Aluminium: Flexible and Light
Towards Sustainable Cities

Michael Stacey
Aluminium: Flexible and Light
Towards Sustainable Cities

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Nottingham + London

Front cover: High Museum of Art Expansion, Atlanta, U.S.A, RPBW, 2005 (Michel Denancé)

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ISBN 978-0-9930162-3-3
Published by Cwningen Press 2016
www.s4aa.co.uk
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aluminium: flexible and light

light and strong: formwork
Aluminium Formwork

When casting flat in-situ concrete slabs aluminium formwork has become the first choice material, as this formwork is both light and strong, furthermore it can be reused hundreds of times. Craned into position it is known as flying formwork. This technique enables large areas of formwork to be rapidly placed, thus shortening the project build time. Whereas the design of formwork to be placed by hand, requires consideration of the weight of individual components, in order to maximise the effectiveness of a two-person assembly crew.
All components of the PERI SKYDECK aluminium formwork system weigh under 16kg for ease and speed of human handling—creating efficient and safely assembled formwork combined with a very high level of reuse. A high degree of usability has been designed into this system by PERI, a family owned firm with its Headquarters, and Research and Development department in Weissehorn, Germany. PERI was founded in 1969 and the SKYDECK aluminium formwork system and related MUTIPROP was launched in 1992. MUTIPROP is based on two aluminium extrusions with self-cleaning thread and a tape measure built into the inner tube to facilitate assembly. The collars are free running to facilitate adjustment.
An MP350 MULTIPROP weighs only 19.40kg, has a maximum height of 3500mm with a bearing capacity of 91kN. The SKYDECK aluminium formwork system is a well-resolved design with a systematic assembly sequence. The beams of the formwork are polyester powder coated to facilitate cleaning and the edges of the formwork panels are self-draining. The drophead has a self-locking coupling for rapid assembly – however the key advantage of the drophead is that it enables the early striking of the formwork. The props remain in place whilst the panels and beams are removed, thus the formwork can be reused or off-hired and returned to PERI. Depending on slab thickness and concrete strength this can be achieved just one day after the pour.
aluminium: flexible and light

light and strong: formwork

SKYDECK and MULTIPROP are excellent examples of sophisticated aluminium-based products designed for the construction industry, based on the close study of casting in-situ concrete slabs combined with the inherent design flexibility of aluminium extrusions.

When large in-situ concrete flat slabs are required and crane access can readily be provided, PERI has developed SKYTABLE slab formwork, which is assembled from ply, timber, steel and aluminium. Figure 5.65 shows a 100m² PERI SKYTABLE slab formwork being lifted into place at Marina Bay, Singapore. The maximum slab area of this system is 150m².
Aluminium formwork is a globally available construction method, specifiable throughout the world. Table 5.3 shows the main providers of aluminium formwork on a regional basis. This is summarised in Figure 5.67.

Table 5.3  Aluminium formwork suppliers globally by region

<table>
<thead>
<tr>
<th>Country</th>
<th>Suppliers</th>
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<tbody>
<tr>
<td>USA + Canada</td>
<td>Aluma  Doka  MEVA</td>
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<tr>
<td></td>
<td>International</td>
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<tr>
<td></td>
<td>PERI</td>
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<td>Doka  MEVA</td>
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<td></td>
<td>PERI</td>
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<td></td>
<td>ULMA Construction</td>
</tr>
<tr>
<td>Japan</td>
<td>Aluma  Doka  PERI</td>
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<tr>
<td>China</td>
<td>Aluma - TLD Metalwork</td>
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<tr>
<td></td>
<td>Doka  PERI</td>
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<tr>
<td>India</td>
<td>Doka  Ishaan Industries</td>
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<tr>
<td></td>
<td>MEVA International</td>
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<td></td>
<td>PERI</td>
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<tr>
<td>Russia</td>
<td>Doka  MEVA</td>
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<td>International</td>
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<tr>
<td></td>
<td>PERI</td>
</tr>
<tr>
<td></td>
<td>ULMA Construction</td>
</tr>
<tr>
<td>South America (Brasil)</td>
<td>Aluma  Doka  PERI</td>
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<tr>
<td></td>
<td>ULMA Construction</td>
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<tr>
<td>Australia</td>
<td>Doka</td>
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<tr>
<td>South Africa</td>
<td>Doka</td>
</tr>
<tr>
<td>Middle East</td>
<td>Aluma  Doka  MFE</td>
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Aluminium formwork is flexible and light, making it ideal for a variety of construction projects around the world.
Aluminium: flexible and light

Light and strong: formwork

Suppliers by Region

Aluma
PERI
ULMA
Ishaan
MFE
MEVA
Doka

Fig 5.67 Aluminium formwork is a global construction product
Concrete Formwork: a Comparative LCA Study

This Life Cycle Assessment (LCA) compares the use of timber formwork and aluminium formwork for the casting of in-situ concrete. The environmental impacts of the use of each type of formwork can be identified as: global warming potential, ozone depletion potential, acidification potential, eutrophication potential, photochemical smog creation potential, depletion of fossil energy resources and use of renewable energy. Human and environmental toxicity results are not reported due to very high levels of statistical uncertainty in the underlying life cycle inventory methodology and characterisation.

The three scenarios of this comparative LCA are:

1. Timber formwork that is used once;
2. Timber formwork that is reused 10 times; and
3. Aluminium formwork (PERI TRIO) reused 250 times.

Scenario One is based on the common twentieth century practice of the single use of timber shuttering and formwork, with 14.5 per cent timber recovered, 22 per cent incinerated with the energy recovery and 63.5 per cent sent to landfill (based on data from the USA). In Scenario Two the timber formwork is reused 10 times, based upon good practice in the USA, as reported by structural engineers D. Davies and R. Klemencic of Magnusson Klemencic Associates, in the construction of concrete structures of tall residential towers in San Francisco, California. For the supporting timber framework of this shuttering a 20 per cent replacement rate has been allowed for each reuse, with a similar end-of-life profile as Scenario One. Scenario Three is based on the aluminium formwork being used 250 times. This is based on the experience of PERI using its TRIO system. PERI TRIO aluminium formwork can be used 250 times before recycling, which equates to four years of use. Other providers of aluminium formwork reported reuse cycles of up to 350 times, however, the lower figure of 250 cycles has been used in this LCA. Scenario Three is also based on replacing the phenolic-faced plywood lining to the aluminium formwork after it has been reused 60 times.

The LCA data has been generated using Tally, a LCA software linked to Autodesk Revit Building Information Model (BIM) software. Tally was developed by KieranTimberlake with Thinkstep (formerly PE International) and Autodesk. It was launched in 2014. Tally uses a GaBi life cycle inventory database and is currently based on a US power mix and US building practice. It runs the LCA using the end-of-life recycling method.
The Functional Unit is a structural 200mm thick in-situ cast reinforced concrete wall, with a compressive strength of 35MPa (5000psi), external plan dimensions of 10 × 10m and a height of 2.5m, including the formwork needed to cast this wall. The plan area of the functional unit is 100m², which allows the resulting data to be readily scaled, if required. The casting of an in-situ concrete wall was selected to illustrate the relative embodied impacts of the use and potential reuse of types of formwork on this construction element. Clearly comparative LCA studies can equally be undertaken for concrete slabs and or concrete frame of construction, as long as the components are modelled accurately to represent the materials used during construction.

The Functional Unit was modelled in Revit BIM software accurately reflecting the complete build up of materials used to fabricate the formwork and cast the wall. Tally was used, by Michael Stacey Architects, to undertake an environmental assessment in real time as part of a design process. Whereas the environmental assessment in the comparative window frame LCA of Report Three was undertaken by specialist in LCAs.6

In order to account for the number of use cycles and working life of each material component, the LCA was run for each material making up the formwork. Tally has certain limits in terms of the life scenarios it can calculate – this LCA software only allows a material to be given a working life in years, therefore when materials have a number of reusable cycles, the data based on the working life of that material component needs to be interpreted outside of Tally. Where, for example, aluminium formwork has 250 reusable cycles, each environmental impact value is divided by this reusable rate. This ensures that the Functional Unit holds the correct proportion of the environmental impact of a reusable component. This, in turn, allows for the accurate measurement of environmental impacts for both temporary and permanent elements of construction.

For example, the LCA comparison for the aluminium formwork assembly includes:

A. Aluminium formwork reused 250 times;
B. Phenolic coated plywood form lining reused 60 times; and
C. Structural cast in-situ reinforced concrete wall, 53MPa (5000psi), with a service life of 60 years.7

Figure 5.71 shows the comparative pie charts for the three scenarios. The primary embodied energy of the concrete remains constant at 99,400MJ. In Scenario One: the single use of timber formwork, the concrete represents 55 per cent of the total energy.
consumed, with the timber framework requiring 50,930 MJ or 28 per cent total energy consumed and the shuttering or form lining requiring 30,547 MJ or 17 per cent total energy consumed. In Scenario Two: timber formwork that is reused 10 times (with a 20 per cent replacement rate of the timber framework for each cycle, as the details are not fully reversible) the concrete represents 91 per cent of the total energy consumed, with the framework requiring 6,366 MJ or six per cent total energy consumed and the shuttering or form lining requiring 3,646 MJ or three per cent of the total energy consumed. In Scenario Three: aluminium formwork reused 250 times and the phenolic coated plywood form lining reused 60 times the concrete represents 98 per cent of the total energy consumed, with the framework requiring only 989 MJ about 1 per cent total energy consumed and the shuttering or form lining requiring 650 MJ less than 1 per cent total energy consumed. Thus it is clear that the reuse of formwork reduces environmental impacts and embodied energy of in-situ concrete. Using aluminium formwork with fully reversible details, means the embodied energy of in-situ concrete is generated almost totally by the permanent works, the concrete itself.

The range of environmental impacts studied for each formwork assembly is quantified in Figures 5.72 to 5.73 including global warming potential, ozone depletion potential, acidification potential, eutrophication potential, photochemical smog creation potential, depletion of fossil energy resources and use of renewable energy. It should be noted that timber formwork and linings specified in the USA benefit from its timber industry being primarily located in a region powered substantially by renewable hydro electricity. Furthermore, the ozone depletion potential for all three scenarios is very low.

The charts clearly show the potential savings in environmental impacts that can be achieved by the use of aluminium formwork, and through the use of reusable temporary components during construction. This could play a key role in the task of reducing the overall environmental impacts of the construction industry.
This LCA, which can be conducted during the design process, essentially on the fly, evidences the significant environmental impact savings that can be made by specifying reusable formwork components during construction, alongside other advantages inherent in the use of aluminium for this purpose, including:

- Speed of assembly;
- Minimises the use of a crane, or maximises a single crane lift;
- Components can be carried by one person;
- Fully reversible and reusable – up to 250 times;
- Economic savings (timber formwork costs around 40 per cent of in-situ concrete construction); and
- Significant savings in embodied energy and embodied CO₂.

Revit is a CAD software utilised by complete design teams in the realisation of architecture and infrastructure for its BIM capabilities. The benefits for architects and engineers of running a LCA via Tally directly through BIM is the ability to understand the environmental impacts of material decisions during the design process. This feedback of information, when working in three dimensional design space, allows architects and design team to visualise and analyse material decisions on many levels, from environmental impacts, appearance, durability, cost and efficiency - giving the design team an informed understanding of the holistic value and benefit of each element to a project. However the current limitations of these computer programmes need to be fully understood by architects and other collaborators in the design team. To generate a fuller understanding of the potential environmental impacts of a project, the addition of LCA expertise to the design team should be considered.
Notes


3 C. McKillop, Engineering Manager, PERI Ltd., by email 27 June 2015, advised that PERI TRIO aluminium formwork has a service life of 4 years based on an average usage of 60 times per year, with a limit of 250 cycles. The 4-year life can be reduced if not handled with care by contractors.

4 C. McKillop, Engineering Manager, PERI Ltd., by email, March 18, 2015, advised that PERI’s phenolic coated plywood form lining has an average life of 1 year based on a usage of 60 times per year, with a limit of 70 cycles. The phenolic coating can be stripped and re-applied if the plywood is in a good condition.


7 Based on industry data: the average use of aluminium formwork is 62.5 times per annum, combined with a 250 uses of this formwork frame before recycling, the replacement cycle is approximately four years. Similarly the phenolic face is replace in just under one year. The number of uses not time is the basis of this LCA.
aluminium: flexible and light

light and strong: bridges
Aluminium in Bridge Design and Construction

The role of bridges in the built environment appears to be well understood and is as ancient as architecture itself. The earliest arched masonry bridge in Rome, the Pons Aemilius, was built between 179-142 B.C., and the Roman aqueduct in Segovia, Spain, completed around A.D. 109, functioned into the twentieth century. Durability is very important in the design and construction of bridges. In the UK, bridges in the public realm are designed to last at least 120 years, subject to annual inspection and appropriate minor maintenance if necessary.

Since the mid 1990s, architects have increasingly become involved in bridge design – linking the art and science of construction. Typically bridges have a very clear identity and the design of bridges is not unlike product design. Martin Heidegger poetically describes the role of bridges in human experience: ‘The bridge gathers to itself in its own way earth and sky, divinities and mortals.’

Architects bring to a bridge design, skills in being able to access and analyse the context, releasing the spatial potential of the bridge. Architects can also bring a holistic approach to all of the components of a bridge, in essence the whole becomes greater than the sum of the parts. To take Jim Eyre’s practice as an exemplar, he stresses the importance of collaborating with highly skilled engineers, he also observes ‘when WilkinsonEyre is involved in a bridge project, more often than not the raw concept comes from that quarter.’ The contribution of architects and engineers is clearly evident in the case studies reviewed below. These case studies are set out in the following order:

- aluminium bridge structures;
- aluminium bridge decks;
- and
- aluminium guarding systems.

The case studies are listed chronologically within each section. Also included are aluminium staircases, as this constructional element demonstrates similar design criteria to bridges and are often made by specialist fabricators who also assemble bridges. The chapter concludes with a brief history of early aluminium bridges.

The brief called for a bridge crossing Floral Street in Covent Garden, to link the Royal Ballet School with the E. M. Barry’s Royal Opera House, and to provide direct access for the dancers to rehearsals and performances. It also encourages young dancers to mix with professionals in the cafés of the Royal Opera House. Two existing openings were identified, however, they were asymmetrically placed in terms of both plan and level above the street. Jim Eyre’s initial sketch, sent to structural engineers Flint & Neill, [truly his first response] was a series of rotating squares in space translating the geometry between the two buildings and resulting in a gently ramped walking plane. This movement of frames in space is reminiscent of the display Ripley (Sigourney Weaver) is viewing in the landing sequence in Ridley Scott’s science fiction movie Alien, released in 1979.

Jim Eyre recalled the rapid design development process:

Initial investigations experimented with the idea of incorporating a twisting profile in order to exploit rather than suffer the effects of rake and skew on what might otherwise be rectilinear organisation to the elevations.

A rapid evolution occurred with the thought that a series of square frames, all at once raking, skewing and twisting, could follow the direction of movement across the bridge. After a sample check to verify that the rotating squares would not be too large yet still allow sufficient space for users, the core principles of the concept immediately became apparent. Incidentally this was the only phase in the design and fabrication process, which was not digitally enabled.
Fig 5.80  Bridge of Aspiration was delivered digitally following the initial sketches – the 23 rotated frames of the bridge.

The realised design is composed of 23 aluminium frames, each rotated in space by $3.91^\circ$. The frames are linked together by a twisting aluminium box beam, which is only apparent during assembly. The bridge is articulated by the rotating aluminium frames and united by a glass skin that is translucent and clear. The translucent glass conceals the structure but more importantly provides privacy for the dancers from the street below. This gives way to clear glass that provides views out for those using the bridge. One way of reading this bridge is the interplay of two forms, each made of translucent and clear glass. Internally the aluminium frames are partially clad in oak, to accommodate the glass that is not parallel with the mullions and to accentuate the reading of the twisting geometry. Oak is also used to form the walking plane or floor.

The Bridge of Aspiration was totally prefabricated by GIG in its North London facility, which is more typically used for prefabricating unitised curtain walling. GIG is an Austrian company that fabricates aluminium systems in Austria. Thus, GIG has all the advantages of the controlled conditions of factory production, yet avoiding transporting large prefabricated assemblies across continental Europe and the Channel. The bridge was craned into position on a quiet Sunday morning with all of the people from WilkinsonEyre in attendance.
aluminium: flexible and light

Fig 5.83  Offsite installation of the oak floor of the Bridge of Aspiration

Fig 5.84  Bridge of Aspiration was fully prefabricated by GIG

Fig 5.85  Bridge of Aspiration being trucked across London to Covent Garden

Fig 5.86  Under a road closure the bridge is craned into place

Fig 5.87  Note the steel strong frame keeps the temporary supports clear of the aluminium frames of the bridge

light and strong: bridges
Jay Merick considers that ‘the vortex-twist of the composite metal – timber frames forming the Bridge of Aspiration across London’s Floral Street that expresses the practices’ attention to detail most exquisitely. The bridge is literally a translation in space; however, it also serves as a metaphor of the movement of a dancer through space, an architectural overture of the performance in the Royal Opera House – just a few dance steps away across Floral Street.

Fig 5.88 Carefully positioning the bridge to match the asymmetrical openings of the Royal Ballet School and the Royal Opera House.

Fig 5.89 Note the precision of prefabricated assemblies as the bridge is eased into place.

Fig 5.90 Bridge of Aspiration crossing over Floral Street.

Fig 5.91 Royal Ballet School, Bridge of Aspiration designed by architect WilkinsonEyre.
Westdork Bridge, Amsterdam, Netherlands: Architect MVSA Architects, 2003

This is a 5m wide and 48m long bridge over an Amsterdam canal for pedestrians and cyclists. The central span is a 16m single-leaf bascule to allow boats to pass. The bridge was designed by MVSA Architects and fabricated by Bayards, it was assembled in 2003. The client for this bridge is the Amsterdam City Development Corporation, the lightweight all aluminium structure of this opening bridge facilitates its day-to-day operation. Bayards actively promotes collaboration with architects in the design of bridges, using its experience in designing and fabricating prefabricated assemblies in aluminium since 1963. Bayards manufactures structural assemblies from aluminium on a bespoke basis using robust and reliable technologies. This can be contrasted with Sapa’s standardised approach to the design of bridge decks, which is discussed below.

Fig 5.92 All aluminium Westdork Bridge designed by MVSA Architects, fabricated by Bayards

Fig 5.93 Westdork Bridge during twilight in Amsterdam

Fig 5.94 Westdork Bridge reveals that it is a 16m leaf bascule
Yanchep Bridge, Australia: Designer and Fabricator, Peter Maier Leichtbau GmbH, 2009

In the western Australian city of Wanneroo, the all aluminium Yanchep pedestrian bridge has been installed to protect the biodiversity of the beach dunes in an area of rapid urbanisation north of Perth. This bridge is 143m long and 2.5m wide, the aluminium is finished with silver anodising. It was fabricated by Peter Maier Leichtbau in Singen, Germany and installed by Landmark Products of Deception Bay, Queensland, Australia. Aluminium was primarily selected on the basis it would be maintenance free even in a coastal environment and that the total cost of ownership would prove beneficial to the owner, the local authority, as is confirmed by the Canadian research cited on pages 438–439. However, the height of the bridge above the dunes has proved controversial with the residents of Wanneroo. In 2012, the State of Western Australia Administrative Tribunal ruled the City should lower the boardwalk from 5.5m at its highest point to 2.1m above the natural ground level. This work to lower and realign this bridge was carried out by R.W.F Robinson and Sons during 2014. Yanchep Bridge is now a long term environmental and community asset on the coastline of Western Australia.

Equestrian Park Bridge, Blainville, Québec: Designer and Fabricator, MAADI Group, 2012

This bridge was designed for use by pedestrians, horses and riders. It is an 18m single span all aluminium bridge with a clear width of 3m and a self-weight of almost 7 tonnes or 380 kg/m. It was fully prefabricated in Boucherville, Québec, by MAADI Group. It is an open truss with a gently curved profile fabricated from MIG welded square hollow section (SHS) aluminium extrusions in two sizes, 125mm and 150mm. This mill finished single span aluminium bridge rests on simple concrete abutments. It has an Ipe hardwood deck and kick plates with aluminium guardrails. The hardwood Ipe is often described as Brazilian Walnut.

Fig 5.95 Aluminium deck of Yanchep Bridge, designed and fabricated by Peter Maier Leichtbau

Fig 5.97 Equestrian Park Bridge, Blainville, Québec

Fig 5.98 Equestrian Park Bridge, Blainville, Québec: Designer and Fabricator, MAADI Group
Oil Rig Pedestrian Bridge: Designer and Fabricator, MAADI Group, 2014

This all aluminium pedestrian bridge was designed and fabricated by MAADI Group. It spans 46.3m between two platforms and is a walk through box truss with a clear width of 1.2m. It has an aluminium grip span® deck, aluminium kick plates and guardrails. The self-weight of the bridge is only 13.7 tonnes or 296 kg/m.

The bridge is fabricated from welded 150mm and 200mm SHS aluminium extrusions, using a combination of 5083-H321 and 6061-T6 alloys, all left mill finish. It will require very little maintenance, even in an exposed maritime location. Both MIG and TIG welding was used to fabricate this bridge. It was fully prefabricated in Boucherville, Québec, shipped to site in five 12.2m (40') shipping containers and installed as a single span element. MAADI Group produce a diversity of aluminium pedestrian bridges, typically based on welded fabrication. However, it has also developed weld-free prefabricated aluminium bridges.

Fig 5.99 46.3m Oil Rig Pedestrian Bridge linking two offshore platforms, published with permission of the oil extraction company

Fig 5.100 46.3m Oil Rig Pedestrian Bridge being craned into position, published with permission of the oil extraction company
Deployable Military Bridge, Canada: Designer and Fabricator, MAADI Group, 2016

This prototype of a rapidly deployable military bridge for the Canadian armed forces has been designed and fabricated by MAADI Group. It is designed for pedestrian and light vehicles to overcome obstacles in the battlefield, such as rivers and ravines. This bridge has an overall length of 18.3m to be able to span a maximum 16m, with a clear width of 1.5m. Eight to ten people can deploy the bridge in 80 minutes. The quick fit prefabricated assembly of aluminium components is locked off with stainless steel bolts, with reusable stainless steel split pins on stainless steel wire tethers. This military bridge is a development of MAADI Group’s patented weld free civic pedestrian bridge range Make-A-Bridge®. It has a capability of being crossed by 127 soldiers if their weight is well distributed. The vertical frequency of this bridge is 5.8Hz, significantly greater than 3Hz required by AASHTO LRFD Code for the Design of Pedestrian Bridges (US 2009). The guidance to this code issued by Association of State Highway and Transport Officials refers to the problems on the Millennium Bridge in London and states that the lateral frequency needs to be above 1.3Hz. The bridge can also carry small vehicles, such as snowmobiles and quad bikes up to 500kg.

The bridge is built up from modular aluminium components and the key detail of the trusses are cast aluminium tripods. The trusses are preassembled into four sections and then bolted together. The aluminium deck panels pivot on one tubular cross beam and clips onto the next one, the deck panels also interlock to help secure the complete bridge deck. Once the bridge has been assembled, typically it is launched into position from one bank. As soon as it is correctly located, each end of the bridge is jacked up and bearings are fixed in place. With training, all this can be achieved in 80 minutes, less time than a feature film. The bridge is operational and the obstacle has been overcome. The military version of MAADI Group Make-A-Bridge® is an exemplar of Design for Assembly (DfA) and Design for Disassembly (DfD) as discussed in Aluminium Recyclability and Recycling.
excellent example of the versatility of aluminium extrusions and casting, providing flexibility in design and realisation. Alexandre de la Chevrotière, CEO of MAADI Group, considers that ‘this product would not be possible without capability of aluminium extrusions’. ¹²

The aluminium extrusions of the prototype rapidly deployable military bridge were fabricated from 6005A-T6 and 6061-T6 alloys, with the nodes cast in AA357-T6 alloy. The stainless steel bolts are coated Xylan® 1424 a fluoro polymer that contains PTFE, providing corrosion protection and friction resistance. The bridge is polyester powder coated in Canadian Army Dark Oliver Green. The complete bridge only weighs 1970 kg or 69.9 kg/m², a direct equivalent to the average weight of a Canadian citizen per m², and at least half the dead weight of an equivalent steel bridge. ¹³
While this book is being produced, the 5e Combat Engineer Regiment of the Canadian Army is testing the prototype for sixth months including airlifting the bridge into remote locations by helicopter. This testing started on 18 January 2016. Prior to this, the prototype bridge was load and vibration tested by the Engineering Faculty of the University of Waterloo. This prototype is part of a research project led by MAADI Group, Make-A-Bridge, funded by Centre québécois de recherche et de développement de l’aluminium (CQRDA), Quebec Aluminium Research Center, with the Programme d’Innovation Construire au Canada (PICC), the Build in Canada Innovation Program (BCIP) and Programme d’aide à la recherche industrielle (PARI), Industrial Research Assistance Program (IRAP).
An example of the deployment of the 100mm deep Sapa aluminium bridge deck system is the Tottnäs Bridge. This multi-span bridge had its deck replaced in 1989, without the need to replace the foundations, the four piers or the abutments. This bridge, which is 55 km south of Stockholm, was inspected in 2014 by a group of specialists from AluQuebec and Aluminum Association of Canada (AAC) who found it to be robust and without any evidence of corrosion. 17

The US Federal Highway Administration in its 2014 National Bridge Inventory identified that over 600,000 bridges in the USA are structurally deficient and thus there is an urgent need for bridge and bridge deck replacement. 18
Fig 5.112  Sapa extruded aluminium bridge deck system: 100mm deep with extrusion 100mm × 250mm, 1:1. note all dimensions shown in mm
Forsmo Bridge, Vefsn, Norway: Design Team, Nordland County Roads Office and Hydro Aluminium Structures, 1995

Norway’s first aluminium road bridge opened in Vefsn in September 1995. It was designed by Nordland County Roads Office and Hydro Aluminium Structures. It is 38.5m long and 7.4m wide, with two spans a little over 19m each, and a structural depth of 1.5m. It replaced a bridge from 1933 that was only 3.8m wide, which was proving very costly to maintain and needed extensive repairs when inspected in 1994. Thus the impetus to design a low maintenance aluminium structure. The bridge superstructure is formed from two aluminium box beams with inclined webs and transverse cross bracing at 3m centres. The box beams are stiffened with longitudinal web stiffeners that were welded to the outside of the beams for aesthetic reasons, breaking up the profile of the bridge structure. The deck is formed of aluminium extrusions, which are 250mm wide and 123.5mm high and in 8m lengths. The wearing surface is 50mm of asphalt on an epoxy/sand layer on the top surface of the deck extrusions. The deck and welded joints were extensively tested by the University of Trondheim (NTNU).

The welding of this aluminium bridge was undertaken by Lievre Sveis, specialists in welding aluminium, based on its experience of welding the living accommodation of offshore platforms in the North Sea Oil Field. The complete bridge that weighed 28.5 tonnes was transported by barge from Leirvik Sveis’ workshop in Stord, and then transferred to lorry for the last 5km. It was then craned into position on new bases. The balustrade that also acts as a crash barrier was also fabricated from aluminium. To protect against bimetallic corrosion only stainless steel fixings were used for bolted details. The old bridge was demolished and the existing foundations extended, the lightness of the bridge meant that the existing foundations could be reused and the new bridge was installed within one week. Markey, Østlid and Solass observe ‘the foundations did not have to be reinforced, only enlarged. This was due to the considerable reduction in dead weight obtained by using an aluminium superstructure. Neglecting the weight of the asphalt, the structure only weighs 100 kg/m$^2$.’

On completion Forsmo Bridge was subjected to extensive monitoring and testing to evaluate the performance of the aluminium superstructure. This was initiated by the design team, which included Nordland County Roads Office, and carried out by three PhD students from NTNU under the guidance of the Norwegian Road Research Laboratory. The test regime included the measurement of temperature and strain, a static load test and a dynamic load test. The bridge was open to traffic during the 15-day testing period. Markey, Østlid and Solass report: ‘To evaluate the importance of on the structure, strains and temperatures were measured over a prolonged period. Seven temperature gauges...’
were installed at midspan: six on the aluminium structure and one for the exterior air temperature. Strain gauges were installed in nine locations on the structure (six rosette and three normal gauges). Five of the gauges \([\text{were}]\) located in the same cross section as the temperature gauges.\(^{19}\) No correlation between temperature and strain was found.

The static load test involved the placement of two 20tonne lorries in the arrangements shown in Figure 5.116. The unloaded bridge was regularly measured during this five-hour test to check the zero measurement. For each of the six loading patterns, three sets of measurements were taken and in total 30 measurements were recorded.\(^{21}\) 'There was a good coloration between the measured and calculated deflection and the maximum midspan deflection under loading patterns A and B, was 10.2mm', observed Markey, Østlid and Solass.\(^{22}\)

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\(A\)

\(B\)

\(C\)

\(D\)

\(E\)

\(F\)

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Fig 5.116 Arrangement of lorries for the load testing of Forsmo Bridge, each lorry weighed 20 tonnes and each arrangement was repeated three times.

Fig 5.117 Two lorries load testing Forsmo Bridge

Forso Bridge is an exemplar of investment in design innovation, securing this with full scale post completion testing. The aluminium superstructure cost £250,000 and the total project including testing, widening approach roads and abutments, cost about £600,000 in 1995.\(^{23}\) The bridge has now provided 20 years of service combined with low maintenance – see the research on the total cost of ownership of bridges on page 436–437.

The River Medway was the main trade artery and the reason for the growth of the county town of Maidstone in Kent, until the arrival of the railways in the mid-nineteenth century. Lockmeadow footbridge, designed by architect WilkinsonEyre with structural engineers Flint & Neill, has a structural aluminium deck that is only 300mm thick and spans 80m supported by cable stays from two masts at mid span that spring from the cutwater. The context of the bridge is Grade One listed buildings that date back to the fourteenth century. All located on the town side, the west bank of the River Medway, as shown in Figure 5.119, WilkinsonEyre’s analysis of the context of the bridge to the north is the Archbishop’s Palace and All Saints Church and to the south the Gateway, which is the remains of All Saints College. Lockmeadow footbridge gently curves on plan as it spans over to the opposite bank of the Medway. It spans beyond the spring points of its masts to allow the water meadow of the East bank to flood. The commission to design this footbridge was won in a competition by WilkinsonEyre in 1997 – the competition brief “called for a design that was sensitive both to the location and to the modern idiom.”

Fig 5.118 Lockmeadow Footbridge designed by WilkinsonEyre, viewed from the Medway

Fig 5.119 WilkinsonEyre’s sketch analysing the context in Maidstone of Lockmeadow Footbridge

Fig 5.120 Cross section of Lockmeadow Footbridge showing the structural extruded aluminium deck
Jim Eyre reports that:

Lockmeadow uses a bespoke aluminium extrusion in a very specific way. Flint + Neill, the structural engineers, and WilkinsonEyre took out a patent on the system. One advantage, other than the ability to ‘laminate up’ a curved plan, was that from the 300mm depth we could get quite long spans, some 16m provided there was continuity over the supports. This was because the whole deck acted compositely.23

WilkinsonEyre’s design for this footbridge combines an economy of means that also minimises the visual intrusion of the bridge as it spans the Medway. The structural aluminium deck is made up of pairs of an open E-like extrusion. This extrusion is handable and balanced, meaning that only one die and one type of section is required to form both sides of the ridged cells, which are linked by solid aluminium central rectangular extrusions and aluminium flats in the top of the deck only. This assembly forms stiff structural cells by post tensioning in the transverse direction, from the penultimate extrusion of each side of the deck. The final extrusions form a clean edge to the aluminium deck as they are only fixed via the balustrade post fixings. Slipping the linear extrusion during assembly enables the gently curved plan to be achieved. The top surface of the E-like extrusions is ribbed to form a safe walking and cycling surface.

Fig 5.121 The structural aluminium deck of Lockmeadow Bridge is assembled from E-like aluminium extrusions

Fig 5.122 Stiff structural cells are formed by post tensioning – achieving a slender deck.

Fig 5.123 The curved plan is achieved by slipping and gently curving the aluminium extrusion in a process of gradual lamination.
The masts are formed from tapering open steel fabrications, using steel rods spaced by a pair of steel flats, topped with castings that pick up the cable stays. The original balustrade posts were fabricated from resin filled carbon fibre, however, due to problems of thermal cycling, they have been replaced by shapely steel flats, coated in micaceous iron oxide. The original balustrade posts were fabricated from resin filled carbon fibre, however, due to problems of thermal cycling, they have been replaced by shapely steel flats, coated in micaceous iron oxide. Lockmeadow Footbridge opened in 1999 and it achieves the architect’s ambitions: ‘Deck, parapet and cables combine to form a lightweight composition that stands in contrast to the mass of the medieval buildings’. On inspection in 2015, this bridge was busy with people accessing the town centre of Maidstone and the architect’s achievement was clear for all to appreciate as they crossed the River Medway.
Aluminium: flexible and light

Light and strong: bridges

Fig 5.126 Seven centuries of construction: All Saints Church viewed through Lockmeadow Footbridge

In 1996 the London Borough of Southwark organised an open competition with the RIBA for the design of a new pedestrian footbridge linking Bankside Power Station, the future Tate Modern, and St Paul’s Cathedral. The first new crossing of the Thames in central London for over 25 years, it formed part of the celebrations in the UK of the arrival of the twenty-first century. This competition was won by Foster + Partners in collaboration with Arup and sculptor Sir Anthony Caro, with a low slung suspension bridge entitled the Blade of Light. Foster + Partners placed the bridge on the axis of Peter’s Hill, to focus the pedestrians on a clear view of St Paul’s when crossing from the south bank of the River Thames.

The bridge is formed of three spans; 108m, 144m and 81m (travelling from the south to the north bank) with two concrete piers in the river. It has a total length of 325m and the aluminium deck is 4m wide, supported by a suspended steel superstructure. Two groups of four 120mm diameter suspension cables span bank to bank, with the cables below balustrade level to maximise views from the bridge deck. The design is mimetic of the Delaware Aqueduct; designed by John A. Roebling and completed in 1850, which is described as the oldest suspension bridge in North America. It comprises four spans with lengths ranging from 40 to 43m. It was constructed from masonry piers, cast iron saddles and iron suspension cables.

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Fig 5.127  Millennium Bridge, London, Foster + Partners with engineers Arup, a new crossing of the River Thames in central London

Fig 5.128  Foster + Partners’ sketch of the Millennium Bridge, London, setting out the key design issues

Fig 5.129  Millennium Bridge, London, photographed 2015
‘The bridge gathers to itself in its own way earth and sky, divinities and mortals.’ Martin Heidegger

Fig 5.130 The low slung suspension cables of the Millennium Bridge, London, create an effortless openness to view and be viewed.
On the Millennium Bridge, fabricated steel box sections form the transverse arms at 8m centres linking the suspension cable groups. Two steel circular hollow sections (CHS) form the edge of deck, spanning onto the transverse arms. The bridge deck comprises aluminium box sections that span between the CHS edge steels. Arup opted to detail the deck as an articulated structure, with sliding joints at regular intervals (16m centres) along the length of the bridge – deciding that a continuous deck would contribute little extra stiffness to the structure. The articulated deck offered two clear advantages: it could be prefabricated in 16m ‘chunks’ and the overall depth kept to a minimum. The walking surface is ribbed extruded aluminium deck sections, which run transversely with matching aluminium edge sections, as shown in Foster + Partners’ section, Figure 5.131, and the detailed photograph Figure 5.133.
Main contractors Monberg & Thorsen with Sir Robert MacAlpine started the construction of the Millennium Bridge on 28 April 1998 and it opened to the public on Saturday 10 June 2000. The bridge cost £18.2m. In its first weekend, the Millennium Bridge had attracted many visitors. ‘Soon after the crowd streamed on to London’s Millennium Bridge on the day it opened, the bridge started to sway from side to side; many pedestrians fell spontaneously into step with the bridge’s vibrations, inadvertently amplifying them.’ 30 This strong lateral response of the Millennium Bridge was caused by resonance, however no excessive vertical vibrations were observed. Readers can see this phenomenon for themselves online, evidence that Arup used in resolving this problem.31
Arup’s design process was thorough, including wind tunnel testing of 1:16 sectional models at RWDI’s laboratories in Canada. Arup had designed the bridge for pedestrian excitation based on BS 5400 and had even tested the bridge with a few people in May 2000 – this appeared to confirm the design calculations. However, it was ‘estimated that about 80,000 to 100,000 people crossed the bridge during the first day. Analysis of video footage showed a maximum of 2000 people on the deck at any one time, resulting in a maximum density of between 1.3 and 1.5 people per square metre’, reported Arup in 2001. On Sunday 11 June the numbers of people crossing the bridge was restricted. On Monday 12 June 2000 it was decided to close the bridge.

Should the large forces generated by synchronised lateral footfall have been anticipated by Arup? Joseph Paxton in 1851 had tested the timber floor units of the Crystal Palace by having soldiers march over them. The Albert Bridge, London, completed in 1873, has a sign stating that marching soldiers must break step whilst crossing. Similarly in circa 1860 a notice was erected on the twin-deck railway suspension bridge spanning the Niagara River at Niagara Falls, designed by J. Roebling and completed in 1854, which states:

A fine of $50 to $100 will be imposed for marching over this bridge in rank and file or to music, or keeping regular step. Bodies of men or troops must be kept out of step when passing over this bridge. No musical band will be allowed to play while crossing except when seated in wagons or carriages.

Following the closure of the Millennium Bridge, Arup set two primary research questions to inform the design of the retrofit:

1. To compare the dynamic properties of the built structure to the analytical predictions;
2. To quantify the forces that were being exerted on the structure by the pedestrians.

Arup would then use the findings of this research to design a retrofit installation that would reduce the movements of the bridge to acceptable levels.
Arup’s research revealed three previous examples of bridges demonstrating resonant excitation by crowds of people, movement was noted on: the north section of Auckland Harbour Road Bridge, New Zealand, completed in 1965, during a demonstration of about 4000 people in 1975; Groves Suspension Bridge, Chester, completed in 1923, during Jubilee celebrations in 1977; and Link Bridge from National Exhibition Centre to Railway Station, Birmingham, completed in 1978, during major events including rock concerts. Not one of these bridges had been the subject of significant research and analysis. However, one of Arup’s conclusions from this programme of research was ‘the same phenomenon could occur on any bridge with a lateral frequency below about 1.3Hz.’ Furthermore, Arup concluded:

The movement of the Millennium Bridge was clearly caused by a substantial lateral loading effect, which had not been anticipated during design. The loading effect has been found to be due to the synchronisation of lateral footfall forces within a large crowd on the bridge. This arises because it is more comfortable for pedestrians to walk in synchronisation with the natural swaying of the bridge, even if the degree of swaying is initially very small. The pedestrians find this makes their interaction with the movement of the bridge more predictable and helps them maintain their lateral balance. This instinctive behaviour ensures that footfall forces are applied at the resonant frequency of the bridge, and with a phase such as to increase the motion of the bridge. As the amplitude of the motion increases, the lateral force imparted by individuals increases, as does the degree of correlation between individuals.35

A possible explanation for this phenomenon proposed by Arup is ‘that pedestrians are less stable laterally than vertically, which leads to them being more sensitive to lateral vibration and to modify their walking patterns when they experience such vibration.’36 Therefore, laboratory tests with pedestrians walking on moving platforms were carried out at Imperial College, London, and the University of Southampton. Arup set the design criterion as 2 people per m$^2$, based on the maximum density of people witnessed on the bridge on the day it opened - 1.5 people per m$^2$. Even though walking slows down in a crowd with a density of over 1.7 people per m$^2$.

Having ruled out restricting the numbers of people using the bridge, two design options for the retrofit were identified: stiffening the structure to move all of its lateral frequencies out of range.
or increasing the damping of the bridge to reduce the resonant response. Stiffening the structure was ruled out, as the remedial work would be extensive and expensive. Furthermore it would have had a dramatic impact on the visual characteristics of the bridge. Therefore a scheme was developed primarily using fluid-viscous dampers. The final scheme specified low friction fluid-viscous dampers, originally developed for NASA space satellites, and subject to a 35-year guarantee with no maintenance except painting periodically with the structural steelwork. 37 fluid-viscous dampers were installed, primarily under the bridge deck, at 16m centres on every other transverse arm. In addition, where ‘possible the viscous dampers are connected to fixed points such as the piers and the ground.’

Although no excessive vertical movements had been noted it was decided to include tuned mass dampers in the vertical plane, as this risk had been identified by some researchers. A total of 26 vertical tuned mass dampers, manufactured by Gerb Schwingungsisolierungen in Germany, were installed, and are guaranteed for 10 years to first maintenance, subject to biannual inspections. Cleveland Bridge UK won the tender for the remedial contract, work commenced at the beginning of May 2001 and completed by the end of that year. The remedial works cost £5 million, increasing the capital cost of the Millennium Bridge to £23.2 million.
The author and design team of Ballingdon Bridge, described below, took part in the final mass pedestrian test on 30 January 2002, along with many other people working at or collaborating with Arup. This would have been like an enjoyable party on the bridge with many friends from the worlds of architecture and engineering, except that we had to march in step like soldiers. Many architects, engineers and even critics consider Arup and Foster + Partners response to the problems on the Millennium Bridge so professional it has enhanced their reputations.39 The British Design Manual for Roads and Bridges (BD 37/01) now includes a clause on synchronous lateral excitation. The Millennium Bridge reopened on 22 February 2002 and it has been estimated that over 3.5 million people cross this bridge every year.

Fig 5.143 Crossing the Millennium Bridge, London, on a sunny autumn day in 2015

Fig 5.144 The Millennium Bridge a ‘blade of light’ reflecting from the aluminium deck, photographed 2015

This is a tale of two cities – Gateshead and Newcastle. In 1997 an international competition was organised by Gateshead Metropolitan Council for a new pedestrian and cycle bridge crossing the river Tyne linking Gateshead and Newcastle, yet allowing river traffic to pass. The bridge was seen as a key act of regeneration for this urban conurbation with a great industrial tradition. The competition was won by architect WilkinsonEyre working with engineer Gifford & Partners. The design of this inventive moving bridge was led by Jim Eyre. The arched form is reminiscent of Hulme Bridge in Manchester, completed in 1997. This was WilkinsonEyre’s second completed bridge, the first was also won in competition. Both bridges take inspiration from Eero Saarinen’s Gateway Arch in St Louis, USA (1964). The inventive design decision in the opening strategy for the Gateshead Millennium Bridge was to curve the bridge deck and the structural arch, thus when it is rotated into the open position, it remains a balanced assembly. In a movement that resembles the opening of an eyelid. Creating a simple and elegant opening bridge. It is an excellent example of the clarity of thought that an architect can bring to the design of bridges, expressed primarily by drawing. Jim Eyre reflected before the completion of the Gateshead Millennium Bridge: “In bridge design, it is generally movement that is the most problematic. When a man-made structure mimics a life form by actually moving the result is often cumbersome. To capture the gracefulness of natural movement in an opening bridge is a serious challenge and I look forward to seeing the operation of the ‘opening eye’ at Gateshead where the whole structure is mobilised.” The bridge clear spans the Tyne in 105m, yet the curved deck is 126m long to accommodate the changes in level and to match the geometry of the slender structural arch that rises 50m above the river, echoing the Tyne Bridge upstream.

Fig 5.145 (above) Jim Eyre’s sketches of the opening strategy of the Millennium Bridge, Gateshead

Fig 5.146 The Millennium Bridge, Gateshead, designed by WilkinsonEyre with Gifford & Partners

Fig 5.147 The Millennium Bridge, Gateshead, rotated into the open position
Jim Eyre’s key thinking on this project was recorded in Exploring Boundaries: ‘The site owes its presence to the array of historic bridges in close proximity.’ The short but memorable journey up the Tyne from Wallsend shipyards past the old cranes, seemingly defies the decline of an era of industrial might, evoking the new, forward-looking and optimistic spirit of the city. ‘At each end the bridge rests on trunnion bearings, which are expressed to reveal the ability of the structure to rotate, powered by hydraulic rams’. The practical constraints of the physical brief (no structure on the quays, the need to avoid an overly step gradient, were the bridge to cross in a straight line and a requirement for a limited 25m clearance) combined with the unwritten aspiration of the cultural civic brief... lead to such a specific design for this bridge.

The doubly curved steel structures of the parabolic arch and bridge deck were realised by Watson, using advances in welding and fabrication technologies developed in the late twentieth century. Both are stiffened by the curved geometry and are linked by 40mm stainless steel rods. It was fabricated in Bolton into transportable section and welded together at the famous Swan Hunter shipyard at Wallsend and transported upstream by barge. The total weight of the superstructure is 850 tonnes. The Gateshead Millennium Bridge opened on 17 September 2001.
The curved deck of the bridge has two distinct zones, the inner deck is an epoxy coated walking surface on the structural steel deck beam for pedestrians, with an outer lightweight cantilevered aluminium deck which forms part of Sustrans [UK] national cycle network. This extruded aluminium gillage, which has a ribbed anti-slip surface was manufactured by Norton Aluminium Alloy Co. Peter Davey observes: ‘The outer deck is for cyclists and has an aluminium grille surface intended to be safe and freely drained in all weathers; in some lights, when the bridge is rotated the aluminium becomes a shining semi-transparent arc leaping between the two cities.’

Jim Eyre observed that aluminium was used for the outer deck of the Gateshead Millennium Bridge for four reasons:
1. to reduce the weight on the extended cantilever;
2. the primary structure wasn’t needed on the outer layer;
3. to enjoy the transparency; and
4. we liked the idea of creating a separate feel to the cycleway.

The context of the Gateshead Millennium Bridge is formed by the quaysides and three earlier bridges across the Tyne. The High Level Bridge is double decked rail and road bridge, designed by Robert Stephenson and it was completed in 1849. William Armstrong’s Swing Bridge is hydraulically operated and pivots about its centre point on plan to allow boats to pass. It opened to road traffic in 1876. The nearest is the Tyne Bridge, a through arch road bridge, designed by Mott, Hay and Anderson, was completed in 1928. The design and construction of the Gateshead Millennium Bridge is a dramatic design response to this context, it is both inventive and an act of cultural continuity.
The design excellence of the Gateshead Millennium Bridge was recognised in 2002, when WilkinsonEyre won the Stirling Prize from the Royal Institute of British Architects for the best work of architecture in the UK.
The Millennium Bridge, Gateshead, is set in the context of the earlier and famous bridges that cross the Tyne.

This bridge was designed by Renzo Piano Building Workshop in collaboration with executive architects Interactive Design Inc. of Chicago. Nichols Bridgeway is 190m long and 4.6m wide. It links Millennium Park with The Modern Wing of The Art Institute of Chicago, which was also designed by Renzo Piano Building Workshop. The steel structure of this bridge was ‘chunked’ into transportable sections, as shown in Figure 5.160, to facilitate its rapid installation during 2008. The aluminium deck was prefabricated in the Netherlands by Bayards in sections 4.6m wide and approximately 2.5m long, to enable the deck components to fit into a shipping container. The deck incorporates electrical heating to enable the bridge to remain safe in the harsh Chicago winters. In collaboration with the architects, Bayards also developed a durable anti-slip finish for the wearing surface of the aluminium deck."
aluminium: flexible and light

Fig 5.162 Site plan of Nichols Bridgeway showing how it links The Art Institute of Chicago with Millennium Park

Fig 5.163 Crossing Nichols Bridgeway at nighttime

Fig 5.164 Nichols Bridgeway integrates with The Modern Wing of The Art Institute of Chicago, which was also designed by Renzo Piano Building Workshop
Nichols Bridgeway crossing East Monroe Street to provide pedestrian access to The Modern Wing of The Art Institute of Chicago.

The setting of Ballingdon Bridge as it crosses the river Stour is a wonderful combination of a water meadow that surrounds Sudbury and the listed buildings that form the town and the village of Ballingdon, Figure 5.166. Completed in 2003, the new trunk road bridge is the first to be built in Britain with an architect leading the design team. The previous bridge, built in 1911, could not sustain 42 tonne articulated lorries (the maximum and norm in the EU) and its closure would have resulted in a 35-mile diversion from the A131. The RIBA competition for a new Ballingdon Bridge was the result of public protest against the design proposed by Suffolk Highway Engineers, the local people thought that their proposal was both ugly and disruptive – it would have taken 3 years to rebuild the bridge with the conventional engineering methods proposed.

Michael Stacey Architects won the limited competition to design Ballingdon Bridge in collaboration with structural engineers Arup and specialist lighting designers Evolution.

Thus Arup won its next bridge commission in the same week that the Millennium Bridge, which it has designed with Foster + Partners, closed on 12 June 2000, due excessive vibration resulting simply from pedestrian footfall, as discussed above.

The materials of the new bridge were carefully selected to respond to the local context and fulfill the performance requirements of a road bridge, including durability, which combine engineering, urban design and architecture. The material palette was discussed in detail with the planning officer, Ruth Stoakes. The primary structure of the bridge is formed from precast concrete, and the mix was selected to match the limestone of All Saints, a twelfth century Norman Church. This palette of materials also includes aluminium, stainless steel, granite and English oak. Even the aggregate within the tarmac of the roadway was agreed with the planning officer. The design of the new bridge is visually calm, respecting the historic context. The view over the bridge remains focused on All Saints Church and, in the other direction, on the seventeenth century timber-framed cottages of Ballingdon, as shown in the design sketches, Figures 5.167 and 5.168.

Fig 5.166 Ballingdon Bridge viewed from the water meadows of Sudbury

Fig 5.167 Michael Stacey Architects’ sketch of the view down Ballington Street over Ballingdon Bridge with the view focused on twelfth century All Saints Church

Fig 5.168 Michael Stacey Architects’ sketch of the view of Ballington Bridge from Sudbury, the architectural diversity resides in the seventeenth and nineteenth century terraced houses
However, the structure has a dynamically changing three-dimensional soft
texture. Designed using a research-based evolutionary
technique, the bridge has an ever-changing and site-specific
genome, see Figure 5.169. The new Ballingdon Bridge was
delivered in partnership with Costain, overcoming a fascinating
set of logistical constraints by collaboration, design and deep
commitment to sustainability. The recycling of the existing bridge is
set out in Towards Sustainable Cities Report 2: Aluminium: Recycling
and Recyclability. By careful study of the construction and phasing of the bridge,
and extensive prefabrication, disruption to Sudbury and Ballingdon
was minimised, and two-way traffic on the Bridge was maximised
during reconstruction. Ballingdon Bridge is an example of fast
construction yet ‘slow architecture’, analogous to the slow food of
the slow food movement. The bridge was rebuilt in 18 months and
has a design life of 120 years. It is now possible to combine robust,
rapidly deployable contemporary technology and the immutable
qualities of architecture. Architecture made of fine ingredients
designed to be purposeful, durable, savoured and enjoyed.
Michael Stacey Architects sought to uphold the rich architectural
traditions and construction quality of Suffolk. Sudbury was the
home of Thomas Gainsborough and the landscape of the river
Stour is set in John Constable country (Figure 5.173). The quality
of design and the quality of thought embodied in this project
represent key components for the creation of a built environment
that will help to sustain human ecology.
Fig 5.173 Ballingdon Bridge set in SSSI of the river Stour. In a flood the bridge will hold back the flood waters saving houses down stream.
The balustrade was designed to be visually open so that the views of the landscape are as uninterrupted as possible. It is capable of arresting a 42-tonne truck yet appears to be an elegant pedestrian handrail, its strength being achieved by a combination of stainless steel castings, stainless steel wires and two bespoke aluminium extrusions, as shown in Figures 5.174 and 5.175. The tensile strength of the aluminium is vital in stopping a truck from falling into the river. The illuminated bollards were designed for the project to avoid the need to use lampposts on the bridge. Cased in waterjet cut anodised aluminium, the core of the bollards is a galvanised circular hollow steel section, which will stop cars from crossing the pavement, but shear off if hit by larger vehicles. The bollards were prototyped at one-to-one using white watercolour paper and discussed with the client on the earlier bridge. The top rail of the balustrade is a combination of extruded aluminium and English oak. This point of human contact is key to its design; to a pedestrian, the vehicular safety role of the balustrade is intended to be an unseen quality. The enlarged oak walkways create a generous provision for pedestrians to enjoy the views of the river and meadows. People enjoying the river and the urban spaces of Ballingdon and Sudbury are the priority within the design of this road bridge.
aluminium: flexible and light

light and strong: bridges

Fig 5.178 Ballingdon Bridge designed by Michael Stacey Architects is an example of “fast construction” yet “slow architecture”
Total Cost of Ownership of Bridges

One factor that has limited the uptake of aluminium in bridge construction has been the relatively high cost of aluminium when compared to steel or concrete (noting the variability of world commodity prices). However, as metals are sold by weight, the lightness of a well designed aluminium bridge may not have a higher first cost when compared to steel or concrete options. Increasingly infrastructure owners and design teams are using Life Cycle Assessments (LCA) to evaluate the full environmental impact of materials in a design proposal, as discussed in TSC Report 3: Aluminium and Life Cycle Thinking.\(^1\) When evaluating the cost of a proposal, the total cost ownership (TOC) should be considered not just the first capital cost.

The TOC for a civil engineering project, for example a bridge, comprises:

- **Acquisition** – typically the purchase of land or assets included any cost related to remediation, if the site is brownfield or demolition and or disassembly of an obsolete bridge.
- **Design and Construction** – cost of the design, manufacture and assembly or construction of a new bridge, including planning and other approvals.
- **Maintenance and Operation** – maintenance costs are the annual expenses required to maintain the assets safety and functionality over its expected lifespan. Operational costs include, for example, the costs and revenue if the new bridge is to be operated as a toll bridge.
- **End-of-Life** – costs and revenues associated with the deconstruction, removal, recycling of materials, and site remediation.\(^2\)

Professional fees need to be factored in each stage.

In 2012 Deloitte published *Life Cycle Analysis: Aluminium vs. Steel*, with input from MAADI Group and the Aluminum Association of Canada. This report presents the total cost of ownership (TCO) of pedestrian bridges in steel and aluminium using the methodology set out above, factoring an inflation and discount rate.\(^3\)

The full report considers two environments, urban and maritime. The three specifications for the corrosion protection of the mild-steel bridges were considered: two-coat paint system, three-coat paint system and hot dip galvanising. In all cases one aluminium specification was used, mill finish 6000 series and/or 5000 series alloys.\(^4\) A single bridge span of 21.3m (70') with a width of 1.83m (6') was used. The aluminium option weighed 3.1 tonnes and the steel option 5 tonnes, thus the aluminium bridge was 38% lighter. An indicative life of 50 years was used for this comparative study.

### Material Characteristics

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<td>CSA G40.21 grade 350W (ASTM 50W), Standard commercial blast SSPC-SP-6, 2 layers 125µm Hi-Build Epoxy</td>
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<td>Steel – 3 coats</td>
<td>CSA G40.21 grade 350W (ASTM 50W), Blast near white SSPC-SP-10, 1-layer 65µm Zinc Rich Epoxy, 1-layer 100µm Hi-Build Epoxy, 1-layer 50µm Polyurethane</td>
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<td>Steel – hot-dip galvanized</td>
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<td>Aluminium – Natural Finish</td>
<td>Aluminium natural finish, 6xx and/or 5xx alloys</td>
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Table 5.4 Comparative bridge specifications in the Deloitte TCO study

The outcome of this analysis on the total cost of ownership of comparative pedestrian bridges showed that over a 50-year timescale an aluminium bridge in an urban environment is significantly more economical when compared to the steel options. An aluminium bridge in an urban environment becomes the better economic option after 33 years when compared to a galvanised steel bridge and only 21 years in a marine environment.\(^5\)

Thus studying the TOC in this case shows clear benefits in the specification and ownership of an aluminium pedestrian bridge. The recommendation of the TSC Research Team is to study the TOC of your proposed projects.

The brief for the external stairs to serve the new Palazzo dei Congressi, which is located in the centre of the coastal town Riccione, required a high capacity to speed up the flow of the large number of people accessing the congress halls. Working with the architect Gianni Ronchetti, Bayards designed, fabricated and installed four staircases, which are airy, safe and attractive, serving the visitor to the Palazzo dei Congressi well.

The staircases were fabricated from 6005A T6 alloy, which was chosen instead of the slightly stronger 6082 T6 to ensure a better quality of anodising. The primary extruded aluminium section sizes used to fabricate the staircases are: 400 × 40mm flooring planks, 345 × 50mm step planks, 400 × 100mm lateral stair stringers, 400 × 200mm central stair stringer, 75 × 75mm handrail posts, and 100 × 20mm handrail top rail. During fabrication both MIG and TIG welding techniques were used. The finish is 20μm of silver anodising. The quality of this set of staircases was recognised by the European Aluminium Association awarding the project a European Aluminium Award in 2008.

The use of cast aluminium as the structure of a staircase designed by architect Julian Arendt with engineer Fluid Structures is illustrated in Towards Sustainable Cities Report 2: Aluminium Recyclability and Recycling.57
Aluminium Staircase in Parc de la Rivière-Beauport, Québec, Canada: Designer and Fabricator, MAADI Group, 2015

Descending 15m (50’) from the street into the park, this staircase, with its welded aluminium structure and timber deck was designed and fabricated by MAADI Group for the local government, Ville de Québec, who are the custodians of Parc de la Rivière-Beauport. This park is located around the river Beauport, which became a focus for the development of industry in Québec city in the eighteenth century. Traces of this early industry can still be found in the otherwise beautiful urban park. Aluminium was selected for the new staircase primarily for its durability and the minimal maintenance required beyond annual inspections. A combination of alloys were used in the assembly of this staircase 6061-T6, 3003-H14. A range of extruded sections were deployed including 50, 75 and 100mm SHS, 40 × 100 RHS and 40 × 40 L-sections, combined with 3mm plate and expanded mesh for the balustrade. All mill finish aluminium. Connections were predominately MIG welded.
In France, three suspension bridges: Montréal and Feyte spanning the Seine river and the Garonne, develop an extruded aluminium bridge deck system. Inventor: Lars Svensson.

In Sweden, 2003, develop an extruded aluminium bridge deck system. Inventor: Lars Svensson.

1975 First aluminium road bridge opens in Vienna, Austria.
1977 Sweden’s first aluminium deck system is installed on the Fridhemsbron, Stockholm, Sweden.
1987 In Sweden, Sapa develop an extruded aluminium bridge deck system. Inventor: Lars Svensson.
1989 Sapa aluminium bridge deck system installed on the Tottnäs Bridge, Stockholms Län, Sweden.
1996 Reynolds Metals Company install a new aluminium deck on the historic suspension bridge, Corbin Bridge, Pennsylvania, USA.
1999 Millennium Bridge, Gateshead, designed by WilkinsonEyre with engineer Flint & Neill.
2000 Millennium Bridge, London, designed by Foster + Partners with engineer Arup.
2003 Bridge of Inspiration, Gateshead, designed by WilkinsonEyre with engineer Flint & Neill.

Fig 5.186 Timeline of Aluminium Bridges from the Jazz Age to the Digital Age

1923 Aluminium decking replaces the timber and steel decks of Smithfield Street Bridge, Pittsburgh.
1933 Aluminium decking replaces the timber and steel decks of Smithfield Street Bridge, Pittsburgh.
1946 First all-aluminium bridge, Grasse River Bridge, Massena, New York, spanning 30.5m.
1948 World first aluminium bascule bridge: Hendon Dock Bridge, Sunderland, is built by Head, Wrightson & Co of Stockton.
1950 Aluminium bascule bridge at Victoria Dock, Aberdeen, opened by the Queen Mother.
1953 First aluminium road bridge in Europe: Schwansbell Bridge, spanning over the Datteln-Hamm Canal near Lünen, Germany, it is still in use today.
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Early Aluminium Bridges

The first use of aluminium in bridge construction is the replacement of deteriorated timber and steel decks of the 1882 Smithfield Street Bridge in Pittsburgh, USA, with aluminium decking in 1933. This is almost 40 years later than the first use of aluminium in architecture. The deck was fabricated from 2014-T6 aluminium alloy and was in use until 1967, when the deck was replaced again with a 6061-T6 aluminium alloy deck. Due to very significant increases in road traffic volume, this deck was decommissioned in 1994, when the bridge was reconfigured to accommodate more lanes of traffic.

The earliest all aluminium bridge was built in Massena, New York State in 1946, the Grasse River Bridge had a 30.5m span fabricated from 2014-T6 alloy. It carried rail traffic serving an Alcoa smelter. Until 2008 Massena was also the location for General Motor plant, where aluminium engine components were cast.

The world’s first two aluminium opening bascule bridges were built in the UK, serving the docks of Sunderland and Aberdeen. Hendon Dock aluminium bascule bridge, Sunderland, 1948, was built by Head, Wrightson & Co of Stockton who had started making mining engineering equipment out of aluminium alloys in the 1930s and they were awarded the contract by the River Wear Commissioners to build this bridge. This bridge was 37m long and 5.64m wide. This bridge has a curved topped truss girder of U-profile cords and I-profile verticals and diagonals, all connected by galvanised steel rivets. The bridge deck comprises a grid of I-profile cross beams, 900mm deep, with 10mm aluminium plate topped with an asphalt-wearing course. Below the railway tracks are two longitudinal beams both 600mm deep. The girders were fabricated from 6151 alloy and the deck from 2014A aluminium alloy, respectively. Siwowski observes that total weight of this bridge span is 40 per cent of an equivalent steel assembly. This bridge was decommissioned and recycled in 1977.

**Fig 5.187** Smithfield Street Bridge, Pittsburgh, completed in 1882, decking replaced with aluminium in 1933

**Fig 5.188** Reproduction of a watercolour painting of the aluminium alloy bascule bridge at Hendon Dock, Sunderland by Leslie Carr, published in Light Metals, December 1948

**Fig 5.189** Aluminium alloy bascule bridge at the entrance to Hendon Dock, Sunderland, which opened in 1948
The second of these aluminium bascule bridges was assembled at Victoria Dock in Aberdeen, by Head, Wrightson & Co, to a similar specification, but it was only 30m long. Named St Clements’ bridge, it was opened by the Queen Mother on 30 September 1953. It is thought that neither bridge proved to be durable in the long term because of a poor understanding of bimetallic corrosion resulting from the use of unprotected steel fixings. St Clements’ bridge was decommissioned and recycled in 1975.

Contemporary examples of bascule bridges built totally from aluminium include Helmond bridge built in 1999 and Riekerhavenburg bridge and Westdork Bridge both completed in 2003. These bridges in Amsterdam were fabricated by Bayards using extruded trapezoidal aluminium profiles. The lightweight yet stiff decks enable these bridges to achieve a low overall weight, which is beneficial installation and day-to-day opening.

Arvida Bridge is a road bridge spanning the Saguenay River at Saguenay–Lac-Saint-Jean in Québec built of aluminium between 1948 and 1950. It is 10.4m wide, 154m long and the primary arch spans 88.4m. This bridge, fabricated from 2024-T6 aluminium alloy, is still performing well having been refurbished during 2013 and 2014.
Between 1946 and 1963, nine bridges were built from aluminium in North America, eight of which are still in service. This includes a bridge on Route 86 over the I-80 at Des Moines, Idaho, assembled in 1958 from 5083-H113 aluminium alloy and it is believed to be the first welded aluminium bridge, as it was prefabricated in four sections: two 21m spans weighing 9.5 tonnes and two 12m spans weighing 7.3 tonnes, which were welded together to form four continuous spans. On which an in-situ concrete slab was cast separated by a coating of zinc rich primer on the top surface of the aluminium. It performed well for 35 years until it was replaced by a larger structure in 1993.

The first aluminium road bridge in Europe that is still in use is the Schwansell Bridge. It was assembled in 1956 using AlMgSi1 alloy, which is equivalent to 6082 aluminium alloy, creating a 44.2m span over the Datteln-Hamm Canal near Lünen in the form of a Warren Truss and it is still in service today. This bridge was prefabricated and transported to site by barge. Walker and de la Chevrotière attribute the durability of this bridge to the quality of its detailing, the components were joined with aluminium rivets, made out of the same alloy as the sections: 'A coating was applied between the overlapping plates to prevent crevice corrosion.' Noting that ‘minimal deterioration can be observed [on this bridge] after more than 50 years of service over a waterway, in a highly corrosive, industrial environment.'

**Role of Aluminium in Restoring Suspension Bridges**

The high strength to weight ratio of aluminium has a key role to play in the restoration of early suspension bridges. In France, during 1975, three suspension bridges: Montmerle and Trevoux spanning the Saône river and Groslée on the Rhône river, have been restored using aluminium deck structures. The bridge at Montmerle, France, is a 190m suspension bridge comprising two spans of 80m. The timber and steel deck structure was replaced with an all aluminium truss suspended from the original pylons. The trusses are made up from U-profile chords, I-profile struts and bracing sections extruded in A-SGMT 6 aluminium alloy. Its deck is assembled from welded aluminium cross beams combined with welded aluminium panels, topped by 7mm bond resin wearing course. Groslée Bridge is the reconstruction of a 174m suspension bridge over the Rhône, originally built in 1912. The steel and timber deck structure was replaced with aluminium truss girders fabricated from extruded sections of 6082 R31 aluminium alloy that acts compositely with a 160mm concrete deck slab.
A North American example of the uprating of a historic suspension bridge is Corbin Bridge, Huntington, Huntingdon County, Pennsylvania. This 98m (322’) span steel suspension bridge across the river Juniata was built in 1937 by Reading Steel Products Inc., using wire rope manufactured by Roebling and Son, Trenton, New Jersey. It replaces an earlier bridge that had been swept way on St Patrick’s Day 1936. Corbin Bridge has only one lane and is 3.8m (12 6”) wide. It was restricted to load capacity of 7 tons (6.35 metric tonnes), see Figure 5.197. In 1996, Reynolds Metals Company installed a new deck comprising 130mm extruded from 6063-T6 with transvers sections 250mm deep extruded from 6061-T6. Enabling the steel suspension structure to be retained. The bridge was reopened with a capacity of 24 ton (21.8 tonnes). However, the clear height remains just over 4m (13 6”) due to the first cross bar of the masts.

Real Ferdinando Bridge crossing the Garigliano River north of Naples is the oldest suspension bridge in Italy. It was designed by Luigi Giura in 1828 and built between 1831-32. The deck of this bridge was destroyed during World War II. This bridge was restored and reopened in 1998, using an aluminium bridge deck comprising 7020-T6 aluminium alloy for the longitudinal girders and 6060-T6 aluminium alloy for the transverse beams. The longitudinal girders are designed as a Vierendeel beam with the vertical components at the same centre as the suspension cable. The stone piers were consolidated, however, the lightweight of the aluminium deck is of vital importance in the restoration of this historically significant bridge.24
Aluminium Bridges

The primary advantages of using aluminium in the construction of bridges are, it is:

• Lightweight, with a high strength to weight ratio, this is particularly important in opening bridges and the refurbishment of existing bridges.
• Durable, offering long-life with low maintenance, subject to appropriate alloy selection, detailing and finishing.
• Flexible in fabrication from the extrusion of large sections and highly developed welding techniques including friction stir welding.
• Rapidly installed, using large prefabricated components that can be readily transported and lifted in to place.

Furthermore, the total cost of ownership of all aluminium bridges can be beneficial. The case studies set out above evidence the benefits of specifying aluminium bridges in many parts of the world, with extant examples dating back over 65 years.

Fig 5.198 Aluminium Bridges from Arvida, 1950, via the Millennium, in London to 2016
Notes

8 A. de la Chevrotière in conversation with the author February 2016.
9 AASHTO (2009)
11 A. de la Chevrotière in conversation with the author February 2016.
12 Ibid.
13 Ibid.
14 A. de la Chevrotière in conversation with the author February 2016.
16 Ibid.
19 Ibid.
20 Ibid.
21 Ibid.
22 Ibid.
23 Ibid.
25 Jim Eyre in conversation with the author December 2015.
26 Jim Eyre in conversation with the author January 2016.
29 Ibid.
35 Ibid.
36 Ibid.
37 Ibid.
39 Ibid.
42 Ibid.
43 Ibid. p. 41.
44 Ibid.
46 Jim Eyre in conversation with the author December 2015.
47 Information provided by Bayards, January 2016.
49 Michael Stacey was Partner in charge of Ballingdon Bridge at Brookes Stacey Randall and on its completion reformed Michael Stacey Architects.
50 One member of the architect’s design team acted as a control on the development of the digital data during the competition by design alternative arrangements for the primary structure of the bridge, many of which anticipated rival designs of our competitors.


57 Ibid.


66 Walker & A. de la Chevrolière (2012), Opportunities for the of Aluminium in Vehicular Bridge Construction, Aluminium Association of Canada, Montreal, p.3.

67 Ibid.


aluminium: flexible and light

light and strong: prefabricated
Aluminium Light and Strong: Prefabricated

Many of the aluminium bridges in the previous section of this chapter were prefabricated. This section focuses on the use of aluminium to form the primary structure of buildings that are also highly prefabricated, noting that the all-aluminium structure of the Comet Flight Test Hanger, completed in 1953, was also highly prefabricated, see pages 300–315. The primary advantages of prefabrication are:

- Speed of construction;
- Factory based quality control;
- Controlled condition of a sheltered factory environment;
- Minimisation of waste combined with short closed loop recycling of off cuts;

and

- A better gender balance is often found in factories compared to building sites.

This section of Chapter 5 has three case studies in chronological order from 1999 to 2011.

Fig 5.199 Lord’s Media Centre under construction clearly showing the prefabricated aluminium components

Fig 5.200 The self supporting aluminium stair tower core was prefabricated in large chunks by Bayards

Fig 5.201 The aluminium structure of Vague Formation Mobile Music Pavilion was prefabricated in large but easily craned chunks
Lord's was a wonder ground to watch test cricket, however, architecturally it was characterised by the handsome faience-clad Victorian pavilion designed by architect Thomas Verity and built in 1889–1890. Starting with the Mount Stand by Michael Hopkins Architects completed in 1987. MCC becomes possibly one of the most unexpected patrons of cutting edge contemporary architecture. Deyan Sudic records in ‘1994, Peter Bell, an architect member of the Lord’s Committee, came to Future Systems in search of some lateral thinking. He had a problem with sights screens, and the gap between two stands that he wanted to use to build more seats’. Peter Bell was the architect who designed the Parsons House overcladding reviewed in TSC Report 1 Aluminium and Durability and referenced in this report on pages 266–267.

MCC staged a competition for the new press box, which was won by Future Systems led by architect Jan Kaplicky with an audacious proposal for a ‘glass-fronted white aluminium disk, raised on two legs’ and hovering above the stands.

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Prefabrication was key to this project, as it had to be built outside the cricket season and thus not disturbing the programme of games at Lords. Kaplicky, who worked at Foster Associates, had a long held interest in new technology, often technology that had long roots but was being under used by the construction industry. The Lord’s Media Centre offered the opportunity to explore and realise a monocoque aluminium structure. The scale of this cantilevered aluminium structure necessitated the use of internal stiffening ribs generating a semi-monocoque structure. Deyan Sudic records that during the design development process glass reinforced plastic (GRP) was considered, however, “Future Systems were determined to use aluminium, conceptually a much more elegant material.” Thickness of aluminium used to form the components or prefabricated ‘chunks’ of this semi-monocoque structure varies between 6mm and 18mm depending on the structural design of the shell.

Pendennis, a shipbuilder in Falmouth in Cornwall, England, was the key link with Future Systems, however the Lord’s Media Centre was fabricated in the Netherlands by Bayards in its main hall in Nieuw-Lekkerland. The prefabricated components were then transported to site in London, temporarily supported and then site welded into a single shell. As discussed in Chapter 2, the welding of aluminium should no longer be considered difficult, although it is a highly skilled activity. By the early 1990s the techniques of welding developed in the factory or fabricating yard could be reliably applied to site conditions. For example TIG welding can be carried out on site based aluminium components at a range of 200m from an appropriately equipped van. On completion of the welding of the semi-monocoque structure of the Lord’s Media Centre a high performance white paint system was site applied. Completion of the project took two winters. The Lord’s Media Centre has proved a great success providing uninterrupted sightlines for journalists and commentators in the comfort of air-

Fig 5.206 Future Systems’ section through the Lord’s Media Centre

Fig 5.207 Future Systems’ drawing of the element of the fabricated aluminium semi-monocoque structure and building fabric of Lord’s Media Centre
conditioning. Deyan Sudic considers the white aluminium shell ‘to hover above the ground, an enigmatic, ambiguous form, whose scale and form are initially hard to read’. It both signals the presence of the Test venue and it ‘has become a defining image of Lords, even though this last quality was never part of the brief.’

In 1999 the Lord’s Media Centre designed by Future Systems won the RIBA Stirling Prize, the highest honour available in UK architecture. Between the Pavilion and the Media Centre at Lords lies a field of dreams and over one hundred years of technological advancement in the potential for constructing architecture.

The capacity of Barcelona Airport has been significantly increased by the opening of a second terminal building and a third runway. This new capacity also necessitated the construction of a new Traffic Control Tower and the modernisation of air traffic control equipment. The new tower, designed by Bruce Fairbanks with engineers M.E. & G.C. Giuliani, is capable of handling 90 aeroplanes per hour.

Overall the tower is 62m high. The first element to be assembled was an octagonal 43m high self-supporting aluminium structure comprising: staircases, lifts and services. This core was prefabricated in large aluminium ‘chunks’ by Bayards, with bolted details to avoid site welding. To this the external hyperboloid concrete exoskeleton was fixed, without the need for scaffolding. The structure of the upper floors were assembled on the ground and then craned into position.\(^9\)

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Fig 5.211  Barcelona Airport Traffic Control Tower, architect Fairbanks Arquitectos with engineers M.E. & G.C. Giuliani, 2005

Fig 5.212  The self supporting aluminium stair tower core was prefabricated in large chunks by Bayards

Fig 5.213  The external concrete exoskeleton, aluminium stair tower and steel structure of the traffic control rooms

This text describing the design and fabrication of Vague Formation, was primarily written by its architects Kristina Schinegger and Stefan Rutzinger of soma. It formed part of their essay Adaptive Formation in Prototyping Architecture. It is reproduced here in edited form with their permission combined with additional commentary by the author.

The proposal for a mobile music pavilion by soma was chosen as the first prize-winner in an open, two-stage competition in October 2010. It was erected for the first time in the historic centre of Salzburg in March 2011 for a period of 3 months and housed the contemporary music festival Salzburg Biennale. Since then it has been assembled in the rural valley Krakautal, in Styria, Austria and in the inner centre of Maribor, Slovenia. At each location a different cultural activity inhabited the pavilion, the events showed a range from concerts, to exhibition, lectures, readings, installations or performances.

The structure can be divided into individual segments. By combining these in different ways or by reducing their number, it can adapt to its location. The removable interior membrane and the adjustable floor increases the flexibility of use. The pavilion’s appearance is intended to provoke curiosity and invite visitors to encounter the unknown and unusual. It emphasises the understanding of art as a cultural process involving many participants within a discourse. This process does not reveal itself at first sight, but unfolds through engagement. The pavilion refers to a theme that is inherent to architecture as well as music – rule and variation. Its design process is based on simple repetitive elements, a set of rules for aggregation, and definition of the desired architectural effects. The single aluminium profiles with a uniform length produce an irregular, mass-like conglomerate that changes its appearance during the day, according to the different light conditions. The structure allows an ambivalent reading as single members and as a merging whole, depending on the distance it is viewed from. The speculative intention behind this obliteration of the pavilion’s structure is to prevent any conventional notion or cliché of construction. Instead the ambiguous mass should invite visitors to come up with their own associations and interpretations.

Thanks to computation, complex structures employing disorder and randomness can be created and controlled. Although these irregular patterns are often applied to special building parts like façades, applications for load bearing structures are still an exception. Furthermore irregular complex structures are often based on highly individual components. The bottom-up strategy

Fig 5.214  Soma digital model of Vague Formation

Fig 5.215  Vague Formation, a mobile Music Pavilion in Salzburg, 2011
of the music pavilion is based on a repetitive linear base element that does not change shape. Furthermore, the aluminium profile is cut from stock ware (6m length) to avoid leftover material. The overall structural system of the pavilion is divided into 5 individual sections to increase flexibility of use. Each section consists of 20 vertical construction layers with a spacing of 200mm, the start and end sections have fewer layers. On each layer intersection curves with the reference surface will host starting points for the structural members. The distribution of points and positioning of the structural members takes place within a range of randomised distances and angles but at the same time prevents intersections. The first layer of structure was successfully prototyped at the fabricators, Unterfurtner GmbH, as shown in Fig. 5.216.

Due to individual positioning of members along each section curve, projection intersections with neighbouring layers are generated. This process produces an interconnected structure. The structural optimisation by Bollinger Grohmann Schneider engineers takes the design rules into account but also considers working loads, amount of connection elements and the maximum

\[ \text{Spannungsanalyse} \]

\[ \text{Perspektive} \]

\[ \text{Ansicht} \]

deflection of each segment. To evolve a structure Karamba\textsuperscript{2} was applied within Grasshopper. Combined with a genetic algorithm the optimised solution was filtered out of the multiplicity of solutions through combination, selection and mutation over many generations. The elements are aligned iteratively and interact in a parallel way. By repetition of the same calculation step and with the feedback of the results, the system is incrementally evaluated until a certain target value is reached or the system converges to a threshold value. Multiplicity denotes the simultaneous and parallel observation and adjustment of the individual elements in a single step. The coactions of multiplicity and iteration result in the system’s ability to adapt to a given task.

\[ \text{Fig 5.216} \quad \text{Welding the aluminium structure at Unterfurtner GmbH} \]

\[ \text{Fig 5.217} \quad \text{Sample images of the design team’s parametric model of the structure of the Music pavilion} \]

\[ \text{Fig 5.218} \quad \text{The structure is formed from standard extruded aluminium box sections linked by tubular aluminium sections} \]

\[ \text{Fig 5.219} \quad \text{The aluminium structure was prefabricated in large but easily craned chunks} \]

\[ \text{Fig 5.220} \quad \text{Prototype arch at Unterfurtner GmbH} \]
Optimisation is here understood by Bollinger Grohmann Schneider Engineers as enhancing structural performance within architectural parameters and aesthetic intents given by the architect. In addition to structural aspects, the number of sections is minimised without losing the mass-like appearance. The parametric model, based on Grasshopper and Karamba, enabled the architects and the engineers to simultaneously design and evaluate the structure. This collaboration cannot be considered as a strictly parametric straightforward generation process, but is rather a back and forth negotiation between architectural aspiration, structural behaviour, buildability, logistics of assembly, and cost control. In the case of the music pavilion the design process is actuated by the set-up of rules and framing conditions that could be understood as the inherent logic of the emerging structure. ‘On this modest project, costing 300,000 Euros’ Michael Stacey’s opinion is that ‘parametric tools and specifically the Grasshopper plug in to Rhino has been used wisely.’

Nevertheless, the experiential qualities of the design and its external expression remain a principal focus. The mass-like appearance aims at underlining the creative character of our perception, since our brains are constantly trying to distinguish figures and patterns within disorder. Rather than to produce forms or meanings, the ambiguous mass of the pavilion triggers visitors to come up with their own interpretations and associations. In this way the pavilion could be called performative, since it wants to engage visitors, not by being complicated or difficult, but by displaying the playfulness of complexity and creating a changing appearance that triggers visitors’ curiosity.
This tendency towards the design of rules and display of inherent principles is also a shift from an interest in external form towards the inner logic or, as Stan Allen puts it, from object to field. Form or figures do not disappear altogether, they rather appear in the eye of the beholder, and step out of a heterogeneous field as a local effect. ‘What is intended here is a close attention to the production of difference at the local scale, even while maintaining a relative indifference to the form of the whole,’ Allen calls these fields ‘systems of organisation capable of producing vortexes, peaks, and protuberances out of individual elements that are themselves regular or repetitive.’ He highlights the ‘suggestive formal possibilities’ and the questioning of conventional top-down form controls. In his opinion fields also have the potential to provoke a re-addressing of use: ‘More than a formal configuration, the field condition implies an architecture that admits change, accident, and improvisation.’ Following Stan Allen adaptability could be understood as a certain openness and experiential ambiguity in architecture that allows multiple readings and therefore multiple uses, that might be unplanned and unforeseen. At soma we advocate that this openness is not composed by the neutral and flexible, but the distinct and complex, the evocative and sensational, the multi-layered and fuzzy.

In 2012 the author reviewed Vague Formation mobile music pavilion for Architecture Today and the following is an edited extract. The structure was designed parametrically, but the diversity of components often associated with freeform geometry was eschewed in favour of aggregating a standard component. Working with engineer Bollinger Grohmann Schneider, SOMA developed a bottom-up design strategy based on a repetitive element that does not change shape, yet creates a palette of spatial patterns depending on the rules of aggregation. The base component is a mill-finish aluminium box section extruded from a standard stock die. To facilitate transportation the structure of the pavilion is divided into five-arched segments that in turn are broken down into six sub-segments.
The architects did not want the construction to be read in a conventional manner – in contrast, for example, to Renzo Piano’s traveling IBM exhibition pavilion from the early 1980s, which was formed from arched bays of polycarbonate and timber linked by elegant aluminium castings. Rather, SOMA’s ‘speculative intention behind the ‘obliteration’ of the pavilion’s structure is to prevent any conventional or cliché of ‘construction’... the pavilion should appear to arbitrarily invite visitors to come up with their own interpretations.’

The structure is prefabricated in segments with 20 vertical and parallel layers, spaced at 200mm centres, except for the rear segment, which has only 15 layers. The 95 layers or arches of the aluminium structure each span 10 metres. Each structural layer has a unique aggregated curvilinear geometry. The aluminium box extrusions are welded together with 90mm long circular aluminium extrusions, where layers of arches are bolted together during erection; 90mm long circular aluminium extrusions conceal the M10 stainless steel connecting bolts. Although the appearance of the aluminium structure is very diverse, the fixing method, whether bolted or welded, appears the same. The expression is based on aggregation rather than articulation of the detailing. The apparent complexity is underscored by the clarity of the fabrication. The exoskeleton of aluminium sections provides a dynamic pattern of shadows in the interior of the pavilion, which is revealed by the translucent membrane. The aggregated aluminium structure formed from standard aluminium extrusions generates a striking and delightful architecture both inside and outside; appropriately, this could be seen as a new example of architecture as frozen music.
Notes:
5. Ibid. p. 188.
8. Ibid.
15. Ibid.
16. Ibid.
aluminium: flexible and light

light and slender
Light and Slender

Windows are apparently simple, yet become surprisingly complex when providing a high performance including: good thermal insulation, natural ventilation, low air infiltration rate (draft proof), plentiful daylight, beneficial solar gains, security, and ease of user operation. Carefully designed glazing systems combine all of these issues, whilst providing a good energy balance. Windows are a familiar component of architecture for everyone and one of the first standardised building products – the timber London sash window was first produced in the eighteenth century.

The inherent complexity of windows is one of the reasons why TSC Report 3 Aluminium and Life Cycle Thinking selected window frames for a comparative life cycle assessment (LCA) of the use of aluminium, wood, aluminium-clad wood and PVCu to form this component of architecture.¹ In this study a reference size of 1.3 × 1.6m was used for all frame types, this is essential in a LCA study to make certain that the assessment is comparable across the four materials. However, this understates the potential of aluminium to support large areas of glass with slender stiff sections.

EN 14351-1 defines two sizes of windows – small windows under 2.3m² in area, with a standard size of 1.23(±25%) × 1.48(±25%)m, and large windows as 1.48(±25%) × 2.18(±25%)m, with an overall area over 2.3m². The size of window can significantly affect the thermal performance and light transmission due to the percentage of framing.

U-values
The measure of heat loss through the fabric of a building is described as a U-value, measured in W/m²K. A low U-value represents a high level of insulation. There are three important U-values to consider when evaluating the thermal performance of a window:

\[ U_w \] (w = window): overall U-value of the window;

\[ U_g \] (g = glazing): U-value of the glazing;

and

\[ U_f \] (f = frame): U-value of the frame.²

Fig 6.1 A diverse set of window selections in an exhibition by Rem Koolhaas at the Venice Bienalle, 2014

Fig 6.2 Schüco FWS 35 PD, triple glazed curtain walling
The heat transfer coefficient of the entire window $U_w$ is calculated in order to understand the overall assembly performance. This value incorporates the U-values for the glazing $U_g$ and the frame $U_f$. The overall value $U_w$ is influenced by the linear heat transfer coefficient of the frame and the glazing, and the sizes of the frame and the glazing.

The following formula is used to determine the $U$-value of the complete window $U_w$:

$$U_w = \frac{(A_g x U_g + A_f x U_f + l_x x \Psi_g)}{(A_g + A_f)}$$

Where:
- $U_g$ = heat transfer coefficient of the glazing;
- $U_f$ = heat transfer coefficient of the frame;
- $\Psi_g$ = linear heat transfer coefficient of the insulated glazing unit (IGU) edge seal;
- $A_g$ = total area of glazing;
- $A_f$ = total area of the frame;
- $A_w = A_g + A_f$;
- and
- $l_x$ = length of inside edge of frame profile (or visible periphery of the glass sheet). \(^1\)

Schüco produces an extruded aluminium window system with a sight line or framing section that is only 60mm wide; the Schüco FWS 60 CV façade system includes inward opening vents that do not increase the sight lines, with no visible framing externally. This system uses glass-fibre-reinforced thermal isolators and provides $U_{cw}$-values down to 0.85 W/m\(^2\)K with a glazing $U$-value of 0.7 W/m\(^2\)K. Schüco observe ‘the systems very narrow face width actually assists in improving its energy efficiency’. \(^4\) $U_{cw}$-value is the overall $U$-value of a lightweight curtain walling in accordance with BS EN ISO 12631:2012, which follows a very similar procedure to that for the window, as set out previously.

Schüco has also developed a curtain walling system with even slimmer sight lines with a face width of only 35mm, which was launched in 2015. This pressure plate extruded aluminium curtain walling system can accommodate double and triple glazed units from 22mm to 50mm thick. The FWS 35PD system in its super insulated format is Passivhaus accredited with an $U_{cw}$ of 0.79 W/m\(^2\)K. \(^5\)
Beyond U-values

Energy efficiency in building fabric is not limited to achieving low U-values; it is also about balancing solar gains (g-values) and providing comfortable internal daylight levels, creating an energy balance. Achieving airtightness or a low air infiltration rate is also of vital importance; because once a building envelope is well insulated, unintended air changes can dominate the heat loss. This needs to be balanced by adequate ventilation to provide fresh air and to control condensation. A carefully resolved design that balances these criteria should be achieved to produce a satisfactory internal environment for building users, whilst minimising energy costs at the same time. 4

The four main criteria that should be considered when assessing the energy balance of glazing are: thermal transmittance (U-value), solar gains (g-value), air infiltration rate, and cooling from ventilation. A window or glazed facade also provides daylight, expressed as light transmission factor (τv). A high light transmission value (U-value) is desirable to maximise daylight, but this should be balanced by controlling excessive solar gain in the cooling season. A g-value indicates the degree to which glazing blocks heat from sunlight and is expressed in a number between 0 and 1. The lower the g-value, the less heat is transmitted. The air infiltration rate is typically measured in m3/m2/hr. For g-value and light transmittance, it should be noted that these typically consider only the performance of the glazing. Hence for a window, it is preferable to consider the performance of the whole window by taking into account the frame fraction, with gav = g x (Ag/Aw) and LTav = τv x (Ag/Aw).

Solar Gain

U-value regulations are now well established and understood, although only forming part of the key design considerations, however, g-values are relatively new to many specifiers and organisations. Solar gain is of particular importance in the regions relatively distant from the equator, where the sun is often at a low trajectory. Although solar gain can be beneficial in winter, as discussed in Chapter 3, the overall energy balance needs to be studied and preferably modelled, including the sizes and orientation of the glazing systems. Solar gain and light transmission are interdependent. Visible light, which can be seen and perceived by humans, is a very small part of the full electromagnetic spectrum, approximately only 3 per cent of this spectrum. The sun emits slightly more infrared than visible light, 52 compared to 48 per cent respectively. Visible light is absorbed and emitted by electrons in atoms moving from one energy level to another, and lies between the infrared and the ultraviolet wavelengths in the electromagnetic spectrum. Electromagnetic radiation (EmI) in the visible light region consists of quanta (called photons) between the invisible infrared, with longer wavelengths, and invisible ultraviolet, with shorter wavelengths. Above the range of visible light, ultraviolet light becomes invisible to humans mostly because it is absorbed by the tissue of the eye.

At the lower end of the visible light spectrum, EmI becomes invisible to humans because its photons no longer have enough individual energy to cause a lasting molecular change, a change in conformation, in the human retina. The aim for any energy efficient glazed facade system should be to achieve a good energy balance, minimising the solar gain, 780-2500nm infrared radiation, whilst transmitting as much visible light as possible, 400-780nm. In this regard, the role and design of solar shading is important, as reviewed in Chapter 3. A good energy balance within a facade will help to create a constant (within an agreed range) and comfortable interior temperature within the building, whilst minimising the need for artificial light. The thermal performance of 6mm single glazing is 5.7W/m2K, where as the U-value of a double glazed unit, comprising clear glass, typically 6mm glass with a 16mm cavity (6-16-6mm), is 2.7W/m2K. By adding a transparent sputtered metal low-emissivity coating to either surface 2 or 3 of a double glazed unit (6-16-6mm) the U-Value can be reduced to 1.4W/m2K. Low-emissivity coated glass (know simply as low-E glass) in an IGU reduces radiated heat loss from the interior, thus reducing the energy required for heating a space. Low-E glass will also absorb and reflect more of the incident solar energy, thus reducing the cooling load. There are two types of low-E coating – soft and hard, selection is primarily dependent on the climatic conditions of the proposed project. The development of low-E coatings began in the 1950s. The thermal performance of glazing can be further reduced by filling the cavity with a gas with lower a thermal conductivity, such as argon and the specification of triple glazing. Leading glass manufacturers including Pilkington, PPG, and Saint-Gobain provide detailed guidance on the performance of their product ranges.

Internal light levels

In the USA, day lighting is a well-proven and accepted part of building envelope design. The guidelines they use are based on an external luminance at ground level of 5000lux, which is equivalent...
to an overcast cloudy day. For an internal space to feel well lit, the average daylight factor should be 5 per cent or more. CIBSE LG10 states that an average daylight factor of 5 per cent or more will ensure that an interior looks substantially day lit. This equates to a light level of 250lux. This may appear to be low but if this level is uniformly achieved from a large proportion of the external wall compared to a smaller more concentrated area such as a window, it will normally satisfy the requirements of BS 8206-2: 2008.

BS 8206-2 2008 highlights three ways that the provision of glazing contributes to the energy balance and the quality of an internal space:

- View – amenity;
- The enhancement of the overall appearance of interiors using direct sunlight and diffused daylight; and
- The use of daylight for visual tasks.

When designing the building envelope of a project the architecture needs to be viewed holistically, including the potential role of thermal mass in the internal structure, the longevity of the façade materials, and the balance of ensuring good daylight and light levels whilst protecting the occupants from unwanted solar gains in the cooling season. This approach can move the project’s budget from primary energy consuming services, such as air conditioning into the architecture and the facades, enhancing rather than limiting the architectural expression and reducing the energy consumption and greenhouse gas emissions of the building over its lifetime. Often defined as a fabric-first approach to building design.

The required light transmission should be calculated alongside the energy balance of the façade. Designers of low energy facades need to balance all five critical factors: U-value, g-value, U-values, a low air infiltration rate and cooling by natural ventilation.

Alongside the glass specification, the sight lines produced by the specified window frame is key to the percentage of glazing, and thus the amount of daylight entering through the façade. Figure 6.7 provides a visual comparison of currently specifiable window framing systems, organised not by material but by the relative slenderness of the framing system.

To provide an indication of sight lines and relative performance of aluminium window frames, the following is a comparison of four extruded aluminium thermally broken windows, using casement or tilt turn windows. In all cases the windows are double glazed with 6mm outer panes of Cool-Lite (SKN 174 I) – a low-E glass, 16mm cavity and 4mm inner pane of Planilux, both by Saint Gobain (6-16-4mm), with the cavity 90 per cent filled with argon. The size of window used is 1.3 × 1.6m, as this is the reference size used in the LCA in TSC Report 3, Aluminium And Life Cycle Thinking. This comparison of available window frames is provided as an indication of the options available to specifiers, and the author would encourage the reader to research potential window framing systems and seek early interaction with manufacturers, many of whom will provide technical guidance and BIM objects for their window system.
Fig. 6.8  Hansen Millenium aluminium casement

- Frame Width (sight lines): 50mm
- Frame Depth: 85mm
- U-value (double glazed): 1.4 W/m²K
- Solar Factor (g-value): 0.41
- % Glazed Area of 1.6 x 1.3m opening: 86%

Fig. 6.9  (opposite) Hansen Millennium window, door and façade system
**Kawneer GT70 Aluminium Renovation**

- Frame Width (sight lines): 69mm
- Frame Depth: 85mm
- U-value (double glazed): 1.5 W/m²K
- Solar Factor (g-value): 0.41
- % Glazed Area of 1.6 x 1.3m opening: 82%

**Kawneer AAS43 Aluminium**

- Frame Width (sight lines): 98mm
- Frame Depth: 63mm
- U-value (double glazed): 1.6 W/m²K
- Solar Factor (g-value): 0.41
- % Glazed Area of 1.6 x 1.3m opening: 75%

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**Fig. 6.10** Kawneer GT70 Aluminium renovation window

**Fig. 6.11** Kawneer AAS43 tilt turn aluminium window

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Kawneer GT70 aluminium renovation series tilt turn frame elevation. Opening size of 1.6 x 1.3m, scale 1:50

Kawneer AAS43 tilt turn aluminium window frame elevation. Opening size of 1.6 x 1.3m. Scale 1:50
Part of the drive to inform the thermal performance of glazed façades has been consideration of the overall U-value, not just the performance of the double or tripled glazed unit, what was once known as the mid-pane U-value. Aluminium alone is highly conductive, as shown by its use in overhead electrical power lines and heat sinks. Therefore thermal breaks and insulation need to be detailed in aluminium curtain walling and windows, to lower the $U$. The past 40 years has witnessed the steady development of thermally efficient extruded aluminium windows frames, offering a frame U-value of 0.85 W/m$^2$K, as demonstrated by the Schüco FWS 60 CV, discussed above. Another example is the PURe® extruded aluminium window system designed and manufactured by Senior Architectural Systems, which incorporates expanded polyurethane (PUR) thermal barriers and provides a $U_{w}$-value down to 0.71 W/m$^2$K.
Once a building envelope is well insulated, the next key challenge is to control the air infiltration rate, as unwanted air changes will dominate the heat loss. Weather tests have long measured the air infiltration rate, weather resistance and stiffness of façade components, as discussed in TSC Report 1, Aluminium and Durability. However, it was not until the mid 1990s that requesting and specifying the performative data on air infiltration rate became part of best practice. For windows and curtain walling this is typically measured in m$^3$/m$^2$/hr; for example the curtain walling of 240 Blackfriars Road by AHMM, reviewed in Chapter 7, achieves an air infiltration rate of 1.5 m$^3$/m$^2$/hr. The Passivhaus Standard takes a whole house approach to air infiltration by specifying the number of air changes per hour. It states an airtightness of 'a maximum of 0.6 air changes per hour at 50 Pascals pressure (ACH50), as verified with an onsite pressure test (in both pressurised and depressurised states).'

Once an airtight building envelope is achieved it is essential to consider the number of air changes required for human inhabitation and the control of moisture in the internal environment, via trickle ventilators and the provision of operable windows, or mechanical air-to-air heat exchangers, which reclaim heat and the latent heat of evaporation from the exhaust air. Openable windows can be linked to a computer controlled Building Management Systems (BMS) and operated by stiff chain drives, which can be built into window transoms. This technique was pioneered on the Powergen Operational Headquarters, in Warwickshire, completed in 1994, designed by Bennetts Associates, with performance specifications written by the author, which in collaboration with E. C. Harris included air infiltration rates for the aluminium windows and curtain walling. At night the BMS of the Powergen offices opens the windows to cool the exposed thermal mass of the concrete structure. Many of the contemporary case studies in this report incorporate BMS as a key means of helping to achieve comfort conditions and a low energy performance.
Fixed Lights and Opaque Ventilators

One design strategy to minimise the slight lines of a glazing system, whilst providing natural ventilation operated by the occupants, is to combine the minimal sight lines of fixed glazing with opaque ventilators. This strategy was often used by Jean Prouvé, Le Corbusier and Louis I. Khan, primarily for its elemental clarity and the elegant simplicity of the fixed lights. Figure 6.16 shows the solid timber ventilators of the Margaret Esherick House, designed by Louis I. Khan and completed in 1962.
In contemporary low energy architecture, architects are increasingly using the minimal simplicity of fixed double or triple glazing in thermally broken aluminium framing, combined with opaque insulated ventilators to provide natural ventilation. The insulated panels used to form the ventilators provide a lower U-value even than high performance triple glazing. The Engineering Building at Lancaster University and Cubbit House are two examples, as set out below.

The Engineering Building at Lancaster University, Lancashire, England, designed by John McAslan + Partners and completed early in 2015, at a capital cost of £8.400,000, is a taut and well considered engineering building that more than just accommodating the diverse functions of an engineering department – placing functions around a central atrium creating visual links between users. The plan is a creative slipping of three rectilinear volumes, sized for their primary function: with 12m clear-span labs, a 6m atrium and a 10.5m clear-span block containing labs and cellular office space.

Fig 6.17 The entrance of Lancaster University Engineering Building, architect John McAslan + Partners, 2015

Fig 6.18 The north façade of Lancaster University Engineering Building
A palette of self-finished materials compliments this clear spatial arrangement. This elegant building achieved BREEAM Outstanding by the integration of passive techniques, sectional geometry and orientation, combined with material selection, which included 50 per cent GGBS in the mix of the creamy coloured exposed in-situ concrete. In 2015 this project received a RIBA National Award.

Part of the elegance of Lancaster University Engineering Building is the use of fixed double glazed anodised curtain walling and windows with insulated opaque opening vents veiled by perforated anodised aluminium panels, set in a framework of yellow brick and creamy coloured precast concrete. Similar perforated anodised aluminium panels are used inside the atrium to accommodate acoustic insulation.
Cubitt House designed by Allford Hall Monaghan Morris (AHMM) is a six-storey housing block of ten apartments that forms part of the 240 Blackfriars Road project, completed in 2014, the office tower of which is described in Chapter 7. Cubitt House is located on the southern end of the site and is articulated as a separate block, yet maintains a related angular geometry. It is clad in dark-reddish brown almost black bricks, sourced from Germany, that form a common field of cladding. The double glazing is full height in each apartment, with simple and unobtrusive recessed detailing, made possible by an inward tilting opaque insulated panel that provides all natural ventilation – operated by the residents. When shut these ventilators read as part of the white internal walls or possibly an integrated cupboard.

Fig 6.21 (left) Cubitt House on Blackfriars Road designed by Allford Hall Monaghan Morris, 2014

Fig 6.22 An all-glazed corner window and opaque insulated ventilator inside an apartment of Cubitt House
In 1996, at a worked-out China Clay pit near St Austell, Cornwall, Tim Smit proposed the construction of an enclosure to grow plants to demonstrate ecology and biodiversity within a range of climates, from Mediterranean to tropical, like the Princess of Wales (Diana’s) Pavilion at Kew Gardens, London, completed in 1987, but on a much larger scale. Grimshaw was a project partner and architect from a very early stage. At first Grimshaw with engineer Anthony Hunt worked ‘entirely at-risk, since the Millennium Commission did not fund feasibility’ studies, records Hugh Pearman. Sir Nicholas Grimshaw observed: ‘The project has held the office in thrall since the moment we got it. The brief was to build the largest plant enclosure in the world, but also to do this in the lightest and most ecological way possible.’


The initial designs resembled Waterloo International (1993) resting on the cliffs left by the extract of China Clay. This developed into a Buckminster Fuller inspired set of domes with a hexagonal geometry. Construction started early in 1999. Grimshaw described the biomes as ‘a sequence of eight inter-linked geodesic transparent domes covering 2.2 hectares and encapsulating vast humid tropical and warm temperate regions.’ Observing the ‘design of the biomes is an exercise in efficiency, both of space and of material. Structurally, each dome is a hex-tri-hex space frame reliant on two layers. The efficiency of the frame relies on the components of the geometric shapes: steel tubes and joints that are light, relatively small and easily transportable. The cladding panels are triple-layered pillows of high performance ETFE foil and environmentally efficient, with maximum surface area and minimum perimeter detailing.’
Fig 6.25 Plan of the eight intersecting Biomes of the Eden Project

Fig 6.26 The geometric basis of the eight Biomes of the Eden Project

Fig 6.27 Section through the Eden Project Biomes

aluminium: flexible and light
light and slender
aluminium: flexible and light

Fig 6.28 The rainforest Biome sheltered by the lightweight ETFE pillows

Fig 6.29 Section through a Biome

Fig 6.30 Openings in the façade provide ventilation, helping to control the internal environment

Fig 6.31 The ‘heart’ of the Eden Project
aluminium: flexible and light

The domes are based on 9-m hexagonal modules each with triple-layered inflated pillow of transparent ETFE foil, secured by aluminium extrusions. Hugh Pearman notes that ‘the ETFE skin represents less than 1 per cent of the [mass] of equivalent glass.’

The combination of extruded aluminium sections securing and supporting inflated pillows of ETFE make the Eden Project Biomes an extreme example of light and slender architecture, minimising the materials needed to form an enclosure and maximising daylight.

At the centre of the plan is an earth-sheltered zone, which contains exhibitions, restaurant and services. The capital cost of the Eden Project was £33 million in 2001. The Biomes officially opened on 17 March 2001 and received almost 2 million visitors in the first year. Eden is now one of the top three attractions in the UK, which charges for admission, and the second most visited destination outside London.
Fig 6.36 The light and slender aluminium framing of the ETFE pillows and steel structure of the Eden Project provides expansive views of the night sky.

‘Work stops at sunset. Darkness falls over the building site. The sky is filled with stars. “There is the blueprint.” they say’ - Italo Calvino, Invisible Cities
Dún Laoghaire Rathdown Lexicon Library & Cultural Centre: Carr Cotter & Naessens Architects, 2014

The fabric of the town of Dún Laoghaire on Dublin Bay, the east coast of Eire, dates from the 1820s. You may know the town by its anglicised name – Dunleary. In the nineteenth century the town grew rapidly due to its large harbour, served by the first railway in Ireland, which opened in 1834.

Dún Laoghaire Rathdown Lexicon Library and Cultural Centre, designed by Carr Cotter & Naessens Architects, is located close to the town centre in an old quarry, from which the granite used to build the harbour’s piers was extracted. The harbour was constructed between 1817 and 1859. The site of the dlr Lexicon looks out onto this harbour across Queen Street. The quarry became a reservoir serving the steamships in the harbour. In 2007, Dún Laoghaire Rathdown County Council selected this site for a new library, cultural centre and enhanced public realm. During 2008, Carr Cotter & Naessens Architects, who are based in Cork, won the two-stage design competition organised by Royal Institute of Architects of Ireland (RIAI). Although controversial, the project survived the recession in Eire resulting from the global banking financial crisis. The Irish Times announced it’s opening on 8 December 2014 with the headline ‘Dún Laoghaire’s controversial library quietly opens its doors’. The local authority had prudently reserved funds for this new civic building. The capital cost of the dlr Lexicon was €29.5million (approximately £23million) in 2014.

The architects found the site to be a neglected pleasure garden encompassing a reservoir. They observed that ‘Moran Park occupies a strategic location in Dún Laoghaire; it visibly demonstrates the natural fault line between the harbour and the town. The old park was dysfunctional; the abrupt changes in level and the walled-in reservoir reinforced the disconnection between the commercial precinct of the town and the harbour. The project was an opportunity to rebalance, and make the park a new centre of gravity that would reconnect these domains.”

Fig 6.37 Dún Laoghaire Rathdown Lexicon Library and Cultural Centre, designed by Carr Cotter & Naessens Architects, viewed from the harbour

Fig 6.38 Carr Cotter & Naessens Architects’ context sketch of the dlr Lexicon
Creating a new public place anchored by a civic landmark, a multi-media library and cultural hub for the whole community, Carr Cotter & Naessens Architects observe; ‘library design has evolved; contemporary libraries are seen as interactive knowledge hubs, a place for public assembly and exchange; this new design paradigm has informed the building design however at heart the building is concerned with universal qualities of space and light, a good public room.’
The dlr Lexicon houses more than just a library; it encompasses a 100-seat theatre, art gallery, café, workshops and meeting spaces. On its opening, county librarian Maireád Owens noted ‘the Lexicon embraces the modern concept of what a library should be, a key community space where all are welcome’.  

Level five:
1. Special collections
2. Void
3. Local studies
4. Community room
5. Information desk

Level four:
1. General lending
2. Void
3. Staff office
4. Information desk
5. Children’s lending
6. Children’s reading

Level three:
1. Lobby
2. Book returns
3. Teenage space
4. Information desk
5. Gallery
6. Workshop
7. Store

Level One:
1. Entrance
2. Café & Ticket office
3. Auditorium
4. Dressing room
5. Green room
6. Backstage
7. Kitchen
8. Coffee room
9. Office
10. Loading bay
Carr Cotter & Naessens Architects combine the form, environmental tectonics and materials of the dlr Lexicon to articulate its civic role and internal life. The carefully considered palette of materials is spare and robust. The plan is structured by a row of concrete piers that become natural ventilation shafts that terminate in a series of roof cowl. This generates two volumes: the southern volume that houses the servant spaces is rectilinear, clad in brick, and continues the scale of Haigh Terrace; and the northern volume facing onto the park houses the public rooms of the library and cultural centre. This is clad in granite, as Dún Laoghaire is a granite town. However, no local quarries were large enough to fulfill this order, thus geologically identical granite was sourced from Galicia.
Services are carefully integrated and a biomass boiler, using timber from the local parks, powers the dlr Lexicon. The principle materials of the interior are a cream white fair-faced in-situ concrete and timber. The exposed 50 per cent ground granular blast slag (GGBS) based concrete provides thermal mass. All public spaces are naturally ventilated. The roof top cowl filter fresh air via house heat exchangers and heated or cooled air is supplied to the floor void for discharge at low level. Louvres located in the V-beam are linked to the Building Management System to exploit the stack effect. Project architect Louise Cotter observes “the building was conceived as a landmark with a minimum design life of 60 years for the components and 100 years for the structure”. The materials selected are low maintenance, however, ease of maintenance has also been designed in to the project.
The change of level across the site of six meters is key to the design of this cultural centre, which can be entered at two levels. At the lower park level is the café/bar and theatre with library administration located behind these spaces. The park level is linked to the street level by internal and external staircases. Street level of the dlr Lexicon accommodates a lobby, book returns and a ‘teenage space’. When the centre is closed the public realm remains linked by the generous external stairs. From the street level of the library the route turns around and the staircase is oriented with the roof that is also rising towards the seashore. The general lending library is located on level four, the ‘piano noble’, with the children’s library, and an almost frameless the ‘sea’ window. The route culminates on the fifth floor and the local studies space, which benefits from the large scaled ‘sea’ window and its views of the harbour. This is the opposite of an Aldo Van Eyck window scaled for the users. This window is a major civic gesture. Louise Cotter notes that ‘as people ascend the building it progressively gets quieter and more tranquil’.25
Daylight is a key quality of the dlr Lexicon. Louise Cotter observed ‘significant design time was expended on working out optimum locations, orientations and specifications’ of the windows and rooflights. The daylight had to be calculated: we modelled the interior of the building, looking at where the sun can in at different times of the day and different times of the year because the windows are a really a critical part of the choreography of the building, it all about light and views really, and also space. The top level, the fifth floor, houses the reference collection, local studies and a community meeting room, here the inclined roof of the dlr Lexicon is formed by V-shaped precast concrete beams. The rooflights are flush with the plane of the roof and made of Schüco FW50+ SG system – a high performance thermally insulated aluminium-framing system. Originally these rooflights had been on the inclined slope of the V-shaped beams, but when the architects modelled this arrangement the daylight was insufficient.
and thus they made the rooflight flush with the roof to maximise the available daylight. As well as daylight, passive solar design was a key consideration in the design of this building, to optimise the amount of energy that can be derived directly from the sun for winter heating, while minimising solar gain in summer to prevent overheating.

Carr Cotter & Naessens Architects prepared a very detailed performance specification for the glazing systems with input from façade consultants Billings Design Associates, founded by Sean Billings. The complete glazing package was won in tender by Schüco; predominately using its thermally efficient aluminium framed glazing systems. The scale of the major civic ‘sea’ window of the library necessitated the use of Schüco Jansen stainless steel sections.
aluminium: flexible and light

carr cotter & naessens
architect’s haigh terrace
elevation, nts

1 roof cowls
2 zinc roofing
3 stone cladding on support system
4 brickwork cladding
5 schueco fw50 + sg window system with inward opening sections
6 bronze anodised aluminium louvres

fig 6.55
carr cotter & naessens
architect’s detailed elevation through the haigh terrace
elevation

1 in-situ concrete structure, 2 bronze anodised aluminium special extrusion transom and fixing brackets, 3 schueco fw50 + sg window system with inward opening sections, 4 bronze anodised aluminium louvres, 5 bronze anodised aluminium cill, 6 stone cladding on support system, 7 fire stopping system, 8 cavity insulation, 9 epdm membrane, 10 oak flooring, 11 trench heater, 12 roller blind

fig 6.56

light and slender
The south east façade responds to the scale of the houses in Haigh Terrace and is a considered composition of bronze anodised thermally broken aluminium windows and zones of bespoke bronze anodised brise soleil shading with inward opening bronze anodised aluminium windows, set in brickwork that is articulated by horizontal bands of stone.

Fig 6.57 Looking out towards Haigh Terrace

Fig 6.58 Carr Cotter & Naessens Architect’s elevation drawing of the construction of Haigh Terrace

1. In-situ concrete structure
2. Stone cladding on support system
3. Schueco FW50 + SG window system with inward opening sections
4. Bronze anodised aluminium louvres
5. Brickwork cladding
6. Timber wall cladding
7. Oak flooring
8. Trench heater
Gary Boyd, writing in the Architects Journal, described dlr Lexicon as ‘an extremely well-worked and considered architectural gesamtkunstwerk – erected in a period of specialisation, austerity, and economic optimisation – it evokes, in almost all of its spaces, an unquantifiable faith in architecture. For Dún Laoghaire and its indefinable hinterlands, it provides not only a library but a beacon for what public architecture can and should be.’

Louise Cotter is justifiably proud of the impact of the cultural centre ‘with over 10,000 visitors a month … and library membership has increased by a third.’ Her practice has contributed to the creation of successful sustainable civic architecture for this Irish seaside town.
Notes
4 The real beauty of the FWS 60 CV façade is what you don’t see, Schüco Partner 01, 2016, Schüco UK, Milton Keynes, p.16.
6 This section has benefited from input by Ron Fitch, Design Manager of Trimo and Justin Furness, Technical Director of CAB.
20 Check Partner p.8 29.5 euros
22 Sourced from CC&N’s unpublished description of DLR Lexicon.
24 New Library and cultural centre is a game-changer for Irish seaside town, Schüco Partner 01, 2016, Schüco UK, Milton Keynes, p.7.
26 Ibid.
aluminium: flexible and light

performative façades
Aluminium: Performative Façades

This chapter focuses on the role of aluminium in creating or supporting performative façades. The first example in the introduction to this chapter is the opaque panels of QbissAir, which uses the reflective quality of aluminium to help create a unitised walling system that provides a very low U-value without conventional insulation products. The introduction concludes with a brief comparison of the pioneering bespoke parametric design of 30 St Mary Axe by Foster + Partners (2004) and Schüco’s parametric aluminium curtain walling system (2015).

This is followed by four case studies, two of which illustrate the performative benefits of double facades: Melvin J. and Claire Levine Hall by KieranTimberlake (2003) and iPADF, an integrated passive and active double facade system (2012), a prototype double façade with distributed services, researched and designed by Dr Aneel Kilaire working with The University of Nottingham Architecture and Tectonics Research Group. Following a case study of the well informed and highly resolved tectonics of 240 Blackfriars Road, London, (2014), by Allford Hall Monaghan Morris, with its crisply detailed unitised aluminium curtain walling. The chapter concludes with the remarkable 360 in Brighton, (2016), designed by Mark Barfield Architects, which uses expanded aluminium cladding to reduce vortex shedding on the this 160.5m tall and elegant tower.

Thus, this chapter incorporates further performative roles for aluminium in the delivery of sustainable architecture and infrastructure or emphasises qualities apparent in earlier chapters. However, the importance of a holistic and collaborative approach to the design and realisation architecture in the twenty first century remains a key theme throughout.

QbissAir is a unitised total wall system designed to maximise the internal floor space of a building by being up to three times thinner than traditional façades, developed by Trimo of Slovenia and launched in 2011. It comprises opaque, translucent and transparent modules, which are designed to self-span between the floor slabs of a building. Each module consists of an inner and outer skin that incorporates internal insulation chambers of still air. The system is designed to be installed from inside the building, eliminating the need for external access. QbissAir is a modular façade system, which demonstrates how the science of thermodynamics can be used to produce a highly insulated product with low g-values and minimum air leakage, whilst maintaining a minimal wall thickness. In other words, it elegantly provides a high performance and low carbon building fabric.
A key feature of the design of QbissAir is its excellent thermal performance, which is achieved by controlling the thermodynamics of the system rather than using solid insulation materials. QbissAir is a range of clear, translucent and opaque modules of identical thickness, which can be installed from inside the building. A QbissAir glazed façade can achieve a U-value of 0.35w/m²k and a G-value of 0.1 at an overall thickness of 133mm. Acoustic performance averages 45db and air tightness is 1.2 m³/m²/hr @50 Pa.

QbissAir opaque façade panels can achieve a U-value of 0.19w/m²k, at an overall thickness of 133mm. It is the reflective quality of aluminium in the form of foil layers that is key to this performance. ‘By using thermodynamics, the development team engineered a solution of internal chambers that reflect radiation, minimise conduction and limit heat transmission. Aluminium foil chambers are used for opaque modules and low-E coated glass is used for clear modules, which also contains inert low conductive gases, such as argon’ observed Ron Fitch, Design Manager of Trimo.²

Also unique to the system is the incorporation of structural members within the modules, eliminating the requirement for a secondary support structure such as a curtain wall. The external skin is normally glass [enamelled, translucent or transparent] but a range of alternative materials and finishes are also available. The system is manufactured using structural glazing technology, therefore no external frames or caps are necessary. QbissAir is offered internally framed by either extruded polymer profiles or extruded aluminium profiles. When installed, QbissAir provides a flush internal and external face with no intermediate mullions or transoms. The joints between modules are sealed with 20mm recessed gaskets.

Fig 7.5 QbissAir unitised cladding system
The first decade of the twentieth first century witnessed the rapid adoption of parametrically designed architecture and building façades. 30 St Mary Axe, London, is a 180m tall, environmentally progressive, office building designed by Foster + Partners, completed in 2004. It is one of the first parametrically designed tall buildings in the world, based on geometry generated by seven tangents rotated through 360°, which results in a gently tapering aerodynamic form. Characteristically of Norman Foster it is also an excellent example of investment in early and experimental design. The development of the parametric modelling benefited from the extended planning approval process on a ‘controversial’ site: the Baltic Exchange was the location of an IRA bomb in 1992.

Although parametrically designed, based on seven carefully chosen tangents, 30 St Mary Axe is a conventionally layered construction, from the planning envelope within which the building could be constructed that is just outside the aluminium curtain walling to the diagrid steel structure. It is clad in 5500 glass panels, which vary dimensionally at each level. One of the aspects of 30 St Mary Axe that remains remarkable is that the doubly curved geometry is delivered by a combination of triangular and diamond shaped panels, thus greatly reducing the cutting and framing required. This is a double façade comprising an outer double glazed unit supported by an aluminium curtain walling, a ventilated cavity incorporating solar control blinds and an inner layer of single glazing. Foster + Partners designed the cavity to act ‘as buffer zones to reduce the need for additional heating and cooling and are ventilated by exhaust air which is drawn from the offices.’ The distinctive spiral bands of grey glazing articulate the internal atria.

30 St Mary Axe is a pioneering, collaborative and bespoke parametric design. Just over 10 years later at Bau 2015, Schüco launched a parametric aluminium curtain walling system combining a high degree of geometric freedom and certainties offered by a well-tested product. Schüco present this system as a risk free route to realising a parametrically designed façade. Many factors can feed into the planning of a façade’s geometry, for example: ‘guided views, optimised daylight conditions, sound reduction or protection against unwanted sunlight.’

Fig 7.6 Seven tangents parametrically define the geometry of 30 St Mary Axe, architect Foster + Partners

Fig 7.7 The openable double glazing of 30 St Mary Axe, is defined by the dark grey tinted glass, architect Foster + Partners

Fig 7.8 The Schüco Parametric Façade System is based on a hierarchy of six basic modules, which can be positioned, edited and combined freely
The University of Pennsylvania’s Melvin J. and Claire Levine Hall establishes a forward-looking character for the School of Engineering and Applied Science, while remaining sensitive to its historic context. Located on a former parking lot Levine Hall stitches together two existing university buildings, Towne Building, architect Cope and Stewardson, 1906, and the Graduate Research Wing, architect Geddes Brecher Qualls Cunningham, 1967, forming a central courtyard and common entrance for the School of Engineering and Applied Science, via Chancellor Walk off 34th Street. The building comprises six floors, with the possibility of adding a seventh floor, housing offices laboratories and meeting space for the Department of Computer and Information Science and a 150-seat auditorium. Levine Hall was designed by KieranTimberlake to maximise long-term flexibility and has a 4.27m (14') floor to ceiling height.

The footprint and massing respond to adjacent buildings, with particular attention to scale and fenestration. The building is articulated as a glazed pavilion presenting luminous, transparent façades to the campus. This strategy allows daylight to be maximised on a dense, urban site, and provides visual interconnections between the life of the campus and life within the building.

KieranTimberlake’s section through the aluminium framed active double façade of Melvin J. and Claire Levine Hall
Fatima Olivier of KieranTimberlake reflecting on the design and life of the project in 2014:

‘A present-day view of Levine Hall from Chancellor Walk makes clear that the building met more than its programmatic requirements; it also set the tone for further development of the precinct. In line with Penn’s tradition of internal pedestrian walks, Chancellor Street, once a city street and later a service corridor, has transformed into a pedestrian path terminating at Levine Hall’s glass façade, enriching the passage between 34th and 33rd streets with a series of interior and exterior public rooms. The walk is now a hub of activity, with students passing to and from class, gathering on benches, and studying on sunny days. Students from different departments use the lobby of Levine as a cut-through, and meetings, bake sales, and study groups take place there throughout the day.’

The west and main façade of Levine Hall incorporates a pressure-equalised and ventilated aluminium curtain wall system, which provides maximum views and day lighting with substantial energy efficiency and interior comfort. Key components of the ventilated system are a double glazed, pressure-equalized unit on the exterior, a single glazed unit on the interior, with air continuously ventilated through the cavity between them. Blinds are housed in the ventilated cavity and are fully adjustable allowing for shading or visibility. Housed in the cavity the blinds should require very little maintenance.

This active double wall was developed by close collaboration between KieranTimberlake and façade specialists Permasteelisa and delivered as bespoke unitised factory glazed aluminium-framed units to rapidly and precisely deliver the façade. It is the first use of an active double glass façade in the USA. KieranTimberlake’s design intent has been achieved: ‘The use of ventilated curtain walling technology allows the use of large expanses of glazed exterior wall surfaces, providing abundant natural light an views, while providing interior comfort and modest energy consumption.’

Double skin facades, as seen in the St Georges Wallasey (1961), Levine Hall (2003) and SIEEB (2006) case studies offer a route to the creation of low energy, low carbon architecture, whilst improving the comfort condition of the occupants. The specific typologies studied by Aneel Kilare in his thesis research were medium to high-rise office or mixed use buildings, in urban locations. The challenge addressed in this research is the integration of services into a double façade to enhance its performance as an environmental filter. Thus reducing the energy requirements and operational carbon emissions, reducing the plant area required and lowering the floor-to-floor height required. Whilst increasing constructional quality by prefabrication, beyond just the unitised façade. Furthermore creating a positive aesthetic, providing visual amenity and comfort for the occupants. A vital element of this research is the importance of the well-being and productivity of the workers in contemporary offices to the success of their organisation.

This challenge was addressed by research, design and production of a full-scale prototype double façade. Following background research and consultation, the design strategy adopted was first to implement all possible passive options for environmental control and then integrate active techniques as necessary, which resulted in an Integrated Passive and Active Double Facade system (iPADF). The project’s overall aim is to provide a specifiable product with a range of design options for the UK and northern European office market. iPADF involved the research, design and development a product range that could be deployed in the construction of sustainable cities. The route to achieving this was collaboration with key participants of the construction industry supply chain. The iPADF prototype was developed as part of a CASE PhD funded by United Kingdom ESRC and Buro Happold and the Architecture and Tectonics Research Group of The University of Nottingham.

The basic elements of the iPADF system are: a unitised aluminium curtain walling comprising an outer skin of low-E double glazing, air cavity with operable and retractable blinds, openable single glazed internal skin, with an overall façade depth 300mm. The integrated services include: a reversible air-source heat pump, refrigeration unit and active chilled beam.

Natural ventilation is provided on a storey by storey basis with aluminium louvres at slab level, at a low level to ensure outside air is brought in which has not had a chance to heat up in the cavity, with exhaust below the next slab or ceiling level. The internal skin is openable for ventilation as well as maintenance. To prove the effectiveness of this opening configuration computational fluid dynamic (CFD) simulations were carried out, which confirmed the concept. The heating and cooling is provided by a reversible air-source heat pump, which provides 3-4kW of heating or cooling for every 1kW of electricity. This is linked to an active chilled ceiling beam and backed up by a trench heater (although this item may prove unnecessary). The distributed approach to the services enables the zonal control by occupants and or a Building Management System.
The full size prototype was developed and fabricated in collaboration with Schüco, Crown Aluminium and Frenger Systems. The prototype had a dimensionally coordinated width of 2400mm and a height of 3100mm responding to the floor-to-floor dimension identified. To build the prototype, on a tight research budget, where possible off-the-shelf products were specified and adapted as necessary. An existing Schüco unitised curtain walling system was used, which accessed the development and testing already carried out by this systems house. The major change was the use of an inner and outer mullion, as shown in Figure 7.16. A further iteration of the design of iPADF would optimise the quantity of aluminium used, as the roles of the two mullions are not identical and could be replaced by a single thermally broken aluminium extrusion.

Fig 7.16 Horizontal section of the iPADF prototype showing the double mullions

The prefabrication of the unitised aluminium framed double façade was developed with the fabricators Crown Aluminium, and its Managing Director Roger Philips in particular. Aneel Kilaire, following training with Schüco and under the guidance of Crown Aluminium, undertook the fabrication himself – a rare example of learning by doing as part of a PhD Thesis. The overall aim of iPADF is to fully prefabricate the curtain walling and the integrated services, for the prototype, the air source heat pump and refrigeration unit were a plug in module and the active beam was a declared component in the room, which could be integrated with LED lighting.

Fig 7.17 The fabrication of the iPADF prototype at Crown Aluminium by Aneel Kilaire
The prototype was assembled and tested at The University of Nottingham. The iPADF was tested and evaluated in terms of the comfort, weather and aesthetic performance. This testing predominantly focused on airflow and the performance of the services components, however, a Centre for Window and Cladding Technology (CWCT) on site weather test was also performed. As part of the research, feedback on the prototype was sought from quantity surveyors, architects, students and maintenance engineers. The responses included that the depth of the double skin at 300mm, was considered comparable with a well-insulated wall and therefore would not affect the gross to floor area ratio of a project. An even greater level of design integration was the response of many viewers to generate a specifyable product, noting they were inspecting the first prototype.

The evaluation of the iPADF prototype revealed that the integrated and distributed services would save almost 50 per cent of the plan area needed for mechanical and electrical services. The omission of a ceiling void provides a saving of façade area of over 12 per cent – an additional floor in a 25m high office building, which can be scaled up as required. In essence achieving more, while using fewer resources. The energy intensity of the iPADF system is calculated as 2.25kWh/m² representing an energy saving of 92.5 per cent when compared to centralised plant.

One of the potential barriers to the adoption of systems such as iPAF is the need to break down barriers between specialist subcontractors with mechanical & electrical and façade specialists working together, which is already happening in the field of the integration of photovoltaics into façades.

The iPADF has been successfully progressed to ‘proof of concept’ stage. It has integrated the functions of heating, cooling and fresh air in both a passive and active way to avoid the need for centralised plant and enable greater space efficiencies. Enhanced occupant comfort for inner-city medium to high-rise offices has been provided by giving occupants maximised external views, daylight, natural ventilation and improved thermal control. The energy and carbon dioxide emissions have been reduced by providing natural ventilation, a dynamic skin, reduced distribution losses, improved zonal control and low carbon heating, cooling and fresh air supply and delivery.

The success of the iPADF project in part led to the construction of a Prototyping Hall in the Energy Technologies Building on the Jubilee Campus of The University of Nottingham. Named the Wolfson Prototyping Hall, when it opened in the autumn of 2012. This 400m² facility has a clear height of 9m. It has been designed to enable the full scale testing of façades and other building elements, with a further 200m² of external hard standing for real time weather and daylight tests.
This recent contribution to the cityscape of London is a 20-storey crystalline commercial volume and a smaller six-storey masonry clad residential block. Haydn Thomas of Allford Hall Monaghan Morris (AHMM) describes how ‘240 Blackfriars Road defines the skyline at a pivotal junction of road, rail and river at the south end of Blackfriars Bridge.’ It provides over 21,132m² of high-quality workspace above ground-level retail units and a new public realm, together with ten residential units in the adjoining brick clad six-storey volume, at a capital cost of £70million. This mixed-use scheme replaced a collection of low-rise unprepossessing and dilapidated light industry and office premises on the Blackfriars Road.

The design development of the crisp crystalline form of 240 Blackfriars Road was undertaken by AHMM beginning in 2005, having gone through a number of iterations, the final 20-storey design is a response to the context and key sightlines including...
St Pauls Cathedral, yet achieving occupancy levels above the British Council for Offices norm. The plan form is very efficient with the servant spaces of; lifts, service voids, escapes stairs and washrooms, all located as a single block, occupying most of the east façade. Above the central entrance atrium the offices form generous spaces that can be open plan from the south to the north façades. The building is topped by a triple height ‘sky-room’, behind which is the plant room.14

AHMM describe the form as being ‘inspired by the strength of natural geological forms, the basic 90m tall trapezoidal extrusion is cut four times to respond to its context: to the south to minimise the impact to Ludgate House; diagonally to the north to orientate the building towards the river and city; at street level to add generosity to the public realm; and across the roof to create a reflective triple-height ‘sky-room’.115 The 90m high office tower of 240 Blackfriars Road, completed in 2014, is a crisp and elegant contribution to the central London skyline and cityscape.

For the top floor of 240 Blackfriars Road, AHMM inventively resolve one of the recurrent dilemmas in the design of tall buildings – where to house the plant room? Mechanically the efficient location is the top of the building making the access to free air for exhausts and flues very simple and direct.

Yet typically this is the most attractive and valuable space created in this form of architecture. Following the language of sculptural cutting of the form of 240 Blackfriars Road, AHMM divided the 19th floor in two, the north and west side of the plan is the triple height sky-room, which is a function room, a celebratory ‘town-hall’ space with sweeping views across London. The east and south part of the plan is the plant room. On the roof of the plant room is a 9kW photovoltaic array comprising 40 panels. 240 Blackfriars Road is predominately a concrete framed structure that utilises post tension concrete slabs, only 275mm thick, combined with a low profile raised floor, and chilled ceiling with LED lights, in a 350mm service zone to achieve an efficient floor-to-floor height, which created an additional one and half floors when compared to a conventional steel frame. The design and coordination of the project was delivered by the use of a Building Information Model (BIM) from RIBA (2013) Plan of Work Stage 4 (Technical Design). AHMM extensively used prefabrication to ‘minimise site waste, increase quality and reduce the construction programme on site. These items included the unitised curtain cladding system, washroom fit out components and three storey high mechanical riser installations.’114

This office building is completely clad in high performance argon filled double glazed units, predominately in the form of silicone bonded unitised aluminium curtain walling providing a flush outer surface and crisply detailed edges – delivering the desired crystalline form. The unitised aluminium curtain walling is set out on 1.5m grid. Solar control is achieved via ‘pinstripe’ fritting and a solar control layer on surface 3. On the sloping north façade, which is visible from the Thames, the fritting is omitted to maximise daylight and views of the city. Throughout the building envelope only glass-to-glass junctions are used contributing to the tectonic crispness of the project. With the exception of the corner-to-corner junctions arising from the projects crystalline form, here black anodised aluminium extrusions were introduced to provide edge protection whilst retaining the sharpness of form and detail. The aluminium extrusions of the curtain walling and roof glazing are the largely unseen helping ‘hands’ of the building envelope. Other aluminium components include the internal shadow boxes at slab level and the aluminium louvres to the plant room at the top of the east elevation. The rainscreen glazing to service cores on the east façade has an additional 80 per cent dark grey frit to the inner face of the glazed unit to maintain visual consistency throughout the curtain walling.
Whereas the aluminium framed curtain walling is fully unitised to facilitate precision and speed of erection. The roof glazing was installed as a ‘stick’ system to accommodate deflections and to ensure drainage continuity. In the sky-room the glazing sections are supported by bespoke steelwork and fixed via silver anodised brackets with countersunk stainless steel bolts. AHMM considered this component to be key and a highly visual part of the roof assembly. To enhance the solar control of the roof glazing, a 45 per cent chrome frit is used to reduce glare while maximising daylight and views of the sky above.

The air leakage rate through the façades was limited to 1.5 m³/hr. This combined with a U-value of 1.4 W/m²K, effective solar control and other measures, some of which are listed above, created a good energy balance in the building fabric of 240 Blackfriars Road. This achieved a 28 per cent improvement on England and Wales Building Regulation Part L 2010 and achieved an Excellent rating under BREEAM 2011.

The building envelope was fabricated and installed by Scheldebouw, who worked closely with AHMM via a process of mock-ups and prototypes in its factory in The Netherlands. This included the design development of a discreet fail-safe mechanical restraint system for the sloping silicone bonded aluminium framed curtain walling.

240 Blackfriars Road is an excellent example of a twenty first century project for a ‘commercial client’, Great Ropemaker Partnership (with Great Portland Estates leading the development on behalf of their joint venture partner), which the architect and design team have thought through in considerable detail and at every level, including: the crisp aluminium framed curtain walling, well informed design of the concrete elements to the tectonic of the internal fit out.

In Brighton on 4 August 2016 the first “flight” of the British Airways i360 took off. Designed by Julia Barfield and David Marks, architects of the London Eye (2000), it is a vertical pier located at the entrance to Brighton’s old West Pier, which opened in 1866, fell into disrepair in 1975, and burnt down in 2003. It follows on from the London Eye, which they invented and designed as a temporary celebration of the millennium. The London Eye is a 132m high Ferris wheel with 32 pods, completed in 2000, is now a permanent landmark on London’s skyline, visited by over 4 million people annually.

Although the i360 shares “DNA” with the London Eye, it has been tailored to work successfully as a regional attraction within a seaside city. Brighton and Hove has a population of over 280,000 people, with about 10 million tourists visiting the city annually. The i360 is a vertical cable car with a single pod that has a capacity of 200 people. It has been designed as a venue, a destination and a symbol of renewal.

The i360 tower is 162.4280m high, measured from the Ordnance Datum, and only 3.9m in diameter. It is officially the slimmest tall tower in the world, with a width to height aspect ratio of 1 to 40. To reduce vortex shedding on this elegantly slender tower Marks Barfield Architects has clad it in expanded anodised aluminium.
During a flight in the i360, up to 200 people rise 138m above the Brighton seaside in a glazed doughnut like pod. This description does not do justice to the elegance of the pod designed by Marks Barfield Architects in collaboration with POMA and the only way to fully appreciate the collective experience of rising gracefully above the townscape and seashore of Brighton is to ride the i360.

Marks Barfield Architects, who conceived and designed the i360, and remain a financial stakeholder in the project, had to wait out the recession arising from the global financial banking crisis for work to start on site in the summer of 2014 – despite the project receiving planning permission in 2006. The construction cost of the i360 on completion was £37 million. To deliver the i360, Marks Barfield Architects in essence reassembled the core team from the London Eye, Hollandia for the prefabricated steelwork and the POMA for the pod. David Marks described Hollandia as a world leader of prefabrication in steel, following an inspection of Maeslantkering storm surge barrage at the Hook of Holland, as part of the process of Hollandia’s selection to fabricate the steelwork of the London Eye.

The engineer of the i360 is John Roberts (B&A i360’s chief engineer). The in-situ concrete foundations of the i360 are 3m deep and 25m square to support the vertical cantilever of the tower. This steel tower was prefabricated by Hollandia in its works at Krimpen aan den IJssel, the Netherlands. The high-grade steel was roll formed by Sif and then welded into vertical tubular sections known as cans, which are coated in zinc rich primer and three layers of marine specification paint.

The tower is formed of 17 steel cans, which are a combination of 6 and 12m high, and were progressively jacked into place. Each can was installed at the bottom, with the preceding cans being hydraulically jacked up. The steel in the tower weighs about 30 tonnes, and was bolted together using 1336 stainless steel bolts.

Once prefabricated by Hollandia, the cans were sailed to Brighton by barge and beached on a specially prepared landing area on the foreshore at the site of the old West Pier. All the cans were fully prepared to receive the expanded aluminium cladding, with cladding rails already in place. The top two cans were installed fully clad. The tower was then clad from the top down.
The single pod is counterbalanced by a weight inside the tower, which is slightly lighter than the pod itself. A cable draws down the counter weight and the pod rises. On the return journey to the ground, 50 per cent of the energy used is harvested by regenerative motors. With the cable passing over a pulley wheel at the top, the i360 is a distant echo of the coalmine pitheads that were once commonplace in many parts of the British landscape, until the 1980s.

The glass pod fabricated by POMA in France, has the feel of a Dan Dare spaceship or flying saucer, an elegant observation deck, which one can walk around and enjoy the full 360° panorama. 18 m in diameter, the geometry of the pod is an oblate ellipsoid, an ellipse rotated through 360° about its minor access, with a cylindrical hole through its centre. The pod is supported by a red painted steel chassis comprising: four masts, a large ring beam supporting the floor structure of the pod and a smaller I-section top ring beam, which picks up the internal structure of the pod. Each of the four masts are linked to the counterweight inside the tower by a high tensile steel cable, which are located behind the expanded anodised aluminium cladding. The masts are equipped with a set of spring loaded guide wheels that run on the steel structure of the tower. The pod is structured and clad in 24 radial segments, the lower ring beam fixes up the cantilevered steel floor structure, the glass is supported by 48 polyester powder coated steel sections, which span from the floor to the upper ring beam. These sections, or ribs, taper towards the top and are elegantly lighted by extended circular cut-outs. For precision, and to speed up assembly, the doubly curved glazed units are unitised with independent steel framing. The tapered ribs are bolted together inside the pod. The red chassis structure is only glimpsed through the inner cylindrical glazing of the pod, which will allow the travel or flight up and down to be calibrated via the visible passage of the 2m-high cladding panels. The floor void houses all the heating, ventilation and air conditioning (HVAC), audio-visual and safety systems of the pod, powered via two bus bars on the tower next to the east and west guide ways.

The pod is glazed in doubly-curved, double-laminated double glazing. The outer surface of the glass incorporates a permanent self-cleaning treatment (the pods of the London Eye are only single glazed). The double glazed units, which comprise a laminated outer pane, a sealed air gap and laminated inner pane, were produced in Italy by Sunglass, using bespoke and patented moulds. As the glass is heated in the moulding process it can be considered to be heat strengthened, but not toughened.

However, the size and details of each pane had to be predetermined, as it is not possible to cut or drill this type of glass after moulding.

The soffit of the pod is also glazed in 24 segments. Here the outer pane of glass has been fully mirrored on surface two. Ian Crockford, Project Leader for Marks Barfield Architects, described “the spectacular iris like effect of watching the pod ascend the tower from the entrance deck level, created by this curved mirrored surface.”

On completion of the glazing of the pod on site in Brighton, 14 January 2016, Julia Barfield observed: ‘This is an extremely important moment for us. The pod is completed and it looks stunning. The fluid form of the glass sits beautifully in its beachfront setting and the mirrored underside will cast reflections of the naturally shifting shapes of the sea and sky.’ David Marks commented: ‘It is incredibly exciting to see the pod finally take shape on the tower. The team from POMA have done a remarkable job, both in terms of the craftsmanship of the handmade pod as well their skilful and swift assembly.’

![Fig 7.32 The Pod of the i360, photographed April 2016](image)
The two-storey podium building and its central circular void are both clad in clear glazed silver anodised aluminium curtain walling installed by Fill Metalbau, using aluminium I-beam mullions. The two original ticket booths of the West Pier have been faithfully reconstructed with a cast iron outer skin; cast by the Swan Foundry of Banbury. A visitor to the i360 enters at the level of the seaside promenade and having risen and returned from 138m, leaves the pod at lower ground level, effectively the top of the beach. This space will house a brasserie, café, tearooms, exhibition, kids soft play zone and shop, some of which will spill out on to the beach.

Fig 7.33 Inside the i360 pod during construction, photographed April 2016
The tower is clad in 5mm thick expanded aluminium, which is finished in 25μm silver anodising in accordance with BS 3987:1991. Expanded with the ‘Bilbao’ pattern from a bespoke aluminium grade 151EX sheet, which combines good ductility for expanding and anodises well. This was supplied to the Expanded Metal Company by James & Taylor who coordinated the cladding, which was installed by Hollandia. The expanded aluminium cladding panels were roll formed to the desired radius and are 2m high with a radial panel width of 3.2m. The anodised aluminium panels, with periodic cleaning, should prove durable for the complete design life of this project, despite the marine location. Although each large format expanded sheet is light enough to be readily carried by four people, weighing approximately 10kg/m², almost 20 tonnes of aluminium were used to clad the i360, covering an area of just over 2000m². One advantage of working with expanded metal to create façade panels is that there are no off cuts produced when processing the sheet material, unlike perforating sheet metal with a punch tool.
The fixing detail of this cladding is shown on site at the base of the tower in Figure 7.38. The anodised expanded aluminium cladding is supported by hollow tee section aluminium extrusions, which incorporate a fixing channel. These cladding rails are fixed back to the steel tower via rowlock like u-shaped steel fabrications, which are bolted to cleats welded to the tower. The potential for bimetallic corrosion, between the aluminium cladding rail and the steel subassembly, is avoided by polymeric isolators.

All structures have a natural vibration frequency, which is a product of its slenderness ratio and the stiffness of the structure. The i360 tower has three modes of oscillation, which are the three lowest natural frequencies of vibration this tower will respond to. The starting point to eliminate the risk of wind-induced vibration was the specification of the expanded aluminium cladding to minimise vortex shedding.

Ian Crockford described ‘the expanded aluminium cladding is a key part of the damping strategy, the surface roughness and air flowing through the cladding disrupts the wind speed thus minimising the vortex shedding on the leeside.’ The design team did not consider it necessary to wind tunnel test the cladding, based on the expert advice of Professor Max Irvine from Sydney, Australia, on the minimisation of vibration risks on the extremely slender tower. The tower is also fitted with three types of liquid filled dampers, each tuned to one of the vibration modes. The dampers were fabricated in New South Wales and were fitted in the steel cans in the Netherlands and the pod in France. In total over 50 dampers have been fitted to the tower, with a further eight located in the pod.
Aluminium was selected for the cladding in competition with grade 316 stainless steel, the role of the cladding is described by Ian Crockford as “a transparent veil combined with its performative function”. The expanded panels with their many edges and the coastal location convinced Marks Barfield Architects that anodised aluminium was the better option. Knowing that the cladding will need to be washed on a regular basis, the tower is crowned by a circular rail to support abseilers.

The expanded aluminium minimises the vortex shedding and thus limits the possibility of vibration in the i360 tower. The anodised expanded aluminium cladding creates a gentle visual softness to this monumental tower. Like Stirling and Gowan’s Leicester Engineering Department Tower (1963) the scale of the i360 is difficult to discern, except this time it is taller than many views suggest. Perhaps this will enhance the experience of riding in the British Airways i360.
aluminium: flexible and light

Notes
10. KieranTimberlake’s Project Data Sheet for Melvin J. and Claire Levine Hall supplied to the author in 2009.
13. Haydn Thomas of AHMM speaking, as one of the 16 architects who contributed to the CAB Thames Journey, 1 October 2105, recorded by the author.
15. Ibid.
16. Ibid.
17. Data provide by Haydn Thomas, Project Architect at AHMM, U-values for other elements on this project: inclined overhead roof panels, $U_{ow}$ value 1.8W/m$^2$K, and Rainscreen panels, $U_{ow}$ value 0.3W/m$^2$K.
21. Data supplied by Marks Barfield Architects to the author, September 2016, noting that this construction cost does not includes fees, interest and other related project costs.
23. Iain Crockford in conversation with the author on site in Brighton 13 April 2016.
25. Ibid.
28. Ibid.

Fig 7.43 The i360 Tower viewed from the Brighton foreshore
Aluminium: Servant of Sustainability

Throughout this report the contribution of aluminium in creating sustainable cities, architecture and infrastructure is demonstrated by quantified case studies that serve humankind well. Many of the projects, such as the overcladding of Guy’s Hospital, are examples of low carbon architecture; in this particular case the pay back period of its embodied carbon is under 13 years. Other case studies demonstrate the durability and long-term service of aluminium-based projects. This chapter focuses on the role of aluminium in delivering and integrating renewable energy into architecture and infrastructure. Aluminium is the first choice material for the support of photovoltaic panels as demonstrated in the three case studies, with a related large-scale infrastructure example, set out below.

In Europe a photovoltaic panel will generate enough energy to offset the embodied energy of its manufacture in about one and half years to two and half years, largely dependent whether specified in southern or northern Europe respectively. Remaining efficiently operational for the subsequent 30 years, if washed on a seasonal basis. However, there appears to be a clear need for more research into the long-term durability of photovoltaic panels, especially when integrated into a facade system. Therefore, disassembly and replacement should be designed in from the outset in a photovoltaic installation.

A good product based example of aluminium, as a servant of sustainability, is Bauder’s Biosolar roofing system, which combines a complete roof of photovoltaic panels with extensive vegetation, whilst maximising the output of the photovoltaic panels. This system comprises a moulded polymer base to which a framework of aluminium extrusions is fixed, that in turn supports a photovoltaic panel above the roof, at the optimum angle for generating solar electricity. The system is ballasted by the growing medium and extensive vegetation. Typically no fixings are required, thus avoiding the complications of fixing details through a waterproof roofing membrane, thus minimising cost and risks of leaking. This makes the Biosolar roof system cost effective and typically it can be retrofitted to existing roofs without any need for structural modifications.

The electrical output of the polycrystalline photovoltaic panels are increased by the cooling effect of the vegetation and the water retained in the substrate, aided by the free passage of air below the panels. Research undertaken by Bauder in Germany shows that the panels should generate 6 per cent more electricity.

Collectively, humankind has the means of cost effectively creating low carbon, carbon neutral and energy positive architecture, which both tackles the risk of climate change and mitigates the risks of increased summertime temperatures. Aluminium can appropriately be described as a good servant of sustainability.

Designed as a striking contribution to the urban landscape of London, this inventive tower of glass, stainless steel and aluminium is a prototype for an environmentally responsible and responsive building. It was built to house a surge pipe on Thames Water’s drinking water ring main; an unseen marvel of hydro engineering serving all of London. The tower was designed by Brookes Stacey Randall Fursdon, in collaboration with students of the Royal College of Art, Damian O’Sullivan and Tania Doufa. The tower celebrates an otherwise invisible engineering achievement, with an amplified electronic barometer in the centre of Holland Park Roundabout, London. The 15m-high tower has a base housing the services, a smooth column of glass, and a capital formed by the solar array. Blue water appears to rise up the tower, layer by layer, in response to climatic conditions and then fall again in times of low air pressure. ‘The approach to the design of the structure and enclosure is one of increasing sophistication as it rises up to the tower to the solar vane’, observed the Editors of VIA Arquitectura. Who continue: ‘The Thames Tower is a working model of a responsive building. In the design of the tower the architects sought to detail the complete assembly in such a way that the play of light is encouraged as it strikes and penetrates not only the glass and water but also the polished surfaces and components within the tower to create a visually poetic effect’.
aluminium: flexible and light

Fig 8.8 Brookes Stacey
Randall Furseon’s initial
perspective sketch of
Thames Water Tower

Fig 8.9 The precise curved
toughened glass cylinder
of the Thames Water Tower
crowned by a
poly crystalline solar array

Fig 8.10 Thames Water Tower,
sketches of effective
communication

Fig 8.11 Shepherd’s Bush roundabout at dusk
**Fig 8.12** Thames Water Tower, initial structural design

**Fig 8.13** Thames Water Tower, initial design of the sprayed water system

**Fig 8.14** The sprayed dyed blue water inside the Thames Water Tower
The project was realised through the research and application of new technologies. The tower is clad with sophisticated, purpose-designed suspended glazing supported by bespoke stainless steel sand castings. All water is fully recycled within the tower. The Thames Water Tower was built by main contractor J. Murphy, for a capital cost of £500,000, using a non-adversarial partnering contract, New Engineering Contract, Option 3.

Fig 8.15 (below left) Brookes Stacey Randall Fursdon’s tender drawing showing an automated solar vane open and closed

Fig 8.16 (below) Tender elevation drawing showing closed solar vane

Fig 8.17 As-built plan of the fixed solar vane, aluminium mast and support structure with access deck and glass roof below
The polycrystalline solar cells of the vane assembly generate energy to power the barometer’s pumps. The solar cells are supported by an elliptical aluminium extrusion that is refabricated and welded to form a curve in elevation. Aluminium arms reach out top and bottom to support the solar cells. The assembly was fabricated by Proctor Masts, who typically fabricate yacht masts. The aluminium is finished in 25μm of dark grey anodising to BS 3987:1991 by LTH Anodisers, now part of United Anodisers. The solar array is topped by a lighting conductor. Building Magazine observed ‘aluminium was used as it offered advantages of ease of fabrication and a high strength-to-weight ratio’, quoting the author ‘the mast was designed and specified to utilise the characteristics of durability and potential malleability inherent in aluminium extrusions’.

The Thames Water Tower was tendered with a solar vane that automatically opened for daylight hours and closed at night when it was not functioning. This design option had to be dropped due to the tight timescale of the project, in line with the completion of the Thames Water Drinking Water Ring Main, and not due to cost constraints. Thus, although a specialist subcontractor responded to the architect’s inquiry eventually, Brookes Stacey Randall Furdon had to design the fixed solar vane that tops the tower in order to meet the completion date.

It was the first public building in London to be powered by photovoltaic. The Thames Water Tower demonstrates engineering excellence and contributes to London’s public realm. It received a RIBA Award and the judges stated ‘such is the inspirational nature of the tower that the panel felt its qualities transcended the question, is it sculpture or architecture?’

Fig 8.18  Maintenance is an essential part of sustainability

Fig 8.19  Thames Water Tower solar vane in moonlight
On the Queen Elizabeth II reservoir at Walton-on-Thames, England, Thames Water has built a ‘solar farm’ of 23,000 photovoltaic panels, with a 6.3MW peak output, generating 5.8million kW per year - enough to power about 1,800 homes, using a Japanese system. It was completed in March 2016.

Construction began in 1959 and was completed in October 1962, at 122m the CIS Tower was the United Kingdom’s tallest building. Built as an expression of the progressive approach of Co-operative movement, it still houses the Co-operative Banking Group. It was designed by G. S. Hay Chief, Architect of the Co-operative Wholesale Society, with Gordon Tait of Sir John Burnett, Tait & Partners. The office tower is 118m tall, with 26 storeys, and accommodates 2500 Co-operative insurance workers, consolidated from disparate buildings in Manchester. The project cost £4 million in 1962.

The CIS Tower was listed Grade II in November 1995 by English Heritage (now Historic England). This listing states “it has a strikingly elegant and sophisticated design inspired by Skidmore, Owings & Merrill’s Inland Steel Building in Chicago (1956-8), which together with its imposing scale and massing, is highly successful in conveying, as originally intended, the status and prestige of the CIS and the wider Co-operative movement, and the strength of the financial community within Manchester.” This listing also observes that both named architects designed other building in England, which are now listed.

The design of the tower was inspired by the work of Skidmore Owings & Merrill and in particular a visit by the client, Robert Dinnage, and the architects to the Inland Steel Building in Chicago. The crisp composition of the CIS Tower comprises a 26-storey office tower, 28-storey service tower and 5-storey podium. The office tower is steel framed and clad in a clear glazed curtain walling, with articulated I-section anodised aluminium mullions and black vitreous enamel spandrel panels. The materials were selected to resist the highly polluted atmosphere of 1960s predominately industrial Manchester. The articulated service tower houses 28 storeys and is 122m high, clad entirely in 14 million one centimetre square grey Italian mosaic tiles (or tesserae), which started to fall off shortly after the completion of the building, due to adhesion failure and lack of expansion joints in the concrete substrate.

In 2005 the service tower was overclad with photovoltaic panels manufactured by Sharp Electronics and supplied by Solar Century, under the design direction of Arup. At the time it was the largest building-integrated solar array in Europe, generating over 180,000kWh of electricity annually. The removal of the mosaic tiles and the installation of the photovoltaic panels, which generate electricity and protect the tower’s building fabric from the weather. This project demonstrates the potential for cost effective and environmentally responsible refurbishment of dilapidated existing buildings.

Generating an estimated annual saving of over 100 tonnes of CO₂ emissions. Solar Century worked with Pluswall to design an aluminium framing system to integrate the installation of the 7,244 photovoltaic panels, which generate electricity and protect the tower’s building fabric from the weather. This project demonstrates the potential for cost effective and environmentally responsible refurbishment of dilapidated existing buildings.
Sino-Italian Ecological & Energy Efficient Building (SIEEB), Beijing, China: Architect Mario Cucinella Architects, 2006

Beijing’s Sino-Italian Ecological & Energy Efficient Building (SIEEB) is the result of a co-operation between Italy and China. It represents a platform to develop bilateral long-term collaboration in the fields of energy and environment and showcases the potential for reducing CO₂ emissions from the building sector in China. The SIEEB is located on the Tsinghua University campus, Beijing, and was designed by Mario Cucinella Architects and the Politecnico di Milano. It houses a Sino-Italian education, training and research centre for environmental protection and energy conservation. It has a floor area of 20,000m² in ten visible storeys and two basement levels. Overall it is 40m high. The public part of the programme is housed on the ground floor and the first basement, including a 200-seat auditorium, main hall and exhibition spaces. The lowest basement level is car parking.

The offices and laboratories are located on the upper nine floors in a u-shape plan, which progressively and symmetrical steps back to allow the sun to penetrate the heart of the plan, which is a landscaped courtyard. The stepped south façades are further enlivened by cantilevered structural elements on which photovoltaic panels are mounted, extending to the south providing shade to the terraces and curtain walling. These assemblies carry 95 photovoltaic panels on each side of the courtyard, with a total nominal peak power of 19.95KWp. This building optimises the production of solar energy in winter and solar protection in summer.

This project is the result of an integrated design process with collaboration between architects, consultants and researchers, a key issue in the design of green buildings. The underlying philosophy combines sustainable design principles and state of the art technologies to create a building that responds to its climatic and architectural context. The design uses both active and passive strategies, through the building’s shape and architecture of its envelope, to control the external environment in order to optimise the comfort and conditions of its internal environment. The building design has been assessed through a series of tests and computer simulations of its performance in relation to its possible shape, orientation, envelope and technological systems to find a balance between energy efficiency targets, minimal CO₂ emissions, a functional layout and the image of a contemporary building. The SIEEB building takes shape from an analysis of the site and of the climatic conditions of the city of Beijing.
The aluminium curtain walling system is a vital component in delivering this holistic architecture. The building is closed and well insulated on the northern side that faces the cold winter winds and is more transparent and open towards the south. On the east and west sides, light and direct sun are controlled by a double skin façade that filters solar gain and optimises the penetration of daylight into the office spaces. As shown in Figure 8.25 this includes bouncing daylight deeper into the office by the use of aluminium light shelves. Artificial lighting in these offices can be controlled both electronically and manually. The double façades facing the courtyard are shaded by laminated glass louvers comprising an 8mm outer pane with PVB interlayer and a 6mm inner pane. The inner skin of the double façade is an aluminium based curtain walling with 8-16-8mm double-glazing units providing a U-value of 1.4W/m²K. The curtain walling systems were fabricated by Permasteelisa and the photovoltaic panels were manufactured by Epitechnologie.

The envelope components, made of extruded aluminium, as well as the control systems and the other technologies are an expression of the most up-to-date Italian production methods, within the framework of a design philosophy in which proven components are integrated into innovative systems of:

- Resource-use minimisation, including construction materials and water;
- Minimisation of environmental impact in both the construction and in-use stages;
- Intelligent control during operation and maintenance;
- Photovoltaic with a combined heat and power system;
- Improved air quality;
- Environmentally sound and durable materials;
- Water recycling and re-use.
The centre of the plan is a courtyard garden generously planted with bamboos and surrounded by water. The two-storey opening in the north façade and the open form of the building ensures this is visible from the surrounding streets, inviting the general public into this environmental institute.

The use of a combined heat and power plant in conjunction with the photovoltaic panels enables SIEEB to sell energy back to the grid in Beijing. Mario Cucinella Architects seeks to reduce the carbon footprint of all the projects it designs. Mario Cucinella attributes 17 per cent of the carbon savings to technology and 36 per cent to the design of the architecture. 

SIEEB is a green building, combining biodiversity and power generation.
Fig 8.30 SIEEB, Beijing, China
The Nottingham House, London, Madrid and Nottingham: Designed & Built by Faculty & Students of the School of Architecture, The University of Nottingham, 2010

The University of Nottingham’s entry into the 2010 Solar Decathlon Europe competition - the Nottingham House, is a prototype of a zero carbon affordable starter home that can be constructed throughout Europe. The research aims included the realisation of a fully prefabricated house providing a comfortable and domestic environment that would have little or no running costs. Thus, simultaneously tackling fuel poverty, eliminating the need for winter fuel payments whilst protecting against over heating in summer, which can be equally injurious to human health and well-being. Underscoring this was a wider societal goal of tackling global warming and reducing our dependence on fossil fuels, seeking to contribute to achieving the carbon reduction of the Stern Review, 2006. However, the design aim of the Nottingham House was firmly focused on domesticity, with technology as a servant of this homely environment. The plan form can be used to create two storey terrace housing and courtyard housing depending on the climatic situation, local traditions and culture. This is based on the placement of the L-shaped plan. The Nottingham House is a prototype for a housing system that is adaptable both culturally and technically so that it can be used throughout Europe. In essence, this means that the Nottingham House is pre-adapted to the risk of elevated temperature ranges in the summers of Northern Europe, as predicted by some climate models, later in the twenty first century.

The Nottingham House was Britain’s only entry into the 2010 Solar Decathlon Competition. This was the first time the competition was staged in Europe having been initiated in America in 2002. The design process started in the form of a competition within the Masters and Diploma (RIBA Part 2) design research studio ZCARS (Zero Carbon Architecture Research Studio), led by Michael Stacey with Swinal Samant and Lucelia Rodrigues, with input from Brian Ford and Mark Gillott. The strict spatial requirements of the competition were included in the ZCARS studio brief, as shown in Figure 8.32, alongside wider issues related to zero carbon housing. The ten tasks of the Solar Decathlon Competition are: Architecture, Engineering, Market Viability, Communications, Comfort, Appliances, Hot Water, Lighting, Energy Balance, Getting Around, thus, the title a Solar Decathlon.

The Rules:
- Plot of 25m x 20m
- 5.5m high
- Site area of 74m²

Fig 8.31 The Nottingham House at Rio Parque, Madrid

Fig 8.32 The strict spatial requirements of the Solar Decathlon Competition, 2010
The students researched the issues influencing the proposed houses collectively from the demographics of European households through to how to achieve super insulation and comfort in all seasons. In particular, they studied and modelled the climate of middle England and the significantly hotter and generally dryer climate of Madrid, in central Spain. Environmental and tectonic strategies were provided to all students by the authors. It is at this stage that the use of passive downdraught evaporative cooling (PDEC), was proposed to cool the house in Madrid, based on previous collaborative EU funded research into this innovative technique, coordinated at the University of Nottingham. In essence, nesting a prototype cooling system within a prototypical house. The 2CARS competition brief also specified prefabrication to minimise waste and to deliver quality in a short construction timescale. The energy targets were set as both Code for Sustainable Homes Level Six and Passivhaus Accreditation.

The 2CARS students competed in teams, typically of three. This internal competition was won with a design authored by Rachel Lee, Chris Dalton and Ben Hopkins; they tested the design as a group of houses in the Meadows Nottingham, Figure 8.35. The spatial arrangement of the winning proposal spoke of homely starter housing. On arrival at the Nottingham House one notices that entry to the front door is sheltered by the first floor above.
Passing through the draft lobby – essential to minimise unwanted air changes - there is daylight and views to the courtyard. Turning left, observing that the house has been designed to Lifetime Homes Standards for accessibility, one enters the house passing the downstairs toilet, which also accommodates hot water storage created by the rooftop solar thermal panel. Passing the stair to the first floor you can either directly enter the kitchen or proceed to the dining room and onto the living room. The corner of the living room is glazed, providing ample daylight and views to both the courtyard and landscape or streetscape beyond.

On returning to the dining room one becomes aware that this is a double height space. This is the heart of the house both socially and environmentally. In essence it is a mini-atrium providing spatial and communication opportunities to the house as well as stack ventilation. At the top of this space, below the openable aluminium framed double glazed roof light, is the PDEC system. In hot dry climates, as found in southern Europe, the house is cooled by a PDEC system, developed by Professor Brian Ford in collaboration with the Spanish company Ingeniatrics-Frialia. The core of this technique is adiabatic cooling from finely misted water linked to a gull wind roof light operated by electrical actuators. The tiny water jet nozzles were developed by Ingeniatrics-Frialia and the system was designed and tested by the University of Nottingham.¹⁷ The performance of the PDEC combined with the relative thermal mass of this lightweight yet very well insulated home proved very successful when tested in Madrid, despite the frequent visitors inherent in this public competition.¹⁸
Fig 8.38  Nottingham House, ground floor plan

Fig 8.39  Nottingham House, first floor plan

Fig 8.40  Nottingham House, section AA

Fig 8.41  Nottingham House, section BB
The kitchen is open to the dining room and is a modest and well-appointed fitted kitchen, not unlike a twenty first century update of the fitted kitchens of AIROH post Second World War aluminium prefabs.\( ^{19} \)

In the corner of the kitchen is a whole house heat recovery system, which remained exposed in the Solar Decathlon Competition for didactic reasons, Figure 8.42. The kitchen ceiling is a little lower to accommodate ducting primarily in the kitchen, which is formed by bringing together Modules 1 and 4. Fair face birch ply is used to delineate the spaces of the home. Ecophon, in a blood orange red, highlights the dining room wall and the staircase wall respectively, both vertical elements in the house design, whilst providing acoustic absorbency. All other surfaces are hard including the bamboo floor. Bamboo was selected as it is fast growing and renewable. Stepping out to the courtyard here we find the homeowners are growing their own fruit and vegetables. The growing of edible plants was an important sub-theme of the Nottingham House, further contributing to reducing the carbon footprint of the family.

The floor area of the house is only 187m². A compact home in many ways reminiscent of a home designed by Sverre Fehn, except a hearth and a fireplace are missing.\( ^{20} \) The excellence of the students’ design was recognised in a RIBA East Midlands Low Carbon Award, 2009, awarded before fabrication had commenced.

The Nottingham House was designed from the outset as a fully prefabricated assembly. Thus the maximum transportable size was an important design constraint, however this was not allowed to dominate the internal domesticity. The house modules were fabricated and assembled by architecture students and staff at the University of Nottingham, coordinated by Mark Gillott. The primary sponsor of materials and components was Saint Gobain and its subsidiaries in the UK, without whom the project would not have been realised.

![Fig 8.42](image)

*Fig 8.42* The module that primarily contains the kitchen, No 1, is the most highly serviced module, incorporating the majority of services of the house

![Fig 8.43](image)

*Fig 8.43* The whole house heat recovery system is left exposed in the kitchen
The final design comprised eight volumetric modules that were transported fully glazed with all services installed and fully finished internally, for final assembly on site in Madrid by a team of students and staff. The ground floor Module 1, which primarily forms the kitchen, is the most intensively serviced. The only services in most other modules are power and lighting, except where Module 5 & 6 come together to create the shower room. The modules are all open on one side and only form the enclosure of the house when all eight modules are in place.

Aluminium plays a vital role in the assembly of the Nottingham House, in part, based on the author’s more than 30-year experience from research and practice in the use of aluminium in component based construction. Stock aluminium angles have been used to create contemporary interpretations of skirting boards and architraves. Stock aluminium angles and channels also support structural glass balustrades. It is surprising that stock aluminium sections are still predominately sold in the UK in imperial sizes, suggesting that some of the dies are over 40 years old. Brackets made of three stock aluminium angles, expertly welded by Faculty of Engineering technicians, support the corners of the ThermoWood timber cladding; the idea that aluminium is difficult to weld is ‘history’ as discussed in Chapter Two. Although the aluminium is conductive, it is only 3mm thick. The essence of this detail is to minimise the material in the insulation zone bridging between the structure and the cladding.
The windows of the house are triple glazed achieving a U-value of 0.5 Wm$^{-2}$K provided by 36mm thick units, comprising three layers of 4mm toughened glass with low emissivity coatings on surfaces three and five, combined with 90 per cent Krypton filled cavities. The window profiles are a combination of timber with insulated inserts, pultruded thermal breaks and polyester powder coated aluminium outer sections, manufactured in Germany by Hermann Gutmann Werke but fabricated in Derbyshire. On completion the windows, equipped with triple glazed low emissivity glazing units, proved to be very heavy. The largest window for the living room on the ground floor required three men to carry and install it. Apart from the fact that these window sections are bulky, they potentially represent the material future of architecture, with each material playing a distinct role; the timber safely in the warm dry interior capturing CO$_2$, the insulation ensuring that the low U-value is achieved, the pultrusion stops thermal loss through the frame and the aluminium retains the triple glazing and provides a guaranteed low maintenance finish via polyester powder coating. The TSC Report provides a life cycle analysis of window framing comparing aluminium, aluminium clad wood, wood and PVCu – interestingly, in the long-term study the all-aluminium window frames offered the best overall environmental performance. All the external aluminium sections, including the window sections on the Nottingham House, are polyester powder coated a warm grey colour, Ral 7022. The house is completed by aluminium rainwater hoppers and downpipes, supplied by Marley Alutec, and press braked 3mm aluminium copings and flashings, manufactured by Crown Aluminium and polyester powder coated by Birmingham Powder Coaters.
The high-performance photovoltaic panels were assembled on the roof using standard Schüco aluminium extrusions, as shown in Figure 8.50. The unseasonal rain in Madrid collected on the flat roof – it was not laid to falls due to competition height restrictions – and as it slowly evaporated, it increased the performance of the solar panels and helped to keep the house cool.

In Madrid, despite torrential rain that flooded our site, the Nottingham House was assembled in 11 days. What was billed as a new public park over a newly sunken urban highway, adjacent to the Palacio Real on the banks of the Rio Manzanares and designed by West 8, on arrival proved to be an un-landscaped building site, which soon became very muddy. After the competition the house was disassembled ready for transportation back to England in 2 days. Today the Nottingham House, following its reassembly, makes a permanent contribution to University Park, Nottingham and housing people from the School of Architecture.

The Nottingham House is a situated domestic ecology that fulfils Feenberg’s recommendation to design to create appropriatable technology. Almost nothing is more important in peoples’ lives than their home and home life. In the twenty first century we have the technology and knowledge to construct a much higher standard of housing, which delights and serves humanity well.
Notes


2 www.bauder.co.uk/renewables/biosolar-system (accessed March 2016)


5 Ibid.


7 Ibid.


9 Co-Operative Insurance Society (CIS) Building, Miller Street, Manchester, Listing Number 1270494, accessed via www.historicengland.org.uk/listing/the-list/list-entry/1270494 (April 16).

10 Ibid.

11 This text is based on information supplied directly by Mario Cucinella Architects and it also forms the basis of the text of this case study in The Future Builds with Aluminium, http://greenbuilding.world-aluminium.org/home.html

12 www.mcarchitects.it/sostenibilita (accessed March 2016)


14 Nottingham HOUSE (Home Optimising the use of Solar Energy)


21 Future Builds with Aluminium, Case Studies curated and written by Michael Stacey see http://greenbuilding.world-aluminium.org/en/home.html


24 Andrew Feenberg, Questioning Technology, Routledge, 1999
aluminium: flexible and light

economical
Economical

This chapter focuses on the affordability of aluminium as a means of providing long-term durability in contemporary architecture. Focussing primarily on aluminium in sheet form, as roofing and cladding systems. The economics of the specification of aluminium is also evident in many other chapters, for example; in the delivery of curtain walling or shelving systems, as discussed in Chapter 2, and in the total cost of ownership of footbridges, discussed on pages 438–439. The long-term durability and successful service of aluminium – including roofs – is reviewed in TSC Report 1, Aluminium and Durability, with exemplars being inspected and tested – dating back to San Gioacchino in Rome, 1897, which is now almost 120 years old and it is still performing well. Furthermore, the earliest aluminium standing seam roof in Europe, the Nuremberg Congress Hall, 1968, is now approaching 50 years of service.1
The high strength to weight ratio of aluminium alloys is of vital importance to the design of roofing and cladding systems – with benefits such as; minimising transport cost, facilitating mechanical handling or the potential of installation by hand. In the majority of examples, the ability of aluminium to readily adopt or be formed into single curvature or double curvature components is key to the realisation of five out of six case studies, which have been set out chronologically. It is noticeable in this chapter that all the projects are of a large scale; from a train shed, via stadia to exhibition and mixed-use projects. However, this technology remains accessible to all architects whatever the scale of his or her project.

Fig 9.3 Aluminium can economically and efficiently clad projects, such as the 2012 Olympic Velodrome by Hopkins Architects

Fig 9.4 Riveting the aluminium cladding of the Dome of Discovery at the Festival of Britain, architect Ralph Tubbs, 1951

Now twenty years old Stratford Market Depot, the train shed for the Jubilee Line extension at the eastern end of the line, was the key break through project for WilkinsonEyre, which fulfilled the intellectual promise shown in Chris Wilkinson’s book Supersheds, published in 1991.2

Stratford Market Depot is a supershed, 100m wide and 190m long, which forms a parallelogram in plan, in part to avoid the archaeological remains of Strafford Abbey at the southern end of the site. Stratford Market Depot accommodates 11 train lines; three lines accommodate the Heavy Lifting Shop, the central five lines – General Maintenance and three lines – Cleaning. Ancillary accommodation is arranged in three blocks to the western side of the Depot with the Control Building articulated on the opposite corner. The steel structure is a diagrid of trusses 9m long and 2.4m deep. The two lines of trusses are at 60° generating parallelogram bays. This diagrid is picked up by tree-like columns in bays of 18 × 40m, creating an 8m clear height above the track level. The Depot has generous eves on all elevations, not just where the trains enter on northern elevation. Chris Wilkinson and Jim Eyre decided to erect the structure first “followed by the roof deck and finishes, in order to provide a dry area to cast the concrete floor slab below.”3

Fig 9.5 North east façade of Stratford Market Depot, designed by WilkinsonEyre

The roof is clad in a Kalzip dual alloy mill-finish aluminium standing seam roof in continuous sheets that are gently curved, thus avoiding internal gutters. This train shed is generously day lit by rooflights throughout, which run broadly east-west in response to the structural grid below. The specialist installer of the aluminium standing seam roof was Prater Ltd.
The southwest wall of the Depot is clad in Kalwall to provide thermal performance and to diffuse direct sunlight thus avoiding glare. (For more information on Kalwall, see page 244). This is a cost effective and hard working industrial building delivered with an elegant economy of means. Colin Amery suggests ‘it will be a pleasure to use while having all the dignity of a modern cathedral’. The Depot, completed in April 1996, was conceived and delivered as a high-quality work of contemporary architecture, in keeping with all of the stations of the Jubilee Line.
WilkinsonEyre went on to design Stratford Jubilee line station, which is also clad with an aluminium seam roof. The design of the Jubilee Line extension was led by Roland Paoletti and it opened to the public in 1999. The excellence of this public architecture and infrastructure was a key factor in London winning the 2012 Olympic bid in 2005. Stratford Jubilee line station served as a major gateway during the 2012 London Olympics.
Three of the watchwords for the design and procurement of the London 2012 Olympics were responsible sourcing and legacy. At one stage it appeared that the Olympic Delivery Authority (ODA) did not understand the environmental credentials of aluminium and that it can be readily sourced responsibly. Furthermore that it can be part of a re-use strategy or recycled, or better still offer long term durability in a legacy mode of continued use. The UK aluminium industry worked hard to secure the role of this light metal in the delivery of 2012 Olympics.

The 2012 Olympic Velodrome, designed by Hopkins Architects, is probably the best example of a venue tuned for Olympic success, with nine new World and Olympic Records with a further two Olympic Records, combined with a future use that was in place before the Olympics, as the Lea Valley Velopark. Richard Arnold, the ODA project sponsor of the Velodrome, observed in 2007 following Hopkins Architects’ appointment, ‘we spent the first four months focusing on the masterplan of the VeloPark, during which, while the facilities stayed the same, we actually increased the overall site area over that identified in the brief’. Following extensive consultation with future user groups and with the legacy secure, only then did Hopkins Architects with its fellow consultants focus on the design of the Velodrome itself. The elegant simplicity of Hopkins Architects’ Velodrome design delivered a world-class arena seating 6000 spectators for a capital cost of £90 million. Following the 2012 Olympics the Velodrome and its site were converted into a VeloPark at a cost of only £4 million. In contrast the main Olympic Stadium, designed by Populous, is currently being converted to a football (soccer) stadium as a retrofit. This was part of the initial brief for the main stadium, which cost £486 million in 2012. The cost of the conversion, which has also been designed by Populous, is a further £272 million.
Hopkins Architects, working with engineers Expedition, won the competition to design the 2012 Olympic Velodrome from a shortlist that included architects without direct experience of designing velodromes. Chair of the judges Nicholas Serota, Director of Tate, recalls that:

The Hopkins Architects team impressed from the earliest stages of the competition. Their personal engagement with the cycling community gave them an understanding of the needs of the prime users of the building. The clarity of their initial concept of a civic building with a lean structure, elevated above the park and lit by natural light, was informed by their knowledge. It has survived the design and construction process by virtue of the skill, determination and sensitivity of the whole design team.
Hopkins Architects observe of this project:

“The Olympic Delivery Authority set a number of sustainability and material targets; through careful consideration and integration of the architecture, structure and building services the design has met or exceeded these requirements. Work started on site in February 2009 and was completed ahead of programme and on budget in January 2011.”

The design and delivery of the 2012 Olympic Velodrome is an excellent example of close collaboration within the design team and with the main contractor ISG, the specialist subcontractors and the complete supply chain. It was delivered using a non-adversarial partnering form of contract, a New Engineering Contract: Option 3.

Ghent Velodrome, designed by architect M.J. Tréfois and completed in 1964, uses a 67m clear span aluminium roof structure, see pages 316–319 in Chapter 2. Whereas the 2012 Olympic Velodrome deploys a steel cable net structure, which is a tension only system that generates the saddle form that characterises this building.
Hopkins Architects’ design for the Velodrome is not directly mimetic of bicycles, however, it does take inspiration from the design of bicycles with all of the components of the building being expressed, combined with a refined level of integration. Mike Taylor, an architect and partner at Hopkins Architects observed: ‘Whereas the design of the bicycle has evolved through numerous evolutionary steps, we had one hit at the Velodrome.’ Noting that it “could not have been designed and built without the latest 3D computer modelling techniques.” Furthermore that the design process began with sketches: ‘Perhaps surprisingly for such complex building, nearly every aspect started life as a sketch by hand on paper.’ He observing the importance of cross-disciplinary collaboration in achieving such a highly integrated design, he stated the need to retain a clear ‘a philosophical and aesthetic vision’ of the project. Revealing his clarity of vision during the design process, ‘the Velodrome sets out to reconcile ambitious engineering and technology with more architectural concerns of form, proportion and composition.’

Chris Wise, founder of Expedition Engineering describes how a ‘striking, doubly curved roof shape evolved as the form which would best answer the stadium’s needs. The saddle-shaped roof ‘shrink wraps’ the building around the track, minimising the interior volume and in turn reducing heating and cooling requirements’.

Figure 9.21 2012 Olympic Velodrome, Upper Tier Plan:
1 Timing/scoring zone
2 Track
3 Safety zone
4 Infield
5 Legacy road circuit

Figure 9.22 2012 Olympic Velodrome section A-A

Fig 9.21

Fig 9.22
The cable net comprises pairs of 36mm diameter spiral strand steel cable set out primarily on a 3.6m grid. The cables running north-south resist gravity and have their high points on the ring truss; those running east-west resist wind uplift in this lightweight roof connected to the roof truss at its low sweep. The cables are locked together with forged steel nodes, which also carry ‘receiver brackets’ that start the roof build up. The design eschews a large ring beam that would have been visually heavy and added significantly to the amount of steel required. Following careful design iterations the forces from the cable net were resolved via the steel frame of the upper setting rack and into the concrete structure below, see Figure 9.23.

Fig 9.23 Diagram of the principal structural load paths in the Velodrome’s steel trusses and piled concrete foundations

Fig 9.24 Study model of the integration of structure, seating and track

Fig 9.25 Detailed cross section through the Velodrome’s seating
Timber cassette panels were placed on ‘receiver brackets’, with a temporary waterproof layer, on the nominal 3.6m grid. There are about 1000 standard panels and approximately 100 non-standard. All are carefully detailed to allow for movement in the cable net and to constrain this in particular directions. A vapour check layer was laid onto the temporary waterproof layer followed by 300mm of insulation and then a Kalzip dual alloy mill-finish aluminium standing seam roof. The thermally efficient Kalzip clip fixing detail for the standing seam roof is attached to the timber cassette panels. These roll formed aluminium roof panels are up to 130m long, in single sheets, and the standing seams run east-west. The specialist installer of the aluminium standing seam roof was Prater Ltd. With a roof area of 1.4ha or 14,000 m² the case for design optimisation including the use of prototypes and mock-ups is very clear. The design team chose not to fill the timber cassette panels with insulation, as this would have created a potential risk of interstitial condensation.
The geometry at the margins of the roof and gutter is resolved by the use of a Sarnafil PVC single ply membrane. The edge of the roof is formed by an aluminium bullnose capping profile, from which the hansom Western Red Cedar wall cladding is set out. Externally only three materials articulate the Velodrome: glass, aluminium and Western Red Cedar, evoking the interior of bicycles and the track on which they race.17

The roof steelwork is only 30kg/m², less than half the weight of the roof structure of the Beijing 2008 Velodrome. The use of a cable net structure saved over £2 million pounds and resulted in a 3-month shorter site time. The use of a cable net, weighing only 100 tonnes, uses 27 per cent less steel by mass when compared to steel arches. It is an excellent example of structural design optimisation, a case of achieving more with less – with the lightweight aluminium roof playing its role in a minimal material strategy. Overall, including the steel cable net, timber cassette panels, insulation and aluminium standing seam sheeting; the roof of the Velodrome weighs 70kg/m². The building fabric accounts for over 50 per cent of the weight of the roof.

The control of the internal comfort condition of the Velodrome were also carefully considered and integrated into the architectural intent from the outset of the design. Klaus Bode, of environmental design consultants BDSP, considered:

One of the key challenges regarding the environmental performance of the Velodrome was to enable the fastest track-level conditions, while keeping spectators comfortable throughout the year and in different types of events, from the Games to school sessions. Passive and active systems had to allow for the high temperature (about 26°) required by the cyclists to achieve record-breaking times.18

Having ruled out an unheated Velodrome, a three part approach was adopted: under floor heating in the infield, which provides the basic background heating; under seat heater air supply, providing
fresh air and extra heat; and a high velocity heated air supply to quickly condition the arena. The components of the ventilation system are integrated below the seating. This is combined with building fabric insulation to a higher standard than required by UK Building Regulations and the exposed thermal mass of the concrete structure. The Velodrome can be fully naturally ventilated in spring, summer and autumn.

Daylight is used to provide an uplifting environment while minimising energy consumption. ‘Rooflights in the main area were optimised to provide sufficient daylight for training in most of the year, resulting in [significant] reductions in energy consumption’, observed Klaus Bode noting that: ‘Extensive computational analysis was used to fine-tune the performance of the ventilation and lighting systems.’\(^\text{19}\) The rooflights use self-cleaning glass with white diffusing PVB interlayers in the inner leaf of the double glazed units, thus the roof does not have cleaning accesses safety systems designed in, even in the context of UK Construction Design and Management Regulations. The acoustical internal environment of the Velodrome was equally carefully studied.

The total embodied CO\(_2\) of the structural elements of the Velodrome is 7,400 tonnes, less than 1,250 kg of CO\(_2\) per seat.\(^\text{20}\) The Velodrome’s predicted reduction in carbon emissions is 31 per cent, more than double the ODA target of 15 per cent and better than another 2012 venue. Although this is aided by the combined heat and power unit, providing district heating to all of the Olympic venues, it is achieved by a fabric first strategy with no on site applied renewables. In essence the design achieves more with less. Demonstrating that environmentally sound architecture can be achieved by integrated design and careful material selection within tight timescales and without costing more.

Nicholas Serota reflecting on the competition to design the Velodrome: ‘In appointing a young and dynamic team, versed in the language of the Hopkins practice, we knew the detail of the design would be elegant, economical and enduring.’\(^\text{21}\)

Attention to material selection and the unity of design intent and detail will, in Nicholas Serota’s opinion, ‘ensure the building is easy to maintain and will look as good in 20 years as it does today.’\(^\text{22}\) ‘The Velodrome promises to enhance the experience of every user and visitor to the building for generations to come.’\(^\text{23}\) This is the very essence of sustainability in the built environment. A well-informed brief, design excellence and high quality execution are the cornerstones sustainability. Yet the needs for such highly skilled processes are hardly mentioned in the conventional discourse of big data and technocratic ‘solutions’.

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Fig 9.33  Commemorative Royal Mail First Day Cover in honour of The Men’s Team Sprint Gold Medals at the 2012 Olympics

Fig 9.34  The 2012 Olympic Velodrome was the first venue to be completed in January 2011

The atmosphere within the 2012 Olympic Aquatics Centre was electric during the 2012 Olympic and Paralympic swimming events. The form of the Aquatics Centre, in the words of the architects is, ‘a concept inspired by the fluid geometry of water in motion’. It has two 50m pools, a competition pool and a warm-up or training pool, with a 25m diving pool – all achieved at a capital cost of £269 million and completed ready for the games in 2011. To meet the audience capacity set out by the Olympic Committee, what became known as the saddlebags were added to either side of the competition pools. Thus increasing the seating capacity to 17,500 spectators – and the sightlines were surprisingly good. The saddlebags were removed after the Olympics and were replaced by curtain walling. Today the Aquatics Centre can accommodate 2500 spectators. The doubly curved wave inspired roof of 1040m is clad in a dual alloy mill finish Kalzip aluminium standing seam roof, with a gauge of 1mm, an upstand of 65mm and module of 333mm for 90 per cent of the roof sheets.

Kalzip XT was specified to accommodate the rapid changes in curvature of this roof. Kalzip XT uses patented roll forming technology to fabricate standing seam roof panels, with concave or convex curvature as required by the geometry of a specific project. It was introduced by Kalzip in 2005 and first used on the roof of Spencer Street Station in Melbourne, Australia, architect Grimshaw (2006), see Figure 1.11.

Lakersmere were appointed as the specialist subcontractor for the Kalzip aluminium standing seam roof of the 2012 Olympic Aquatics Centre, in part due to their experience of installing Kalzip XT. Zaha Hadid Architects’ original geometry of the roof required the use of 40 per cent Kalzip XT, in collaboration with Lakersmere and Kalzip this was reduced to only 10 per cent, without compromising the geometry. The aluminium roofing contact contributed only £3.5 million to the capital cost of the Aquatics Centre.

The thermally efficient Kalzip fixing clips are fixed to cladding rails, which are in turn fixed, via the vapour check layer, to a trapezoidal roof sheet – this zone was then filled with insulation. The soffit of the roof is clad in reddish Louro timber strips, which articulate the direction of the swimming lanes below. Just four concrete columns support the dramatic roof. The steel roof structure was fabricated in Wales by Rowecord Engineering and weighs 3200 tonnes.
Today any citizen of London and visitors to the capital can swim in the elegance of the Aquatics Centre for just £5 for 60 minutes in the competition pool and 90 minutes in the training pool. Nearly two million people have used the pools in the two years since it re-opened to the public in March 2014.
Soho Galaxy, Beijing, China: Architect Zaha Hadid Architects, 2012

Soho Galaxy is a large mixed-use development in central Beijing designed by Zaha Hadid Architects as a singular flowing geometry, yet it comprises four towers that rise up 15 floors, with three floors of retail including the ground floor and 12 office floors above, providing over 360,000m² of accommodation. Between the towers are surprisingly spacious courtyards, which Zaha Hadid Architects describe as a reinvention of the classical Chinese courtyard, which generates an immersive, enveloping experience at the heart of Beijing.  

Soho Galaxy was designed between 2009 and 2011, using digital form finding. The initial concept was developed via ‘surface subdivision’ in Maya. This was then used as the geometry that formed the basis of the architect’s coordination of the project via a Building Information Model (BIM) in CATIA/Digital Project. Cristiano Ceccato, Associate Director and lead architect on Soho Galaxy, observed a ‘project of the size and complexity could not be accurately coordinated using 2D drawings alone.’ Noting that mock-ups and prototypes were vital in the design and delivery of the flowing white façades. ‘As part of the design process Zaha Hadid Architects and the client elected to build a series of façade mock-ups in different materials to assess geometric complexity, contractor capability in China as well as material performance constructability and aesthetics.’
An identical area of façade was prototyped in sheet metal, steel plate, glass-reinforced polymers (GRP) and glass-reinforced concrete (GRC). This process led to the selection of 3mm thick polyester powder coated aluminium sheet, with 4mm thick sheet when the panels need to be walked on for maintenance. The first façade prototype, using 3mm thick polyester powder coated aluminium sheet, was produced by Permasteelisa in October 2009.

At this early stage, Zaha Hadid Architects continued to optimise the geometry of the façade in order to minimise the areas of double curvature, which in turn reduced process costs associated with the delivery of the façade, whilst retaining the flowing design intent of Soho Galaxy. Cristiano Ceccato observed 95 per cent of the façade could be ‘implemented as single-curve sheet metal’. Taking this optimisation process a step further Zaha Hadid Architects replaced as many of the developed surfaces with cones as was possible. Cristiano Ceccato notes that ‘within each conical strip, each constituent facia panel is identical’ with a parametric definition of cant angle, radius height and panel arc length. An indicative size of a panel is 1200 x 2000mm with a controlled dimensional variation. The third stage of optimisation was to group the cones into families of components. Cristiano Ceccato recorded the outcome as a ‘total of over 52,000 different façade components, of which 18,000 were glazing units and 34,000 façade panel units’, in 800 families of components.

The façades were tendered using a combination of 3D BIM and 2D formal documentation. A 497 page A0 façade 2D package was produced by the architect in September 2010. Each potential façade contractor was required to produce a 1:1 façade prototype. Figure 9.49 shows the 1:1 façade prototype produced by Yuanda as part of the tender process, again using 3mm polyester powder coated aluminium sheet. In areas needing maintenance access the aluminium sheet thickness was increased to 5mm. During this period the steel frame was rapidly being erected on site with cladding starting during the first quarter of 2011. Soho Galaxy opened in November 2011. This project, with its unitary geometry yet diversity of uses; retail, entertainment and offices, opened to critical acclaim – offering a potential new urbanism for China.
Danish National Aquarium – Blue Planet, Copenhagen, Denmark: Architect 3XN, 2013

Major aquaria are local and regional tourist attractions that typically don’t have local rivals. The Blue Planet Aquarium designed by 3XN opened in March 2013, and is one of the largest in Northern Europe. It replaced a white modernist building in Charlottenlund designed by C.O. Gjerrild-Knudsen (1939), which was too small after over 60 years of collecting aquatic specimens. In 2007 an architectural competition was held and won by 3XN. The new site is a promontory in Amager, on the coast just north of Copenhagen, yet accessible from Kastrup Metro station. The architects took inspiration from a vortex in a shoal of fish; to some, the new Danish National Aquarium is reminiscent in form of a starfish. It is the fish and other aquatic life, in 53 tanks with over 20,000 specimens, who are the stars of this tourist destination.

The aquarium is organised around a central circular void, which continuously shows the BBC documentary by David Attenborough, Blue Planet, from here all wings of the vortex are perceivable; from the Ocean to the Faroe Islands and even the restaurant and auditorium, all the potential routes are clearly understandable by the visitors. Administration is housed in the wing next to the entrance.

Fig 9.51 Danish National Aquarium – Blue Planet, architect 3XN, who drew inspiration from the vortex generated by a shoal of fish

Fig 9.52 The perspex wall of the Ocean Aquarium

Fig 9.53 Plan of the Blue Planet, architect 3XN
1 The Amazonas
2 School Service
3 Restaurant
4 Auditorium
5 The Faroe Islands
6 Sea Lions
7 Coral Reefs
8 Octopusses
9 The Ocean
10 The Lakes of Africa
11 The Cave

Fig 9.54 The Blue Planet Copenhagen, 2013
Blue Planet is clad in a continuous surface of aluminium shingles. This is 1.2mm thick rolled and coil-coated aluminium Falzonal® manufactured by Novellis in Göttingen. Novellis’ Falzonal® is finished with clear PVDF 25µm on the external surface and 3µm on the inner surface. Rainwater can be collected from this roof and used in the aquarium without treatment. The architects’ confidence in the aluminium cladding is demonstrated by it plunging directly into the reflecting pools that collect the rainwater. Noting that aluminium has longer durability if it is washed by rainwater as discussed in TSC Report 1, Aluminium and Durability.40

The rhombic shingles are about 0.5m² in area and 40,000 identical shingles clad the aquarium. Identical except where they have been folded or cut in response to the form of the building and are joined and sealed with a lapped and welted detail. 200,000 stainless steel FliSs were used for the non-visible fixing of the shingles, installed by specialist subcontractor Kai Andersen A/S.

The scale like skin of the Danish National Aquarium should remain reflective due to the clear PVDF coating. It renders the form of the building ambiguous in scale and continuously adapts with the weather in its seaside location.
Fig 9.56 Clear PVDF coated aluminium shingles of the Blue Planet reflects the changing environmental conditions of its setting.

Fig 9.57 Rainwater is collected from the reflective pools and used in the aquarium.

Fig 9.58 Winter time at the Blue Planet, Copenhagen.
Manor Works, Sheffield, England: Architect Architecture:00, 2014

Manor Works has been carefully designed in the context and topography of its site by architect Architecture:00, making the most of a back lands site in southeast Sheffield. This industrial incubator building is robustly detailed with an internal palette of exposed concrete, timber and plywood. It offers managed workspace for local start-up businesses from industrial or workshop units to offices, combined with shared resources for the local community. The workspace is arranged to encourage the workers of the start up companies to meet and share experiences and opportunities. In essence the opposite of the earlier lock-ups on the site. The interior would not look out of place on a university campus. It is robust yet has an almost domestic quality. This very economic building is part of the knowledge economy, yet it costs less than £1700/m² providing 1,600m² of occupiable space for a capital cost of £2.7million. The section makes the most of the site offering a range of spaces, with the communal areas located along the south façade, relating to a pedestrian footpath and local playing fields beyond. At its lowest level, Manor Works opens out on to this footpath onto a modest play area, commissioned as part of the project.
The north and west façades comprise standard composite metal panels. The east and south are unified by perforated aluminium rainscreen panels, which become the skin of the project and act as solar shading and securing screens. These generously perforated aluminium panels also act as supports for climbing plants. Manor Works opened in February 2014 and won a national RIBA Award in the same year. The RIBA judges observed ‘Manor Works balances the need to be secure with a real and tangible desire to be welcoming and accessible, inviting the local community to explore and make it their own.’

Fig 9.61 The perforated aluminium sheet is simply folded to form the corner of the east and south façades
Fig 9.62 The perforated aluminium cladding also provides support for climbing plants
Fig 9.63 Manor Works by Architecture: 00, photographed 2014
Notes

6 www.bbc.co.uk/sport/olympics/15149865 (accessed March 2016)
11 Ibid. p. 39.
12 Ibid. p. 38.
13 Ibid.
16 S. McLeman of Kalzip in conversation with the author March 2016.
17 The timber of the track is Siberian Pine.
19 Ibid.
22 Ibid.
23 Ibid.
26 S. McLeman of Kalzip in conversation with the author March 2016.
27 Ibid.
Interim Conclusion

Aluminium, as evidenced in this report, can be reasonably described as a good servant of sustainability and an ally in the pursuit of excellence in architecture and infrastructure. It may form the highly visible and durable surfaces of overcladding, such as Guy’s Hospital, or as an unseen ‘hand’ supporting photovoltaic panels. The former has a carbon payback period of only 12.5 years and the latter is increasingly contributing the carbon balance of projects, such as 240 Blackfriars Road, with a clear progression from low carbon projects to architecture that is carbon neutral and even net contributors to the local energy grid.

The contribution of aluminium to design excellence is clear throughout this report, be the date of a product 1948, as in the Jaguar XK 120, or the 606 Universal Shelving System design by Dieter Rams in 1962. This shelving system is still on sale today and fully compatible, whatever the date of your first or latest purchase. This adaptable, extendable and fully reusable system is an excellent example of a sustainable product that has its roots in an era known for the ‘white heat of technology’ – to quote the future British Prime Minister Harold Wilson in the autumn of 1963.¹ Architectural examples of aluminium and excellence include the Comet Flight Testing Hanger in 1953, the Climatron in 1960 or the Hive in 2015.

To construct the Comet Flight Testing Hanger in 1953, just over 180 tonnes of aluminium was used to form the aluminium structure, decking and cladding, see page 303 for the detailed breakdown. Figure 10.1 takes the mass of the Comet Flight Testing Hanger as the base case and calculates how far this quality of aluminium will go to produce other case study projects or products featured in this report, all examples have been rounded to the nearest whole or half, as necessary, in all examples only the mass of the aluminium components is used to form the comparison.

What will you do with 1 tonne or 1 kg of aluminium in your next proposal, project or product?²
The Stirling Prize, awarded by the Royal Institute of British Architects, is one of the best accolades a project, its client and design team can receive and it is held in high regard the world over. The award was founded in 1996, in honour of the architect Sir James Stirling (1962–1992). This report includes a number of Stirling Prize winning projects that utilise the qualities of aluminium alloys, from the Gateshead Millennium Bridge, 2001 by WilkinsonEyre to the Everyman Theatre by Haworth Tompkins Architects in 2014.

In the past two years the Stirling Prize shortlist of six projects per year, has included eleven aluminium-rich projects.
aluminium: flexible and light

Fig 10.3 Library of Birmingham designed by Meccano Architects for Birmingham City Council, shortlisted for the Stirling Prize in 2014, its building fabric includes silver and backmetallic polyester powder coated solar shading

Fig 10.4 London Bridge Tower (the Shard), designed by Renzo Piano Building Workshop for Sellar Property Group, shortlisted for the Stirling Prize in 2014, its aluminium curtain walling

Fig 10.5 Manchester School of Art, designed by Feilden Clegg Bradley Studios for Manchester Metropolitan University, shortlisted for the Stirling Prize in 2014; its building fabric includes black anodised curtain walling

Fig 10.6 London 2012 Aquatic Centre designed by Zaha Hadid Architects for the Olympic Delivery Authority, shortlisted for the Stirling Prize in 2014, its building fabric includes a mill-finish aluminium standing seam roof

Fig 10.7 Everyman Theatre, designed by Haworth Tompkins for Liverpool and Merseyside Theatres Trust, winner of the Stirling Prize in 2014, its building fabric includes black anodised waterjet cut solar shading
The beneficial qualities of aluminium appear to be well understood by architects and it has become the background material of contemporary architecture. However, if the wide-ranging benefits of this durable and lightweight material were better understood – it has a much greater potential, especially in the realm of lightweight structures.
On the 4 July 2012, CERN (European Organization for Nuclear Research) announced the discovery of the Higgs Boson, a particle with a mass region around 126 GeV, arising from the ATLAS and CMS independent experiments, both conducted on the Large Hadron Collider (LHC). Located near Geneva, the LHC is the world’s most powerful particle accelerator, with a 27-kilometre circumference that is 175m below Switzerland and France. The LHC became operational in September 2008. CERN describes the LHC:

Inside the accelerator, two high-energy particle beams travel at close to the speed of light before they are made to collide. The beams travel in opposite directions in separate beam pipes – two tubes kept at ultra high vacuum. They are guided around the accelerator ring by a strong magnetic field maintained by superconducting electromagnets. The electromagnets are built from coils of special electric cable that operates in a superconducting state, efficiently conducting electricity without resistance or loss of energy. This requires chilling the magnets to -271.3°C – a temperature colder than outer space.

Aluminium gets stronger at very low temperatures. Bayards manufactured the bottom tray of the LHC from aluminium extrusions, which were friction stir welded with a precision 360° orbital welding machine. High technology from the aluminium industry enables the fabrication of sophisticated research equipment. Aluminium not only contributes to people’s lives and culture, it contributes the cutting edge of particle physics and our understanding of the composition of the universe.
aluminium: flexible and light

Notes
2 The Higgs Boson is named after Peter Higgs, a theoretical physicist at the University of Edinburgh, who in 1964 identified the mathematics that proposed the existence of this subatomic particle.

Fig 10.13 Bayards fabricated the bottom tray of the Large Hadron Collider at CERN from friction stir welded aluminium extrusions
aluminium: flexible and light
Aluminium: flexible and light

Glossary

Age Hardening: precipitation from solid solution resulting in a change in properties of a metal alloy, usually occurring slowly at room temperature (natural ageing) and more rapidly at elevated temperatures (artificial ageing), typically resulting in components with higher yield stress.

Air infiltration rate: is the tested measure of the rate of airflow through a building fabric and it is typically measured in m$^3$/m$^2$/hr.

Alloy: combination of a metal with other chemical elements (or chemical element) to form enhanced properties, with the parent metal such as aluminium as the primary material.

Angularity: conformity to, or deviation from, specified angular dimensions in the cross section of a shape or bar.

Annealing: heating and gradual cooling to modify the properties of a metal, alloy or glass, to attain acceptably low internal stresses or desired structure or both.


Anodising quality: describes material with characteristics that make it suitable for visible anodising, after appropriate preliminary treatment.

Anthropocene: proposed term for the current geological epoch where humankind has altered the environment and ecology of Earth to the extent that it is being recorded in the Earth's crust.

Bayer process: the most commonly utilised industrial process for extracting alumina from bauxite ores.

Billet: a cast aluminium product suitable to use in an extrusion press, usually of circular cross-section but may also be rectangular, or elliptical.

Bow: the deviation in the form of an arc of the longitudinal axis of a product.

Buffing: a mechanical finishing operation in which fine abrasives are applied to a metal surface by rotating fabric wheels for the purpose of developing a lustrous finish.

Building Information Modelling [BIM]: a holistic approach to the design of architecture and infrastructure, based on the shared use of three-dimensional digital models. Building Information Models include data on materials, scheduling and performance, among other categories, for the purpose of design, visualisation, simulations, and structural and environmental analysis.

Burr: a thin ridge of roughness left by a cutting operation such as routing, punching, drilling or sawing.

Circumscribing circle diameter (CCD): the smallest circle that will contain the cross section of an extrusion, designated by its diameter.

Cold work: plastic deformation of metal at such temperature and rate that strain hardening occurs.

Composite construction: the combination of materials with very different mechanical properties to form a single component.

Concavity: a concave departure from flat.

Concentricity: conformity to a common centre, for example, the inner and outer walls of round tube.

Container: a hollow cylinder in an extrusion press from which the billet is extruded, the container can be rectangular or elliptical.

Conversion coating: treatment of material with chemical solutions by dipping or spraying to increase the surface adhesion of paint.

Corrosion: the deterioration of metal by a chemical or electrochemical reaction with its environment.

Design for Disassembly (or Design for Deconstruction) [DfD]: a principle applied during the design process that results in the detailing of reversible joints, connections and attachment mechanisms between building materials and components, thus enabling future reconfiguration, relocation, reuse and recycling.

Die-casting: metal casting formed in a mould, typically steel, appropriate for high volume production.

Direct extrusion: a process in which a billet, in a heavy walled container, is forced under pressure through an aperture in a stationary die.

Draft angle: taper on vertical surface of a pattern or mould to permit easy withdrawal of pattern or product from mould or die.

Drawing: the process of pulling material through a die to reduce the size and change the cross section.

Drift test: a routine sampling test carried out on hollow sections produced by bridge or porthole methods, in which a tapered mandrel is driven into the end of the section until it tears or splits.

Electrolytic colouring: a two-stage colour anodising process.
**Etching:** the production of a uniform matt finish by controlled chemical (acid or alkali) treatment.

**Etching test:** the treatment of a sample using a chemical reagent to reveal the macro-structure of the material.

**Elastomer:** this is the general term used to describe a material, synthetic or naturally occurring, which has rubbery or elastic properties.

**Embody energy** (also known as cumulative energy use): the sum of all energy consumed in the production of materials, goods or services including extraction, manufacturing and fabrication, often described through embodied energy assessments. Recurring embodied energy: energy needed over time to maintain, repair or replace materials, components or systems during the life of a building.

**Extrusion die:** metal plate or block, typically steel, used for forming materials in the extrusion process, where the cross section of the extruded material takes the negative form of the die.

**Extrusion ratio:** the ratio of the cross-sectional area of the extrusion container to that of the extruded section (or sections in the case of multi-cavity dies).

**Fillet:** a concave junction between two surfaces.

**Free machining alloy:** an alloy designed to give small broken chips, superior finish and/or longer tool life.

**Full heat treatment:** solution heat treatment followed by artificial ageing.

**G-value** indicates the degree to which glazing transmits heat from sunlight, expressed in a number between 0 and 1. The lower the g-value, the less heat is transmitted.

**Grain growth:** the coarsening of the grain structure of a metal occurring under certain conditions of heating.

**Grain size:** the main size of the grain structure of a metal, usually expressed in terms of the number of grains per unit area or as the mean grain diameter.

**Hall–Héroult process:** an electrolytic process for the reduction of alumina into liquid aluminium. It is the most commonly utilised industrial method of primary aluminium production.

**Hardness:** the resistance of a metal to plastic deformation usually measured by controlled indentation.

**Heat treatable:** an alloy capable of being strengthened by appropriate heat treatment.

**Holocene:** a geological epoch that began about 11,700 years before 2000AD, and simply means entirely recent, in ancient Greek.

**Homogenisation:** a high temperature soaking treatment to eliminate or reduce segregation by diffusion.

**Indirect method:** a process whereby a moving die, located at the end of a hollow ram, is forced against a stationary billet.

**Life Cycle Assessment (LCA):** an approach to quantifying the environmental impacts of a product or service across its life cycle.

**Cradle-to-grave Life Cycle Assessment (LCA):** considers all the aspects of a product’s life cycle (i.e. raw material extraction and processing, manufacture, transportation, use, repair and maintenance, and reuse, disposal or recycling).

**Cradle-to-gate Life Cycle Assessment (LCA):** an alternative LCA scope that focuses on the environmental impacts associated with material extraction, manufacturing, transportation, construction or assembly. For building products this scope is often used to represent materials at point of sale, when they are more easily compared and delineated, as well as when use and end-of-life processes are uncertain. However, cradle-to-gate assessments do not capture the full environmental impacts of goods or service and are not permitted for life cycle comparisons between materials or products (see ISO 14044).

**End-of-life recycling method:** a methodology for the treatment of recycling in LCA that is based on a product life cycle and material stewardship perspective. It considers the fate of products after their use stage and the resultant material output flows.

**Recycled content method:** a methodology for the treatment of recycling in LCA that looks back to where a material was sourced, and provides a measure of waste diversion. This approach is based on a waste management perspective, where the general aim is to promote a market for recycled materials that is otherwise limited, uneconomic or underdeveloped.

**Light transmission:** a LT-value indicates the amount of visible light that progresses through a glazed façade.
Lightweighting: the process of removing mass from a design, such as a car, whilst maintaining (or improving) all other functional performance criteria.

Logs: a cast aluminium product suitable for extrusion shipped in lengths of 7-8 metres.

Lost foam casting: a metal casting formed in a ceramic ‘jacket’ or investment mould from which the foam pattern is vaporised by the action of the hot metal as it is cast.

Lost wax casting: a metal casting formed in a ceramic ‘jacket’ or investment mould from which the wax pattern has been removed by heating, prior to casting.

Mandrel: core or former used in filament winding or the extrusion of hollow sections.

Mean diameter: the sum of any two diameters at right angles divided by two.

Mean wall thickness: the sum of the wall thickness of tube, measured at the ends of any two diameters at right angles, divided by four.

Mechanical properties: those properties of a material that are associated with elastic and inelastic reactions when force is applied, or that involve the relationship between stress and strain. These properties are often incorrectly referred to as ‘physical properties’.

Method: the system of gates, feeders and risers used to feed a mould cavity to ensure an even distribution of metal with a constant rate of solidification, avoiding the formation of unwanted cavities in a casting is called the method.

Mig welding: in Metal Inert Gas welding a direct current of reverse polarity is struck between the work piece and a continuously feed welding rod, which acts as filler and electrode. Penetration cannot be as closely controlled as in TIG welding.

Monocoque: a structure in which the stiffness is generated by the form of the skins or shell only. Monocoque is literally French for ‘single shell’.

Operational energy: the energy required to provide a comfortable and productive internal building environment. This includes the energy required to heat, cool and provide electrical services such as artificial lighting to a building during its use. Energy efficiency measures [EEM] (or energy conservation measures [ECM]): measures implemented to reduce energy consumption in a building. These may include changes to technologies or human behaviour.

Overcladding: the process of placing insulation and a new durable skin over an existing building without removing the existing building fabric, to improve the thermal performance of the building whilst also addressing other issues such as water ingress or interstitial condensation, air infiltration and appearance.

Pattern: a pattern is a positive of the finished cast component and incorporates the feeders and risers. It is used to form the mould cavity.

Pit corrosion: localised corrosion resulting in small pits in a metal surface.

Platen press: used for laminating, a platen press comprises a rigid frame that supports two rigid and flat plates or platens, which can be brought together to under pressure. The flat plates can be heated to reduce cure time.

Porthole die: an extrusion die, also known as a hollow die, which incorporates a mandrel as an integral part. A bridge die and a spider die are special forms of a porthole die – all used to produce extruded hollow sections from solid billets.

Polymer: organic chemical compound of molecule(s) formed from repeated units or chains of smaller molecules or atoms.

Power mix: the specific mix of electricity generation energy resources such as: hydro, nuclear or thermal (coal, oil and gas).

Primary energy: an energy form found in nature that has not been subjected to any conversion or transformation process. It is energy contained in raw fuels, and other forms of energy received as input to a system. Primary energy can be nonrenewable or renewable.

Press brake: method of forming sheet metals into profiled linear component(s) using the action of a top and bottom tool, forming the component under pressure.

Pultrusion: lineal component, typically incorporating fibre reinforcement, which is also drawn through a die.

Quenching: controlled rapid cooling from an elevated temperature by contact with a liquid, gas or solid.
Rainscreen cladding: an external cladding that forms an airspace that is drained, ventilated and can be pressure equalised. It protects the inner layers from heavy wetting and solar radiation. Typically the joints are open. The thermal performance and control of permeability are within the inner layer of the wall and do not form part of the rainscreen.

Recyclability: the quality of a product or material in which all or part of its value can be recovered at the end of its useful life, with minimal loss or change of quality and properties.

Recycling: the process of recovering valuable materials or resources from products at the end of their useful life, from waste streams or from production processes.

Reuse: the process of using something again or more than once. Often the reuse of a building will involve the introduction of a new programme of use – for example, changing the use from office to residential. The reuse of components will typically involve the same function but in a new assembly. Reuse can also refer to the use of reclaimed materials for their original purpose.

Roll forming: a method of producing a profiled linear sheet metal component by the progressive development of the shape by roll form tools.

Sand casting: a metal casting formed in a sand mould.

Spinning: a flat sheet of the metal is rotated at speed and formed over a hardwood or steel tool. Forming components with a rotated geometry only.

Strain: defines how far the atoms or molecules of a solid material is being pulled apart by an external force.

\[ \text{Strain} = \varepsilon = \frac{\text{increase in length}}{\text{original length}} = \frac{\Delta L}{L} \]

Strain is a ratio and therefore has no units.

Stress: is a measure of how hard the atoms and molecules of a solid material are being pulled apart or pushed together as a result of an external force.

\[ \text{Stress} = \sigma = \frac{\text{Force}}{\text{Area}} = \frac{F}{A} \]

Stress is measured in N/m².

Solution heat treatment: a thermal treatment in which an alloy is heated to a suitable temperature and held for sufficient time to allow soluble constituents to enter into solid solution, where they are retained in a supersaturated state after quenching.

Superplastic alloy: an alloy with high ductility, which is the product of a fine and stabilised grain structure. A superplastic alloy is capable of elongation of up to 1000 per cent.

Temper: stable level of mechanical properties produced in a metal or alloy by mechanical or thermal treatment(s).

TIG welding: in Tungsten Inert Gas welding, fusion between the metal components is induced by the arc, which burns between the electrode and the work piece, with filler rod being fed independently. This is shielded from the atmosphere by an inert gas such as argon.

Thermal conductivity or k-value is a measure of how easily heat passes through 1m² of material 1m thick under the influence of 1°C temperature difference and is measured in W/mK.

Thermal resistance or R-value: the measure of resistance to heat flow through a material, measured in m²K/W. U-Value is the inverse sum of the thermal resistances of all of the layers of a construction including the inner and outer surfaces.

Thermal transmittance or U-value: the property of a building fabric element, which describes the steady state heat flow, denoted by the symbol U, hence U-value, measured in W/m²K. It is defined as the quantity of heat, which flows in unit time through one unit area of an element, when the difference between the temperature of the air on the two sides of the element is 1°C.

Specific U-value terminology:
- Ucw: thermal transmittance of the total curtain walling (cw = curtain walling).
- Ug: thermal transmittance of the glass or glazing (g = glass).
- Uf: thermal transmittance of the frame (f = frame).

and
- Uw: thermal transmittance of the total window (w = window).

Twist: a winding departure from a flat plane.

Ultimate tensile strength: the maximum stress that a material can sustain in tension under a gradual and uniformly applied load.

Young’s modulus: expresses how stiff or floppy a material is, designated by E.

\[ \text{Young’s Modulus} \quad E = \frac{\text{Stress}}{\text{Strain}} \]
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Peter Bell & Partners 4.2–4.3
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Wolfgang Buttress, 2.131–2.132, 2.141, 2.143, 2.146
Yuando, 9.49
Zaha Hadid Architects, 1.2, 9.45–9.48
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acknowledgements
The Towards Sustainable Cities Research Team

Michael Stacey Architects

The practice has a thoughtful approach to the design of architecture. Michael Stacey Architects’ aim is to contribute to people’s lives and the culture of contemporary society through the informed knowledge of humanity, study of architectural precedents and urban habitats, combined with a detailed understanding of materials and fabrication processes. This knowledge base is underscored by a long-term commitment to research. The benefit of using a component-based architecture and off-site manufacturing is that it is possible to create high-quality and cost-effective architecture delivered with the shortest possible site time. This has been demonstrated on projects at a number of scales including the Regional Rail Stations, Cardiff Bridges and Ballingdon Bridge. The approach of Michael Stacey Architects is based on systems of components, yet each architectural project is client and site specific.

www.s4aa.co.uk

KieranTimberlake

The practice brings together the experience and talents of nearly 100 professionals of diverse backgrounds and abilities in a practice that is recognised worldwide. KieranTimberlake’s projects include the programming, planning and design of new structures as well as the conservation, renovation and transformation of existing buildings, with special expertise in education, government, arts and culture, civic and residential projects. KieranTimberlake seeks ways to improve the art, quality and craft of architecture through research into new materials, processes, assemblies and products.

www.kierantimberlake.com

Acknowledgements

The Towards Sustainable Cities Research Team would like to acknowledge the input into this research of:

- Chris Bayliss (Deputy Secretary General) and Marien Bertram (Director – Product Stewardship) of the International Aluminium Institute (IAI);
- Professor Philip Beesley, Philip Beesley Architect and The University of Waterloo, School of Architecture;
- Professor Brian Ford, emeritus Professor of Architecture at The University of Nottingham;
- Laura Gaskell, architect and editorial assistant on this report;
- Stephanie Carlisle, Efré Friedlander and Billie Faircloth of KieranTimberlake;
- Alexandre de Chevrotière, CEO of the MAADI Group;
- Cyriel Clauwaert, Director of the Aluminium Centre, Belgium;
- Jim Eyre, founding partner of WilkinsonEyre;
- Ron Fitch, Design Manager of Trimo;
- Bernard Gilmont, Director of Building & Transport Groups, European Aluminium (EAA);
- Jenny Grewcock of Hopkins Architects;
- Dr Anel Kilaire, Façade Consultant at Wintec;
- Christian Leroy, Founder and Director of Metals Sustainability Consulting;
- Justine Furness, Technical Director of the Council for Aluminium in Building (CAB);
- Jan Lukaszewski, Technical Manager of the Aluminium Federation (ALFED);
- Joachim Maier, Managing Director of Wefa;
- Ho-Yin Ng, Director of AL_A;
- Tom Siddle, Technical Manager of the Aluminium Federation (ALFED);
- Professor Bob Shell, Director of the Bartlett, University College London and sixteen*(makers)
  and
- all the fabricators, manufacturers, project directors, project engineers and project architects referred to in the text.

MSA IAI Cynigen Press Llundain, 2018
Aluminium Recyclability and Recycling

Aluminium is almost infinitely recyclable and this is well understood. This research identifies that aluminium-based projects dating back to 1950 that have been disassembled have all been recycled. 1950 is the first year of entries in IAI’s global mass flow model. The research reviews the reasons why buildings are demolished and rates of material recovery at the end of use. Key examples of short-life and relocatable architecture are set out, alongside the future role of Design for Disassembly (DfD). This research also identifies that there is a much wider uptake of cast aluminium components in architecture than may have been expected.

Written by Michael Stacey.

Aluminium and Durability

The durability of aluminium is probably one of the most important qualities of this metal when used to form architecture and infrastructure.

Charting almost one hundred years of the use of aluminium in architecture and the built environment, based on 50 built works from 1895 to 1986, with four historic exemplars being inspected and presented in depth. Twelve twentieth century award winning and historically significant aluminium based buildings were inspected leading to the successful non-destructive testing of aluminium finishes on three of these projects.

Written and edited by Michael Stacey.

Aluminium and Life Cycle Thinking

Life cycle thinking challenges architects, engineers and contractors to be mindful of the life history of any manufactured product and more specifically to understand the inputs (energy and water) and outputs (emissions to the environment) that result from the transformation of matter into product and from product to disposal. This report uses Life Cycle Assessment, a modelling method, to quantify and compare the environmental impacts and benefits associated with aluminium building components to those associated with alternative materials.

Written by Stephanie Carlisle, Efrie Friedlander, and Billie Faircloth.
The Hive at The Milan Expo 2015, designed by artist Wolfgang Buttress.
Aluminium: Flexible and Light
Towards Sustainable Cities

Aluminium: Flexible and Light, written by Michael Stacey, with contributions from Philip Beesley and Brian Ford, additional research by Michael Ramwell and Philip Noone, and further input from Stephanie Carlisle, Efrie Friedlander and Billie Faircloth of KieranTimberlake.

The forms part of the Towards Sustainable Cities – Quantifying the In-Use Benefits of Aluminium in Architecture and the Built Environment Research Programme, funded by the International Aluminium Institute [IAI] and undertaken by Michael Stacey Architects with KieranTimberlake and the Architecture and Tectonics Research Group [ATRG] at the University of Nottingham.

The Towards Sustainable Cities Research Programme is structured around the primary benefits of aluminium, as articulated by the Future Builds with Aluminium website (http://greenbuilding.world-aluminium.org), which is a sector specific component of the Aluminium Story (http://thealuminiumstory.com). Towards Sustainable Cities is a three-year programme quantifying the in-use benefits of aluminium in architecture and the built environment.

A primary aim of this research is to quantify the in-use carbon benefits arising from the specification of aluminium in architecture and the built environment, to complement the relatively well-understood emission savings from the use of aluminium transportation applications and through the recycling of aluminium scrap. A vital goal of this research is to quantify the potential contribution of aluminium towards the creation of sustainable cities – a key task now that over half of humanity lives in urban areas.

Key case studies demonstrating and quantifying the carbon savings arising from the specification of aluminium based architecture include: Kielder Probes by sixteen*(makers), Guy’s Hospital Tower by Penoyre & Prasad, dlr Lexicon by Carr Cotter & Naessens, i360 by Marks Barfield Architects and the Large Hadron Collider at CERN.

“Aluminium is an exceptional material because of its shear versatility. Used carefully, it can achieve a feeling of lightness, which is a form of power in itself. Not used carefully, it can be very heavy and appear heavier than steel!” Jim Eyre MBE