the lower level to the upper, a high level downstand around the lower floor opening was required, and it was also demonstrated that the downstand can prevent smoke spilling to the high level, using existing ventilation louvres for smoke outlets.

27. Arup assessed materials for glazing the cable car cabins.

28. Computational evacuation software was used to address the means of escape provision by calculating total evacuation time. This showed the risk of exposure to fire and smoke to be low, as the total evacuation time is less than five minutes.



Risk assessment

MTRCL also appointed Arup to assess the preferred materials for glazing the cable car cabins (Fig 27). These included polymethyl methacrylate (PMMA), polyethylene tetrephthalate copolymer (PETG), and polycarbonate (PC). An assessment of the implications of these products from the fire hazard point of view was required for MTRCL to come to a decision with the cabin manufacturers, who preferred a more expensive material.

Arup's fire hazard assessment of these glazing materials included identification and assessing the likelihood of potential ignition, fire scenarios during operation, related combustion behaviour and hazard levels, and a literature review of their use on similar projects. Based on the risk assessment, MTRCL was able to select the appropriate material that was also acceptable to the cabin manufacturers.

Value engineering

During Stage 2, Arup and Maeda proposed several value engineering initiatives. Once agreed with MTRCL, these were implemented and factored into the gainshare/painshare equation agreed between MTRCL and Maeda.

At the Tung Chung terminal, the main structural frames were altered to use edge cantilevers for structural efficiency, and to resolve headroom problems. The roof geometry was developed with straight members and the elimination of purlins for simplicity of fabrication, in spite of the complex roof shape (Fig 29).

Foundation savings in the detailed design of the piles were achieved, but the more radical alternative of a raft instead of bored piles, which would have saved around 20% of the building cost with appropriate detailing, was not adopted due to MTRCL's concerns over the uncertain fill properties in the area.

29. Value engineering at Tung Chung terminal: the roof geometry was developed with straight members and elimination of purlins for simplicity of fabrication, in spite of the complex shape.

As already noted, the application of Arup's fire engineering skills resulted in the deletion of a large drencher tank and system, whilst the foundation solutions for the AIAS achieved reduced pile quantities following the critical review by Arup of the piling design.

At the two angle stations, Arup achieved reduced steel roof weights of around 50% compared to the target cost figures by using more structurally efficient trussed frames, which also simplified the lifting problems for those stations in the country park areas. In addition, the minipile sizes were reduced and the excavations minimized by raising the foundation levels, thus reducing the amount of material to be disposed of by helicopter or mule.

At the Ngong Ping terminal and theme village, steel frames were generally changed to concrete frames, and foundations reduced in size as well. Again at the theme village, the stream diversion gabion layout was reduced to take advantage of existing rock outcrops found during excavation. Taking into account the approvals timing and design change costs, each works proposal was evaluated on its merits and agreed with MTRCL before implementation within the target cost contract. The benefits of the target cost approach were clear from the alignment of all parties' mutual interests towards seeking the most cost-effective solution overall for the project, using planned and agreed redesign, with extra design costs, to yield larger savings throughout construction.

30. Ngong Ping Village.

Conclusion

Ngong Ping 360 was a challenging project that required, and received, dedication from the design team. As noted previously, this included staff not only from Arup's Hong Kong office, but from the offices in Shenzhen and Manila as well. As far as the overall design and construction were concerned, the target cost contract environment worked well to align the interests of Maeda and Arup with the MTRCL. The partnering process enabled all parties to take a joint view of whether design changes would add value to the project, in the light of ground conditions uncovered in the field and other issues, such as timing and approvals, that impacted the design and construction.

Ngong Ping 360 opened on 18 September 2006, but the detachment and fall of one of the cars during a night time emergency drill on 11 June 2007 – fortunately without injury or loss of life - caused the system to be shut down while the accident was investigated. It reopened to the public on 31 December 2007.

As for the public response to this new tourism highlight for Hong Kong, the government's initial study predicted 1.5M visitors in the first year of its opening but on 9 March 2007, less than six months after opening, Ngong Ping 360 was traversed by its millionth passenger.

31. Cable car approaching Ngong Ping, showing the Tian Tan Buddha, Tower 7 and the rescue trail, with the theme village in the background.

John Batchelor is a Director of Arup in the Infrastructure London Group. He was Project Director for Ngong Ping 360.

Suresh Tank is an Associate of Arup at the UK Midlands Campus. He was Project Manager for Ngong Ping 360.

Credits

Client and design/build contractor: Maeda Corporation **Promoter:** MTR Corporation Ltd Hong Kong **Architect:** Aedas Ltd **Civil, SMEP, geotechnical, and fire engineer:** Arup – Roger Alley, John Batchelor, Arnel Bautista, Ambrose Chan, Kenneth Chan, Man-Lung Chan, Paul Chan, Spencer Chan, Henry Cheng, Calvin Cheung, Cici Cheung, Hung-Cho Cheung, Robot Chiang, Kenneth Chiu, Joanne Choi, Stephen Chow, Sidney Chu, Stuart Cowan, Angus Fong, Sandy Fong, Wendy Fong, Matthew Free, Jim Haley, Johny Ho, Stephen Hope, Ji-Guang Kuang, Oi-Yung Kwan, Nelson Kwong, David Lai, Vivian Lai, Ernest Lam, Maggie Lam, Eric Lau, Catherine Leung, Ryan Leung, Steve Leung, Vincent Li, Patrick Lit, Andy Liu, Darwin Lo, Rock Lo, Martino Mak, Wilson Mak, Jack Pappin, Nelson Pong, Lioni Ramos, Grant Robertson, Richard Scott, Kin-Piu Shum, Edith So, David Song, Timothy Suen, Alan Tam, Christine Tam, Suresh Tank, Wai-Shing Tang, Kwok-Kei Tse, Evan Tsui, David Vesey, Colin Wade, Mark Wallace, Hou-Ju Wang, Kelvin Wong, Louis Wong, Stella Wong, Eric Wu, Thomas Yeung, Xue-Ning Zhang, Jeanne Zhao, Longde Zhao **Ropeway designer:** Leitner GmBH **Operator:** Skyrail-ITM **Specialist contractors –** ***Minipiling:*** Simon & Sons ***Bored piling:*** Bachy Soletanche ***Roof steelwork:*** Kepple ***Cladding:*** Craft ***Mechanical and electrical:*** Kinden ***Landscape:*** Tarzan **Specialist attractions –** ***Client:*** Dedica Group ***Architect:*** Leigh & Orange ***Mechanical and electrical:*** Meinhardt, BMMK **Illustrations:** 1, 3, 6-11, 14-16, 18-20, 23, 25, 27, 29-31 Colin Wade; 2 Arup/Marcel Lam; 4 Google Earth/Digital Globe; 5 Arup/Nigel Whale; 12, 13, 17, 28 Arup; 21, 22, 24; Damon Yuen; 26 Leitner.

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(3) BAYLISS, RF, *and* CHUNG, L. The Tung Chung cable car – A new icon for Hong Kong *[paper presented to HK Institution of Engineers Electrical Division seminar, October 2004]*.

(4) http://www.np360.com.hk

1. Humans use the term "waste" to describe materials that have been used but are no longer wanted.

Waste as a driver of change

Part 1: The nature of the problem and why we have it

> "People will need to readopt this sense of rarity that has been lost or forgotten over the last two centuries. Humans will need to collect, sort, recover and recycle, going back to the old ideal of alchemists: complete the material cycle, turn waste into a resource..."[1]

Rachel Birch

Introduction

No organism is 100% efficient. As resources are consumed, wastes inevitably are generated. The actions of humans are no exception, and waste is an unavoidable aspect of our existence. However, as human society has developed, the wastes it produces have changed, in both nature and quantity.

"Waste" is the general term used for any unwanted or undesired material, yet it is not easily definable. No definitive list exists of what does and does not constitute "waste". Under European legislation, it is "any substance or object the holder discards, intends to discard or is required to discard"[2]. The legislation states that once a substance has become waste, it will remain waste until it has been fully recovered and no longer poses a potential threat to the environment or to human health.

Interestingly, this definition highlights the important notion that "waste" is an anthropogenic concept. Humans use this term to describe materials that have been used but are no longer wanted, either because they have no more value to us or because they no longer serve the desired function. In contrast, natural ecosystems have evolved to be highly efficient, with the waste products produced by one organism becoming the feedstocks for another. In this sense wastes are not "wasted" but instead used as resources. "Waste" as we know it does not exist.

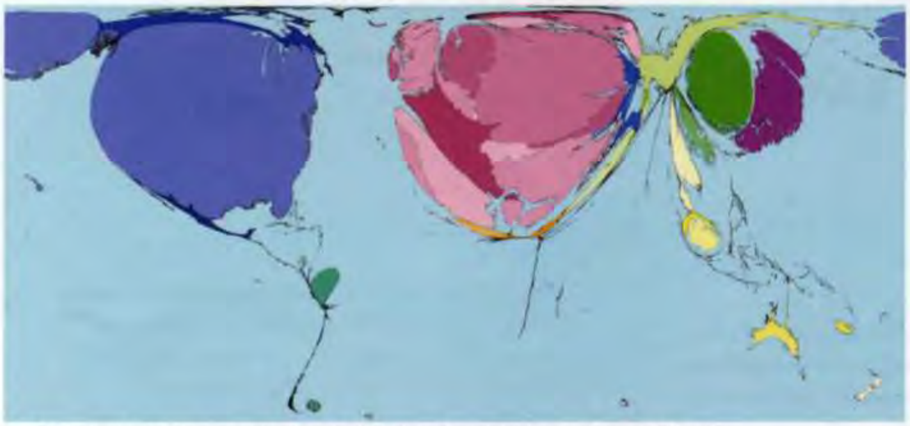
The problem for us is not the production of waste in itself, but rather the quantity now generated by society, its toxicity, and the impact that our inefficient use of materials has on resource depletion, climate change, the environment, and human health in all corners of the planet.

Managing the waste we generate is a formidable challenge for governments around the world. How to dispose of refuse economically and without degrading the environment is a problem shared by developed and developing countries alike. Yet, are governments missing the point? Should we not be addressing the causes of the problems, rather than just looking for end-of-pipe solutions?

This is the first of two articles exploring the issues of waste. It continues the "Drivers of Change" research theme in *The Arup Journal*, which has so far included water, climate change, energy, demographics and urbanization[3-7].

2. Territory size shows relative proportion of the world's population living there[9].

3. Territory size shows proportion of total global municipal waste generated there[9].



4. Territory size shows proportion of total global municipal waste recycled there[9].

What is the problem?

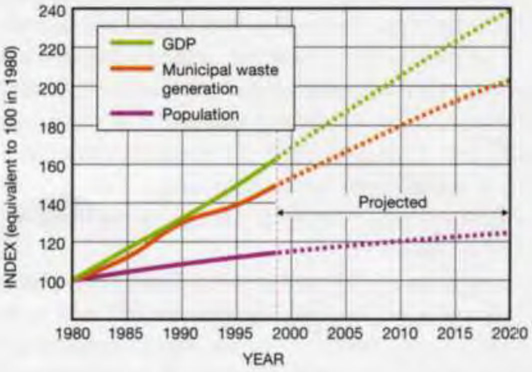
The scale of the problem

Calculating the amount of waste generated on the global scale presents several issues. There are numerous ways to define, describe, and monitor waste. Some countries, on the other hand, lack reporting of any kind. These factors together present significant issues when attempting to generate and examine comparable data from one country to the next. A recent report[1] estimates that 1.2bn tonnes of municipal waste* were collected worldwide in 2004. The main producers of municipal waste are the United States and Europe, each collecting more than 200M tonnes of waste per annum. The US seems to be the worst offender, with over 700kg of domestic waste per person generated every year. The US is closely followed by Australia and parts of Western Europe, with 600-700kg per year. In contrast, the average resident of Nairobi in Kenya generates only 220kg per year; in Mumbai in India, annual waste generation is as low as 120kg per person[1].

These trends can be mapped graphically. When comparing total municipal waste generation against the population of countries across the world, it highlights that although China and the US generate similar net quantities of municipal waste, the latter produces a much higher rate per capita. In terms of recycling, developed economies collect a high net quantity of waste for recycling, but this is in part due to them producing large amounts of waste in the first place. Interestingly the US, which collects a high net volume of material for recycling, does not appear in the list of the top 10 countries with the highest recycling rates (Figs 2-4).

Waste is generated in many ways, but its composition and volume largely depend on country-specific consumption patterns and industrial and economic structures. It has been widely observed that the generation and collection of waste are globally linked to both GDP (gross domestic product) and urbanization. The economies of developed countries depend on the consumption of goods and services to drive the economic growth seen as fundamental to meeting society's needs. This leads to the increasing production and use of natural resources that are required to keep consumers spending. Unsurprisingly, as consumption increases, so too does waste generation (Fig 5). Future population projections indicate that the situation is likely only to get worse, with a suggested 9bn people living on the planet by 2050[11], and there are no signals to suggest that global levels of consumption will decrease in the near future (Fig 6).

5. Waste and wealth: links between increasing GDP and waste generation[10].



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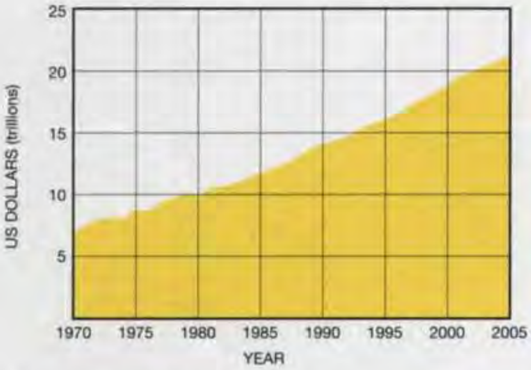
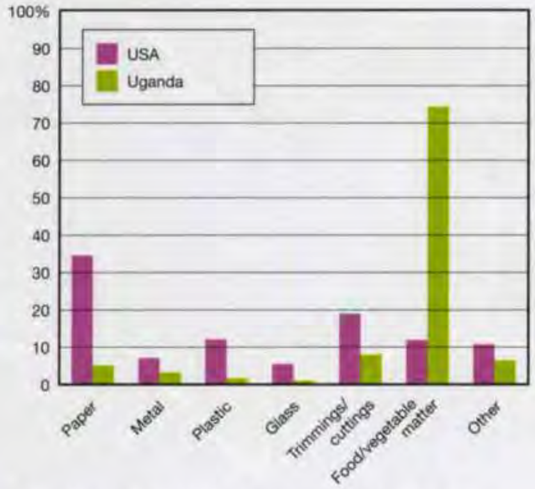
*Municipal waste is waste from households, plus other waste which, because of its nature or composition, is similar to waste from households[8].

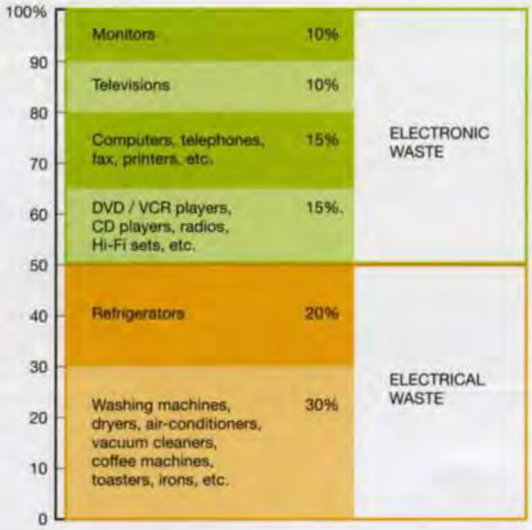


6. Global household expenditure[12].



7. Composition of municipal solid waste (MSW) in the USA and Uganda (%)[13].

8. What is e-waste[1]?



Additional categories: lighting equipment (fluorescent tubes); toys, sports and recreational equipment; electrical and electronic tools (drills, sewing machines, lawn mowers, etc); surveillance and control equipment; medical instruments; automatic ticket machines.

Source: EMPA Swiss Federal Laboratories for Materials Testing and Research (definition according to the European Union WEEE Directive).

What are we producing?

Only 75 years ago, people were living in a pre-plastic, pre-chemical, and pre-electronic era. Humanity's waste was a much less volatile commodity than it is today. As with total volume generated, the composition of waste is also strongly linked to a population's wealth. As GDP increases and people migrate from rural to urban environments, waste streams become more sophisticated, containing a much lower proportion of biodegradable food waste and far more plastics, metals, glass, and toxic products that are increasingly difficult to manage and dispose of safely. An individual living in an emerging country with limited contact with Western society produces a domestic waste stream that can be almost entirely composted (Fig 7). It is estimated that in Uganda approximately 82% of the waste consists of food, vegetable or garden matter[13]. In rich countries the opposite is the case, with the amount of compostable waste dropping to approximately 31% and the remainder comprising man-made products[14].

The nasty side of waste

The wastes produced by modern society and industry can have far-reaching and sometimes long-term and irreversible consequences for human health and the environment. Of particular concern are the hazardous wastes that lie behind the luxury and convenience of modern living. Even the materials simply thrown away in our own bins can be (1) ecotoxic - causing damage to the environment; (2) carcinogenic - causing cancer; (3) persistent - remaining dangerous for a long time; and (4) bioaccumulative - accumulating as it makes its way up the food chain. Although it is very difficult to place a figure on the global generation of hazardous waste due to un-uniform definitions as to what does and does not constitute hazardous waste, it is estimated to be upward of 150M tonnes every year*.

Of particular concern are electronic wastes (Fig 8), a category near non-existent just 20 years ago but now rapidly becoming a global issue[1]. Currently e-waste makes up ca.4% of waste in the EU, but it is increasing fast, at ca.3-5% annually, three times faster than the growth in total waste flow[15]. In developing countries the situation is similar, with e-waste estimated to triple between 2006 and 2010[16].

E-waste is of concern because electronic commodities contain a complex mixture of materials and chemicals, which are very difficult to separate and recover, and can be harmful to humans and the environment if not disposed of correctly. A typical computer comprises 23% plastic, 32% ferrous metals, 18% non-ferrous metals (lead, cadmium, antimony, beryllium, chromium, mercury), 12% electronic boards (gold, palladium, silver and platinum), and 15% glass[12]. The toxicity of the waste is mostly due to the lead, mercury, and cadmium, with the non-recyclable components of a single computer containing almost 2kg of lead[12]. An additional factor is that much of the plastic used in computers contains flame retardants, which makes it difficult to recycle. Old computers tend either to end up on landfill or be exported to developing countries for reuse. However there are many reported cases of exported computers being dismantled and contaminating the environment.

Waste affecting human health

If hazardous waste enters the environment it can have devastating consequences. One of the earliest waste disasters took place in the Japanese fishing village Minamata, where in 1953 people began to experience headaches, convulsions, and blindness. By 1966, 43 people had died and 66 had become permanently disabled by the illness. "Minamata Disease", as it became known, was caused by the release of methyl mercury in industrial wastewater from the Chisso Corporation chemical factory between 1932 and 1968. The mercury bioaccumulated in the food chain and poisoned the local inhabitants when they ate locally-caught fish and shellfish, resulting in the deaths of over 2000 people in the area[17].

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*This figure has been estimated by looking at selected countries, including those of the EU, South Korea, USA, Canada, Mexico, India, Japan, Thailand, China, and South Africa.

As of March 2001, 2955 individuals had been officially identified by the Japanese government as having contracted Minamata Disease, but the real number is likely to be significantly higher, with around 20 000 people having applied to the Japanese government to be recognized as sufferers[18].

Chemicals are still regularly contaminating the environment and finding their way into the food chain (Fig 9). This can happen through direct discharge from industry as at Minamata, via waste leaching at disposal sites, through direct application of pollutants into the environment, or accidental spillages and leaks. The issues of bioaccumulation of wastes in the food chain were first presented to the general public in 1962 by Rachel Carson[19]. Her famous book, focusing on the dangers of the agricultural pesticide DDT, shocked the public and triggered awareness that hazardous wastes can persist in the environment and build up in the bodies of wildlife and people. DDT was eventually banned in many countries, but it is still used in parts of the developing world.

Today, new chemicals are causing problems. A 10-year study by WWF[20] looked for chemical contamination in a wide range of food items in seven European countries and found it in all of them. For example PCBs (polychlorinated biphenyls), which are globally banned and have been shown to adversely affect neurological development, were found in every food item in the analysis. Phthalates are used to soften plastics and are found in numerous consumer products from vinyl flooring to cosmetics, but they are also endocrine-disrupting chemicals that interfere with hormones. Being soluble in fat, they bioaccumulate in fatty foods causing health risk to those who consume them[21]. As previously noted, mercury can enter the environment through waste streams, and it is estimated that up to 10% of American women carry mercury concentrations near the levels considered to put fetal development at risk of neurological damage[22].

Waste on the move

Wastes, including extremely hazardous radioactive material, toxic heavy metals, and poisonous PCBs, are routinely transported around the world on the path of least economic resistance. Waste materials are often sent for recycling to countries with lower labour costs, fewer regulations, little import control, and a market for reuse. However sometimes they are just dumped. China is the world's biggest importer of waste and secondary raw materials, bringing in more than 4bn tonnes of plastics waste, around 12bn tonnes of waste paper, and over 10bn tonnes of scrap iron and steel in 2004[12].

E-waste is one waste stream routinely exported by developed countries to developing countries, sometimes in violation of international laws such as the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal, which was designed to reduce the trans-boundary movement of hazardous waste and specifically prevent its transfer from developed to less developed countries[23]. Inspections of 18 European seaports in 2005 found that as much as 47% of waste destined for export, including e-waste, was illegal.

It is estimated that, just from the UK, at least 23 000 metric tonnes of undeclared or "grey" market electronic waste was illegally shipped to East Asia including China, to India, and to Africa[24] in 2003 alone. In the US, it is estimated that 50-80% of the waste collected for recycling is exported in this way and up to 75% of these "goods to be recycled" arrive unusable. In the US this practice is legal because it has not ratified the Basel Convention[25].

In many countries entire communities, including children, earn their livelihoods by scavenging metals, glass, and plastic from discarded electronic waste. This is unsurprising given that the average computer yields approximately US$6[25] of materials and there are some 2.7bn people living on under $2 per day[26]. It has been estimated that in China alone over 100 000 people earn a living from dismantling electronic waste, where they make on average US$1.50 per day[25].

9. Bioaccumulation.

When e-waste is recycled or disposed of in developing countries where treatment methods are still fairly basic, toxins may be released into the air and local water sources contaminated, posing significant risks to local populations and the environment. The cathode ray tube of a typical monitor contains not only 2kg of lead, but also phosphorous, barium, and chromium[27]. Toner cartridges are removed from printers, and the ink, a human carcinogen, is dusted out by hand with no respiratory equipment. Cables are extracted and the plastic coating burnt off in open fires to remove the copper, releasing highly toxic furans and dioxins. Computer chips are dropped into baths of steaming sulphuric acid to remove tiny amounts of gold. Such activities pose serious threats to human health and the surrounding environment, notably through deterioration of local drinking water. A river water sample from the Lianjing river near a Chinese "recycling village" revealed lead levels 2400 times higher than World Health Organization Drinking Water Guidelines, and sediment samples showed lead levels to be 212 times higher than the European hazardous waste threshold[28].

Many cases of illegal waste dumping occur across the globe, some with very severe consequences. On 19 August 2006, liquid sludge containing large quantities of hydrocarbons was dumped at over a dozen sites in and around the densely populated city of Abidjan in Côte D'Ivoire. At least 10 people were killed and over 30 000 became violently ill[29], suffering from symptoms including respiratory problems, nausea, dizziness, burns, and irritation from the foul-smelling waste[12]. It is still unclear where the waste originated from, though investigations determined that a ship attempted to unload its slops (residue from washing cargo tanks) in the Netherlands. Realizing that the contents were non-standard, the waste management operations at the harbour demanded more money, resulting in the waste being pumped back on board and the ship sailing off to find an alternate place to unload its toxic residue.

Inefficient use of our resources

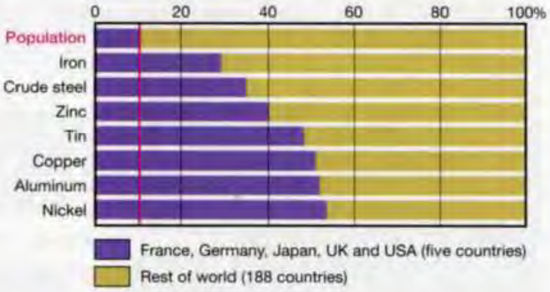
In the past, with limited technologies, humans regarded many of their resources as rare, with the demands being placed on them far outweighing availability. Pretty much everything then was used, and very little went to waste.

The Industrial Revolution at the end of the 18th century was the turning point in our relationship with resources, which from then on became increasingly reachable and extractable[1]. Advancing technology has allowed people to travel further, move quicker, dig deeper, and become thoroughly used to discovering and exploiting resources.

In more recent years the world has become increasingly aware of its limits. Indicators such as the Ecological Footprint and Living Planet Index[30] show that year-on-year, the world's population is consuming products and producing wastes much faster than the planet can keep up with; at the same time, global ecosystems are on the decline. Despite these realizations, the upward trajectory continues, with people using resources faster than ever before.

The consumption and depletion of fossil fuel stocks has already been discussed in this series[3], but it is not only oil and gas that are being used at an alarming rate. In the 20 years ending in 1994, the world population increased by 40%; in that same period, world consumption of cement increased by 77%, and plastics (which are derived from oil) by just under 200%[10]. It has been estimated that the supply of indium, a metal used in the production of LCDs for flat screen television sets, will run out in 10 years at the most[31]. Its impending scarcity has already been reflected in its price which increased from $60/kg in 2003 up to over $1000/kg in 2006.

The same study estimated that zinc reserves could be depleted by as soon as 2037, and hafnium, an important metal used in the production of computer chips, could be gone by 2017. Unsurprisingly a small minority of rich countries are responsible for the majority of raw material consumption. Altogether the developed countries comprise only 22% of the world's population, but they consume over 60% of the industrial raw materials[10] (Fig 10).



10. Consumption of selected industrial raw materials compared to global population[10].

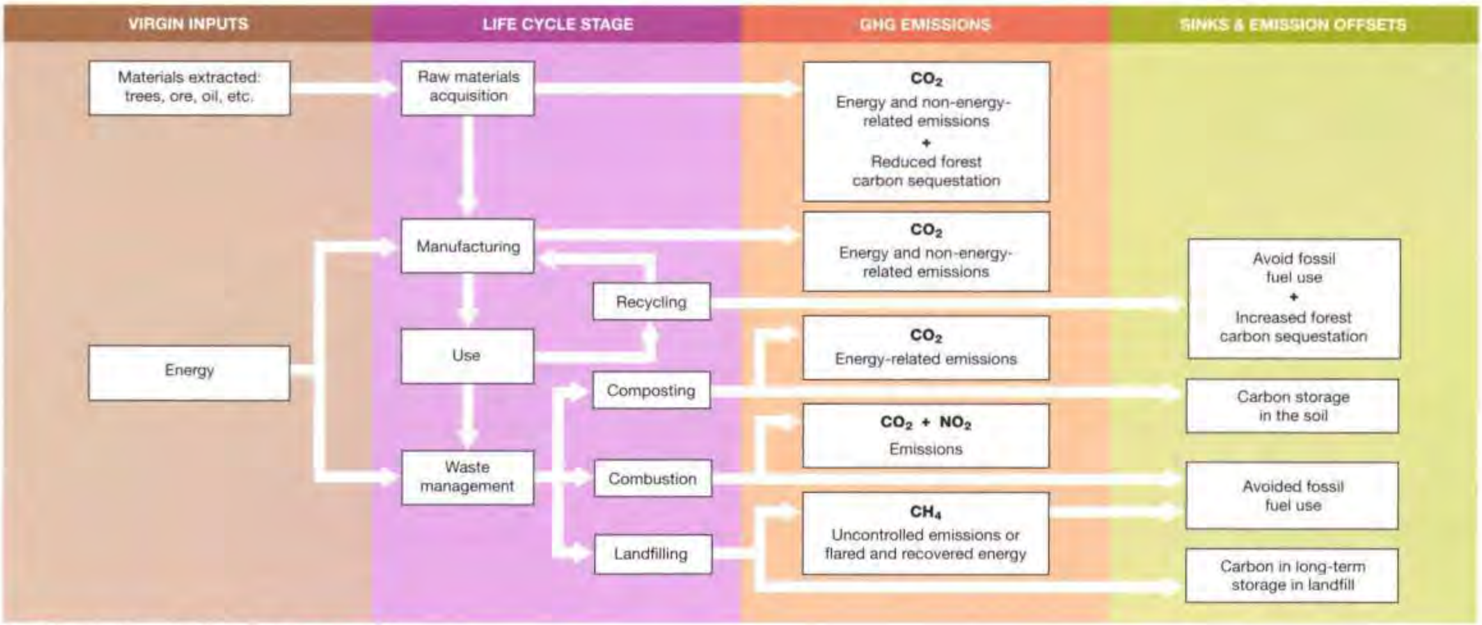
The waste we see is only the tip of the iceberg

Most consumers in the developed world only see the waste produced in their home or at their place of work, which is then conveniently left outside and taken away for disposal. Most of the lifecycle of consumed items is thus hidden from the consumer, both before and after the products are used.

As a result, people pay very little attention to the raw materials and energy that go into producing, transporting, and distributing products, or to the environmental and economic costs of treating the associated waste. To generate a clearer understanding of the true impact of living in such a wasteful society, it is important to consider products over their entire lifecycle, from extraction of material to final disposal.

It is estimated that about 94% of the materials extracted for use in manufacturing durable products become waste before the product is manufactured[12]. This "hidden" waste associated with products or materials can be termed the "ecological rucksack" - for example, a single 3g gold ring will leave behind a staggering 3 tonnes of toxic mining waste[32]. An item as small and innocuous as a toothbrush is responsible for on average 1.5kg of unseen waste[10] and the extraction of the metals in a PC produces a total of 1.5 tonnes of waste[12].

11. A single 3g gold ring will leave behind 3 tonnes of toxic mining waste[31].



12. Climate change and waste management[35].

The first stage in the manufacture of any product, the mining of raw materials, generates huge quantities of waste and often forms most of the ecological rucksack, as well as creating some lasting environmental impacts. This is because only a small portion of the materials removed in mining contain the desired minerals and even then they are found at very low concentrations that require physical and/or chemical processes to refine them to suitable concentrations - and leaving behind significant quantities of waste.

During the extraction of common metals like copper, lead, or zinc, both the metal-bearing rock (the ore) and the overburden (the dirt and rock that covers the ore) are removed. At a typical copper mine, some 125 tonnes of ore are excavated to produce just one tonne of copper[10].

The mining process can also create long-lasting environmental impacts. The techniques involved in extracting some metals from their ore depend on the use of toxic chemicals including cyanide, mercury, and sulphuric acid. Although the chemicals can be recovered and reused, some contamination and residue remains in the tailings (the materials discarded at the end of the mining process). This can cause significant problems in developing countries where tailings are often dumped directly into rivers or lakes, contaminating the local environment and entering the food chain.

Even in countries where mining waste is carefully managed, accidents can happen. In January 2000, much of eastern Europe suffered serious environmental damage when over 100 000m^3 of cyanide-rich tailings waste from a Romanian gold mine was released into the area's river network when a dam failed[33]. Up to 100 tonnes of cyanide were released into the river, a tributary of the Danube, affecting the drinking water supply for more than 2M people. Within hours, dead fish were seen washed up along the river and within weeks virtually all aquatic life in the Tisza River, which flows through both Romania and Hungary, had been killed[34].

Waste warming the planet

The creation of the products we consume, and the disposal and treatment of our waste, can generate emissions of several greenhouse gases (GHGs) that contribute to global climate change[5]. GHG emissions are generated at every stage in the lifecycle of materials, from raw extraction, transportation, and manufacturing, to use and final treatment or disposal (Fig 12). When we dispose of products we are, in effect, not only discarding the direct and hidden materials contained within the products, but also losing the embodied GHG emissions generated over the product's lifecycle. Waste prevention, reuse, and recycling all help to address global climate change by decreasing the amount of GHG emissions embodied within products, and saving energy otherwise used to produce materials[36].

The measurement of these total emissions associated with the lifecycle of a product is termed its "carbon footprint", and this information can assist in assessing the relative benefits of consuming different products and using different waste management options. In particular, the carbon footprint highlights the relative importance of avoiding and minimizing waste. Such strategies will reduce the carbon footprint by 100% for a particular item: it is only common sense that a product not produced and consumed will have no impact.

Many materials in the waste stream contain carbon. Organic substances like paper, card, and kitchen waste contain biodegradable carbon-based matter; other products such as plastics contain carbon derived from fossil fuels. The treatment and disposal of these wastes determine the way the carbon is released back into the environment, and so few disposal routes are free from climate change effects.

The most significant GHG produced from waste disposal is methane. It is released during the breakdown of organic matter under anaerobic conditions which often occur at landfill sites, although over 90% can be captured for energy recovery in modern landfills[37]. Other forms of waste disposal also produce GHGs but these are mainly in the form of CO_2 (a less powerful GHG). Even recycling waste produces some process-related emissions, but these are usually offset by the reduction in fossil fuels needed to obtain new raw materials from the environment.

Why do we have this problem?

The consumer society

Waste is the symptom of a broader problem; we are addicted to throwing things away. Modern economies can produce huge quantities of goods at very low costs, which leads producers and consumers to regard a growing number of products as little more than commodities to be discarded relatively quickly, rather than as items embodying valuable energy and materials that should be well maintained and designed for long lifespans.

Perhaps the throwaway society that much of the developed world lives in today began in 1895, when a travelling salesman named Gillette invented the disposable razor blade, a product that consumers would have to keep coming back for again and again. Sales of the blades soared, reaching 70M by 1915, and it was then that manufacturers began to realize the seemingly endless commercial potential of short-lived products.

Today the list of commodities we used to keep for years and now dispose of almost instantly is vast, from tissues and nappies (diapers) to cameras and barbeques. Every year US consumers, for example, throw away tens of billions of items of disposable cutlery and plastic and paper plates[10].

Part of the problem stems from the sheer volume of stuff that is given out for free - plastic toys in cereal boxes, free bags with cosmetics, free TV guides with newspapers, to name but a few. It has been estimated that 80% of products consumed are thrown away after a single use, and 99% of the materials used in the production of or contained within goods are discarded in the first six weeks[38].

This global appetite for goods and services is driven by an advertising industry that constantly persuades us to buy new products or upgrade the ones that we already have. World advertising expenditure reached $446bn in 2002, nine times that of 1950. Over half this total is spent in the USA where ads take up two-thirds of a typical newspaper, a quarter of all TV programming, and half of all mail[27].

Every year more and more people join the consumer society, especially in the developing world where consumerism is strongly linked to urbanization. Moving from rural to urban areas gets people closer to shops where they can purchase goods and services not formerly available to them[39]. It has been estimated that for the first time in history, in 2008 half the world's population (6.6bn) will be living in urban areas, and the number is expected to swell to almost 5bn by 2030, with towns and cities of developing countries housing 81% of urban humanity[40].

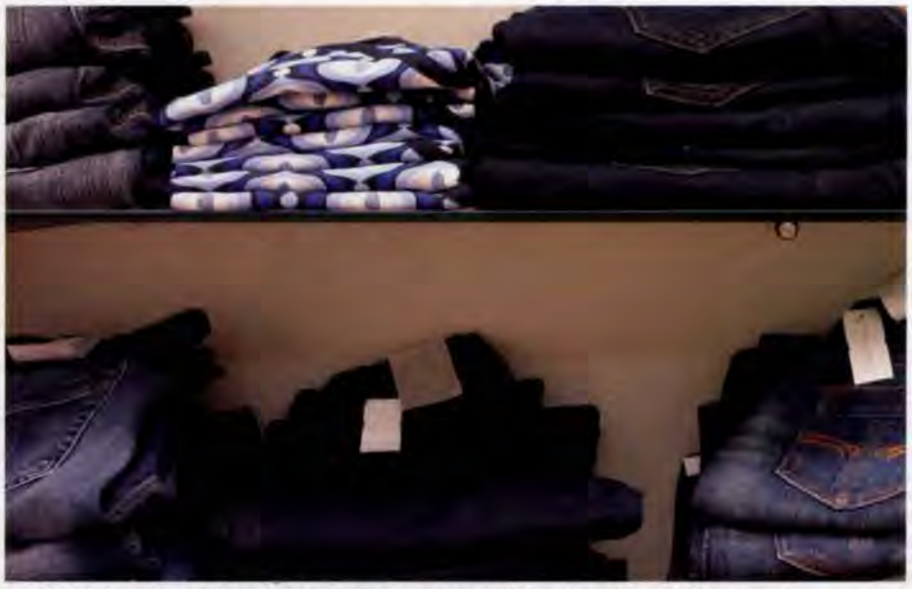
These rapidly multiplying urban households in developing countries often generate far more solid waste than the authorities can handle. In the large cities of some developing countries only 25-55% of waste is collected by municipal authorities and up to 95% of this ends up on open dumps, which can render land unusable and endanger human health[41]. The lack of sufficient resources severely limits the range of options, where the disposal of solid wastes created by households and industries often consumes up to half of municipal budgets.

Cheap goods

All over the world people can buy goods at increasingly affordable prices. In Britain, like other high-income countries, recent years have seen a drastic reduction in the cost of consumer products. Since 1995, the price of women's clothing has fallen by 34%, the price of home audiovisual equipment by 73%, and of personal computers, adjusting the price index to take account for their improved capabilities, by 93%[42]. With such low prices there is little incentive when purchasing new goods to be thrifty, which is causing a change in people's relationships to their possessions. Items that used to be mended are now thrown away without a second's thought and replaced with brand-new. When electronic equipment malfunctions, it is often as cheap to buy a new hi-fi, i-pod or radio as it is to have the item repaired.

The clothing sector is another good example of these changes. Clothing shops that once had a new range only twice a year update their shelves every few weeks. The cost of clothing is falling so low that it is now not unusual to be able to buy a new pair of jeans in a supermarket for the same price as a cup of coffee! Such drastic price reductions encourage people to make purchases by the dozen rather than just one or two items at a time, and these goods of today inevitably pile up as the wastes of tomorrow.

When we look at how today's society can be so wasteful we find a rather disturbing truth. In December 2006, War On Want conducted a study entitled "Fashion Victims"[43]. As part of this analysis, six factories were visited in Dhaka, the capital of Bangladesh, where 2.2M jobs depend on the textile industry. The investigators discovered that textile workers were paid a meagre UK5p an hour for their 80-hour week, totalling UK£9 per month, which is a little over one-third of the national minimum living wage.



13. Textile workers in Bangladesh are paid a meagre UK5p an hour for their 80-hour week.

Product obsolescence

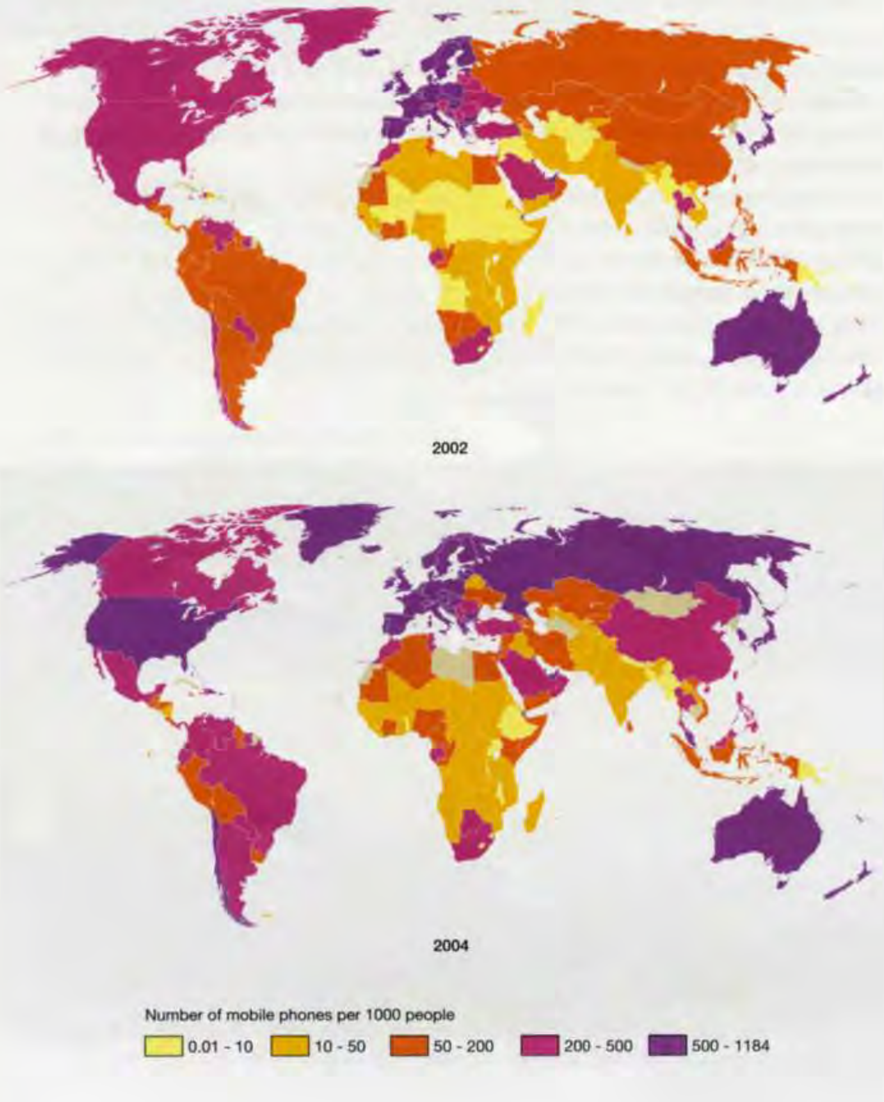
In our throwaway culture nothing is designed for the future. The black-and-white TV went to colour, then to wide screen, and then to flat screen. Records were replaced by cassettes, then CDs and mini-discs, and now many people store their music on an MP3 player. People are constantly required to buy new computers as a year-old model can no longer handle the latest software.

As we continually update and invent new products, the life of the old ones is getting shorter and shorter.

Planned or built-in obsolescence is the conscious decision to produce a consumer product that will become obsolete and/or non-functional in a defined timeframe. It has great benefits for a producer as it means consumers will buy their product repeatedly, as their old ones are no longer functional or desirable. Planned obsolescence exists in a huge range of products, from vehicles to light bulbs, from buildings to software. As our consumption increases, the average lifespan of these products decreases.

Mobile phones are a good recent example. Since the launch of the first mobile phones in 1984, the market has boomed (Fig 14). In 2005 over 825M mobile phones were produced, compared to 707M in 2004; it is estimated that there will be two billion mobile phone users in 2008[12]. In developing countries in particular, good and workable mobile phones become junk as soon as manufacturers launch a new range.

14. Mobile phone growth[12].



In Europe, the average mobile has a shelf life of 18 months, which is only 20% of the seven years they are designed to last. Even more worrying is that in Europe only 2% of mobiles are recycled. In the US it is estimated that 130M mobile phones (cellphones) were discarded in 2005 alone, resulting in 65 000 tonnes of waste[12].

As for computers, for every new one put on the US market in 2005, one became obsolete[45]. In 2004 an estimated 315M working computers were made redundant in North America alone and of these only 10% were reused and refurbished, the remainder being disposed of in landfills.

This is a significant increase from the 63M working computers disposed of in 2003. In 1997 a PC lasted six to seven years, but in 2003 people expected to discard their computer after just two to three years of use[46].

Many have suggested that this mass production/consumption/disposal system is no less than sheer economic necessity. As long ago as 1955 the economist Victor Lebow wrote:

"Our enormously productive economy demands that we make consumption a way of life, that we convert the buying and use of goods into rituals, that we seek our spiritual satisfaction, our ego satisfaction, in consumption. We need things consumed, burned up, replaced, and discarded at an ever-increasing rate."[47]

Packaging

Packaging represents a growing share of household waste, a stream that in Europe grew by 8.3% between 1997 and 2001[48]. There are many reasons for this increase: changing demographics, the increasing use of convenience food, and higher hygiene standards all encourage the use of disposable packaging.

Globalization has also played a role, with basic goods such as bottled water sometimes travelling half-way across the world and significantly adding to the packaging problem.

Factory packaging protects items from dirt and damage during distribution, as well as assisting in effective storage. In modern times, of course, it is also used to make products look more appealing.

One packaging manufacturer states on its website that "a good packaging solution should ultimately save more than it wastes". In 2005 this company worldwide produced 121bn packages, ie 18 for every man, woman and child on the planet.

15. In Europe approximately 50% of all products are wrapped in plastic.

Even the best packaging solutions cannot avoid their ultimate destiny: 121bn used packages are 121bn items of waste.

Packaging is a problem for more than one reason: firstly, there is its use of natural resources. About 8% of global oil production is used for making plastics, of which about one-quarter is thought to end up in packaging[49]. It has been estimated that in Europe approximately 50% of all products are wrapped in plastic.

Second is the disposal problem, partly due to it being a highly mixed waste stream, with average UK composition of 33% plastic, 32% glass, 19% paper and card, and 14% metals[12]. Plastic packaging is a particularly difficult issue. The products we buy are encased in numerous different types of plastic, but recycling schemes will only collect one or two varieties. This not only makes it impossible for shoppers to recycle all their waste, but also leads to a high possibility of contamination in plastic recycling schemes as shoppers unwittingly try and recycle the wrong types of plastic.

Thirdly, packaging does actually cost. It has been estimated that an average family in a developed country unknowingly spends a sixth of its food budget on packaging every year!

Plastic bags are another key packaging issue as they are used in huge quantities the world over and have become a major problem for many countries. One plastic bag takes a second to manufacture, is 20 minutes in use, but takes 100-400 years to degrade naturally![15] Although they didn't come into widespread use until the early 1980s, today 500bn bags are distributed every year, equating to 16 000 a second[50]. Most of these are used only once before being thrown away. In France alone 60 000 tonnes of plastic per year are estimated to be used in disposable bags. Not only do they add to waste in landfill as they have very limited recycling value, but they have been blamed for flooding in India and Bangladesh through the clogging up of drainage systems.

Demographic change

Global demographic change is an importance factor influencing the amount of domestic waste generated, the most significant trend being changes in the number of people living in a single dwelling. This influences the rate at which several specific categories of waste are generated, including packaging, kitchen waste, and miscellaneous plastics.

The explanation lies in the ability of larger households to share in the consumption of products. For example a family can share a TV guide or a newspaper. Food and other consumable items can be bought in bulk, which reduces the total volume of packaging waste generated per individual.

Another influencing factor on the type of household waste generated is the age of the people living there. One study found that households with people aged over 60 produced less aluminium waste, but showed an increase in the amount of textiles and non-packaging metal waste[51].

Conclusion: waste management options

In the past the amount of waste produced was generally so small that dilution in the environment was seen as a suitable management option. However, with the scale of industrialization and urbanization that the world has seen in recent decades this is no longer viable, and organized waste management is now a necessity to assist in the global issues of environmental protection, resource management, and combating global climate change.

Until recently, waste management focused on end-of-pipe solutions. However, it can be suggested that this approach has fundamental flaws and to achieve a thoroughly effective waste management system we need an entirely new way of looking at waste. Instead of seeing it as a "waste" we need to view it as a resource and identify viable opportunities for waste reduction at its source.

This will involve a fundamental change in the design process. Instead of designing items that can be harmful to the environment and will become waste at the end of their useful life, it will mean creating products whose materials can be perpetually recycled in closed loop systems, maximizing their material value. The second part of this article will survey the range of waste management options available to us, their appropriateness and likely effectiveness, and how they are and may continue to be implemented around the world.

Rachel Birch is an environmental scientist with Arup in the Leeds, UK, office. She is the lead researcher on waste in the Drivers of Change programme.

Credits

Illustrations: 1 Stephanie DeLay/iStock.com; 2-4 Worldmapper; 5-8, 10, 12, 14 Nigel Whale; 9 Øystein Paulsen, Felix Möckel/Ivan Cholakov/ Bartlomiej Stroinski/Oliver Anlauf/David T Gomez/ iStock.com; 11, 13 iStock.com; 15 Sean Locke; 16 Lya Cattel/iStock.com.

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Textus

Mark Fletcher Richard Greer
Dan Lister Karen Walters

Introduction

Arup has often worked with artists to deliver innovative public realm projects, most notably in the case of *The Angel of the North*[1]. *Textus* is a very different kind of artwork, created with animated light - a large-scale projection on a prominent development site at Leeds in the north of England.

It began as a collaboration between Arup Director Mark Fletcher and Peter Coates, an internationally recognized artist[2] who has been supported by Arup through his NESTA Fellowship (National Endowment for Science, Technology and the Arts) since 2005. Both had envisaged an artwork to celebrate the 800th anniversary of Leeds' establishment by charter in 1207.

As a sculptor and carver, the artist had previously produced several prominent pieces, including the James Hill monument at Gateshead, UK, *The Present Order* in Barcelona, and collaborative work at the Tate Triennial, London, with Ian Hamilton-Finlay. Through the NESTA partnership, he was considering the exploration of new media in his work, and felt a temporary piece using light would both extend his artistic range and be an innovative work appropriate for the occasion.

Coincidentally, as part of the 800-year celebrations for the city, Leeds Light Night was to take place on 12 October 2007. This annual festival is run by the City Council to encourage arts professionals to engage with businesses and communities across the city. It was decided that the development of an innovative light art piece was feasible, and an Arup project team was established to deliver *Textus*. The brief included working with Peter Coates to develop the work, locating a viable site in central Leeds, securing arts funding for the piece, and ensuring that it was delivered in time for the Light Night deadline. It would then display for two weeks.

The project drew on a range of Arup skills, including marketing professionals to communicate the importance of supporting *Textus*, not only in terms of generating cultural value but also to enhance the profiles of the artist, the developer, the sponsors, and the city.

1. *Textus* drew on the Latin text from the 800-year-old charter that marked the founding of Leeds, digitally rendered into 800 layers that independently and randomly moved to create a new and unique visual every 30 seconds for the two-week projection period.

> "*Textus* is an extension of my interest as a sculptor in civic inscription... Using the Lifting Tower as a cypher of Leeds' industrial past, the artwork seeks to give status to the structure, to allow it once again to inhabit the space through the exploration of its distinctive character and bring it forward as an object for commemoration."
>
> Peter Coates, artist and NESTA Fellow

2.

The site: Wellington Place

Wellington Place is a large (approximately 250 000m^2) mixed-use development - one of the biggest outline planning applications ever granted by a UK local authority. It is significant by the city, transforming its West End into a vibrant and active quarter. When complete, the 5.6ha site will provide office, retail, residential, hotel, cultural showcase, and public entertainment accommodation. Arup is the prime engineering consultant, with a multidisciplinary team incorporating site development, infrastructure, utilities and energy, civil, geotechnical, SMEP, building physics, acoustics, and fire engineering.

As part of this major development, MEPC intends to host cultural events on the site during the 10-year construction period – and this made Wellington Place a logical choice to host *Textus*. After examining other possible locations, the team confirmed Wellington Place not only because *Textus* would fit into MEPC's cultural strategy for the development, but because the historic grade II listed Lifting Tower on the site was a highly appropriate location for a commemorative piece. It also enabled the Arup team to work very closely with an important client to deliver something truly unique to the client's public realm offering.

All key partners involved in Wellington Place, including Arup, supported *Textus* financially. This, with arts and business funding also secured by the Arup project team, made the project feasible.

3. A potential setting for the Lifting Tower within the future development.

Listed building as artistic canvas

The former truck-lifting tower once formed part of Wellington Street station, and is the only surviving building of the Great Northern Railway Central Station complex in Leeds. It dates back to 1848 and was used to lift trucks from the low-level goods station to the high-level passenger line on the nearby viaduct arches, which now only exist as ivy-covered fragments. The station closed in 1967, but the Lifting Tower escaped demolition and was eventually listed. It is surrounded by the new developments of West End Leeds, and future buildings such as Lumière Tower will soon rise beside it. The Lifting Tower thus looks both forward to the reborn, regenerated area of the city that West End Leeds is becoming, and back to the transport hub of which it was once a part and which made Leeds a crucible of the Industrial Revolution.

The bold rectilinear profile of this prominent heritage feature at the site entrance made it highly suitable to form a giant "canvas" for the *Textus* projection. As it was listed, however, the tower was subject to preservation orders, and so the work had to respect this and have minimum physical impact. The building's useable façade was some 14m wide by 22m high. A single cladding sheet of this size would have been costly and create handling difficulties, so the chosen material approved by the artist was a series of vinyl-coated fabric scrim pieces. The three 5 x 25m pieces had less wind resistance, and at 35kg each were lighter to handle but still durable.

4. The Lifting Tower façade was ideal to display Textus.

This project was particularly weather-sensitive. The cladding could easily turn into a "wind sail" - a hazard to site staff and members of the public alike. To minimize this risk, and the impact of the work on the building, the team erected a proprietary system-built scaffold, braced to the façade by tubes attached to horizontal foam-wrapped tubes behind the window openings. This avoided any mark or damage to the building. The scrims were attached by tensioned cables to the frame, which was then secured at ground level.

Site constraints

The first task was to pinpoint a suitable location for the projection equipment. There being no appropriate enclosure, a temporary housing was constructed on the perimeter of the Lifting Tower square. The tower is on the periphery of a demolition site and the edge of the construction area for the development's marketing suite. These works around the tower were phased so as to limit their impact on the two-week temporary installation.

5. Site plan.

There was also the constraint of existing light sources, but it proved possible for the existing ambient light levels within the Lifting Tower square to be reduced and thus maximize the visual experience of *Textus*. Following the success of the event, the client requested that the proposed exterior lighting scheme be altered to allow for similar projection events in the future.

Lighting design and digital animation

The team engaged an expert digital consultant to advise on the best application and approach to the use of projections for *Textus*, and thereafter to manage the technical aspects of the projected content.

Rather than the final projection be of a pre-recorded sequence, it was decided that the artwork would be generated "live" for the entire duration of its installation. The piece of abstracted Latin text from the original charter script that formed the basic content of *Textus* was digitally rendered into 800 layers that independently and randomly moved to create a new and unique visual every 30 seconds for the two-week projection period. The final piece was thus an evolving animation, and programming language was needed to dictate the random movement of the 800 individual graphic sheets of the artwork. Not only were the graphics themselves subject to linear movement, but an invisible "camera" moved across the overall visual, giving the impression of significant movements in three-dimensional space.

The image was projected onto the side of the Lifting Tower using two 12 000 lumen LCD projectors (the brightest available) mounted one on top of the other in the projection box. The computer-generated image was split within the software and outputted to each of the projectors so that each unit displayed half the overall image. This ensured that the viewing public saw no repeat footage.

Marketing campaign

Alongside the technical challenge of designing and mounting *Textus*, Arup managed the marketing campaign to support the project. Marketing activities, undertaken in collaboration with the client, MEPC, included media relations, which involved bringing on board two major regional newspapers, *Yorkshire Post* and *Yorkshire Evening Post*, as partners to secure positive and wide-ranging media coverage. In addition Arup worked to ensure that the project was prominently featured in local council literature, on its website, and via other electronic communications tools promoting the 800th anniversary events.

A new website on Light Night was launched, together with brochures, invitations, and flyers promoting the launch event with sponsor logos and associated branding; *Textus* became an integral part of all these. This major promotional campaign raised awareness of the initiative in and around the city regions, encompassing pre-launch publicity and profile-building initiatives, and culminating in the major launch event at the site, which attracted more than 1000 visitors on the first night.

Conclusion

Textus showed how exciting and innovative public realm art can inspire communities and generate profile for the artist, the host city, and sponsors. Arup was proud to be a driving force in making the project happen. *Textus* was the first opportunity that MEPC had to showcase the site to the general public, and Arup's drive delivered a project that was a collaboration between the arts and business to deliver a unique work, an undertaking that was of value to the artist, the city, and the developer.

In technical terms, *Textus* demonstrated the use of innovative solutions to complex design challenges, including cladding a 22m structure without touching the body of the building, and finding ways around the restrictions of delivering the project on a working building site. In addition, state-of-the-art digital technology was mobilized to deliver an animated piece of considerable magnitude.

6. *Textus* contemplated by the citizens of Leeds.

Mark Fletcher is a Director of Arup, based in the Leeds office. He was the Project Director for *Textus*.

Richard Greer is an Associate Director of Arup in the acoustics group, based in the Leeds office. He was the Technical Director for *Textus*.

Dan Lister is a senior engineer with Arup in the Sheffield office. He led the lighting design of *Textus*.

Karen Walters is marketing manager for Arup's Leeds office. She was the Project Manager for *Textus*, and also organized the supporting marketing campaign.

Credits

Client: MEPC **Artist:** Peter Coates **Marketing, site development, lighting design, and electrical consultant:** Arup - Richard Bickers, Julia Brown, Mark Fletcher, Richard Greer, Dan Lister, Karen Walters **Digital animation consultant:** Paul Emery **Arts consultant:** Sue Ball **Illustrations:** 1, 2, 6 Adrian Murray; 3 MEPC; 4 Richard Wall; 5 Nigel Whale.

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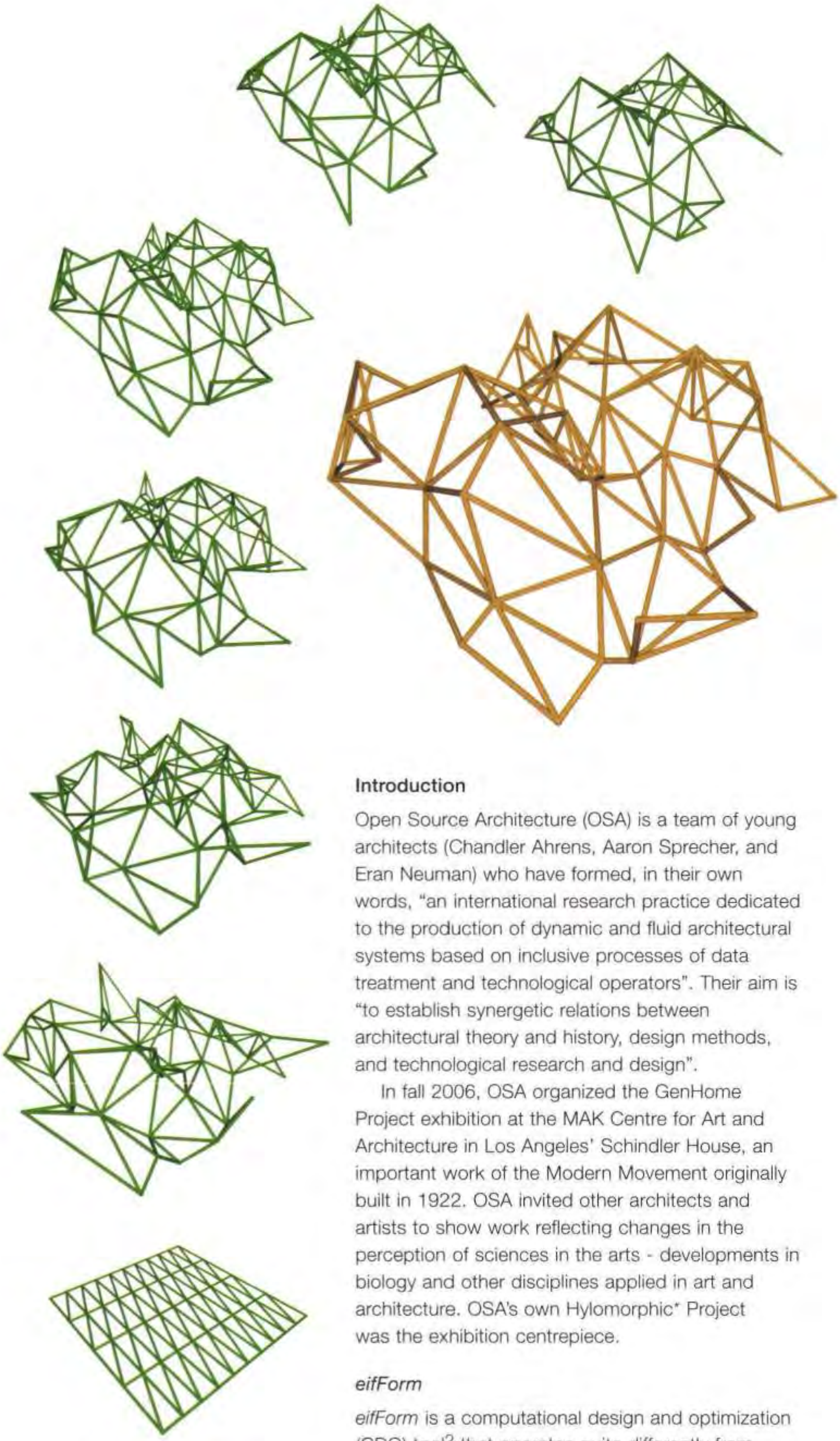

1. Some of the stages in the *eifForm* generative process.

The Hylomorphic Project

Judith Leuppi Kristina Shea

Working with state-of-the-art design software, Arup helped create an innovative timber canopy for Open Source Architecture's contribution to the GenHome Project at the MAK Centre in Los Angeles.

Introduction

Open Source Architecture (OSA) is a team of young architects (Chandler Ahrens, Aaron Sprecher, and Eran Neuman) who have formed, in their own words, "an international research practice dedicated to the production of dynamic and fluid architectural systems based on inclusive processes of data treatment and technological operators". Their aim is "to establish synergetic relations between architectural theory and history, design methods, and technological research and design".

In fall 2006, OSA organized the GenHome Project exhibition at the MAK Centre for Art and Architecture in Los Angeles' Schindler House, an important work of the Modern Movement originally built in 1922. OSA invited other architects and artists to show work reflecting changes in the perception of sciences in the arts - developments in biology and other disciplines applied in art and architecture. OSA's own Hylomorphic* Project was the exhibition centrepiece.

eifForm

eifForm is a computational design and optimization (CDO) tool[2] that operates quite differently from usual structural design software in that it actually generates a structural design, rather than just analyzing a design that has already been proposed. The overall structural form is generated in response to a model input by the user and can be adapted to individual design scenarios. *eifForm* can optimize both the topology and geometry of a structure by minimizing the design objectives, eg material quantity for the given loads, while respecting the constraints.

It outputs a structurally efficient and often visually interesting 3-D truss of linear members joined at nodes by pin connections. For some scenarios, alternative solutions with similar performance may be generated, though with too stringent input constraints, there might be no solution.

Previously, *eifForm* had been used to design a canopy built from standard wood sections and ad hoc eye-hook joints in an architectural school workshop[3], and a precision cantilever structure forming part of a permanent sundial installation in London[4]. The Hylomorphic Project was innovative in that the design was conceived from the start through direct interaction between OSA, the academic researchers, and Arup structural engineers, globally distributed between the US, UK, Germany, and Israel, who never all met. Instead, the project was carried out through transfer of digital models, images, and e-mails. Arup's role was to advise on creating the structural performance model and constraints to ensure buildability.

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* "Hylomorphism" is the Aristotelean philosophical concept that all things are essentially composed of "matter" and "form"[1].

The initial design idea was a planar grid that pushes itself off the ground to create a canopy for people to walk through. The input parameters were a 2-D regular triangulated truss system, with six members connecting at each joint. The constraints were the base points (the joints that need to meet the ground), the spatial limitations (maximum height, boundary lines, internal headroom), the maximum number of members meeting in any one joint, the maximum and minimum lengths of each member, and the minimum angle between two members at any one joint.

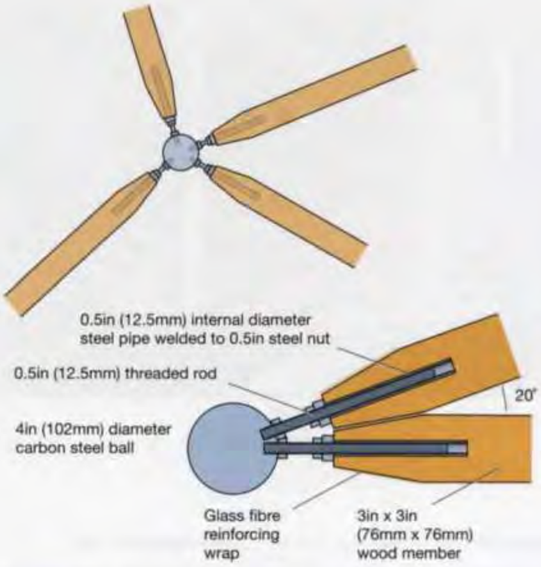
During the generative process, node positions in the grid were moved around as well switching the direction of cross-members in the grid. OSA was keen to keep the grid intact in the final design. In this case, *eifForm* was used to carry out geometric optimization only by minimizing member lengths while meeting all geometric constraints.

Three design alternatives were produced, all of which met the set constraints, but with significantly different forms and visual qualities. The unique forms stem mainly from the centre support location and definition of two boxes on either side as walking zones. Full structural analysis was then carried out by Arup.

Creating the canopy

Despite its small scale, the project raised several design challenges by its "pure" nature, and consequent nonconformity with conventional construction detailing. Also, only a very small budget was available to build it. The individual members were therefore manufactured in a home shop (partly living room!) by the architects themselves, with materials from a DIY supply store and with conventional DIY tools. The 6.7m x 5.18m (22ft x 17ft) canopy itself had to be assembled on site with the help of a few (unskilled) friends in limited time before the exhibition opened, and be easily demountable at the end after three months.

The 3.66m (12ft) tall structure comprises 63.5mm x 63.5mm (2.5in x 2.5in) and 76.2mm x 76.2mm (3in x 3in) Douglas Fir timber members, 133 in number and totalling 152.4m (500ft) in length, connected by 55 spherical aluminium nodes with threaded holes that receive threaded steel tubes glued by epoxy into each end of the timber members. The individual pieces were manually screwed together and secured by nuts. The threads were longer than strictly necessary, to allow for tolerances and adjustment during assembly, which took six people a day and a half. Douglas Fir was chosen as it is the most commonly used and readily available timber in Southern California; the timber type had minimal effect on the design compared to the other constraints.



2. Structure of the node connections.

End wood connections

Another design challenge was the connections. Compared to the rather slender timber section (the size of which was not desired to be controlled by the connection design), the tension and compression forces passing through the steel inserts into the end wood of the members were large. There were also some bending forces due to accidental eccentricities.

Connections to end wood are difficult because wood fibres tend to split at ends (timber has very low tension and shear capacity perpendicular to its fibres). In this case, long steel inserts and large edge distances would have been ideal, but neither was achievable for this timber canopy. The structure's geometry required the timber ends to be tapered, reducing the edge distance to almost nothing, and the length of the steel inserts was limited by the availability of the drill.

Fibre wrapping

To work with these limitations, and stop the timber splitting, the ends were wrapped in glass fibre. This is transparent and barely visible, so the visual impact was minimal and acceptable from the architectural viewpoint. However, though glass fibre is economical, easy to apply without expensive tools, and becoming common in construction applications, this type of use is not regulated by building codes or other literature available in the USA. Arup therefore performed some tension and bending load tests at the University of California Los Angeles (UCLA) structural engineering department. These gave a failure load of roughly three times what was required - enough assurance that the chosen method would withstand the applied loads.

3. Tapered end wood wrapped in fibre.

4. Drilling an aluminium node.

5. Completed aluminium node joint.

6. The Hylomorphic Project in the central court of the Schindler House.

Aluminium nodes

The aluminium nodes were fabricated in China, by the only manufacturer that offered to produce this small a quantity to the level of precision required, and within the available budget. The threaded inserts were drilled by the manufacturer from 2-D plans produced by the architect. The nodes arrived three months after the agreed date - just three days before the exhibition opening - but their finish was very satisfactory and roughly 95% of the holes were drilled in the correct locations. The remaining 5% had to be redrilled on site.

Anchorage to the ground

The canopy was placed in the central court of the Schindler House where, as a historic preserved site, no permanent installation or alteration is allowed. Concrete foundations for the canopy were therefore not possible, and so soil anchors, as normally used for tents and fences, were employed.

Conclusion

Working on this project aligned with Arup's belief in supporting the development of innovative design and promoting engineering excellence to the general public and architectural community. It received good feedback and was published in a book^5; after the exhibition, it was taken apart with the aim of eventually being reassembled at Syracuse University.

This project illustrates a unique design process that does not start by the definition of geometry but rather a computational model of a process, including both architectural and structural viewpoints, through which structural forms are generated. The resulting form is a response to the input models and a degree of randomness in the algorithm. By using new computer tools to tackle problems with too many parameters and constraints for the human brain to process, solutions that balance visual intrigue with optimality from different viewpoints can be found that might seem arbitrary to the casual spectator.

It could be argued that the structurally ideal solution would have been to rationalize the nodes, so that their geometry was identical. However, this also limits the geometric expressiveness of the canopy and would drive the generative process towards more regular, conventional designs, thus deviating from the architects' primary design intent. As more and more manufacturers invest in computer-controlled production methods, the price premium paid for unusual geometries should drop and the overall economics shift in favour of designs that can use complexity to save resource or time, or produce an exciting visual result.

Though the connection design with fibre wrapping needs more scientific testing, the concept underlying this project could be repeated for many other, and practical, purposes and situations with different constraints, sizes, etc. The underlying idea and details would remain the same even though the geometrical output could vary greatly depending on project-specific needs.

Judith Leuppi is a senior engineer with Arup in the Bristol, UK, office.

Prof Kristina Shea, the developer of *eifForm*, is a professor in virtual product development at the Technical University of Munich. She was formerly with Arup.

Credits

Client: The MAK Centre for Art and Architecture **Architect:** Open Source Architecture **Researchers:** Prof Kristina Shea and Marina Gourtovaia **Structural engineer:** Arup – Judith Leuppi **Load testing:** Harold Kasper, UCLA **Fibre wrapping supplier:** Scott Arnold, Fyfe Co **Node fabrication:** Herschel Poger, The Federal Group **Welding:** Gabriel Renz, Name Brand Label **Base plates:** John Burgardt, Weld Engineering **Illustrations:** 1, 3, 4 Open Source Architecture; 2 Nigel Whale; 5, 6 Joshua White.

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Złote Tarasy, Warsaw, Poland

Darren Anderson Zbigniew Czajewski Stuart Clarke Ian Feltham Paul Geeson Marcin Karczmarczyk Richard Kent David Killion Zbigniew Kotynia Maciej Lewonowski Robert Lindsay Philip Monypenny Chris Murgatroyd Johnny Ojeil Raf Orlowski Andrzej Sitko Darren Woolf

1. The main north-south canyon.

History and background

Złote Tarasy (Golden Terraces) takes its name from Złota (Golden) Street, one of the "metal streets" established in the 18th and 19th centuries in central Warsaw that also included Iron, Silver, Copper, Platinum, and Cast-Iron Streets. In 1854, Złota Street had 27 houses and five tenement buildings, mainly of timber. During the second half of the 19th century, these were gradually replaced by masonry buildings, some very stylish. Then, in the early 20th century, it became a place of urban innovations - gas lights, sewerage systems, and trams.

World War 2 put an end to the golden years. Nazi bombs fell on Złota Street in 1939, causing much damage. During the 1944 Warsaw Uprising, the street was barricaded; temporary hospitals and shelters were set up, but the buildings were devastated. A few survived the War, only to be demolished to make way for the Stalinist Palace of Culture, completed in 1956, that occupied the street's central section. The Złote Tarasy site, between the surviving section of Złota Street and Warsaw Central railway station, had remained undeveloped since the War except for some roads, car parks, and a bus terminus.

Client and designers

ING Real Estate began operating in Poland in 1995, where its first developments included some modern high-quality bank and office premises, and apartment blocks in central Warsaw. ING recognized the Złote Tarasy site's unique development opportunity: a new city centre for Warsaw, linking into a multi-modal transport interchange. As the land was owned by the city, an agreement was negotiated by ING whereby the city provided the site in exchange for a share in development profits.

> "ING Real Estate aimed to create the hallmark of the city of Warsaw, and thus breathe new life into the capital's city centre...
> The design team and contractors did a marvellous job in creating this hallmark."

Marcel Kooij, Deputy Director, ING Real Estate

2. The atrium cascade and the sunken plaza.

The Los Angeles-based Jerde Partnership was appointed as concept architect early in 1997, at the same time as Arup's Warsaw office was being established. Arup was initially involved in traffic and transportation studies related to relocating the bus station onto the railway station "deck", so as to vacate the site. Later in 1997, the firm was commissioned for the concept engineering design of the whole development, a geotechnical desk study, and a full site investigation. As the project expanded, the scope grew to include the entire structural, civil, and geotechnical design, transportation planning, acoustics, façade engineering, pedestrian modelling, building physics, and fire strategy. This harnessed key Arup specialist advice from many different disciplines, offices, and groups.

Project overview

The vision for Złote Tarasy was for a vibrant destination, revitalizing the area around the station and including offices, retail, dining, and entertainment in the premier mixed-use centre in Warsaw. Jerde's design, inspired by the historic parks of Warsaw that were saved from wartime destruction, had as its main focus four retail levels grouped around a central atrium, with an undulating glass roof reminiscent of tree canopies. The atrium area is carved through with canyons to allow light to penetrate to the lowest levels, while on the south side the retail and dining areas step back in a series of curved terraces. Above the terraces, the atrium roof flows down to a sunken plaza, with pedestrian links to the station on two levels (Fig 2).

These terraced retail and entertainment levels are surrounded by two curved 11-storey office buildings ("Lumen"), a 22-storey office tower ("Skylight"), and a multi-screen cinema. Below ground are four basement levels, with 1600 parking spaces. The scale of the project speaks for itself. A total area of 200 000m^2 includes 54 000m^2 of retail, restaurants and department stores, 24 000m^2 of offices, an eight-screen cinema including a premier auditorium of 780 seats, 14 000m^2 of public areas and malls, 40 000m^2 of underground car parking, a 6000m^2 truck service yard, and 6000m^2 of terraces and gardens.

The engineering challenges were immense. The basement car park occupies the site's full extent, requiring deep retaining walls next to live carriageways, and a raft foundation below the water table. The concrete frame had to be designed to counteract the overturning of the outwardly leaning "Lumen" office blocks, and to support long cantilever walkways around the curved atrium perimeter. And the atrium roof was of such convoluted geometry that it required some of the most complex analysis ever undertaken by Arup. Added to this, every specialist discipline faced complex, taxing challenges.

The concept and scheme design were done in Arup's Birmingham office before relocation to the Arup Campus in Solihull in January 2001. As the project progressed, and the Warsaw office grew, responsibility for the detailed design was passed there. In recognition of the project's size, the structural design was split between offices, with the substructure, superstructure, and atrium roof design each being handled separately by complementary teams in the UK and Warsaw. Arup's full-time project-manager, resident in Warsaw, was responsible for co-ordinating these teams and all the other Arup specialists.

The site

The 32 000m^2 site is bounded by roads on three sides and the railway station to the south. Roughly rectangular, it is 215m long and 165m wide. Across Złota Street, on the north side, are the "City Center" shopping centre and the Holiday Inn Hotel. To the east and west are the busy six-lane Emilii Plater Street and Jana Pawła II Avenue (Figs 3, 4).

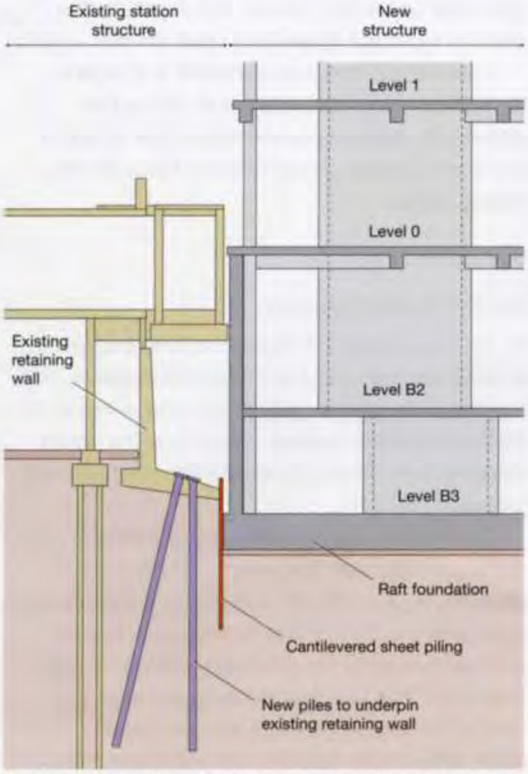
A grassy embankment up to 4m high divided the site in two, with the bus station occupying the half nearest the railway station, and access roads and a large surface-level car park elsewhere. Most of it was covered by tarmac, concrete or compacted stone. The southern half was considerably lower than the surrounding streets, the step being typically formed by retaining walls, up to 6m high.

The underlying ground is of good load-bearing capacity, but quite complex due to the numerous and uneven strata. Several metres' thickness of made ground and thin layers of sand and clay overlie a stiff glacial till, up to 24m thick, below which is a thick layer of dense fluvio-glacial sands and gravels, overlying Pliocene clays at depths greater than 40m.

Of the two groundwater tables, the upper forms a series of relatively flat levels and non-continuous surfaces, about 4m below ground level, whilst the main pressurized water table is 10m below ground level, in the sand layer under the till. Perched water was also found in numerous sand lenses within the till. This unusual combination of water tables proved a major challenge in designing the basement and retaining walls. The top of the pressurized water table is up to 3.5m above the lowest foundation level, resulting in considerable flotation forces.

3. Location plan.

4. The site during basement excavation in April 2003: (a) Jana Pawła II Avenue, (b) Złota Street, (c) The Palace of Culture, (d) Emilii Plater Street, (e) Warsaw Central Railway Station, (f) Złote Tarasy.



5. Cross-section through the basement abutting the existing station retaining walls.

Basement and foundations

Excavation

The Złote Tarasy basement, up to 13.5m deep, is one of Poland's largest. The site perimeter had all the usual problems of a congested inner city, with adjacent roads and buildings, and buried services close to the boundary. The railway station was tight against the southern boundary with a two-storey gravity retaining wall, and all the station's complex exhaust ventilation shafts crossing onto the site. Stone-clad concrete retaining walls, 6m high, supported the perimeter of the adjacent roads on the east and west sides, and an elevated ramp and access tunnel had to be incorporated into the scheme or reinstated, to serve the relocated bus station. Next to the railway station, the existing gravity retaining wall was underpinned with piles, and the new foundations at a lower level were built against a permanent cantilever sheet piling system (Fig 5).

Diaphragm walling was selected as the best solution for the perimeter retaining walls, both temporarily and permanently. In the temporary case, an 800mm thick diaphragm wall was designed to accommodate excavations up to 16m below the adjacent pavement level. In the permanent case, the basement floor slabs provide sufficient lateral restraint to resist not only the earth and surcharge pressures but also water pressures from the main water table and the large areas of perched water at higher levels.

Ground anchors were selected as ideal for supporting the diaphragm walls in the temporary state, providing the maximum working space whilst minimizing potential movement of the gravity walls next to the main carriageways. The contractor's final design incorporated multi-strand anchors into the glacial till, which proved to be very successful (Fig 6).

On the northern side, the proximity of existing retail buildings with basements ruled out ground anchors, so a raking prop scheme was planned and incorporated in the contractor's temporary works.

The need for over 1600 parking spaces meant that a fourth basement level was required over 60% of the footprint. This B4 level, 13m below ground, resulted in construction below the water table, so Arup specified a dewatering programme.

6. Diaphragm retaining wall with ground anchors, along the east edge of the site.

Raft foundation

To minimize the costs of retaining walls, Arup kept the deepest excavation to the site centre, for the B4 level. Slabs were kept at the higher B3 level on the critical north and south ends and along the western perimeter. This resulted in several folds in the lowest slab, further complicated by the need for lift pits and lowered plant areas (Fig 7).

A continuous raft, free of movement joints, was the ideal choice to control the risk of differential settlements and future cracking of the finishes. As the loading intensity varied significantly, Arup's in-house *GSA* (general structural analysis) software was used to predict the raft settlements, which were initially significantly higher under the "Skylight" office tower. Using iterative analysis, Arup optimized the design, equalizing predicted settlements under the critical sections with settlements of the surrounding areas. This was achieved by a piled-raft solution under the tower footprint, with 900mm diameter bored piles up to 20m deep beneath the raft on a closely spaced 3.6m x 4.0m grid. The piles were empty bored from the existing ground level, using support fluid, and founded in the fluvio-glacial sand and gravel layers overlying the deep Pliocene clay. The raft is typically 1.6m thick, varying between 2.65m under the tower to 1.0m under the lightly-loaded northern end.

Basement structure

Basement levels B1-B3 have reinforced concrete flat slabs, typically on a 10.8 x 8.0m grid supported by 800mm diameter circular columns with drop heads. In the more heavily-loaded areas, grid and column size could not always be maintained, so vary locally. Major core structures and ventilation shafts further complicate the layout. The principal car parking is on levels B3 and B4, with smaller zones above.

Conforming with local special fire requirements, the basement levels are divided by two perpendicular movement joints to form four independent quadrants. Due to the required four-hour fire resistance for the quadrant beneath the "Skylight" tower, it was separated at each level from the rest of the slab by a special movement joint. Although designed for 25mm movement under normal conditions, it has special crush zones capable of 200mm expansion in a fire.

7. Raft foundation under construction at B4 level. On the left is the soil berm left in place to support the diaphragm wall along Złota Street, on the other side of which are the "City Center" shopping centre and the Holiday Inn Hotel.

Due to architectural and functional constraints, the "Skylight" tower's structural core is limited in the basement levels to only 40% of its area on the upper floors. The loads are transferred to a set of push-pull columns by very large shear walls, 3.7m deep and 1.6m thick. The complex geometry of this transfer structure required a special finite element analysis, using *ROBOT Millennium* and Oasys *GSA* software, for its behaviour to be understood and the reinforcement designed accordingly. Apart from this unique structure, there are many transfer structures in the basement, and discontinuities of some columns from the upper levels resulted in some complex beam arrangements. Arup's design, however, ensured that the car park's functionality was never compromised.

Other features of the basement include the service yard, sunken plaza, and access ramps. The 6000m^2 service yard is formed by a double storey-height space at B2 level, providing sufficient space for deliveries to all the shops and restaurants, as well as emergency vehicle access down a central road. The sunken plaza in the south-east corner of the same level forms an open-air space with water features, and direct access to the lower levels of the railway station.

The main car park access ramp is from the centre of Złota Street, while on the site's north-west corner an existing tunnel under Jana Pawła II Avenue was used to provide the principal delivery and lower basement access. This tunnel is also used by municipal buses to access the bus station.

A new in situ concrete perimeter wall next to the railway station boundary, built off the raft foundation, incorporates the station link structure and the two newly-routed exhaust ducts for the railway station.

Superstructure

Basic structural concepts

To minimize basement excavation it was essential to avoid transfer structures wherever possible, and use the same column grid for the retail areas as for the basement car parking. Maximizing the latter's efficiency was the key to developing the basement and retail area grid.

The starting point was the use of 5.0m x 2.5m parking spaces with 0.8m-wide column zones, intended to give the high turnover of shoppers easy parking and a general high-quality feel. Column spacing parallel to the driveways was set at half a "bin width" of 8.0m. In parking terminology, one "bin" is the width of an aisle plus the parking bays either side. In this case the bin width was 16m (6m aisle plus two 5m parking bays).

8. Plan of level 3, showing movement joints and prestressed beams, together with part of the 3-D structural analysis model.

Perpendicular to the aisles, the grid was set at four parking spaces plus the 0.8m column zone, totalling 10.8m. Although columns every three spaces was less costly, the four-space solution was adopted because it gave greater flexibility in the retail floors above.

Arup accepted from the beginning that major transfer structures would be needed at level 3 between the retail floors and the offices and cinemas above to provide column spacing appropriate to each of these uses. Although the basic grid was intended to suit retail and parking, the complex geometry of the main retail circulation areas was expected to generate serious structural challenges at the interface between these uses. However, costly transfer structures were minimized through imaginative and well-integrated architectural and structural design.

An early requirement of the developing brief was that the structural design must accept post-construction changes by retail and office tenants, and be tolerant of on-going design development due to the scheme's geometrical complexity. Arup provided flexibility in both these aspects by using traditional in situ concrete beam and slab construction rather than the increasingly popular flat slabs. This had two benefits: individual slab panels could be removed after construction with minimal effect on overall structural integrity, and small column offsets could be introduced along beam lines, as was required in later design stages.

The use of in situ reinforced concrete for most of the structure acknowledged the track record of high-quality Polish concrete production, and the relatively low use of steel in Warsaw buildings in 2001-03. It was also eminently suited to the architects' complex curved shapes.

Sets of in situ concrete cores and shear walls provide overall stability. Local fire regulations necessitated structural separation joints which split the otherwise uninterrupted 215m x 165m building's lower-level footprint into four quadrants, each stabilized by at least two cores or sets of shear walls, and two smaller central islands, each with its own core. The complex arrangement of the cores in plan is matched by their vertical complexity: the cores are used for structural stability, stairs, lifts, and service risers, all with wide variations of space requirements at different heights.

A structure suitable for high specification retail

Jerde envisaged a characterful retail area with imposing circulation spaces and clear uninterrupted views of shopfronts across internal streets and open spaces, all within a large open atrium. From early in the concept design, the primary circulation routes were two "canyons", one oval in plan, the other a straight north-south axis crossing the oval at two points. Central to the concept were canyon-side walkways with edges stepping back at each floor level, and inclined columns and balustrades. These followed the lines of the inclined "Lumen" office blocks above the atrium roof, so from the walkways there are impressive views of the towers above, as well as wide uninterrupted views around the canyons.

This ambitious combination of wide walkways, uninterrupted views, and complete departure from the regular basement parking column grid, set two major structural challenges: the design of numerous long cantilever beams, and the provision of transfer structures without creating headroom problems below (Fig 8).

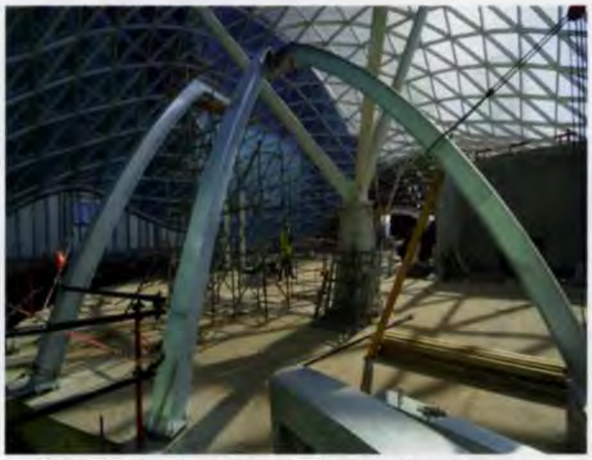
For the cantilever design, the challenge was to provide large spans without excessive structural depths. Arup's solution emerged from a realization that the cantilever depths were controlled by deflection rather than strength. The team adopted an innovative system of partial prestressing, incorporating ducted post-tensioned tendons. These provide sufficient prestress to control deflection only, strength being supplemented by traditional unstressed reinforcement. This "hybrid" technology was untested in Poland. Initially it attracted some scepticism from potential contractors but, once accepted, there was universal recognition of its merits, simplicity, and relative ease of construction. Arup's innovative approach gave the architect and client the uninterrupted views around the walkways that they wanted. Each shop front has maximum exposure to shoppers on both sides of the canyon, with no column obstruction.

In a building of such complexity it was difficult to ensure that prestress forces were transferred into the intended beams rather than absorbed by nearby stiff elements such as cores. The distribution of cores and shear walls was also a reason why wholesale prestressing could not be adopted. But its selective use in controlled situations like cantilevers and long-span beams provided the optimum solution.

Software used for the structural analysis included *GSA*, *ROBOT Millennium* (the 3-D finite element analysis model included 20 000 nodes and 30 000 elements), *Plato* and *ABC Plyta* for 2-D finite element analysis of slabs and beams, and *RM-Win* for steel elements. Complex structural analysis was required for the many curved structures, including the "banana columns" (Fig 9), the "Helmet" (Fig 10), and the "icon" on top of the "Skylight" tower (Fig 11).

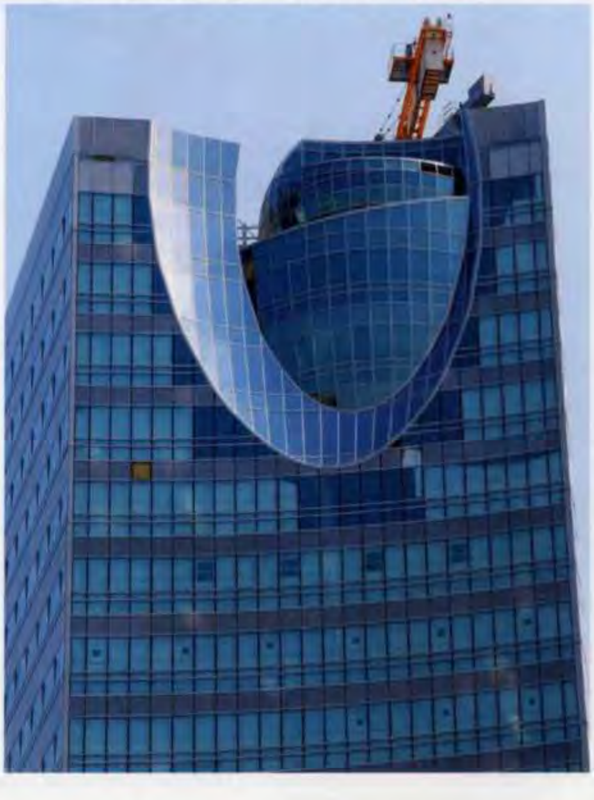
In the central retail area around the edges of the canyons many transfer structures were needed to marry the layout of the columns to the parking grid below. Minimizing structural depth was again a key to essential cost control. The floor-to-floor heights had to be kept to an absolute minimum to reduce the total cost of the high quality finishes and elevational treatments in the public retail areas as well as maximising the visibility of shopfronts between levels and shortening staircases and escalators. The solution was a two-part strategy involving detailed co-operation and co-ordination between Jerde and Arup. The first part, the wholehearted adoption of inclined columns, stemmed naturally from the architecture. The second part required extensive and detailed 3-D modelling and column-positioning workshops, aiming to transfer column positions in small steps over several floors to minimize transfer beam depths. This strategy successfully minimized floor-to-floor heights without compromising headroom requirements in the retail areas and walkways.

9. "Banana columns" for the "Bowl", and cantilever support platform for escalators.



10. Steelwork under construction for the "Helmet".

11. The "Icon" on top of the "Skylight" office tower.



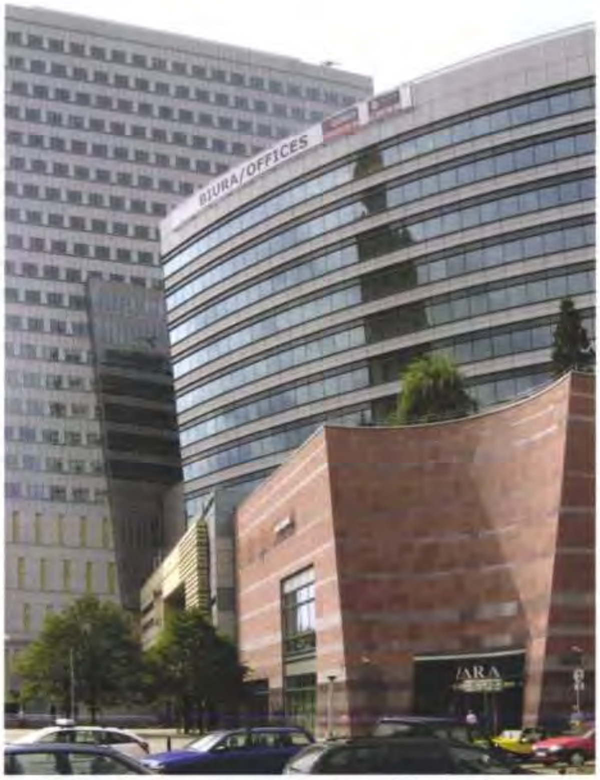
Office blocks, level 3 transfer structures, and cinema

The two northern "Lumen" blocks are approximately semi-circular in plan, and slope outwards towards the surrounding streets. The inclinations vary from vertical at the axis of the main north-south "canyon" to about 1:10 at the extreme eastern and western ends. Early studies of these blocks aimed to assess cost-effective ways of achieving the inclined façades. Inclined columns would have created excessive overturning moments in the relatively small cores, so vertical columns were used throughout, with varied-length cantilever beams at each floor to suit the angles of inclination (Fig 14). In situ reinforced concrete is used for framing all the office blocks. Primary beams form the cantilever back-spans and contain various holes for main building services distribution, taking full advantage of the high quality of Polish concrete production and again minimizing floor-to-floor heights. This helped minimize overall costs, due to the expense of the inclined cladding.

There is a major mismatch between the heavily loaded columns for the curved eight-storey Lumen offices blocks above level 3, and the regular column grid of the retail floors below. Initially a complete storey height had been allocated between levels 3 and 4, to accommodate the transfer structures required. However, Arup's design refinements, including extensive finite element analysis, led to the transfer structures being fitted within a slightly thickened structure at level 3.

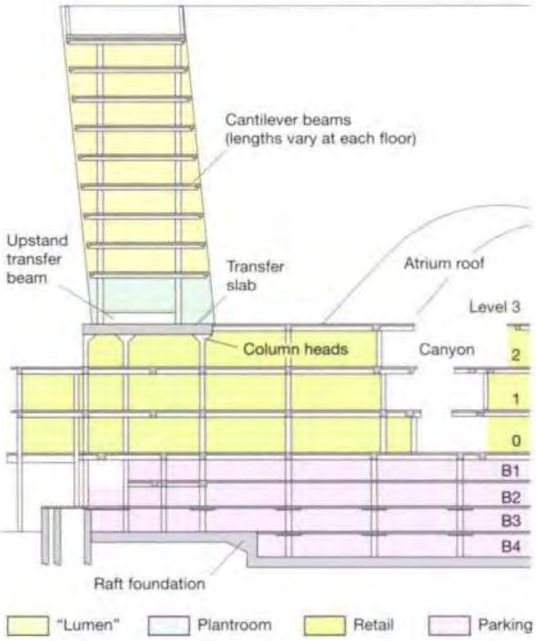
This was a major cost saving, as it permitted much of the plant to be relocated from the roof of the office blocks to the newly-created level 3 plantrooms. The final transfer structures include a 1.2m thick slab with upstand beams connecting pairs of office columns and dropped areas of slab with column heads below (Fig 14).

Structural steelwork was used for the cinema structural framing, due to the need for long spans, and precast concrete for the seating areas. Steelwork was also used for the complex three-dimensionally curved structures in the atrium, such as the "Helmet" (Figs 10, 15), the "copper houses", and the "Bowl" (Fig 9), as well as for the architectural "icon" on top of "Skylight" (Fig 11).



13. The "Skylight" office tower and one of the "Lumen" leaning office blocks.

12. The "Skylight" office tower, the "Lumen" blocks and cinema from above.



14. Typical cross-section through one of the "Lumen" blocks.

The atrium roof

Concept

The spectacular glazed atrium was conceived as the project's heart. As well as enclosing the central malls, terraces and food court, it was intended to be an instantly recognizable icon, establishing the development's brand values.

Three years' concept development between Arup and Jerde led to its unique shape; from 1998 to 2001, the roof evolved from a single overarching dome to a free-flowing, undulating form. Jerde's concept was a symbiosis of nature and technology, combining the natural forms of trees, forest canopies, falling water, soap bubbles, and soft textiles with mathematical concepts, scientific observations, and technological tools. By adopting this undulating form, Jerde created an intimacy with the structure that gives rise to constantly changing views as one moves around the atrium.

Due to limitations of engineering design and fabrication, roofs on this scale have historically followed geometrically defined shapes that can be readily analyzed, designed, and built with a large degree of repetition. Two recent developments have, however, combined to liberate architects from the straitjacket of regular geometrical forms: the increased power of computer-aided analysis, and advances in computer-controlled manufacture.

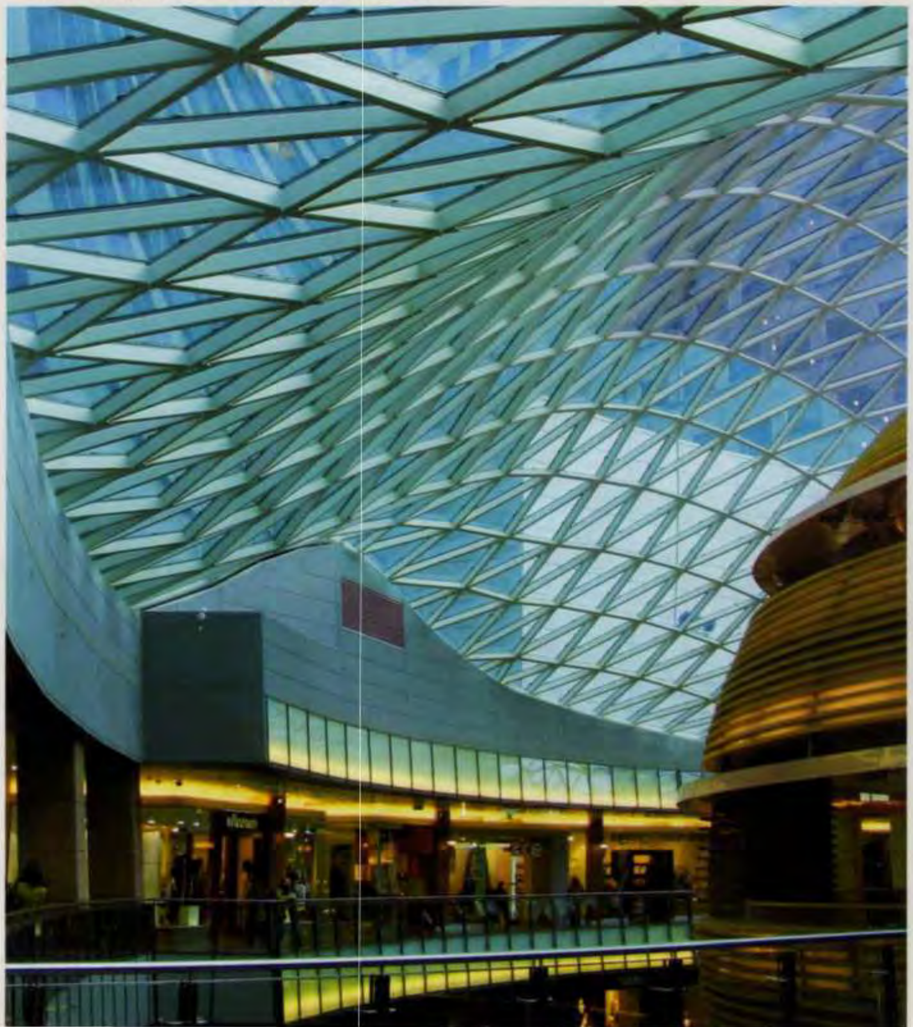
Roughly elliptical in plan, the 116m long x 100m wide roof rises in the centre to a series of domes, up to 35m above ground level, and on the south-west side flows into a spectacular cascade, dropping 25m in a column-free span to ground level (Fig 54). It thus forms the development's focal point, surrounded by the "Skylight" tower, the "Lumen" office blocks, and the multi-screen cinema, and links them with the main entrance from the railway and bus stations. It connects the heart of the development with the sunken plaza, allowing light to permeate the four retail levels, and opens up external views from the retail terraces, cafes, restaurants, and performance spaces.

Once the roof geometry was fixed, Arup's challenge was to develop a structurally efficient, buildable, economic, stable, and robust design. Due to the geometrical complexity, this required the highest levels of expertise, ingenuity, innovation, and teamworking.

Although the roof and its supporting structures (including the tree columns) act interdependently, they posed very different challenges, as discussed in the following pages.

15. Internal view of atrium roof and the "Helmet" at the level 3 food court.

16. Curved canyon around perimeter of atrium.



Generating the roof geometry

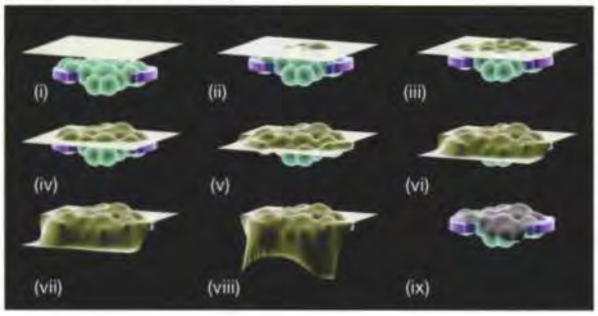
Jerde generated the undulating free-form geometry from an iterative computer simulation whereby a virtual cloth was "draped" over a series of spherical deflectors (Fig 17). Hundreds of alternative shapes were explored, varying the numbers of deflectors, their sizes and relative heights, the mesh size and "stretchiness", and the "gravity" force applied. The drivers for the overall shape were to:

- ensure a positive rainwater flow across the whole roof, avoiding ponding
- maintain double curvature to the roof shape, as any "flat" areas would deflect too much
- create a variety of intimate spaces, hugging the profile of the stepped terraces and maintaining the minimum headroom at pinch points around the perimeter.

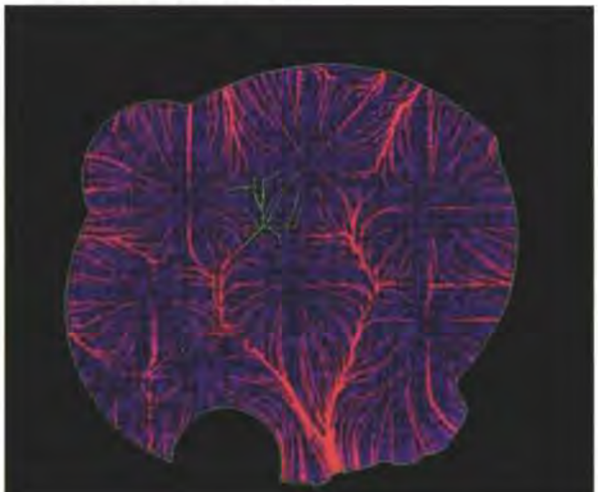
Detailed tracking of rainwater flows (Fig 18) showed unacceptable areas of ponding, which required adjustment of the roof geometry. The whole central area drains down to the front "cascade" above the main entrance at plaza level, and this feature resulted in some critical snow loading cases.

A function of the modelling was that although the glazing grid started as a regular mesh of isosceles right-angled triangles, the "draping" process introduced distortions as the mesh was moulded over the spherical deflectors. This stretched and twisted the grid, so that no two panels ended up the same size.

17. "Draped cloth" sequence.

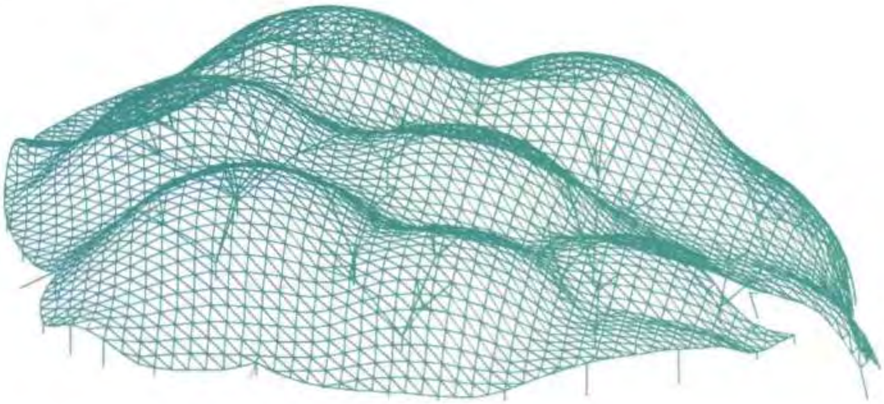


18. Rainwater flow modelling.



19. Perimeter smoke extract.

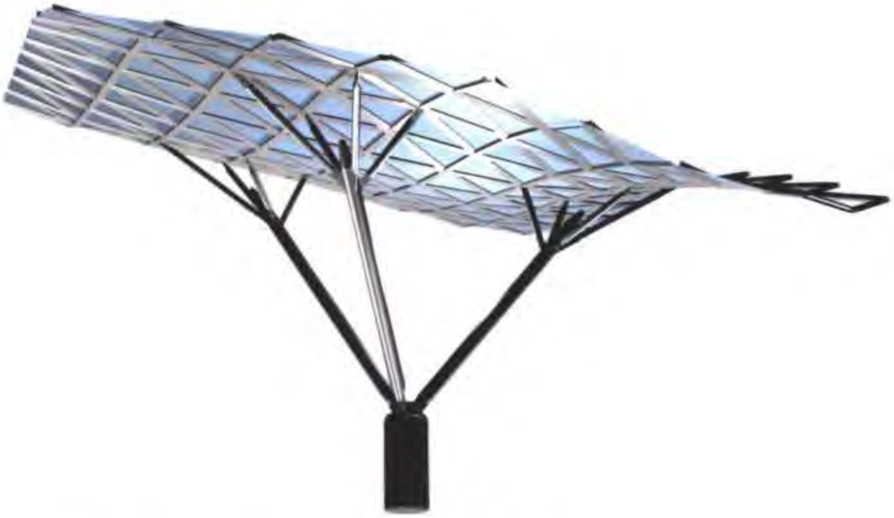
20. *GSA* image of final roof mesh geometry.



With the basic roof shape established, a long period ensued of developing and optimizing the mesh grid size. To fit the warped surfaces, the grid had to be triangular, as there was too much twist for square or rectangular panels to fit.

Arup explored numerous variations of size and angle, including grids based on isosceles and equilateral triangles. Structural and glazing costs, as well as aesthetic requirements, had to be balanced in the optimization process. Large panel sizes were the cheapest structural option, with the fewest members and connections, but the glazing would have been prohibitively expensive, and large panels would have created a faceted shape rather than a smooth change in gradient. Small panels would have given the smooth shape, but with too many structural members and connections.

The optimum (Fig 20) proved to be a mesh of approximately right-angled triangles, with short sides around 2.1m long. This size and shape of glass units was the most cost-effective for glass manufacture. Although the basic shape was established early on, some significant changes followed during design development, most importantly a lifting of the "skirt" of the roof mesh in five locations around the perimeter, to allow space for smoke extracts (Figs 16, 19).



21. 3-D studio visualization of tree with branches and quads.

Structural design

Roof mesh and nodes

The over-riding architectural ambition was for the whole roof to appear as a uniform mesh, with constant-sized members. This proved extraordinarily difficult, and was achieved only through Arup fine-tuning the mesh design and its supports.

The end result is a continuous triangulated grid of steel rectangular hollow sections (RHS) of constant size, 200mm deep by 100mm wide, with wall thicknesses varying from 5mm-17.5mm depending on the forces in each member. Most are of grade S355 steel, but the 213 most heavily stressed members are in high-strength steel grade S460 - not normally used for building structures. By using the high-strength steel, every member was fabricated from standard hot-rolled RHS, avoiding the need for any fabricated box sections.

Six RHS members intersect at every node, a star shape with six arms, each arm bisecting the angle between two adjacent members. During design development, Arup tried to achieve some standardization of glass panel size, member length, and node geometry, but without unacceptable distortions of the roof geometry, the small level of standardization achievable had negligible cost advantage. In the end, each of the 2300 nodes, 7123 RHS members, and 4788 glass panels has a unique geometry.

Due to the internal supports (see below), the roof mesh spans are mostly less than 15m, except at the cascade and in the north-west corner, where spans of up to 25m are achieved by using the arching action of the mesh, making the roof exceptionally slender. The maximum deflection at any point is 43mm under maximum snow loads (Fig 22).

The most complex part of the roof mesh design was the node connections. Early analyses showed that they would need to transfer large bending moment forces. Most areas of the roof had insufficient curvature for a "pinned" node design to work. Each node therefore has to transfer a unique combination of axial forces, shear forces, and bending moments from one side of itself to the other. To help develop the most economic form, Arup involved specialist contractors at an early stage in the design.

Bolted and welded solutions were developed in tandem, with different contractors favouring different types of node. The welded option was preferred aesthetically, as it gave the most "invisible" connection, but the option of a bolted node was included in the tender documents to allow contractors maximum flexibility in their designs. It became clear that the node design would also influence the forces in each member, so the atrium roof specialist contract included the final design of the RHS members and nodes.

The chosen contractor, Waagner Biro, developed a fully welded node, as described later. The end result is a continuous, fully-welded, seamless structure, rigid enough to withstand wind and snow loading, yet flexible enough for thermal movements.

Supports

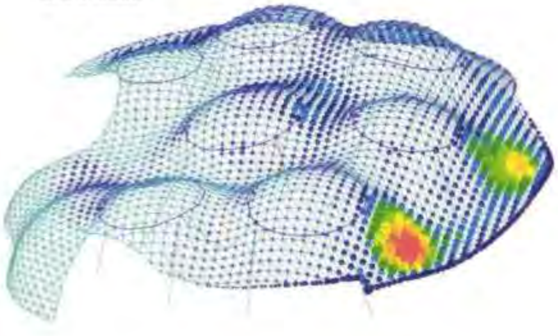
The roof is too convoluted to span 100m across the whole atrium, so it needed internal columns, as well as supports around the perimeter. Their number, nature, and location was a major challenge for Arup, and the subject of long design development through the examination and refinement of numerous options. The main drivers for the design of the supports were to:

- provide stability to the roof mesh
- avoid excessive deflections
- minimize local stress concentrations to achieve the required uniform mesh
- allow thermal expansion of the mesh without building up excessive stresses
- be structurally efficient
- be elegant and visually interesting
- bear on optimum locations in the reinforced concrete structure below
- minimize obstructions at floor level, allowing clear walkways and maximizing the lettable area
- allow ease of cleaning and maintenance of the glazing underside.

These often conflicted, and extensive parametric studies and much ingenuity were needed to satisfy them all with minimum compromise. Initial concepts, with relatively few columns, resulted in local instability, large deflections, and excessive stress concentrations in the roof mesh.

Arup's final solution was to provide 11 internal trees (reduced from an initial 16), 26 perimeter posts at level 3, two sliding bearings at the drum, two rotational bearings near the "Lumen" office blocks, two "flying struts" near the "Skylight" tower, and 16 supports at the base of the cascade.

22. *GSA* model: atrium roof deflections under drifted snow loads.



23. Cow parsley - inspiration for the trees.

The internal trees were carefully located to minimize impact and obstruction in the prime rental space at level 3. Each tree has a 2m high tapered steel tubular trunk, filled with heavily reinforced concrete. They are located directly above the reinforced concrete columns below, into which they transfer some large out-of-balance bending moments. Splayed out from the top of each trunk at different angles are three tubular steel branches, each of which in turn splits into a "quad" of four tubular members that connect to the roof mesh (Fig 21).

The trees are located outside the pedestrian walkways, with minimal loss of lettable area. The number and orientation of their branches was optimized primarily through the structural criteria of stability, stress, and deflection, but there was also a strong aesthetic element. The design was informed by natural tree and plant forms, particularly cow parsley (Fig 23).

Early designs included anything between one and seven branches per tree, refined as the design developed into a unified three-branch form whose angles and orientation have a pleasingly organic feel as well as being structurally efficient (Fig 24).

Around the whole atrium perimeter above ground level is a 355mm diameter steel tube, tying together the ends of the roof mesh and supported, above the level 3 roof, by perimeter posts and bearings.

Up to tender stage, the perimeter tube was connected to the adjacent structures at frequent intervals by "flying struts" to counteract the "spread" which occurs at the base of a simply supported arch. But as Arup refined the design it became clear that these flying struts gave too much restraint against thermal expansion. By allowing the atrium roof mesh to "float" above the level 3 roof, it could "breathe" in and out as temperatures changed, and the perimeter posts were given articulated joints to allow horizontal movement in all directions (Fig 25). Only two "flying struts" and two rotational bearings were retained to prevent excessive horizontal movement where the perimeter tube changes direction sharply. Similarly, the tender design included seven bracket supports from the drum columns around which the atrium roof wraps, but during detailed design these were reduced to two by using the arching action of the roof mesh, with elastomeric bearings provided to avoid imposing high forces onto the drum structure (Fig 26).

25. Perimeter post detail.

26. Elastomeric bearing at the drum bracket support.

Atrium roof numbers

Plan size: 116m x 100m

Glazed area: 10 240m^2

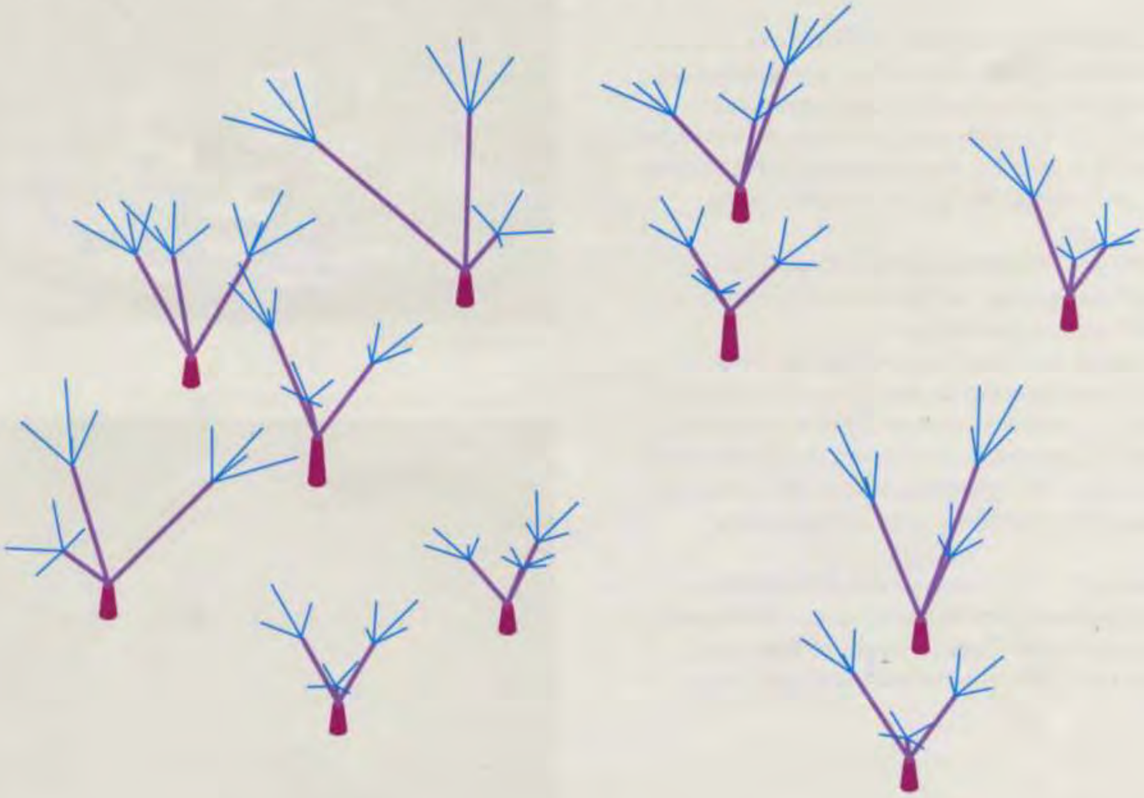
Steel weight: 630 tonnes

Number of steel RHS members: 7123

Number of steel nodes: 2300

Number of glass panels: 4788

24. Each of the 11 trees was unique in the length and orientation of its branches and quad members.



27. The main entrance at ground level, approaching from the station.

At the base of the cascade, the roof mesh lands on the reinforced concrete structure at 16 points, each of which provides vertical support to the roof, and resists horizontal thrusts and wind loads. The base of the cascade includes three large openings for the main entrance doors, but the triangulated form of the roof mesh makes it stiff enough to span across these (Fig 27).

Wind and snow loads

The roof geometry was far beyond anything envisaged by the Polish wind and snow codes, British Standards, and Eurocodes. Dr Jerzy Żurański, of Warsaw's Building Research Institute and one of the authors of the Polish wind and snow codes, undertook research into possible effects. In parallel, Arup commissioned a specialist testing company, RWDI from Canada, to carry out wind tunnel testing (Fig 28), and snow drift (Fig 29) and sliding snow modelling. This proved invaluable for the detailed design.

The wind load results from RWDI were substantially lower than predicted by Polish codes, resulting in significant cost savings, but by contrast some of the predicted snow loads were higher than code predictions.

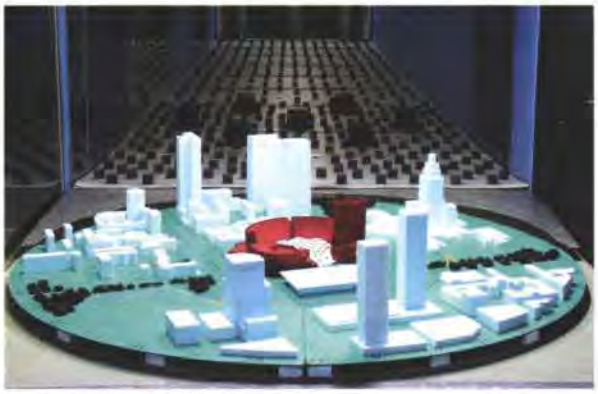
RWDI used three methods to predict snow loads: physical testing, computer modelling, and hand calculations. The physical testing was done with fine sand in a water flume, mimicking the effects of snow drifting under different wind speeds and directions. This qualitative method revealed areas of the structure where snow drifts could occur, and some were surprising, including a series of drifts along the tops of the domes, caused by downdrafts and eddies from the surrounding buildings (Fig 29).

The physical testing was backed up by FAE (finite area element) modelling, based on 50 years of recorded temperature, snowfall and wind speed data from Warsaw. The FAE modelling gave quantitative values for maximum snow loads, which could be combined with the basic uniform snow loads, and drifted snow load patterns.

Due to the uncertainty revealed by the water flume tests in predicting where snow would drift, Arup approached the problem from two directions: the likely locations, and where the most adverse effects on the structure would be. The former included predictable areas such as against adjacent buildings, and on the leeward side of the domes, together with areas highlighted by the water flume study. Locations with particularly adverse structural effects included loads on areas identified by the buckling analysis, and areas that would cause the maximum out-of-balance forces on the trees. In total, nine different drifted snow load patterns were included in the final analysis.

The combination of RWDI's testing and Dr. Żurański's research enabled Arup to establish a conservative set of uniform and drifted snow loadcases, typically with a peak value of 1.75kPa.

Of greater significance to the structure were the predicted loads from sliding snow. For most normal structures, vertical loads from sliding snow are less than those from drifted snow, so are commonly ignored. But due to the roof shape, large quantities of snow could partially melt and slide from the domes into the valleys and thence down to a relatively flat area above the cascade. Meltwater from the domes could collect in the lower areas and refreeze. The combination of these effects gave rise to predicted snow loads up to 10kPa, far in excess

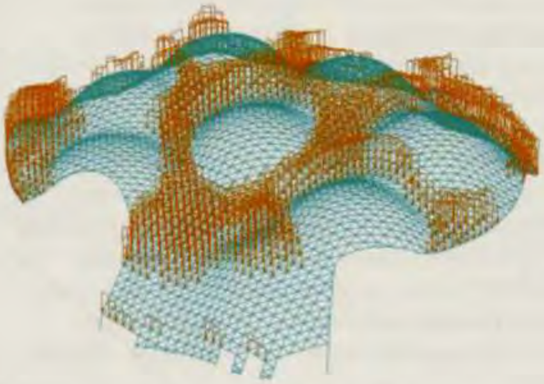


28. Wind tunnel test.

29. Snow drift modelling in water flume.

of what could be taken by the glazing without a very large cost increase. The valley areas of the roof mesh were also the most heavily stressed, and this additional load would overstress some members. Rather than design for these loads, Arup's solution was to avoid them by providing a series of snow fences around the domes and in the valleys to limit snow accumulation to 2.5kPa. A typical sliding snow loadcase included in the structural analysis model is shown in Fig 30.

Arup, RWDI, Jerde, and Waagner Biro together designed what ultimately were minimalist fences made from stressed wires (Figs 31, 32) supported by stub posts projecting from the roof nodes. Similar solutions support the *Latchways* safety system for external maintenance, the lightning protection, and the external roof-mounted lighting. The lowest snow fence incorporates a heated tube to gradually melt snow and avoid icicles or slabs of snow falling down the cascade, which could otherwise injure pedestrians below.



30. Sliding snow loadcase 2 modelled in *GSA*.

31. Snow fence detail.

32. Snow retained on the roof by the snow fences.

To allow for hanging loads, every node was provided with a threaded socket designed for a single point load of 500kg, or a simultaneous load of 20kg at every node. This means that the atrium has built-in flexibility for uses such as displays, performances or product launches.

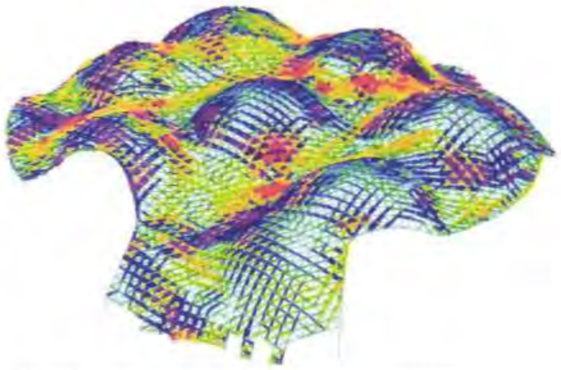
Thermal movements and differential settlements

Since the roof has no movement joints and is over 100m long, with steel members directly below the glazing, thermal movements were always likely to be significant. To establish a likely range of temperatures for the steel, Arup performed some finite element modelling of the RHS members with the aluminium glazing bars and glazing fixed above them. This determined maximum likely temperatures, but also revealed significant difference in temperature between members depending on their angle of incidence to the sun. With it directly overhead, the steel is sheltered by the glazing bars, and at shallow inclinations most sunlight is reflected off the glazing. At moderate angles, though, there could be significant heat gain, so among the thermal loadcases investigated were those with a higher temperature for members running east-west, compared to a more north-south direction.

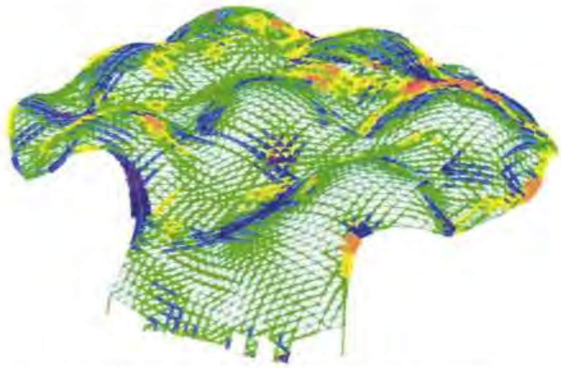
The design of the articulated perimeter posts and bearings that allow the roof perimeter to "breathe", as already described, meant that thermal expansion was not critical for most roof members.

Another major influence on the design was the fact that the atrium structure is supported on six different reinforced concrete structures below, all separated by movement joints. The atrium roof is seamless, so its design had to cater for differential movements of the supporting structures - horizontally due to shrinkage and wind loads, and vertically due to foundation settlements, and beam deflections, including some significant long-term creep deflections.

These vertical deflections were in some cases substantial, as many of the beams were long span or cantilevered, and some post-tensioned. Since the triangulated mesh is relatively stiff in plane, the relative deflections of adjacent supports makes a large difference to the forces in the mesh, even to the extent of causing load reversal. Close liaison between the roof designers and those of the concrete structure was needed to establish maximum and minimum boundaries for likely movements, as well as the relative stiffness of each support point.



33. *GSA* model: typical distribution of axial stresses.



34. *GSA* model: typical distribution of bending moments.

Structural modelling

The roof was modelled using *GSA*. Support conditions were modelled using output from the *ROBOT* model of the reinforced concrete superstructure, ensuring compatibility. Jerde's basic roof mesh geometry was imported from AutoCAD, and manipulated using additional software to orientate every RHS member perpendicular to the bisector of the angle of the two glass panels it supports. Some Visual Basic routines were also developed to map the wind loads from the wind tunnel test directly from each pressure tap location onto every structural member.

As the design developed and the wind tunnel, snow modelling, and thermal modelling results became available, the number of loadcases and load combinations grew to include 14 wind loadcases, 12 snow loadcases, five thermal loadcases, and 98 differential settlement loadcases, including individual loadcases with each support settling more or less than the adjacent ones. Altogether there were 1700 different load combinations for the ultimate limit state.

The numbers of members and of loadcases made this one of Arup's largest *GSA* model analyses, stretching computing power to the limit. Typical results of the static analysis are shown in Fig 33 (axial loads) Fig 34 (bending moments), and Fig 22 (deflections).

To provide greater confidence in the results, Arup insisted that the atrium roof contractor carry out a completely independent analysis, using different software. The results were compared, and by the end of the final design, agreed to within 5%. Increased safety factors were also used, in view of the complexity of fabrication and erection, and the possibility of eccentricities and stresses being introduced due to lack of fit.

Second-order and buckling effects

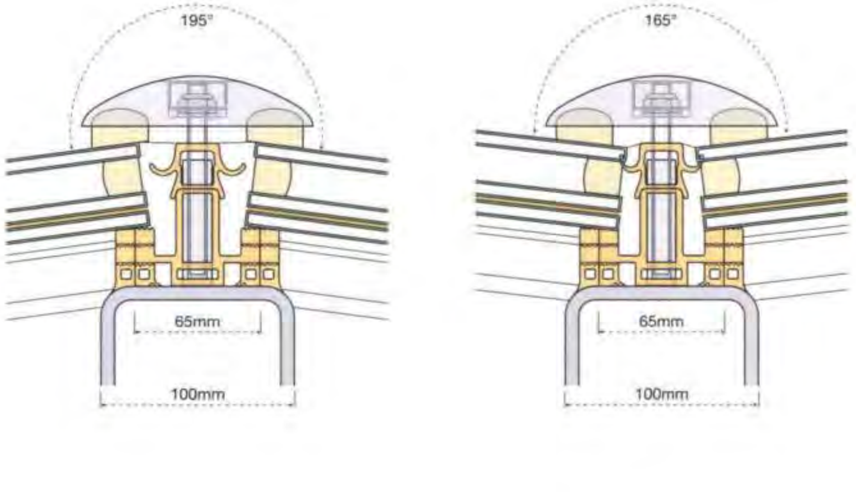
In addition to the static analysis, second order buckling effects were also investigated. Simple linear static analysis is based on the assumption that straight members are perfectly straight, but in practice any member may have fabrication imperfections. When compressive forces are applied, these imperfections cause additional bending moments, known as P-Delta effects, to arise (the bending moment is equal to the axial load "P" multiplied by the deflection "Delta"). Bending moments are also magnified as a result of buckling. These additional stresses in members are collectively known as "second-order effects".

The design rules in structural codes ensure that standard components like columns and the compression flanges of beams have sufficient stiffness to prevent buckling, and are strong enough to resist not only the applied forces but also any secondary forces that arise because of their flexibility. However, these rules do not cover structures as complex as the atrium roof, which have to be designed from first principles in a similar way to the development of the code methods. Fundamental to any procedure is determination of the buckling mode shapes, buckling loads, and their associated deformations. Simple estimates of these properties are very difficult and any approximation is necessarily very conservative, leading to a much heavier roof design.

The procedure to check the second order and buckling effects of the atrium roof was developed in Arup several years ago, but its use was complicated by the size of the necessary *GSA* model compared with the computing power available. Buckling and second order analyses are more complex and take much longer than standard linear static analyses, and over an hour was needed on the highest specification PC then available (1GB RAM) to run an analysis that gave the lowest 25 buckling modes. Analysis time increases exponentially with the number of modes required, so when 50 modes were later determined on the same computer, the analysis took over 12 hours.

The buckling analyses for the atrium roof produced a series of buckling mode shapes, with a critical load factor for each mode. Because most of the roof is highly curved in two directions, no overall buckling modes affected the whole roof. The significant buckling modes only affected local areas of it – generally an out-of-plane "dimple" comprising an area which is relatively flat, or of long span, or highly loaded. For each mode shape, the dimple diameter was measured, together with

35. Glazing system with glazing buttons, showing the range of angles of inclination of glazing.



36. Glazing gasket installation.

the amplitude of deflection. From the analysis results and subsequent calculations, the additional bending moments due to the second order effects were estimated for each "dimple" with a critical load factor less than 10. For most areas of the roof, these were less than 5% but in the worst cases, the moments were increased by 25%. The lowest mode had a critical load factor of 4.9 for the combination of dead, live and full snow loads. The deformed shape comprised an out-of-plane dimple with a diameter of about 8.8m.

Another form of instability called snap-through buckling - as when an umbrella blows inside out - was also investigated by comparing the small changes in curvature of the roof from the P-Delta analyses with the initial curvature. It was found that snap-through buckling cannot occur under normal loads, because the roof is sufficiently curved to prevent it.

Procurement route and programme

Such an adventurous architectural concept was a high-risk item, requiring an extended design period with early input from specialist contractors. The roof fabrication and erection was on the critical path, so a two-stage tender procedure was developed by Arup and the project manager, Mace. This enabled the design team to harness specialist contractor expertise in advance of the main contractor appointment to Skanska, and allow sufficient time for detailed design, fabrication, and erection. Input from steelwork contractors and glazing suppliers to inform the design before tender gave greater confidence in the roof's feasibility and practicability, and ensured that the tender documentation allowed sufficient scope for the tenderers to incorporate their own designs.

Arup developed the atrium roof design up to tender, and submitted the design for building permit in November 2001. The design was then refined as wind and snow test results became available. The atrium roof first stage contract was awarded to Waagner Biro in July 2002, and six months' design development followed. During this stage, responsibility and "ownership" of the design remained with Arup, as did control of geometry. By the end of the first stage tender, Waagner Biro had completed an independent analysis. This was verified by Arup, who then handed over responsibility to Waagner Biro to complete the design and detailed calculations for the node connections.

Waagner Biro's specialist expertise proved invaluable, in particular its experience of the detailed design and construction of the glass roof for the British Museum Great Court in London, which has some parallels with the atrium roof, though with much simpler geometry. Arup and Waagner Biro's combined experience and expertise reassured the client that such an innovative and unusual design could be confidently designed and built on time and within budget.

Final structural design and glazing system

In parallel with the structural design, Waagner Biro developed a unique four-part silicone gasket system to support the glass panes and accommodate the wide variety of glass angles, while also providing a second line of drainage (Fig 35).

The glass design was informed by the structural loads, and by the tough performance requirements determined from Arup's CFD analysis together with the requirements of the specialist lighting designer. The sealed double-glazed panels have an outer layer of 8mm toughened glass with a "low E" coating, a gap of 16mm, and an inner layer of 16mm laminated glass (2 x 8mm). The total glazed area is 10 240m^2 with a combined weight of 555 tonnes, and 17.5km of silicone gaskets (Fig 36).

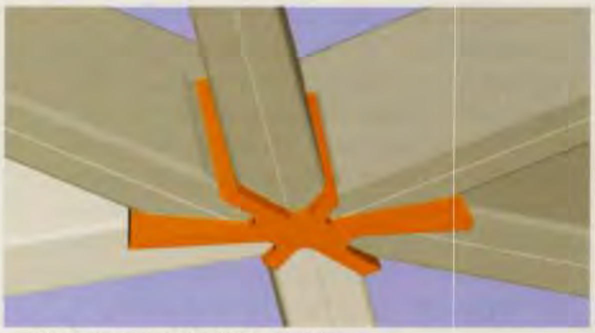
The original design was based on using structural silicone to retain the glazing, but this proved unacceptable to the Polish building authorities, so a "button" fixing was developed, with two stainless steel buttons on each side of each glazing panel to restrain the glazing (Figs 35, 37).

Following handover of final design responsibility, Waagner Biro made two small but crucial changes to the geometry. The first related to the glazing and gaskets. The original geometry had the centrelines of the six RHS members at each node intersecting at the same point, but due to differences of angle and twist between each member, this resulted in unacceptable steps in the level of the tops of the RHS members - and highly complex and expensive glazing gaskets. The geometry was subtly shifted so that at each node, the six planes of the underside of the glazing panels coincided at a single point.

This simplified the gasket details, but added another layer of complication to the steel nodes. With the centrelines of the top flanges almost intersecting, any twist in the axis of the member is magnified in the offset of the bottom flange. In addition, since the centrelines of the six members no longer intersect, extra bending moments are induced in the RHS members, the eccentricities increasing local stresses in the steel.

37. Glazing buttons.

38. Node visualization.



39. Visualization of node in position.

The other change in geometry was due to the construction process. The roof mesh was designed to be erected on scaffolding with frequent props to hold each node in the correct position. But after depropping, the roof would deflect under the steel and glazing self-weight. Waagner Biro therefore calculated a new "zero geometry". The level of each node was raised by a value equal to the predicted deflection, so that after depropping, the roof would achieve the original geometry.

The shape and design of the steel node connections were unprecedentedly complex. Many areas of the roof are like a saddle, convex in one direction and concave in the other. Achieving a smooth flow in these areas required a high degree of twisting of one RHS member relative to its neighbours. This effect was magnified by the eccentric offsets described above, so that each node became a complex three-dimensional form. (Figs 38, 39). To verify this innovative node design, Arup specified the destructive test of a sample node in September 2003 (see opposite page).

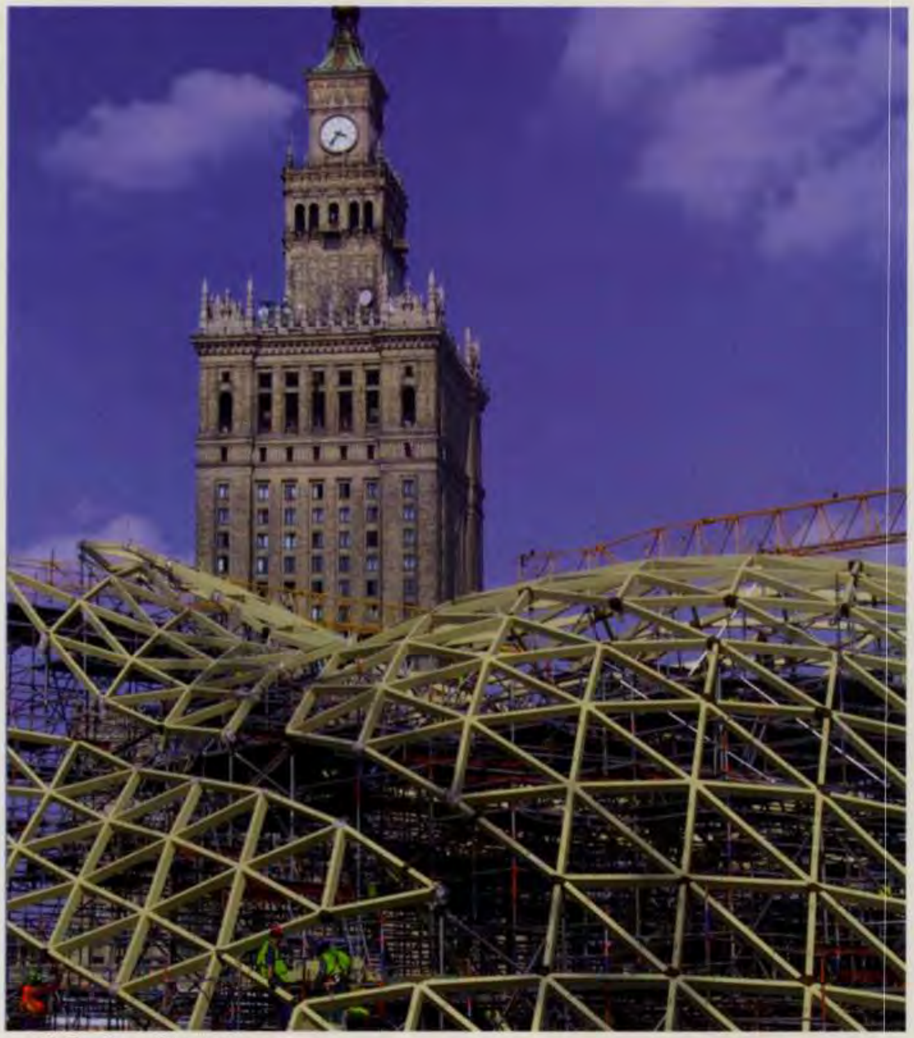
Waagner Biro's engineers developed an automated design process, whereby the geometry of every node and member could be automatically generated from the "zero geometry". Each was designed and checked for stresses from the combination of self-weight, snow loads, wind loads, thermal loads, and differential settlements.

Construction

The 630 tonnes of steel for the atrium roof were fabricated in Katowice, Poland. Having completed the final design, the geometry of every member and node was automatically passed to the fabrication workshop. To hand-cut the ends of each RHS member and node would have been prohibitively expensive, time-consuming, and probably inaccurate. Fabrication was only possible by automating the cutting process, including developing new equipment to do so. The unique pattern of each end of every member, node, and glass panel was fed from the computer model to the cutting robots and to the glass production factory.

To maximize off-site fabrication, the roof was subdivided into 129 "ladder frames", each the maximum size that could be transported to the city-centre site by low-loader. The tree columns were erected with temporary props and internal bracing between the branches, and surrounded by scaffolding. The ladder frames were then lifted onto adjustable props, connected to the trees, and set to the precise level and location of the "zero geometry". Once several ladders had been erected, the gaps between them were filled with individual "loose" RHS members, site-welded in place (Fig 40). Erection of the roof steelwork took seven months, from May to December 2004.

Glazing installation started once a sufficient area of steelwork had been fully welded and painted (Figs 36, 41). On completion of a significant area of glazing, the steelwork was sequentially depropped in small increments, then the scaffolding removed to allow following trades to start below.



40. Erection of ladder frames.

41. Glazing sealant installation.

The team recognized this early on and to counter it, emphasized adherence to the use of approved welding procedures, the use of approved welders (important for all welding, but essential for site welders as the skill requirements are greater), and supervision. One problem was that the specification for welding procedures is based on standard test pieces that do not reflect the difficulty of many connection types.

Initial teething problems were due to the lack of fit-up in assembly, before welding. Mostly this was evident during prewelding visual inspection - essential if the connection prevented the use of ultrasonics for final inspection. Typical defects included porosity, lack of penetration, lack of fusion, or cracking. Other problems arose from the incorrect use of welding consumables, and failure to preheat prior to welding. Similar problems were encountered on site, exacerbated by the additional problems of overhead welding. Nonetheless, Waagner Biro and its subcontractor overcame the difficulties and achieved the required standards of structural integrity and aesthetic consistency.

Node mock-up and testing, and weld testing

As part of the node design development, Waagner Biro made several mock-ups (Fig 43). The nodes are prominent in the finished building, so the mock-ups allowed their appearance to be approved by the architect, and any fabrication difficulties to be resolved before production started. In addition, Arup specified a destructive test to verify the design, which was far beyond the scope of normal codes and standards. This was done in September 2003 at the Technical University of Graz in Austria in the presence of Arup and Waagner Biro engineers. The mock-up comprised six RHS members welded to a node, with their far ends supported and restrained from moving while an upwards force was applied to the node by a hydraulic press. Strain gauge rosettes were attached to the top of the elements at 20 points, with strain gauges on the top and bottom side of sections close to the node and deformation readings at the joint and member ends (Fig 42).

As predicted, collapse was not through failure of the node or any of the welds, but by plastic deformation of the walls of the weakest RHS member (Fig 42). The force required was within 6% of calculation. The test not only helped verify the design, but also provided reassurance that the node connection was stronger than the members to which it was connected, ensuring considerable built-in robustness in the atrium roof. In the unlikely event of local damage to any roof member or tree, disproportionate collapse would be prevented by the stiffness of the geometry, and the strength of the nodes.

The mock-ups and testing also enabled Waagner Biro to understand the complexities and practicalities of the welding operations to come. The welding details at the nodes were of particular concern due to the differing geometries involved, making the use of precision jigs of great importance to ensure that dimensional stability and fit-up was achieved. The small number of higher strength grade S460 members required more onerous welding procedures than usual (including greater preheating) and more rigorous inspection - visual, dye penetrant, magnetic particle, and ultrasonic where possible.

The fabrication, complicated enough on the drawings, was yet more challenging in reality. Many of the connections had physical limitations, making access for welding difficult and inspection either limited or ineffective.

42. Destructive node test.

43. Partial node mock-up.

44. Looking up inside the drum from level B2.

The drum

The drum is a free-standing cylindrical tower enclosing a bank of escalators that rise from the car parking and sunken plaza at the B2 basement level right up to the food court and cinema entrance at level 3. The escalators pass up a four-storey high void in the centre of the drum (Fig 44), surrounded by a doughnut ring of floor slab at each level. This provides a major hub for pedestrian circulation right by the main entrance from the station.

The drum is framed in reinforced concrete below level 3, and tubular steelwork above. Due to the complex and sinuous interface between drum and atrium roof (Fig 45), the drum steelwork and glazing were included in the atrium roof sub-contract. The scheme design had connected the atrium roof to the drum, so that the latter could provide stability, but thermal expansion of the roof was found to induce unacceptable stresses in the drum steelwork, so the two structures were separated by a movement joint. The geometry of the atrium roof is such that at level 3, on one side of the drum people can walk through to the food court, below the atrium roof, while only a short distance away, they can see out through the drum to the roof exterior (Fig 46). This "inside-outside" feeling is repeated at other areas around level 3 where from inside the atrium, you can see through one part of the roof to view the outside of another part.

To avoid any diagonal bracing members, the drum steelwork was designed as a vierendeel frame, with fully welded connections between the columns and ring beams. The structure for the circular lid of the drum was inspired by a bicycle wheel, with radiating spokes all connecting to a central hub (Fig 44).

Building physics

The building services were designed by Tebodin in the Netherlands, but informed by building physics studies undertaken by Arup specialists in London. One major area of focus was comfort and condensation within the atrium. The atrium design studies had the following major objectives:

- environmentally, to control comfort temperatures within acceptable limits, minimize solar gain in summer, and minimize condensation risk in winter
- daylighting, to limit average light transmissions, with targets set for different regions
- architecturally, to maximize façade transparency with no fixed shading, and with low reflectance to the surrounding buildings.

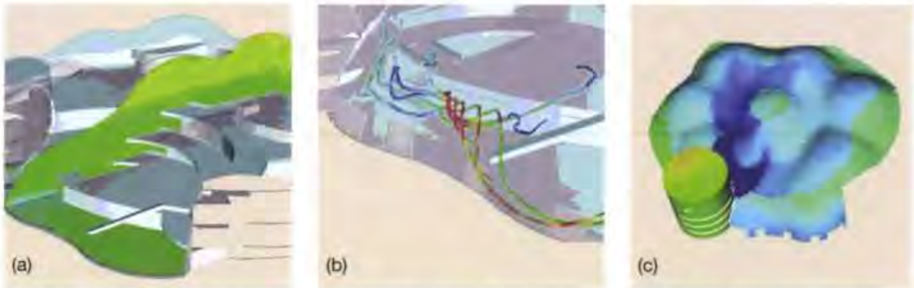
To some extent these conflicted, for example the requirement to maximize transparency while minimizing solar gains. The environmental analysis study carried out by Arup's fluids team included dynamic thermal modelling and CFD (computational fluid dynamics) (Fig 47).

Comfort study

For summer conditions, the interaction between the space and external environment had to be understood, particularly the influence of solar gain, which proved to be the most important factor. The study was then used to optimize space conditions by guiding the choice of glass and the location of the radiant floors. For winter conditions, understanding of likely comfort conditions together with the potential for downdraughts was the aim. Interactions between the perimeter heating, radiant floors, and mechanical air supply systems were investigated. The comfort study became a primary driver for the design development of the atrium space, ultimately providing confidence that internal conditions within the occupied areas were likely to be acceptable with a high-performing façade and large areas of radiant floors. By controlling solar gains, the mechanical air system was then able to maintain air temperatures to within acceptable limits.

45. Interface between the drum and the atrium cascade.

46. View from inside the drum at level 3.



47. CFD models: (a) air temperature distribution; (b) air movement; (c) difference between the dew point and surface temperatures.

Condensation study

For condensation to form, the temperature of a surface must be lower than the dewpoint of the air in the space. This often occurs on clear, cold nights with maximum radiation losses from the surface. For the atrium roof, however, the highest condensation risk is when external air temperatures are quite moderate but there is high internal humidity - a combination of high internal moisture gains and very moist air entering. This is partly due to the glazing's high thermal performance and the fact that the space dewpoint temperature is mostly dominated by the moisture content of the supply air and air transferred from the retail units. The mass of moisture gains from people in the atrium is only a small proportion of the total in the space. Taking these factors into account, the "worst case" or design scenario combined a design time of 5pm on a September day, the atrium roof fully "wetted" on a very rainy day, and 50% of the people having wet raincoats.

An innovative three-part study was carried out, comprising:

- a dynamic thermal model for the whole year on an hourly basis, to determine the design time and provide the CFD model with surface temperatures
- a CFD analysis for the design time, to assess the air temperature and moisture distributions
- a thermal bridge model at the design time, taking boundary conditions from the CFD analysis to assess the risk of condensation at the fixing bolt connection detail of the roof glazing. The CFD analysis provided realistic design moisture content levels close to the glazing for this analysis.

Assessment of condensation risk was thus possible, based on actual moisture sources, its transport, spatial, and detailed structural considerations, and the conclusion was that condensation was very unlikely.

Acoustics, noise, and vibration

The initial acoustic concern was the railway station's proximity to the multi-screen cinema and the possibility of low frequency groundborne train noises being heard during screenings. Extensive vibration measurements on the cinema site and subsequent predictions of residual noise in the auditoria indicated no need for special vibration isolation measures, despite the cinema operators' stringent background noise requirements. Rigorous standards were also set for sound transfer from cinema to cinema, down to the lowest audible frequencies (31.5Hz octave). Sound insulating constructions were recommended, based on Arup's considerable experience of cinema design. Once construction was complete, the final commissioning tests, witnessed by Polish acousticians, showed performance to be satisfactory.

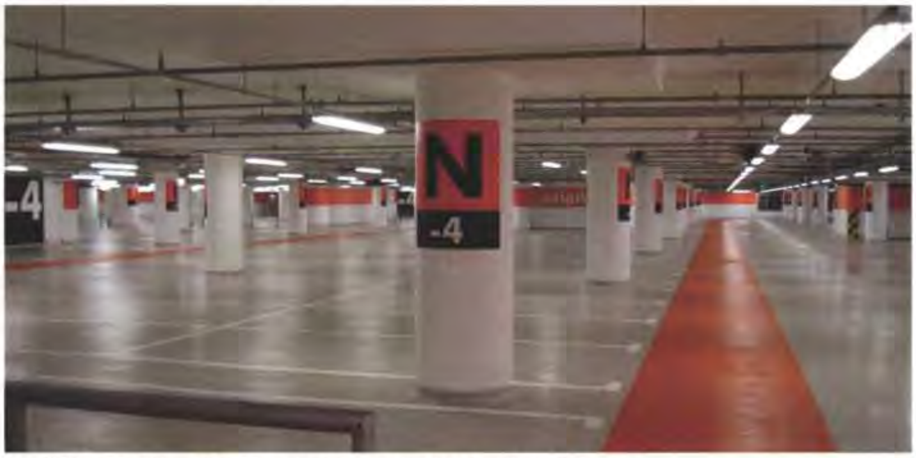
The atrium area also presented an acoustic challenge. As glass is highly acoustically reflective, such a large public space covered by a glass canopy could prove excessively noisy. Initially, Arup recommended incorporating acoustic absorption into the glazing framing, where it would have been highly effective, but this proved too difficult in practice. Instead, the absorption was located in the walkway soffits in the main circulation areas, where it controls noise locally as well as throughout the whole space.

Transport planning and pedestrian modelling

Arup's initial commission was for a transport assessment to support the principle of a mixed-use development here. A local sub-consultant, BPRW, was engaged to run a traffic model that it had developed for the central Warsaw area. This enabled Arup to formulate the access principles and advise on major improvements, including a completely new bus station integrated with the site and the railway station. The design for the new bus station was formulated, including altering the main access area and providing space for taxis and general traffic to circulate, drop off, or pick up.

Working closely with the architect, Arup advised on several additional aspects including car parking, service yard planning, signage, access issues, pedestrian planning, and detailed design and contract documents related to the car park.

Key output from the traffic assessments included advice on the quantity of car parking required. This was based on local and European experience of similar developments, most notably in Budapest, Hungary. Spreadsheet models were derived to produce daily parking demand profiles for 1600 car spaces, and potential conflict periods between the various land uses were identified.



48. Basement level B4 car park, showing the drop heads to the columns.

49. The new bus station.

Technical details determined by Arup included car park dynamics, layout efficiency, layout allocation, ramp locations, and internal flow search patterns. Arup also provided technical advice on car park equipment, eg barrier quantity and layout, payment machine quantity and location, and white line measures with pedestrian corridors. The scope of work expanded to designing a car park colour code that integrated into the architect's vertical design elements (Fig 48). The team then provided car park contract documents that included equipment schedules, white line requirements and VMS (variable message signs) proposals. Detailed signage proposals were produced for each level of car parking both for vehicles and for pedestrians accessing the lifts to the various areas above.

In addition, Arup advised the architect on internal pedestrian movement requirements between the levels and within each level. Daily footfalls were determined and converted into hourly profiles for each level. Based on experience elsewhere, shared trips for various level uses were established. A pedestrian flow model was built using *Saturn* software and spreadsheets, and applied to *FRUIN* pedestrian planning software to determine the levels of service at key locations throughout the building. This enabled Arup to advise on entry widths for doorways, escalator numbers, corridor widths, and staircase requirements.

Detailed highway designs were provided for the adjoining network, which also integrated with proposals for nearby land usage. Integrating Arup's proposals with the bus station and railway station was very challenging, as the area available for the bus station was very limited (Fig 49). Much consultation was required with the local highway authority, ZDM, other developers in the area, and local bus operators.

Façade engineering and stone selection

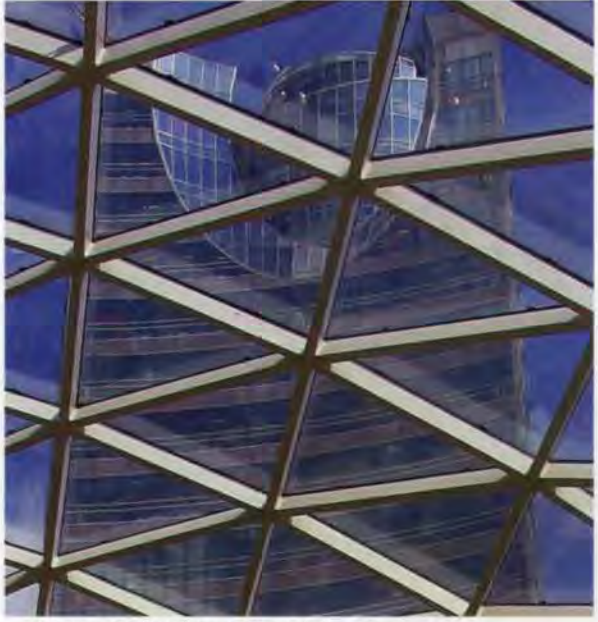
Working closely with the architect to enable the concept design to be realized into a readily procurable building envelope, Arup's façade team used its knowledge of manufacturing techniques and procurement options to fine-tune the geometry to allow repeatability of panel size on the curtain walls for the three office buildings, and for the "icon" feature at the top of the "Skylight" tower (Fig 11). For the cinema foyer's "popcorn windows" (Fig 50), the team helped the architects to rework a complex design with tricky interfaces into a robust and readily installable system that was aesthetically acceptable, controls staining from water run-off, and allows easy glass replacement.

Arup's extensive knowledge of materials and building envelope physics also helped with the optimum specification of envelope materials. The resulting documentation reduced the normal tender stage risks, due to the clarity of design intent, performance requirements, and co-ordination with structural and mechanical systems.

In 2002 Arup stonework specialists became involved in pre-tender design discussions with the architect, who visualized three different types of coloured stone as part of the external cladding. Notably important were technical assessment of the materials, the guidance on sensible panel sizing and thickness, the methods of fixing the stone to the structure, and various detailing issues such as water run-off and staining, as sandstones are relatively porous and susceptible to deterioration through frost damage or visual degradation from biological growth. The stonework package went out to tender on the basis of using three sandstones and a granite.

In 2004, the curtain walling sub-contractor asked Arup to help assess and select the stone, as it had limited experience in projects with stone cladding. The team visited eight quarries - three in south-west Poland for yellow sandstone, two in the Beskid Śląski region in south Poland for green sandstone, and three in the Mainz region, south-west of Frankfurt, for red sandstone – and assessed them for extraction methods, achievable panel sizes,

50. "Popcorn windows" on the cinema foyer façade.



51. The "Skylight" tower through the atrium roof.

52. The five construction zones.

stone availability, and production quality and output at their works. All this helped the subcontractor agree a realistic visual range for each stone with the supplier and architect.

Construction

Enabling works

The first major task was to relocate the bus station onto the front platform deck of the railway station. The enabling works included strengthening the station structure, new roads and bus platforms, and two rows of cantilevered glazed canopies (Fig 49). Also needed were relocation of two enormous air exhaust ducts from the station, numerous service diversions, and demolition of several old viaducts and other structures within the site boundary. All this allowed the whole site to be handed over to the main contractor at the end of 2002.

Construction sequence

This was carefully developed by Skanska to minimize the overall programme. The lines of the previously-described movement joints in the basement and retail levels delineated five zones (Fig 52). Skanska chose to start in zone 3 (under the cinema) and zone 5, then zone 4 (under the "Skylight" tower), then zone 1, and finally zone 2. When concrete construction had reached level 3 in zones 3 and 5, and the atrium roof erection had started, the concrete slab at level 0 was still not complete in zone 2. The structural concrete works were practically completed in May 2005, while the cinema steelwork, above level 3, had not yet begun, due to revised permit issues. Cinema steelwork erection began in August 2005 and was completed in May 2006.

Construction methods

At the peak of construction the programme necessitated over 1000 workers on site. Skanska used up to seven tower cranes, including one on tracks at level 0, with temporary props down to the foundations. Apart from the atrium roof construction described earlier, several other unconventional construction methods were used, including temperature control of large concrete pours, the use of special formwork, and the partially post-tensioned beams referred to above.

Temperature control was crucial for the raft foundation, and for the transfer slab at level 3. Due to the scale, areas of the raft were cast in different seasons – some in winter, some summer. The raft concrete was poured in bays up to 650m^2, using a special low-energy mix with furnace-ash cement replacement, and the concrete was wrapped in thick thermal insulation until it had cooled. The temperature was closely monitored in each pour to ensure that the maximum temperature gradients were not exceeded; despite the summer heat, no internal cooling was required.

Arup's careful reinforcement detailing for the sloping car park surfaces, together with a thorough curing system, resulted in crack-free concrete for the car parking areas. For the level 3 transfer slab, due to a shorter overall casting time and the longitudinal shape, gaps were left in the slabs to allow for short-term shrinkage.

Special formwork was needed for several unusual elements such as the banana columns. An automatic self-climbing formwork system was used for the core of the "Skylight" tower, and a semi-automatic one for the "Lumen" office block cores.

International working

A key feature was the close co-operation of the design team, despite being spread over 20 different offices. The project could not have been accomplished without the internet, which enabled designers in six countries to work closely together; Arup's designers in Birmingham and London were linked to Jerde in Los Angeles, Epstein in Chicago, Tebodin in Holland, RWDI in Canada, and Waagner Biro in Austria, as well as the Warsaw offices of all the consultants, the client ING, and all the contractors. From the outset, Arup had a resident project manager and two assistants in the site office. During the first 28 months of the contract, Arup issued over 5400 structural and reinforcement drawings and 360 sketches - an average of nine drawings a day. The Arup team was closely involved at every stage of construction, reviewing over 1000 submittals from Skanska, to ensure compliance with the specification.

From 1998, when the first workshop was held in Jerde's offices in Los Angeles, frequent design workshops, often lasting several days, brought together all of the design team. These were key to establishing a collaborative partnership approach, and a vital source of inspiration, creativity, problem-solving, and trouble-shooting, enabling complex issues to be addressed and resolved as rapidly as possible. They also proved a vital way to communicate the design with ING. Particularly with complex elements such as the atrium roof and the transfer structures, these workshops allowed Arup to explain the design issues and reassure ING as to the feasibility of design and construction.

Arup exemplified the design-sharing approach for the atrium design, by making available free software to the whole team. The *GSA* viewer enabled the team and the specialist contractor to view the same set of data, including the geometry and all the loading data as well as the results of the analysis. This proved invaluable in the design workshops as well as in detailed design.

Mace, the project manager, was also instrumental in arranging the early involvement of contractors and suppliers to inform the design at key stages before tendering. This was particularly important for the atrium roof, where input from glass suppliers and specialist steel fabricators had a major influence in shaping the design to achieve the most cost-effective solution.

Another reason for the project's success was electronic data transfer, as the complex geometry would have made manual transmission of data a potential source of errors. Mutually compatible software allowed the same set of co-ordinates for the atrium roof to be shared among all the designers. The geometry was originally generated by Jerde in Los Angeles, taken by Arup in Birmingham and developed into a workable structural model, and then transferred to Waagner Biro in Austria, adjusted for fabrication, and fed directly to the workshops in Poland.

See&Share software enabled Arup staff in any office to share their computer screens with each other, or with those outside the firm. Any party can mark comments on the screen in real time with a mouse. This was particularly useful for the atrium design. Trying to describe a 3-D object with 2-D drawings and sketches is extremely difficult, but *See&Share* allows a phone conversation with simultaneous on-screen showing of what is being discussed.

53. Atrium escalator, with "Lumen" office block beyond.

Completion and opening

In summer 2005, as the atrium roof was nearing completion, a film was made about the project by the Discovery Channel. When interviewed about the atrium roof, Eugene Houx, then the project developer and a former board member at ING Real Estate, said: "If I look back at those long days when we were discussing the atrium roof with the people involved, from Arup, Jerde Partnership, and later with Waagner Biro, then those moments now seem to me very special. Because at that moment we were working very hard, and we didn't know if it would come true. But we also realized that it was going to be a very special roof. It had the full engagement, the enthusiasm, the intuition, and the ingenuity of a lot of people - especially the engineers, the architects, and many others. At this particular moment, we can start to see what it looks like. It's becoming reality. It's not a strange idea any more on the drawing board, and we are very happy with the way it looks, and what it is doing for this project. We think the roof has fulfilled several functions. It has become an icon for this part of the city. It might become an icon for Warsaw, a symbol for the new Warsaw, that is renewing, innovative, avant-garde, and looking into the future".

Złote Tarasy opened on 7 February 2007, with 100% occupancy of all retail units, over 200 000 visitors on the opening weekend, and almost 8M in its first six months. The project's success was summed up by Marcel Kooij, Deputy Director of ING Real Estate and President of Złote Tarasy's Management Board:

"ING Real Estate aimed to create the hallmark of the city of Warsaw, a new "living room" and a meeting point for the inhabitants, and thus breathe new life into the capital's city centre. After over half a year since opening, I can proudly say that Złote Tarasy came up to all these expectations. The success of this exceptional retail and leisure scheme should be attributed to several factors, related to its offer, functions, architecture and unique atmosphere. But also the role of Złote Tarasy in terms of improving the infrastructure, influencing the local job market, and stimulating the development of the city's central district must not be forgotten.

"Over 200 renowned Polish and international brands opened their flagship stores in Złote Tarasy, newcomers to the Polish market like Next, MAC and The Body Shop decided to start their expansion in Poland from our project, and over 30 restaurants, cafes and music clubs such as Hard Rock Cafe or Jazz Club Akwarium have opened here. All these examples show that Złote Tarasy is important for both Polish customers and international businesses.

"Every attention was put to the urban planning and architecture. The undulating 1ha glass roof, illuminating the interiors 365 days a year, has already become a Warsaw hallmark. The design team and contractors did a marvellous job in creating this hallmark.

"Złote Tarasy is an important investment for the city of Warsaw. It has revitalized the 3ha area dominated by road traffic and parking next to the Central railway station, created over 2000 new jobs, and has been supporting charities and local organizations. Złote Tarasy is meant to be "the stone in the pond" that triggers other developments in the neighbourhood and helps to create a modern city centre next to the central business district.

"The mixed-use project is also an integral part of Warsaw's CBD. Highest quality office space is provided by two office buildings rising above the shopping centre - Lumen and Skylight. The Lumen tower gracefully frames Złote Tarasy in the north, while creating a new icon for Warsaw. As the arc of the tower rises, it widens to open the interior of the workspaces up to natural light. Skylight is the distinctive element of the CBD skyline. It fits perfectly into the sequence of hotel and office blocks along ul Emilii Plater and is visible from all the main roads leading to the centre. At the same time its architectural details, such as the icon on the side façade and elegant curves, make it one of the most original buildings in the capital.

"Złote Tarasy is a unique combination of retail, leisure and offices. The centre's popularity among clients and the interest of the tenants proves that we have achieved our goal."

54. The cascade.

Credits

Client: ING Real Estate **Concept architect:** The Jerde Partnership **Executive architect:** A Epstein & Sons International **Project manager:** Mace **Cost consultant:** Gardiner & Theobald **Structural, transport planning, pedestrian modelling, building physics, acoustics and façade engineer, and stonework consultant:** Arup - Darren Anderson, Keith Beckett, Rabinder Singh Bhachu, Christine Blanch, James Bodicoat, Nick Boulter, James Boyes, Tom Brooks, Chris Bruce, Michelle Butler, Duncan Campbell, James Casson, Chris Chan, Wayne Charles, Gurpreet Chawla, Stuart Clarke, Matt Collin, Adrian Collings, Keith Crothers, Zbigniew Czajewski, Piotr Czapko, Marek Dabrowski, Iain Dick, Rafał Duszczyk, Ian Feltham, Damian Friel, Hanna Gadzalska-Syfert, Paul Geeson, Yvonne Griffin, Jagienka Harrison, Christina Jackson, Richard Jackson, Piotr Jez, Tony Jones, Marcin Karczmarczyk, Marcin Kasprzak, Olga Kasprzak, Richard Kent, David Killion, Andrzej Kocmierowski, Zbigniew Kotynia, Radosław Krzeminski, Andrew Lambert, Isabelle Lavedrine, Maciej Lewonowski, Robert Lindsay, Monika Malczewska, Bartek Małetka, Piotr Marszałek, Pieter Mattelaer, Andrew McCulloch, Martin McGrellis, Edyta Miazga, Andrew Minson, Philip Monypenny, John Moss, Edith Mueller, Chris Murgatroyd, Paweł Norek, Andew Norrie, Johnny Ojeil, Paweł Opolski, Raf Orlowski, Chris Parsons, Barbara Pawełek, Ewa Pawlak, Shokrollah Pilwar, Krzysztof Pogłód, David Preece, Barbara Próchniewicz-Pudełko, Piotr Rebajn, Jag Riat, Tomasz Rybus, Neil Scott, Jeff Shaw, Roy Shields, Peter Simmonds, Tristan Simmonds, Annalisa Simonella, Brian Simpson, Andrzej Sitko, Simon Small, Lee Smith, Artur Soluch, Joanna Swiderska, Sebastian Szafarczyk, Sławomir Szumierz, Rob Talby, Ian Thompson, Tim Thornton, Andy Thorpe, Richard Thurlow, Jon Toy, Wiesława Trochymiak, Alan Turner, Martin Vanicek, Jared Waugh, Mel West, Paweł Wewiór, Hilary Williams, Darren Woolf **Sub-consultants:** ProjArt (structural) Billings Design Associates (façades) BPRW (transport planning) Prof Wojciech Wolski/Geoteco (Polish code and technical review/advice: geotechnics) Dr Jerzy Żurański (Polish code and technical review/advice: wind and snow issues) **Site supervision:** SAP-PROJEKT **Main contractor:** Skanska **Atrium roof contractor:** Waagner Biro Stahlbau AG with Zenkner & Handel (atrium design) and Zeman HDF (atrium fabricator) **Sub-contractors:** Exbud (northern half concrete; cinema and "copper houses" structural steelwork) Hydrobudowa 6 (southern half concrete) Freyssinet (northern half post-tensioning) BBR (southern half post-tensioning) Salgeo (piling) Soletanche (diaphragm walling) Permasteelisa (office blocks and cinema façades) Axima (M&E installation) Scheldebouw (curtain walling) **Illustrations:** 1-2, 15, 18, 38-39, 54 Waagner Biro; 3, 5, 14, 24, 52 Arup/Nigel Whale; 4, 6-7, 10, 36, 41 ING Real Estate; 8, 11, 20-22, 25-26, 30, 33-34, 40, 47, 50 Arup; 9, 16, 27, 44-46, 51, 53 inblanco.pl; 13, 19, 23, 31-32, 37; Richard Kent; 12 Tomasz Szymanski/ iStockphotos.com; 17 Jerde Partnership; 28-29 RWDI; 35 Waagner Biro/Nigel Whale; 42-43 Marcin Karczmarczyk; 48-49 Radosław Krzeminski.

Awards

MAPIC Plaza Retail Future Project Awards 2005: Best of Show, and Best Large Retail Development Scheme

Institution of Structural Engineers (IStructE) Midland Counties Branch: Structural Commercial Project 2005 Award for the atrium roof

Architectural Review MIPIM Future Project Award 2006, Retail and Leisure category

European Convention for Constructional Steelwork 2007 European Steel Design Award

IStructE Structural Awards 2007: nominated for Commercial or Retail Structures

MAPIC Awards 2007: Best New Shopping Centre.

Darren Anderson is a senior geologist with Arup's Façades London Group. He provided specialist input for the building façades, particularly on the stone selection.

Zbigniew Czajewski was formerly a structural engineer in the Warsaw office. He was involved throughout the project, as a structural engineer, then as the design and construction co-ordinator, and finally as Arup Project Manager for the final phase.

Stuart Clarke is an Associate of Arup and now leads the Façades Group in Dubai. He was responsible for the façade engineering.

Ian Feltham is an Associate Director of Arup with the Advanced Technology & Research Group in London. He provided specialist technical input on second-order effects for the structural design of the atrium roof.

Paul Geeson is a Director of Arup and leads the Warsaw office. He was the Project Director throughout.

Marcin Karczmarczyk is a senior engineer with Arup in the Building London Advanced Geometry Unit. Formerly in the Warsaw office, he was responsible for the detailed analysis and design of the atrium roof.

Richard Kent is an Associate of Arup in the Building Midlands Group, and was responsible for the atrium roof concept and detailed design from inception to completion.

David Killion was formerly an Associate of Arup in the Warsaw office. He was the Arup Project Manager for the project until 2004, with the main responsibility for managing and co-ordinating the input of the numerous Arup disciplines and offices.

Zbigniew Kotynia is an Associate of Arup and a senior structural engineer in the Warsaw office. He was the structural team leader for the detailed design of the foundations and substructure.

Maciej Lewonowski is an Associate of Arup and a senior structural engineer in the Warsaw office. He was structural team leader for the detailed design of all the superstructure concrete and steelwork design.

Robert Lindsay is an Associate of Arup with the Gulf Group in Abu Dhabi. He was the structural engineer responsible for the concept and scheme design of the foundations and substructure.

Philip Monypenny is an Associate of Arup in the Building Midlands Group. He was the structural engineer responsible for the concept and scheme design of the superstructure.

Chris Murgatroyd is an Associate of Arup in the Materials Consulting London Group. He provided specialist input on materials and welding for the atrium roof steelwork.

Johnny Ojeil is a Director of Arup in the Infrastructure and Planning Midlands Group. He was the team leader for the transport planning input to the project.

Raf Orlowski is an Associate Director of Arup in the Acoustics Group in Cambridge, UK, and provided the acoustic input to the project.

Andrzej Sitko is a Director of Arup in the Warsaw Office, and was responsible for overseeing the structural engineering design throughout the project.

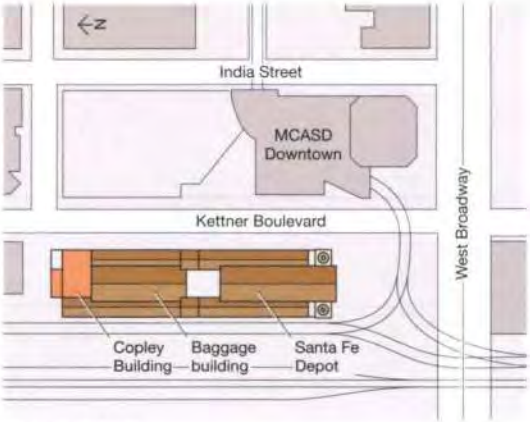
Darren Woolf is an Associate Director of Arup in the Building London Environmental Physics Group, and was responsible for the building physics studies, including the CFD modelling.

1. The MCASD Downtown extension, showing the Copley Building on the left, the Jacobs Building in the centre, and the 1001 Kettner Boulevard premises behind.

MCASD Downtown expansion:

The Joan & Irwin Jacobs Building and the David C Copley Building

Peter Berry Jeffrey Huang Ricardo Pittella



2. Location plan.

San Diego's new cultural landmark includes extensive exhibition spaces in a refurbished 1915 baggage handling building.

Introduction and background

Recent renovation and new premises have given the Museum of Contemporary Art San Diego's MCASD Downtown facility more than 16 000ft^2 (1490m^2) of exhibition space – including large light-filled galleries in which site-specific work can be presented - plus a new lecture hall and education room for hands-on, interactive art activities.

Originally founded as The Art Center in 1941, the MCA's main site is at La Jolla, in what was once the residence of Ellen Browning Scripps (1836-1932), the millionaire philanthropist and educator. This historic building, designed by Irving Gill and completed in 1915, was renovated and expanded in 1996. In San Diego itself the Museum has the MCASD Downtown satellite facility at 1001 Kettner Boulevard, but this had always suffered from limited gallery space, so the search was on for expansion alternatives. These included the nearby baggage building that adjoins the city's well-known Santa Fe Depot, facing Broadway near San Diego Bay. Both buildings were designed by Bakewell & Brown of San Francisco in the Mission-Spanish Revival style, and originally opened in time for San Diego's 1915-1916 Panama-California Exposition.

The Depot remained in continuous use ever since and is, with the baggage building, listed on the National Register of Historic Places. In the 1960s, however, the baggage building ceased to be used for its original function, and became empty. Its grand spaces, bathed in natural light from a clerestory and huge arched windows, were successfully used by the Museum's former chief curator for several temporary installations. These captured the attention of both the public and the redevelopment authorities a dozen years ago, and so the city's Redevelopment Agency asked the Museum to undertake the restoration and renovation of the baggage building as permanent exhibition space in addition to that already in use at 1001 Kettner Boulevard.

To design the project, the Museum chose Milford Wayne Donaldson, FAIA, a San Diego-based preservation architect (who subsequently left to become California's state historic preservation officer) and Richard Gluckman, FAIA, of Gluckman Mayner Architects PC of New York. In 2002 Gluckman Mayner commissioned Arup to provide SMEP, fire, and IT engineering services.

Donaldson's successor firm, Heritage Architecture & Planning, restored the exterior of the baggage building (now named the Joan & Irwin Jacobs Building, after the scheme's principal sponsors), and worked with Gluckman to keep the interior renovations, including seismic retrofit, to a minimum. To leave the maximum area possible for art and new media installations, the Museum demolished an adjacent non-historic railway building and replaced it with the new three-storey David C Copley Building (again named for a principal sponsor), a 13 680ft^2 (1271m^2) addition for offices, education rooms, meeting space, and Amtrak storage. All this was achieved with just $9.75M from donors (even so, a larger sum than the original, unrealistic, 2002 budget figure). The international lineup of commissioned and opening artists included Eija-Liisa Ahtila, Roman de Salvo, Jenny Holzer, Ernesto Neto, Richard Serra, and Richard Wright.

Copley Building structure

The new three-storey addition was designed to be structurally independent from the baggage handling building, which was seismically upgraded by others at the time of Arup's design work. (The seismic upgrade comprised a new complete roof diaphragm connected to the existing masonry walls, which were reinforced with 4in (100mm) of shotcrete. Arup's structural work for this building was to remove the existing slab on grade and replace it with a new doubly-reinforced concrete slab designed to support heavy sculptures.)

The Copley Building was conceived as a steel frame with reinforced concrete shear walls to resist lateral loads. The floor structure is lightweight concrete topping on composite metal decking spanning between composite beams and girders, in turn supported either by wide steel flange columns, structural steel tubular columns, or the stair concrete shear walls.

The design of the lateral load-resisting system was challenging, due to the high seismic loads and the restrictions on location imposed by the architectural design with its reduced floor plate area. Braced frames or shear walls were unacceptable along the building perimeter, which resulted in the two stair shafts - the only possible place for the lateral load-resisting system - having to be built as reinforced concrete shear walls. The stairs are in the south of the building, and thus eccentric relative to its centre of mass, resulting in a structure with a dominant torsional behaviour. To resist the torsion, the shear walls around the stair shafts were designed as reinforced concrete boxes (Fig 3) attached to the foundations, which were large diameter caissons connected by a thick reinforced concrete pile cap.

The seismic design was initially done in accordance with the requirements of the California Building Code and then subsequently checked using a performance-based design and a modal analysis to confirm that the large torsional behaviour had been properly considered.

All concrete floors and the stair concrete shear walls are architecturally exposed concrete. Despite the large amount of reinforcement, the contractor achieved very good results, even when shotcrete had to be used to build concrete walls that were tight against existing masonry piers, which could not support the wet weight of concrete.

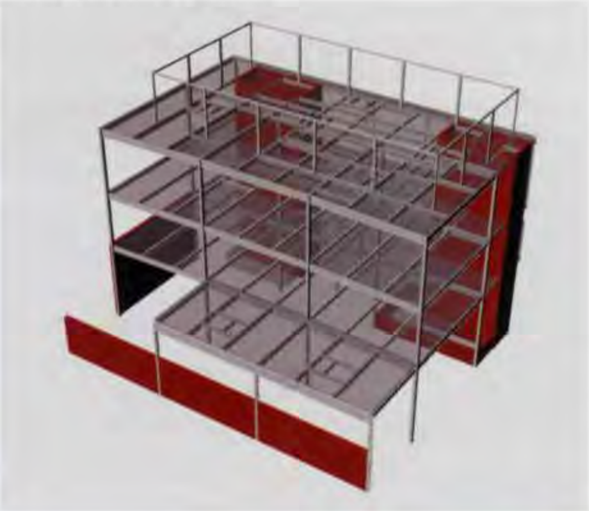
Mechanical system design

The Copley and Jacobs Buildings share a rooftop mechanical heating and cooling system. Its design was constrained by the existing historic structure and by limited roof space due to municipal setback requirements. However, with careful planning and co-ordination with the architect and contractors, the mechanical system was seamlessly integrated into both the old and new buildings.

Copley Building

As well as perimeter cellular offices and open interior work areas, the new building has a large teaching classroom on its second floor and a conference room on the third floor. These are used for both formal and informal gatherings, often with high occupancy densities. The building's external glazing comprises large sheets of floor-to-ceiling laminated glass that allow natural daylighting without mullions, and a large vertical swath of channel glass on the east entrance façade.

3. Copley Building structure.



4. The front entrance.

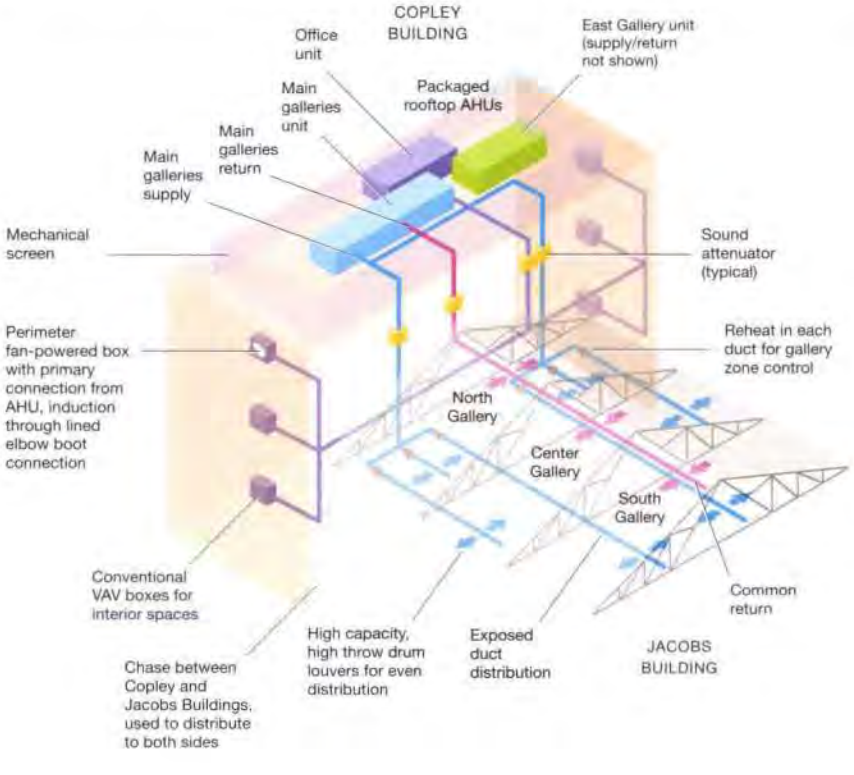
Although San Diego's Southern California location requires a design cooling temperature of 85°F (29.4°C), the design heating temperature is 44°F (6.7°C). Given the likelihood of discomfort due to downdrafts from the large glazing areas and the low outdoor design temperature, fan-powered boxes serving the perimeter zones draw in ceiling air, ensuring that it is delivered down to the floor in the winter without requiring active reheat within the terminal devices, and thus reducing the reheat energy costs. Interior zones are served by conventional, cooling-only, variable air volume (VAV) air-handling units (AHUs). This design also allowed Arup to avoid the cost and complication of a water-based reheat system. Primary air to the fan-powered boxes is through a roof-mounted VAV AHU with factory-mounted VFDs (variable-frequency drive) and full economizer capability (Fig 5).

Jacobs Building main galleries

It was an architectural priority to retain and maintain the baggage building's dramatic, light-filled, double-height space. This necessitated exposing the original truss structure that supports the roof, which in turn meant that the exposed ductwork had to be carefully threaded through it. The bare finish of the ductwork juxtaposed with the structural trusses de-emphasizes the mechanical HVAC system's separateness from the building, while retaining the industrial feel of the building's original use. The elevated air distribution within the structural zone provides clean lines for the exposed ceiling space, and allows for flexible partitioning and distraction-free gallery space below.

The main galleries are served by a dedicated, constant volume AHU with four scroll compressors running the zero ozone-depleting refrigerant R407-C and hot gas bypass to finely control the cooling capacity. Heating is through a high turndown gas burner. Carbon-impregnated filters were included to remove diesel odours from the working Amtrak trains directly west of the building. Ductwork, including sound attenuation and acoustic lining, is distributed from the top of the Copley Building back into itself and the Jacobs Building through the shaftway between the two buildings, which also provides seismic isolation between them (Fig 5).

5. Mechanical system design for Copley Building and Jacobs Building main galleries (not to scale).



Each of the three galleries is zoned through separate branch ducts, and air is distributed through high volume drum diffusers installed on the exposed spiral duct. This directs the flow of air towards the clerestory glazing to manage the heat loads and create a well-mixed environment.

The size and location of the ductwork had to be carefully co-ordinated. The shotcrete walls that separate the galleries were poured prior to any work for the Copley Building. The ductwork exists as a continuous element to serve the three main galleries, thus requiring core holes penetrations through the walls. These were drilled before any ductwork was on site, but had to be carefully measured so that the ductwork could thread through the trusses and the predrilled holes without requiring any offsets or transitions to maintain a consistent appearance.

Jacobs Building East Gallery

The East Gallery was designed as a closely controlled space to house art that needs a highly stable environment. As the condition of the original façade – to be kept due to its historical significance - was unknown, and to reduce the effects of solar gain and air infiltration, the East Gallery was designed as a fully enclosed box within the building; the close control conditions would have been impossible without decoupling the existing building from the new conditioned space. Small cavity pressurization ducts were included between the existing façade and the new East Gallery walls to help mitigate uncontrolled infiltration air ingress from the more naturally "leaky" windows and frames.

The East Gallery is served by a dedicated constant volume AHU on the Copley Building roof, with a similar set-up to the main gallery unit. In-duct electric reheat coils and an in-line humidifier trim the discharge air from the unit to provide the desired conditions within the space through triple-redundancy temperature and humidity sensors. Although the calculations had to comply with California's stringent energy code, the historic Jacobs Building and the associated galleries were exempt from those specific "Title 24" requirements.

Although the mechanical system had a dichotomy of constraints - the concealed but congested services in the Copley Building as opposed to the exposed and expansive distribution in the Jacobs Building - careful collaboration with the architect and co-ordination with the contractor allowed the realization of a system that met the client's diverse needs.

6. Typical gallery in the Jacobs Building.

Audiovisual design

The AV design for the MCASD expansion focused on three main areas. Firstly, the Jacobs Building galleries were provided with high quality sound reinforcement systems, as well as cabling infrastructure designed to allow easy deployment of portable AV presentation equipment. The design of the sound system for the main gallery was challenging, as the space has a high ceiling and is designed to be configured in various orientations depending on use. Arup's original design used distributed overhead-mounted loudspeakers, but this scheme was later revised to use movable "line array" column loudspeakers for better speech intelligibility (Fig 7).

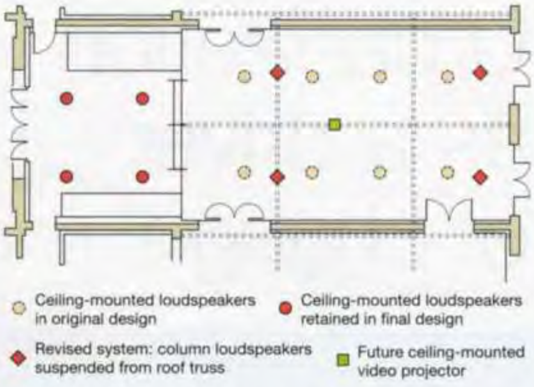
Secondly, the Copley Building classroom was designed as a fully equipped presentation space, with video projection, speech reinforcement, and stereo "program" audio systems, used in conjunction with the video projection. This room is used for a range of presentations, so a comprehensive remote-control system was provided to allow simple operation of all the AV equipment in the room. Finally, the conference room, smaller and intended more for internal usage, also has AV presentation equipment.

The galleries and the classroom include wireless "assistive listening" systems for the hard-of-hearing. The provision of these systems is mandatory in the USA under the Americans with Disabilities Act in places of assembly with fixed sound reinforcement systems.

ICT design

The information and communications technology infrastructure include a structured cabling system compliant with the *TIA/EIA-568-B* standards, dating from 2001, of the US Telecommunications Industry Association, a 1998 offshoot of the Electronic Industries Alliance. The design includes a main telecom room, satellite distribution closet and entrance facility, as well as risers to connect these rooms together.

Telecom outlets are strategically located in the galleries to allow them to be used both for voice/data and for distribution of other signals. This is done in conjunction with media converter devices known as "baluns" that enable signals that would otherwise require discrete, shielded cable (such as high-resolution computer graphic RGBS signals) to utilize the unshielded twisted pair (UTP) cable provided for voice/data. This design approach provides great flexibility for configuring exhibits, and has also been used in other USA museum projects engineered by Arup (eg Seattle Art Museum, the Muhammad Ali Center, Louisville, and the new Museum of Contemporary Art in New York).



7. Original and revised sound system for the Jacobs Building galleries.

Conclusion

The Jacobs and Copley Buildings have transformed MCASD's capability to present new artworks on a very large scale, as well as providing a new lecture hall and education room for hands-on, interactive art activities.

The project's success was due to the client, construction manager, design team, and contractors working together to solving the various design and construction issues. Although sustainability was not a formal objective, the end result incorporates sustainability principles in its positive contribution to culture and the community, and minimizes embodied impacts due to the adaptive re-use of the baggage building.

Peter Berry is an Associate of Arup in the New York office. He led the audiovisual and IT design for the MCASD expansion project.

Jeffrey Huang a senior engineer with Arup in the New York office. He led the mechanical engineering design for the expansion project.

Ricardo Pittella is an Associate Principal of Arup in the New York office. He was Project Manager for the MCASD expansion project.

Credits

Owner: Museum of Contemporary Art San Diego
Architect and client: Gluckman Mayner Architects pc
Construction manager: HR Weatherford Company
SMEP, audiovisual and ICT designer: Arup – Alex Acero, Leo Argiris, Peter Berry, Ho-Yan Cheung, Petronella Digeratu, Jeffrey Huang, Ivan Jelic, Fathi Kashkoush, Diego Lozano, Andrew McNeil, Aidan O'Dwyer, Ricardo Pittella, Emma Shepherdson
Main contractor: Rudolph & Sletten **Illustrations:** 1, 4, 6 David Heald; 2, 5, 7 Nigel Whale; 3 Arup.

Urbanization as a driver of change

Susan Thomas

Introduction

Urbanization is defined in most dictionaries as the process of growth in the proportion of a country's population living in urban areas.

The 20th century witnessed rapid world urbanization, with the global urban proportion rising from 13% in 1900 to 49% in 2005. In terms of numbers this is a change from 220M urban dwellers in 1900 to 3.3bn in 2007 –a 15-fold increase[2].

This article looks at what has caused this change and what it may mean to have half the world's population living in urban areas – a proportion that is set to increase. It follows previous *Arup Journal* articles[3-7] that have examined energy, water, climate change, demographics, and waste in a series looking at the "Drivers of Change" identified by Arup's Foresight Group.

> "The growth of cities will be the single largest influence on development in the 21st century."[1]

Key urban statistics

Currently:

- Half the world's 6.6bn population live in urban areas – 1bn in more-developed countries, and 2.3bn in less-developed countries.
- Half the urban population live in settlements of fewer than 500 000 people, while megacities house only 9% of urban inhabitants.
- One out of every three urban dwellers lives in slum conditions – 1bn people.
- The urban population increases by 200 000 people every day, more than 70M people a year.

Forecasts for 2050:

- 70% of the world's population will be urban - 6.4bn people.
- The towns and cities of the less-developed world will make up 83% of urban humanity.

Table 1. "Urban" definitions from selected countries[9].

Africa	South Africa	"places with some form of local authority"
	Tunisia	"population living in communes"
	Zambia	"localities of more than 5000 inhabitants, the majority of whom depend on non-agricultural activities"
North America	Greenland	"localities of 200 or more inhabitants"
	Nicaragua	"administrative centres of municipalities and localities of more than 1000 people with streets and electric light"
	United States	"agglomerations of 2500 or more inhabitants, generally having population densities of 1000 persons per square mile or more"
South America	Chile	"populated centres which have definite urban characteristics such as certain public and municipal services"
	Ecuador	"capitals of provinces and cantons"
	Peru	"populated centres with 100 or more dwellings"
Asia	Cambodia	"towns"
	China	"cities only refer to the cities proper of those designated by the State Council"
	Japan	"50 000 or more inhabitants with 60% or more of the houses located in the main built-up area and 60% or more of the population engaged in manufacturing, trade or other type of urban business"
Europe	France	"communes containing an agglomeration of more than 2000 inhabitants living in contiguous houses or with not more than 200m between houses"
	Denmark	"localities of 200 or more inhabitants".

Definitions

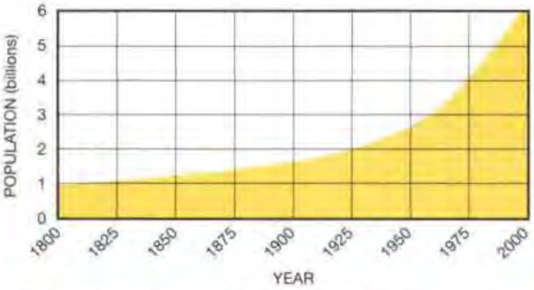
While there is general agreement that urbanization is growth in the proportion of a country's population living in urban areas, there is less agreement about what constitutes an urban area – and there is no common definition of the word "urban". Different criteria and methods are currently used by governments to define urban, as noted in the UN-HABITAT report on the state of the world's cities 2006/7[8]:

- In 105 countries, urban data are based on administrative criteria, limited to the boundaries of state or provincial capitals, municipalities, or other local jurisdictions. In 83 countries this is the sole method of distinguishing "urban" from "rural".
- In 100 countries, cities are defined by population size or population density, with minimum concentrations ranging broadly from 200 to 50 000 inhabitants. In 57 countries this is the sole urban criterion.
- In 25 countries economic characteristics are specified as significant, though not exclusive, in defining cities – typically the proportion of the labour force employed in non-agricultural activities.
- In 18 countries the availability of urban infrastructure is counted in their definitions, including the presence of paved streets, water supply systems, sewerage systems, or electric lighting.
- In 25 countries there is no definition of urban at all.
- In six countries the entire population is regarded as urban.

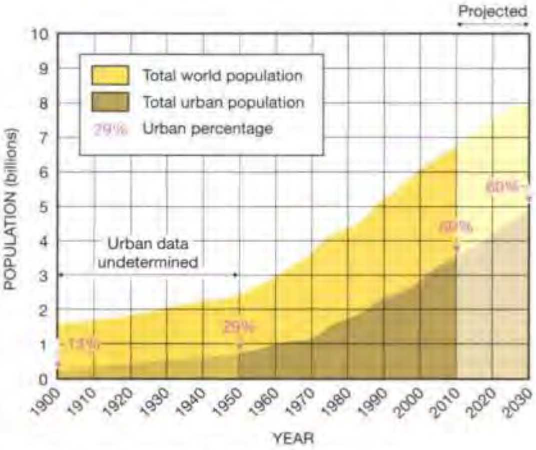
The terms "urban" and "cities" are often taken to mean the same thing, but it is important to note that not all urban areas are cities. Urban areas include towns and other smaller settlements. Some specific country examples are given in Table 1.

Causes of urbanization

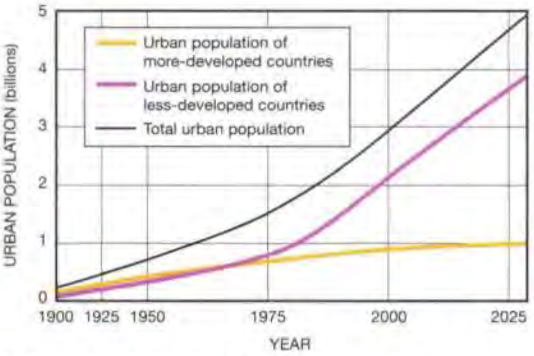
Urbanization has three components: natural increase, migration, and the reclassification of rural areas as urban or a change in the criteria for "urban". Many consider that migration is the dominant factor, but the main cause today is generally natural increase. The latest comprehensive research effort to separate it from other components of urban growth puts its contribution at about 60% in the median country. The remaining part of urban growth - roughly 40% - is a combination of migration and reclassification[10].



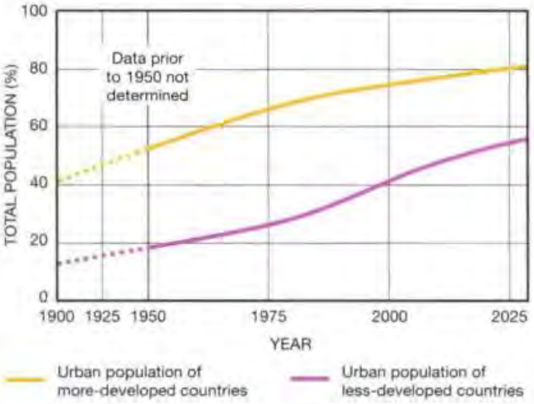
1. Rate of population growth to 6bn in 1999[12].



2. Actual and projected global populations and urban percentages[2].



3. Actual and projected urban population growth in more-developed and less-developed countries.



4. Actual and projected urban population growth expressed as percentages.

The situation in China, where rural to urban migration has recently predominated, is unusual. The prosperity of China's cities is largely a result of economic reform policies with a pro-urban focus. Since the mid-1980s China has pursued an aggressive urbanization policy as a way to stimulate both rural and urban economic development. The policy aims to absorb the hundreds of millions of farmers who flock to cities as a result of economic reforms and easing of previously strictly enforced "urban residency permits"[8]. It is estimated that in the next two decades, about 12M people will relocate from rural to urban areas every year, and China is planning to build another 400 new cities with populations averaging 600 000 people[11].

Urban growth also reflects the hopes and aspirations of millions of new urbanites. Cities have enormous potential for improving people's lives, with urban areas offering better access to health, education, basic infrastructure, information, knowledge, and opportunity.

In many developing countries, urban areas are therefore magnets that attract people from small towns and rural areas, because cities offer more hope of jobs and better living standards. As well as the "pull" factor of greater opportunity, there are the "push" factors of stagnant rural economies, inequitable land distribution, and degraded environments. Migration persists from rural areas without unemployment to urban areas showing high unemployment on the basis of expectations of long-term income and substantial increases in living standards.

In some parts of the world, the primary influence on urbanization is the movement of people uprooted by drought, famine, ethnic conflicts, civil strife, and war. Conflicts and crises in war-torn countries often result in the mass exodus of rural communities to urban areas, where most end up in low-income, poorly-serviced settlements or slums.

The rise of the modern city – the first wave of urbanization

The modern city arose, above all else, from major innovations in combustion technology. Industrial cities began to develop in Britain in the 18th century, and in the 200 years between 1750 and 1950, Europe and North America experienced the first demographic transition, the first industrialization, and the first wave of urbanization. This produced the new urban industrial societies that now dominate the world. The process was comparatively gradual and involved a few hundred million people; in 1804, the world's population reached 1bn (Fig 1), and by the end of this 200-year period, in 1950, the world had two "megacities" (ie populations of >10M): New York-Newark (12.3M) and Tokyo (11.3M). In the past half-century, the less-developed regions have begun the same transition, and the fact that they greatly outnumber in total population the more-developed regions implies huge future urban growth (Figs 2-4).

The second wave of urbanization

A recent United Nations Population Fund (UNFPA) report[10] notes that the huge increases in urban population in poorer countries are part of a "second wave" of demographic, economic, and urban transitions, much bigger and faster than the first. Of the world's urban growth over the next two decades, 95% will be in less-developed countries.

Mortality rates have fallen rapidly and dramatically in most of the less-developed regions, achieving in one or two decades what developed countries accomplished in one or two centuries. Cities in poorer countries will need to build new urban infrastructure – houses, power, water, sanitation, roads, commercial, and productive facilities – more rapidly than cities anywhere during the first wave of urbanization.

The next few decades will see an unprecedented scale of urban growth in the developing world. This will be particularly notable in Africa and Asia where the urban population will double between 2000 and 2030 - so the accumulated urban growth of these two regions during the whole span of history will be duplicated in a single generation.

India is rapidly industrializing and urbanizing. Its population is currently less urbanized than China's (29% compared to 37%), and while China's population is forecast to grow by 10% between 2006 and 2050, the forecast for India is 45%, taking its population to 1.6bn and making it the most populous country in the world by 2050. Taking Africa as a whole, the continent is currently 37% urban, and the population is forecast to more than double between 2006 and 2050, from just under 1bn to almost 2bn. By 2030, the towns and cities of the developing world will make up 81% of urban humanity.

The UNFPA stresses the importance of three policy initiatives regarding this forecast growth.

First, preparing for an urban future requires, at a minimum, respecting the rights of the poor to the city. Secondly, cities need a longer-term and broader vision of the use of urban space to reduce poverty and promote sustainability. Thirdly, population institutions and specialists should play a key role in supporting community organizations, social movements, governments, and the international community in improving the nature and form of urban expansion, and thus enhancing its power to reduce poverty and promote environmental sustainability.

Megacities

Rome was the first city to have a population of 1M people, around AD 250, but it later contracted to around 30 000. In 1800 there were two "million-cities", London and Beijing, and by 1900 there were four, Tokyo and Delhi having reached that status. A century later, the number of "million-cities" had increased to 200, with a further 100 having between 1M and 10M inhabitants, and 19 megacities with populations exceeding 10M[11] (Table 2).

Much attention in the past half-century was given to the rise of megacities. Some regard them as the "global urban future"[13], but in 2007, less than 9% of the world's urban population lived in megacities, and this proportion is forecast to be little more (<10%) in 2025[2]. This means that less than 5% of the world's total population live in megacities (Fig 6).

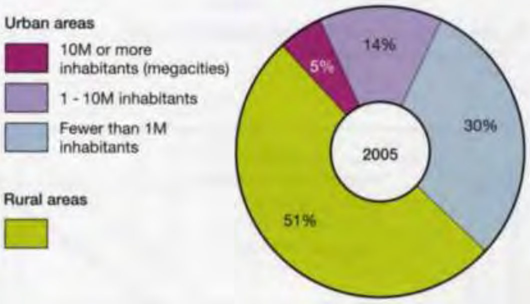
Eight more megacities - Kinshasa, Lagos, Jakarta, Guangzhou, Lahore, Chennai (formerly Madras), Shenzhen, and Paris - are projected to emerge over the next two decades, making the total 27 by 2025, with 18 of them in developing countries.

5. With a population of 35.7M, Tokyo is by far the world's largest megacity.

Table 2. Rankings and populations in 2007 of megacities[2].

1	Tokyo	35.7M
2	New York–Newark	19.0M
3	Cuidad de Mèxico (Mexico City)	19.0M
4	Mumbai (Bombay)	19.0M
5	São Paulo	18.8M
6	Delhi	15.9M
7	Shanghai	15.0M
8	Kolkata (Calcutta)	14.8M
9	Dhaka	13.5M
10	Buenos Aires	12.8M
11	Los Angeles–Long Beach–Santa Ana	12.5M
12	Karachi	12.1M
13	Al-Qahirah (Cairo)	11.9M
14	Rio de Janeiro	11.7M
15	Osaka-Kobe	11.3M
16	Beijing	11.1M
17	Manila	11.1M
18	Moskva (Moscow)	10.5M
19	Istanbul	10.1M

6. Megacities as a proportion of total population[14].



Tokyo is by far the world's largest city region, with a population of 35.7M. By 2025 its population is forecast to be little more, at 36.4M, with the next largest becoming Mumbai with 26.4M[2].

Attention has focused on megacities because they represent an extreme, but there are not as many, nor are they as big, as was forecast. For example, in the 1970s it was projected that by the year 2000 there would be 27 megacities and that the population of Calcutta would be 40-50M and Mexico City 31M. São Paulo, Rio de Janeiro, Seoul, Chennai, and Cairo are among the many other large cities that, by 2000, had several million fewer inhabitants that had been predicted[15].

The reasons for these predictions not materializing are unclear. There is much debate about whether cities have a "natural maximum size", and whether there is an optimum size for urban areas in terms of environmental impact, sustainability, and quality of life.

A brief history of urban areas[11]

Human settlements are generally thought to have originated with hunter-gatherer bands setting up temporary camps or occupying caves in areas where fruits, nuts, fish, or game were plentiful.

The beginnings of farming go back to around 10 000 BCE. The emergence of settled living, with tens or even hundreds of people inhabiting a shared space, was only possible through the deliberate concentration of food production - a clear departure from nomadic hunting and gathering.

The first sedentary farming villages emerged around 8500 BCE, with concentrations of people living in one space by growing crops on clearly-defined areas of land, and fishing in rivers, lakes, or the sea. It is disputed whether early towns were built in coastal locations during the last Ice Age (23 000-12 000 BCE) and subsequently inundated by rising sea levels.

The earliest town to have been excavated so far is Jericho, considered to have been founded about 8000 BCE. Jericho's fortifications enclosed about 4ha of land with space for a permanent population of some 1200 people. Others would have lived outside and sought protection within its walls in times of siege. The destruction of Jericho is dated at around 1400 BCE.

Çatal Hüyük, 1000m above sea level in Anatolia (a peninsula of Western Asia), is regarded as the world's first substantial town, its 13ha site thought to have had a population of some 6000 people. It dates back to 7100 BCE and existed for some 1500 years. Towns like Çatal Hüyük set a new trend in human endeavour. In Iraq, Greece, and Italy, fully-developed agricultural and trading settlements started to appear between 6400 and 5800 BCE.

Archaeology indicates that the first complex urban societies originated in Sumeria, southern Mesopotamia (today's southern Iraq), about 3500 BCE. Within a few hundred years, dozens of cities including Uruk and Ur emerged there. They owed their sustenance to another invention – irrigation-based farming systems, which seem to have originated about 6000 BCE. Uruk was criss-crossed with navigable canals, and here archaeologists have also discovered the earliest recorded remains of wheels. During the third millennium BCE, Ur had up to 360 000 inhabitants. Early cities like it had a substantial environmental impact, depending on ever more resources from an ever larger hinterland as they grew.

The eventual demise of Ur and other Sumerian cities was linked to use of irrigation water that led to the salinization of farmland, with catastrophic consequences for food supply. Hostile invasions also played a role in their downfall, with jealousies and wars over wealth. As the cities of Sumeria declined, Babylon in northern Mesopotamia took over as the dominant city-state. From 3000 BCE onwards, cities had also been built in the Nile Delta in Lower Egypt and the valley of the Nile in Central and Upper Egypt.

Cities arose in Greece from about 750 BCE. Urbanization here, as elsewhere, was made possible by the bio-productivity of forests and farmlands outside the cities. But the hilly terrain was not very fertile and easily eroded, so with a growing population, Greece needed to diversify its economy, exporting pottery, wine, and olive oil in exchange for grain. The success of Greek cities was achieved at considerable environmental cost in terms of deforestation.

The story of Rome also starts around 750 BCE, when it was a small village. Rome thrived because it straddled a trade route and was on the banks of a river. It grew to a population of some 1.2M in about 1000 years, becoming, as already noted, the first "million city" around AD 250. Most Roman citizens chose to live in the city, with its paved roads, aqueducts, schools, temples, libraries, markets, arenas, and public baths. The majority lived in apartment blocks shared by several families. There were around 45 000 such blocks, some rising 10 storeys.

To meet the needs of the growing city, Rome had to keep improving its water supply system, and nine separate aqueducts were built as demand grew. Its armies' conquests gave Rome access to a great variety of trade goods that contributed to affluence and luxury, but it also relied on forests for timber and fuel. With its massive use of resources, the city pioneered a highly-developed economy that also caused major environmental problems as a result of deforestation.

7. Complex urban societies, from the earliest times to later civilizations such as the Assyrians, had substantial environmental impacts.

Between AD 500 and 1000, Rome contracted in size to a town of just 30 000 people. There were many reasons for its decline and fall – invasions, punitive taxes in the colonies, civil wars, corruption, famines, plagues – but there is little doubt that environmental factors like deforestation, soil erosion, and salinization also played a major part in the drawn-out demise of the Roman Empire.

This brief look at the earlier history of urban areas shows that many of the issues and problems associated with urbanization today, such as how to provide urban populations with water and with food, are nothing new. Likewise, the environmental degradation arising from urban areas obtaining resources from a growing hinterland, with consequences such as deforestation, is not a new problem.

The difference now is the scale on which such problems are happening. The next sections look at some of these issues in some more detail in the context of current urbanization, including urban agriculture, the urban ecological footprint, and the relationship between urbanization and the climate. Influences on urban growth, such as the role of employment, are also discussed.

Urban agriculture

The development of urban areas was made possible through the concentration of food production to create a surplus, but many cities have now come to depend on highly unsustainable supplies for the bulk of their food. In Britain, for example, the components of a typical Sunday lunch for four people travel a total of something in excess of 24 000 miles[11].

In many cities, particularly in the developing world, urban agriculture - the practice of growing, raising, processing, and distributing food in and around an urban area - contributes significantly to urban food supply and household food security, particularly among low-income groups[8]. Shanghai is one of the world's fastest-growing cities, yet half the 630 000ha administered by the authorities has been set aside for urban agriculture[11].

This can also be a more sustainable way of providing food, by reducing the energy and environmental costs. Cuba has become a world leader, with food production decentralized from large mechanized state farms to urban cultivation systems. In Havana, more than half the fresh produce consumed is grown within the city[11]. There are some concerns about the quality and safety of food produced in urban or peri-urban areas where soil and water contamination levels are higher than in rural areas - but research has shown there are ways of dealing with contamination. Demand for local produce in cities is likely to increase, so future urbanization is likely to require land to be set aside for food production.

Urban footprint

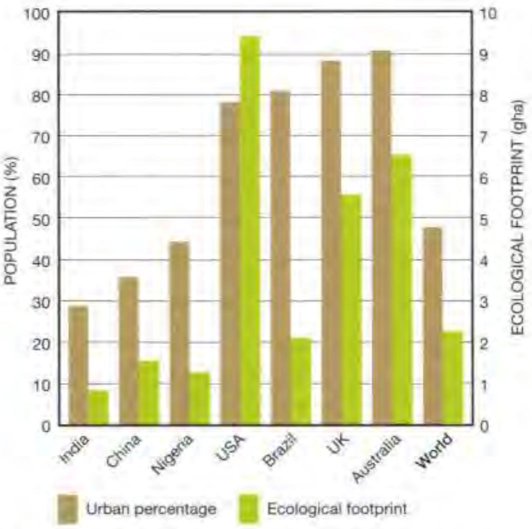
The ecological footprint measures humanity's demand on the biosphere and it is referred to in terms of global hectares (gha) per capita, this being a hectare with world-average ability to produce resources and absorb wastes. In 2003 the world's biocapacity was 11.2bn gha, equivalent to 1.8gha per person based on then current population numbers - however the average global footprint was 2.2gha per person. In practice, this "overshoot" means that it took approximately a year and three months for the Earth to produce the resources used and absorb the wastes generated in that year[16]. The more urbanized parts of the world have significantly larger ecological footprints – whilst the average in Africa is 1.1gha, in North America it is 9.4gha per person (Fig 8).

Two-thirds of the world's ecosystems are now severely damaged, with most of this impact being due to global urban consumption and waste disposal. It is widely assumed that urbanization will continue, but the growing scarcity of water and the high cost of the energy invested in transporting it over long distances may begin to constrain urban growth. For example, some 400 cities in China are already facing a chronic water shortage[17], while in the US the cases of Los Angeles and Las Vegas have received much publicity. (That said, water shortage shows few signs yet of actually curtailing urban growth either in the US or China.) The annual report by the Water Services Association of Australia found that after a decade of punishing drought, authorities in all of Australia's mainland capital cities will need to find new ways to provide water, such as desalination and recycling, in the next 5-10 years[18]. In a world of land, water, and energy scarcity, the value of each resource may increase substantially, shifting the terms of trade between rural and urban areas.

Urban areas and the climate

Urban areas are both subject to, and an increasing component of, regional climate change[19]. Most of the increase of CO_2 in the atmosphere is attributable to energy consumption in the world's cities. The highly urbanized developed regions of the world generate by far the greatest proportion of CO_2.

While many countries are putting in place reforms to limit CO_2, emissions are on the rise in the industrializing cities of Asia. With CO_2 emissions increasing to record highs, global warming will soon reach the point of no return; 11 of the last 12 years (1995 - 2006) rank among the 12 warmest years in the instrumental record of global surface temperature (since 1850)[20].



8. Ecological footprint of selected countries and their levels of urbanization[15].

There is growing consensus that the populations, infrastructure and ecology of cities are at risk from the impacts of climate change. Water and food shortages and an influx of "climate refugees" are just some of the impacts of climate change likely to occur unless drastic action is taken to reduce the emission of greenhouse gases. Rising sea levels due to global warming will take a heavy toll on cities because many are located on low ground close to the sea; 40% of the world's population lives within 65km (40 miles) of the sea. Many non-coastal cities would also face problems of flooding as they are beside rivers or in foothills of mountains in locations vulnerable to intense rainfall or snowmelt.

Large cities can also disturb weather patterns, creating a microclimate called an urban heat island (UHI). Urban areas can have UHIs that may be up to 5-6°C warmer than the surrounding countryside.

Compared with vegetated surfaces, building materials retain more solar energy during the day, and have lower rates of radiant cooling during the night. Urban areas also have lower wind speeds, less convective heat losses and evapo-transpiration, yielding more energy for surface warming.

Artificial space heating, air conditioning, transportation, cooking and industrial processes introduce additional sources of heat into the urban environment causing distinct weekly cycles in UHI intensity[19].

UHIs are considered to have only a negligible effect on climate change, but the local effects are real. In addition, as the impact of rising temperatures is likely to be more severe in major cities, this will exacerbate the urban heat island effect, and the associated health impacts. The heat wave in Europe in August 2003 was considered to be responsible for some 35 000 deaths[21].

Employment and globalization

Employment and economic opportunity are key factors driving urbanization, attracting people from rural to urban areas. In many developing countries, particularly in Africa and Asia, the formal employment sector has not been able to provide adequate jobs for rapidly growing urban populations, leading to more than half of those economically active being employed in the informal sector.

Approximately 85% of all new employment opportunities around the world are created in the informal economy[22], characterized by local resources, family property, and small-scale operations, with a lack of legal protection, no minimum wages, low standards of security and hygiene, and no environmental controls. Unemployment was described as the "top urban concern" at the 1997 UNDP Colloquium[23]. High youth unemployment, particularly within marginalized ethnic minorities, can create urban unrest, as demonstrated by the Parisian riots in late 2005.

Employment is also a primary reason for immigration. In 2005 there were more than 191M international migrants in the world, the highest number ever, equating to one person in 35. The country that attracts the most people from abroad is the United States (35M), followed by Russia (13.3M) and Germany (7.3M). China sees the most people leave, followed by India and the Philippines. In Doha, capital of the Gulf state of Qatar, more than half of the population are migrant workers - mostly cleaners and builders[24].

Cities are the great engines of economic growth. Over the last 50-100 years most growth in economic activities in all parts of the world has been in urban centres. Economic globalization has resulted in changes to employment structures, with fewer workers employed in agriculture and manufacturing, and more employed in services. Today, around 65% of the world's economically active population work in industry and services, mostly in urban areas. Many cities owe their prosperity to their roles within the increasingly global production and distribution system. In some parts of the world however, particularly in Sub-Saharan Africa, cities have grown without an associated expansion of economic activity.

9. Sub-Saharan Africa has the world's highest poverty levels overall[8].

Increasingly, urban growth is influenced by continued global economic integration. Sir Peter Hall, a renowned expert on urban trends, predicts[23] that the 21st century will see a resurgence of economically powerful global cities in Asia, specifically Beijing, Shanghai, and Mumbai. The globalization process has had a very uneven impact across the world, with both positive and negative impacts on cities. The positive include rising prosperity, the enduring importance of urban cores, and increased democracy, while the negative consist of sharpening imbalances, increased social disorder, and greater citizen expectations.

The urbanization of poverty

The link between urbanization and socioeconomic development is rarely disputed - but in many cities of both the developed and the developing world, economic growth has not resulted in prosperity for all. Instead, intra-city inequalities have risen as the gap between rich and poor has widened.

UN-HABITAT states[8] that many cities are now effectively two cities within one - one part of the population has all the benefits of urban living, but the other, the poor, are in slums and squatter settlements (globally these are now home to 1bn people), often in worse conditions than their rural relatives. The problem is not urbanization *per se*, but the fact that it has not resulted in greater prosperity or more equitable resource distribution.

Sub-Saharan African countries have some of the world's highest levels of urban poverty, extending to more than 50% of the urban populations in Chad, Niger, and Sierra Leone. In Asia, India has the highest urban poverty levels, at 30%[8].

While rural areas are currently home to most of the world's poor, World Bank estimates indicate that by 2035 cities will have become the predominant sites of poverty[8]. The high costs of items such as transport, health, education, and water, coupled with poor living conditions including inadequate housing and poor access to basic services, adversely impact the ability of the urban poor to rise out of poverty. The Executive Director of the UN Human Settlements Programme, Anna Tibaijuka, has described the urbanization of poverty as the "weakest link" in sustainable development[25].

From Brundtland to GEO-4

Two decades ago, the Brundtland Commission report "Our Common Future"[32] challenged policy-makers to consider the interrelationships of environmental, economic, and social issues in when attempting to solve global problems. The report examined emerging global challenges in population and human resources, food security, species and ecosystems, energy, industry, and urbanization.

When it was published, the world's population was some 5bn people, with an urban population of 41% (just under 2bn). The more-developed regions were 71.5% urban and the less-developed regions 31.2%. The report noted that projections put the urban challenge firmly in the developing countries, and drew attention to "the crisis in Third World cities", as illustrated by the following quotes: "In most Third World cities, the enormous pressure for shelter and services has frayed the urban fabric." "A growing number of the urban poor suffer from a high incidence of diseases." "The uncontrolled physical expansion of cities has also had serious implications for the urban environment and economy." "In general, urban growth has often preceded the establishment of a solid, diversified economic base to support the build-up of housing, infrastructure and employment."

The urban challenge in developing countries was set out in terms of the need for national urban strategies, strengthening local authorities, self-reliance and citizen involvement, housing and services for the poor, tapping more resources, co-operation among developing countries, and international support... "given urbanization trends in most developing countries, there is no time to wait for slow and uncertain programmes".

In October 2007, the United Nations Environment Programme published *GEO-4*[33], which assesses the current state of the global atmosphere, land, water and biodiversity, describes the changes since the 1987 Brundtland report, and identifies priorities for action. *GEO-4* is the most comprehensive UN report yet on the environment, prepared by about 390 experts and reviewed by more than 1000 others across the world. It notes the significant pressure that urbanization can exert on the environment, and draws attention to the critical issue of urban air pollution in particular. Table 4 shows some of the links between human well-being and urban expansion.

As far as sustaining a common future is concerned, the reports selects key priority issues for its seven GEO regions. The urban aspects of these issues in six of the regions are as follows:

- Africa: land degradation and the world's highest rate of urbanization
- Asia and the Pacific: rapid urban development and urban air quality
- Europe: urban air quality
- Latin America and the Caribbean: growing cities (in the most urbanized region in the developing world) and urban air pollution
- North America: urban sprawl
- West Asia: urban management, as intense urbanization has overstretched urban infrastructure.

The seventh is the Polar regions, where the key priority issues are climate change, persistent pollutants, the ozone layer, and development and commercial activity.

Table 4. The links between human well-being and urban expansion.

Environmental impact	Disruption of hydrological and biological cycles; loss of habitat and biodiversity; concentration of pollutants; solid and organic wastes; urban heat islands.
Material needs	Increased access to food, water and shelter; increased choice, but satisfaction of material needs highly dependent on income.
Human health	Respiratory and digestive tract diseases due to air pollution, poor water supply and sanitation; higher incidence of stress- and industry-related diseases; higher incidence of heat stroke.
Safety	Increased exposure to crime; traffic and transport hazards; increased risk of flooding caused by soil sealing and occupation of hazardous sites.
Socio-economic	Increased opportunity for social and economic interaction and access to services; increased competition for financial resources; diminished sense of community; increased sense of isolation.

10. Rapid urbanization of the coastal fringe is highlighted as a particular area of concern.

Rapid urbanization of the coastal fringe is highlighted as a particular area of concern in terms of the human dimension. Problems include danger to lives and material assets from floods and landslides, health being at risk from poor sanitary conditions when urbanization is unplanned, and strong distributional impacts.

Four scenarios for the world to the year 2050 are explored, and the implications examined at both the global and regional level. The scenarios are: (1) markets first, (2) policy first, (3) security first, and (4) sustainability first. Overall, they point to both risks and opportunities. Of particular significance are the risks of crossing thresholds, the potential of reaching turning-points in the relationship between people and the environment, and the need to account for interlinkages in pursuing a more sustainable path. Common to all four scenarios is that the long-term unfolding future depends very much on the decisions individuals and society make today.

GEO-4 affirms that 20 years on from the Brundtland Commission report, its findings are more pertinent than ever. The concluding chapter "From the periphery to the core of decision-making – options for action", sets out two tracks for the new environmental policy agenda for the next 20 years and beyond:

(1) expanding and adapting proven policy approaches to the more conventional environmental problems, especially in lagging countries and regions

(2) urgently finding workable solutions for the emerging environmental problems before they reach irreversible turning points.

In *GEO-4*'s own words: "Alternative development paths that protect the environment are available. Human ingenuity, resilience and capacity to adapt are powerful forces from which to draw to effect change".

Urbanization and the growth of slums

A slum household is defined by the UN[8] as a group of individuals living under the same roof in an urban area who lack one or more of five conditions (Table 3). Alongside the criteria are some current statistics.

Table 3. Defining conditions for slum dwellings.

1	Durable housing: a house is considered "durable" if it is built on a non-hazardous location and has a structure permanent and adequate enough to protect its inhabitants from the extremes of climatic conditions, such as rain, heat, cold and humidity.	18% of all urban housing units are non-permanent structures.
2	Sufficient living area: a house is considered to provide sufficient living area for the household members if not more than three people share the same room.	Some 20% of the developing world's urban population live in houses that lack sufficient living area.
3	Access to improved water: a household is considered to have access to improved water supply if it has a sufficient amount of water for family use, at an affordable price, and available to household members without being subject to extreme effort, especially on the part of women and children.	Only two-thirds of the world's urban population gets water from a tap.
4	Access to sanitation: a household is considered to have adequate access to sanitation if an excreta disposal system, either in the form of a private toilet or a public toilet shared with a reasonable number of people, is available to household members.	Over 25% of the developing world's urban population - 560M city residents - lack adequate sanitation.
5	'Secure tenure: the right of all individuals and groups to effective protection against forced evictions. People have secure tenure when there is evidence of documentation that can be used as proof of secure tenure status or when there is either de facto or perceived protection against forced evictions.	Non-empirical evidence from UN-HABITAT indicates that 30-50% of urban residents in the developing world have no legal document such as title deed or a contract to prove tenure security, and without such documents, forced urban evictions can result.

The problems of poor-quality housing are exacerbated by the fact that 75% of the world's population lives in areas affected at least once by an earthquake, a tropical cyclone, floods or drought, between 1980 and 2000. Poor people in developing countries are particularly vulnerable to disasters as they are more likely to live on dangerous floodplains, river banks, steep slopes and reclaimed land, and their housing is less likely to survive a major disaster. For example, an investigation into the 2003 earthquake in Bam, Iran, found that most of the 40 000 people killed lived in housing that was built in the traditional mud-brick style without the necessary supportive structures to withstand tremors[8].

Given the forecast growth in urbanization in less-developed countries, problems such as non-durable housing and lack of security of tenure are likely to become exacerbated.

Governance

Some contemporary prognoses are far from positive. The American urban theorist and historian, Mike Davis, has written[26]: "Thus, the cities of the future, rather than being made out of glass and steel as envisioned by earlier generations of urbanists, are instead largely constructed out of crude brick, straw, recycled plastic, cement blocks, and scrap wood. Instead of cities of light soaring toward heaven, much of the 21st century urban world squats in squalor, surrounded by pollution, excrement and decay. Indeed, the 1bn city-dwellers who inhabit post-modern slums might well look back with envy at the ruins of the sturdy mud homes of Çatal Hüyük in Anatolia, erected at the very dawn of city life 9000 years ago."

Nonetheless, it remains true that urbanization can offer significant opportunities to reduce poverty and gender inequality, as well as promote sustainable development. But without effective preparation for the massive increase in the number of poor people, slums will multiply and living conditions will continue to deteriorate. In view of this, it is increasingly clear that improved urban governance (ie government responsibility and civic engagement) is essential if cities are to avoid calamity and make the most of their opportunities.

For humankind to benefit from the urban transition, leaders must first accept it as both inevitable and important for development. However, three-quarters of all governments have reported[27, 28] that they are dissatisfied with the spatial distribution of their populations, and almost three-quarters of developing countries have enacted policies to reduce the flow of persons moving to urban areas. These have included the following strategies:

- policing measures - returning rural-urban migrants to their home or other rural areas and prohibiting migration to cities (through population registration, resident permits and charges, food and other material rationing, etc, as in China's permit system)
- incentives measures - to keep population in rural areas; reducing the flow of migrants at source through rural development measures, land reform, etc
- new areas measures - promoting the development of alternative urban centres, redirecting migrants to intermediate "growth poles" or "new cities" (eg Brasilia)[27].

Rather than attempt to prevent urban expansion, planners must examine the available policy options for addressing it and building on its possibilities. Examples of the differences made in some cities by mayors in recent years highlight some of the possibilities. The potential for strong political leadership can come with urbanization, and such leadership can in turn strengthen a city's position. In Curitiba in Brazil, for example, the leader of the winning team of a masterplan competition held in the 1960s to develop the city was subsequently elected as mayor three times, and is credited with transforming Curitiba into a city considered one of the best examples of urban planning world-wide[29].

In Bogotá, a series of co-ordinated actions by successive mayors has turned a once-violent, car-dominated city facing dramatic levels of in-migration from its rural hinterlands into a calm and well-managed city - with an efficient rapid transit bus system, a network of cycleways, public parks, and urban plazas that have changed life for the city's inhabitants, improving its quality and reducing crime.

In Barcelona three successive mayors have undertaken over the last 20 years a series of visionary urban projects that have had a lasting impact on its economy.

During the 1990s, London, Tokyo and Seoul all elected mayors for the first time in modern history[30]. The strong political leadership of London's mayor resulted in the introduction within two years of a charging scheme that reduced congestion in the city centre significantly[31].

People +

Physical infrastructure - facilities

Housing
Education - nurseries, schools, colleges
Healthcare - surgeries and hospitals
Employment - offices, factories, etc
Transport - roads, rail, airports, walkways, cycleways
Open space - parks, communal gardens, orchards
Retail - shops
Leisure - entertainment, theatres, etc
Sports
Cultural - arts and museums/galleries

Systems/utilities

Sanitation
Water
Waste (recycling, disposal)
Technology
Energy
Communication systems
Drainage
Connectivity and/or networks
Food/urban agriculture
Coastal defences

Services

Money/financial services - banking, insurance etc
Police/emergency services
Resources
Planning (masterplanning, urban design)
Governance
Information

Desirable attributes

Robustness
Security
Community
Happiness/hope
Opportunity
Clean air
Views/topography
Information/legibility
Contrasts/surprises
Iconic buildings
Escape routes
Equity

11. Some "urban ingredients".

Many politicians and planners regard slum formation as temporary - the less intervention, the better - but forecast increases in the world's urban population will require significant infrastructure provision. Rapid population growth severely hinders the capacity of poorer cities to increase infrastructure per head, to provide an adequate number of homes or school places. Many urban neighbourhoods in less-developed countries lack any effective infrastructure for water supply, sewage disposal, and waste management, resulting in health-threatening environments.

The cost-effectiveness of infrastructure investment is greatly reduced once informal settlements have been allowed to proliferate; if they are not provided with basic services like water and sewerage, pollution problems arise and retrofitting such services is both difficult and expensive. Spontaneous development tends to take place at city peripheries. It is rarely possible to provide public transport once a settlement has developed, so workers face long, inconvenient, and congested journeys. Uncontrolled physical expansion destroys natural landscapes that should be preserved as parks, reserves, or open space – and once open area is built up, it is very difficult and expensive to remedy its lack. Public space is the only place where all citizens meet as equals in cities, and, as such, can be regarded as the great equalizer.

Some low- or middle-income countries (eg Brazil, Colombia, Philippines, Indonesia, South Africa and Sri Lanka) have managed to prevent some slum formation by anticipating and planning for growing urban populations. They have achieved this by expanding economic and employment opportunities for the urban poor, by investing in low-cost affordable housing for the most vulnerable groups and by instituting pro-poor reforms and policies that have had a positive impact on low-income people's access to services.

The absence of effective governance structures results in a lack of planning, development control, and infrastructure provision. In an increasingly urbanized world, effective planning policies are needed for both urban and rural areas.

Conclusion

Population and urban forecasts have not always materialized, and it is important to recognize that forecasts are just that – forecasts. The population in 2050 may not reach over 9bn people, and it may be that not as many as 70% of the world's population will be living in urban areas. However, what does seem to be beyond doubt is that for the foreseeable future, urban population is set to increase.

There is clear evidence that urbanization can play a positive role in social and economic development. Historically, the statistical association between urbanization and economic growth has been strong. Today, cities generally have greater potential than rural areas for reducing poverty, and there is growing recognition that by concentrating half the world's population on less than 3% of its land area[10], urban settlements and demographic concentration give sustainability a better chance. However, in many cities in both the developed and the developing world, economic growth has not resulted in prosperity for all. Instead, intra-city inequalities have risen as the gap between rich and poor has widened.

Cities also draw together many major environmental problems - population growth, pollution, resource degradation, waste generation – but while some statistics linked to urbanization are depressing, it is important to understand the negatives and see these in terms of opportunities and chances to do things differently in the future. The potential benefits far outweigh the disadvantages.

The key issues are the scale of urban growth and where it is taking place. Every week for the next 30 years, the equivalent of a new million-city is needed to accommodate the doubling of the urban population of developing countries from some 2bn to 4bn[8]. While new towns and cities will play a role, the importance of existing, and expanding, urban areas is fundamental. China and India together contain 37% of the world's population; their approaches to urban growth are particularly critical to humankind's future.

Long-term planning for urban areas needs to be looked at holistically. Any town or city has many components or "urban ingredients" (Fig 11), and there are complex relationships between them: the facilities, in terms of physical infrastructure; the systems and utilities that an urban area needs to function; the services that urban residents require; and the attributes that it is desirable for an urban area to have. Considering, comprehending, and balancing all these urban ingredients requires the input of many disciplines, as well as respect for the local environment, both geographically and culturally, and its people.

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Credits

Illustrations: 1-4, 6, 8, 11 Nigel Whale; 5 Ingmar Wesemann, 7 John Said, 9 Adrian Beesley, 12 Gunther Beck/iStockphotos.com; 10 Jupiterimages.

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To celebrate its 60th anniversary in 2006, Arup partnered with the international charity WaterAid in the Arup Cause initiative, which focused Arup's mission to "shape a better world" on the provision of safe domestic water, sanitation, and hygiene education to the world's poorest people.

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Illustrations: 1. Spectators with neon-lit jackets enjoying *Textus*, the digitally animated light artwork at Leeds, UK, in October 2007: Adrian Murray; 2. The Ngong Ping 360 cableway in Hong Kong: Arup/Marcel Lam; 3. Typical gallery space in the refurbished Jacobs Building at the Museum of Contemporary Art San Diego: David Heald; 4. Disposal of obsolete electronic equipment (e-waste) is a global problem: James Blinn/Dreamstime.com; 5. Detail of atrium roof at Zlote Tarasy, Warsaw, Poland: inblanco.pl; 6. Ngong Ping Village, Hong Kong, with the 34m tall Tian Tan Buddha in the background - the final destination of Ngong Ping 360: Colin Wade; 7. Urbanization has many guises, some of them affluent: Bill Grove/iStockphoto; 8. Roof detail of Tung Chung terminal building, Ngong Ping 360: Colin Wade; 9. "Copper houses" at Zlote Tarasy: Richard Kent; 10. Aluminium node joint for the Hylomorphic Project exhibition structure, Los Angeles: Joshua White.

Front cover: Zlote Tarasy, Warsaw, Poland: inblanco.pl.

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