Design for manufacture and assembly: its benefits and risks in the UK water industry

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A study was undertaken to investigate the impacts of design for manufacture and assembly (DFMA) on one of the UK's largest water companies. The study collected data on historic and new building projects that, in some part, used DFMA principles. This was supplemented by qualitative data from interviews conducted with senior engineers and managers from across the company and its direct tier 1 supply chain. The study shows DFMA to be poorly defined within the UK water industry, and a new definition is presented here. This is supplemented with a scoring tool that enables users to state clearly what they want with regard to DFMA and provides a means of assessing its potential during project tenders. The data support the perception that it can deliver cost, time and quality improvements and show that early DFMA-focused management is essential in delivering these improvements. However, the study also reveals that DFMA carries risks common to the application of new technologies, so risk management tools need to recognise the additional risks associated with it. A method for reviewing specific operational risks typical to the water industry against product uncertainty is presented here.

1. Introduction

Design for manufacture and assembly (DFMA) has recently become a hot topic in the UK water industry. As a concept, it is not new. Standardisation and pre-assembly have existed as a means to streamline manufacturing since the 1970s and contributed to significant savings and increased production efficiency. However, in contrast, construction within the water industry typically employs unique project teams to deliver bespoke products constructed on-site, and this approach often fails to meet client expectations on cost, time and quality. Now, UK water companies are seeking to gain efficiencies in their capital programmes and there is an increasing awareness across the water industry that DFMA will help to achieve these efficiencies. Through the collection of novel data on its current use in the UK water industry, this study defines DFMA in the context of the UK water industry and establishes its benefits, barriers and risks.

1.1 Background

Standardisation and pre-assembly have existed in construction before the term DFMA became common. Standardisation and pre-assembly are not new and, in some cases, not innovative (Gibb, 2001). Many historic structures incorporate these construction principles, such as the Crystal Palace of 1851 and the UK's first Iron Bridge of 1779 (Phillipson, 2003). Other examples begin as early as 1624, when England exported pre-fabricated, standardised houses, churches and hospitals to the colonies (Smith, 2010). Mass pre-assembly was, for a short time, a standard delivery model for UK housing following both the First and Second World Wars. Local demand generated by unusual circumstances exceeded the local capacity to supply urgently the needed housing (Gibb, 2001). Bad workmanship during this period led to poor-quality structures. In 1968, 2 months after completion, the high-rise pre-assembled residential block Ronan Point in London catastrophically failed following a gas explosion (Phillipson, 2003).

In the 1970s, lean processes began to appear in manufacturing, principally design for manufacture (DFM) and design for assembly (DFA). In 1988, the Ford Motor Company reported that DFA had contributed to billions of dollars in savings (Boothroyd *et al.*, 2010). At that time, DFM also became popular but conversely focused on the ease of component manufacture. DFA often conflicted with DFM. To achieve ease of assembly, parts become more complex, requiring more difficult manufacturing. DFMA is the combination of DFA and DFM; it strives to achieve the optimum process considering both manufacture and assembly. Gilligan and Dewhurst (2009) suggested that DFMA saves manufacturers, on average, 50% of their total product cost; this is a significant saving but one that is echoed closely by others (Ashley, 1995; Danford, 2008; Kobe, 1990; O'Donohoe, 2010).

House builders were early pioneers of DFMA. Architects saw connections between their own and the automotive industry; Buckminster Fuller wanted to create 'houses like Fords' (Ägren and Wing, 2014). This is perhaps the first instance where the similarities between construction and manufacturing were voiced. Today, Laing O'Rourke manufactures building components through a mechanised production line similar to that seen in the car industry (Laing O'Rourke, 2013) and many large building projects employ DFMA (Vernikos *et al.*, 2012).

United Utilities (2014) is the UK's largest water company, serving 3.2 million homes and businesses in the north-west of England. During the privatisation of UK water and sewerage authorities in 1989, the Water Act 1989 created three industry regulators: the Environment Agency, the Drinking Water Inspectorate and Ofwat. Water companies must meet the standards set by these authorities, and this need principally drives their capital investment programmes. Since privatisation, legislation has required UK water companies to work in 5-year cycles; in the current cycle (2015–2020), companies

will invest £44 billion (Pitcher, 2014). Recent amendments to the Water Act 1989 will introduce competition into the water industry, permitting companies to supply business customers outside of their historic supply areas. This is a move away from the monopolies of the past, presenting companies with both threats and opportunities. Water companies will need to operate more efficiently to achieve lower bills and retain customers; this includes faster and cheaper delivery of capital projects. Some across the water industry believe that DFMA will achieve this.

1.2 Benefits and drawbacks of DFMA

Many suggest that DFMA can achieve cost savings in construction (Egan, 1998; Fox *et al.*, 2001; Gibb, 2001; Gilligan and Dewhurst, 2009; Jonsson and Rudberg, 2014; Vernikos *et al.*, 2012). This view is complemented by several UK water industry-specific news articles (Bancroft and Thomson, 2013; Cuthbert, 2013; Gaines, 2013; Lennen *et al.*, 1996; Smith, 2013). A study by Pan and Sidwell (2011) within the building industry showed cost savings of up to 13%. However, comparable cost profiles for water industry-specific projects delivered by DFMA and traditional construction methods (TCMs) are not readily available. Gilligan and Dewhurst (2009) note the need for robust cost modelling to prove the benefits of DFMA. Others note that DFMA is not always the cheapest option (Goodier and Gibb, 2006; Nadim and Goulding, 2011; Pan *et al.*, 2007; Rahman, 2014). High factory start-up costs and limited demand for mass-produced products drive higher prices (Jaillon and Poon, 2010; Pan *et al.*, 2007; Rahman, 2014; Winch, 2003). Fox and Cockerham (2000) recognised the influence that clients have in driving the demand required to enable manufacturers to establish mass-produced products.

Designers must optimise for standardisation and assembly, not minimum parameters (Boothroyd *et al.*, 2010; Ciria, 1999). Up to 80% of project cost is committed to the design phase (Kamara *et al.*, 2007; Prasad, 1995), while this phase accounts for only 6% of the total cost (Wallace and Sackett, 1996). DFMA forces designers to incorporate construction into the early design phases when changes are less costly (Alarcón and Mardones, 1998; Ciria, 1999; Olawale and Sun, 2010; Stecklein *et al.*, 2004; Wallace and Sackett, 1996).

Deliberate, systematic use of DFMA throughout a project increases productivity and reduces production durations (Ciria, 1999; Gilligan and Dewhurst, 2009; Liao *et al.*, 2011; Phillipson, 2003; Wallace and Sackett, 1996). Off-site manufacture is less vulnerable to delays from poor weather (Phillipson, 2003), and standardised components lead to fewer complications in purchasing, inventory management and manufacture (Wallace and Sackett, 1996). Clients therefore have greater confidence in their ability to deliver on schedule when using DFMA (Gibb, 2001). DFMA integrates design and construction, achieving shorter overall project durations (Larsson *et al.*, 2014; Walker, 2007). Time savings of between 50% (Smith, 2010) and 70% (Kamara *et al.*, 2007) have been shown compared to TCMs.

Compared to TCM, the use of off-site factory environments improves quality control, supervision and testing, delivering higher-

quality products with less frequent and severe defects (Jaillon and Poon, 2010; Johnson and Meiling, 2009; Li *et al.*, 2011; Wallace and Sackett, 1996). In part, these improvements can reduce waste by up to 84% (Jaillon *et al.*, 2009; Lau and Yuanb, 2013; Quale *et al.*, 2012; Tam *et al.*, 2007) and improve health and safety. The severity and frequency of injuries on-site are reduced with the adoption of simpler assembly tasks (Court *et al.*, 2009; Rubio-Romero *et al.*, 2013). These studies, however, contrast with the poor performance and failures seen in the past (Nadim and Goulding, 2011; Parker, 2014). Historic poor workmanship has resulted in the perception that pre-assembly means poor quality and reduced asset life (Phillipson, 2003). This perception is difficult to overcome in an industry that is risk-averse.

Modular construction requires interchangeable, predictable interfaces (Ciria, 1999). Achieving accurate fit between components is a prerequisite for DFMA. Skilled labour is needed to achieve accurate on-site assembly (Rahman, 2014), which needs to be supported with modern data management tools. Building information modelling is seen by some as a key enabler of DFMA (Ågren and Wing, 2014; Gilligan and Dewhurst, 2009; Wallace and Sackett 1996). Standardisation limits design flexibility and requires early design freezes to enable factory production. These points are barriers to DFMA (Gibb, 2001; Gibb and Isack, 2001; Jonsson and Rudberg, 2014; Lu and Liska, 2008; Pan *et al.*, 2007; Phillipson, 2003; Rahman, 2014; Walker, 2007). Transportation, restricted site access and small working areas are other potential barriers (Cole, 2014; HMRC, 2014; Lau and Yuanb, 2013).

DFMA removes team fragmentation seen in TCM (Alarcon, 1997; Egan 1998; Li *et al.*, 2011; Rahman, 2014). It forces collaboration between clients, contractors and suppliers (Chena *et al.*, 2009; Gibb, 2001; Jaillon and Poon, 2010; Kamara *et al.*, 2007). The integrated team is principal to DFMA success in construction (Doran and Giannakis, 2011; Kamara *et al.*, 2007). To achieve this, DFMA requires an industry change from traditional contracting that forced sequential engineering and the separation of design and construction (Larsson *et al.*, 2014; Prasad, 1995). Walker (2007) suggests that traditional procurement, with a clean contractual break between design and manufacture, limits the opportunity for DFMA.

2. Study methodology

A mixed research approach was used to collect novel data on the current use of DFMA in the water industry. Data were sourced from interviews with senior engineers and managers in the UK water industry and from project case studies that incorporated specific aspects of DFMA at United Utilities (UU). This combined approach was used to remove the barriers associated with single-source data collection and enhanced the validity and reliability of results (Abowitz and Toole, 2010).

2.1 Case studies

Fifteen historic UU projects were identified as case studies to provide evidence of the previous use of DFMA at UU. Restricting

research to only UU projects removed confounding variables associated with multiple worldviews. Only projects that incorporated aspects of off-site manufacture or standardisation were included in the study. Case studies were reviewed by examining project documents and through discussions with both project managers and engineers. As far as possible, information on the cost, time and quality implications of incorporating DFMA into these past projects was ascertained, although the extent of accessible data varied between projects.

2.2 Interviews

Fourteen people took part in the interviews. Eight interviewees were employees of UU, and six were from the construction delivery partners (CDPs) Laing O'Rourke, Imtech and Atkins; Advance; C2V+; and Mott MacDonald Bentley. All held senior positions, affording visibility of multiple projects; thus, all were considered able to provide informed data based on a range of real project experience. Interviews were conducted on a one-to-one basis and lasted approximately 1 h. Participants were posed with the following five standard questions, which guided discussions throughout the interviews.

- What is DFMA?
- What are the barriers to DFMA?
- What are the benefits of DFMA?
- What are the risks of using DFMA?
- What impact do contract and procurement structures have on DFMA uptake?

Detailed notes were taken throughout the interviews, and participants were asked to elaborate on and clarify comments made where necessary. This resulted in the collection of detailed qualitative data concerning the use of DFMA in the water industry.

2.3 Analysis

Using the data collected from both the interviews and case studies, content analysis was used to identify trends within the qualitative data based on methods presented by Taylor-Powell and Renner (2003). Interview responses and information from case studies were categorised into the following six predefined primary groups depending on the aspect of DFMA represented

- definition
- benefits
- risks
- barriers
- contract
- others.

Each data row was reviewed and assigned to an emergent category. The emergent categories were developed during data analysis to provide a means of identifying trends and producing results. The data collected from the interviews were then considered alongside those collected from the case studies.

3. Results

3.1 Case studies

Data collected from the project case studies are summarised in Table 1. It shows how a project's use of DFMA impacted cost, time and quality. In some instances, the case studies did not provide enough data to describe the impact of DFMA. Typically, DFMA has a positive impact. The case study projects characteristically achieved faster delivery at lower cost by adopting DFMA. Fewer quality improvements were seen, but this seems to stem from poor historic product selection and not as a direct result of DFMA. The case studies highlighted a need for improved delivery processes and communication between parties. The lack of focused DFMA experience hindered construction, and many difficulties were seen at the bespoke interface (i.e. ground and existing asset interfaces). These points support the theory that DFMA requires a different delivery approach to TCM.

Case study data were not always complete and may not reveal all key aspects relevant to the study. The case studies that used DFMA would have showed clear benefits over TCM at the tender stage and hence may represent only instances where DFMA is clearly the better-value solution. The study did not consider other variables that impact solution delivery; it used no control groups to remove these variables. The low number of projects delivered by DFMA, compounded with limited available data, prevents deeper analysis. As project administration was not preset to inform this study, the extent of data and the ability to analyse them were limited. DFMA is complex and incorporates several distinct elements. The case studies do not represent DFMA at its greatest potential; hence, the data collected may not present the full breadth of benefits and risks.

3.2 Interviews

Figure 1 presents the percentage split of data rows across each primary category. In total, the analysis considered 454 lines of individual qualitative data. It shows a similar spread of percentage of responses between the primary categories from the CDPs and UU interviews. However, there is a noticeable difference of 5–10% in the 'risk' and 'benefits' primary categories. This potentially indicates a cultural difference between UU and the CDPs, where UU sees greater risks with DFMA and the CDPs see greater benefits.

Four categories emerged in the 'definition' primary category: modular, off-site, collaborative delivery and standardisation. Figure 2 presents the spread of responses across the emergent categories. Off-site construction was the most common response. Standardisation and new delivery methods were the next most common responses. Two responses voiced concurrent engineering as an aspect of DFMA, and modular construction was often directly mentioned.

The analysis identified six emergent categories in the 'benefits' primary category (Figure 3). Responses indicated improved

Table 1. Overview of cost (C), time (T), quality (Q) and other notable performance elements identified within the case studies

	Operation	C	T	Q	Others
1	Shallow (<15 m) rectangular storm storage tank	?	Yes	?	■ Poor control and application of the ground-to-product interface resulted in cost increase and delays during construction. ■ Lack of site staff experience in assembling the DFMA product led to on-site difficulties. Inflexibility of precast concrete (PCC) units made this worse. ■ When other parties became involved in the PCC design, the design period grew. Better communication is required between parties with faster agreement on design options and earlier design freezes.
2	Post-tensioned circular storm storage tank	?	?	No	■ Difficult to predict total life-cycle cost. These tanks now require regular inspection and costly maintenance. ■ PCC units require careful transportation, storage and assembly. Poor management of these elements results in reduced asset life.
3	Chemical dosing modular units	Yes	Yes	Yes	■ Standard modular design provided by a framework supplier. ■ Is the standard approach for delivering dosing units.
4	Modular stairways	Yes	Yes	?	■ Less vehicle deliveries compared to TCM alternative. ■ Reduced customer impact compared to TCM alternative.
5	Modular above-ground water filter units	?	Yes	?	■ PCC off-site solution was offered as an alternative, offering a time saving. ■ Maturity of solution was deemed inadequate, with no operational experience of the PCC system being used in this application. Risk was deemed too high. ■ Traditional in situ build was used.
6	Modular above-ground water filter units	?	Yes	Yes	■ Material selection impacts asset life and whole-life cost. Units were steel in place of traditional concrete. ■ Reduced the construction duration from 30 to 10 months. ■ On-site solution could not achieve the delivery date; off-site solution was significantly faster to deliver.
7	Deep (>15 m) rectangular storm storage tank	?	?	?	■ Off-site solution was considered during concept design, but lack of flexibility in systems made it unsuitable for the local site conditions. ■ Ground conditions made design/installation of off-site PCC units difficult. ■ Depth of tank was fixed by local storm network. This would require a deep excavation and large working area that reduced the cost and time benefits of using a PCC system. ■ A diaphragm wall construction was used instead.
8	Deep circular (>15 m) storm storage tank	No	No	No	■ DFMA components place greater value in the parts off-site. Any incidents during transport are more severe as these parts are costly and timely to replace.
9	Below-ground sewer overflow chamber	Yes	Yes	Yes	■ Safer with less working at height and confined spaces compared to TCM alternative. ■ Chamber constructed from plastic in place of concrete – enabling the chamber to be manufactured in one piece, transported to the site and lifted into place.
10	Above-ground wastewater filter units	Yes	Yes	Yes	■ Safer, less working at height and exposed reinforcement. ■ Construction complete – estimates against TCM show cost saving of 12% and an on-site time saving of 46%. ■ Just-in-time delivery removed double handling and the need for a large storage area.
11	Rectangular large water storage tank	?	?	?	■ Off-site solution was selected to reduce time on-site and customer impact. ■ Solution provides operational redundancy, reducing the risks associated with using a system with limited UK operational experience. ■ Construction is ongoing.
12	Water pumping stations	Yes	Yes	Yes	■ Used a standard supplier product customised to individual project needs. ■ Standard product used across several projects facilitated by batch procurement, enabling the supply chain to develop the standard product. ■ Faster on-site installation reduced impact to customers.
13	Manholes	Yes	Yes	Yes	■ Safer, less confined working spaces. ■ Faster on-site assembly, removing the need to cast in situ benching.
14	Modular water treatment works	Yes	Yes	?	■ Contract let under a performance specification, enabling the contractor to develop the design. ■ Asset near the end of life and approaching replacement (built in 1980s). ■ Steel tanks have degraded; it has been noted that similar assets constructed of in situ concrete have a longer asset life.
15	Above-ground circular wastewater filter units	?	?	?	■ Design-and-build contract. ■ Performance specification gave the contractor greater freedom to integrate definition and construction stage design.

Figure 1. Percentage of data rows in each primary category

Figure 2. Percentage of data rows across the emergent categories within the 'definition' primary category

Figure 3. Percentage of data rows across the emergent categories within the 'benefits' primary category

quality stemming from the factory environment. Several responses also cited improved certainty of project outcomes. Improved quality was a more frequent response in the UU interviews. The factory environment was also noted to increase productivity. Points noted included longer working hours, cheaper labour, improved logistics and less exposure to on-site unknowns. Productivity was a more frequent response in the CDP interviews. Most respondents stated reduced time as a key benefit. They saw DFMA as a faster delivery approach compared to TCM. Reduced time on-site also led to reduced disruption for both external and internal customers. Improved health and safety were also identified as a benefit of better working conditions found in the factory environment and less exposure to on-site risks. Several

responses indicated reduced total project cost. This was the third most frequent response behind time and quality.

The analysis identified six emergent categories in the 'barriers' primary category (Figure 4). Several responses considered traditional delivery a barrier to DFMA. This included limited contractor input at design; lack of DFMA-focused processes; no means of identifying, requesting or scoring DFMA at tender; and non-integrated team structure. One noted the large number of client stakeholders required for project approval as a barrier. The CDP responses considered traditional delivery as a barrier twice as frequently as the UU responses. DFMA needs programme-level management to deliver the benefits associated with standardisation. One response also noted the need for programme-level scheduling to enable the supply chain to plan factory schedules and purchase through bulk buying. UU response frequency in this category was nearly five times greater than those by the CDPs. Some identified UU's standards as restricting the contractor's ability to deliver DFMA solutions. Several questioned whether UU should move away from their in-house standards and adopt those developed by other water companies or the supply chain. However, others considered UU's in-house standards as protection against low-quality solutions. Also noted was that UU's standards do not fully consider the consequences of some new technologies and for them to do so would require lessons learnt from completed projects. Several noted the lack of cost and operational data to support the use of DFMA as a barrier. Some believe that UU is risk-averse and blocks the adoption of new technologies. Culture represented the greatest number of responses (nearly 50% of the total). Many believe UU's culture is not in line with DFMA principles and that a significant change is required for DFMA to be successful.

The analysis identified seven emergent categories in the 'risk' primary category (Figure 5). Risk management represents the remarks that consider poor project risk management regarding the use of DFMA. Prominent remarks were the difficulty in selecting

Figure 4. Percentage of data rows across the emergent categories within the 'barriers' primary category

Figure 5. Percentage of data rows across the emergent categories within the 'risk' primary category

projects for trialling DFMA and the lack of awareness when considering the implications of using new technologies. Risks are located in different elements of a DFMA project compared to TCM, requiring a different resource profile to manage them. Risk management was a more frequent response by the CDP than by UU and includes the highest number of responses in the seven emergent categories. Data show quality as a key risk. This includes the lack of quality assurance or technical governance on the long-term durability of products. The number of UU responses in this category suggests that UU sees quality as the key risk of using DFMA. Several UU and CDP responses considered cost a risk. Higher cost was associated with limited opportunities for reuse and standardisation of solutions or poor whole-life costing. Some responses identified DFMA solutions as demanding more cost for maintenance, operation and demolition as a result of designing a solution based on ease of construction and not on operational performance. CDPs see cost as a greater risk than the UU does. Responses noted less flexibility in standard products resulting in less efficient assets, design compromises and complexity of interface with existing assets. Responses included the difficulties of achieving the same asset life as TCM and the inability to make changes to products to meet changing operational requirements. DFMA requires integrated teams, and several responses identified poor communication and team structure as risks to project success. Some noted poor links between the assembler and supplier as a source of on-site difficulties. CDP noted communication as a greater risk than UU did. Several responses noted on-site assembly's not achieving the tolerances or methods specified by the supplier due to unskilled labour. Off-site, the lack of skills to deliver DFMA may result in poor construction scheduling and poor designs.

4. Discussion

4.1 Defining DFMA

The construction industry lacks a suitable definition for DFMA. With industry differences preventing a direct transfer of definitions from manufacturing, construction must suitably modify DFMA to meet its own needs (Ciria, 2013; Li *et al.*, 2011). Interviewees were asked what they believed DFMA meant to construction, and three clear themes emerged – namely, DFMA was (a) off-site, (b) modular and (c) standardised. These themes are fundamental to modern manufacturing, where products are

commonly standardised and mass-produced. Conversely, in construction, they are often seen as innovative and in stark contrast to the typical one-off, bespoke construction product.

Construction typically undertakes production activities on sites located at the point of final placement (Kamara *et al.*, 2007). To facilitate centralised mass production of construction products, pre-assembly is required. In the interviews, off-site manufacture was the most frequent description of DFMA, with standardisation being second. Standardisation is the extensive use of processes, products or components, in which there is regularity, repetition and a record of successful practice (Gibb and Isack, 2001). The case studies showed that pre-assembly and standardisation are separate processes. For example, a product with a standard design made from standard parts could be wholly constructed in situ, on-site. Alternatively, a bespoke design comprising bespoke parts could be wholly pre-assembled prior to final placement on-site.

Fox and Cockerham (2000) recognised concurrent engineering as a prerequisite for DFMA. In concurrent engineering, the end product and manufacturing designs are developed in parallel. Conversely, traditional construction contracting adopts sequential engineering (Walker, 2007), which separates these activities. Typically, the tendering process separates the final product design as undertaken by a client or consultant from the detailed design and construction completed by a contractor. Two interviewees described DFMA as concurrent engineering, and many recognised poor project team integration as a barrier. Others see the integrated team as a key enabler of DFMA (Doran and Giannakis, 2011; Kamara *et al.*, 2007). The interview data showed that many see DFMA as the use of standard off-site solutions, which supplements the most frequent description seen across literature. Considering these points, DFMA can be defined as the off-site manufacture of standard products delivered through concurrent engineering.

Therefore, it can be shown that DFMA incorporates two distinctive elements.

- Pre-assembly, which is literally to assemble before, refers to the manufacture, in a factory, of structures or parts, in advance of final placement (Ciria, 1999). A DFMA project incorporates the extensive use of pre-assembled elements, also known as off-site manufacture.
- Standardisation is the extensive use of processes, products or components, in which there are regularity, repetition and a record of successful practice (Gibb and Isack, 2001). A DFMA project incorporates a high degree of standardisation. It shares design, construction and operation philosophies with other projects.

Existing definitions for off-site manufacture (Ciria, 1999) and standardisation (Fox and Cockerham, 2000) provide a means to measure a product's adoption of DFMA. However, standardisation is not recommended here as a measure of DFMA potential. In the interviews and case studies, it became apparent that water

industry clients often provide input into product development. This model is unlike manufacturing, where clients typically purchase a completed product and have no input or authority in the product design, manufacture and assembly. Client input during production limits the potential to standardise and mass-produce.

A product's DFMA potential is therefore a combination of pre-assembly and production strategies. Utilising the production models of Winch (2003) and the pre-assembly categories of the Construction Industry Research and Information Association (Ciria, 1999), a DFMA scoring tool is derived.

Figure 6 shows the proposed scoring tool, which describes projects as either DFMA or as traditional construction. A higher score indicates a greater potential for achieving the benefits associated with DFMA. The scores presented are intended to push innovation and are weighted towards modular standard assets. This takes into account the use of traditional DFMA parts such as pre-cast concrete covers or blocks, which can be described as DFMA but add limited benefits. In the scoring tool, these items are described as non-volumetric/sub-assembly. The tool highlights the impact that client input has on mass production and the ability for manufactures to standardise. Where client design input is reduced, the score increases as it recognises how this aids design reuse and standardisation. The tool has been developed based on the data collected in the study but can be used in the wider construction industry. Clients may wish to alter the scoring to

award and promote specific elements. For instance, a greater emphasis may be placed on the extent of work undertaken off-site with less points awarded against the use of standard products. The current scoring is set to promote the use of standard off-the-shelf products – for example, the use of prefabricated modular waste water pumping stations that come complete with the civil, mechanical and electrical installations fully integrated.

4.2 The benefits

Existing literature supports the view that DFMA delivers cost savings in construction and within the UK water industry. Reduced cost was the third most frequent interview response regarding the benefits of DFMA, and nine projects reviewed in the case studies reported cost savings as a result of using DFMA. However, these data are anecdotal as cost comparisons against traditional builds were not undertaken as the data required to do so were not available. Off-site factory production reduces the risk of on-site unknowns and enables leaner schedules by overlapping production activities. The interviewees recognised increased productivity and reduced construction durations as a key benefit. Time was the most frequent benefit seen in the case studies. Interviewees recognised improved quality as the second benefit of DFMA, and this was realised in six of the 15 case studies. Health and safety improve with increased use of off-site manufacture, which was also recognised by the interviewees. Asset operation and maintenance are simplified with increased standardisation, with asset operators requiring less training to operate multiple sites.

Figure 6. Proposed DFMA scoring system based on on-site activity and client influence during design

Figure 7. The benefits associated with both off-site working and standardisation

The degree by which a project incorporates off-site manufacture and standardisation dictates the realisation of these benefits. Figure 7 presents a full list of benefits identified by the study.

4.3 The risks

The adoption of new processes and technologies inherently generates risk, and DFMA is no exception. Any new product will bring uncertainty until proven successful through implementation and operation. If not managed correctly, this uncertainty could lead to long-term operational problems. All construction projects will leave clients with some level of ongoing operational risk. This long-term risk is easy to miss when assessing project solutions as it relates to asset operation rather than construction. In theory, client standards and specifications protect operability and product quality. However, new innovative solutions may sit outside these standards, leaving clients vulnerable to operational risks. Figure 8 shows the risks identified during the study.

Analysis of the interview data identified seven themes associated with risks and barriers. Risk management and quality accounted for almost half of these responses. Interviewees noted a lack of industry awareness to the long-term risks of untested products. Prominent remarks were the industry’s inability to select appropriate projects for trialling DFMA and the lack of awareness when considering the implications of using new technologies. Interviewees noted integration difficulties between DFMA products and existing on-site assets. Similarly, ground conditions

were seen as a barrier to standardisation across sites. The limited on-site flexibility of DFMA products makes integration with existing assets and ground conditions challenging.

Operational risk is a function of failure impact and likelihood. This can be managed through increased redundancy or maintenance provision, both of which impact whole-life costs. Operational risk therefore needs early consideration in a project’s life cycle where innovative technology is intended for use. To assist with this, a risk assessment is presented below in Figure 9. A risk score is given for ground and asset integration, asset criticality and maintenance requirements. By combining the scores of these four elements, a total project risk score is derived. From this, the suitability of using DFMA products can be analysed for specific sites by comparing the site risk score against product uncertainty.

Product uncertainty can be defined by assessing maturity and location of use (Hoyle *et al.*, 2013). From these two points, uncertainty can be reviewed against the project risk score. Operational experience considers the location of past use, and uncertainty increases as the information source becomes more distant from the company and the industry wishing to use it. Solution maturity considers the volume of available operational data, and uncertainty increases as data sources decrease. Figure 10 presents a simple and quick method for determining which products are suitable for which sites. A provisional maximum risk score is presented for each uncertainty category, with high uncertainty

Figure 8. Key risks across the project life cycle; planning, construction and operation

products identified as unsuitable for high-risk sites. The scores shown here can be amended to suit an organisation's stance on risk, with the scoring system proposed here based on data collected by the study.

Product uncertainty provides a simple method for assessing product suitability on specific projects. A high-uncertainty product is perhaps not suited for a high-risk project. However, it may be suitable for low-risk projects. Alternatively, additional features could be added to a project's scope to increase robustness and reduce operational risk. Once operational data are collected, uncertainty decreases and products become more suited for higher-risk projects. With this approach, organisations can evaluate and appropriately allocate risk against their desire to deliver innovative solutions.

5. Conclusion

DFMA can deliver cost, time, quality and health and safety benefits for the UK water industry. DFMA helps to deliver sustainable construction by generating less waste and carbon dioxide. The factory is a safer environment to work in compared to on-site

construction sites where activities can generate greater health and safety risks. These benefits stem from the use of standardisation and off-site manufacture, and as such, these terms are used here to define DFMA as the off-site manufacture of standard products delivered through concurrent engineering. The data showed that DFMA solutions come in many forms with varying use of standard, off-site manufactured components. To address this, a DFMA scoring tool is presented that enables solutions to be described against their use of off-site manufacture and degree of standardisation. This provides a means for assessing the DFMA credentials of a solution. This, in turn, provides a process for describing requirements, setting targets and scoring tenders.

The data highlighted a need for better DFMA-focused risk management. Existing risk assessments often focus on design and construction and give little thought to long-term asset operation. The operational uncertainty of new, innovative solutions requires management to mitigate risks. To assist with this, a new risk assessment is presented to help evaluate product suitability on specific projects. This assessment requires minimal site data to complete and enables users to determine product suitability early

Figure 9. Project-specific risk assessment based on the risk elements identified in the study

		Data reference source			
Solution maturity		Within own company	UK water company	A water company	Other industry sector
Proven	- Data from two projects show successful operation. - Data collected over an adequate operational period. - Product is of a similar scale and operational philosophy to reference assets.	Max. risk score 30	Max. risk score 30	Max. risk score 15	Max. risk score 8
	- Data from one project shows successful operation. - Data collected over a limited operational period. - Solution is of a different scale but of a similar operational philosophy to reference assets.	Max. risk score 30	Max. risk score 15	Max. risk score 8	Max. risk score 5
Unproven		Max. risk score 15	Max. risk score 8	Max. risk score 5	Max. risk score 5

Figure 10. Risk assessment, considering solution maturity and project-specific risks

in a project's life cycle. If clients wish to be innovative, they will need to accept some level of risk. These risks can be managed through increasing solution robustness or reducing product uncertainty through testing on suitable sites.

Further work must be undertaken to clarify the full potential of DFMA. The case study projects did not incorporate all aspects of DFMA as data were limited depending on where a project was at in its life cycle. Therefore, to understand the full potential of

DFMA, future case studies should represent the full range of project life-cycle stages. With this additional information, the DFMA scoring tool could be calibrated against actual projects. This would help users to understand better the extent of the benefits associated with each DFMA score.

In most instances, DFMA has clear benefits over traditional construction. It does have a new set of risks, but these can be mitigated through good management processes. Clients must be clear on their desire to deliver by DFMA and be equipped to invest time and resources into implementing this new delivery method. Without this drive and investment, the benefits of DFMA will remain untapped.

REFERENCES

- Abowitz DA and Toole MT (2010) Mixed method research: fundamental issues of design, validity and readability in construction research. *Journal of Construction Engineering and Management* **136**(1): 108–116, [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0000026](https://doi.org/10.1061/(ASCE)CO.1943-7862.0000026).
- Ågren R and Wing RD (2014) Five moments in the history of industrialized building. *Construction Management and Economics* **32**(1–2): 7–15, <https://doi.org/10.1080/01446193.2013.825374>.
- Alarcon L (1997) *Lean Construction*. Balkema, Rotterdam, the Netherlands.
- Alarcón LF and Mardones DA (1998) Improving the design construction interface. *Proceedings of the 6th Annual Meeting of the International Group for Lean Construction, Guaraja, Brazil*.
- Ashley S (1995) Cutting costs and time with DfMA. *Mechanical Engineering* **117**(3): 74–77.
- Bancroft A and Thomson R (2013) *Clay Mills STW, Innovative Approach to Design and Construction of the New Bio-P Activated Sludge Plant*. UK Water Projects, Manchester, UK.
- Boothroyd G, Dewhurst P and Knight WA (2010) *Product Design for Manufacture and Assembly*, 3rd edn. CRC Press, Boca Raton, FL, USA.
- Chena Y, Okudan GE and Riley DR (2009) Sustainable performance criteria for construction method selection in concrete buildings. *Automation in Construction* **19**(2010): 235–244, <https://doi.org/10.1016/j.autcon.2009.10.004>.
- Ciria (Construction Industry Research Information Association) (1999) *Standardisation and Pre-assembly Adding Value to Construction Projects*. Ciria, London, UK, Report 176.
- Ciria (2013) *Implementing Lean in Construction, a Guide for Client Organisations*. Ciria, London, UK.
- Cole M (2014) Still waters run deep. *New Civil Engineer*, 19 June. See <https://www.newcivilengineer.com/latest/water-still-waters-run-deep-at-barrow-hill-reservoir-london/8664410.article> (accessed 11/09/2014).
- Court PF, Pasquire CL, Gibb GF and Bower D (2009) Modular assembly with postponement to improve health, safety, and productivity in construction. *Practice Periodical on Structural Design and Construction* **14**(2): 81–89, [https://doi.org/10.1061/\(ASCE\)1084-0680\(2009\)14:2\(81\)](https://doi.org/10.1061/(ASCE)1084-0680(2009)14:2(81)).
- Cuthbert N (2013) Beckton STW, £190m upgrade of one of Europe's largest STW's near completion, helping to create a cleaner, healthier River Thames. In *UK Water Projects 2013*. UK Water Projects, Manchester, UK, pp. 115–158. See http://ukwaterprojects.com/publication_date/2013.htm (accessed 04/06/2014).
- Danford MD (2008) Survey: DFMA techniques reduce costs. *Modern Machine Shop*, January.
- Doran D and Giannakis M (2011) An examination of a modular supply chain: a construction sector perspective. *Supply Chain Management: an International Journal* **16**(4): 260–270, <https://doi.org/10.1108/13598541111139071>.
- Egan J (1998) *Rethinking Construction: the Report of the Construction Task Force to the Deputy Prime Minister, John Prescott, on the Scope for Improving the Quality and Efficiency of UK Construction*. Department of the Environment, Transport and the Regions, London, UK.
- Fox S and Cockerham G (2000) Designing for orders. *Manufacturing Engineer* **79**(2): 63–66, <https://doi.org/10.1049/me:20000203>.
- Fox S, Staniforth I and Cockerham G (2001) Design authority, bespoke as standard. *Manufacturing Engineer* **80**(3): 139–142, <https://doi.org/10.1049/me:20010312>.
- Gaines M (2013) *Engineering Innovative Solutions*. WWTonline, East Grinstead, UK. See <http://www.wwtonline.edie.net/features/engineering-innovation-solutions> (accessed 23/07/2014).
- Gibb A (2001) Standardization and pre-assembly, distinguishing myth from reality using case study research. *Construction Management and Economics* **19**(3): 307–315, <https://doi.org/10.1080/01446190010020435>.
- Gibb A and Isack F (2001) Client drivers for construction projects: implications for standardization. *Engineering and Architectural Management* **8**(1): 46–58, <https://doi.org/10.1046/j.1365-232x.2001.00184.x>.
- Gilligan J and Dewhurst N (2009) Establish real-world costs up-front, concurrent engineering works, and DfMA can help break down the wall between design and manufacturing. *Manufacturing Engineering* **143**: 45–49.
- Goodier C and Gibb A (2006) Future opportunities for offsite in the UK. *Construction Management and Economics* **25**(6): 585–595, <https://doi.org/10.1080/01446190601071821>.
- HMRC (HM Revenue & Customs) (2014) *Guidance, Moving Goods by Road*. HM Revenue & Customs, London, UK. See <http://www.gov.uk/moving-goods-by-road> (accessed 04/07/2014).
- Hoyle K, Oliver S, Tsai N et al. (2013) Composite concrete cryogenic tank: a precast concrete alternative for LNG storage. *Proceedings of the 17th International Conference and Exhibition on Liquefied Natural Gas, Houston, TX, USA*, pp. 1139–1157.
- Jaillon L and Poon C (2010) Design issues of using prefabrication in Hong Kong building construction. *Construction Management and Economics* **28**(10): 1025–1042, <https://doi.org/10.1080%2F01446193.2010.498481>.
- Jaillon L, Poon CS and Chiang YH (2009) Quantifying the waste reduction potential of using prefabrication in building construction in Hong Kong. *Waste Management* **29**(1): 309–320, <https://doi.org/10.1016/j.wasman.2008.02.015>.
- Johnson H and Meiling JH (2009) Defects in offsite construction: timber module prefabrication. *Construction Management and Economics* **27**(7): 667–681, <https://doi.org/10.1080/01446190903002797>.
- Jonsson H and Rudberg M (2014) Classification of production systems for industrialized building: a production strategy perspective. *Construction Management and Economics* **32**(1–2): 53–69, <https://doi.org/10.1080/01446193.2013.812226>.
- Kamara JM, Anumba CJ and Cutting-Decelle A (2007) *Concurrent Engineering in Construction Projects, Introduction to Concurrent Engineering in Construction*. Taylor & Francis, Oxford, UK.
- Kobe G (1990) DfMA: design for manufacture and assembly. In *Automotive Industries*, March, pp. 34–38.
- Laing O'Rourke (2013) DfMA is the future of construction. *Engineering Excellence Journal* **1**: 1–76. See <http://www.laingorourke.com/media/publications/eej-landing.aspx> (accessed 01/02/2018).
- Lennen R, Miller G and Prussack C (1996) Precast pre-stressed concrete solution of choice for Lincoln Heights water tanks. *PCI Journal* **41**(1): 20–33, <https://doi.org/10.15554/pci.01011996.20.33>.
- Larsson J, Eriksson P, Olofsson T and Simonsson P (2014) Industrialized construction in the Swedish infrastructure sector: core elements and barriers. *Construction Management and Economics* **32**(1–2): 83–96, <https://doi.org/10.1080/01446193.2013.833666>.

- Lau NW and Yuanb H (2013) Investigating waste reduction potential in the upstream processes of offshore prefabrication construction. *Renewable and Sustainable Energy Reviews* **28**: 804–811, <http://dx.doi.org/10.1016/j.rser.2013.08.048>.
- Li H, Guo HL, Skitmore M et al. (2011) Rethinking prefabricated construction management using the VP-based IKEA model in Hong Kong. *Construction Management and Economics* **29**(3): 233–245, <https://doi.org/10.1080/01446193.2010.545994>.
- Liao PC, O'Brien WJ, Thomas SR, Dai J and Mulva SP (2011) Factors affecting engineering productivity. *Journal of Management In Engineering* **27**(4): 229–235, [https://doi.org/10.1061/\(ASCE\)ME.1943-5479.0000059](https://doi.org/10.1061/(ASCE)ME.1943-5479.0000059).
- Lu N and Liska RW (2008) Designers' and general contractors' perceptions of offsite construction techniques in the United State construction industry. *International Journal of Construction Education and Research* **4**(3): 177–188, <https://doi.org/10.1080/15578770802494565>.
- Nadim W and Goulding JS (2011) Offsite production: a model for building down barriers: a European construction industry perspective. *Engineering, Construction and Architectural Management* **18**(1): 82–101, <https://doi.org/10.1108/09699981111098702>.
- Pan W and Sidwell R (2011) Demystifying the cost barriers to offsite construction in the UK. *Construction Management and Economics* **29**(11): 1081–1099, <https://doi.org/10.1080/01446193.2011.637938>.
- Pan W, Gibb AGF and Dainty ARJ (2007) Perspectives of UK house builders on the use of offsite modern methods of construction. *Construction Management and Economics* **25**(2): 183–194, <https://doi.org/10.1080/01446190600827058>.
- Parker D (2014) Manchester guided bus shuns precast. *New Civil Engineer*, 17 July: p. 9.
- Phillipson M (2003) *Defining the Sustainability of Prefabrication and Modular Process in Construction*. Building Research Establishment, Watford, UK, project report number 203032.
- Pitcher G (2014) AMP6 Water spend to top £44bn. *New Civil Engineer*, 12 December. See <https://www.newcivilengineer.com/amp6-water-spend-to-top-44bn/8673965.article> (accessed 20/11/2017).
- Prasad B (1995) Sequential versus concurrent engineering, an analogy. *Concurrent Engineering* **3**(4): 250–255, <https://doi.org/10.1177/1063293X9500300401>.
- O'Donohoe N (2010) DfMA hits the jackpot. *Desktop Engineering*, July: pp. 59–62.
- Olawale Y and Sun M (2010) Cost and time control of construction projects: inhibiting factors and mitigating measures in practice. *Construction Management and Economics* **28**(5): 509–526, <https://doi.org/10.1080/01446191003674519>.
- Quale J, Matthew EJ, Sloditskie G and Zimmerman JB (2012) Construction matters comparing environmental impacts of building modular and conventional homes in the United States. *Journal of Industrial Ecology* **16**(2): 243–253, <https://doi.org/10.1111/j.1530-9290.2011.00424.x>.
- Rahman MM (2014) Barriers of implementing modern methods of construction. *Journal of Management in Engineering* **30**(1): 69–77, [https://doi.org/10.1061/\(ASCE\)ME.1943-5479.0000173](https://doi.org/10.1061/(ASCE)ME.1943-5479.0000173).
- Rubio-Romero JC, Suárez-Cebador M and Abad J (2013) Modelling injury rates as a function of industrialized versus on-site construction techniques. *Accident Analysis and Prevention* **66**(2014): 8–14, <https://doi.org/10.1016/j.aap.2014.01.005>.
- Smith R (2010) *Prefab Architecture: a Guide to Modular Design and Construction*. Wiley, New York, NY, USA.
- Smith T (2013) Crossness STW, part of Thames Water London Tideway improvements programme to create a cleaner, healthier River Thames. In *UK Water Projects 2013*. UK Water Projects, Manchester, UK, pp. 181–184. See http://ukwaterprojects.com/publication_date/2013.htm (accessed 04/06/2014).
- Stecklein JM, Dabney J, Dick B et al. (2004) Error cost escalation through the project lifecycle. *Proceedings of the 14th Annual International Symposium, Toulouse, France*.
- Tam WY, Tam CM, Zeng SX and William CY (2007) Towards adoption of prefabrication in construction. *Building and Environment* **42**(10): 3642–3654, <https://doi.org/10.1016/j.buildenv.2006.10.003>.
- Taylor-Powell E and Renner M (2003) *Analysing Qualitative Data*. University of Wisconsin-Extension, Madison, WI, USA.
- United Utilities (2014) *Corporate Responsibility Report 2013*. United Utilities, Warrington, UK. See <http://corporateresponsibility2013.unitedutilities.com/aboutus.aspx> (accessed 24/05/2014).
- Vernikos VK, Goodier CI, Gibb AGF, Robery PC and Broyd TW (2012) Realising offsite construction and standardization within a leading UK Infrastructure consultancy. *Proceedings of the 7th International Conference on Innovation in Architecture, Engineering and Construction, São Paulo, Brazil*, pp. 58–67.
- Walker P (2007) *Concurrent Engineering in Construction Projects, Procurement, Contracts and Conditions of Engagement within a Concurrent Engineering Context*. Taylor & Francis, Oxford, UK.
- Wallace G and Sackett P (1996) Integrated design for low production volume, large, complex products. *Integrated Manufacturing Systems* **7**(3): 5–16, <https://doi.org/10.1108/09576069610116887>.
- Water Act 1989. Chapter 15. Her Majesty's Stationery Office, London, UK.
- Winch G (2003) Models of manufacturing and the construction process: the genesis of engineering construction. *Building Research and Information* **31**(2): 107–118, <https://doi.org/10.1080/09613210301995>.

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