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Terminal 5, London Heathrow:

3-D and 4-D design in a single model environment

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2. The location.

Introduction

In November 2001 the British Government assented to the construction of London Heathrow Airport's fifth terminal, one of the largest civil engineering projects in Europe. BAA, the airport operator, was to develop a 260ha site at the western end of the airfield between the two existing runways, providing Heathrow with the capacity to handle an additional 35M passengers per year, and thereby gaining maximum use from the runways. Terminal 5 is currently one of Europe's largest construction sites (opposite, and Fig 1).

Phase 1 of the vast project calls for the construction of a main terminal and satellite linked by underground transit system, a new control tower, ground transportation interchange, and car park. New infrastructure connects the development with neighbouring utilities and transport networks, including London Underground and Heathrow Express railways and London's orbital M25 motorway.

1. The site.

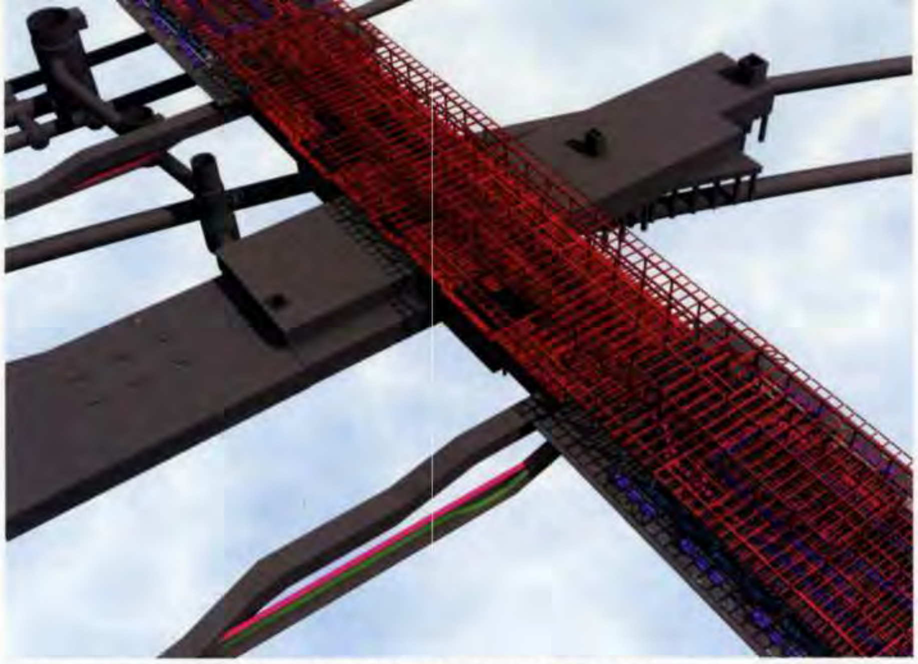
—— Site limit Ⓐ Main terminal building Ⓑ Rail station and ground transport interchange Ⓒ Multistorey car park
Ⓓ Hotel Ⓔ Energy centre Ⓕ Ancillary buildings Ⓖ Satellite 1 Ⓗ Satellite 2 Ⓘ New fuel farm
Ⓙ New Mainenance hangar Ⓚ New control tower Ⓛ Existing Terminal 3

By the time of the Government's assent, construction documentation was well under way, and after a long period of detailed planning applications the five-and-a-half year site programme commenced in December 2002. Now past the halfway mark, Phase 1 of T5 is on course to open in 2008.

Arup is a partner with, among others, Richard Rogers Partnership, Pascall + Watson, HOK, Mott MacDonald and Laing O'Rourke in the T5 framework that BAA set up in the mid-1990s to implement the programme. This gave Arup an excellent platform from which to bring its wide-ranging skills to bear, and further *Arup Journal* articles will detail the firm's involvement as the project proceeds.

From the outset, BAA set out to show the productivity achievable by framework partners working closely in teams, sharing the same offices and resources, and using their skills as effectively as possible. Fundamental to this was a desire to harness the collective experience of the various CAD teams to develop an effective tool for computer-aided design, draughting, and manufacture. BAA wanted a system that not only aided design co-ordination and drawing production, but one that would also help them plan T5's construction and future maintenance.

The framework partners collaborated closely in order to bring this about. This article describes the CAD systems developed for T5 and shows how they were implemented to achieve BAA's vision.



3. Satellite 2 building: Scheme stage 3-D model showing substructure, superstructure frame, and baggage systems.

The single model environment

BAA's vision

The technical complexity of T5 demanded excellent co-ordination across the many design teams to prevent drawing errors leading to programme delays on site. If co-location was to be effective in achieving this, a single CAD system was needed to create, store and share data. Everyone would work within this one system, known as the Single Model Environment (SME).

The system could also be an essential tool for managing the terminal beyond handover. The process of acquiring and maintaining assets (AMA) is a key part of BAA's business. Its aim was to minimize waste and simplify the planning of effective maintenance by capturing asset data (information describing each component in the project) in the SME during the development of 3-D models at the design stage. This asset data could then be processed to generate economies in the organization of maintenance contracts, replacement of equipment and suchlike.

But in 2000, at the start of concept design, no such system existed. Sophisticated 2-D and 3-D CAD programmes and file managers existed but a framework to bind them into an SME did not, so BAA and their partners developed it themselves.

Background to the SME

The SME is a simple concept: a set of directories and folders that store the CAD data for every discipline on the project. Folders are protected to ensure each discipline maintains authorship over the information it produces. Any discipline can access the information of another for its own purposes, but only after that information has been officially released by the author.

SME data are organized in "layers" for identification (ductwork, flooring, etc) and referenced in position and space to a consistent set of rules. All SME users can quickly and easily access the latest available information automatically with the aid of X-refs (external references, links from CAD drawing files back to source "graphic" files that automatically update once a source file is amended and released). On a project the size of T5 this saves hugely in time and paper. During design this is useful for all disciplines, and will continue to increase in value for AMA.

The key to the SME is organization. Although simply stated, it is difficult to achieve in practice because CAD users from different organizations use different standards, limiting the benefits of sharing data. It only works if everyone adheres rigorously to one set of standards and processes.

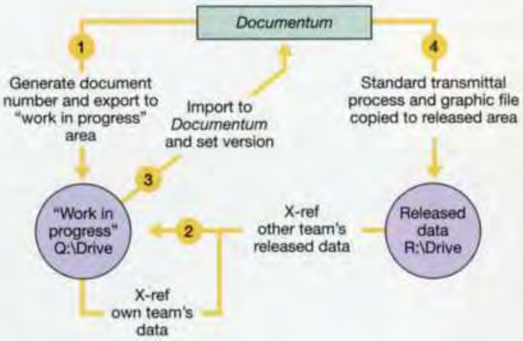
Ensuring this happens on T5 has been a major achievement; since 2000, 473 CAD users and 3879 other document users have all worked in the SME. By September 2005 it contained 16 124 2-D graphic files, 12 335 3-D model files, and 85 945 CAD paper-space drawing files, all organized to the required single set of CAD standards.

Developing the SME

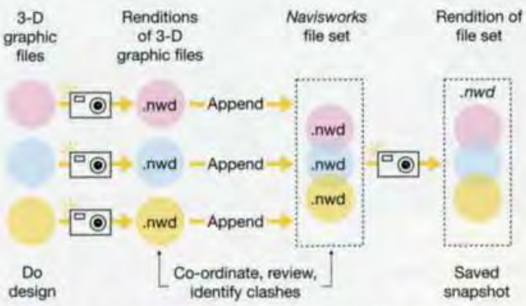
When concept design began in January 2000, the project inherited *AutoCAD MAP* as a CAD platform and *Documentum*™ as a document management platform. However, *AutoCAD MAP* was inappropriate to produce the 3-D data T5 needed and was unsuited to X-refs, which are essential for sharing data between teams. *Documentum*™ would not allow for X-refs either, nor would it allow different teams to share information from a single source.

So as the project grew and user requirements became more demanding, the system was significantly upgraded:

- A T5 Windows Explorer environment was introduced with dedicated drives. This gave complete freedom to work on CAD data within the various disciplines, and allow users to take full benefit of X-refs, etc (Fig 4).
- *AutoCAD 2002* replaced *AutoCAD MAP*, which enabled the use of X-refs by all disciplines.



4. Windows Explorer environment.



5. Manipulation of 3-D graphic files in the SME.


6.

Focus on physical modelling

One aspect of the programme's investment in 3-D was that a model shop was set up and permanently employed producing physical models, some of them extremely elaborate, to test ideas and interfaces as the design developed. This 1:20 scale model of the Main Terminal roof and façade was built in the middle of the design office. It was used as a tool for design development, particularly for testing the design of interfaces between systems.

It was useful for many other purposes as well, especially to give people outside the design team a very quick understanding of what this major element of T5 was all about and how it would go together on site. The physical model shop's contribution was invaluable in achieving the high design quality required.

- The program *Architectural Desktop™* (ADT) was introduced, greatly improving the system's 3-D capability.

A small T5 CAD co-ordination committee, comprising CAD leaders from the partner companies and BAA, steered the development process. Their role included:

- defining user requirements for the SME
- getting feedback from their teams on the CAD systems in place
- giving input on all basic aspects of the CAD standards such as font style, text size, hatching styles, layer naming, etc.

The software was developed and implemented by BAA's IT consultant EXCitech, which was also represented on the committee.

How the Single Model Environment works

All the basic 2-D and 3-D CAD data that describe the project are stored in the SME as AutoCAD (.dwg format) graphic files. Drawings are also produced in AutoCAD format – these are 2-D graphic files that are X-referenced into a drawing border.

When drawing files are issued, a "rendered" version in .dwf format is created and stored with the drawing. Non-CAD users use this to view and plot. The .dwf file is extremely useful as it can be printed at any scale while maintaining relative line thickness definition, unlike other forms of rendering, (eg .pdf).

3-D graphics files are converted by the program *NavisWorks* (Fig 5) into a format (.nwd format) that enables clash detection software to be run and renderings, images, fly-throughs, animations, etc, to be produced, as well as 4-D construction planning (this is described on p7 overleaf).

Without comprehensive CAD standards it is impossible to achieve the high levels of consistency and quality required, and allow for confident sharing of CAD data. Essential aspects of this are:

- Spatial co-ordination: all plans, elevations, and cross-sections are spatially located and orientated relative to the World Co-ordinate System and Ordnance Datum.
- Layering: an automatic layer manager system allows layer names to be selected and ensures that the CAD operator uses layers from the list already approved by BAA. The allocation of entities or objects to the correct layer is vital for the manipulation of CAD data, and for the SME's success.
- CAD tests: all CAD technicians are tested to ensure their proficiency and understanding of the CAD standards before they are given access to the SME.
- Checking: checking software has been implemented to ensure all data comply with the T5 CAD standards.

Design co-ordination is done in several ways (including the "old-fashioned" method of comparing various suppliers' drawings together and checking off dimensions). The SME helps particularly by its use of clash detection programmes. Because the standards are maintained across the SME, designers are confident that when they run the software, all the elements are present.

As for technology platform and applications, as noted previously, BAA selected ADT as its CAD platform and *Documentum™* as its document management platform. ADT was chosen because of its construction-based modelling capability, but several additional applications are being used to support the different needs of each delivery team (see Table1).

By ensuring that software is networked, the number of licenses required and therefore the cost can be drastically reduced.

Table 1 Additional software

2-D/3-D building design	AutoDesk ADT	250 licences
3-D steelwork and concrete design	CSC 3D+	5 licences
3-D steelwork production detailing	Tekla Xsteel	3 licences
3-D modelling (steel casting, etc)	Rhino	1 licence
2-D reinforced concrete detailing	CADD RC	25 licences
2-D survey and map layouts	AutoCAD MAP	15 licences
3-D building services	CAD Duct	70 licences
3-D baggage system	Villa	7 licences
3-D ground modelling	MX	5 licences
3-D highway design	MX	5 licences

Working in 3-D

The requirement for 3-D

There were several strong drivers for using 3-D on T5:

- BAA needed the whole project to be modelled in 3-D with all elements asset-coded for use as its AMA tool.
- The design teams needed 3-D capability to develop the design, especially the services and baggage teams who required 3-D software to plan the complex routes of their equipment through the buildings.
- Several fabricators wanted to import design information in a 3-D format that their manufacturing programs could interpret.

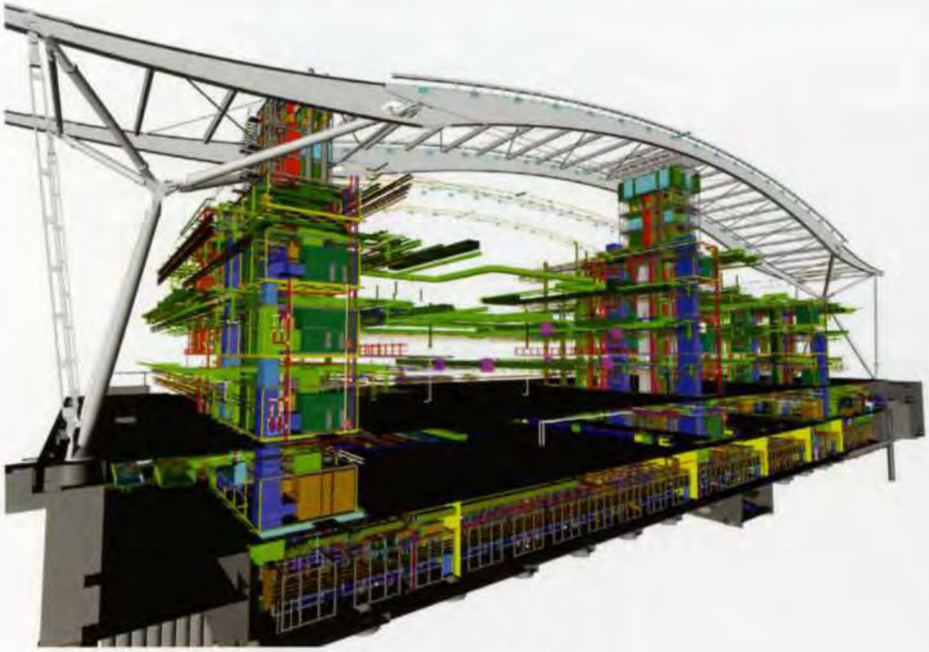
Background to 3-D modelling

Many commercially available packages can create 3-D "solid" models, but their usage in practice has been limited, for several reasons. Producing them is usually a separate exercise from the drawings, so they are often regarded as non-essential, and as they are not "linked" to the drawings, the models get out of date as the design develops.

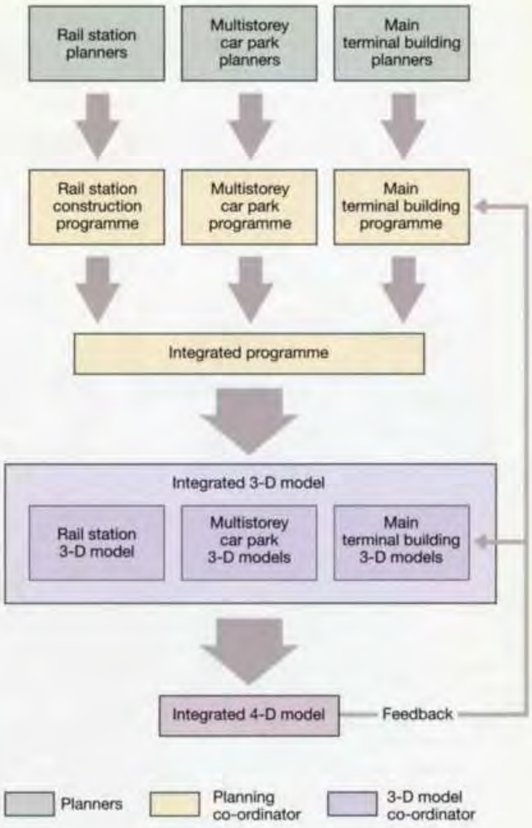
Also, without the rigorous SME layering system, sharing design models between teams has limited use since recipients have difficulty interpreting the model. Again, they have no attributes (data that describe material, serial number, length, etc), so they cannot be interpreted by a manufacturer's 3-D production software.

Finally, because design models get out of date, when the project gets to production stage the manufacturers produce new models from the drawings, which is wasteful.

Because clients and manufacturers alike increasingly demand 3-D information, the ideal is for teams to work in 3-D from the outset, using the models to generate their drawings automatically as they go along.



7. 3-D image of main terminal building envelope and services.



8. Interchange 4-D model information flow chart.

9. The south-west corner of the main terminal building.

4-D construction planning

General

T5, comprising 16 projects and 147 sub-projects, is managed by a high-level programme constructed from the individual project plans. One, the Interchange Plaza, was deemed to require an extra level of planning and management due to the interface of three separate teams for the multistorey car park, main terminal building, and rail station, in close proximity.

The Tri-Project Forum was formed to deal with this, and it developed the Interchange management plan which identified how the three projects could best deliver the Interchange Plaza safely, with quality, within budget, and on target. One activity that required attention was site logistics and potential areas of contractor conflicts.

The complex interfaces led BAA to decide on a 3-D form of planning, and Arup in turn was commissioned to facilitate "4-D" construction planning. This has been used successfully on other projects, linked to 2-D and 3-D models; at T5, many 3-D models already existed for manipulation by the 4-D CAD engineer. Where none was available it was locally modelled.

What is 4-D construction planning?

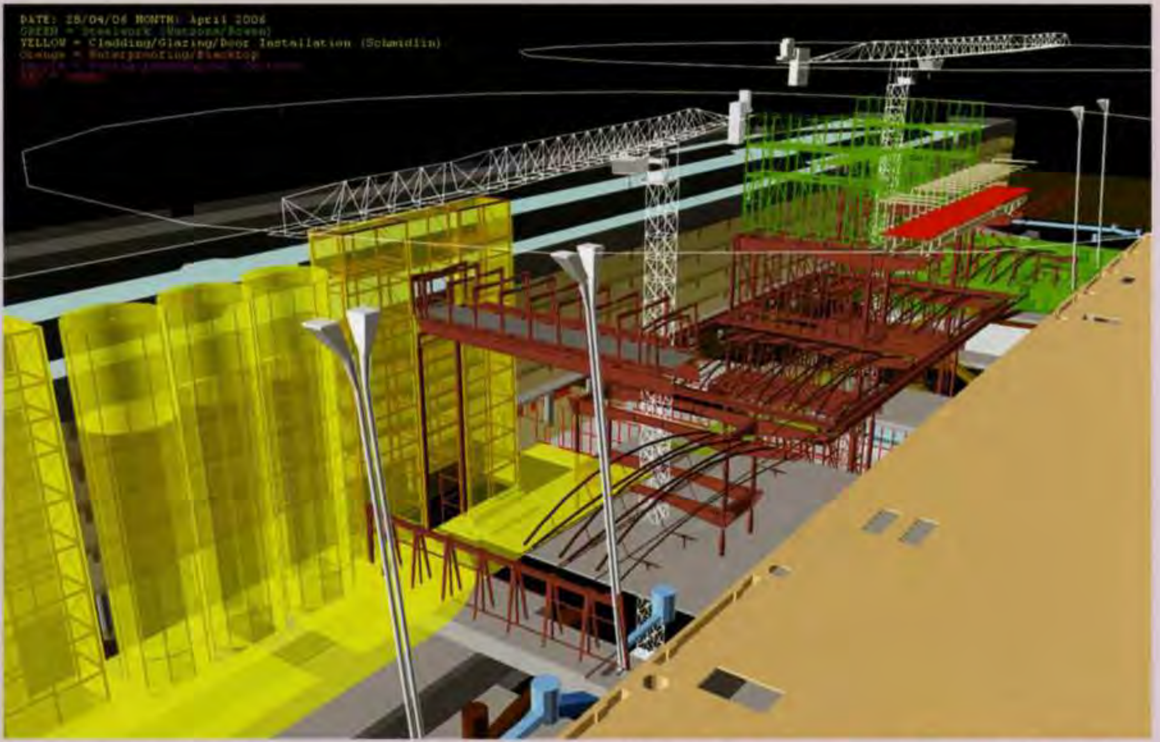
Essentially, it is a work planning process that adds time as a fourth dimension to programmes with CAD data (2-D or 3-D), creating a real-time graphical simulation of planned works. Key benefits include:

- clear visual communication of construction sequence to all
- early and ongoing co-ordination between contractors and stakeholders
- easy comparison of various programme phasing options
- immediate comparison: automatic link between graphics and programmes
- usefulness as a tool for reporting progress on site
- ability to be used at a macro or micro planning level
- overall time savings, due to increased logistics efficiency.

Programme activities are modelled either as specific work elements (in 2-D or 3-D), or more general worksites that cover the plan area relating to the activity. Programme dates are then linked to the worksites and elements to generate a live sequence showing where different trades/contractors, etc, are working at any one time. Public access routes and specific temporary works, like crane positions, can also be added. If the programme changes, the CAD model automatically changes to suit.

By reviewing the resultant sequences and interrogating them, potential clashes of different trades or contractors (and also scope gaps) can be identified months ahead of them occurring.

The simulation also serves as an important tool for pre-planning and communicating the project plan to all involved - particularly useful on large projects where one contractor may not be fully aware of the plans of others.



10. "Snapshot" of the Interchange 4-D model programme for 11 April 2006. The colours are contractor/discipline-specific and appear when work elements or exclusion zones are planned to be active/under construction on that day. When each activity is complete its colour reverts to a uniform realistic colour.

4-D at T5

BAA discussed, with Arup and others, the benefits and practicalities of 4-D planning for the Interchange Plaza, and appointed an Arup planner to co-ordinate the 4-D workstream alongside a 4-D CAD engineer. The commercially available 4-D software was studied, and *NavisWorks Timeliner* chosen as it was compatible with the SME, with *Primavera P3* planning software.

To set up the 4-D model, the team had to:

- clarify the 4-D construction plan's ultimate aim - who was it intended to benefit? BAA and contractors or primarily BAA? (answer: both)
- establish common structural terminology (to reduce any confusion)
- generate the organizational breakdown structure (including responsibilities and lines of communication)
- communicate to stakeholders the benefits of investing time and money in the exercise (and thus manage expectations)
- build an integrated programme with various project sections to be maintained by the four responsible planners
- establish existing CAD geometry and break down the elements to suit programme tasks
- establish the reporting process and weekly review meetings.

Initially a high-level integrated 4-D model was established identifying the overall build sequence, comprising the model geometry and programme generated from the planners' own detailed plans. As well as 3-D structures, the model geometry included contractor exclusion zones, crane usage, access, and general site logistics.

The steelwork and cladding contractors had to provide early input to the 4-D model - critical due to the impact and quantity of their works. A high-level strategy for the programme was then decided based primarily around these key activities.

Once the model contained sufficient detail, weekly planning sessions attended by all relevant personnel were held to continue the model construction as well as debate site clashes. The 4-D model simulation was projected on a large screen, showing sequences at any time interval, as little as daily in some critical instances. Once individual clashes or issues were resolved or a "best fit" way forward was decided, the master programme was revised, along with the graphics.

In addition to this weekly process of programme and model modification, followed by review, clash reports (looking three months ahead) and AVI (movie) files are produced ahead of the next meeting to improve communication on issues that still need attention.

Overall benefits

A primary benefit of the 4-D model is that the 3-D visualization of all construction works over time facilitates communication between T5 suppliers, forming a central forum for issues relating to construction of the interrelated works. During the 4-D model construction it was this buy-in and enthusiasm for the tool that contributed largely to its success.

Key target milestones were established for the 4-D model, and all were met. A high-level integrated 4-D plan was completed two months after initiation, and the detailed 4-D plan three months later.

These demonstrated that efficiencies of six months could be gained against the initial Tri-Project master programme. The 4-D model highlighted certain clashes and facilitated workable solutions to problems that could otherwise have caused delays, saving some £2.5M.

Additional benefits were in scouting ahead and risk mitigation. The visibility of the works, and the regular review meetings, prompted discussion of issues not yet considered or widely communicated, pre-empting them long before they would otherwise have become apparent. These discussions also included topics relating to design, scope of works, procurement, and others that were not construction planning-related.

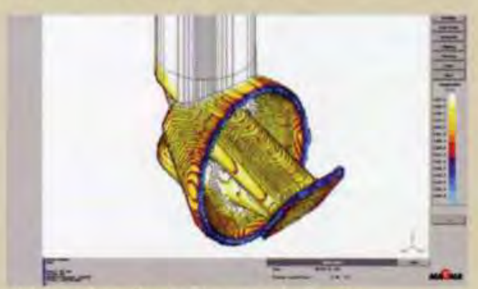
Follow-on works

To date, 4-D planning at T5 has shown that although the final product is an impressive and useful communication tool, the process itself is of the greatest value to the project. It has proved so successful that BAA has asked Arup and others to maintain 4-D modelling right to the end of the Interchange programme, as well as taking steps to implement the process on other areas. The underground transit system that links the main terminal building to its satellites and the area west of the multistorey car park have complex discipline interfaces and limited space. Both these 4-D models are well under way and will continue throughout construction.

11. Castings development.

a) Early physical model.

b) Architect's 3-D design model.



c) Image from the casting manufacturer's solidification simulation programme and using imported 3-D geometry.

d) Casting manufacturer's half-scale prototype.

e) Castings on site.

The object-model environment

Introducing ADT made this ideal possible on T5. ADT was based on standard AutoCAD, making it easy to use, and it was adaptable within the SME. ADT was fully co-ordinated with all disciplines and enabled 3-D models to be produced and viewed from any angle (Figs 3, 11). Also it enabled "object models" to be produced, whereby doors, beams, pumps, etc, could be identified as entities. The move to an "object-model environment" enabled objects to be asset-coded within the SME, very important for its ultimate purpose as a building management tool.

ADT also allowed consistent construction plans, sections, and elevations to be generated efficiently from the models. This was extremely important because it enabled the design teams to work in 3-D without affecting drawing production. The link between the drawings and the models was "live", so updates to the model were automatically imported when drawings were regenerated.

Applications of 3-D CAD on T5

There are too many such applications to list, but three varied examples are:

The main structural castings (Fig 11): These were developed completely in 3-D. The model shop produced many early physical models, from which 3-D design models were produced, which were imported to generate the structural drawings. They were then exported to the casting manufacturers as input data in their heat-dissipation analysis software and for use by their pattern makers.

4-D construction planning: as already described, 3-D CAD data were instrumental in bringing about Arup's 4-D planning work on T5.

Building retrofit: As the fit-out works advance, the "retrofit" team uses the SME to generate slices through the building 3-D model to assist with locating new openings and trimmers.

Conclusion

Within the T5 framework, Arup has contributed to producing a workable system to deliver BAA's vision for the SME on an extremely complex project. This has involved developing 3-D CAD design technology within the SME, developing CAD standards and processes, improving communication between teams, ensuring a complete and efficient handover of "as-built" 2-D and 3-D graphic files, and delivering BAA's AMA integration requirements. All this has undoubtedly contributed to reducing design and construction costs, and the T5 CAD standards now also form the basis for those used on BAA's other airport projects.

In a wider context, and perhaps even more importantly, T5 has shown a direction the future development of CAD systems in the construction industry might take, and how important are unified standards if maximum advantage is to be made of the CAD technology already available. There is much industry interest in the T5 example and the systems, standards, and processes developed here are already becoming the seeds of industry-wide standards.

Credits

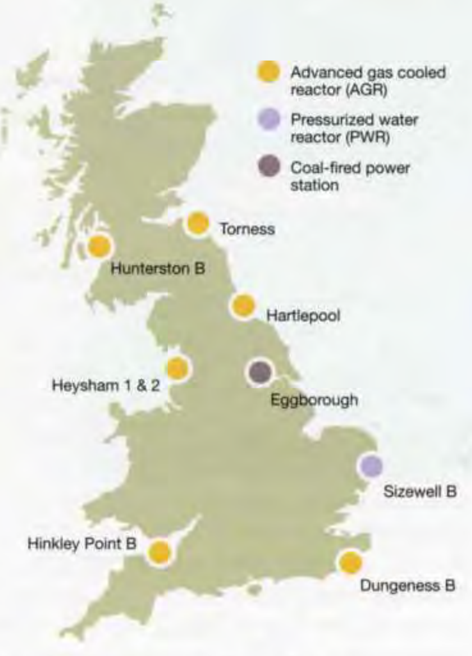
Client/developer/operator: BAA **Main tenant:** British Airways **Lead architect:** Richard Rogers Partnership **Production architects:** Pascall & Watson/HOK **Multidisciplinary engineer:** Arup – Graham Beardwell, Matthew David, Tarsem Kainth, Richard Matthews, Dervilla Mitchell, Alan Pepper, Simon Reynolds, Steve Roberts (principals) – Jon Attwood, Chris Bailey, Trevor Baker, Dominic Carter, Brendon Connelly, Robert Embury, Valerio Gianfranco, Chris Godson, Tom Honnywill, Bradley Jones, Vince Keating, Jonathan Lock, Gareth Mooney, Graham O'Driscoll, Nazir Omerji, Grant Ridley, John Wick, Adam Wildon, Jim Williams (CAD draughting/project management) **Substructure civil engineer:** Mott MacDonald **Campus civil engineer:** TPS **Services engineer:** DSSR/Arup **Principal contractor:** BAA/Laing-O'Rourke/Amec **Principal contractor (rail):** Balfour Beatty **Steelwork contractor:** Severfield Rowen Structures **Cladding contractor:** Schmidlin **Illustrations:** 1, 3, 9, 10, 11e BAA; 2, 4, 5, 8, Nigel Whale; 6, 11a, 11b, 11d Richard Rogers Partnership; 7 Amec; 11c William Cook, Burton

1. Sizewell B.

The regeneration of British Energy:

Partnering to deliver business benefits

Andrew Champ Caroline Passey



2. Location of British Energy power stations.

In 2002 the privatized UK nuclear power generator British Energy was in severe difficulties, and an unprecedented turnaround programme was required. Arup was appointed to restore British Energy as a "safe, profitable, and proud" organization.

Background

Wholesale changes have taken place in the UK electricity sector over the last 20 years. In the 1980s generation, transmission, and supply were under the jurisdiction of the Central Electricity Generating Board (CEGB) for England and Wales and the South of Scotland Electricity Board (SSEB) for Scotland. Under the Conservative Government of the 1990s the electricity sector was divided up and privatized. This resulted in:

- a small number of private wholesale generators supplying power into a "pool"
- regionally-based, privately-owned supply companies
- a transmission network operator (the National Grid).

Sensitivities around nuclear fuel caused the nuclear generation facilities to be excluded from the first round of privatizations, but in the mid-1990s a strategy was devised to take this sector into private hands. Two companies were formed. The first was British Energy (BE), to run Britain's eight most modern nuclear power stations. The second was Magnox Electric, responsible for the older stations based on the Magnox technology. Magnox Electric subsequently joined with British Nuclear Fuels Ltd (BNFL). In addition, the United Kingdom Atomic Energy Authority (UKAEA), the pioneering statutory body originally set up in 1954 as responsible for the whole of Britain's atomic research programme, refocused on decommissioning.

In March 2001 the New Electricity Trading Arrangements (NETA) replaced the "pool" in England and Wales. The market subsequently expanded to include Scotland and is now referred to as BETTA (British Electricity Trading and Transmission Arrangements), a bilateral (supply-and-demand) trading market for the sale and purchase of electricity, with physical balancing carried out by the National Grid. This market includes both generators and consumers, and relies on free market, supply-and-demand mechanics to set prices. The obligation is on the contracted parties to physically, or financially, fulfil their contracts.

The net effect is that, in times of excess, like summer, supply prices are low, but when demand outstrips supply prices rise. Equally, any imbalance on the supply and demand caused by failures in the generators or consumers to fulfil their contracts is penalized, eg any inability to meet supply obligations leaves the market short, which in turn drives prices up. In such circumstances the supplier is obliged to meet his contract and has to "buy in" the power from the market, therefore penalizing the supplier's unreliability. Retail pricing is regulated by Ofgem (Office of Gas and Electricity Markets), to protect consumers from volatile pricing and overcharging by the supply companies.

Structure of British Energy

BE is a UK electricity generator wholly owned by private investors, and listed on the UK stock exchange. It has a unique position in respect of its market influence and size, as it generates approximately 20% of the entire UK power supply. At the time of privatization, the primary components of BE's business were six nuclear power stations in England (registered capacity 7281MW) and two in Scotland (registered capacity 2539MW). BE continues to operate these stations, with a total registered capacity of 9820MW. Seven are advanced gas-cooled reactors (AGRs), a design and technology unique to the UK. The eighth, Sizewell B, is a pressurized water reactor (PWR), based on Westinghouse design and technology and widely adopted internationally, but here tailored specifically to a UK design.

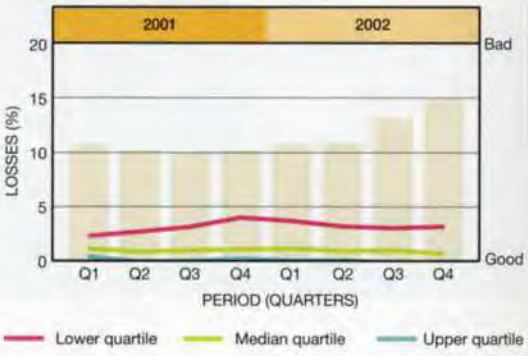
In 1999 BE acquired the retail supply business of South Wales Electricity, but it was sold shortly after in 2000. The same year also saw the acquisition, from the generation/supply/retail company National Power, of the 1970MW Eggborough coal-fired station in England, in an effort by BE to try and gain greater flexibility and a measure of security against outages of its nuclear plants.

BE was structured as follows:

- British Energy Generation Ltd (BEGL), owning and operating the six English nuclear stations and holding the supply licence for the direct supply business
- British Energy Generation (UK) Ltd (BEG(UK)L), owning and operating the two Scottish stations
- Eggborough Power (Holdings) Ltd (EPL), owning and operating the Eggborough coal-fired station
- British Energy Power and Energy Trading Ltd (BEPET), selling all of BE's output (other than in relation to the direct supply business), and managing market risks.

BEGL and BEG(UK)L later merged and became a single generation division. Eggborough was operated as a standalone business, as was BEPET. It was the performance of the core nuclear generation business that was letting BE down, and this became the focus of the Performance Improvement Programme (PIP).

3. Hinkley Point B.



4. The decline of British Energy, showing the overall increase in its Unplanned Forced Loss Rate (UFLR) compared to WANO (World Association of Nuclear Operators) quartile rates.

British Energy performance

Following privatization, BE's strategy was to focus on generation and not become a fully vertically-integrated electricity company, ie a generation, supply, and retail business like EDF Energy, National Power, etc. It also specifically focused on nuclear generation (with the exception of Eggborough) and did not horizontally diversify into a mixed portfolio player in order to match the flexibility demands under NETA. Also, it became a low-cost generator, reducing costs by cutting investment in asset renewals, recruitment, and training.

In this role BE seemed to perform well for a time, but the assets were being "sweated", ie made to work as hard and as long as possible to maximize revenue whilst minimizing maintenance and downtime to restrict costs. This could not last. The privatized electricity sector meant that new international competitors could now compete in the UK market, resulting in an influx of generators, greater choice for consumers, and reduced wholesale electricity prices. This, coupled with the now poorly-performing BE fleet, meant that revenues generated by BE's power stations decreased markedly during 2002. By now the eight nuclear stations had an average capability of 63% (ie their actual generation as a proportion of their theoretical optimum), driven by lack of investment.

The high proportion of non-avoidable costs (those that cannot be avoided by ceasing to generate or shutting down stations) in BE's cost structure associated with its nuclear stations gave little opportunity to respond by lowering prices yet further. Outside BE's control, a price fall of £8.50/MWh (Megawatt-hour) occurred between 2001 and 2003, equivalent to an annual reduction of income of £642M pa on a total output of 75TWh (Terawatt-hours). Neither electricity trading contracts nor the direct sales business had sufficiently mitigated the effect of this price fall on BE's income.

As a result of these factors, BE's cash position deteriorated significantly during summer 2002, with the cash balance reducing from £231M at the beginning of April to only £78M at the end of August. In September 2002, in the light of a failed bond offering and a decline in the company's credit rating (below that of "investment grade"), BE's board received legal advice that the company would not be able to draw down credit facilities. Indeed, drawing down on these facilities would have been equivalent to trading without any reasonable prospect of avoiding insolvent liquidation.

Government intervention

In consequence, BE sought financial support from the UK Government in order to avoid administration proceedings. The Government approved the offer of £600M of working capital and trading collateral credit facility, but on condition that BE put in place a restructuring plan and a PIP.

BE being a private company, any Government aid could be seen as unfair to the other private operators in that sector, and so on 7 March 2003 the UK Government notified BE's restructuring plan to the EU Commission. It consisted of seven measures agreed between BE, its major creditors (including the nuclear fuel processing company BNFL), and the Government. Targeted at turning around the root causes of BE's current plights, these were:

- *Measures A & B:* linked to the funding of nuclear liabilities and concerning the fuel cycle agreed with BNFL, respectively
- *Measures C & D:* targeted at the standstill measures (performance improvement) and significant creditors' restructuring package
- *Measure E:* introduction of a new trading strategy to counter the lack of current hedges, ie trades in the opposite direction to offset any risk, in the manner of an insurance policy
- *Measure F:* asset disposals to help finance the restructuring
- *Measure G:* local tax deferrals.

Arup involvement

As a consequence of the aid package, BE invited companies to tender for the PIP. Arup was selected in open competition, firstly to identify the areas of attention and secondly to deliver the required operational improvements. The overall programme strategy (Fig 5) was developed in three main phases:

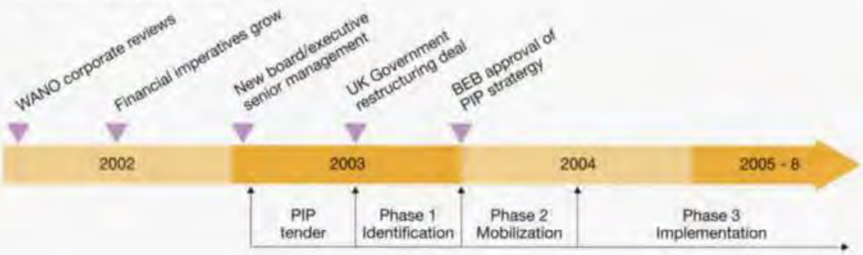
Phase 1: Investigation. This was to identify the areas of improvement and establish the vision.

Phase 2: Mobilization. This would involve setting up the programme office and establishing the infrastructure for change whereby new people would be put in place and new processes embedded in the stations.

Phase 3: Implementation. This would be a three-year programme of asset management, "soft" cultural changes and "hard" plant renewals, all aimed at delivering affordable, sustained improvements.

In October 2003 Arup embarked on the initial investigation, the findings of which were presented to the BE Main Board of Directors in December 2003.

5. Overall programme strategy.



Phase 1: Investigation

Around 20 Arup technical personnel (including Rossmore, Severn Trent and Entergy) observed and shadowed all departments of BE's headquarters and the eight stations for 10 weeks. The teams reviewed operational performance, asset condition, organizational alignment, processes, procedures, and human behaviours across the entire company. The teams were divided up to review various sites at the same time for maximum efficiency, and were co-ordinated by an Arup project manager. The information was gathered and distributed in real time via a secure Arup extranet site.

The key financial driver for change was the high cost of unplanned losses. In the three preceding years these had amounted to 32.5TWh of generation, with an estimated total cost to BE of £925M. Fundamental issues in equipment reliability (systems health, asset management, investment prioritization and planning, and project delivery) and work management (schedule adherence, supply chain management) needed to be addressed.

An output of 73TWh over four years - an increase of 9.6TWh over the 63.4TWh output achieved in 2002/03 – was deemed to be a feasible improved target level of fleet output. The programme to achieve self-financing of this and improve fleet reliability highlighted operational focus and human performance - in particular, the need to address the issues at the root of the persistently high levels of unplanned losses.

Industry benchmarking, especially from the USA, indicated that a sustained focus on cost reduction had reduced both staff numbers and expenditure on maintenance and equipment (20% underspending year on year), taking BE well below internationally recognized benchmarks for the industry.

The Arup team saw these reductions, and a loss of emphasis on good operational and managerial processes, as the root causes of the problem. A programme of targeted recruitment and training was required, and an essential restructuring of the company's management. A basic shift in the cultural foundation of the company behind a solid leadership and shared vision was critical to success.

This turnaround programme would cost BE £700M-£1bn over five years in "hard" capital expenditure, in addition to the cost of "soft" people and process issues. BE absorbed the findings over several months, and then made a positive decision to press ahead with what would be the biggest-ever turnaround programme in the nuclear world. No one had ever tried to improve the performance of eight operating nuclear power plants at the same time.

The PIP strategy

The PIP strategy breaks down into six fundamentals:

Foundation

The three foundation workstreams of "organization and structure", "people and leadership", and "culture change" lie at the root of the PIP. The Arup team's summary conclusions were that without them, nothing of substance could be sustained, and that BE's organizational structure required fundamental change to restore a proper balance between safety, reliability, and cost. To achieve this, BE would need powerful and positive leadership, underpinned by a culture that encourages learning and development.

The workstreams' overall objectives are to:

- implement a corporate and site reorganization to ensure that competency, operational focus, and accountability exist at every level
- instigate a cultural transformation, moving employees from "Can't do; think 'station'" attitudes to "Can do; think 'fleet'", through establishing clear leadership, formalizing standards, and holding people accountable for executing company initiatives and standards to support nuclear excellence
- put the right people in the right place, with the right leadership skills and attitudes to do the job, and so close the gap between the overall leadership abilities existing within the organization and what is required to deliver the necessary changes
- change the values of the organization so that it is driven consistently by quality and not just by cost
- rebuild trust with the staff, and challenge every individual to move out of his or her "comfort zone".

Training

Training is fundamental to BE's recovery, and essential for sustained performance improvement in all areas. As such, training has a long-term indirect impact on all the key performance indicators (KPIs), and develops and maintains a knowledgeable and skilled nuclear workforce by:

- creating a standardized and structured approach to the training and qualification of personnel
- reinforcing management expectations
- appropriately engaging management to ensure training effectiveness and performance improvement
- ensuring training is provided to the people who need it, when they need it, and eliminating the role of training as a "standard" corrective action for all performance deficiencies.

Human performance

The human performance strand in the PIP strategy reviews organizational/workplace factors that prevent individuals achieving the performance level required. It delivers:

- increased and more consistent use of human performance tools throughout the organization
- BE-wide human performance training, including task observation and coaching (training and support from credible coaches with support from WANO and the Institute of Nuclear Power Operators), human performance leader authorization training, and team-specific training
- more and better task observations throughout the organization, resulting in a consistently heightened profile of the human performance tools
- reduction in Nuclear Reportable Events over time (there may be a perceptible increase as the tolerance for events is reduced)
- focus by the human performance authorized leaders on timely support to staff and managers.

Equipment reliability

Phase 1 identified that the material condition and equipment performance of the nuclear stations needed significant improvement, and were adversely impacting the stations' reliability with many long-standing problems. It was necessary to:

- establish system health departments with system health engineers, using a proven, fleet-wide approach to improving overall plant reliability
- introduce system health indicator programmes to drive management attention
- reduce defect backlogs through using dedicated additional resources while improved processes take root
- implement leak reduction programmes in conjunction with additional training for the stations' craft resource
- establish a proper planning capability to manage the company's asset investment plan, aimed at delivering company strategy set by the Executive
- oversee the additional capital expenditure available to improve plant material condition and overall equipment reliability
- make the existing risk assessment tool consistent with other company risk registers
- ensure that these changes are internally consistent with proposals within BEGL's Engineering Division and the new project delivery organization.

Work management

A better understanding was needed across the fleet of the work management process, and of the roles and responsibilities of those engaged in it. The process delivery organization needed to be developed and enhanced, and management information on this process's effectiveness be improved so that managers could focus their efforts on problem areas and drive improvements to achieve desired outcomes. Actions were to:

- develop a common understanding of the management of work process
- clarify roles and responsibilities and empower people to achieve the required performance
- deliver integrated work schedules developed through multi-disciplinary input and work group accountability
- develop enhanced management understanding of, and commitment to, the work management process
- implement a new station organizational structure and develop the station resource plans and secure resources
- commit to removing barriers to improving process performance
- improve teamwork, communications, ownership, and accountability
- ensure that the work management process supports long-term equipment reliability and reliable post-outage operations
- develop and deliver a role-based training programme
- deliver the supporting enablers that were needed to maximize the effectiveness of the work management process
- deliver measures that support station accountability and benchmarking
- develop an organization flexible enough to respond to emerging station needs, ie protect the plan

Table 1: Benefit alignment

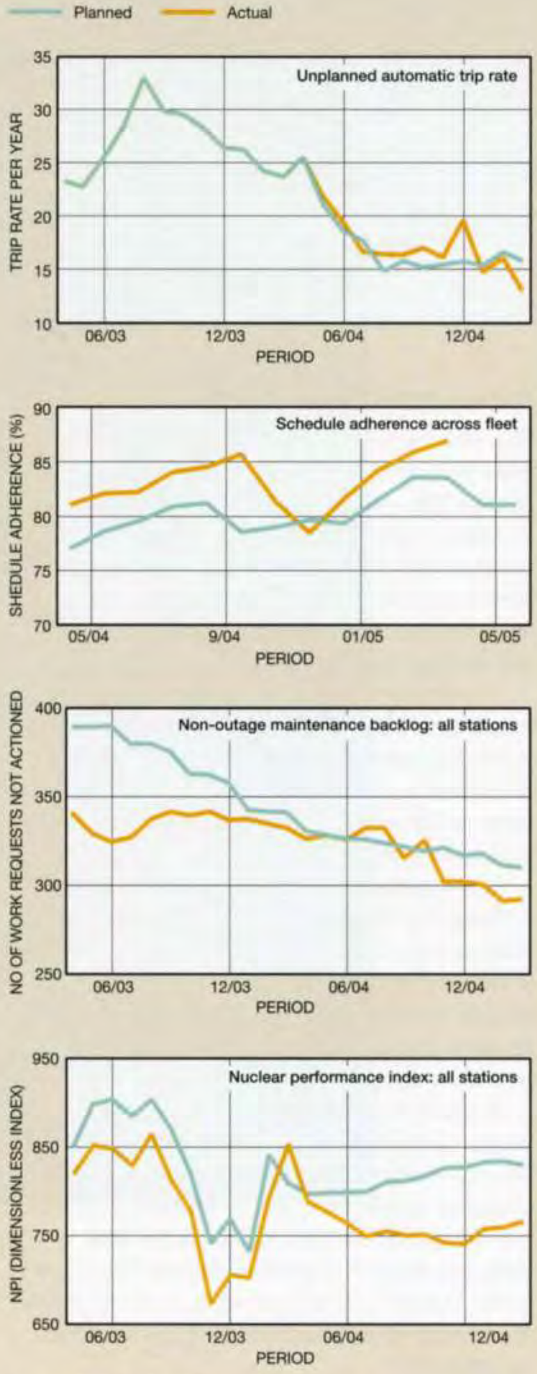
Tier	KPI	Foundation	Training	Human performance	Equipment reliability	Work management	Operational focus
1	Accident frequency rate						
	Nuclear performance index	●	●		●	●	
	Nuclear reportable events	●	●	●	●	●	
	Non-outage defect backlog	●	●		●	●	●
	Output	●	●		●	●	
	Unit capability factor						
	Environmental incidents	●					
2	Scope stability	●			●	●	
	Forced loss rate						
	Unplanned automatic trip rate	●			●		
	Work schedule adherence	●			●	●	
	Lost time accidents	●					
	Trainee withdrawal rate		●				
	Station condition reports generated		●			●	●
	Standing CCR/MCR alarms				●		●
	Overdue CAPRs						●
3	Open simulator work requests		●				
	Management observations of training		●				
	Percentage of statutory essential training "in ticket"		●				
	Training assessment pass rate		●				
	Training schedule adherence		●				
	Overdue corrective actions						●
	Average age of open investigations – ACINs						●
	Average age of open investigations – SACI						●
	Average age of open corrective actions – CORR						●

- ensure that the work process and results are continually tracked, trended, evaluated, and improved
- address data issues
- deliver data enhancement
- enhance product to enable the corrective action programme
- improve outage planning, process, and readiness indicators, and adopt a standard approach across the fleet
- introduce minor maintenance process and "tool-pouch" working across the fleet.

Operational focus

Finally, for sustained performance improvement, there was a need to drive a step change in BE's operational focus, such that all staff would be obliged to support the safe and reliable operation of the nuclear stations. To ensure that operational challenges are identified and aggressively solved before they impact on the stations, the operational focus fundamental would deliver:

- an embedded corrective action programme that effectively identifies documents and resolves conditions that are adverse to quality
- an enhanced operating experience process that effectively evaluates and disseminates information in a way that can be used to improve plant safety and reliability
- a greater fleet-wide focus through a number of corporate functional area managers
- a consistent approach to the use of and adherence to procedures, with the management visibly reinforcing expectations
- BE-wide training on the meaning of operational focus, so that each work group can achieve a company-wide understanding of how activities need to be aligned in order to achieve safe, reliable operation
- a culture where it is recognized that "nuclear is different" and where a questioning attitude is consistently demonstrated.



6. Leading KPI trends.

7

Phase 2: Mobilization

BE's new vision was to become a "safe, profitable and proud" company. Arup's Phase 1 report detailed 250+ recommendations to be carried out, as well as the £700M-£1bn expenditure on resources and plant. All this would require considerable planning and management, and so Arup was retained to deliver a tangible action plan and strategy for the execution.

The Phase 1 findings identified the extreme sensitivity of BE cash-flows, and hence affordability of the programme at any phase, to further unforeseen and substantial disruptions to output which could curtail the high levels of expenditure associated with the programme.

Based substantially on the work Arup had done in Phase 1 in international comparisons and best practice experience, the structure of the recovery programme revolved around six fundamental strands: foundation, training, human performance, equipment reliability, work management, and operational focus.

These involved addressing the so-called "soft issues" of management and operational practice (such as maintenance procedures) through a range of training programmes and other initiatives to improve work processes, accountability at all staffing levels, and behaviours. Re-installing a true "safety culture" was recognized as a priority, around which many other aspects of performance would be addressed.

Arup recognized that in order to deliver change within BE's organization, that organization itself needed to be brought into the change, which had to occur at all levels and at all locations across the BE fleet.

To facilitate this, the programme structure (Fig 8) was put in place during the mobilization phase, and Arup supplied specialists in asset management, cultural change/human factors, project management, operational focus, human resources, risk management, processes and systems, planning, supply chain, and commercial/transactions.

The formation of this programme structure had numerous clear benefits:

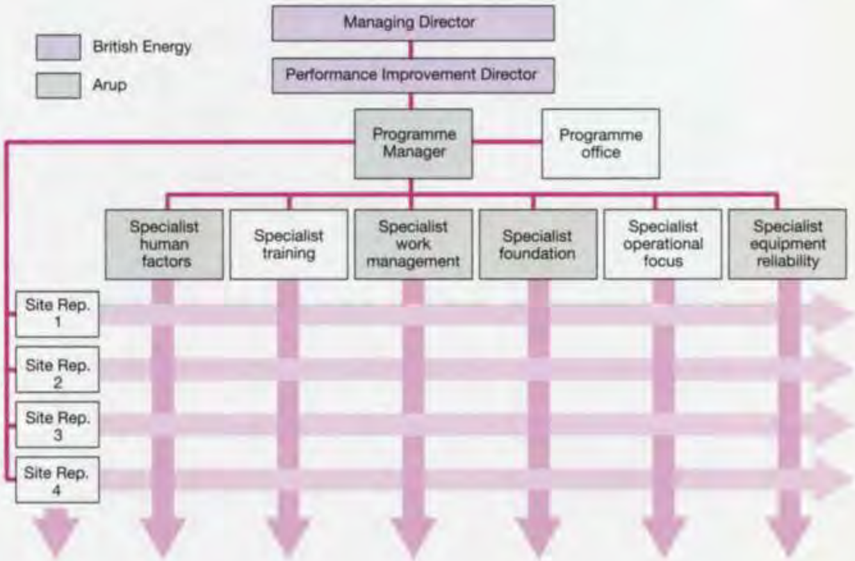
(1) It allowed for senior BE management to retain "sponsorship" and "visibility".
(2) It gave BE retained ownership.
(3) It concentrated effort on the delivery of an action plan (ie conversion of the recommendations into scope statements).
(4) It enabled BE site-based staff to have input into the formulation of the plan.
(5) It allowed interface with operational issues.
(6) It maximized BE staff involvement for transparency.
(7) It maximized the value of international experts (not all Arup).
(8) It gave a clear management structure that could be seamlessly transitioned into the delivery phase.

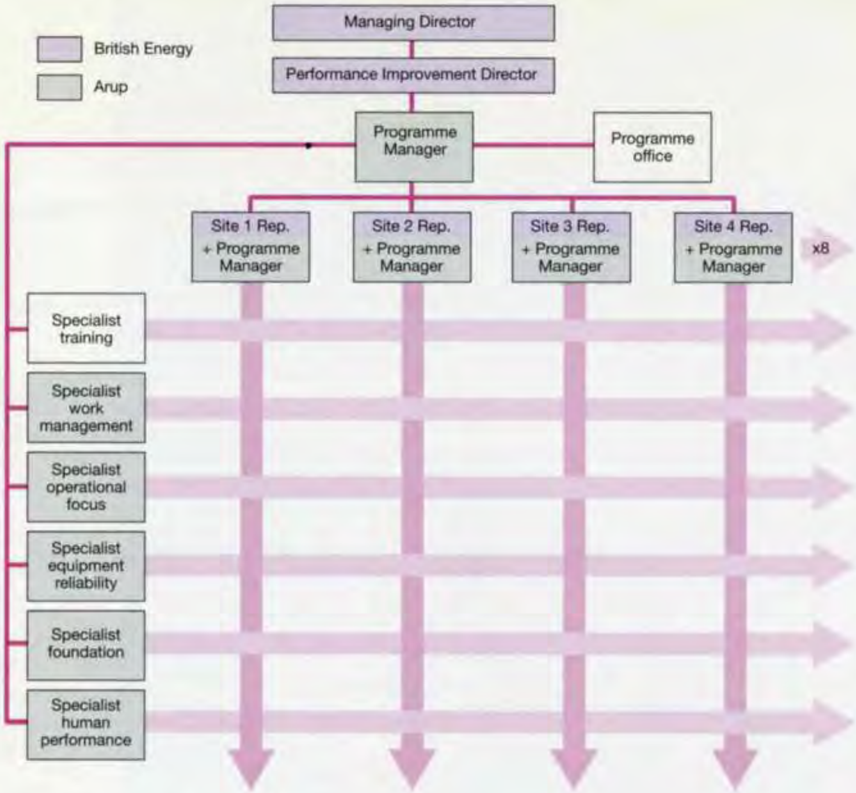
As a result, Phase 2 gave:

- clearly-defined scope statements for each work-stream across all locations
- an integrated *Primavera P3e/c* cost and resource-loaded schedule of work over three years. (*Primavera P3e/c* is planning/scheduling software that can operate and integrate across numerous locations at the same time, allowing – in this case – nine operators to update and monitor progress against the plan in nine different locations at the same time.)
- an established programme office with risk, change, systems, stakeholder, communications, and reporting management established
- buy-in from the BE staff
- sign-off from the BE Board to proceed with Phase 3.
- a clearly-defined cost/benefit tracking system.

Due to the high profile and the potential national consequences, external interest in BE was high. Subsequently this plan was reviewed and approved by the UK Government's Department of Trade and Industry, the private shareholders and investors, and the BE Board of Directors.

8. Phase 2 (mobilization) structure.





9. Phase 3 (implementation) structure.

The rise of British Energy

Phase 3: Implementation

While the emphasis of Phase 2 was on an action plan, Phase 3 concentrated on delivering the required actions at the required locations. The nuclear stations now took the primary role of delivering the programme of work prescribed in the scope statements under the guidance of local project managers, while the specialists transferred to roles that would monitor the quality, consistency, and effectiveness of the actions across the fleet (Fig 9).

One year into Phase 2 (after two years' involvement with BE) the effectiveness of the programme across the entire BE fleet was assessed in April 2005.

The benefits

Reductions in expenditure were dictated by the business because of substantial expenditure on legacy issues in 2004/2005 (ie replacement of large amounts of old cast iron pipework on numerous sites), and consequential financial implications of the loss of output. Emergent work amounted to £59.4M in 2004/2005, instead of the £12.1M planned, so that planned capital expenditure amounted to £53.2M rather than £92.6M as intended. Despite this significant underspend in 2004/2005, the intended work had been completed 10% ahead of schedule, and material performance improvements were achieved.

10. Torness.

Table 2: Performance of key performance indicators (KPI) ahead of WANO "Best in Class" targets for 2004/05.

KPI	Value improvement on year
Non-outage defects backlog	+55%
Accident frequency rate	+40%
Unplanned automatic trip rate	+30%
Work schedule adherence	+28%
Other benefits include:	
Nuclear reportable events	38%
Scope stability	20%

Conclusion

The April 2005 effectiveness review also noted that of the 10 WANO and BE-identified KPIs, from December 2003 and November 2004 respectively, four (see Table 2) outperformed the "best in class" targets set for 2004/05, and excluding exceptional items, positive trends were visible across all 10 WANO/BE KPIs. Overall progress was as planned, with transition of fundamentals into line on target to be completed by October 2005. A further indication of progress came in January 2006 when BE moved from FTSE 250 up to FTSE 100 Index status.

WANO itself acknowledged the positive turnaround of BE to have been "exceptional" following its review of BE's progress with PIP, and all indications were positive for the achievement of the longer-term PIP objectives. "However, this will depend on continuing support of the BE Board and the level of investment in PIP."

Andrew Champ is an Associate Director of Arup with the Major Projects group in London. He is development director of the group's expansion on major programmes and projects.

Caroline Passey is Marketing Officer with Arup's Major Projects group in London, tasked with the generation of new projects and market and investor analysis.

Credits

Client: British Energy Generation Ltd **Performance improvement consultant:** Arup – Graham Bell, John Bond, Andrew Butt, Jonothan Carver, John Cavill, Andrew Champ, Mike Coburn, Clive Cooke, Keith Evans, Matt Exton, Nick Field, Bob Foden, Adrian Fox, Olivia Gadd, Jim Gallagher, Annie Gavin-Adamson, Peter Gist, Mike Grayson, Bob Gregory, Colin Harris, Richard Hatton, Terry Hill, Clement Ho, Andy Horton, Mark Judge, John Lyle, Michael Lytrides, John Miles, Paul Misson, Nigel Morris, Ed Pask, Lee Pascoe, Azhar Quaiyoom, John Robson, Chris Royle, Richard Sands, Sam Skivington, Miriam Staley, Warren Steele, Alan Thomson, Martin Treharne, Gary Walker, Jacqui Walker-Sutton, Alan Walne, Ian Webb, Nick Whiting, Justin Wimbush, Martin Young **Illustrations:** 1, 2, 4-6 Nigel Whale; 7 Duncan Walker/iStock; 3, 10 British Energy

Why rails crack

Gauge corner cracking on the British network: Analysis

Robert Care Steve Clark
Mark Dembosky Andy Doherty

Background

On 17 October 2000, a high-speed *Intercity* train from Leeds to London on the East Coast Main Line derailed at Hatfield, Hertfordshire, resulting in four deaths and over 30 injuries. It soon became clear that a break in the high rail on a 1500m curve was to blame. Investigations revealed numerous cracks on the running band surface. When one of these penetrated to the base, multiple fractures of the railhead led to disintegration over some 30m. The potential for gauge corner cracking (GCC), as the phenomenon was initially called, to lead to railhead break-up made the then UK rail infrastructure operator, Railtrack, begin a rigorous system-wide inspection programme.

The first part of this article[4] outlined the role of Arup, together with Transportation Technology Center Inc, in the five-year investigation, and showed how the cracking was more properly ascribed to "head checking', a particular type of the more general phenomenon of rolling contact fatigue (RCF).

How was this caused? Further investigation demonstrated at least three separate modes of RCF initiation and growth:

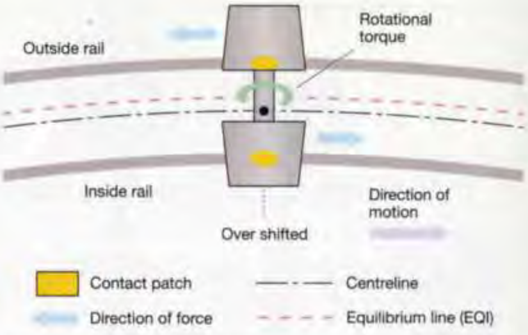
- *Mode 0: steady state, generally occurring on tight curves*
- *Mode 1: bi-stable contact, generally on medium curves*
- *Mode 2: convergent motion, generally on shallow curves, straight track, and switches and crossings (S&C).*

The mechanism of RCF generation

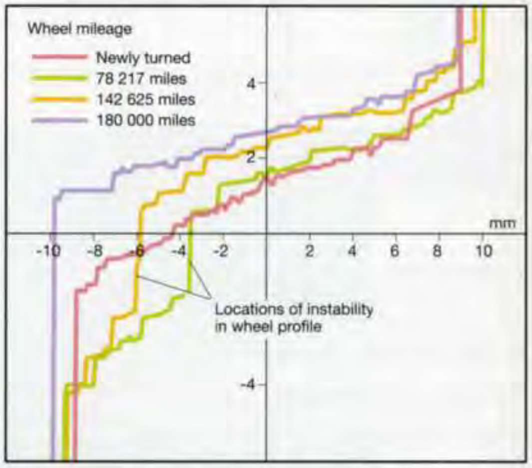
To illustrate Mode 0 RCF initiation, Fig 12 shows a wheelset negotiating a curved section of track. The longer length of the outside rail relative to the inside rail, and the tapered profile of the wheels, dictates that the equilibrium line (EQI) is offset from the centreline of the two rails. When the axle shifts past EQI, it attempts to steer back towards the centre of the track, applying longitudinal steering forces to the rail at the wheel-rail contact patch. These forces are opposite to the direction of motion on the outside rail, but in its direction on the inside rail. Because of the wheel-rail geometry, accompanying lateral sheer forces are also generated at the wheel-rail contact patch. Together, these tangential forces generate shear stresses in the rail that, when excessive and exceeding the shakedown limit of the rail material, can cause RCF. In tight curves, this steering behaviour of the axles, particularly the lead axles, can become "saturated", leading to Mode 0.

This can occur irrespective of the profile condition of a wheelset with typically tapered wheels. As conformal wheel wear occurs, or with highly conformal profile designs, initiation is thought to shift towards Mode 1.

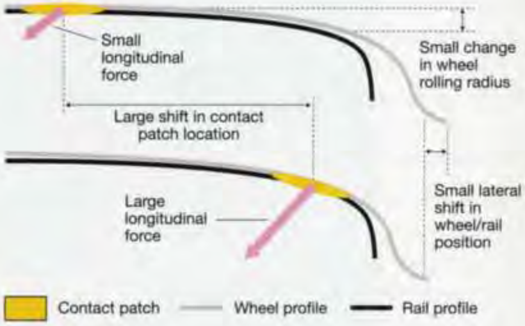
In a rolling radius difference plot (Fig 13) for a group of wheels measured from an electrical multiple unit operating on the British network, the wheelset mileages for the profiles are zero (newly turned), 78 217 miles, 142 625 miles, and approximately 180 000 miles. The horizontal axis is the wheelset lateral shift between the rails, and the vertical axis the rolling radius difference.



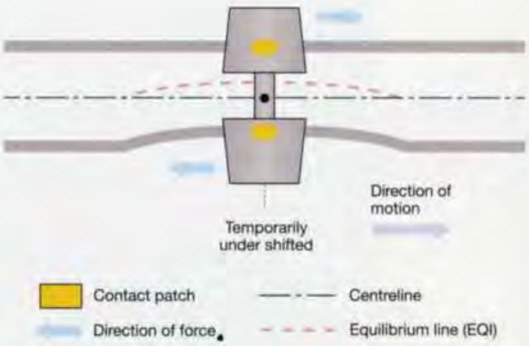
12. Steady state steering behaviour.



13. Rolling radius difference plot showing bi-stable behaviour.



14. Conformality and bi-stable behaviour.



15. Convergent motion steering behaviour.

In the rolling radius difference plot for the 78 217-mile and 142 625-mile wheels, locations of conformality are pointed out. If the wheelset shifts to these points of conformality, the contact patch is thought to become unstable and vacillate between the high and low rolling radius differences. Thus if the wheelset shifts across these points of instability, even a very small change can cause significant 'step changes' in rolling radius difference (Fig 14). These are thought to cause rapid and transient tangential forces at the wheel-rail contact patch that can generate the high shear stresses that cause RCF. This is Mode 1 of RCF generation.

Modes 0 and 1 generally depend on curved track as one element in the mix of events that generate RCF. Fig 15 helps explain how RCF can occur in straight track or track with very shallow curves (Mode 2). Here the wheelset is traversing a straight section of track, the lower rail having a lateral alignment perturbation (highly exaggerated for illustration). This shifts the track centreline and results in a shift of the equilibrium line (EQl). When such a lateral shift requires a dynamic response faster than the kinematic wavelength of the bogie, the wheelset experiences a very rapid lateral shift relative to the rail. This results in a rapid change in rolling radius difference that, like Mode 1, generates a large tangential force and accompanying sheer stresses. This is Mode 2, and is what appears to be the mode of RCF generation most often seen in straight track and junctions.

Mode 2 RCF in S&Cs

The occurrence of RCF in S&Cs merits further discussion. Most RCF found in junctions is in clusters, and generally occurs where there are lateral geometry misalignment features, and therefore, is thought to be initiated through Mode 2. Importantly, these features tend to be of a short wavelength and are typically well within the railway's prescribed operating standards.

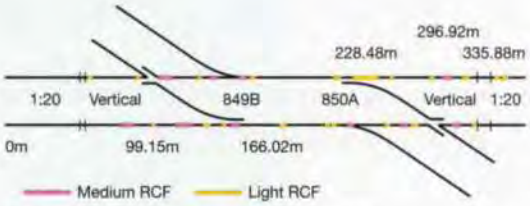
Ruscombe Junction on the Great Western Railway (Fig 16) was chosen for detailed inspection, dynamic modelling, and analysis in a WRISA study[5]. The test site comprises a trailing and leading switch in a crossover, and visual inspection identified short clusters of RCF (Fig 17) that often changed from one rail to the other within one sleeper length.

Detailed vehicle dynamic modelling quantified the wheel-rail interface behaviour of a Class 43 locomotive through this site, and analysis of the output (Fig 18) demonstrates Mode 2 RCF generation. The top plot shows vehicle dynamics output of wheel and rail positions. The axle length is replaced with a nominal 8mm flange-gauge face distance to demonstrate the lateral displacement of the wheel with respect to the rail. With the wheelset moving from left to right, the top line represents the left rail, the bottom line the right rail, and the middle line the axle centreline (less the axle length).

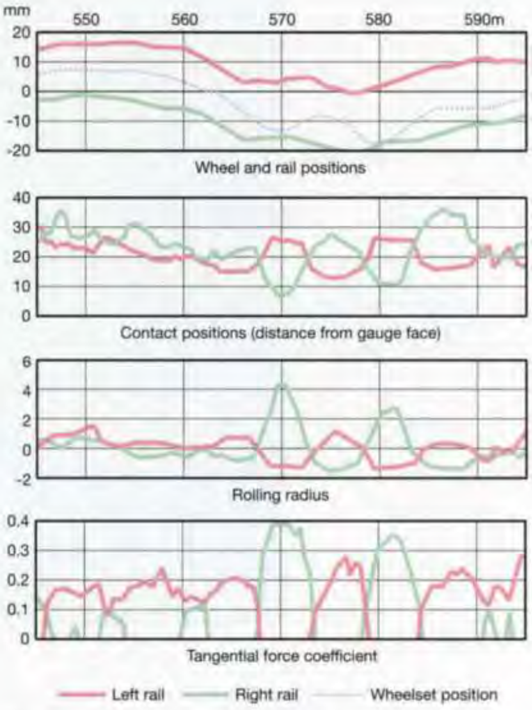
The rails have a continuous lateral shift towards the right of approximately 10mm over about 20m. The wheelset can negotiate this shift through its designed steering capabilities because the rate of change is within the kinematic wavelength of the bogie. At approximately 23m (about 568 on the horizontal axis of the plot), the change lateral shift abruptly stops. The wheelset - already moving towards the right following the previous lateral shift - cannot negotiate the rapid rate of change and converges onto the gauge corner/gauge face of the right-hand rail (at about 570 on the horizontal axis). Attempting to correct the over-steer condition, it then moves away from the right-hand rail, but over-corrects its motion. The rails then begin a lateral shift to the left, but the wheelset is moving to the right due to its attempt to correct the previous over-steer. Again, the wheelset converges on the right-hand rail before starting to correct itself to the left-hand lateral shift of the rails.

Fig 18's second plot presents the contact position as distance from the gauge face. At the points of convergence, the wheels have moved towards and away from the gauge faces of the right-hand and left-hand rails respectively, and away from the gauge face of the left-hand rail. The third plot shows, again at the convergence locations, significant and rapid change in rolling radius difference. The fourth plot presents the tangential force coefficient (ratio of tangential to normal force).

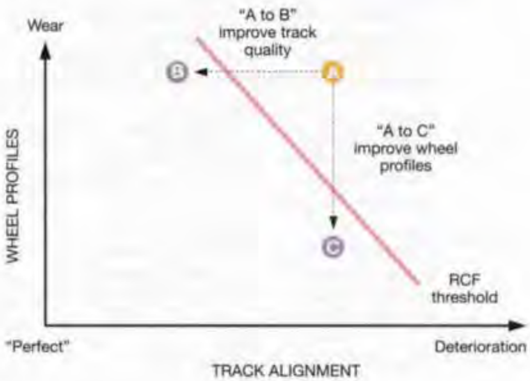
16. Ruscombe Junction on the GWR; the "kinks" in the track that contributed to its choice for analysis and study are clearly visible.



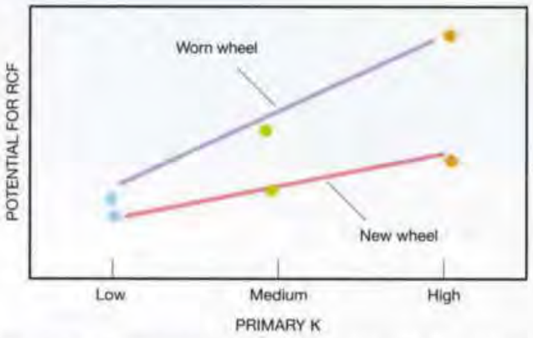
17. Ruscombe Junction and RCF locations.



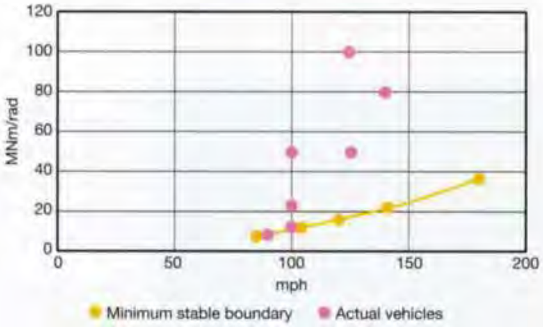
18. Output from VAMPIRE modelling of Ruscombe site.



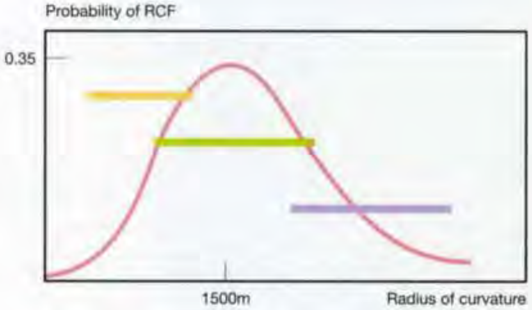
19. RCF threshold and the wheel-rail interface system.



20. RCF potential as a function of primary yaw stiffness and wheel wear. Higher stiffness means higher curving forces. More tread wear means more conformality, increasing contact on the RCF-sensitive gauge shoulder.



21. Sample distribution of primary stiffness of British fleet. The minimum stable boundary is an estimate of the lowest values necessary to maintain stable running at the indicated speed. For various reasons, many vehicles have much higher stiffness.



	TRACK	VEHICLE
🟨	**Mode 0** **Steady state curving** Remadial measures: Primary - Grinding Secondary - Lubrication	**Mode 0** **Steady state curving** Remadial measures: Primary - Primary stiffness Secondary - Lower conformality
🟩	**Mode 1** **BI stable contact** Remadial measures: Primary - Grinding Secondary - Alignment	**Mode 1** **BI stable contact** Remadial measures: Primary - Lower conformality
🟪	**Mode 2** **Convergent motion** Remadial measures: Primary - Alignment Secondary - Grinding	**Mode 2** **Convergent motion** Remadial measures: Primary - Lower conformality

22. RCF modes and corrective actions.

The high tangential forces at the locations of convergence are easily seen, and it is here that RCF is observed and thought to be generated by Mode 2.

Further analysis was performed, taking into account improved track geometry and improved wheel profiles. While some benefit would have resulted in this instance from operating the rolling stock with newly profiled wheels, the major improvement would be achieved through reducing track geometry misalignments. This is consistent with the mechanisms of Mode 2 of RCF development.

Measures to control RCF in S&C on the British system

Studies show that wheel wear, track alignment, and bogie lateral yaw suspension stiffness are all crucial factors in RCF initiation and growth. In Fig 19, if the state of the wheel-rail interface system is at A, then improving wheel profiles can move it to C, and below the RCF threshold. Likewise, improving track alignment can move the system from A to B, and below the RCF threshold. Consequently, it may be assumed that if either or both are at the limits of the standards, RCF is probable but, by reducing either, that probability is reduced. Clearly, both factors can also be improved to move the system below the threshold.

A study on the *c2c* line[6] identified a relationship between bogie primary stiffness and the probability of RCF as wheel wear increases (Fig 20). The increase in RCF potential with bogie yaw stiffness can be attributed to the higher curving forces required to deflect the suspensions during curving. Tread-worn wheels had the most pronounced effect due to the increase in conformality that affects both Mode 0 and Mode 1 RCF initiation.

As it appears that bogie stiffness plays a role in RCF initiation, should all bogies be equipped with soft primary suspensions? The result would be reduced curving forces, leading to less curve wear and less RCF, but unfortunately high values of bogie stiffness are essential for stability at speed on straight track. In general, bogie stiffness must increase proportionately to the square of the operational speed if hunting* is to be avoided. Modern rolling stock must be stable at high speed to satisfy the demands of today's travelling public.

Fig 21 shows a sample of bogie stiffness in the British fleet as a function of speed. The quadratic curve at the bottom of the plot was derived from the values of MK-II, typical EMU, and Mk-III suspension stiffnesses, three vehicle types that are generally regarded as stable vehicles. This curve assumes a square law stiffness-speed relationship and may be considered an estimate of the minimum stiffness required for a stable vehicle as a function of speed.

This is important because many vehicles in the British fleet have far higher stiffness values than may be neessary. Although engineering and financial issues such as ease of construction and maintenance may have influenced the designs, they are not optimized for the wheel/rail interface and result in bogies prone to both RCF and wear. Investigations are ongoing and some new vehicles being introduced to the British system are already exhibiting excessive wheel RCF. Many conclusions can be drawn from the existence of the distinct RCF initiation modes and from the pervasive influence of profile shape:

- Track and vehicle conditions well within current group standards can create RCF.
- Distinct conditions contribute to separate RCF initiation modes and specific remedies exist.
- A reduction in track alignment quality and higher wheel wear may remain within standards but result in an increase in RCF.
- Increased bogie yaw stiffness may be necessary to meet current operational demands but will generally increase the probability of RCF.
- Conformality and conicity are both linked to initiation modes and are a function of both wheel and rail shapes. Control of these variables falls to both track and fleet operators through better management of rail grinding and wheel turning.

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* The phenomenon whereby the bogies move from side to side on straight track approximately at the kinematic wavelength of the bogies and vehicle – typically 7-15m. It is avoided as it makes passengers feel "seasick".

- The general increase of conicity and conformality that has occurred with the replacement of the P1 by the P8 indicates a potential increase in the probability of RCF.
- Reduced intervals between wheel turnings may have cost benefits to operators but the resultant increase in conformality can increase the probability of RCF.

Given the foregoing, the British railway industry is accepting that both sides of the wheel-rail interface require attention in order to manage and control RCF on the network. As Fig 22 shows, to control Mode 0 RCF in tight curves, the control measures for track are profile grinding to an anti-RCF profile (to provide relief to the gauge corner and gauge shoulder of the rail), and gauge face lubrication (to minimize wear and changes to the wheel-rail profile). Lubrication can also suppress GCC to some extent if some lubricant travels up onto the gauge corner of the rail. The control measures for vehicles are to reduce primary suspension stiffness to allow better curving performance, and to reduce the conformality between the wheel flange root and gauge shoulder and corner.

To control Mode 1 RCF in moderate curves, the control measures for track are (1) grinding to provide gauge corner relief, (2) reducing conformality between the wheel flange root and the rail gauge shoulder and corner, and (3) improving track alignment. Grinding will reduce the wheel-rail conicity and the system sensitivity to small changes in wheel-rail relative positions. Improving track alignment includes correcting tight gauge, excessive twists, and in particular, short wavelength lateral misalignments with rates of change below the kinematic wavelength of the bogies. The control measure for vehicles is to lower conformality between the wheel flange root and rail gauge shoulder and corner.

To control Mode 2 RCF, the primary measures for track are improving alignment and grinding to control the wheel-rail profiles. As with Mode 1, the control measure for vehicles is to lower conformality between the wheel flange root and rail gauge shoulder and corner.

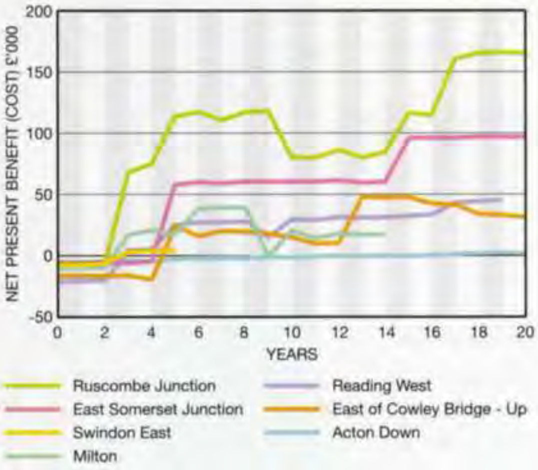
Whatever the solutions, they must represent improved value for the British railway industry. Phase 5A of the WRISA GWZ project analyzed several RCF sites by comparing two maintenance schemes: the existing "standard" practice and a proposed "RCF enhanced" practice, with preventative and remedial procedures.

With RCF enhanced maintenance, there is always a negative cost benefit during the first years due to the initial increase in cash outlay. However, this is usually paid back in the first few years and the net present benefit (NPB) increases for the life of the asset even when some additional investment is necessary. This is because most anti-RCF measures have the long-term effect of reducing loads on the track components in general, reducing the level of routine maintenance and, in some cases, delaying or eliminating the need for major renewals. At Ruscombe, for example, the initial payback occurs in the first two years and there is a significant reinvestment at year nine. The final NPB after 20 years is £166k for just this one site, indicating that anti-RCF maintenance can potentiallly give a substantial reduction in expense to the overall infrastructure system (Fig 23).

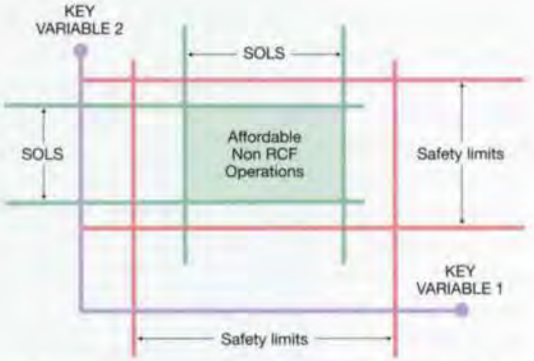
Conclusions

At present, many key factors in the operation of the railway system are limited by the Group Standards that are primarily focused on safety. Since the WRISA research has shown that key system variables within the safety limits can contribute to RCF, it follows that the generation of Sustainable Operational Limits (SOLs) will be necessary to reduce RCF to acceptable levels (Fig 24). Such SOLs restrain key system variables to levels that increase asset life, reduce the need for maintenance, and act as best practice limits on component design. These may well apply to other crucial aspects of system performance such as ride quality and component wear.

Without question, however, the generation of SOLS will require the participation of all stakeholders so that limits may be derived that are practical as well as affordable, leading to an optimized railway system.



23. Net present benefit (NPB) of seven RCF sites subject to anti-RCF maintenance, showing the net cash value to the stakeholder at various times. The initial negative values reflect the initial investment. The crossing of NPB=0 indicates the time to investment payback. Large negative slopes indicate major reinvestments such as renewals.



24. Sustainable operational limits (SOLs): examples of RCF key variables are track lateral alignment and wheel wear.

Credits

Illustrations: 12-15, 17, 19-22, 24 Network Rail/Arup/TTCI/Nigel Whale; 16 Network Rail; 18 AEAT/Nigel Whale; 23 Arup/TCCI/Nigel Whale

The authors wish to acknowledge the contribution of many people in the British railway industry to the research that underlies this paper. Full author and project credits were given in the first part of this article.

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New signalling technology:

Sheerness branch line, Kent, UK

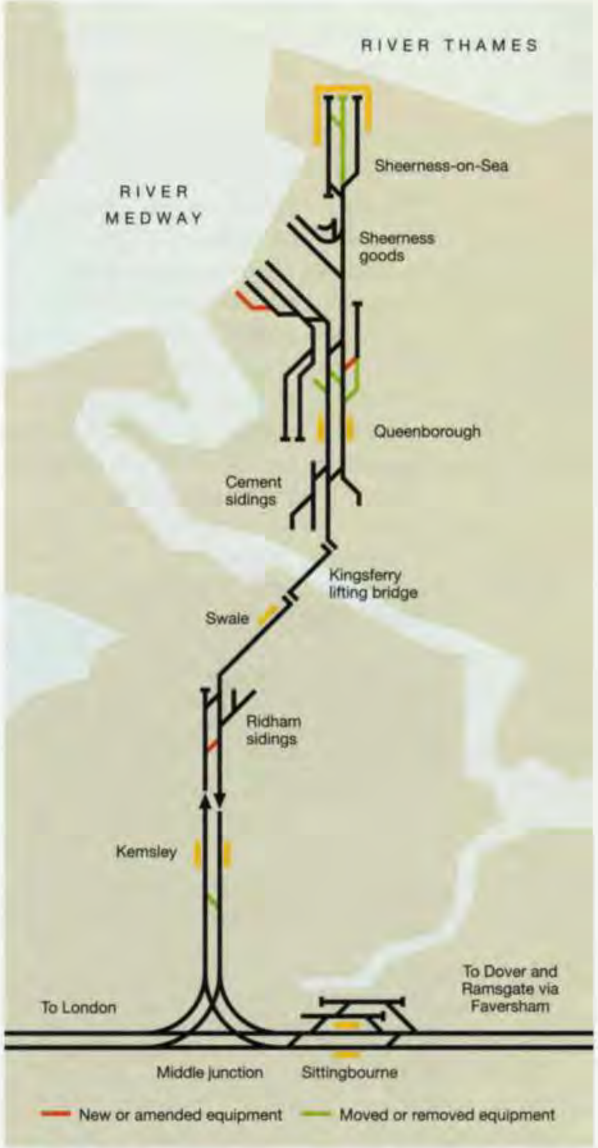
Simon Tomes

Introduction

At noon on 28 March 2005, the first test train was run on the Sheerness branch line resignalling scheme, and the full branch line and signal-box control panel were signed into service 14 hours later. This was the culmination of a 100-hour blockade possession for the final (main) commissioning, and a project that began in October 2001 - Arup's first full resignalling design in the UK. The scheme heralded the third UK usage of GE-Transportation (GE) VHLC signalling control technology. It was the first VHLC scheme fully designed in the UK and its first application in the South East Territory of the UK rail infrastructure operator Network Rail.

The existing signalling was installed by Siemens and General Electric Railway Signal Co Ltd (SGE) in the late 1950s. A centralized traffic control system communicated between the signal-box at Sittingbourne station, from where the seven mile (11km) branch line runs, and local "interlockings" (areas where points, signals, etc, are interlocked) at the line's four stations. Sittingbourne box controls the branch line and sections of the London-Ramsgate main line, with interfaces to Rainham and Faversham signal-boxes. Train operations are controlled by colour light signalling with "track circuit blocks" (sections of line where a train can be detected by the axles shorting a circuit formed by the rails).

The signalling system was deteriorating, in particular the transmission system linking the signal-box to the interlockings, and Network Rail determined to replace it "like-for-like" to current standards and methods of working. Where possible, rationalization was to be considered where it offered cost-neutral or whole life cost benefits. Network Rail selected the GE VHLC (Vital Harmon Logic Controller) system as part of the rationalization; not only could capital and whole life costs be delivered, but an additional UK computer-based interlockings manufacturer would offer greater choice and competitiveness to the market.



1. Schematic layout of the project.

The branch line has a half-hourly service from a bay platform at Sittingbourne. The Kemsley, Swale, and Queenborough stations can accommodate eight-car trains, while the Sheerness-on-Sea terminus has a six-car and a 10-car platform (platforms 2 and 1 respectively). Headways must be no closer than four minutes, with a maximum permissible line speed of 70mph (113km/hr).

The line has standard DC third rail electrification, using the running rail for return. Route setting of trains on the signalman's panel is achieved by turning a switch at the signal entrance. If more than one route is possible, additional selection for the route is provided by exit push buttons. The time taken from the signalman selecting the route and it being set, the "signal route setting performance", is not permitted to exceed five seconds.

Project summary

The following signalling equipment was to be designed, manufactured, installed, tested, and commissioned:

- a new turn-push route setting panel at Sittingbourne signal-box with two *Delphin 1024* TDM PIIUs
- five VHLC interlockings housed in REBs with *Sapphire T48* communications processor and LCP
- 55 LOCs (line-side signalling equipment cases) for the five interlockings, plus additional power LOCs
- one axle counter section over the Kingsferry lifting bridge
- 17 train protection warning systems (TPWS) train stops and nine TPWS overspeed loops
- 20 new green extra strength automatic warning system (AWS) magnets (permanent and electromagnets, plus some suppressor magnets)
- six advance warning indicator boards and associated magnets
- five shunters releases with associated phones
- two train ready-to-start plungers at Sheerness-on-Sea
- seven single and seven double-ended HW 1121 point motors with plug couplers
- 29 three, two and one aspect signals (SL35 lamps); 20 single rail (HVI) and 33 double rail (TI21) track circuits replacing existing AC 50Hz circuits
- one "limit of shunt" signal and four ground position lights
- one electronic banner signal
- 32 speed sign boards and eight whistle sign boards
- three telephones at accommodation crossings

The project

The main signalling works include new multi-aspect colour light signals, point machines, track circuits, and a single axle counter section for train detection in the absence of track circuits. Five individual relocatable equipment buildings (REBs) at Kemsley, Ridham sidings, Swale, Queenborough, and Sheerness-on-Sea house the VHLC chassis and cards. Additionally, each interlocking is provided with a local control panel (LCP) inside the REB, to be operated by maintainers for fault diagnosis.

A new signal-box control panel (again with turn/push route setting switches) was installed at Sittingbourne to control all new equipment on the branch line and also the existing main-line controls. Additional track indications on the down main line between Sittingbourne and Faversham were provided to assist with the safe operation of the accommodation crossings at Bax and Frognal Farms.

A panel interlocking interface unit (PIIU) connects the new panel to the existing Sittingbourne interlocking for the main line. This was specified as the *GE Delphin 1024* Time Division Multiplex for defining the meshing and control functions in the field for the indications and hardware for the control switches. The remote control system between the Sittingbourne panel and the VHLC interlockings uses the *GE Sapphire T48* communications processor. The scheme also incorporated track layout changes and other alterations to replace some existing permanent way assets, and to cater for the improved operational flexibility needed both now and in the future. These included the removal of track, points, cross-overs, ground frames, trap points, over-runs, conductor rails, points heating, and replacement of the new track infrastructure, signalling, power supplies, and telecommunications networks. The signalling design by the Arup signalling and train control group had to interface with all the railway infrastructure equipment and systems, and maintain the existing and revised operation performance requirements.

Project organization

Implementation

When implementation originally began in 2002, the then UK rail infrastructure operator, Railtrack, set up an alliance-type organization with itself as funder, GE as designer and manufacturer, and Balfour Beatty Rail Projects as principal contractor. A management board of these three parties supplied all the communications, decisions, and instructions, and subcontracted additional roles individually. Arup was contracted by GE to carry out the signalling design of the VHLC system data and the REB layout and wiring.

With Railtrack's reorganization, however, and the emergence of the new company Network Rail Ltd, the project was put on hold and a review of the implementation phase timescales and scheme out-turn costs carried out.

Remobilization

The project got under way again in September 2003, and was delivered under a modified organization that met Network Rail's preferred UK-wide "hub" contract management model. The project review also led to a change of principal contractor, which now became ServiRail, and was also brought into the management board.

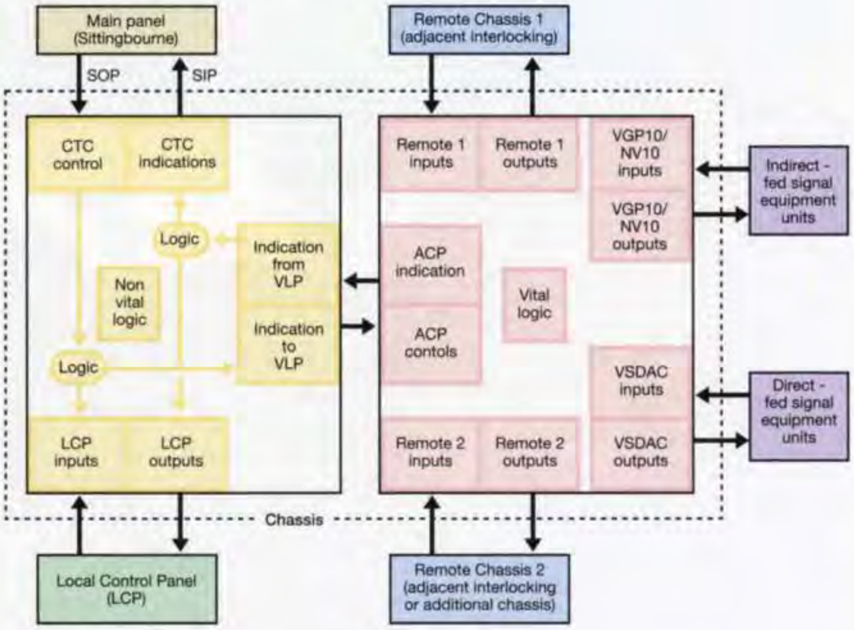
All other interfaces were retained, although the contracted scopes were adjusted to create efficiencies in carrying out the design and implementation. This included a greatly enlarged scope for Arup to perform all the signalling design for implementation. There were also revised possession arrangements, with staged enabling works to be carried out prior to the main commissioning, thereby reducing the risk of the latter over-running due to the level of physical installation and testing works required.

VHLC

Early UK train signalling technology used banks of relays in trackside storage buildings, controlled centrally by a signalman who could command these interlocking areas, located some miles apart, via a centralized traffic control. When the signal-box sent a control message to the trackside buildings, the destination address was decoded first and if it matched that location, the rest of the message was decoded and acted upon to move points, change signal aspects, and set the routes. This technology used many electro-mechanically complex units. These were prone to malfunction, and thus installed to enable quick disconnection and replacement in situ when they failed.

GE developed a microprocessor-based vital (safety-critical) interlocking system for vital control of hardware and all safe execution of signalling principles through the software's "application logic", providing a robust system for controlling the railway and signalling infrastructure.

2. Schematic diagram of VHLC interfaces.



3. Signalman's panel being manufactured in the GE factory.

Arup designed the vital and non-vital (lesser level of security) signal logic, creating ladder logic diagrams within the VHLC software package. The diagrams were produced to closely resemble standard relay circuits, which enabled thorough evaluating and checking by the project teams and quick interpretation by other parties such as the testers and maintainers. The VHLC product allows technicians to carry out diagnostics (remotely or locally) using a laptop, and maintain an event history log. The basic VHLC system hardware consists of the chassis, the vital logic processor, the site-specific module, the auxiliary communications processor, and the input/output modules (Fig 2 previous page). Arup has also written a data applications manual that will ensure a consistent approach to the design of vital and non-vital future applications of the VHLC in the UK rail network.

Kingsferry lift bridge

The project was complicated by the presence of the spectacular 1960s Kingsferry rail/road vertical lifting bridge over the Swale (a tributary to the River Medway between the mainland and the Isle of Sheppey), which was to be retained as part of the scheme with the existing controls replicated within the VHLC system. The railway is a double line unidirectional up to Swale station, changing to a single bi-directional line passing over the lifting bridge and onwards towards Queenborough station.

The lifting bridge is protected by a colour three-aspect signal on the Queenborough (island) side and a colour two-aspect signal on the Swale (mainland) side. Trap points with sand drags are located in advance of each signal for protecting the bridge from over-running trains. The protecting signals can be replaced in an emergency by the bridge operator who has a clear view of the bridge area.

The Swale is a navigable waterway that must be kept open at all times. This necessitates the operation of the lifting bridge for high vessels as a higher priority than train operations, including during all the commissioning periods. For the final commissioning period, Arup designed a temporary control circuit that enabled the deck to rise for passing boats.

This temporary circuit enabled the bridge to be operated from the start of the possession until the functions were transferred to the new panel and the VHLC installation was operating.

4. New two-aspect signal protecting the bridge just beyond Swale station.

Signalman's panel

Due to the large number of infrastructure alterations on the branch line, the existing SGE turn-push panel at Sittingbourne signal-box was completely replaced. The requirement was for a "one-off" design with the main-line controls hard-wired to the existing relay interlocking, and the main-line indications going via the PIIU, as do the branch line controls and indications. Arup's design ensured that all indications were as consistent as possible to avoid confusion on the part of the signaller.

The new panel also differed from the old layout due to track circuit changes on the main line at Bax and Frognal crossings (between Sittingbourne and Teynham) and the recovery (removal) of points no 54 at Sittingbourne. Panel arrangement drawings were provided to enable a mock-up to be constructed and an ergonomic assessment of its operation.

Separately, alterations to the old panel had to be designed for an early possession, to encompass modifications to the wiring in the signal-box relay room (the panel interface wiring) and enable the swap from the old to the new panel to take place during the main commissioning. The new panel was temporarily placed behind the old one before being moved into its final position.

The original wiring between the panel and the signal-box relay room was originally "free-wired". This was replaced with a multicore cable to allow testing of the new panel in parallel with the old, during installation. Arup carried out all the wiring design to ensure that control of train movements would be maintained during the installation, testing, and commissioning of the new panel.

Trackside equipment buildings (REBs)

These five container-shaped buildings house all the electrical and communications control equipment for railway route control within the interlocking, and communication links to the interlockings on either side. Arup designed and analyzed all the signalling equipment in each REB, which was then manufactured by GE prior to installation by crane.

As well as housing the VHLC equipment, the REBs function like relay rooms, with air-conditioning, power supply, lightning protector, telephone, heating, telecoms and, of course, all the necessary relays.

The outlying railway control equipment is served by the LOCs, which house the circuitry and fuses for signals, points, AWS transformers/rectifiers, etc, and also contain the necessary heating and lighting facilities with earth test points and earthing. Arup designed and analyzed all 55 of these which, like the REBs, were then manufactured by GE.

5. New signal opposite new REB at Kemsley station.

Local control panels

The LCP's principal use is for maintenance, although operations staff may also use it to control the interlocking locally. The maintainer technician must obtain permission from the signaller prior to switching the LCP into local operation using the direct line telephone. The front panel of the LCP bears a diagram of the interlocking area with indications of the points and track circuits, and with toggle switches for points control and route selection.

The LCP design formed part of the overall REB design, and the application logic design within the VHLC ensured that the LCP control hierarchy would have a lesser priority than the VHLC diagnostic port. The application data also ensures that the control of the interlocking reverts back to the signaller if the LCP operation is interrupted.

Stageworks

The alternative commissioning strategy specified after the project's deferment and remobilization involved three enabling (stage) works prior to a shorter blockade period for the final commissioning. The enabling works were carried out in 52-hour possessions a month apart, to perform permanent way alterations (track recoveries, plain lining, point conversions and insulated block joint installations). The stageworks design identified temporary signalling arrangements to be installed during the scheme commissioning stages.

All signalling circuitry to be amended required full correlation to ensure that the design alterations proposed would have no surprises during stageworks commissioning. Due to the age of the wiring, significant discrepancies were found and had to be fully resolved and traced, to guarantee that the design was robust.

Summary

Four years after Arup decided to develop its rail signalling and train control capability to support the multidisciplinary rail business, the growth of these specialized skills has resulted in the Sheerness branch line resignalling project. Arup's involvement on this scheme has been a watershed in its signalling design capability, enhancing and expanding the firm's skills and demonstrating this to the rail industry as a whole with proven delivery.

And not forgetting the rest of the deliverables...

Signalling design requires specific designs and specifications to be produced so that the rail infrastructure system operates in accordance with performance and operational requirements safely and robustly. All had to be designed and checked by the Arup rail signalling and train control group, using procedures critical for the accuracy of the design. These deliverables included:

- control tables: the design drawings specifying the conditions for setting the routes, clearing signals, setting and locking points, and locking ground frames (mechanical sets of levers on the ground)
- track plans: specifying the location of signalling equipment interfacing with the railway
- correlation: locating all railway equipment and wiring
- fringe interface designs: designing system tie-ins to all other equipment on the railway network
- cable schematics: cable layout and sizing
- aspect sequence charts: drawings showing the circumstances under which each signal will display each of its possible aspects
- route cards: Instructions giving the details of each route that can be set.

Credits

Promoter: Network Rail Ltd (South East Territory) **Client:** GE-Transportation (GE) **Signalling designer:** GE and Arup - David Atkinson, Michael Chai, John Cooper, Paul Dixon, Andrew Gardner, Ross Haden, Simon Hose, Pav Kuner, Coppel Lai, Paul Marshall, Asif Pathan, Fiona Pearce, Shaun Pearce, Craig Purcell, Frank Sahota, Alex Shah, Tim Shah, Greg Simpson, Paul Tipper, Simon Tomes, Tony Vidago **Signal installation and principal contractor:** ServiRail **Testing:** Atkins Rail **Permanent way design:** Balfour Beatty Rail Projects **Permanent way construction:** Carillion Rail Projects **Power (E&P) design:** Corus Rail Consultancy **Power (E&P) construction:** Giffen Group plc **Traction power design:** Atkins Electrification **Traction power construction:** Giffen and Carillion **Civil engineering design:** Frankham Consulting Group **Civil engineering Construction:** ServiRail **Telecommunications:** Marconi Communications Ltd **Illustrations:** 1, 2 Heather Harding/Nigel Whale; 3-5 Simon Hose

1. Completed stadium, May 2005.

The Allianz Arena:
A new football stadium for Munich, Germany

Stephen Burrows Konrad Ecker Joachim Guesgen Rüdiger Lutz Burkhard Miehe Pieter Moerland J Parrish Roland Reinardy Florian Schenk Ian Thompson Eugene Uys

Arup undertook the competition and structural design of the bowl for the new home to the Bayern Munich and TSV 1860 football clubs. The Allianz Arena will also host the opening ceremony, first game, and one of the semi-finals of the 2006 World Cup.

Introduction

Dramatic, exciting, and iconic architecture enhances and amplifies everyone's experience. In the modern world, where image is critical, it can also significantly increase the brand values of a stadium and its sporting team. Modern stadia have become complex and sophisticated buildings, providing a range of facilities for spectators, the media, participants, and operators. But although the mix and standard of facilities can have a significant impact on the user's experience, the key to a stadium's success is its heart - the viewing bowl.

The Allianz Arena in Munich sets a new architectural milestone in stadium design. It opened in May 2005, replacing the city's old Olympic Stadium as the new home to the football clubs Bayern Munich, in *1 Bundesliga*, and TSV 1860 Munich, in *2 Bundesliga*. Designed and built purely as a football stadium, it will also host the opening ceremony and initial game on 9 June for the 2006 World Cup, as well as five subsequent matches including the second semi-final on 5 July.

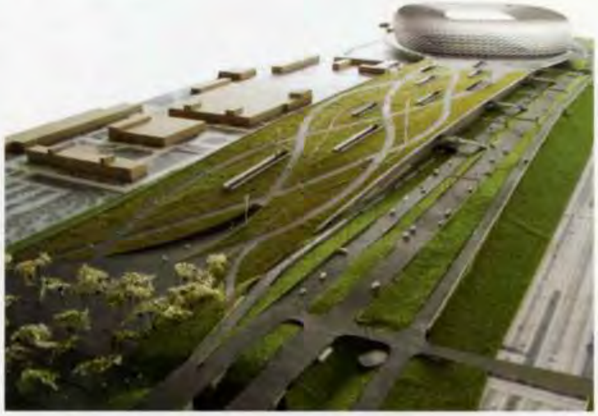
In 2001 a design competition was instigated by the two clubs and the city council. ArupSport and the Swiss architects Herzog & de Meuron joined a team led by Alpine Bau and HVB Immobilien Management GmbH, and secured the job despite strong competition from architects such as German-based Gerkan/Marg (runner-up), Foster, Murphy/Jahn, and Eisenmann.

The competition called for a 66 000-seat arena with a closing roof, but it was immediately clear that this brief and the budget were not compatible. The design team aimed, therefore, for a visual impact that would be undiminished if the moving roof was not built - of all eight finalists this was the only one with this approach.

The most striking – and currently unique - feature is the façade, made of ETFE (a polymer of tetrafluoroethylene and ethylene), which can be illuminated in the colours of whichever home team is playing. This simple but very effective idea makes the stadium immediately identifiable. The enclosure design evolved from a basket-like arrangement of woven ribbon elements to diamond-shaped ETFE pillows patterned in similar fashion to the Bavarian flag (Figs 2, 3).

As the site is some distance from the city centre, and near a major motorway, a huge car park was needed, as well as a rail station. The team decided to conceal the 12 000 parking spaces beneath a planted plaza deck stretching from the rail station to the main entrance (Fig 4). The result is a long, rising, curved plinth that imparts a sense of excitement for spectators as they approach the glowing stadium destination emerging over the horizon. On arrival they encounter another unique architectural feature of the building, the geometrically extremely complex "cascade" of stairs that wrap around the perimeter of the building, just visible behind its glowing, translucent skin.

3. Stadium illuminated in TSV 1860 Munich colours.



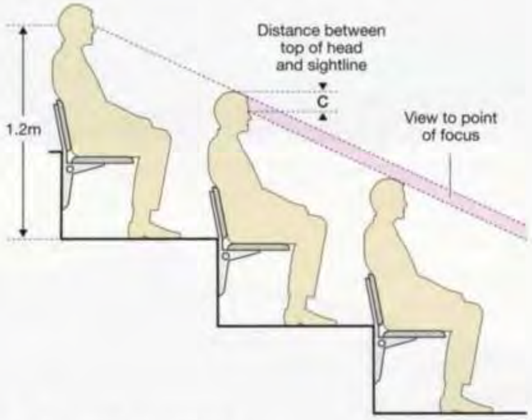
4. Model of approach plinth with car park beneath.

2. Stadium at dusk showing the ETFE pillows illuminated in the Bayern Munich colours.

ArupSport was jointly responsible for the competition architectural design, design development for the planning submission, and subsequently for the preparation of production information for the viewing bowl. ArupSport was also responsible for the overall structural design for the competition and planning stages, and Arup GmbH for the on-going design of the substructure, frame, and seating bowl.

The very tight time schedule between winning the project in February 2002 and start of construction the same October led to an early decision to create a "design village" in Munich. While the detailed structural analysis and design were still carried out in Arup offices, the design partners, including the ArupSport team and the contractor, used the design village for co-ordination and meetings, which enabled everyone to contribute far quicker to design solutions. Thus value engineering was exercised from the very outset of the project.

Table 1. Timetable	
Competition	August 2001 – February 2002
Scheme design	March 2002 – May 2002
Detailed design	May 2002 – June 2003
Construction of stadium bowl	October 2002 – March 2004
Completion and handover	30 April 2005



5. Sightline development.

6. The cascading stairs, visible through the stadium's translucent façade.

Bowl geometry

Soccer stadium geometries must fulfil a complex range of requirements:

- life safety
- regulations - for the Allianz Arena these were local, UEFA (Union of European Football Associations), and FIFA (Fédération Internationale de Football Association)
- spectator satisfaction
- the client's objective to generate the highest possible revenue.

Good spectator viewing is a function of the three-dimensional bowl geometry; spectators should be brought as close to the action as possible - optimizing the "C" value or view over the row in front - and be as high as possible, to maximize the vertical angle of view of the whole field of play (Fig 5). Further improvements are gained by a slight but distinct front-edge curve in plan, which helps both diagonal and sideways views.

ArupSport's three-tier design brings spectators as close as possible to the pitch action, and at the same time takes in emergency strategies - the width of escape routes and numbers of vomitories and stair cores being determined to allow for smooth egress should the stadium have to be evacuated. The height of the spectator positions and hence the vertical angle of view of the arena were optimized by balancing the tier sizes and overlaps to create a smoothly flowing bowl form. The design even allows the option of changing some corner areas from seating to standing, still not uncommon in German stadia.

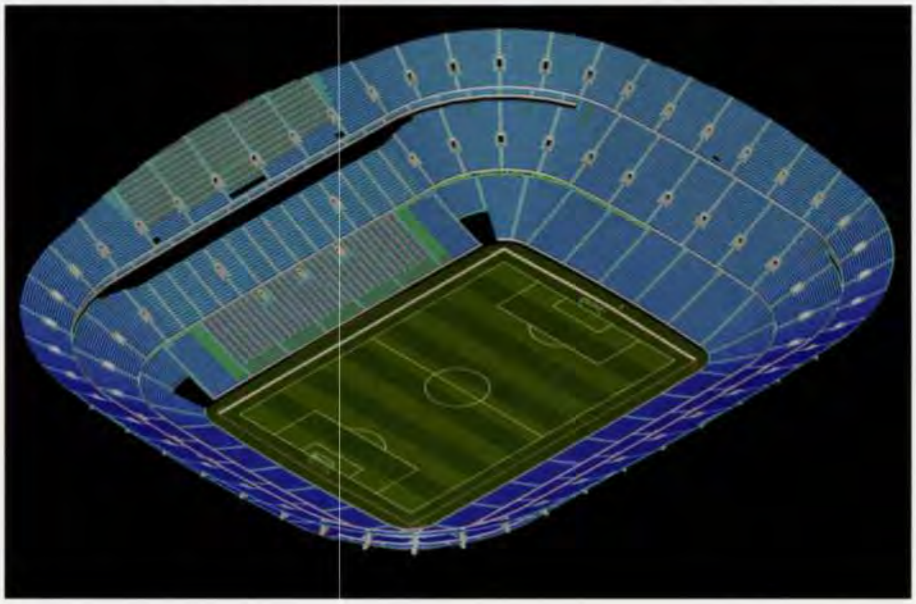
The quality of view for spectators in the lowest tier of a stadium is often compromised, as viewing standards that are appropriate for upper tiers tend to result in poor views of play near the touch and goal lines for those in the first tier. At Munich this has been avoided by lifting the first row of seating slightly, thus making the lower tier steeper than usual. The spectators are happy, though raising the first row even slightly has a significant impact on the overall size and cost of a large stadium.

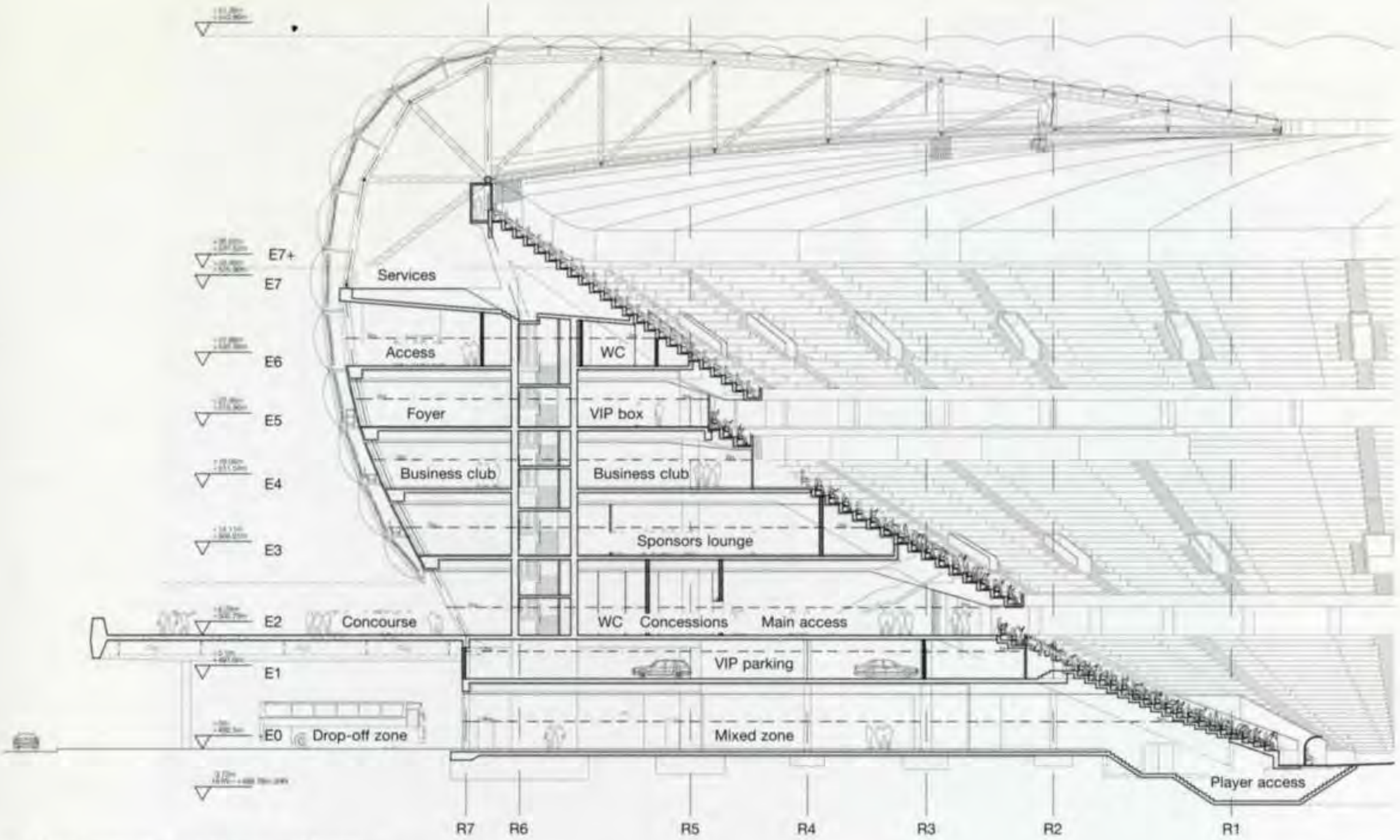
From the external concourse, a perimeter 'apron' to the stadium gives access to the lower and the middle tiers, whilst the upper tier is reached via 15 cascading façade stairs (Fig 6). The VIP and press seating areas have their own dedicated circulation routes.

The brief required the stadium to be designed for a range of games from *Bundesliga* to the World Cup, and two separate seating layouts and facilities plans were developed to accommodate the very different media numbers and requirements. Also each of the two resident clubs had different requirements for its fans and facilities, and these overlays needed to be added to the design.

Design of the seating bowl started with FIFA and UEFA's requirements for the pitch, the pitch margins, and the now obligatory pitch-side advertising. The form of the seating bowl and the distribution of seating types within determine or influence almost every other aspect of a stadium's design, from the shape and structure of the roof to the levels and areas of the concourses and premium facilities, from the positions of the giant screens to the amount of sunlight, daylight, and wind reaching the pitch. Even the number, size, and distribution of stairs, lifts, and escalators are effectively set by the bowl design, and the decision to bring most of the spectators into the stadium at the top of the lower tier significantly reduced vertical travel distances and helped separate spectators from the participant, media, and operational facilities.

7. Bowl design, version 31 of 33.





8. Elevation/section west: areas and functions.

Design tools

Design tools evolve constantly, and much of the Allianz Arena was developed using ArupSport's specially developed parametric stadium design software. Parametric software developed for the aerospace industry is also used, and key features of other ArupSport projects, such as the new Beijing National Stadium and "Water Cube" Swimming Centre being built for the 2008 Olympics and the new 50 000-seat UEFA five-star stadium for Ukrainian club FC Shakhtar, would not be practicable without these sophisticated new tools.

ArupSport works with "live" computer models of stadia that can be adapted and modified easily to optimize the design and investigate alternatives. In all, 33 subtly different designs for the Allianz Arena bowl were produced before the final form was agreed, and the end-result is far more refined than would have been possible with conventional design techniques (Fig 7). This approach had the additional advantage of enabling the whole design team to work with accurate information from the very beginning of the design process when most key design decisions were taken.

Internal planning

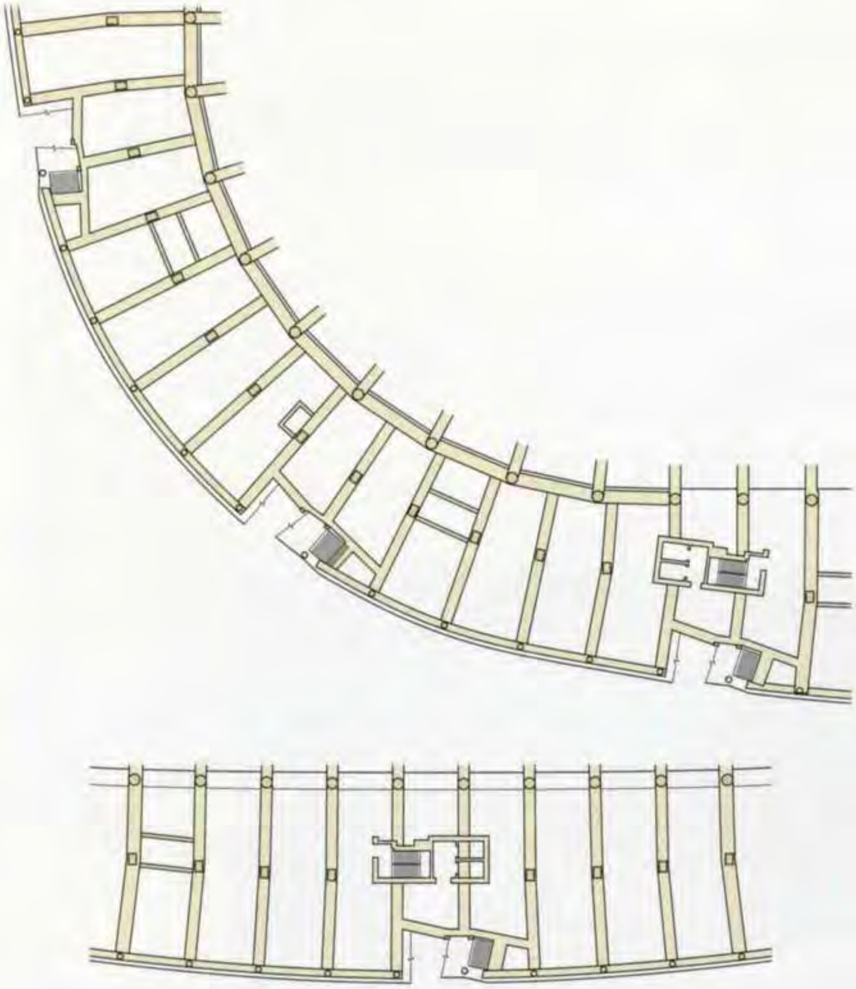
Aside from the seating bowl, the stadium occupies around 160 000m^2 of floor area, arranged over seven levels (Fig 8). The lowest, E0, is reserved for team changing rooms and recreation areas, the press, some plantrooms, and car and bus access and parking. Level E1 is mainly used for VIP parking, and together these levels contain some 1100 car parking spaces. Level E2, effectively ground level, serves as the main concourse and provides access to the lower and middle tiers (= 44 000 spectators). It also houses concession areas and lavatories.

Fan restaurants, shops, and the Hall of Fame are on level E3, the business club on E4, and VIP boxes positioned on the east and west sides of E5 (the Allianz Arena is unusual in that it has two, rather than one, hospitality floor levels behind an enlarged middle tier). Level E6 gives access to the upper tier, and finally E7 is reserved for plantrooms and operational services, containing all technical equipment apart from sprinkler tanks and few ventilation plants. Vertical services distribution follows the stair cores from top to bottom. Ventilation and smoke extract units are included for the internal parking areas on levels E0 and E1.

Overall structural concept

The structural system for the bowl is based on multi-storey reinforced concrete sway frames with some stability provided by the eight stair and lift cores. The frames are approximately 8m apart and placed concentrically on 96 gridlines around the pitch. Some variants and auxiliary gridlines were required in the corners.

The cantilever roof comprises steel trusses spanning up to 60m to cover the entire seating area. This solution was preferred by the contractor, as it fitted the construction sequence much better. ArupSport previously showed that overall material savings were possible with alternative solutions such as a suspended spoke wheel roof, but the cantilever was favoured mainly on grounds of programme and sequence.



9. Typical plan view of a corner (above) and middle (below) sections.

The bowl structure

General

The structural elements of the stadium bowl comprise suspended floor slabs, wide and shallow floor beams, precast terraces, deep raking beams to support the tiers, columns, and large pad foundations in a variety of sizes and depths.

The bowl is divided into eight independent structures: four corner and four middle sections (Fig 9). Not only the scale of the building but also its concentric geometry contributes to the generation of such enormous forces from shrinkage and temperature effects that the frame would not have coped as a single structure, as is usually the case with large rectilinear buildings. The millimetre-scale sensitivity of the bowl section, in terms of the sightline design, was also guided through construction optimization by ArupSport.

Generally, suspended floor systems resting on downstand beams were used for the structural slabs, as it was necessary to create the much-needed frame action. However, the contractor asked for flat slab solutions where possible to reduce construction time, and these were widely used in the lowest levels E0 and E1. Elsewhere the contractor also requested precast slabs with concrete topping to reduce formwork costs.

The columns are mainly cast in grade B45 concrete, though for some higher stressed columns the greater strength of B55 had to be employed. The circular columns at the back of the bowl are of a special spun concrete type prefabricated in Switzerland and delivered on site with connection plates at top and bottom. These act as tension ties to hold down the cantilever steel roof. They follow the curved façade line, changing direction at each floor level and thus imposing additional horizontal forces on the frame.

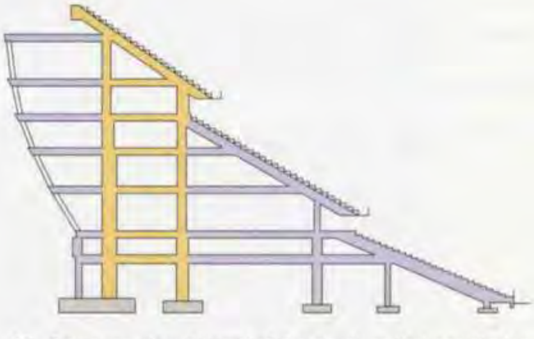
Middle sections

Each middle section comprises a series of 10 reinforced concrete frames with a single central stair core. Whereas the core alone stabilizes the segment circumferentially, radially there is an interaction between the core and the frames. The core also absorbs torsion generated from eccentric forces. The frames in the middle sections are almost parallel to each other, making analysis - and understanding the analysis results - much easier than for the corner segments.

Corner areas

Each corner extends over 16 radial gridlines with an approximate length of 120m to the outer circumference. In their geometric conditions the corners are entirely different from the middle sections. The radial gridlines meet at a central setting-out point close to the segment itself. However the varying plan form of efficient seating blocks on each tier required the columns to be offset from each other between the different tiers. Transfer beams had to be introduced and it became impossible analytically to separate the frames from each other.

As with the middle segments, the main frame action takes place between circumference points R5 and R6. Here, the ring beams on R5 and R6 are essential to transfer column loads and ensure the horizontal rigidity of the corner sections.



10. Corner section; the part of the structure that contributes most to stability is highlighted.

11. Bowl under construction, July 2004.

Cascade stairs

A vital issue for all stadia is to safely and efficiently control the flow of fans before and after the match. The Allianz Arena incorporates an innovative concept for connecting the upper levels - the 15 cascade stairways that start on level E2 and allow rapid movement up to E6. Their design and construction were complicated by the need for double curvature both horizontally and vertically, as well as by the disturbance they impose on the frame action by regularly cutting through the radial beams (Fig 12).

The architectural concept also included a continuous band of openings in the external wall running all the way up along the stairflights and the landings, and this further complicated the structure. Thus the edge beam at R7 is frequently interrupted by the light well, creating cantilevers up to 6m long.

On their inside face the cascade stairs are closed off by a masonry wall, whilst above, a concrete slab following the same profile and inclination as the stairflights covers them, creating a tunnel-like atmosphere.

Precast concrete terraces and vomitories

For aesthetic reasons and speed of construction, all the terrace units were precast, spanning between the raking beams as simply-supported beam/slab elements. To avoid excessive stresses on the main frame from thermal expansion of the exposed precast elements, one end of each unit is on a sliding bearing. The elements are connected to each other at the sides with dowels along their contact edges. The connection ensures that no gaps arise between the step and the riser, and the elements jointly carry the gravity loads.

The vomitory stairs and walls are also precast, making the whole installation of terraces and vomitories independent of the main concrete frame.

12. Cascading staircase under construction.

Bowl interfaces

The steel cantilever roof is fixed to the primary concrete frame at the back of the bowl, where the cantilever moments are split into their push-pull components and transferred to the bowl structure. The design of the concrete frame is thus very much governed by the roof loadings, including upward and downward wind pressure.

A 30m wide perimeter walkway winds around the stadium bowl, extending the concourse on level E2. Its floor slab rests on radial reinforced concrete beams, approximately 30m long, spanning onto the columns on gridline R7. Corbels are designed to allow for a sliding bearing and a movement joint between the walkway and the stadium bowl.

Bowl analysis

Middle sections

As already noted, the middle sections feature a much simpler geometry and fewer abnormalities than the corner segments. Unlike these, all the frames could be represented and analyzed with 2-D sub-models, although the horizontal loads in each middle segment had to be distributed in accordance with the individual frame stiffness, taking into account the central stair core's contribution. The 2-D analysis models were used for linear analyses, load take-down, and the determination of element forces for the design of single members.

The main frame elements that provide radial stability are the two columns on gridlines R5 and R6. With the spacing between these two grids varying from the centreline of the middle section to the north and south stands, each frame has different geometry and therefore different resistance to lateral front-to-back forces. Non-linear effects such as second order effects and cracked section analysis were investigated but found to be negligible.

A 3-D model was also set up to compare results, to obtain in-plane stresses for the floor slabs, and to solve the design challenge imposed by the cascade stairs as described above. The results of both approaches showed good conformity.

Corner sections

Simple separation into 2-D models was not possible for the corner segments due to the geometrical constraints, and these areas had to be designed using 3-D models. These employed a combination of stick elements for columns and beams, and shell elements for large surface areas such as walls and slabs. The foundations were analyzed using shell elements. The models served to carry out the complete analysis for stability, element design, and the design of walls and foundations at the same time. Due to the complexity of the models it was crucial to fully co-ordinate any changes made by the architect and the contractor as early as possible, so they could be implemented without design delays.

The analyses also took account of effects such as shrinkage and temperature, and deformations were calculated to determine appropriate movement joints. As with the middle segments it was shown that second order effects were of minor magnitude and could be neglected.

Structural design aspects

Loadings

The design is based on the relevant German DIN building codes. The standard dead and live loads are in accordance with *DIN 1055*; wind loads to *DIN 1055: Part 4*; notional loads to *DIN 1045, Section 15.8.2.3*; equivalent dynamic loads on the slab to *DIN 1055* (5% of the vertical live load); and equivalent dynamic loads on the terraces to the new draft of *DIN EN 13200* (0.35kN/m per seating row longitudinally and 0.2kN/m per seating row perpendicularly). The equivalent dynamic loads were purely for the purpose of stability analyses.

Dynamic assessments had to be carried out separately for the slabs and terraces to prove their dynamic performance acceptable.

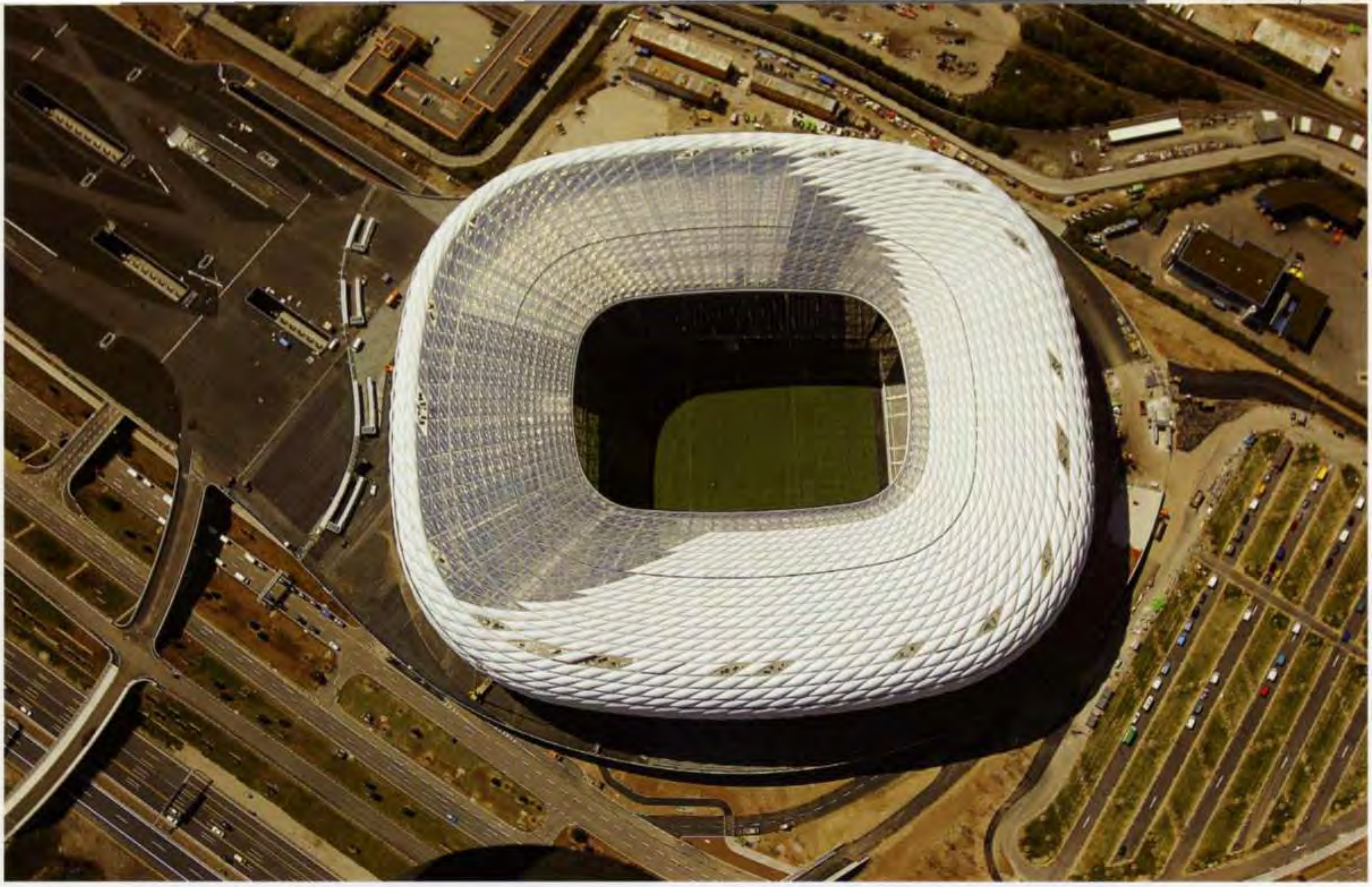
Temperature, creep, and shrinkage

To take account of temperature, creep, and shrinkage, a set of appropriate load cases was defined. *DIN 4710* gives a range of maximum and minimum design temperatures; the mean temperature is 8°C, the minimum external air temperature -10°C, and the maximum external air temperature 26°C. Since the main structural elements are not directly exposed to sunlight (except for the terrace units, which can freely move at one end due to sliding bearings), the air temperature is decisive.

The resulting temperature range for the design is therefore taken as ±18°C for the overall structure and +10°C for slab areas above the concourse (levels E2 – E5). Predicted shrinkage effects were converted into an equivalent temperature range of DT= -10°C. Creep was taken into account by using a long-term Young's Modulus of 10 000N/mm^2.

The resulting load cases for temperature and shrinkage were summarized in load combinations, which in turn were used in the finite element models and their analyses. Reinforcement results were then added to the reinforcement quantities calculated for gravity loads and stability (German design standards recommend a factor of safety of 1.0 for temperature and shrinkage effects). The analysis also utilized cracked section properties for beams and slabs, while columns were assumed to remain uncracked.

13. One of the many hospitality areas.



14. The completed stadium.

Dynamics

Many human activities can cause significant dynamic loads, particularly when groups of people act in unison. Co-ordinated repeated jumping is the most severe form of vertical excitation that humans can create. If a structure's natural frequencies are higher than the frequencies at which significant excitation forces are anticipated, then the structure is deemed acceptable and no further checks are required. If the natural frequencies are lower than these targets, the dynamic response of the structure must be checked explicitly and the results compared against acceptable criteria for acceleration, velocity, or displacement.

There is no explicit guidance document for sport facilities in Germany, though the team made reference to a paper by Prof Kasperski of Bochum University[1]. However, there is a relevant UK standard for dynamic loading of stadia[2]. This sets out a minimum natural frequency of mode shapes with predominantly vertical components of 3.5Hz for stadia that house sport events only, whilst 6Hz remains the lower limit for structures that may host pop concerts. Left-to-right or front-to-back swaying of a crowd can cause lateral forces, but this is normally assumed to occur at frequencies below 1.5Hz. The Allianz Arena functions solely as a football stadium, and since the vertical natural frequencies for the tiers are above 3.5Hz there was no requirement to check vertical response levels.

Conclusion

Many consider the 1972 Munich Olympic Stadium, designed by Gunter Behnisch, to be the best of its era. The Allianz Arena opened in May 2005 to critical acclaim as the city's second such example, not just for its innovative and iconic appearance but also for the excellent viewing and great atmosphere in its viewing bowl. Interestingly, its authorship is acknowledged and has often been described as the "British style", in spectator proximity and atmosphere, by the German press.

Credits

Client: München Stadion GmbH **General contractor:** Alpine Bau Deutschland GmbH **Project management and quantity surveyor:** HVB Immobilien AG **Architects:** Herzog & de Meuron **Sports architecture:** ArupSport – Anthony Day, J Parrish, Roland Reinardy, Eugene Uys **Bowl and roof structural design (competition/scheme):** ArupSport - Fergus Begley, Stephen Burrows, Burkhard Miehe, Darren Paine **Bowl structural design (construction):** Arup GmbH – Aysen Agirbas, Ute Bobzin, Christopher Clifford, Thomas Dossenberger, Konrad Ecker, Jens Eisner, Joachim Guesgen, Sorabh Gupta, Volker Hass, Eva Hinkers, Christiane Kleinke, Patrick Luermann, Volker Luschnitz, Rudiger Lutz, Pieter Moerland, Jochen Ristig, Nina Rutz, Florian Schenk, Ian Thompson, Christian Wrede **Roof structural design (construction):** Sailer Stepan and Partner GmbH, Munich **Façade structural design:** R+R Fuchs, Munich **ETFE façade manufacturer:** Covertex GmbH, Obing **Building services design:** TGA-Consulting, Munich **Checking engineer:** Dr D. Linse, Munich **Illustrations:** 1, 3, 13, 14 Covertex/B Ducke; 2, 6, 11, 12 Ulrich Rossmann-Arup; 4 Herzog & de Meuron; 5, 9, 10 Nigel Whale; 7ArupSport; 8 Herzog & de Meuron/acadGraph

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(1) KASPERSKI, Prof M. Menschenerregte Schwingungen in Sportstadien. *Bauingenieur*, *76* (December), 2001.

(2) Guide to safety at sports grounds. (The "Green Guide"). The Stationery Office/DCMS/The Scottish Office, 1997.

BP Sunbury:

The 20% cost challenge

Malcolm Barrie Mike Carter Gabriel Hyde
Charlie Martin Ian Wallace

BP's facility at Sunbury-on-Thames, England, grew from a single mansion set in farmland to a large array of laboratories, pilot plants, fuel stores, offices and other buildings, surrounded by housing. The phased redevelopment of this enclosed semi-industrial estate to an open business park of high quality offices is a story of environmental transformation through design and construction skills and continuous improvement.

1. The site is reunited across the calmed road, with demisable buildings.

History

BP traces its roots to the Anglo-Persian Oil Company, originally formed in 1909. Eight years later, it founded a research facility at Meadhurst, a mansion outside Sunbury-on-Thames, England, and subsequently grew into one of the world's largest energy companies, active in 100 countries and rated as "best in class" in the energy industry for its social performance.

From 1917 BP's Sunbury facilities expanded piecemeal, with the addition of single-storey offices, laboratory and storage buildings, and pressure vessels and storage tanks. Meanwhile, gravel extraction pits outside the site supplied the growing urbanization of the surroundings. Originally a country village, Sunbury was being swallowed up by outer London's suburban sprawl. Later, more buildings were added, and some of the earliest ones replaced by pilot plants and medium-rise offices and laboratories. The site expanded northward across the adjacent Chertsey Road into a backfilled gravel pit, where a multi-storey car park was built.

Most of the buildings had specific purposes based on then-current research practices and technology, but by the 1990s many were unsuitable or inefficient for modern purposes. BP came to realize that it owned 13.5ha of real estate with a stock of buildings whose functions were incompatible with the location - a site without significant asset value.

Unlocking the project

The competition

In 1996 BP Properties invited four architectural practices to submit proposals for redeveloping the Sunbury site. Following an earlier challenging and successful collaboration between Broadway Malyan Architects and Arup to increase car parking for a building that BP wished to dispose of at Stockley, Arup was invited by Broadway Malyan to join its Sunbury team.

The key elements of the entry were:

- the redevelopment of the site as a business park with each building on a self-contained plot that could be sold on individually - the buildings kept and occupied by BP or disposed of if it wished to reduce its Sunbury presence
- the unification of the two sites, with traffic calming and design features to give Chertsey Road the feel and look of an estate road
- the design of a generic building, able to be developed in various sizes and capable of housing offices, laboratories or pilot plants, giving BP optimum flexibility
- a masterplan, so that BP would be able to redevelop the entire site sequentially if required, as well as maintaining its existing operations.

BP judged that the Broadway Malyan/Arup team had best understood and interpreted its needs and awarded the commission.

Commerciality

BP is not a monolith. It has many autonomous business areas, all with different needs and objectives, and several were present at Sunbury. BP Properties saw the redevelopment's success as being crucially dependent on maintaining an overall commercial focus, while at the same time satisfying resident businesses' requirements and making Sunbury a desirable place for others to relocate to.

Previous experience had shown that, in a fast-changing technological environment, it was essential that the new Sunbury buildings should not be "bespoked" to immediate needs at the expense of future adaptability. In BP's own words, "BP needs to be saved from itself".

The team adopted this as a guiding principle. The redevelopment was conceived as a speculative business park. Each of the new buildings was to be considered as a separately demisable office building, complete with its own parking, frontage and access. British Council for Offices (BCO) standards were applied and the offices were benchmarked against developments such as the nearby Stockley Park[1-3], which was taken as the standard to be achieved. At the same time, the buildings needed to be able to house laboratories and other technical functions in case BP decided that it needed these facilities on site.

Adaptability

From the first, a detailed brief for the redevelopment was impossible. Options had to be kept open. BP sustains a high level of churn and must respond rapidly to changing markets. Even if individual businesses could provide a brief for their immediate needs, it was clear that these might be very different by the end of a redevelopment that would span eight years or more.

Under these circumstances, the team progressed by maintaining a very high level of flexibility. While the buildings were sized as if they were speculative offices, based on efficient extruded floor plates, their shells were developed so that façades did not rely for support on internal floors, and the roofs above each potential floor plate did not need internal columns for support.

This approach enabled the standard buildings to accommodate offices, laboratories, pilot plants or other uses, occupying one, two or three storeys or a combination of these (Fig 3). While internal BP discussions continued on details of proposed uses of the buildings, the design team was able to progress the broader issues such as overall site planning, the reconfiguration of services, and discussions with the planning and highway authorities.

At this stage the procurement route was also kept open. BP required the options to redevelop the site itself for its own use, to redevelop it and sell it on, or to sell the site or parts of it to a developer prior to commencing construction.

Teamwork

The project management team

Once the concept was proven as viable, BP established a project management team (PMT) in an office on the site, led by a professional BP project manager and supported by staff both from BP and from the construction industry, including secondments from Arup and other team members.

Property development is not a usual BP function, but the strong project management skills developed by BP on major capital projects such as oil refineries proved readily transferable to the building industry when supported by professionals from the team - indeed, the Sunbury project benefited hugely from such BP experience as applying the energy industry's very rigorous safety culture.

A major PMT function was to be BP's single contact point for the design team, avoiding multiple interfaces with the various BP businesses at Sunbury, all with varying objectives. The team communicated with users to establish a detailed brief, but all decision-making flowed through the PMT. A single PMT manager was the interface to the existing site management and facilities managers.

Co-location

The design team joined the PMT on site, in refurbished offices in a laboratory building scheduled for demolition. Architects and building services, structural and infrastructure engineers, drawn from three different consultants, occupied the same open-plan office.

2. Contrasting with the central public spaces, the courtyards between the southern buildings have a contemplative character.

Construction procurement was to be by construction management, and this team also took up residence in the co-located office.

Co-location, combined with activities such as lunchtime five-a-side football, worked well in fostering team spirit as well as simple communication across disciplines. Both the project itself and the personal development of team members benefited from co-location. Junior staff gained much more exposure to other disciplines than normally, as well as making decisions in relation to co-ordination of construction issues, a task usually handled by more senior personnel.

Co-location is a two-edged sword, however, and at the end of the project some found the return to their more confined office roles difficult. For organizations where site-based activities are not the norm, the personal development of staff who are separated from their base for long periods requires special attention, both in ensuring that their technical skills do not suffer from reduced interaction with their peers and also in relation to exclusion from normal office socializing and organizational development.

Deploying Arup resources

The complexity of the Sunbury site's previous uses, current activities, and potential future needs led to diverse use of Arup resources, developing from the initial provision of infrastructure and structural engineering design.

Planning supervision was added as soon as the project was clearly shown to be viable.

The site's history of semi-industrial activity suggested the possibility of chemical spillages so as well as geotechnical investigations, Arup conducted a desk study and site investigation of the likely degree of ground contamination. This was extended to a series of interviews and a further desk study of possible contamination within the fabric of the existing buildings, to facilitate their safe demolition. To satisfy the authorities that no valuable historical materials were going to be destroyed, the firm undertook an archaeological desk study and site investigation specification.

Arup Project Management was the planning supervisor, also providing secondments to strengthen the construction management capability of the PMT.

Arup Security Consulting designed the external security infrastructure, enabling the site's transformation from a "secure perimeter" to open business park mode of operation, with specialist support from Arup Lighting to mitigate the effect on adjacent houses of possible light pollution when the perimeter fence was removed.

Arup Communications undertook a study that allayed fears about the effect of the new buildings on TV reception in the adjacent suburbs.

Arup Fire enabled non-standard solutions to be applied to the effects of common spaces and demisability on the building fire strategies.

Arup Acoustics carried out a numerical vibration study, backed up by measurements on a suspended floor of the first new building, which established the suitability of Corus's *Slimdek* floor system in potential laboratories.

Arup Materials Consulting provided specialist advice, eg investigating defects in structural steelwork corrosion protection systems and the performance of a new restaurant's floor screed.

Phase 1: the standard building

The extruded shell

The shell concept, enabling single, double or triple storey-height use within the standard three-storey building, has already been described. The Phase 1 scheme design developed the standard building for office use and, if required, for laboratories to be incorporated in a notional 10% of the floor area. The latter's heavy servicing led to large floor and

Safety and sustainability

The exacting approach to health, safety, and environment (HSE) that BP's project managers brought from their petrochemical industry background far exceeded the construction industry norm, but matched the designers' aspirations and was welcomed by them. Consultants and contractors were chosen for their cultural match with BP, as well as their ability to do the job. Indeed, the decisive factor in Schal's appointment as construction manager was its effective solution to safely segregating construction traffic from the main site circulation during the sequential redevelopment.

As a part of BP's formal project approval process, the design and its implementation relative to HSE were independently reviewed at critical stages.

The project's primary safety target was a "days away from work cases" (DAFWC) frequency of 0.2 per 100 000 hours worked. This was a five-fold improvement on the construction industry norm, requiring exceptional effort to raise standards. All, from senior management to the workforce, took part in training and induction. HSE was the first agenda item at every meeting and the first issue covered in every monthly report. When things did or could have gone wrong, either on site or elsewhere in BP, safety stand-downs, meetings and regular walkabouts ensured that lessons were comprehensively learnt and future mistakes avoided.

A succession of initiatives included a stop card system - with all workers encouraged to report near misses and safety concerns – and universal use of gloves and of eye protection. Worker buy-in was encouraged by sanctions ("3-6-9" warnings) and rewards (a monthly safety award, with free meals for the winning contractor's staff).

Actual performance was monitored by methods such as analysis of near misses and trends in issuing stop cards and in hours worked per minor injury. With manpower exceeding 100 000 hours per month at the project's peak, great care was taken to ensure that the intense level of site activity required to achieve the programme did not compromise safety.

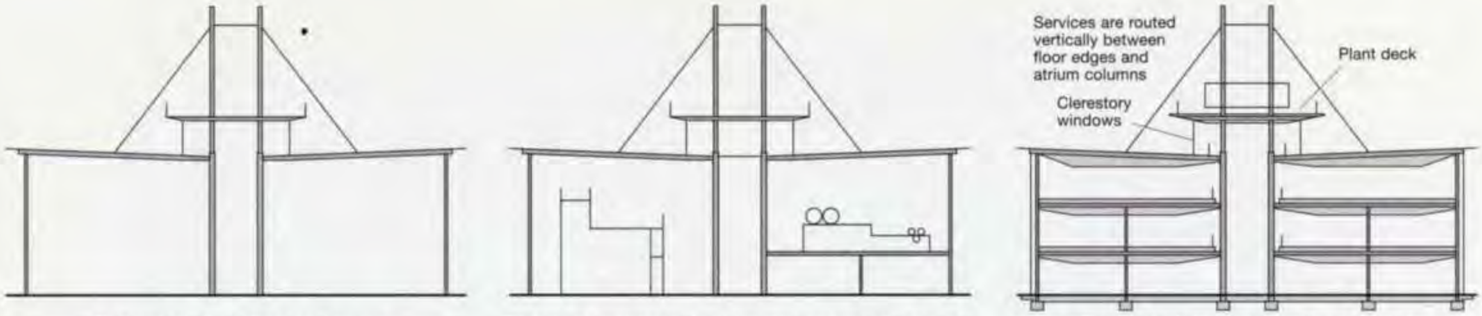
BP's broader environmental aspirations were met by the benefits provided to the adjacent community in opening up the closed, secure site into a shared amenity with road calming, contributions to public transport improvements, and a central green space with a water feature.

Neighbours were kept fully informed of the redevelopment details and programme, and children from the adjacent primary school decorated site hoardings. Within the site, existing buildings were retained and refurbished where possible; an existing bomb shelter became a plantroom. Facilities that could not economically be reused were demolished and replaced by energy-efficient buildings.

The primary sustainability target was an "Excellent" BREEAM (Building Research Establishment Environmental Assessment Method) rating for the standard office buildings. Building A was tested, achieved the rating, and established the template for the rest of the offices. The non-standard Link building provided the opportunity for further features to limit environmental impact. During construction itself, waste reduction and recycling targets were set, monitored, and progressively improved.

BP's HSE targets were met and exceeded, demonstrating what can be achieved when clear client goals match the aspirations of design and construction teams. The result has been a project achieving exemplary results:

- safety: five times better than the UK construction norm, with over 1M hours worked without a DAFWC as Phase 2 neared completion
- waste reduction: 80% of all waste produced during construction recycled
- building space utilization: 250% improvement over the previous buildings on the site
- airtightness: 300% improvement
- sustainability: BREEAM "Excellent" rating
- CO_2 emissions: typically half those of other BP buildings in the UK
- user satisfaction: top 85th percentile of UK office users.



The empty shell - no floors or columns

Pilot plants and laboratories in one, two, or three-storey spaces

The standard office extrusion as constructed

3. Flexibility within the basic structural concept.

ceiling zones and 4.15m floor-to-floor height. This was generous for offices but well suited to the environmental strategy, which incorporated displacement ventilation supplied via floor plenums, and chilled ceilings and beams.

In cross-section, two 15m wide floor plates flank a 6m wide atrium. Daylight is admitted by clerestorey windows beneath the plant deck that surmounts the atrium. By offsetting the atrium columns 600mm or so from the floor edges they support, a continuous servicing strip is provided adjacent to the floors to accommodate the service risers that connect the floor and ceiling voids to the equipment on the plant deck. The very different servicing requirements of offices, laboratories, or other uses could thus be accommodated in whatever length of servicing strip was required, without affecting the primary floor structure.

The pairs of atrium columns in each bay support the plant deck, above which they rise as masts. From the tops of the masts, raking bars descend to support the mid points of the adjacent roofs.

This arrangement - which might seem self-indulgent if considered only as a structural solution - contributes internally and externally to a distinctive aesthetic, combined with the crisply detailed façades. The hung roof enables the upper floors of the offices to be free of internal columns. The regular array of masts imposes order on the plant deck, where most equipment is externally exposed.

Standardization and individuality

The office structural grid is 6m x 7.5m. On the façades, each 6m bay is subdivided into a 3m wide panel flanked by two 1.5m wide panels. For cellular offices this mullion rhythm is suited to combinations of 3m, 4.5m, or larger partition spacings, but most offices were expected to be open plan and the fully glazed facades and raked ceiling profiles were designed to maximize daylight penetration in the floor plates. Phase 1 comprises 17 700m^2 of offices in three buildings. An average net-to-gross ratio of 89% indicates the design's efficiency.

Though the buildings had to be standardized and modular - clearly members of a single family - they needed individual identities. This was achieved with variations in internal colour schemes and modifications to suit orientation and location. Building A has an offset entrance hall, with its two wings staggered to suit the plot shape; building B a central entrance with a deep, shading canopy; building C a side entrance. Also the façade shading varies, with photovoltaic panels on the southeast and southwest façades of buildings A and C.

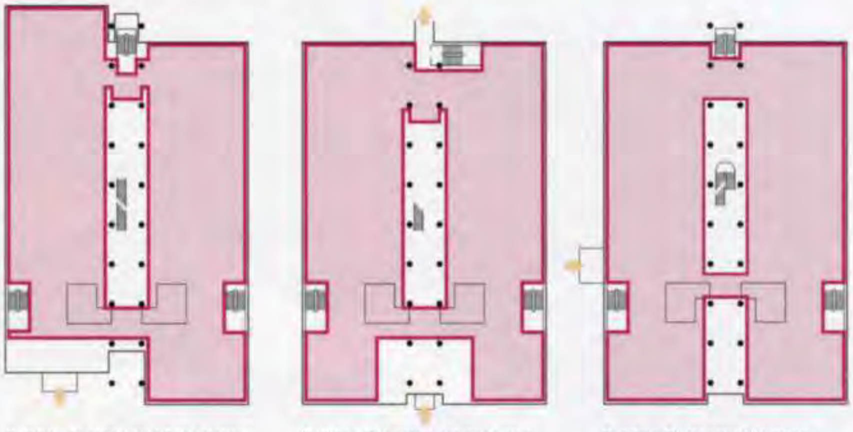
Construction

Building A, on the site of a former car park, required no prior demolition and so was built first. It was one of the first large-scale uses of the *Slimdek* flooring system, which comprises long-span composite metal decking supported on the bottom flanges of asymmetric beams. These beams, buried to most of their depth in the concrete slab, need no applied fire protection to achieve the required one-hour fire resistance. The floor structure is slightly deeper than an equivalent in situ concrete flat slab, but much lighter.

Building C followed, after demolition of the laboratory occupying its site. In the meantime, building B went through three separate design proposals, first as a large office, then as a laboratory, and finally in its constructed form as a smaller office with a linked technology building.

At the same time, the substantial road remodelling necessary to achieve the external environmental improvements also progressed, together with major services rerouting and other external works and ancillary buildings. Construction of the three main buildings overlapped and was completed within budget and programme, with building A taking 15 months, building C 14 months, and building B 13.5 months.

4. Variations on the template.



Building A: staggered floor plates to suit irregular plot, with offset entrance and hall.

Building B: central entrance and hall, offset rear stairs for link to technology building.

Building C: standard building with side enterance.

Industrial legacy

Many hydrocarbon-based industrial and research processes had been carried out over much of the site in the past eight decades. Recognizing that the older processes were undertaken when society was less concerned about environmental impacts than now, BP saw the redevelopment as an opportunity to thoroughly investigate and clean up unacceptable contamination.

Fortunately, BP had very good archives on processes and possible spillages, and drawing on these, plus personal recollections, aerial photography and other sources, Arup desk studies identified the nature and location of the contamination sources. These included flare stacks and fuel storage, blending and testing (diesel, petroleum, marine fuels, and kerosene), as well as general workshop activities.

Among the resulting potential contaminants were hydrocarbons (including polycyclic aromatic hydrocarbons), chlorinated solvents, and heavy metals like mercury. Soakaways and sumps had been used to collect and dispose of products and wastes, so leakages and spills were likely, potentially contaminating the subsurface.

Two main factors governed the approach. For the site's commercial value to be maximized if it was later disposed of, purchasers had to be confident of its "cleanliness". Secondly, the sequential construction of new buildings, preceded by vacation of existing ones, meant that there would always be only a short period after demolition for any investigations. These were addressed by agreeing stringent trigger levels with BP for contaminants above which they would be disposed of or treated, and by ensuring close liaison between environmental engineers and programmers, as the latter responded to the constantly fluctuating progress in decanting the existing site.

For each phase, Arup devised and managed a ground investigation. Most of the site is underlain by some 5m of river terrace gravels overlying London clay. The gravel is an unconfined major aquifer of local importance, from which BP itself abstracts. Groundwater movement is very slow because of the aquifer's shallow hydraulic gradient.

In Phases 1 and 2, the first stage of each investigation was limited by the presence of the existing, working buildings. Trial pits, boreholes, and window sampling were mainly in roadways, avoiding the dense underground services but getting as close as possible to likely contamination sources. In neither phase was any significant contamination so far revealed, indicating that little migration had occurred and any contamination was likely to be confined to "hot-spots" under buildings and other sources. Ground investigation verified this as each existing building was vacated and demolished.

Phase 1 was complete and Phase 2 under way before the first of several anticipated instances of subsurface contamination was exposed, each primarily hydrocarbon in nature and located in conjunction with the groundwater table, about 2m below ground level. In each case, the full extent of contamination was delineated, laterally and vertically. Using soil and groundwater samples, a targeted suite of laboratory testing confirmed levels of contamination, with gas monitoring where necessary.

Arup undertook quantitative risk assessments for both human health and the environment. By now it was clear that BP would retain the whole site in the medium term and therefore that natural attenuation was a viable option for achieving a site clean enough to sell on, without costly and environmentally undesirable off-site disposal. The risk assessments concluded that in general the contamination presented no significant human health risk. Subsurface conditions were such that groundwater contamination was very unlikely to reach the site boundary and present a risk to offsite groundwater. So, with the Environment Agency's agreement, the contamination was left to undergo natural attenuation, with a long-term monitoring programme to ensure that conditions on the site remained acceptable.

Where contamination could be a health or environmental risk, or where construction would be in its presence, remedial strategies were devised. For example, where contamination might have crossed the site boundary, sentinel boreholes were installed nearby, with air sparging wells, as a contingency to allow construction to continue to programme. From analysis of the samples, the calibrated model provided reassurance that there was no significant migration of contamination. Further groundwater monitoring showed that conditions were suitable for contamination remediation by monitored natural attenuation, a strategy accepted by the EA.

The most critical contamination occurred when free phase hydrocarbon product was encountered at a crucial stage of the Link's construction, following delays in handover to the project team of an existing facility being decanted to an industrial site elsewhere. Arup led a small taskforce to investigate and effect remedies to the satisfaction of BP, the EA, and other statutory bodies, and minimize any adverse effect on the overall programme. Construction of a full-length service trench below the Link required temporary dewatering. To minimize risk to site workers and ensure correct management of excavated material, contaminated groundwater, pumped from the excavation, was treated via interceptors (to remove free product) and an air-stripping tower (to remove volatile hydrocarbons) prior to discharge to the foul sewer in accordance with a consent agreed with the drainage authority.

Throughout the project, the priority was to correctly assess any contamination and handle it with minimum impact on the programme. Local hot-spots were excavated and removed to landfill, but quantitative risk assessments showed most contamination to be low-level enough to allow natural attenuation, avoiding the cost and environmental burden of disposal to landfill. Permanent groundwater monitoring was put in place to verify the progress of attenuation. Arup worked closely with BP's experts and the construction management team and regulators, in particular the EA, to ensure that all parties bought into the strategy.

5. The site prior to redevelopment.

6. By the end of Phase 2, only the buildings in the south-east corner of the site (centre-left foreground) were still served by centralized systems.

Phase 2: the 20% challenge

Continuity

With construction of Phase 1 progressing, attention moved to the next stage. Phase 2 would be larger, comprising 26 000m^2 of offices and other accommodation in four buildings. While Phase 1 was clearly going to be successful, BP's culture of continuous improvement required more of Phase 2 than a simple repeat.

How to lower costs? Reducing specification quality was considered but rejected when a study showed that 10% or so could be saved anyway, without quality reduction, simply by replicating the standard building. Experience from Phase 1 would reduce design time and construction costs, but to secure the benefits it was obviously essential for the work to be carried out by the same contractors.

Discussions on how best to proceed coalesced into the following stretch target: to deliver the Phase 2 buildings to the same specification as Phase 1, but at 20% lower cost, with defined contributions to this reduction from the design team, construction management organization costs, and key trade contractors.

Controlled change

A fundamental tenet of the 20% challenge was to "copy exact", yet the designers obviously also wanted to improve on Phase 1, as well as respond to BP's current needs. For example, developments in glass technology enabled solar shading to be omitted from the façades without increased solar gain or glare.

Change was implemented on the basis that it be self-contained, ie not affecting other elements of the design. Fully-developed building designs are highly integrated and run the risk of unravelling as an unforeseen consequence of change. This approach became a criterion for acceptance of any further changes proposed under what became formalized as the "Innovations Process".

The project leaders were aware of the danger of staleness in a team implementing "copy exact" designs, and the Innovations Process was devised both to address this and to promote continuous improvement. Team members were invited to propose design improvements that were clearly self-contained. This had an element of competitiveness, with proposals publicised on a whiteboard, and the further incentive that any cost savings would be shared between client and team. Design costs were reimbursed for innovations that were taken forward.

The process was a success, although there was lively debate as to whether some proposals qualified as "innovations" rather than the value engineering that was undertaken in any case.

Keeping BP working

A key task was to ensure that construction did not compromise the site's day-to-day operations. With over 2000 BP staff in Sunbury and some buildings in use 24 hours a day, all infrastructure networks feeding existing buildings had to be kept fully operational for the entire duration of the redevelopment.

The site had evolved incrementally from the single country house to over 50 varying buildings, reflecting BP's expansion in various areas of the petroleum industry and resulting in the continual construction and reconstruction of buildings. They were served by centralized networks for electrical power, cooling water distribution, boosted wellwater, compressed air, etc, all distributed as primary and secondary ring mains to ensure that most buildings had security of supply, with radial feeds generally only to individual buildings. Many systems were, however, nearing the end of their operational life.

The masterplan adopted a completely new site layout, and this presented a major challenge for the interim infrastructure design as many of the systems fed via ring main networks lost the potential to be supplied from two directions. To avoid any adverse impact on BP's operations, it was essential to retain secure supplies at all times to all parts of the site, so that in the event of maintenance work or damage, every building site could still be fed without interruption.

During Phase 1 construction, ring main supplies were maintained relatively easily through minor diversionary works, but construction of the five Phase 2 buildings decimated the original infrastructure networks: not only were the ring mains severed, but many existing buildings were totally cut off from their original site-wide supply networks. BP, however, still wished to retain these for the shrinking number of original buildings, to prevent additional expenditure on existing buildings soon to be demolished.

Most did not have their own independent plants for heating and cooling, etc. As shutting down all the site-wide networks and providing individual plant to each building would be too expensive, temporary diversions were continually provided to ensure that all retained buildings were fed throughout the construction period.

The new buildings were far less problematic. As the brief was to develop buildings with the potential to be released to the open market at a later date, there was no need to provide site-wide networks for systems such as cooling. Every new building was therefore independent and supplied more conventionally with water, gas, electricity, and drainage only.

Nonetheless, some infrastructure networks were installed to enable the site to operate as a single entity. These were primarily for communications: separate systems were installed for telecommunications, fire alarms/security, and IT. In addition, to minimize the development's long-term water supply costs, the original site boreholes were re-used to provide water for fire hydrants, landscaping and water features, plus cooling of the Link building and the kitchen in building H.

During Phase 3a, the infrastructure services for the remaining original buildings were rationalized and upgraded where necessary. The only major centralized system still required was heating, for which a new boilerhouse was built. Because of critical 24/7 operations, a "hot" switchover of services was required, preceded by a full load test on the boiler to ensure that no interruptions occurred.

7. Breakout areas overlooking Building D's atria.

Prior to the redevelopment, BP owned and operated all the conventional utility networks such as water, gas, electricity and drainage, downstream of site-wide meters, substations, gas governors, and the like. The redevelopment provided the opportunity to ensure that, for the new buildings, all the networks and associated long-term liabilities could be removed by designing systems to be fully adopted once complete. As a result, BP now owns a set of buildings that can, if it wishes, be split up and sold off individually.

A major concern of the local authority and the Environment Agency (EA) was the site's sustainability in relation to the surrounding surface water drainage network.

Most of the site originally drained to Feltham Hill Brook, a culverted watercourse that crossed from west to east. Two major issues arose: firstly, the original location of the brook clashed with buildings in the proposed masterplan for Phase 2. Secondly, flooding downstream was likely, because peak flows from the redeveloped site were likely to be increased due to the nature of the new design and the higher quality of the materials used.

The first issue was resolved by diverting the culverted brook in its entirety between its site entry and exit points. As for the second, no drainage connections were made to the brook. Instead, all surface water run-off from the buildings, roads, and hardstandings drains to soakaways. This sustainable approach greatly assisted the relief of capacity constraints within the local drainage network.

Two other fundamental decisions were made that flew in the face of "copy exact". The first was to abandon the standard extrusion for building D, adopting instead a triangular plan in response to the plot shape, and thus produce a distinctive gateway building at the site's main approach. Although building D's form is entirely different from standard, its specification and detailing followed the "copy exact" principle. The second major decision was to introduce a Link building at the front of buildings F, G and H. This was in no sense a copy of the standard building, but the value it added to Phase 2 was irresistible.

The Link building

It is sometimes easier for an outsider to an organization to see "the wood for the trees" than it is for an incumbent. Sunbury has a substantial cross-section of the BP organization and when the team arrived there were approximately 2000 highly qualified people working in 89 separate buildings within a bonded and secure site. It was an insular fortress and there was nowhere to go. There was minimal opportunity for cross-fertilization of ideas and the neighbours were excluded.

The "big idea" the designers brought to BP was "communication and community". Sunbury is now a major hub for BP in the south-east of England, accommodating more than 4000 people, and everywhere there is opportunity to interface. The whole campus, in effect, brings a community together. This is exemplified in the Link building, which provides an emotional focus as the main entrance to the Sunbury business park and addresses a major new open space with fountains, trees, and soft landscaping for the whole community to enjoy. Providing transitory space between buildings, the Link achieves multi-functional accommodation - main site reception and security, restaurant dining, break-out space, convenience shopping and "town hall" meeting space for 400 people - and was negotiated without any increase in town planning area to the site masterplan.

8. Restaurant dining area in the centre of the Link building.

The Link demonstrates close integration of architecture, structure, and environmental engineering, adopting simple but effective technology. It is about 20m wide by 100m long, a double storey-height hall with a mezzanine floor at the back, and connects the fronts of three standard buildings. The mezzanine includes break-out spaces from the adjacent meeting rooms and offices, with touchdown facilities and coffee/tea points which promote more productive use of office space. The Link's curved form embraces the central open space and creates a simple screen between landscape and interior, changing its appearance depending on the time of day.

Orientation is the greatest influence on building environment. The Link's main facade faces north-west. The roof bays are tilted into a sawtooth profile, supported on 19m span exposed trusses with clerestorey windows, which spill natural light into the building's furthest recesses. The trusses are skewed diagonally across each grid to bring the windows closer to north-facing, and support exposed-soffit precast concrete roofs that span from the bottom boom of one truss to the top boom of the next.

The combination of the Link's arcing form and the skewed trusses means that the surface created by the precast soffits is tapered in both directions, and warped. Yet each precast unit is a simple 200mm wide straight beam with a uniform cross-section; only the length varies, the tapering soffit geometry being achieved with small variations in the gaps between units.

The sides of the precast units slope inwards so that these gaps, about 50mm wide, are the openings to re-entrant recesses. The gaps between the tops of the units are bridged with plywood, to the underside of which is attached absorbent material that helps to soften the Link's acoustics, while the exposed concrete moderates the internal environment. This and other passive measures provide the default systems for the Link's mixed-mode environmental control.

In summer, natural ventilation is relied upon, with hand-openable low-level windows and automatically-opened vents in the clerestorey. Advantage has been taken of BP's historical groundwater abstraction licence to provide free cooling. Photovoltaic "eyelids" shade the clerestory windows and produce electricity to power the well-water pumps transferring cooled water to the air-handling units in two plant towers, when the building is operating in mixed mode. The system creates a virtuous cycle when increased sunshine produces more electricity through the PVs, to pump more cooled aquifer water to supply the air of the AHUs.

9. The façade of the Link building: Sunbury is now an attractive destination for BP staff.

Vindication of the Link design was proven by peak loading during the hottest summer for 200 years, just as the building opened in 2003. Running under passive measures with low and high-level windows creating cross-ventilation and with the thermal mass of the precast roof planks providing radiant "coolth", the space was perceptibly cool and enjoyable.

The result is a trouble-free, delightful environment which imaginatively responds to the client's brief and helps BP to a better, more productive, enjoyable, and interactive workspace.

Phase 3a: preparing for completion

The BP Sunbury masterplan has not yet been completely implemented, as part of the Phase 3 site is occupied by buildings with substantial residual value. However, in preparation for the completion phase, a smaller project has been undertaken by the team, comprising demolitions, enabling works, temporary landscaping, and rationalization of the central plant that supplies the remaining buildings. For this phase, Arup's scope has been expanded to include leading the design team and designing the building services.

Conclusion

The redevelopment of BP's Sunbury site has transformed an inefficient and enclosed, semi-industrial estate into an open and attractive business park. The benefits extend beyond the site boundary, with public transport improvements, a shuttle bus to the nearest railway station, and road calming measures that have benefited the adjacent primary school. BP has achieved its objective of making Sunbury its primary UK office location, with only essential functions carried out at the London headquarters.

The redevelopment was carried out on time and within budget. It met the 20% challenge and achieved an exemplary safety record. In awarding the project the "Quality in Construction" Major Project Award, the judges said "This is a wonderful example of what we're all trying to push forward. You couldn't hope for a better illustration of what we need in this industry."

Ian Wallace is a Director of Broadway Malyan with responsibility for Workplace and the BP Sunbury project.

Credits

Client: BP International Ltd **Masterplanner/architect:** Broadway Malyan **Lead consultant (Phase 3), multidisciplinary engineer/planning supervisor:** Arup – Nick Ashby, Hannah Babor, Nicholas Bailes, Charlie Baldwin, Phil Barker, Malcolm Barrie, Matthew Blackburn, Simon Brimble, Caroline Burt, Chris Carter, Mike Carter, Bob Cather, Hugh Cherrill, Stewart Christie, Paul Coe, Phil Coomer, Gary Davies, Natalie Davies, Anthony Ferguson, Graham Gedge, Anne Gilpin, Martin Gormley, Liz Harris, Richard Hughes, Graham Humphreys, Gabriel Hyde, Hywel James, Chris Jofeh, Geraint Jones, Kevin Jones, Tanya Locks, Barbara Marino, Charlie Martin, Paul Morgan, Archie Mundegar, Fiachra Page, Geeta Patel, Keith Patterson, Howard Porter, John Scullion, Clem Smoothy, Michael Statham, Angus Stephen, Glen Swinney, Bob Venning, Tony Wallace, Terry Watson, Mike Willford, Richard Wilson **Building services engineer (phases 1 & 2):** Hoare Lea & Partners **Quantity surveyor:** Davis Langdon **Construction manager:** Schal Construction Management Ltd **Illustrations:** 1, 3, 4 Nigel Whale; 2, 5, 8, 9 Morley Von Sternburg; 6 Arup/Broadway Malyan; 7 Andrew Peppard

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"This project is a real statement of BP's brand and core values. It has a proven track record of delivery and has high green credentials. It sets the standard for future BP-owned office developments."

Martin Wells, General Manager, BP Sunbury

1. The new Olympic ice hockey venue and, behind, the 1934 World Cup stadium.

The Olympic ice hockey stadium, Turin, Italy

Mark Chown Gabriele Del Mese George Faller Richard Greer Berthold Keck Maurizio Teora John Waite

Turin's new stainless steel-clad ice hockey venue for the XX Olympic Winter Games 2006 is designed to become a flexible, multi-purpose, sports, entertainment, and cultural centre following the Olympics.

Introduction

In 2002 Agenzia Torino 2006, the public body created to carry out the works for the XX Olympic Winter Games in Turin, launched an international architectural competition for the design of the ice hockey stadium. The winning entry was by a team comprising three design offices: Arata Isozaki & Associates, Tokyo, and Archa, Turin, as architects, with Arup Italia as engineer.

Turin has a stadium built for the 1934 World Cup. Nearly 70 years on, this new scheme had two guiding principles: to redefine the urban space developed around the 1934 site, and to provide a "flexible machine" for events after the Games.

The latter was particularly appreciated by the competition jury. The interior is flexible enough to house a diversity of events. Its demountable seating and movable floor plates will allow not only ice events and other indoor sports, but also concerts, shows, conventions, parades, religious gatherings, etc. The stadium will be an "events machine", an important hub for Turin's social and cultural life.

General description

Located close to the old stadium (Fig 1), and overlooking a re-landscaped park, the building has a footprint of 183m by 100m. Externally it is a rectangular stainless steel box above a 5m high supporting glass base. The stainless steel cladding panels are not smooth, however. Rather, their irregular patterns and openings are designed to emphasize the building's dynamism.

The Olympic seating requirement was for around 13 000 spectators, and the Olympic ice rink measures 60.96m x 30.48m. To achieve the required post-Olympics flexibility, temporary floor slabs can be installed at the top level of the lower stands, creating a larger space, 130m x 61.4m, for events with a maximum capacity of 15 000 spectators (Fig 2). The emergency exits are all at ground level, providing direct access to the outside without external stairs.

The internal space has four levels (Fig 3):

- Basement (-7.50m): the ice rink itself, together with quarters for athletes and coaches, and the plantrooms
- Intermediate level (-3.75m): the Olympic "family", the media, the sports federations, and the plant management
- Ground level (0.00m): main public access, circulation, and space for movable stands
- Upper level (+6.00m): a raised walkway around the perimeter to accommodate standing spectators during special events in a post-Olympic configuration. Catering and refreshment areas are also at this level.

The stands are in three groupings to allow a truly flexible use of the space. The lower ring, between levels -7.50m and 0.00m, is retractable. After the Olympics a new raisable floor will be built. This will either be kept at -7.50m or, when the retractable stands are closed, raised to 0.00m. The second ring of stands is between levels 0.00m and +12.00m, and of these the ones on the long sides of the building, including areas for the media and VIPs, are fixed. The third grouping, the stands at each end of the building, are in six movable banks, each of 400 seats, which are lifted and transported by remote control to the different configurations required by the various planned post-Olympics uses.

The main body of the building, above level +5.00m, has a double wall. The external panels, each 5.4m x 0.5m, are of stainless steel sheets with internal stiffeners and an opaque surface relief. The internal panels are in perforated aluminium with internal sound insulation, and the inner space contains a further layer of thermal and acoustic insulation to avoid disturbing the surrounding residential area during concerts or other large gatherings.

Engineering design team

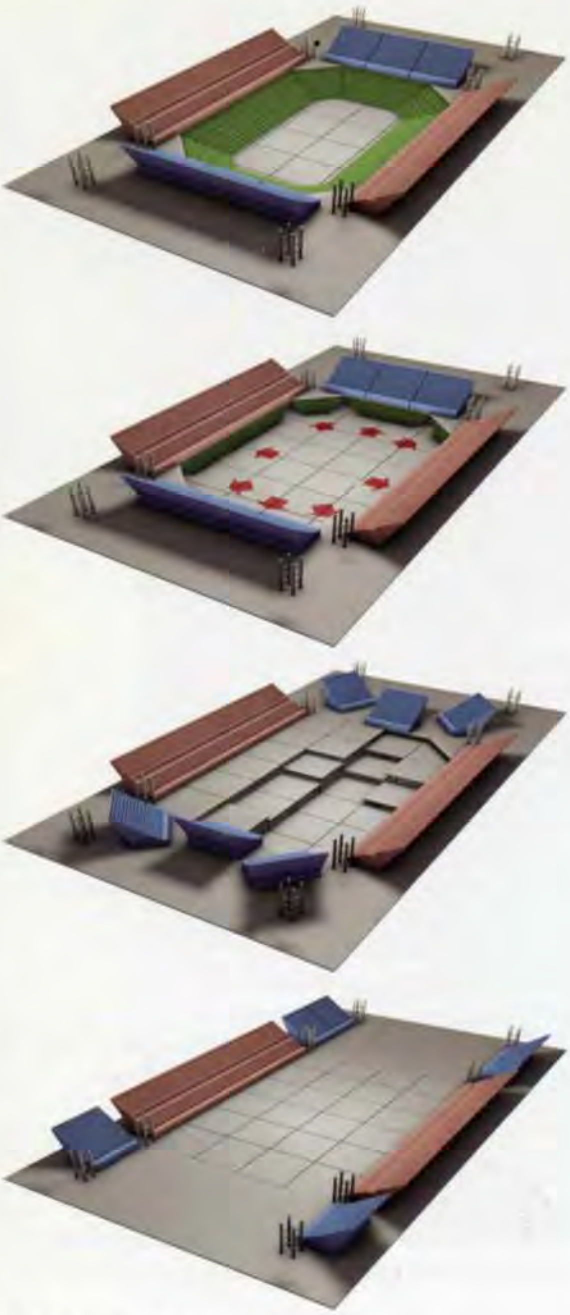
The team drew on the diverse skills of Arup worldwide. The project was led by the Milan office. ArupSport in Manchester, UK, helped with the design of the stands and the sports lighting. Mechanical and electrical services were carried out with the help of the Madrid office. Acoustics was a collaboration between the New York and Manchester, UK, offices, whilst Arup Fire in London and Madrid dealt with the fire design challenges. Geotechnical support was provided by the London office. This proactive and enthusiastic team interacted and integrated well with the architectural team in Tokyo and Turin.

The structural design

General structural approach

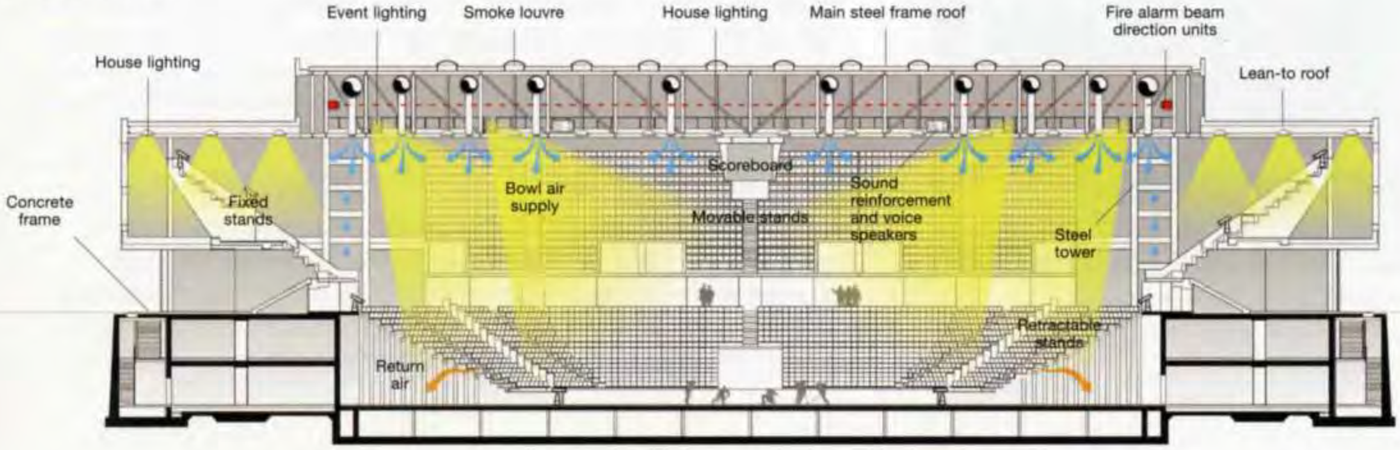
The building had to adapt to the future envisaged uses without limiting its primary but temporary function during the Olympics, keeping the view over the playing arena unimpeded by columns or any other vertical structure. This led to the long-span roof structure solution using eight 24m tall "mega-columns", 3.2m square on plan, like sets of vierendeel ladders, each with four vertical square hollow sections.

The overall structure resembles a huge "space-table" with no additional stability elements like shear walls or braced bays. It resists considerable vertical and horizontal loads, and provides maximum flexibility. The main services distribution is combined within the few vertical columns and runs through the horizontal structure, keeping the areas between columns free from risers and the roof structural zone visible and readable. The structural elements required by this design concept were reducible to relatively simple components, increasing repetition and improving buildability. This approach also helped with reducing costs and site control.



2. Flexibility of use post-Olympics.

3. Cross-section.



Geotechnics and foundations

The soil profile comprises a layer of muddy sand up to 3m deep above sandy gravel, with a layer of mud every 3m or so. The water table was measured at -20m. Initially soil was excavated 8m deep over an area of 210m x 125m, creating 200 000m^3 of excavated material. At basement level, retaining walls contain the ground.

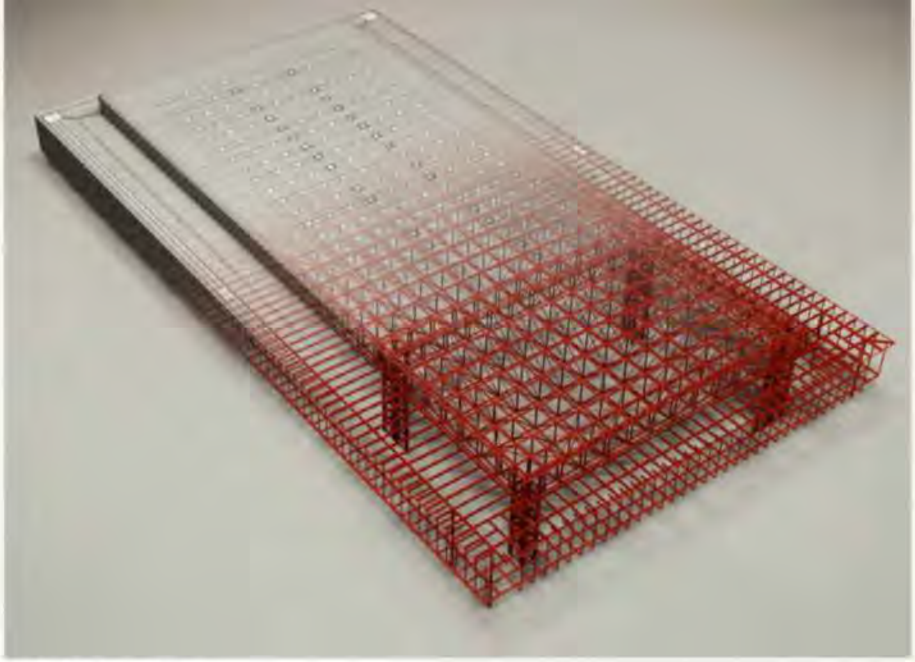
The foundations under the eight mega-columns are at -10m. The four corner columns are each supported by four 1.20m diameter piles, 15m long, augured under bentonite. To limit overall and differential settlements between corner and internal supports, the four internal towers, which carry larger loads, are each supported on two sets of 1.20m thick foundation barrettes, 6.20m long and 12m deep, also cast under bentonite. All pile caps are 6.2m square and 1.5m deep. Other minor foundations are generally shallow strip or pad footings, with a raft under the plantroom area.

The stands

The fixed stands on the building's long sides mainly comprise in situ raking beams, supporting a series of L-shaped precast concrete elements forming the stepped profile of the arena and spanning either 5.4m or 10.8m.

The six movable stands each weigh around 120 tonnes, are 17m x 16m on plan, and 11m tall. They include spectator access stairs and public corridors serving the lower ring, and their steel structure supports concrete planks and structural screed. Motorized trolleys with lifting mechanisms are positioned through openings directly under the stands in order to lift each one individually.

4. "Mega-columns" and roof under construction.



5. Main structure.

The main steel roof

The main steel roof structure (Figs 4 & 5) is a rigid diaphragm within its own plane and distributes vertical and horizontal forces to the eight supporting towers. These behave as propped cantilevers with intermediate lateral support at -7.5m -3.75m and 0.00m. They are irregularly spaced at 30m, 90m, and 42m longitudinally, and have a transverse span of some 65m.

The 162m x 70m roof is a two-way spanning lattice frame, its top and bottom booms 5m apart. Around the perimeter and between pairs of towers are strips of trusses with greater rigidity to better define the structural behaviour of the central bay. The orthogonal grid of the lattice frame is 5.4m x 5.4m in plan. Each of the roof's edge strips is stiffened by two parallel trusses 3.2m apart to align with the towers' structure. To reduce steel weight, a series of sections with different geometric properties according to the distribution of forces was used. The upper and lower chords are column sections with depths as close to 300mm as possible to achieve the required architectural simplicity and to ease connection details. In places, to avoid local instability, additional welded plates were introduced.

The roof cladding - metal deck sandwich panels with integrated insulation and waterproofing - is supported on the top chords of the lattice structure. The panels also guarantee the required acoustic performance. Roof skylights on each 5.4 x 5.4m bay allow natural light into the building and are also used for smoke extract in case of fire. Within the lattice are catwalks for maintaining the high level services and the roof itself.

Lean-to structure

Around the entire perimeter, starting at level 0.00m, is a secondary lean-to structure that joins the façade to the main roof. It comprises perimeter steel columns bearing on an external retaining wall, and supports the building's outer skin. At level 6.00m there is a composite slab, supported by the façade columns. This area, following the perimeter of the whole building, is a public space accessed from the stands by stairs and lifts - an important and visible element for all on the ground floor.

Roof fabrication and erection

Altogether there are some 5000 tonnes of fabricated structural steelwork. The mega-columns and roof structure were made in segments, transported, and assembled on site. Each mega-column in three sections and placed with a 700 tonne crane. Each truss was also subdivided into elements and assembled using two 500 tonne cranes. Fabrication and erection took eight months.

Mechanical services

General approach

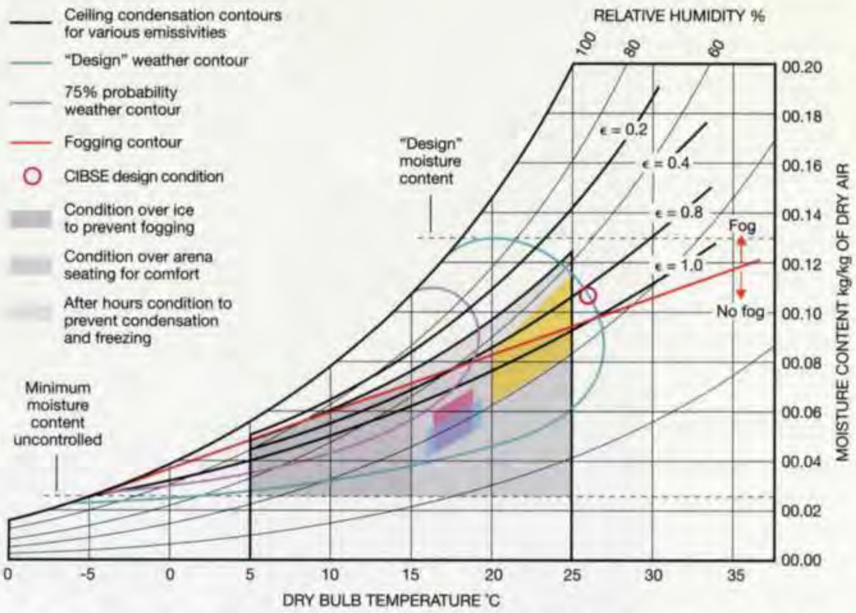
The mechanical services similarly were designed to be flexible enough to provide adequate conditions for the ice rink and the associated sports and press facilities, and also allow for future activities such as indoor athletics or exhibitions.

The air-conditioning system for a large open space with around 20m floor-to-ceiling height would normally be based on a low-level, underseat ventilation supply. This would optimally ensure spectator comfort, keep air away from the ice, and take advantage of stratification. However, as the seating was to be moveable, it was too complex and expensive to try and integrate the air supply within it, and so the concept quickly moved to a high-level supply system with low-level exhaust.

Plantrooms and services distribution strategy

The main arena has an all-air system sized to supply three air changes. Four 47m^3/sec basement air-handling units (AHUs) were built in situ at the building's corners, the highly insulated plantroom walls forming each unit's outer casing. From these, four vertical ducts rise within the structural columns to roof level. Header ducts connect the two vertical risers, and horizontal circular ducts distribute across the roof space in the structural trusses to supply the high induction swirl diffusers. Return air is extracted through the seating, at the low-level entrances, before dropping to a basement trench duct that takes air back to the AHUs.

The main energy plant is in an "energy centre" outside the main arena, to distance and control noise breakout and keep the roof free of services, supporting the architectural concept. The air-conditioning systems are cooled by four air-cooled chillers with heat recovery producing 3MW of cooling at 2°C. Heating is via the local district heating loop and heat exchangers with a total capacity up to 7MW at 80°C. A separate air-cooled chiller provides supercooled glycol mix chilled water at -9°C for the ice floor. Backup generator electrical supply is provided for this.



6. Psychometric chart showing the fogging line, based on an ice surface temperature of -5°C.

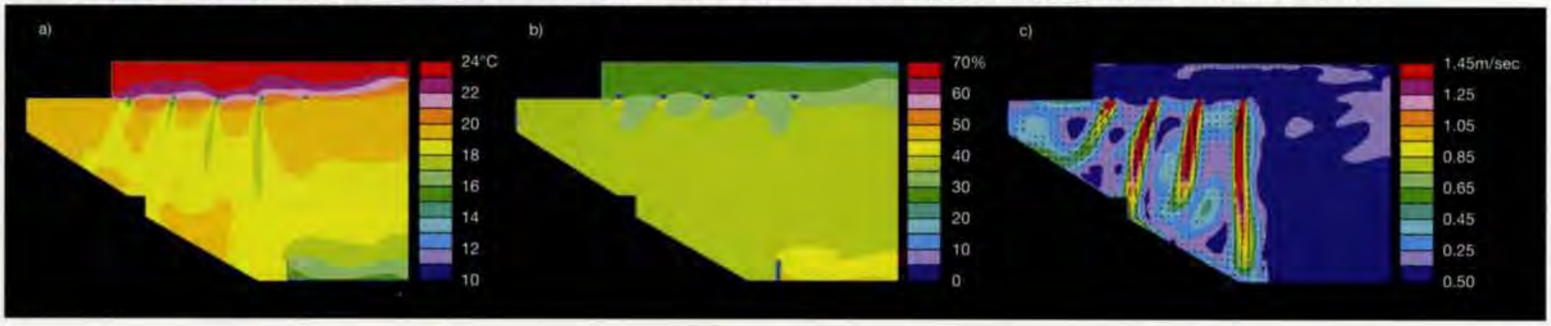
Fogging

A key design challenge was fogging close to the ice level and obscuring the puck during play. Warm moist air condenses as it meets cool air close to ice, forming tiny water droplets. The only way to eliminate this is to control the maximum humidity level in the space and minimize air movement across the ice. Air within the space will not form fog as long as it is maintained below the fogging line (Fig 6).

The high-level air distribution uses Halton jet diffusers either as jet nozzles or as swirl diffusers depending on the supply temperature. To maintain spectator comfort at all levels, the diffuser throws are adjusted according to their position relative to the stands. Under pre-heating conditions air must to get down to spectator level, while under cooling, air velocities must be controlled to avoid discomfort. The nozzles are directed away from the ice surface to reduce the flow of air over it, and the glazed barrier around the pitch also helps to prevent this.

To test the design concept and confirm design parameters, a CFD analysis model comprising some 400 000 fluid cells calculated temperature and humidity distribution across a vertical slice through half the stadium, including the spectator seating grades and ice rink floor (Fig 7). Analysis under summer conditions indicated a risk of fog forming over the ice layer and the client was advised accordingly. It is not envisaged that the ice rink be maintained during the summer months. A full-scale model test installation of the diffuser operation was then carried out in Halton's laboratory, confirming the diffusers' correct performance under heating and cooling.

7. Example CFD model showing (a) temperature, (b) relative humidity, and (c) wind speed in the winter case under cooling mode with maximum occupation.



Electrical services

General approach

Supporting the overall architectural goals, the electrical services design is fully integrated with the structure, using the most appropriate technology for both efficiency and economic viability.

The Olympics are short in duration, but the electrical services must deliver an uninterrupted supply even in the case of a technical fault, as well as provide full flexibility in future use. The key design drivers were safety and reliability in installation and operation; versatility to embrace multiple equipment changes; flexibility to cope with future IT and electrical technological advances; minimal visual impact; and execution to the relevant standards for sporting venues and public buildings.

Supply and distribution

Power comes from two independent 22kV local main supplies, and an internal 22kV high voltage ring links three strategically located substations to supply a total of 6840kVA. Each substation has two dry type 22kV/400V transformers. One substation is in the "energy centre", supplying the equipment for chilled and hot water, and for ice production. The other substations are in the main building and serve secondary supplies to all floors by four main core risers in the corner mega-columns. Three diesel generators provide enough back-up power for essential loads for an international event to continue uninterrupted even with a full mains failure.

Lighting

The ice hockey event and house lighting design for the inner bowl had to meet the requirements of the International Olympic Committee, European Broadcasting Union, and national Italian TV (Torino Olympic Broadcasting Organisation) broadcasting standards, as well as the stipulations of the Commission Internationale De L'Eclairage. The TV lighting brief had to cover the ice hockey field of play, warm up, "kiss-and-cry" (where athletes wait for their score), spectator seating, and flags of nations areas. This was achieved by providing 1400lux in the vertical plane with a uniformity of 0.7 in all camera viewing directions at 2m intervals at a height of 1.5m above the ice rink.

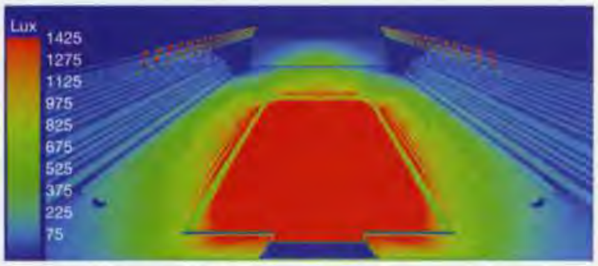
The lighting design brief also required event lighting for various post-Games sports and functions at the -7.5m floor level. Thus all the Games lighting system was retained, with a minimum number of additional floodlights. Innovative re-aiming of the Games floodlights provides total flexibility for the lighting system to be reconfigured, with minimum disturbance to the Games installation, for no less than 11 activities: athletics, badminton, basketball, gymnastics, hockey, tennis, soccer, volleyball, concerts, parades, and motor shows. These events will be capable of providing lighting levels in 250lux steps from 500lux to 1250lux at floor level (Fig 8), with a uniformity of 70%.

A total of 232 floodlight units, using 1kW and 2kW metal halide lamps, were installed for the Games and post-Games events (Fig 9). They operate on two electrical phases to prevent stroboscopic effects: multiple images of the moving puck and swinging hockey stick could otherwise occur. Good glare control is achieved by mounting the floodlights on a high-level gantry outside the main field of view. Aiming angles are below the critical value of 55° to reduce risk of direct and reflected glare from ice to players and spectators. Each floodlight unit has a bespoke arm bracket supported from the gantry, where a hand-operated winch allows the units to be raised and lowered for ease of maintenance.

The events lighting control strategy allows users to select event scene settings from preprogrammed modes, using a dedicated intelligent lighting control system.

Should normal power fail, the emergency TV lighting mode provides 800lux vertically as the minimum to maintain TV broadcasting, facilitated by an automatic changeover to two alternative power supplies. An on-site generator acts as a primary or secondary supply source beside the mains supply, and each designated emergency TV floodlight has a hot restrike control gear module to instantly re-ignite the lamp should normal mains be interrupted for more than two milliseconds.

The house lighting provides 300lux with a uniformity of 0.4 using QL induction lamps. These generate high frequency light by magnetic induction (for high reliability and long life), and are recessed into the metal plank ceiling towards the rear of the stands. The lighting brief required that no house lighting luminaires be mounted within or below the metal mesh ceiling system above the ice rink and perimeter seating, so they were specially designed to operate above it.



8. Horizontal illumination levels.

9. Typical floodlighting units.

The emergency lighting is designed to aid safe evacuation of spectators and players in accordance with *UNI 9316* standards. The requirement for emergency lighting at a minimum 10% of the average event floodlighting level is achieved by 40 1kW floodlights connected to two uninterruptible power supply systems.

Communications and audiovisual systems

The challenge here was to define camera locations for both the Olympics and the legacy applications - not fully defined at the time of the study. The team looked for standards and precedents for ice hockey but quickly found there were few. The approach was therefore to look at all possible uses and distil a set of locations that struck a balance between best coverage without excessive provision. TV cabling is provided to scoreboard studio, administration and operation rooms. The systems include voice and data to press rooms, internal administration offices, and the rest of the building using fibre optic and copper cabling.

Acoustics

General design strategy

There were tight budget restraints on the prime client goal of a wide range of post-Games legacy activities. The main acoustical issues impacting the engineering design were:

Environmental noise impact and sound insulation: Italian national and local codes strictly limit noise in leisure buildings, particularly one destined to be a rock/pop concert venue. The performance of all building elements has to be predicted and documented in the *Definitivo* design phase for official approval before construction can proceed.

Room acoustic response: Reverberation and room reflections had to be carefully controlled to achieve the correct ambience. A balance must be struck between maintaining spectator excitement (which requires reflections from cheering, clapping etc, to be sustained) and acoustical control (from sound absorbing finishes) to ensure optimum performance for the sound systems.

Electroacoustic design: In accordance with BSEN and IEC codes of practice, a place of public assembly must have a voice alarm system achieving a specific minimum speech intelligibility requirement, in this case 0.45STI (speech transmission index). This involves selecting, locating, and orienting the loudspeakers as well as designing and locating sound-absorbing finishes. Also, the room has to support full touring rock band sound systems supplemented by the in-house sound system to achieve the sound levels and qualities expected for this type of event.

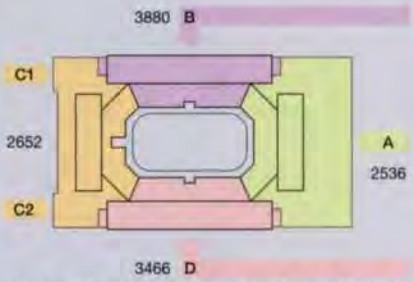
Approach

An initial site noise survey documented and compared levels to Italian codes. Using this and measurements of activities in similar Arup-designed venues (ie the Radsporthalle, Berlin[1, 2] and Manchester Arena[3]), noise levels were predicted at each receiver for sports, convention/exhibition and concert events. Arup predicted that approximately STC50 would be needed, equivalent to 150mm dense concrete. The long-roof span made this structurally impractical: a lightweight solution was needed. A composite metal deck roofing system (approximately 45kg/m²) was designed to achieve the relatively high sound insulation requirement (by combining lower mass layers with significant airspace separation) and further developed by the architect and the Arup team to meet other performance demands.

Fire engineering

Computer analysis: egress (Olympic mode)

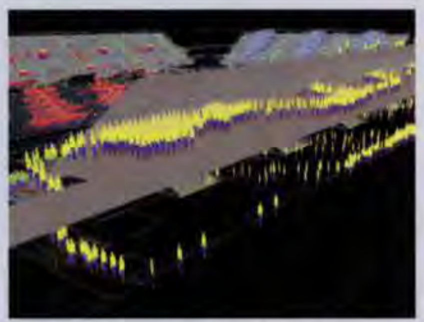
Under Italian law for enclosed sports arenas, this arena is divided into fire sectors, each limited to 4000 persons. In Olympic mode, the actual population of 12 534 was distributed over four sectors, designated A-D. Sectors were also defined for the building's external perimeter, via which the internal sectors have to be accessed and exited. To allow people to access directly the sector they will be sitting in, there is an 800m zone that only ticket-holders can enter. People arriving at Sector C to be seated in Sector A, for example, are directed there via a perimeter route (Fig 10).



10. Sector arrangements, internal and external.

Though egress provisions were thus prescribed, the client wanted to know how long people would take to leave the stadium and get through the perimeter fencing. This was modelled using the STEPS program (Simulation of Transient Evacuation and Pedestrian movementS), which simulates how people move during normal as well as emergency evacuation scenarios.

Three STEPS scenarios showed that the total evacuation time (modelling the scenario above) was within limits acceptable under Italian law. This also highlighted areas of excessive queuing, allowing the team to make design changes and implement management procedures specific to the building (Fig 11). As with any major sporting event, crowd management is essential in ensuring a smooth flow of people into and out of the arena.



11. Typical frame of the STEPS model.

CFD study: tenability conditions

This was to evaluate fire hazards in the stadium bowl, either at ice rink level (7.5m below ground) in Olympic mode, or ground level (concert mode). The investigation reviewed smoke conditions in the arena for three scenarios. Two assessed tenability conditions on escape routes during an emergency evacuation, with and without wind conditions, whilst the third examined heat radiation intensities at high level, to ensure that roof structure integrity would not be compromised were there a larger fire on the movable ground-level timber floor.

Since transient smoke behaviour and complex 3-D gas effluent modelling were required, the FDS (Fire Dynamics Simulator) program - developed by the US National Institute of Standards and Technology and used to help understand the World Trade Center twin towers collapses - was chosen as most suitable tool. The domain - the simulated space in the structure - is first divided into several thousand control-cells. The fire is then modelled for convection and large scale radiative transport, linked with combustion and radiation emission models for small eddies. The transfer of energy between small and large eddies has to be defined, leading to accurate modelling of smoke and gas development in the domain.

The results show smoke reaching the skylights with enough buoyancy to exit the building without affecting tenability conditions throughout evacuation, including the upper levels, in the event of a 5MW design fire scenario. Smoke temperatures at roof level were predicted not to exceed 350°C in a large upper limit 15MW design fire.

During construction, the contractor proposed a change to the natural smoke ventilation system as originally modelled. Arup Fire re-modelled the arena using automatically opening skylights uniformly distributed over the roof surface instead of vertical louvres on the perimeter, and showed that this alternative was acceptable.

In general, keeping an arena space easy to clean and maintain requires sound-reflecting architectural finishes. Sound-absorbing material is usually limited to the ceiling and the seating. It is important to minimize variation between the occupied (when sound is mainly absorbed by spectators) and unoccupied conditions, so that in a worst-case scenario, like a sound check for a rock band, there is no need for changes to the sound system settings and set-up is rapid. In this building, however, the architect wanted to make the seats almost "invisible", using transparent plastic, rendering this goal much more difficult to achieve.

A seat design was developed from the original solid version to achieve optimum transparency using slots, without loss of structural integrity (Fig 12). Behind the seat is a perforated metal panel incorporating mineral fibre (mimicking the wall finishes) that is sound-absorbing. When the building is unoccupied most of the sound passes through the seat and is absorbed by the panel behind. The remainder is reflected to the sound-absorbing treatment suspended below the main roof.

Given the relatively high cost of sound-absorbing treatment, as well as its effect on roof weight, the performance and coverage area were computer-modelled to just achieve the speech intelligibility targets. Once determined, this option (about 75% of the ceiling plan area) was also compared to predictions of 0, 25, 50, 65, 85, and 100% sound-absorbing treatment coverage. The difference in performance is marked and subjectively noticeable in the range 65-85%. Given the budget and cost implications, the design team and client required convincing that the approach was valid. Arup SoundLab was used to create auralizations (sound renderings) of each design option, for speech, pop, rock, and techno music. This allowed parties to listen to the subjective implications of too little sound-absorbing treatment as well as the audible improvements with more sound absorbing. A clear and defendable decision was made for the 75% coverage.

Acoustically, the final roof design comprises three elements. The external roof deck with optimized mass provides the required sound insulation and some low-frequency absorption. A vertical arrangement of 100mm thick panels hanging 1.5m below the ceiling absorbs sound mostly at mid and high frequencies, and a sound-transparent metal mesh on the bottom of the truss forms the architectural ceiling, with the sound-absorbing treatment, loudspeakers and lights in the upper roof void.

Large flat vertical surfaces in the bowl all incorporate sound-absorbing 50mm thick mineral fibre, spaced 25mm from the wall, with a protective perforated metal panel having 33% open area.

The voice alarm system is fully integrated with the fire detection system. Achieving the required 0.45STI rating throughout required not only the sound-absorbing treatment but also careful selection, location, and orientation of the loudspeakers. The performance sound system in the arena is a fully distributed, high power, full frequency range system for high quality music and speech reproduction. Three different types of loudspeaker are arranged in concentric rings, covering the event floor, lower bowl seating, and upper bowl seating respectively.

A central computer controls the system. The user selects performance based on the event type, and system signal processing is automatically configured to suit that event. This facility is particularly useful in the concert modes, where a side stage or end stage arrangement is used. In this situation, specific time delay relative to the stage location is required, so that listeners place the sound source on stage and not in the nearest loudspeaker. This allows the system to be used with touring sound systems to improve sound coverage, particularly at the bowl's upper levels.

The result is a world-class Olympic event space that, within a very tight budget, is also highly flexible in legacy use, to generate increased operational income for the operator and continued national, regional and local community benefit.

12. Sound-absorbing seat design.

Site construction

The perimeter retaining walls were excavated and built in September-December 2003. Stage 2, the building construction itself, lasted from January 2004 until December 2005. In accordance with recent Italian regulations for this type of development, the building went to tender with a set of very advanced scheme design information, calculations, and specifications; the successful contractor was entrusted with developing this information to detail design standard. Arup and its joint venture partners were responsible for site supervision throughout construction.

Conclusion

The Turin hockey stadium for the 2006 Winter Olympics is a truly multidisciplinary collaboration by a team of engineers and architects whose design gave priority to high performance within achievable cost. In an era of profound and at times radical transformation of modern architecture, this building shows a rare equilibrium between architectural form and technology.

Credits

Client: Agenzia Torino 2006 **Client co-ordinator:** G Fassinotti **Architects:** Arata Isozaki & Associates Co Ltd; ArchA spa **Structural, geotechnical, MEP, fire, acoustics, and communications engineer:** Arup - Ambrogio Angotzi, Rosario Arvonio, Gianfranco Autorino, Daniela Azzaro, Mike Banfi, Alban Bassuet, Richard Bickers, Giorgio Buffoni, Stuart Bull, Stephen Burrows, Diane Burt, Luca Buzzoni, Pablo Checa, Mark Chown, Matteo Codignola, Cinzia Cordiè, Gavin Davies, Gabriele Del Mese, Mark Elsegood, George Faller, Chris Fulford, Andrew Gardiner, Heros Gnesotto, David Graham, Richard Greer, Pietro Guarisco, Barnaby Hall, John-Jo Hammill, Berthold Keck, David Lakin, Florence Lam, Davy Leroy, Massimo Marcelli, Giovanni Marforio, Fabio Minciarelli, Richard Morris, Dario Parravicini, J Parrish, Raj Patel, Pier Paolo Pilla, Stuart Redgard, Roland Reinardy, Alberto Rossi, Matthew Salisbury, Bob Senior, Jim Smith, Stuart Smith, Tudor Salusbury, Maurizio Teora, Cyrus Toms, John Waite, Andrew Woodhouse **Cost consultant:** J&A **Security project consultant:** Studio Proges **Project manager:** Gian Mario Accamo **Contractors:** Phase 1, Vitali; Phase 2, Torno spa, Lorenzon, Carlo Gavazzi, Edoardo Lossa **Illustrations:** 1 Agnese-AgenziaTO2006; 2, 3, 5 Arup/Matteo Codignola; 4, 12 Ambrogio Angotzi; 6, 10 Nigel Whale; 7, 8, 11 Arup; 9, 13 Arup/John Fass.

13.

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Arup is a global organization of designers, founded in 1946. It has a constantly evolving skills base, and works for local and international clients throughout the world.

To celebrate its 60th anniversary, Arup is partnering with the international charity WaterAid in a new initiative, The Arup Cause, which focuses 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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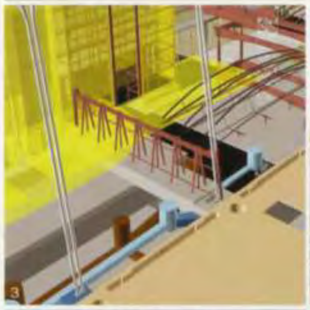
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Illustrations: 1. BP business park, Sunbury-on-Thames, UK: Morley Von Sternburg; 2, 3, inside front cover. Terminal 5, London Heathrow: BAA; 4. New signalling technology, Sheerness branch line, Kent, UK: Simon Hose; 5, 6. Olympic ice hockey stadium, Turin, Italy: Arup/John Fass; 7. Sizewell B nuclear power station (regeneration of British Energy): Nigel Whale; 8. Allianz Arena, Munich, Germany: Covertex/B Ducke; 9. Rail lines at Ruscombe Junction, GWR, UK (gauge corner cracking on the British network): Network Rail

Front cover: The design for the bowl of the Allianz Arena brings spectators as close as possible to the pitch action: Ulrich Rossmann

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