BRIDGES AND VIADUCTS DfMA GUIDE

buildoffsite

rail hub

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Executive summary

This guide illustrates the benefits of combining Design for Manufacture, Assembly and Offsite Construction in the context of long-term, large-scale bridge and viaduct projects. It explores how these innovative approaches work together to provide benefits at every stage throughout the infrastructure's lifetime, in terms of cost, time and fit, which benefit every stakeholder, from funder to the construction team, local population and the people who use the bridges and viaducts daily.

Offsite Construction enables more precise manufacturing, using components designed with longevity in mind that can offer additional functionalities, with the opportunity to build-in services for electricity, water and waste water, for example, as well as monitoring technology that facilitates better and more efficient lifetime management of the bridge or viaduct. Through careful design to achieve these functionalities, this guide also explores how Design for Manufacture and Offsite Construction can offer more aesthetically pleasing designs, because a larger proportion of infrastructure can be built in. This streamlines the overall design, resulting in a lighter weight product that is less dominant in its surroundings.

In addition, the guide considers the practical benefits of Offsite Construction, which include a reduced impact on the local population during assembly, thanks to the majority of components being pre-constructed to highly precise measurements, thus only requiring assembly on site. In the context of bridges and viaducts, this speed of assembly has the additional benefit of minimising disruption and risk, given that many of these infrastructure projects span existing road, rail or waterways. Offsite Construction can further improve safety, as well as productivity, by offering greater opportunity for longer term analysis and learning.

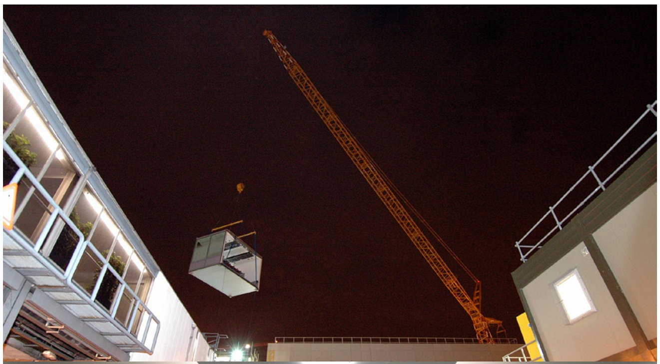
This guide reveals how Design for Manufacture, Assembly and Offsite Construction encourages innovation, in terms of design, materials and future-proofing, when designers, manufacturers and clients work collaboratively. It explores the specific example of how modularisation and mass customisation can enable the efficient creation of new products or families of products, which meet cost, design, functionality, safety and longevity requirements at every step of the process, from architectural concept through to procurement considerations and the logistics of assembly. The guide highlights key benefits, challenges and considerations for different stakeholders at each stage.

As a result, the guide also encourages a forward-thinking, forward-planning approach, which maximises the opportunity to incorporate specialist suppliers and facilitates the mass customisation of designs, where desired, to occur within an acceptable lead time, all while working efficiently within pre-established parameters, such as weight and dimension requirements. The guide highlights how this process of working also applies Lean principles, reducing waste and ensuring the project progresses at a time and cost-efficient rate.

The guide concludes with an overview of how designing not only for manufacture, but also for assembly consolidates many of these benefits for many stakeholders. For example, the guide encourages the reducing of component numbers while increasing their functionality, as well as designing to simplify logistics where possible, in order to capitalise on the benefits of Offsite Construction and Design for Manufacture and Assembly when building bridges and viaducts.

Case Study To Set The Scene

COURTESY OF BRYDEN WOOD



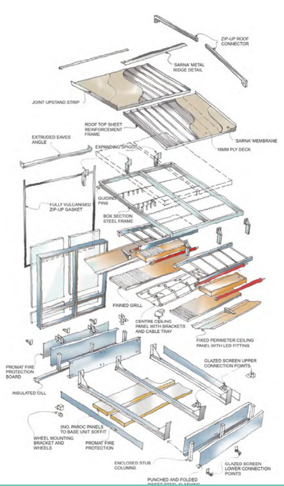
A new pedestrian bridge at Heathrow Terminal 3, the redevelopment of the central terminal area with car park, hotel and train station.

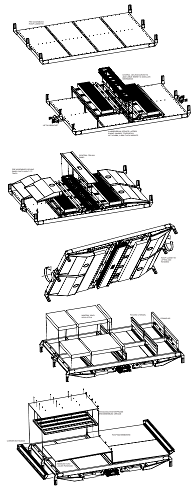
Replacing an existing bridge, the new link bridge spans 50m between the multi-storey car park and the arrivals area, forming a highly visible landmark in the Heathrow complex. The design of the bridge faced particular difficulties: its purpose is to connect two points that are offset and on different levels, and it spans 50m over a road that could not be closed for construction and also needed to take account of the requirement for future bridge connections at the ends.

To complicate matters further it was also designed to withstand possible impact loads from cargo vehicles and bomb blasts. The solution was a corridor made from 6m long, 5m wide prefabricated modules, suspended from a sloping arch.

The factory-assembled modules form fully serviced, interlocking corridor units, providing the only effective solution to this otherwise virtually insurmountable construction problem. As well as responding to the airports drivers for speed and reduced impact it was found that the corridor product improved safety through reduced site work (80% of work was taken offsite), quality through the manufacturing approach, and predictability through pre-engineering.

Wherever possible, pre-assembly was used to minimise on-site works and the number of deliverable components were reduced to a minimum. In addition, all modules were transportable by conventional haulage methods, reducing cost and delays.





2 Introduction

In such guides about Design for Manufacture, it has been suggested that the WHAT and the HOW are always focused on, but further questions need to be asked about the WHY and for WHO. This guide aims to address all four of these aspects so the benefits of Offsite Construction can be understood in the widest terms. Digital engineering is generally deployed when designing and constructing bridges and viaducts, so this guide does not attempt to explain the overall role of digital surveying or modeling.

This guide is aimed at a range of users, from clients and their commercial advisers, through to designers and contractors. Some sections are more relevant to some than others. The table below facilitates the dipping into this guide in a manner that suits different types of user. There are, however, some general points for all to consider.

WHY build bridges and viaducts with extensive use of offsite methods?

- These structures are some of the largest we build in our landscapes. As a result, they need to consistently be products of satisfying and enduring quality.
- Transport systems are more energy efficient if they can run on a relatively level route. DfMA can help with numerous aspects that can refine this, e.g. through the integration of alignment systems and positioning aids.
- Increasingly these structures are becoming multi-functional, integrating both the means of transport, communications and control systems, alongside impact mitigation measures (e.g. acoustic barriers). Integrating different materials and processes is easier in a more controlled factory environment (e.g. where dimensional tolerances are easier to achieve consistently).
- Bridges and viaducts become significant parts of the environments that they are constructed in. They therefore need to fit the context. The aesthetic must be appealing, and there is often the need to minimise the perceived visual impact upon the countryside or urban areas affected. More controlled offsite production processes enable the reduction of material content, allowing the use of lighter weight designs.
- Using offsite methods facilitates the process of documented learning and improvements over time, increasing productivity and safety.

WHO is impacted by the project and could benefit from offsite delivery methods?

- Direct users, transport system operators and passengers who could benefit from quicker delivery and more predictable performance.
- Those who have to live with the disruption and dust created by the construction process.
- Communities who need to pass over or beneath the structures, who may benefit from longer, more efficient spanning structures.
- Those who need the system to have an acceptable noise impact with consistent performance, achieving the design intent.
- Funders who need to have affordable, predictable solutions, in terms of cost, time and quality.
- The construction teams, with more of their members having a regular, local and safer workplace and reduced exposure to working in inclement weather.

WHAT can be built offsite?

- Almost all of a structure can now be produced off site.
- The scale of a project or programme may make it possible for specialist manufacturers to tool up for designs that they may not have previously offered, providing they are given sufficient notice.
- Design for manufacture and assembly does not necessarily mean design for standard products and DfMA should equally be considered as a way to provide a bespoke solution using elements produced offsite.
- For smaller scale projects, it is important for designers to understand manufacturers' cost drivers and capabilities where further capital investment is not feasible.
- It is recognised that the more offsite components are used, the more joints may be created, which could create corrosion risks if not adequately protected. While sealing joints is feasible, for greater durability, protection of vulnerable joints (e.g. using corrosion monitoring and impressed current cathodic protection) should be considered as part of the bridge or viaduct's structural health care management system. These can be incorporated during the manufacturing process.

HOW can offsite facilitate this?

- Just as designers need to consider manufacturability, manufacturers need to develop flexible production systems that enable the above.
- The ultimate goal of lean manufacturing is to be able to have an economic batch size as close to one as possible, with quick changeovers between the manufacture of different products.
- One objective of this guide is to help manufacturers meet demands for mass customisation, rather than just offering mass production.
- Manufacture and construction needs to be made safe and predictable, as well as economical, all of which can be enabled using offsite methods.
- Manufacturers and some major contractors know how to increase capacity in existing facilities or set up temporary factories relatively quickly, provided there is visibility of future requirements.
- Integration of onsite and offsite works is critical to delivering the potential efficiencies, in terms of cost, time and fit (dimensional) considerations.
- Even quite large (e.g. long) components may be transported by road, but logistics and siting of temporary factories are major considerations.
- Fortunately, design for assembly will tend to reduce the number of components, while design for manufacture will tend to simplify them (see works by Boothroyd and Dewhurst).

When specifying requirements, the above points should be addressed in the performance requirements and a design vision statement.

3

Who should use this guide?

Much of this guide will be of interest to all parties to a project. That said, clients might not want to delve into the detail of how to design for manufacture and assembly.

User	Sections
Clients	1, 2, 3, 4, 5, 6, 11
Client advisors (commercial cost, environmental risk - Construction and Design Management Regulations etc.)	1 to 11
Designers	1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12
Main contractors	1 to 12
Specialist Suppliers	1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12

Client needs

It is not only the construction process that is important – design is too. The structure must perform to meet the clients' and stakeholders' needs, including safety, cost, function, timing, aesthetic and other aspects. They all impact upon how the project quality considerations required by the client are met.

Performance, in this context, is a wide subject itself and defining it is not always straightforward. However, with some thought, it is usually possible to define requirements in performance terms. The client's advisers may well play key roles in facilitating this. The list below is not limited to designing for manufacture, logistics and assembly, nor is it presumed to be exhaustive, more an illustration of how many things can be defined in performance terms. Topics that could tend to favour offsite solutions are highlighted.

Health and safety

- **Compliance with the client's health and safety policies.**
- Compliance with CDM regulations.

Function as a bridge or viaduct

- What/who will cross it.
- Range of transport modes.
- Their frequency of use.
- Loads in the limiting conditions.
- Grade (incline) limitations.
- Weather considerations (temperature, wind, rain and snow loadings etc.).
- **Containment of vehicles.**
- **Integration of services:**
  - **Potable water;**
  - **Waste water;**
  - **Power;**
  - **Combined cooling, heat and power (CCHP);**
  - **Communications (including signaling);**
  - **Other distribution systems.**
- **Acoustic containment.**

Aesthetic

- How does the client and those who will live with the structure want it to sit in their landscape or townscape?
- Is there a requirement for structural and visual consistency with either:
  - A new network (such as a high speed rail system);
  - Existing network structures (such as London Underground or the canal and river networks).
- **Bridge strike risk sensing and management requirements.**
- Planning authority's preferences or imposed constraints.
- **Light-weight structures (which can be assured and repeatable when produced in a factory).**
- **What finishes are desired and to what quality?**
- Is there a requirement for contextual decoration (e.g. to reflect what characterises the area the bridge or viaduct is carrying people through) or to establish the 'brand' of a project (e.g. HS1 parapets)?

Innovation

- **Invite designers and suppliers to be innovative:**
  - **Allow time for technology suitability demonstration;**
  - **Specify how innovations should be presented for acceptability assessment.**

Continued...

Environmental

- **Compliance with the client's environmental policy or commitments.**
- **Minimising materials waste.**
- **Objectives for embedded carbon content.**
- Objectives for energy in use:
  - For the owner;
  - For the user (e.g. a flatter alignment helps because it uses less energy to cross than taller arches).

Logistics

- Limitations on transport loads.
- **Opportunities for temporary local manufacturing/pre-assembly sites.**

Impact on the local community during construction

- **Duration.**
- **Timing during the day.**
- **Noise limits.**
- **Dust management.**

Maintenance

- **Monitoring and control of structural health.**
- Access to and removal of replaceable elements (e.g. bearings, suspension cables, communications equipment, lighting etc.).
- Access to adjustable elements (e.g. tensioning of cables or rods).

Budgets

- Whole life cost to the bridge or viaduct operator:
  - Cost of capital to the owner (for use in discounting cash flows);
  - **Capital cost:**
    - **Total;**
    - **Interest charges;**
    - **Depreciation.**
  - Routine operating costs (energy use, monitoring and control systems and performance analysis reporting);
  - **Maintenance costs (planned and condition based/unplanned);**
  - **End of life costs.**
- Cost of use of vehicle operators.
- **Construction cost (part of the overall capital cost above).**

Dates

- Site availability to contractor (N.B. it can be counterproductive to specify a start on site date when the bulk of the work is to be completed in factories).
- **Hand-over to client.**
- **Opening.**

Clients are encouraged to express a need for good design that responds to the above performance requirements through their bid assessment criteria. One method of doing this would be to award bonus points for great design and not just settle for compliance with minimum criteria.

At the Offsite Construction Show in October 2017, The HS2 Project summarised their needs as:

- Speed – of trains and of construction.
- Safety – of system and construction.
- Environment
  - Noise;
  - Landscape;
  - Disruption.
- Durability (e.g. avoiding corrosion).
- Design quality – while achieving all of the other aspects.

Potential conflicts between these, such as increasing the depth and mass of the resulting viaduct designs to achieve functionality, were highlighted and suggestions as to how they may be addressed considered.

Clients generally have a project process requirement. In the case of the rail sector in the UK, one such example is known as Governance for Railway Investment Projects (GRIP). Such processes typically have a number of stages. For the purposes of this guide, the following GRIP stages are used to identify when different aspects of DfMA may be applied. GRIP is product (deliverables) focused, which is helpful in a DfMA context. The stages are:

1. Output Definition – establishes the scope of investment and, if needed, asset renewal.
2. **Feasibility – defines the investment goals and constraints to ensure that they can be achieved both economically and in line with the strategy.**
3. **Option Selection – assesses potential options and selects the best fit with client and stakeholder requirements.**
4. **Single Option Development – the implementation of the selected option.**
5. **Detailed Design – the creation of a detailed engineering plan that provides definitive costs, times, resources and risk assessments.**
6. Construction Test & Commission – the project will be completed to the design brief and plan.
7. Scheme Handback – the transfer of asset responsibility to the operators.
8. Project Closeout – contracts are settled, warranties established and benefits analysed.

These highlighted stages will be revisited in the forthcoming sections.

5 Architectural context

Other points to consider:

- Consider exploiting new materials and materials in new ways and combinations. It is important to question the norm in design (e.g. why use a certain material, and why use it in a certain way). Asking such questions is important in the creation of innovative designs.
- Designs need to be attractive and also deliverable for a competitive and affordable cost.
- The installation method can help to save costs/be more efficient.
- Quality, cost and time don’t need to be exclusive of each other. They can be compatible.
- Infrastructure is for people and is effectively forever. It is therefore critical that design is embedded in the process.
- This is a challenge for designers and clients, because the client has to put a value on design and not at the expense of cost. Supplier selection should include bonus marks for good design – not just compliance.
- Contractors also need an understanding of the value of design. Specialist contractors who manufacture offsite need to understand what flexibility they need to offer to meet clients’ needs and designers’ aspirations.
- Good design is about future-proofing.

Procurement considerations

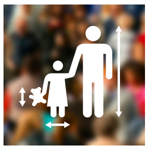
6

- Major infrastructure projects tend to be less problematic where a collaborative approach is adopted. (ICE https://www.ice.org.uk/news-and-insight/the-civil-engineer/march-2016/benefits-and-need-collaboration-in-supply- chain)
- Determine whether the requirements represent a family or portfolio of related products, if so:
- Consider commissioning a design for such a product range, including associated verification and validation testing, prior to procuring the overall project or programme that will use them;
    - Consider intellectual property ownership and design authority/responsibility aspects so that the resulting product family can be deployed through the preferred procurement process with responsibilities for the management of risks allocated to the parties most capable of managing them;
    - Consider who is best placed to fund the development activity;
    - Consider the role of product liability insurance;
    - Initiate the above early in the programme so that there is time to develop the product range.
- Define performance requirements, including:
- What it needs to span(s);
- What it needs to support;
- Environmental conditions it will need to function in;
- How it will need to fit into its architectural context (see the HS2 Design Vision below).
- Use a procurement process that:
- Invites and rewards innovation;
- Recognises value in the quality of designs submitted.
- Avoid creating firm expectations among stakeholders before DfMA opportunities have been explored.

HS2 Design Vision
Summary quick read version

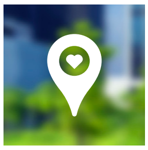
We aim to enhance the lives of future generations of people in Britain by designing a transformational rail system that is admired around the world.

Our work for HS2 is based on three core design principles of people, place and time.



People
Design for everyone to benefit and enjoy

1 Design for the needs of our diverse audiences
2 Engage with communities over the life of the project
3 Inspire excellence through creative talent



Place
Design for a sense of place

4 Design places and spaces that support quality of life
5 Celebrate the local within a coherent national narrative
6 Demonstrate commitment to the natural world

Time
Design to stand the test of time

7 Design to adapt for future generations
8 Place a premium on the personal time of customers
9 Make the most of the time to design

What design success looks like

→ Everything we make works intuitively and well for all our audiences
→ And contributes to one seamless and enjoyable experience
→ We deliver above and beyond the design brief
→ Bringing benefits of many kinds to UK citizens

→ All the elements are fit for purpose and sensitive to their context
→ National pride in the system is matched by a sense of local ownership
→ Small elements and big schemes meet rigorous environmental standards
→ And, collectively, add to our cultural and natural heritage

→ Every requirement for a high-speed rail system is met
→ And we have designed in the needs of the future too
→ We have joined up the nation with a system to last and evolve
→ And created a national project to be proud of for many years to come

Adaptability

7 Designing to adapt for future generations

HS2 must be designed and built to last.

The system will need to evolve over time in order to meet socie changing needs and take advantage of new technologies. It is that we make room for technologies that have not yet been in

Design decisions should help optimise the value of taxpayers' over the short- and long-term.

We are developing our Design Vision to gu decisions on related priorities, including:

→ Future-proofing

→ Whole life costs

Reproduced with permission from HS2 Ltd

7 Design for logistics

This would be a consideration in the UK rail sector project management "GRIP" process, Feasibility and Option Selection stages and would involve the following:

- Design needs to accommodate transport and lifting constraints.
- Primary and secondary routes need to be planned and validated.

Image courtesy of Knight Architects / McConnell Dowell Transfield JV

Image courtesy of Shay Murtagh Precast

Image courtesy of ARUP Ltd ©

- But these are not always limited by road constraints, as demonstrated by BAA at Gatwick Airport:

Image courtesy of ARUP Ltd ©

Image courtesy of R Fraser

Image courtesy of West One Management Consulting Ltd

- Business park access bridge across the M42. Assembled next to the site and launched across the motorway over night.

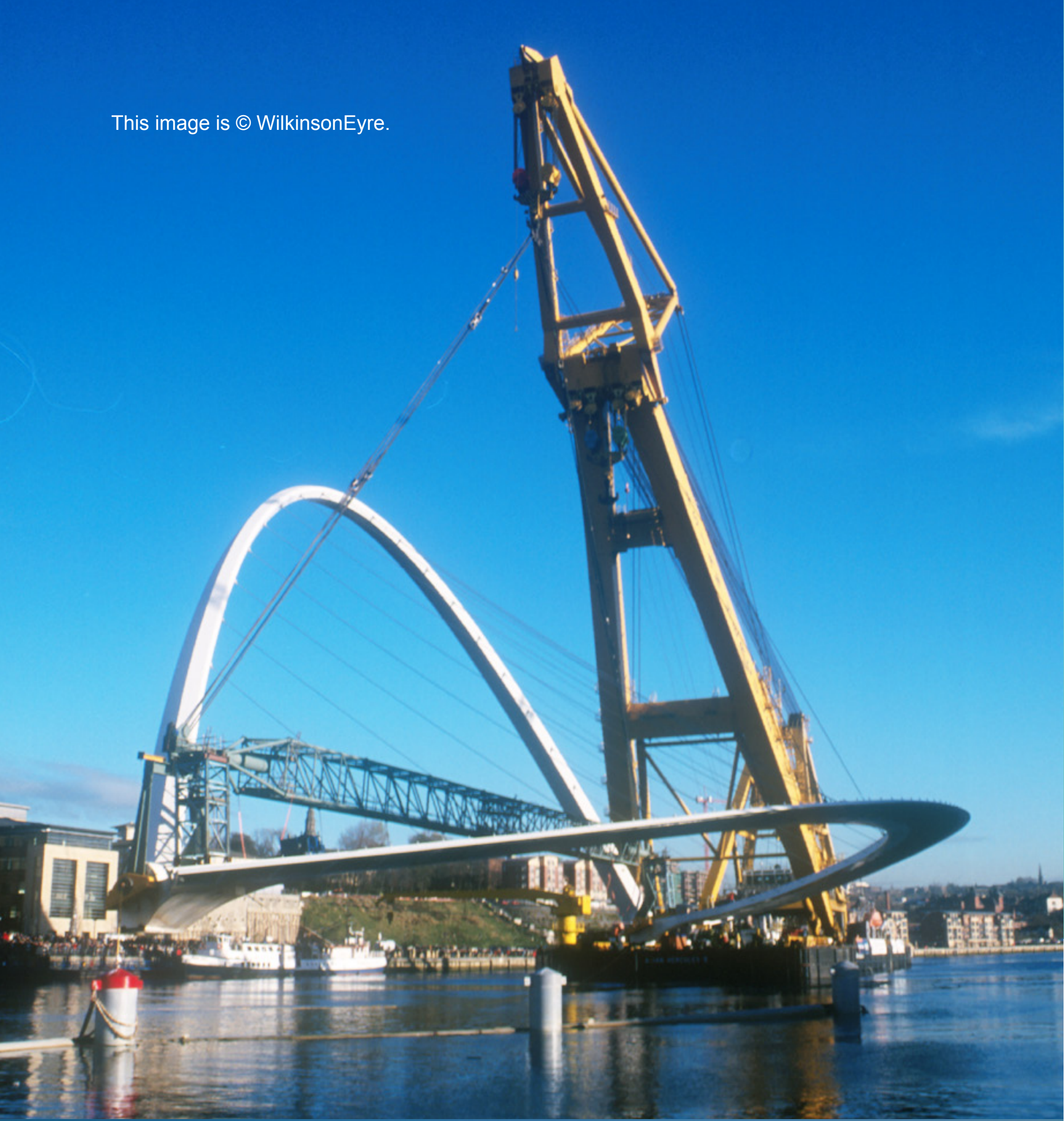


Image courtesy of Transport for Scotland

- And rivers can provide different opportunities:

- Crane and jacking plans require detailed planning, with an understanding of what equipment is available within what time frame.

- For the Queensferry Crossing, Hochtief brought in large steel deck modules from China, which were used as form work for concrete pre-casting at an adjacent site, before being floated under the lifting location.

Design for manufacture

8

It is key that designers understand the process capabilities of potential supply chains, including lead times for introducing different tooling or increasing capacity. When considering bridges, a lot rides on whether they are to be individually designed, or in a series or location where individual design is less of a requirement. For larger bridges and viaducts there is likely to be scope for project specific tooling. For bridges where the client would not have repeating elements, the use of standard designs may reduce cost and lead times significantly.

This should be considered initially at the GRIP Option Selection stage but will be considered further in the Single Option Development and Detailed Design stages.

Designing site works and interfaces to exploit known product parameters (weight, dimensions etc.) avoids unnecessary uniqueness.

The following points have been highlighted by manufacturers:

- Specification requirements that lead to product choice include:
  - Design life;
  - Durability;
  - Embedded carbon/whole-life carbon;
  - Architectural aspects;
  - Interfaces and associated tolerances;
  - Materials (concretes/steels/composites).
- Applying lean principles to production aids:
  - Flow;
  - Fast change overs (to enable small batch sizes);
  - Process stability (e.g. through product selection and project planning).
- Component sizing:
  - Existing asset and process capabilities;
  - Component weight vs crane capacity/reach/availability;
  - Component storage and handling techniques and capabilities, in plant logistics.

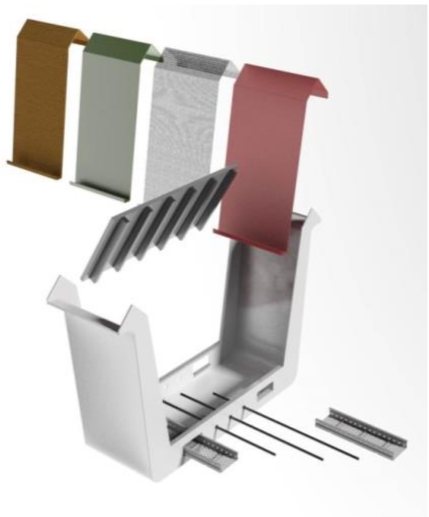
Other considerations include:

- Opportunities for modularisation for mass customisation (component sharing/swapping, cut to fit, mix, bus and sectional – Ulrich and Tung, 1991).
- Design for productivity (e.g. the use of programmable machines/CNC/robotics).
- Reinforcement design for modularisation and production automation.
- Design to make manufacture easy (e.g. reduced axis machining, fewer processes etc.).
- Design to exploit suppliers' process capabilities (e.g. where these are superior to minimum requirements of standards, or limitations in pre-stressing processes).
- Connection design and integration.
- Potential added value elements, i.e. the integration of components and systems into modules.
- Programme demand compared to production capacity.

With steel, concrete and composite structures, there are opportunities to use off the shelf designs.

Example 1: Shay Murtagh: Online design guidance for pre-cast concrete bridge beams – Bridge Beam Technical Manual available at: https://www.shaymurtagh.co.uk/bridge-beam-technical-manual-edition-3/

Example 2: Mabey Bridge: A small number of pre-engineered girder sections, in combination, enable efficient production of a wide range of spans.



Illustrations courtesy of ARUP Ltd ©

Example 4: Arup Ventures/Mabey Bridge composite modular footbridges – the Pedesta® product range.

9 Design for assembly

Design for assembly tends to reduce the number of components required, while incorporating a wider range of functions to those components. This is mainly considered in the GRIP Detailed Design stage and then exploited in the Construction, Test and Commission stage. Things to consider include...

- Programme demand compared to production capacity.
- Minimising and managing interfaces.
- Simplifying and reducing (combining) sub-assemblies and component parts.
- Site constraints, including space for delivery, storage, safe lifting and temporary works.
- Reducing assembly risks and using error proofing.
- Making assembly easy, e.g. by reducing the range of tools or lifting equipment required.
- The compatibility and accumulation of component tolerances.
- Design for easy handling by...
  - The inclusion of well positioned lifting points that enable components (or assemblies) to be presented to their counterpart in the correct orientation;
  - Positioning aids, matching components using cones or spheres.
- Incorporation of added value components, for example...
  - Efficient methods of jointing;
  - Electrical systems, including sensors;
  - Abutments;
  - Containment;
  - Acoustic barriers;
  - Ducting;
  - Drainage.

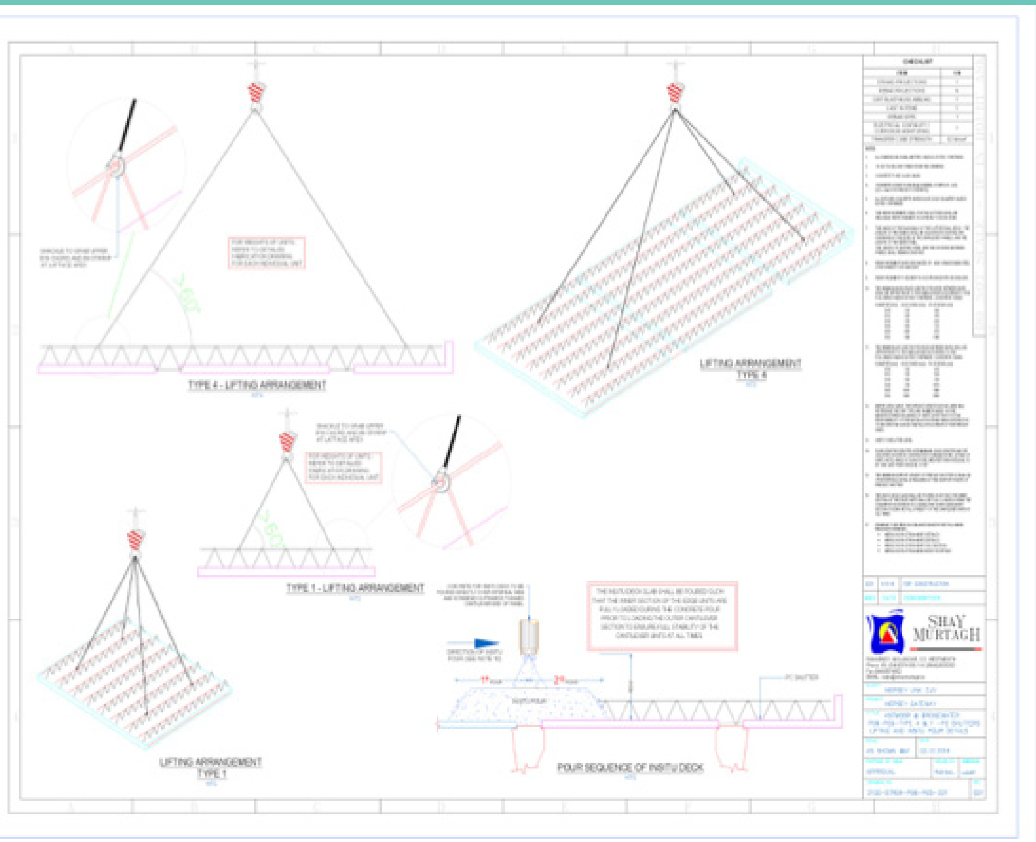
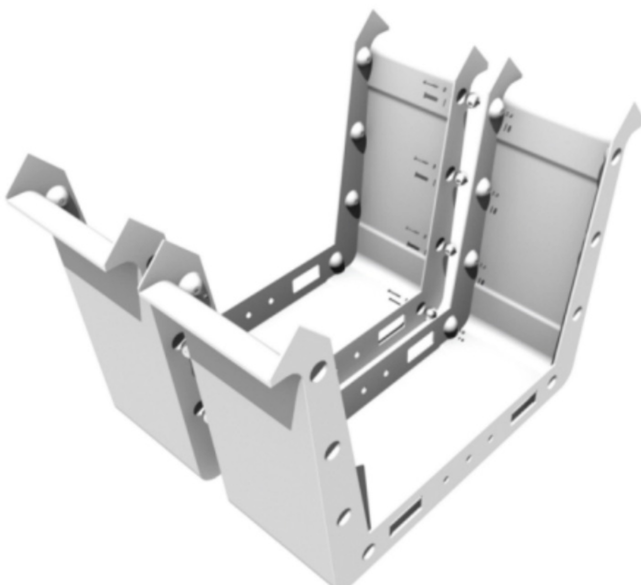


Image courtesy of
Shay Murtagh

- Incorporation of temporary works, for example:
  - Edge protection;
  - False-work, propping and access equipment;
  - Participating permanent formwork, e.g. on the Mersey Gateway project:

- Integration of in-situ reinforcement (e.g. using 3D scanning and modeling).
- Integration and assembly of following trades and equipment.

The example to the right includes aides for alignment of adjoining modules as the connecting cables are put under tension.



Illustrations courtesy of ARUP Ltd ©

10 Design for maintenance and durability

In order to ensure longevity of the designed components it is useful, if not essential, to consider maintenance and durability as part of the GRIP Detailed Design process that will inform and facilitate the Scheme Handback stage.

There are two principles to follow:

- How do we know there is a problem that needs addressing? This is structural health monitoring (SHM).
- What do we do to address the identified problem? This is structural health care (SHC).

The first principle requires intelligent infrastructure sensing that can take many forms, such as structural sensing (for example, load, stress/strain, vibration, movement, impact and wear) and influence of environment monitoring (for example, corrosion potential and rate, moisture ingress, chloride ingress, carbonation, chemical degradation and fire). The influence of both these modes of monitoring on the service life of the structure can be built into the design of the element as well as the overall structure to track issues and identify problems early and therefore cost-effectively.

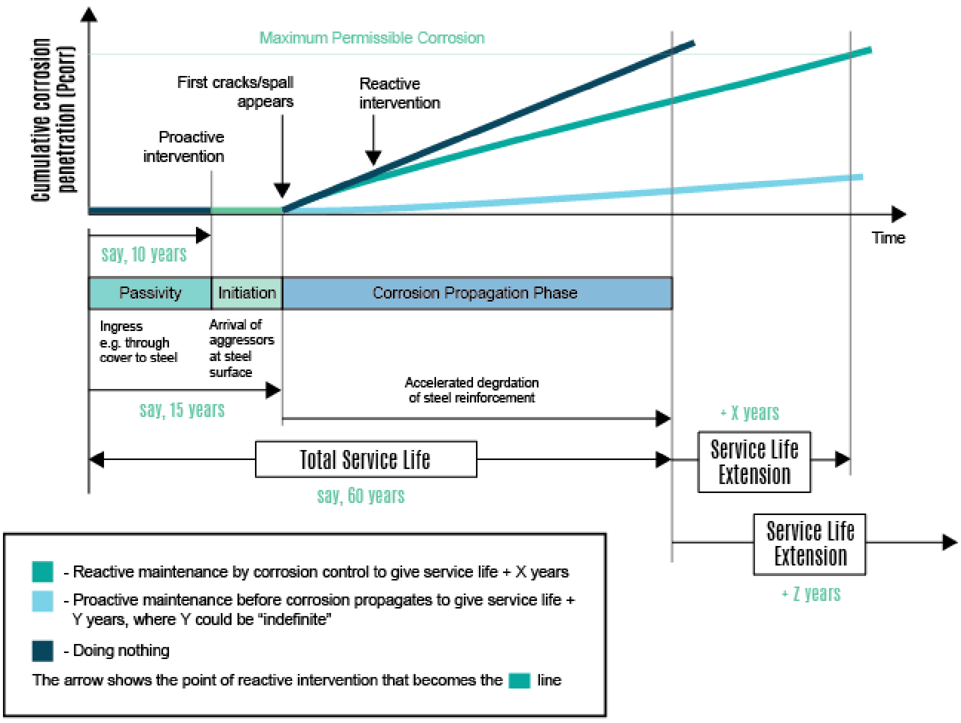
The second principle requires consideration of mitigation techniques within the structural design, materials choices and building in of direct measures, such as cathodic protection for corrosion control (see ISO EN BS 12696:2016). An example of designing direct control measures would be where the use of multiple precast elements results in the presence of additional joints. These in turn are vulnerable to future degradation through the ingress of environmental accelerants and would therefore benefit from early designed mitigation systems.

Technology has emerged and continues to develop to target future vulnerabilities of structures that aim to provide sustainable service life* for all structure types.

Another issue to consider during the design for maintenance is the ability to interchange structural elements from old to new whilst minimising disruption to the usage of any structure. An example would be the ability to remove and replace post-tensioning tendons within ducts or replacement of bearing components with limited impact on the operation of the viaduct. Again, the answer may lie in the designed use of technology at the “cradle” stage to extend the “grave” stage by building in control features.

It is essential therefore within Design for Maintenance and Durability to consider monitoring, control and ease of replacement strategies to futureproof the structure.

*Buildoffsite has a complimentary presentation on designing structures for “indefinite” service life that develops this theme further.



Schematic plot demonstrating service life extension principle based on Tuutti model for corrosion progression with time.

Illustration courtesy of C-Probe Systems Limited

11 Conclusions

DfMA has a significant role to play in delivering stakeholder value, in terms of the quality of the end product, and how it can be delivered efficiently. In getting to this point, it is essential that the team considers why the bridge or viaduct is needed and for whom. Value needs to be understood in the wider stakeholder context and then used to inform decision making at all project stages, based upon an agreed set of performance requirements and a design vision endorsed by the client.

Client leadership is needed to achieve the above and to enable a project to exploit DfMA in a collaborative manner, using an appropriate procurement method.

The architectural context must be considered. Whilst standard products have a role to play in reducing cost, the principles of mass customisation need to be applied and a range of different types of modularisation exploited to achieve the client's vision, or that of their architect.

A lot can be defined in performance terms.

The procurement method can facilitate or frustrate obtaining the benefits of DfMA, and guidance has been provided in Section 6.

Section 7 has demonstrated that the logistics of delivering and assembling large structures will have a significant influence on how DfMA is applied to bridges and viaducts, but large elements can be moved and jacked or craned into place, as illustrated by the 2,900-tonne bridge over a taxiway at Gatwick Airport and several road and river crossings.

Design for manufacture requires an understanding of supply chain capabilities and capacities, along with the lead times for changing them or introducing new capabilities. It is therefore important to consider DfMA from the early conceptual stage of a project. Manufacturers have listed a wide range of points to consider in Section 8 and signalled that given sufficient time and scale of demand, they are willing to develop their capabilities to meet a client's needs. If it is left too late, they can only offer a product based on their existing capabilities and mould designs etc.

Design for assembly is particularly relevant for bridges and viaducts. They are often built over or next to operational roads, railway lines, waterways and areas of natural beauty or scientific interest. Assembly needs to be quick and predictable, deliver the design vision and, above all, be safe. Section 9 provides a wide range of things to consider that will help achieve all of this.

Bridges and viaducts are, with very few exceptions, long term additions to our land and townscapes. We need to design them to be durable structures that can be monitored, controlled and maintained cost effectively. They can be designed for indefinite life, but in the past decades we have seen such structures taken out of service earlier than planned and become an onerous maintenance burden. Taking a whole-life, cost-based approach can avoid this, with Section 10 providing practical guidance.

Overall, DfMA can have a very significant beneficial impact on a project or infrastructure system. The application of composite materials, robotics and additive manufacturing (e.g. 3D printing) to construction is going to make it even more attractive. Let's use it more often!