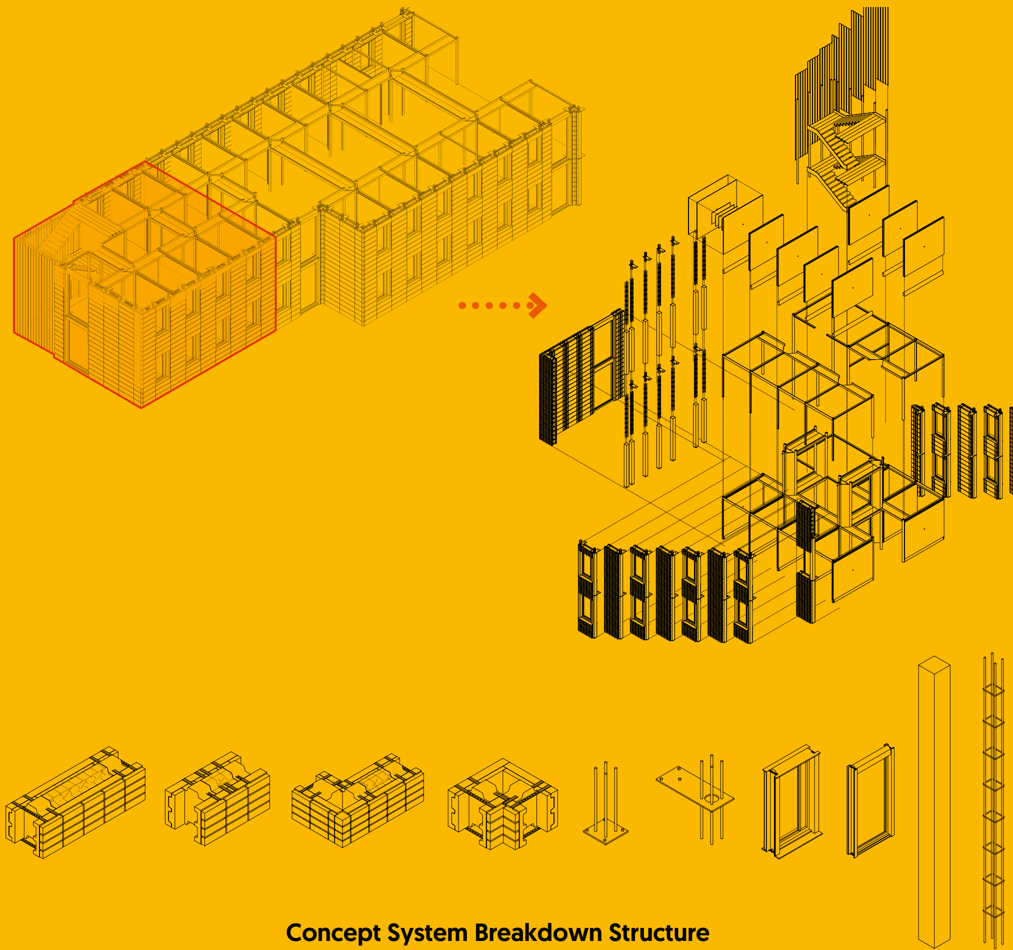
mtc
Manufacturing
Technology Centre

TRANSFORMING PERFORMANCE AND PRODUCTIVITY IN THE CONSTRUCTION INDUSTRY



Concept System Breakdown Structure
Image by Bryden Wood

Foreword

Neil Rawlinson, Strategic Development Director, MTC

In a fast-changing world, no industry sector can have the luxury of operating in isolation. If the UK is to compete with the best in the world it is vital that innovations are shared across sectors, for the benefit of all.

The construction sector is a case in point. Despite being one of the largest sectors in the UK economy, turning over £370 billion a year and employing more than three million people, it is beset by historical problems which are holding back its potential. Margins in the sector are low and subject to huge, often unpredicted variations, productivity is poor, the workforce demographic is high with skills in short supply and the industry has shown a resistance to accepting technological advances.

This book, produced by the MTC, describes a suite of tools and systems that were used on a major project in collaboration with the MOJ, and Bryden Wood and their delivery partners. The tools and systems were adapted from the manufacturing sector, where they have been proven to deliver step change improvement. These can be applied to the construction sector to help address government set challenges of improving productivity, build delivery and cost and time performance. They will also help to transform the entrenched practices and mind sets which have held the sector back in the past.

Using these tools and systems in a real-life construction project scenario, the important contribution that they can make to transforming performance and productivity in the construction sector was recognised by the Ministry of Justice:-

"The Ministry of Justice is one of the five government departments that has signed up to the Government's 'Transforming Infrastructure Performance' programme. This programme reflects the government's plan to increase the effectiveness of investment in infrastructure by improving productivity in the way we design, build and operate assets. As part of this we have committed to procure buildings with a presumption in favour of offsite construction by 2019.

To achieve the goals set we recognise that we must drive change in the way we work and deliver projects through adoption of practices such as those outlined in this book. The collaboration with the MTC and Bryden Wood provided us with an opportunity to pilot these approaches and enable our own workforce to start to challenge the way we delivery vital public infrastructure.

The work has strongly influenced our strategy for future estate development and I'm sure that the impact of adopting these manufacturing approaches in collaboration with our partners will deliver significant impact in our drive to improve productivity, efficiency and increase value for money"

Anna Evans, Technical Services Director – Ministry of Justice

Foreword

Bryden Wood, a major partner in the delivery of the MOJ Project, also champions the benefits that come from drawing on manufacturing expertise and practice in the design and delivery of construction projects:-

"For over 20 years Bryden Wood has been working with the most forward-thinking clients to lead the construction industry's adoption of more advanced construction techniques. While we have achieved some significant successes, the slow uptake by the wider sector has been frustrating.

However, we are now seeing an alignment of several key factors (including a £600 billion national infrastructure and construction pipeline, to be delivered at a time when construction productivity is notoriously low and the workforce demographic is increasingly high) that make the traditional practices untenable; the question is no longer whether the industry needs to move forward, but in what direction.

The commitment by the Government to drive adoption of modern methods of construction therefore means that we are about to see dramatic changes in the industry. A key catalyst will be the adoption of expertise from the manufacturing sector; combining this with existing and emerging best practice in construction will transform our industry.

The work to date with the MTC, that is described in this book, demonstrates how valuable the exchange of ideas between construction and manufacturing will be, and offers a tantalising glimpse of how our buildings and infrastructure will be delivered in future.

This is just the start of a huge undertaking, but we hope the work outlined here will inspire others to join us".

Jaimie Johnston – Head of Global Systems – Bryden Wood

The purpose of this is book is to describe how the transformation and performance tools were used to support the MOJ project team and how they can be applied in both large and small organisations in the construction sector to benefit project delivery.

I would like to thank all of the project partners for their enthusiastic commitment and contribution working with the MTC team in the development and use of the tools and systems which are described in this book.

Neil Rawlinson

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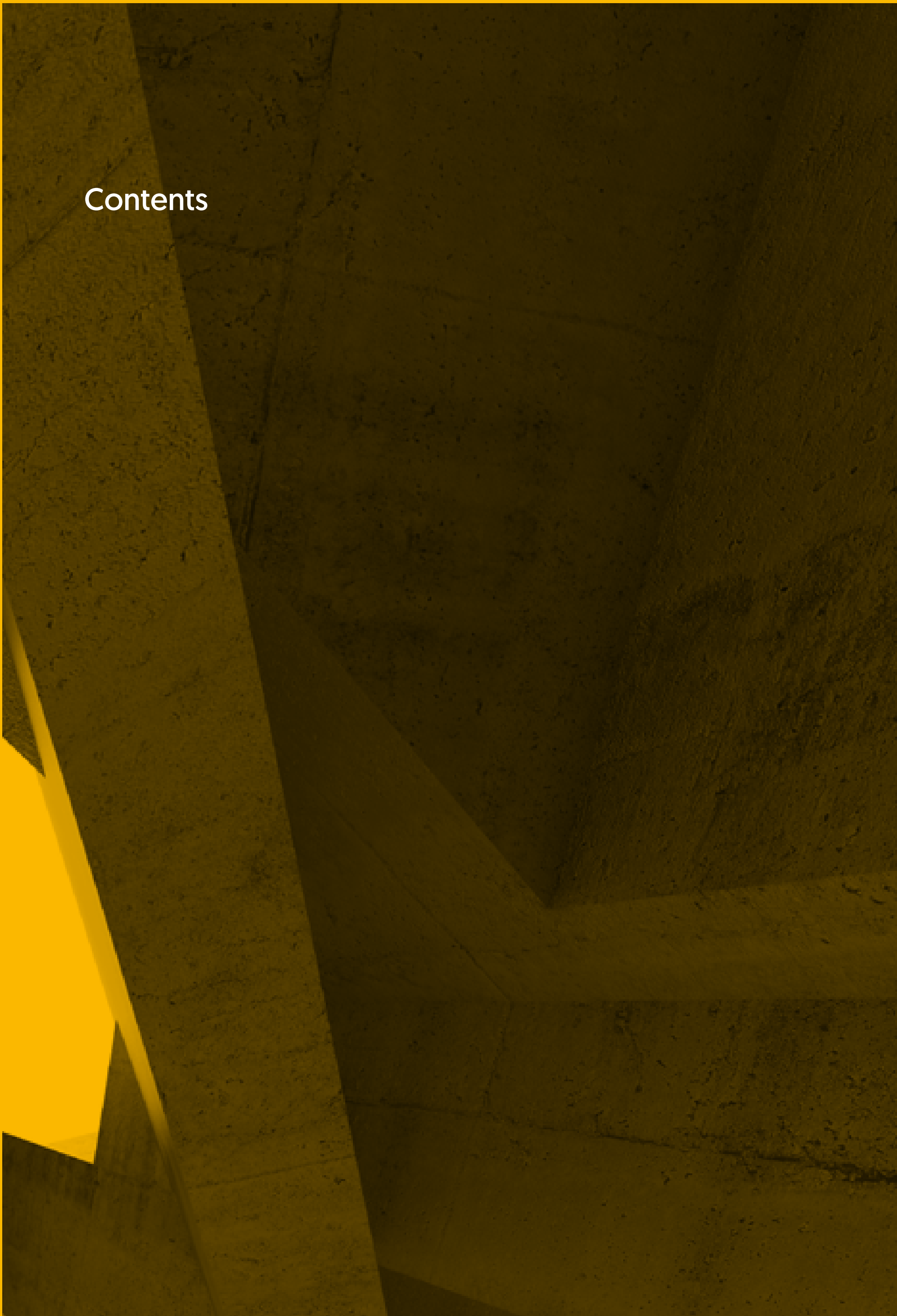

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OVERVIEW

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1 – Overview

1.1 Introduction

The construction industry is vital to the UK and is one of the largest sectors with a turnover of £370bn contributing £138bn to the economy and employing 3.1 million people. It is challenged by low margins and high risk business models. Through working with partners in the construction industry, the MTC sees numerous opportunities to deliver step change improvement in performance and productivity.

The construction sector is entering a period of significant growth driven by a government target of 250,000 new homes annually, together with five major infrastructure projects HS2, Thames Tideway, Hinckley Point, Heathrow Third Runway and Crossrail 2. There is a strong drive within the sector to encourage innovative thinking in all aspects of design and delivery, to ensure the end products provide exceptional value for money.

Against this background, the construction sector in the UK has challenging targets, 33% reduction in the initial cost of construction and whole life cost of build assets and 50% faster delivery of new build and refurbished build assets by 2025 (Construction 2025 Report), see Figure 1 below. The 'Transforming Infrastructure Performance' report (2017), see Figure 2 below, highlights the importance of improving productivity, build delivery, and cost and time performance, in the construction sector, see paragraph 2 – The MTC and the Construction Industry.

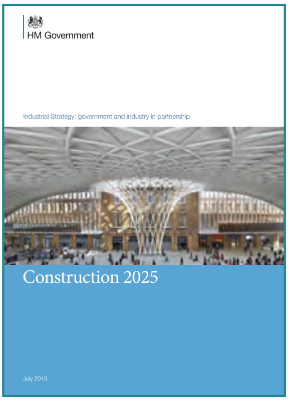

Figure 1. Construction 2025 Report

Figure 2. Transforming Infrastructure Report (2017)

1 – Overview

Building Information Modelling and Digital Construction techniques remain a core part of central government construction delivery and are contributing to the ongoing achievement of £1.7Bn of efficiency savings by departments committed to the Government Construction Strategy 2016-20.

At the March Spending Review of 2016, HM Treasury funded the next level of research for Building Information Modelling, Level 3, via the Department for Business, Energy and Industrial Strategy's Digital Built Britain programme.

As part of the Transforming Infrastructure Performance government programme the Ministry of Justice (MOJ) stated commitment to move to a presumption in favour of off-site construction by 2019, where it is appropriate.

The Manufacturing Technology Centre (MTC) was awarded funding via Innovate UK as part of the ongoing work of Digital Built Britain with support from the Infrastructure and Projects Authority and Central Government. The funding was used to demonstrate how the use of leading edge manufacturing transformation systems and tools, set within a standardised Quality Assurance approach such as APQP, can make a significant contribution to efficiency and reduction in costs using modern methods of construction.

The MTC believes that, with its leading edge manufacturing research and technology themes, transformation and improvement systems and tools and the experience gained working across all industry sectors, it has the capability to make significant contribution to this challenging environment.

1.2 About this Book

This book, produced by the MTC, describes how the adoption of manufacturing transformation and improvement systems, tools and techniques can deliver step change improvement in performance and productivity in the construction sector.

The approaches described draw on the MTC's experience of developing and applying such systems and tools, widely used and proven in the manufacturing, automotive and aerospace sectors where, historically they have supported transformation. The MTC is supporting the adoption of these approaches by the construction sector and has demonstrated how they can make a significant contribution to the development and delivery of a major MOJ project.

This book describes a generic approach on the use of a selection of these manufacturing systems and tools, which can be used by small or large organisations in the construction sector.

It also outlines the approach used for the specific requirements of the MOJ Project and the specific benefits delivered. These systems and tools can deliver step change improvement, reduce costs and development time, improve efficiency, quality and safety.

Quote:-

"The MTC has brought their insights from the world of Aerospace and Automotive, showing us how to master and continuously improve on design, quality, supply chain analysis, collaboration and delivery. Cross pollination such as this must be the way to address productivity and efficiency in construction."

Dries Hagen, Head of Property, Bryden Wood

1.3 What is the MTC?

The MTC was established in 2010 as an independent Research & Technology Organisation with the objective of bridging the gap between academia and industry. The MTC develops and proves innovative manufacturing processes and technologies in an agile, low risk environment, in partnership with industry, academia and other institutions.

The MTC operates some of the most advanced manufacturing equipment in the world, and employs a team of highly skilled engineers, many of whom are leading experts in their field. This creates a high quality environment for the development and demonstration of new processes and technologies on an industrial scale. Adoption of these new processes and technologies leads to operational efficiencies in terms of improved quality, reduced costs and improved delivery performance.

The MTC's areas of expertise are relevant to both large and small companies, and are applicable across a wide range of industry sectors, where it has helped hundreds of companies. The MTC's extensive skills mean it is able to adapt and translate highly evolved and proven manufacturing processes to address the many challenges in the construction sector.

The MTC provides support across the whole spectrum of business activity and many of the clients that have been supported have become members of the MTC. At present the MTC has more than 100 members from SMEs to some of the biggest brands in the world such as Unilever, Rolls-Royce, BAE Systems and Siemens, with a growing Construction and Infrastructure membership cluster which includes Network Rail, Skanska, Kier, Forterra, Amey and HS2.

1.4 What Does the MTC do?

The MTC helps companies manufacture faster, at a consistently higher quality and lower cost, in an agile environment. It does this in partnership with industry and academia and has a flexible approach to working with companies of all sizes – from SMEs to Tier 1s and large OEMs.

It supports companies by providing relevant, integrated design and modelling manufacturing system solutions for customers large and small, across sectors as diverse as automotive, aerospace, rail, informatics, food and drink, construction, civil engineering, electronics, oil and gas and defence.

The MTC's strategic aim is to strengthen the UK's global position and export potential through:

- improved productivity
- greater investment in research and development
- addressing the skills gap
- development of new market opportunities
- implementation of new technologies

The MTC strives to create innovative technology and business solutions that are relevant to client's issues and challenges and which contribute to the achievement of business goals. The MTC does this by providing the very best innovative manufacturing processes and technologies drawing on the skills and expertise of its engineers and by having access to some of the most advanced manufacturing equipment in the world.

1 – Overview

The MTC has a range of technology themes which are at the core of its research programme. These technology themes have the capability to make a significant contribution to improving performance in the construction sector.

Examples of these themes are shown at Figure 3, 4, 5 and 6 below:

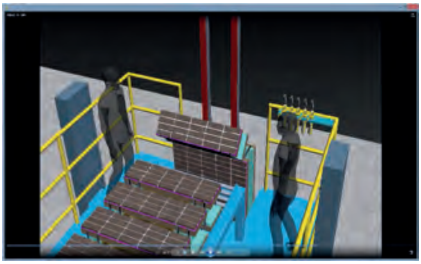

Figure 3. Design & Simulation

Figure 4. Robotics & Autonomous Systems

Figure 5. Advanced Tooling & Fixturing

Figure 6. High Integrity Fabrication

For more information go to www.the-mtc.org

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2 – The MTC and the Construction Sector

2.1 The MTC and the Construction Sector

Drawing on the experience of developing and using transformational systems and tools, now widely used and proven in the manufacturing and other sectors, the MTC has developed a suite of manufacturing systems and tools adapted for the construction sector.

The MTC has extensive experience of working with the construction and infrastructure sector delivering bespoke solutions by using innovative approaches and state-of–the-art technologies.

The following abbreviated case studies demonstrate some of the MTC's capability:-

2.1.1 Project – Firm foundations with 3D Concrete Printing

A consortium of Skanska, Foster and Partners, Tarmac, ABB, and Loughborough University wanted to further develop and industrialise the 3D concrete printing (3DCP) system, originally developed by Loughborough University, by increasing the scope of pre-cast 3D concrete printing. The aim was to become the world's first high-value commercial 3DCP system and the requirement was that the system would offer endless variability, increase productivity, reduce lead times and waste, compared to current casting methods.

Working in collaboration with the consortium the MTC introduced a number of changes to the existing system which resulted in a number of improvements, these included:-

- improvement in print design complexity and flexibility
- repeatability and consistency
- elimination of manual handling activities
- improved safety and reduced complexity for 3DCP operators
- increased productivity, with reduced lead time and process downtime
- reduced production of waste

Quote:-

"Up until November 2016 we were doing everything ourselves and had taken it as far as we could, but by joining the MTC we now have proper lab and research facilities to conduct further tests and work on the project full-time."

David Lewis, Innovation manager, Skanska UK

2 – The MTC and the Construction Sector

2.1.2 Project – The MTC Discovery Process – The Future of Technology in Construction

The MTC has been working with a consortium called i3P, which involves construction companies and their major clients, using the MTC Discovery Phase 2 process to explore the next steps for technology in the construction industry. The MTC Discovery Process is a standardised approach which looks at the technology developments needed for capability step change and assesses what is ready to go, what needs to be developed and how this will be done.

i3P members undertook a technology road mapping exercise with the MTC in 2017, Robotics and Automation was identified as one of a series of strategic priority areas for exploration across the group of companies; however, given the maturity of the technology in the sector, it was not clear how best to progress this opportunity.

After application of the MTC Discovery Process a clear direction on how the sector can collaborate in the development activities has been identified and shared with the i3P consortium.

The output from the Discovery Phase 2 project will be contained in 'The Robotics and Automation Report' which is one of a suite of 12 Discovery Projects released in 2018.

Quote:-

"Looks fantastic, a really great and thorough piece of work. The 'next steps' in the development strategy are ideal and I look forward to mobilising the i3P consortium around these"

George Holder, Analyst, Costain Group PLC

3. The MTC and the MOJ Project

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3 – The MTC and the MOJ Project

3.1 How is the MTC involved in the MOJ Project?

The MTC developed a proposed suite of systems and tools to support the manufacturing work stream within the Digital Build Britain programme. The MOJ, were already working with Bryden Wood on a platform assembly design and this offered the ideal testbed opportunity for developing the systems for application and to demonstrate the approach and potential benefits to the construction sector.

The MOJ project involved the manufacture of standard component parts that could be mass produced and then delivered to the construction site where, due to the simplicity of component connections it could be assembled by a lower than normal skilled workforce.

The MTC support included the manufacturing design of elements that would form some of the key components of the Platform 1 system. (a building unit of consistent and repeatable design elements.) In particular, the MTC's knowledge and expertise in manufacturing was harnessed to create "elements" that would be easy to manufacture and assemble at full scale production.

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4 – Transformation Improvement Systems and Tools

4.1 The Manufacturing Systems and Tools used to support the MOJ Project

The systems and tools used to support the MOJ Project have been widely used across many industry sectors where they have a proven track record of delivering:-

- step change improvement
- reduced waste
- reduced costs and development time
- improved efficiency
- improved quality and safety

The systems and tools, set within a standardised Quality Assurance approach, which includes Advanced Product Quality Planning (APQP), is shown in Figure 7 below:-

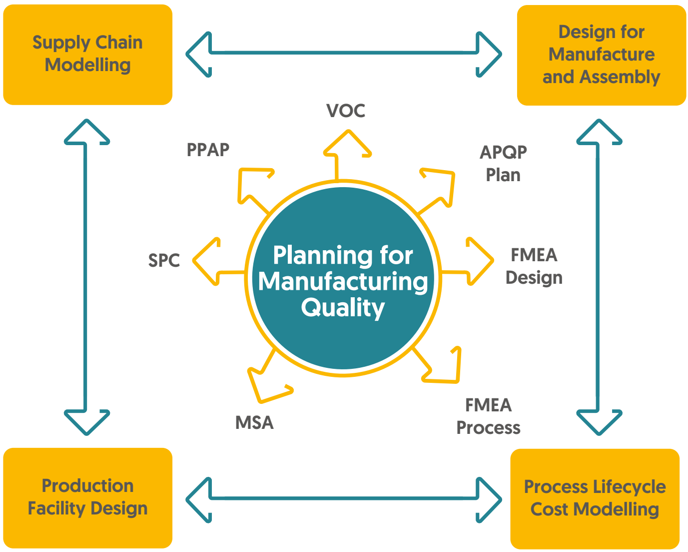

Figure 7. Systems and tools used within a standardised Quality Assurance Approach

4 – Transformation Improvement Systems and Tools

An overview of the Planning for Manufacturing Quality systems and tools are given in paragraphs 4.1.1 – 4.1.5 below and are described in detail in Chapters 2 to 6 in this book

4.1.1 Planning for Manufacturing Quality

Currently within the construction industry there are a variety of quality management systems used which are characterised by significant duplication of effort and lack of clarity. With mass production and modern methods of construction there is an opportunity to focus on standardising a quality assurance approach to address common challenges within the sector.

The MTC's approach to Planning for Manufacturing Quality uses a set of well-defined techniques and procedures used extensively in the Automotive and many other industries and are proven to deliver many benefits with new product introduction. The techniques and procedures are part of the APQP methodology which was developed by a number of major US companies.

Figure 8 below shows the five main phases of APQP:-

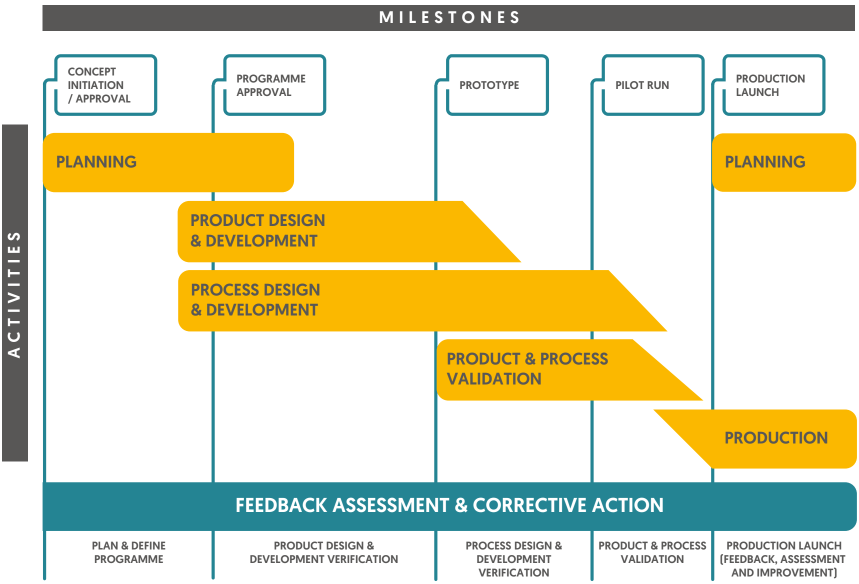

Figure 8. Phases of Advanced Product Quality Planning (Source: China Manufacturing Consultants, 2018)

Benefits of adopting a Planning for Manufacturing Quality approach include:-

- improved collaboration and communication
- improved risk management
- reduced costs
- less rework and waste
- meeting customer wants and needs

Quote:-

"With regard to the activities that the MTC supported us on, the journey proved both informative and confirmative."

"The construction industry is yet to offer a set of tools which raises the profile of lean thinking and productivity against a backdrop of Health & Safety & risk management. We found the DFMEA, PFMEA process of particular use as it introduced a very balanced, auditable process through which we could drive the management of risk whilst keeping the key design team and client aspirations in the forefront. Two systems which also found immediate resonance was (1) the Voice of the Customer (VoC) which helped summarise the 600 page Riba stage 2 report into an easy to use single page chart, and (2) Bill of Materials (BoM) which gave us a strong tool to understand, articulate and manage the variety of components associated with our platforms."

Dries Hagen, Head of Property, Bryden Wood

4.1.2 Design for Manufacture and Assembly

Design for Manufacture and Assembly is a methodology that revolves around the design of standard component parts which can be mass produced and then delivered to the construction site for assembly by a lower than normal skilled workforce.

Using Design for Manufacture and Assembly (DfMA) tools and techniques at the earliest possible stages of the RIBA Plan of Work in a "virtual manufacturing environment" allows new concepts to be fully explored and validated, in terms of manufacturing feasibility, assembly process sequence, human factors, health and safety and cost.

4 – Transformation Improvement Systems and Tools

Figure 9 below shows how the DfMA design concepts can be validated in a virtual environment:-

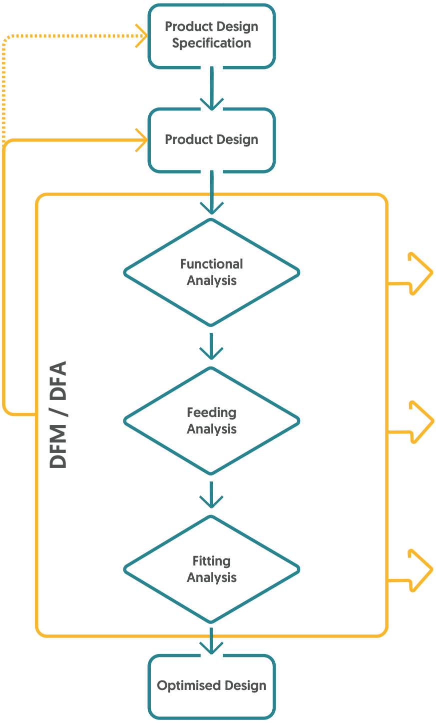

Figure 9. Design for Manufacture and Assembly validated in the Virtual Environment

Benefits of validating DfMA in a virtual environment at an early design stage include:-

- consideration of alternative design and manufacturing methods
- early elimination of risk associated with the "unknowns" between RIBA stages
- reduced duplication of effort and "reinvention on-the-fly"
- increased competitiveness
- validation of investment in physical equipment or facilities
- improved productivity and reduced overall project costs

Quote:-

"The MTC has opened our eyes further to the wider benefits that production manufacturing approaches can bring to the construction industry and have set the stakeholders on a collaborative path that we believe will see the construction industry's can-do attitude harnessed to reap the benefits of DfMA"

MOJ project team member

4.1.3 Process Lifecycle Cost Modelling

Process Lifecycle Cost Modelling is concerned with evaluating cost and provides information to inform the selection of suppliers and manufacturing processes.

Process Lifecycle Cost Modelling enables comparison of different manufacturing options of components and processes as shown in Figure 10 below. This illustration demonstrates the types of outputs the Process Lifecycle Cost Model can provide e.g. the operational cost per component manufactured and the total non-operational cost

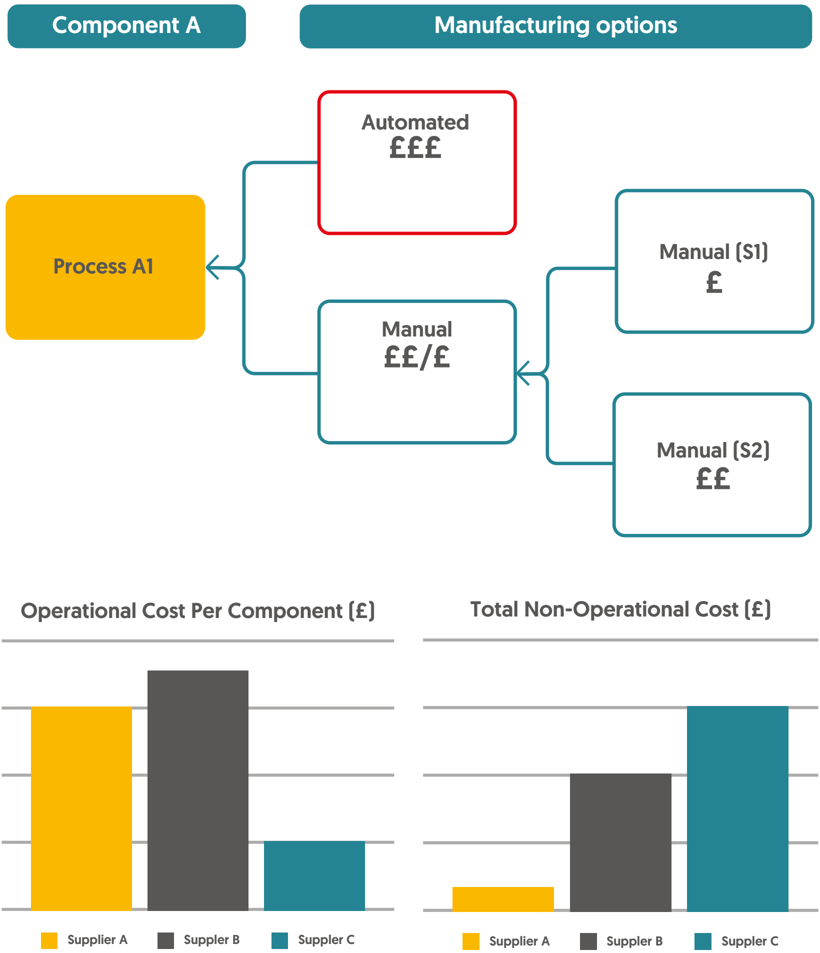

Figure 10. Example of outputs from a Process Cost Model

Benefits of Process Lifecycle Cost Modelling include:-

- enabling assessment of the cost and environmental impacts of the process to be undertaken
- providing a decision making support tool for strategic process and supplier selection when conducting a componentised construction programme
- reduced probability of increased contract costs
- improved decision making during programme development

Quote:-

"The MTC provided a better understanding of the requirements of process flows and time management for setting up workshops which is key to our public sector industry business with the complicated skilled workforce we have".

MOJ project team member

4.1.4 Production Facility Design

Using 3D simulation and models in design and construction de-risks investment decisions and ensures that optimal design is achieved first time. Where off-site manufacturing or component assembly for construction are intended to be used, the tools enable the analysis of the supply of materials to the process and allows comparison with demand, to identify potential issues. A Discrete Event Simulation Model evaluates the robustness of the manufacturing process, measuring variability, which informs changes to improve efficiency and throughput.

This approach is equally applicable to the building design and can be used in all projects to enable optimisation of the design, layout and configuration of the environmental factors and operations. It enables design teams, contractors, customers and stakeholders to experience and interact with the physical aspects of the facility without investing time and cost in physical prototyping.

A simulated 3D model has the capability to animate the flow of materials and components between work stations and can be used to assess layout flow and space constraints. The model can also be used for an "immersive reality" review.

An example of a simulated model layout created in 3D is shown in Figure 11 below:-

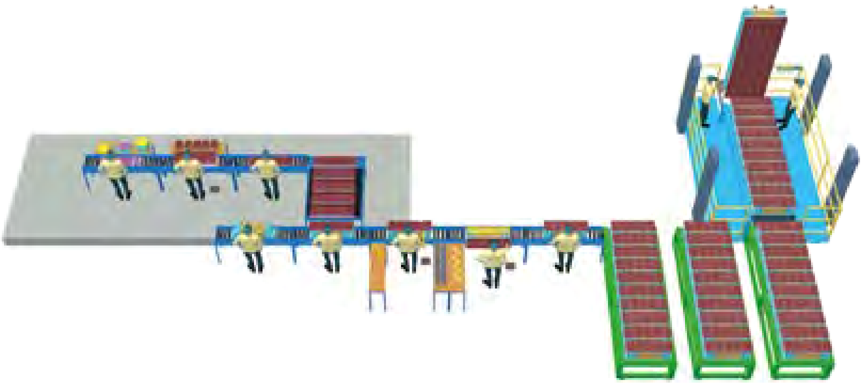

Figure 11. Example of a 3D simulated production facility

The benefits of developing a simulated 3D production facility include:-

- reduced cost of development of the product and production facility
- ensuring right first time products and production facilities are developed
- enabling the impact of variability to be assessed and managed
- improving communication of design and method of operation to contractors

Quote:-

"Just a quick note to express my sincere gratitude for your contribution this week. Between last week and this week we managed to reach a crescendo on Wednesday whereby the visualisation of, and immersion into, the VR prototypes, assembly sequences and methods of manufacture had the contractors "dancing in the aisles"

"The way the material was prepared and presented suddenly brought the art of the possible to life." ....."Having you guys alongside us has been a great help".

Dries Hagen, Head of Property, Bryden Wood

4.1.5 Supply Chain Modelling

Supply chain modelling can support decision making in the early stages of construction projects. Simulating the supply chain provides a way to understand the configuration of the supply chain by creating different scenarios and allowing evaluation of various impacts on supply chain performance before finalising the supply chain design.

Supply chain modelling enables the identification of uncertainty, risks and mitigation actions associated with the new supply chain configuration and provides an end to end view of the supply chain before it is created and finalised.

The MTC has developed a Supply Chain Model Development Process to ensure consistency of approach and this is shown at Figure 12 below:-

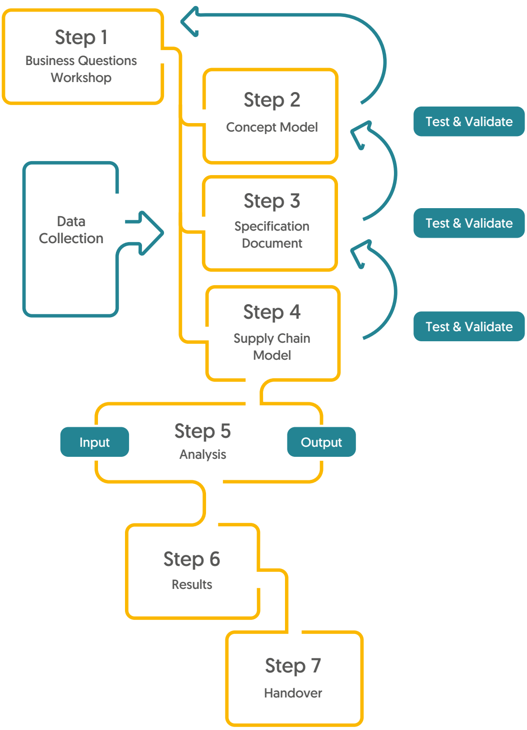

Figure 12. The MTC Supply Chain Model Development Process

4 – Transformation Improvement Systems and Tools

There are many benefits from supply chain modelling, including:-

- testing different supply chain infrastructure variants and assessing their impact on performance
- building understanding of supply chain requirements for construction projects
- building smarter commercial relationships with suppliers and mitigating uncertainty and risk against supply chain underperformance
- improved value for money in construction projects
- involvement of multiple stakeholders which encourages stronger relationships to be built early in the programme

Quote:-

"I'd like to thank the team at the MTC for leading the work we have undertaken on supply chain modelling. The MTC team level of knowledge, professionalism and insight has being very impressive. But the greatest skill the team has shown is the ability to listen and learn about why construction is or can be different to other industries. The approach to supply chain modelling has opened my eyes to dynamic modelling and its ability to simulate the many variables of construction such as weather, labour output and supplier failure. This has provided us with a great level of insight and surety on the supply chain modelling. I can see dynamic modelling having a much wider application in construction and could have great impact on areas such as logistics mapping, crane usage, line of balance planning and failure assessments."

John Handscomb, Pre-Construction Procurement Lead, Kier Construction

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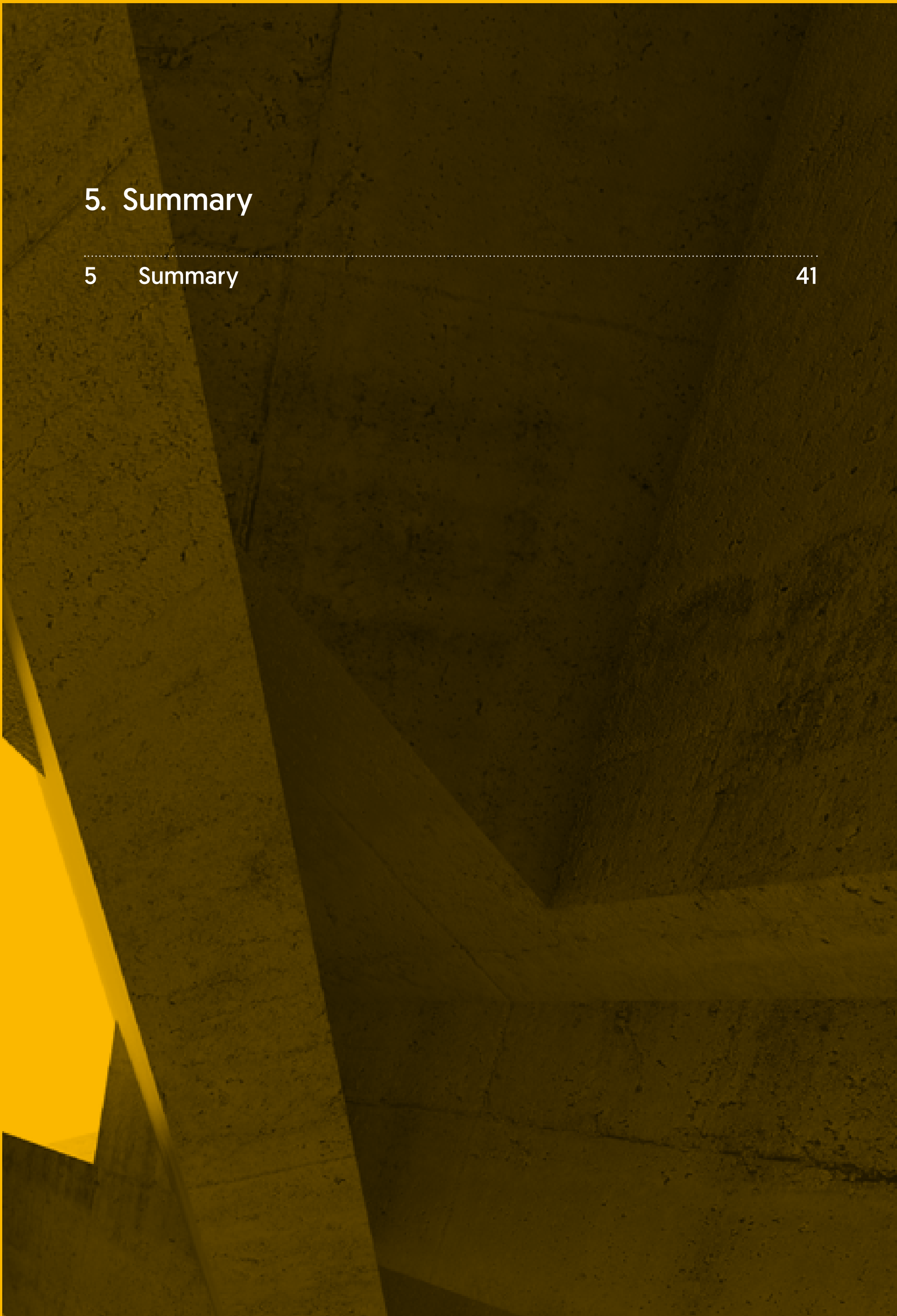

5 Summary

The systems and tools featured in this Overview are described in Chapters 2 to 6 of this book, both in terms of a generic approach and in specific terms with regard to the MOJ Project.

If you want to get started and/or want further information on the systems, tools and approaches described in this publication, visit the construction website at www.the-mtc.org/construction

2

PLANNING FOR MANUFACTURING QUALITY

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1 – Introduction and Overview

1.1 Introduction

As detailed in Chapter 1 – Overview of this book, the construction sector is vital to the UK and is contributing £138 billion to the economy. The UK government has challenged the construction and infrastructure sector to construct buildings faster, cheaper and more sustainably.

Estimates of the economic impact of poor quality for construction (direct and indirect costs) are varied. The Egan Report (1998) states, for USA, Scandinavia and the UK, up to 30% of construction is rework. The Get It Right Initiative (GIRI, 2015) estimates direct costs of errors along with unmeasured and indirect costs are between 10% and 25% of project cost – or £10bn to £25bn per annum across the UK construction sector.

It is starting to be recognised within the construction industry that the adoption of a standardised approach to Quality Assurance (QA), drawing on the principles widely applied in manufacturing industries, will provide a strategic platform to deliver transformation and significant improvements in quality, cost and time benefits.

Many companies using a standardised quality approach use Six Sigma. Six Sigma is an approach that seeks to improve quality by measuring how many defects there are in a process and systematically eliminating them until there are as close to zero defects as possible. The effects of deploying a standardised QA approach are shown at Figure 1 over the page.

Typically, a company without a QA system operates at 2 to 3 Sigma level producing 7 to 31 errors per 100 opportunities. Successful deployment of QA to an organisation improves the Sigma level to 4 and reduces errors per 100 opportunities to 0.6.

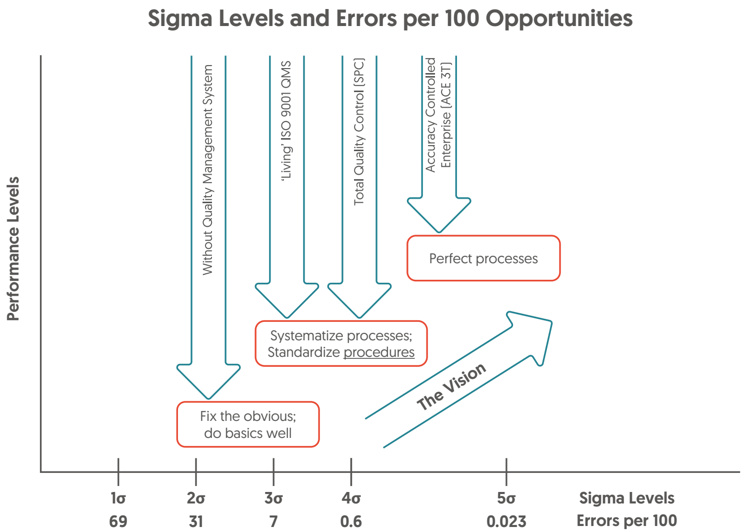

Figure 1. Improvement in sigma levels and reduction in errors on successful deployment of QA

There are a number of Quality Assurance Frameworks that the construction sector could adopt, the MTC discovery report "A Quality Oriented Approach to Construction" – 2017 recommended that the construction industry apply the proven Quality Assurance (QA) approach known as Advanced Product Quality Planning (APQP) to the manufactured product. Many of the features of APQP have been incorporated into ISO9001, which is being used in the construction sector.

QA and the APQP methodologies can be adapted and are appropriate for both large scale and bespoke projects for all types of goods and services. The versatility of QA tools and techniques, and the success they have achieved has led to many industries such as aerospace, defence, ICT and bio-medical developing and deploying industry sector quality standards.

1 – Introduction and Overview

The MTC understands that using best practice approaches adapted from other industries, such as QA frameworks, can de-risk the design and delivery of safety critical construction projects. The MTC worked with the MOJ Project team to demonstrate how APQP principles with the relevant supporting supporting systems and tools can be applied in the construction sector, how it can support the delivery of MOJ Projects and the benefits which can be realised.

This chapter describes the standardised QA approach based on APQP that the MTC used in the MOJ Project and the systems and tools used. It also describes the benefits that this approach can bring to the construction sector and the specific benefits delivered for the MOJ Project.

Quote:-

With regard to the activities that the MTC supported us on, the journey proved both informative and confirmative.

The construction industry is yet to offer a set of tools which raises the profile of lean thinking and productivity against a backdrop of Health & Safety & risk management. We found the DFMEA and PFMEA (which are core tools of the APQP approach) process of particular use as it introduced a very balanced, auditable process through which we could drive the management of risk whilst keeping the key design team and client aspirations in the forefront. Two systems which also found immediate resonance was (1) the Voice of the Customer (VoC) which helped summarise the 600 page RIBA stage 2 report into an easy to use single page chart, and (2) the Bill of Materials (BoM) which gave us a strong tool to understand, articulate and manage the variety of components associated with our platforms.

Dries Hagen, Head of Property, Bryden Wood

1.2 Overview

For more than 30 years QA approaches such as APQP (US and Europe) and Total Quality Management (TQM) have been widely used in Lean Manufacturing environments to:-

- improve safety
- improve reliability and competitiveness
- decrease lead times
- decrease cost and waste
- ensure non-conforming product does not reach the customer

Both QA methodologies draw on the Plan Do Check Act (PDCA) Cycle and the Statistical Process Control (SPC) tools developed in the US during the 1920s by William Deming and Walter Shewhart. The methodologies provide a systematic, integrated collection of common tools and processes to manage both change and New Product Introduction (NPI). NPI is a staged process that new products pass through in order to get a product prototype from design to market introduction.

The APQP process shown at Figure 2 below, consists of five phases: – Plan and Define Programme, Product Design and Development, Process Design and Development, Product and Process Validation, Production Launch.

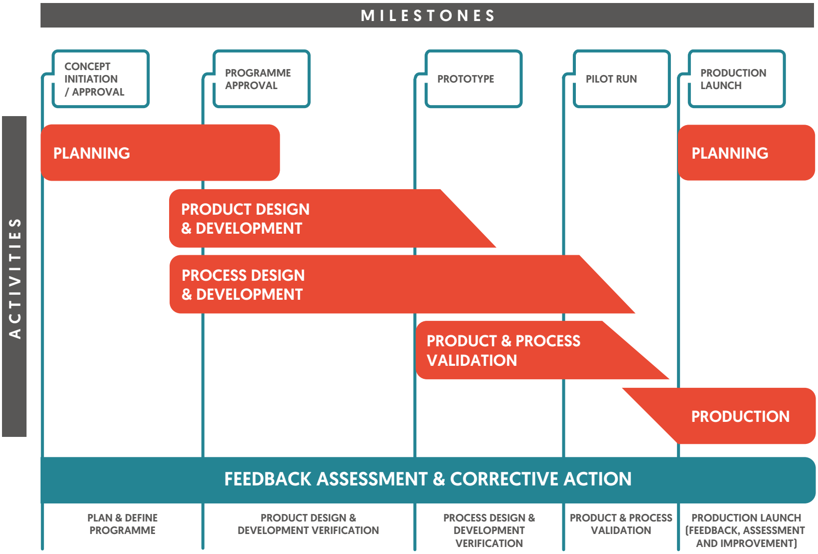

Figure 2. The Advanced Product Quality Planning process (Source: China Manufacturing Consultants, 2018)

Figure 3 below represents the four key principles of APQP with customer satisfaction (on-time, on-quality, shorter lead times) being symbolised by the roof of a house and supported by three columns made up of the remaining APQP principles of:-

- organisational commitment and management support
- cross functional team
- effective project planning

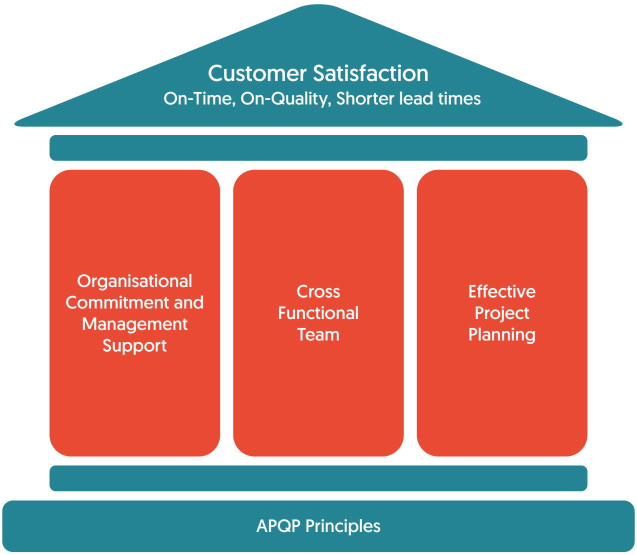

Figure 3. APQP principles (AIQG, 2013)

Customer Satisfaction is the core QA principle and a market research technique known as "Voice of the Customer" or VoC (McGraw Hill, 2008) is used to identify and agree customer requirements and priorities. VoC should be undertaken at the very start of the project lifecycle during the planning phase, along with effective planning and de-risking activities (other QA principles).

It is essential to carry out the 'front end' QA actions during the early phase of a project as this is where the greatest opportunity exists to improve NPI success rates (Smith and Reinertsen, 1991; Cooper, 1997; Khurana and Rosenthal, 1997).

QA and APQP are described in more detail in paragraph 2 of this chapter.

For the MOJ Project, the construction 'product design' had to meet the wants, needs and expectations of several stakeholders, including the MOJ and statutory and regulatory requirements. The product design also had to meet the requirements of Design for Manufacturing and Assembly (DfMA), see Chapter 3 of this book – Design for Manufacture and Assembly.

DfMA necessitates early cross-functional working and supplier collaboration (the central pillar of the QA principles) for timely issue resolution at the earliest possible point where there is the most control and the least cost.

Figure 4 below illustrates how the cost incurred in fixing a mistake increases along the life-cycle phases:-

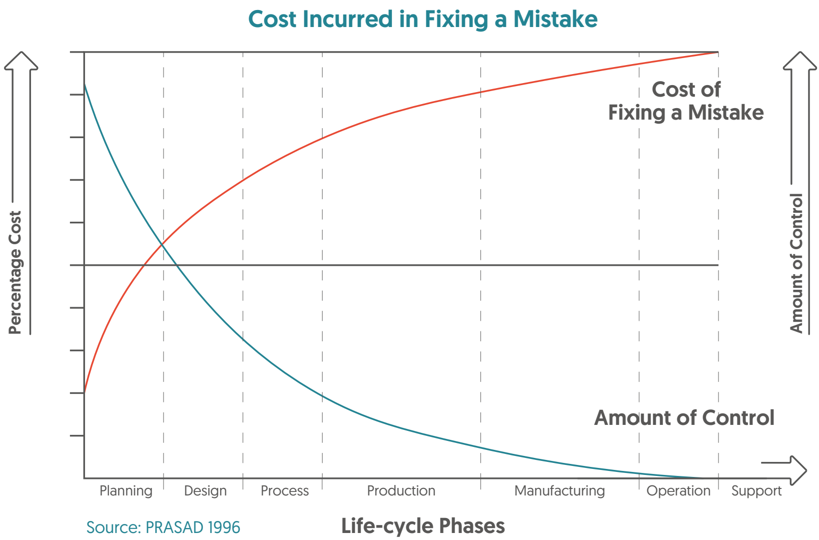

Figure 4. Cost incurred in fixing a mistake (Prasad, 1996)

1.3 Where have the systems and tools been used?

The APQP methodology was introduced by "The Big Three" from automotive (General Motors, Ford, Chrysler) in the early 1980s as a response to increasing competition from companies in Japan who, with the support of W E Deming, an American Engineer, successfully resurrected their economy by implementing Total Quality Management (TQM) during the 1940s and 1950s.

Later Deming assisted Ford in developing and implementing a QA process for their fragmented 10,000 strong supplier locations. The Ford methodology combines the "Juran Trilogy" of planning, control and improvement with established techniques such as Statistical Process Control, PDCA (Shewart and Deming) and FMEA (US Military) which have delivered consistently impressive results in quality and performance across many industries for decades.

1.4 Why these systems and tools for the Construction Sector?

With a quarter of a million existing workers in the UK construction sector needing retraining and 182,000 vacancies anticipated by 2018 (Guardian.com, 2017), the UK skills shortage is threatening major infrastructure projects. In England, in the 12 months to September 2015, due to the lack of capacity in the supply chain, only 135,050 houses were built (DCLG, 2015) versus the 250,000 target.

Labour reducing methods of off-site construction, such as modular, panelised and component are recognised as key strategies to mitigate against the housing and skills shortage and offer financial benefits of up to 7% on project costs and up to 30% of portfolio savings (Southern, 2016).

An example of a building with modular exterior sections is shown in Figure 5 below:-

Figure 5. A building with modular exterior sections

For the UK to succeed with off-site opportunities, it will need to address productivity and other QA related issues in order to be competitive with countries such as Germany and China. German manufacturers of prefabricated building modules already have stringent quality processes, and a government national strategy of standardisation which is seen as key to economic prosperity and technological convergence (www.din.de, 2017). Against this background it is clear that a standardised QA approach needs to be adopted across the UK construction sector.

1 – Introduction and Overview

It is also acknowledged by the construction sector that the lack of focus on QA contributes to the high level of construction waste (Ucatt.org.uk, 2017):-

- the UK construction industry is responsible for 32% of all landfill waste
- more than 400 million tons of materials are delivered to site each year, of which 60 million tons go straight to landfill due to over ordering or damage due to poor storage
- energy from fossil fuels utilised in the construction and operation of buildings accounts for approximately half of the UK's emissions of carbon dioxide
- building materials are estimated to account for 20% of the UK's carbon footprint, 30% of all UK freight transport and 19% of the UK's total greenhouse gas emissions

As mentioned in paragraph 1.1, estimates of the financial and economic impact of poor quality for construction are varied, however the cost of errors are estimated at £10bn to £25bn per annum.

For the construction sector as a whole, improving quality would mean less defects and rework, reduced waste, greater sustainability, cost savings, shorter lead times, enhanced customer satisfaction, improved reputation and greater competitiveness.

However, quality is not just about reducing the number of defects, it is also about:-

- assuring fitness for use
- meeting customer expectations
- outperforming competitors

It is recognised by the construction sector that challenges of poor productivity, competitiveness and customer satisfaction are all linked by a lack of collective focus on quality assurance and standardisation.

Farmer (2016) found similar recurring themes in the construction sector symptomatic of non-standardised quality management, these include:-

- low productivity
- small margins and adversarial pricing models
- low predictability of financial outcomes and financial fragility
- structural and leadership fragmentation
- dysfunctional training funding and delivery model
- absence of a collaboration and improvement culture
- poor image of construction sector
- lack of investment in innovation

The application of QA standards based on APQP together with QA proven tools and techniques, relevant to construction, will provide a standardised way of carrying out construction projects, give all the stakeholders a common language, avoid duplication of effort and ensure, right first time. The reduction in defective product, in turn, will reduce construction waste.

1.5 Benefits

The adoption of a standardised QA approach tailored to needs of the construction sector would deliver many benefits, these include:-

- **improved collaboration and communication** – the QA methodology and core tools encourage cross-functional collaboration and clear communication throughout the supply chain from the commencement of the project
- **meeting customer 'wants and needs'** – one of the key issues cited in The MTC's discovery report – "A Quality Oriented Approach to Construction" – 2017 was the lack of upfront definition and late design change requests by the customer. The lack of clarity is time consuming and compromises design and process quality
- **improved risk management** – a well-executed risk management exercise such as FMEA described paragraph 2.5 of this chapter, ensures there is a traceable record of all design and process risks, and that timely decisions and mitigation actions are made according to the risk priority

- **reduced costs** – the cost of implementing a quality standard is dependent on company turnover and other factors, but the AIAG/ASQ Quality Survey Results (1997) found a 3 to 1 return on total cost and an average saving of 6% as a result of registration to a quality standard
- **increased loyalty and sales** – from a quantitative perspective, according to the results from Forrester's US & European State of Customer Experience Programs Online Survey (Powton,2017), companies with superior Customer Experience had a growth rate of 17% (CAGR) vs 3% for the Customer Experience (CX) 'laggards'
- **less rework and waste** – the Get It Right Initiative (GIRI, 2015), estimates direct costs of errors along with unmeasured and indirect costs between 10% and 25% of project cost – or £10-25bn per annum across the sector
- **less public sector budget overruns** – the Taxpayers' Alliance (Taxpayers' Alliance, 2007) investigated cost overruns in public sector capital procurement projects and the total net overrun for 305 projects was over £23bn above initial estimates – which equates to over £900 for every household in Britain. A streamlined QA process would significantly reduce overrun on public sector projects

Quote:-

"The APQP process ensures that new methods and products come to market fully thought through, tested and accredited. This is a must in ensuring that any new modern method of construction is fit for purpose".

John Handscomb, Pre-Construction Procurement Lead, Kier Group plc

1.6 The MOJ Project

An MTC discovery report "A Quality Oriented Approach to Construction" – 2017 was published by the MTC proposing that the lack of capacity in the construction supply chain, high levels of waste, delays and low productivity could benefit from a standardised QA approach particularly for manufactured components. Subsequently, the MTC were requested to demonstrate the way in which a Quality Assurance approach based on APQP could deliver benefits and savings over and above the traditional approach being used.

Working closely with the MOJ Project team, QA tools and techniques were demonstrated for the key components of a building (superblock, windows, risers, market stall and portal frame) and this is described later in this chapter.

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2 – Planning for Manufacturing Quality

2.1 Quality Assurance Framework

Quality assurance (QA) is the part of quality management focused on providing confidence that the quality requirements will be fulfilled. QA is a process-driven approach that facilitates and defines goals regarding product design, development and production. Key elements of QA are:-

- **Customer focus** – the need to understand and meet customer requirements
- **Leadership** – the need for all leaders at all levels to provide purpose and direction and create the conditions in which people are engaged in QA
- **Engagement of people** – the need to ensure people are competent, empowered and engaged at all levels to create and deliver value
- **Process approach** – the need to ensure that processes are understood, managed and improved
- **Improvement** – the need for an ongoing focus on continuous and step change improvement

QA includes two principles, fit for purpose' (the product should be suitable for the intended purpose), and 'right first time' (mistakes should be eliminated) and includes the management of the quality of raw materials, assemblies, products and components, services related to production and management, production and inspection processes.

As mentioned in paragraph 1.1 – Introduction, the MTC recommended the use of APQP in the MOJ Project, as it is a proven QA methodology that can address many of the challenges in the construction sector.

2 – Planning for Manufacturing Quality

2.2 MTC's Approach to Planning for Manufacturing Quality and APQP

Complex products and supply chains present many possibilities for failure, especially when new products are being launched. A standardised QA approach based on APQP is a structured framework aimed at ensuring customer satisfaction with new products or processes.

The MTC's QA approach uses a set of well-defined tools and techniques used extensively in the automotive and many other industries which are proven to deliver many benefits in the development of new products. The 5 core tools and techniques described below, are part of the APQP methodology:-

1. **Quality Planning** including Plan-Do-Check-Act Cycle (PDCA) is the process of planning how to fulfil process and product (deliverable) quality requirements, and also includes the Voice of the Customer (VoC) which captures and ranks customer requirements
2. **Failure Mode and Effects Analysis** (FMEA) is a step-by-step analytical technique for identifying possible failures in a design, a manufacturing or an assembly process, or a service or a product. "Failure modes" means the ways, or modes, in which something might fail
3. **Measurement Systems Analysis** (MSA) is an experimental and mathematical method of determining how much the variation within the measurement process contributes to overall process variability emphasising repeatability and reproducibility of the measurements (R&R). The method considers equipment, human factors, process, samples, environment and management. It ensures different people using the same device achieve the same average result
4. **Statistical Process Control** (SPC) is a tool for quality control employing statistical methods to monitor and control a process using real-time data
5. **Product Part Approval Process** (PPAP) is a tool used to establish confidence in suppliers and their production processes.

The five basic core tools of APQP are detailed in separate Automotive Industry Action Group (AIAG) handbooks.

2 – Planning for Manufacturing Quality

APQP identifies 23 elements that must be considered and addressed at the appropriate phases during the development of a product or service. These are shown in Figure 6 below:-

	APQP Element		APQP Element
1	Sourcing decision	13	Measurement system evaluation
2	Customer input requirements	14	Manufacturing process iterations
3	Craftmanship	15	Packaging specifications
4	Design FMEA	16	Production trial run control plan
5	Design verification plan and report	17	Production trial run
6	Prototype build control plan	18	Preliminary process capability study
7	Prototype build(s)	19	Production validation plan and report
8	Drawings and specifications	20	Production control plan
9	Manufacturing feasibility commitment	21	Production part approval process
10	Manufacturing process flowchart	22	Design manufacturing review(s)
11	Facilities, tools and gauges	23	Subcontractor APQP status
12	Process FMEA		

Figure 6. APQP elements (El-Haik and Mekki, 2011)

2 – Planning for Manufacturing Quality

2.3 Quality Planning

2.3.1 APQP and Quality Planning (Generic Approach)

APQP is a structured approach to product and process design with a standardised set of requirements that enable suppliers to design a product that satisfies the customer requirements. An integral part of this approach is the use of the Plan-Do-Check-Act (PDCA) cycle and this is described in more detail later in this paragraph.

The APQP methodology uses phased gateway reviews that must be satisfied before a project can move to the next stage in the project plan and each gateway articulates the criteria that needs to be satisfied. The deliverables have defined Pass and Fail criteria that are communicated, agreed and refined by the stakeholders throughout the Design, Development, Validation and Build phases of a project. APQP is scalable and applies to both large and bespoke projects.

APQP necessitates cross-functional communication and collaboration as early as possible in a product cycle and particularly with marketing and manufacturing, to ensure the customer's wants and needs are clearly understood and that the proposed design solutions can be manufactured.

APQP supports the early identification of change, both intentional and incidental and uses tools and methods for mitigating the risks associated with change of the new product or process.

The APQP process has five stages:-

1. Plan and Define Programme
2. Product Design and Development
3. Process Design and Development
4. Product and Process Validation
5. Production Launch, Assessment and Improvement

2 – Planning for Manufacturing Quality

Figure 7 below shows the 5 phases of the APQP process from product concept to product launch:-

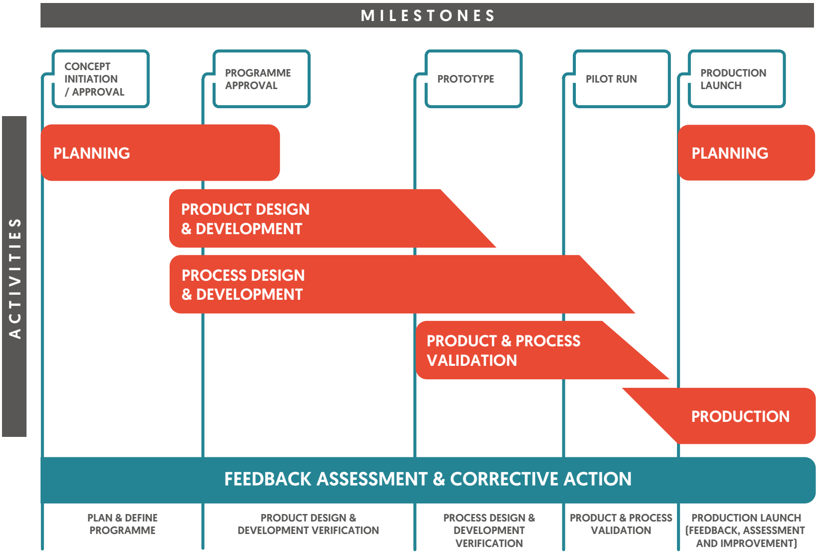

Figure 7. Phases of Advanced Product Quality Planning process (Source: China Manufacturing Consultants, 2018)

2 – Planning for Manufacturing Quality

The table in Figure 8 below shows the activities that should be considered in the phases of the APQP process up to and including product and process validation:-

Plan and Define Programme	Product Design and Development Verification	Process Design and Development Verification	Product and Process Validation
Design Goals	Design FMEA	Packaging Standards and Specifications	Production Trial Run
Reliability and Quality Goals	DfMA	Product/ Process Quality System	Measurement Systems Evaluation
Preliminary Bill of Materials	Design Verification	Process Flow Chart	Process Capability Study
Preliminary Process Flow	Design Reviews	Floor Plan Layout	Production Part Approval Process (PPAP)
Preliminary Listing of Special Product and Process Characteristics	Prototype Control Plan	Characteristics Matrix	Production Validation Testing
Product Assurance Plan	Engineering Drawings	Process FMEA	Packaging Evaluation
	Engineering Specifications	Pre-launch Control Plan	Production Control Plan
	Material Specifications	Process Instructions	Quality Planning Sign-off
	New Equipment Tooling and Facilities Requirements	Measurements Systems Analysis Plan	
	Change Control for Drawings	Preliminary Process Capability Study Plan	
	Special Product and Process		
	Gauges/ Testing Equipment Requirements		

Figure 8. APQP outputs by Phase (Quality-one.com/apqp)

2 – Planning for Manufacturing Quality

The key elements of the APQP methodology are:-

- understanding and meeting the customer requirements (VOC and Quality Function Deployment)
- proactive feedback and corrective action (PDCA, Planning, Lessons Learnt, customer feedback, warranty data)
- designing within process capabilities (FMEA, Statistical Process Control or SPC)
- risk management (analysing and mitigating any potential failure modes through FMEA and PDCA tools)
- validation and verification (Testing and PDCA)
- design reviews
- controlling special/critical characteristics (Control Plan)

As mentioned earlier in this paragraph, PDCA is an integral part of the APQP process and is an iterative four-step method used for the control and continual improvement of processes and products.

PDCA should be used at all stages of the project to confirm the validity of the information provided, the solutions identified and the actions agreed.

The 4 stages of the PDCA Cycle and a description of each stage are shown in Figure 9 below:-

Plan	Recognise an improvement opportunity and plan a change
Do	Test the change and carry out a small-scale study
Check	Review the test, analyse the results and identify what has been learned
Act	Take action based on what has been learned, if the change did not work, go through the cycle again with a different plan. If it was successful, incorporate what was learned from the test into wider changes and use what was learned to plan new improvements and begin the cycle again (Reference, ASQ)

Figure 9. Plan-Do-Check-Act cycle

2 – Planning for Manufacturing Quality

2.3.2 MOJ Project – Quality Planning

The standardised QA approach, based on the APQP methodology was adapted by the MTC for use in the MOJ Project and the following paragraphs describe how APQP and the supporting tools and techniques were used.

As the MOJ Project was at an early stage, only the APQP planning elements and associated core tools including the Voice of the Customer, FMEA, Preliminary Process Flows and Preliminary Bill of Materials could be demonstrated. The remaining tools, Measurement Systems Analysis, Statistical Process Control and Production Part Approval Process were not demonstrated, but are described in paragraphs 2.7.1, 2.7.2 and 2.7.3.

The RIBA Plan of Work 2013 is the definitive UK model for the building, design and construction process. It comprises eight work stages, each with clear boundaries, and details the tasks and outputs required at each stage.

The eight RIBA stages are:-

0 – Strategic Definition

1 – Preparation and Brief

2 – Concept Design

3 – Developed Design

4 – Technical Design

5 – Construction

6 – Handover and Close Out

7 – In Use

2 – Planning for Manufacturing Quality

The MTC created the QA Plan for the MOJ Project together with gateways that were mapped onto stages 0-5 of the RIBA Plan of Work, see Figure 10 below:-

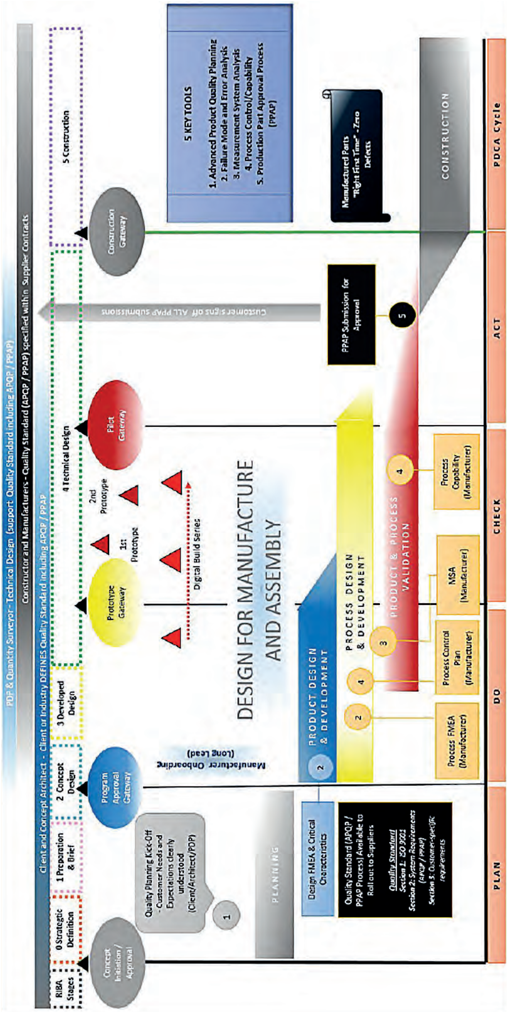

Figure 10. High level QA plan with mapped RIBA gateway

2 – Planning for Manufacturing Quality

For gateway 1, 10 elements from the 23 elements of the APQP process were identified, considered and addressed as part of the MOJ Project. Figure 11 below shows the full list of 23 elements of the APQP process, and Figure 12 shows the 10 elements considered in the MOJ Project:-

	APQP Element		APQP Element
1	Sourcing decision	13	Measurement system evaluation
2	Customer input requirements	14	Manufacturing process iterations
3	Craftmanship	15	Packaging specifications
4	Design FMEA	16	Production trial run control plan
5	Design verification plan and report	17	Production trial run
6	Prototype build control plan	18	Preliminary process capability study
7	Prototype build(s)	19	Production validation plan and report
8	Drawings and specifications	20	Production control plan
9	Manufacturing feasibility commitment	21	Production part approval process
10	Manufacturing process flowchart	22	Design manufacturing review(s)
11	Facilities, tools and gauges	23	Subcontractor APQP status
12	Process FMEA		

Figure 11. Full list of APQP elements (23) (El-Haik and Mekki, 2011)

	APQP Element
1	Sourcing decision
2	Customer input requirements
4	Design FMEA
5	Design verification plan and report
7	Prototype build(s)
8	Drawings and specifications
10	Manufacturing process flowchart
11	Facilities, tools and gauges
12	Process FMEA
22	Design manufacturing review(s)

Figure 12. MOJ Project APQP elements (10)

2 – Planning for Manufacturing Quality

In addition, for Gateway 1, the APQP phase outputs and APQP elements were compiled into a list of deliverables. The deliverables were then reviewed, refined and agreed with the MOJ Project team, and the responsibilities assigned. An extract of the agreed deliverables are shown in Figure 13 below:-

Quality Gateway 1 Deliverables
Engineering
Initial manufacturing feasibility assessment compiled for product selection
Baseline demonstrator parts defined and agreed
DFMEA
RIBA 2 completed CAD models released into CDE and available to MTC to start work
Preliminary test schedule
Manufacturing
Outline specification for manufacturing process (including steps) for each component
Outline specifications for tooling, fixturing and materials handling defined for manufacturing NOT construction.
Preliminary structured and costed (BOM)
Quality Assurance
Design Goals (VOC)
Preliminary listing of critical and special product and process characteristics
Quality Assurance Plan
Preliminary process flow charts for key elements
Factory
Preliminary strategy and location for production facilities and logistics hub
Commercial and Industrial Engagement and Exploitation
All potential project participants have been contacted and interest level is categorised
All key assemblies are listed and potential industrial suppliers listed against each
Programme Management
Required resources and timings for project and next gateways have been identified and confirmed available
Budget summary and forecast timings have been agreed including gateways
Supply Chain Management
Long lead suppliers contacts established for windows, steel frame, partitions and superblocks

Figure 13. An extract of quality gateway 1 deliverables

2 – Planning for Manufacturing Quality

To support delivery of the Quality Gateway 1 deliverables, the MOJ Project team were provided with a full set of templates, training material and copies of the Gateway 1 document submissions.

The Gateway 1 process, demonstrated to the MOJ Project team the detailed steps that should be followed when undertaking a Gateway meeting, this included:-

- setting a date for the Gateway meeting
- issuing the agenda
- organising a pre-brief
- ensuring all documents were submitted on time
- discussing any concerns with the panel
- ensuring rework of documents is completed before the Gateway meeting
- holding the Gateway meeting
- taking notes of the Gateway meeting
- chasing up any corrective actions

2.4 Voice of the Customer

2.4.1 Voice of the Customer (Generic Approach)

Voice of the customer (VoC) is a term used to describe the in-depth process of capturing customer needs, wants and expectations, (stated and unstated). Quality Function Deployment (QFD) is a methodology developed in Japan by Yoji Akao in 1966, which can be used to transform the VoC into the products' engineering characteristics, technical specifications and requirements.

The QFD is then used to organise the VoC into a hierarchical structure, and prioritised in terms of relative importance and satisfaction.

The VoC – QFD, is conducted at the start of any new product, process, or service design initiative in order to better understand the customer's wants and needs, and is the key input for new product introduction and the setting of detailed design requirements.

2 – Planning for Manufacturing Quality

An example of a completed VoC – QFD is shown in Figure 14 below:-

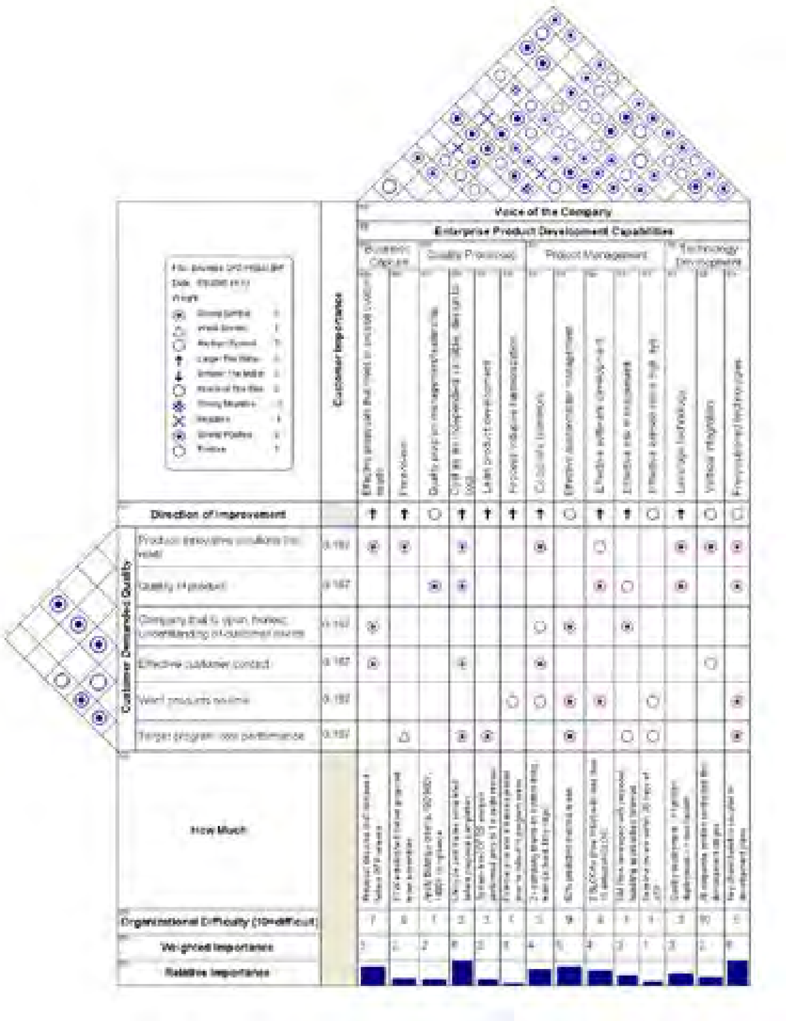

Figure 14. Example QFD – Enterprise product development processes (Wikimedia, 2018)

2.4.2 MOJ Project – Voice of the Customer

A VoC workshop was undertaken with a cross-functional team from the MOJ Project to summarise and rank the customer requirements distilled from the 600 page RIBA Stage 2 report and then translate these wants and needs into ranked design requirements.

The MTC team provided a VoC tutorial to the MOJ Project team ahead of the workshop to provide background information prior to the workshop. At the workshop the MOJ Project team brainstormed and agreed the customer requirements (vertical axis) before developing the technical engineering requirements to be met by the design (horizontal axis), in order to populate the QFD.

After the workshop and several iterations, the completed QFD, similar to the QFD shown in Figure 14, was presented at the pre-Gateway 1 meeting for review and sign-off by the MOJ Project team.

The VoC process enabled the MOJ project team to gain consensus and agreement on the common goals of the project and the customer priorities.

2.5 Failure Mode and Effects Analysis

2.5.1 Failure Mode and Effects Analysis (Generic Approach)

Failure Mode and Effect(s) Analysis (FMEA) is described in Chapter 3 of this book, Design for Manufacture and Assembly, paragraph 2.3.1. However, it is repeated here because it is an integral and important tool within the APQP process.

Failure Mode and Effects Analysis (FMEA) is a step by step analytical technique for identifying possible failures in a design, a manufacturing or assembly process, or a service or product. 'Failure mode' means the ways, or modes in which something might fail.

The FMEA process is designed to identify 'failure modes' early in a project and increase the opportunity to mitigate against or ideally avoid them before capital is committed. The later in a project a 'failure mode' is identified, the more expensive and difficult it is to execute mitigating and corrective actions.

FMEA is designed to:-

- identify potential 'failure modes'
- understand the direct causes and effects of such failure
- assess the risks associated with the failure mode and prioritise them for corrective action
- identify and carry out appropriate corrective actions to address the most serious concerns

FMEA is carried out in the Design Review Workshop by a cross-functional team of subject matter experts and stakeholders, in order to identify weaknesses in the design or process and mitigate against failure before the product is produced.

2 – Planning for Manufacturing Quality

There are many types of FMEA with Design and Process being the most common in manufacturing industries, the relationship between Design and Process FMEA is shown in Figure 15 below:-

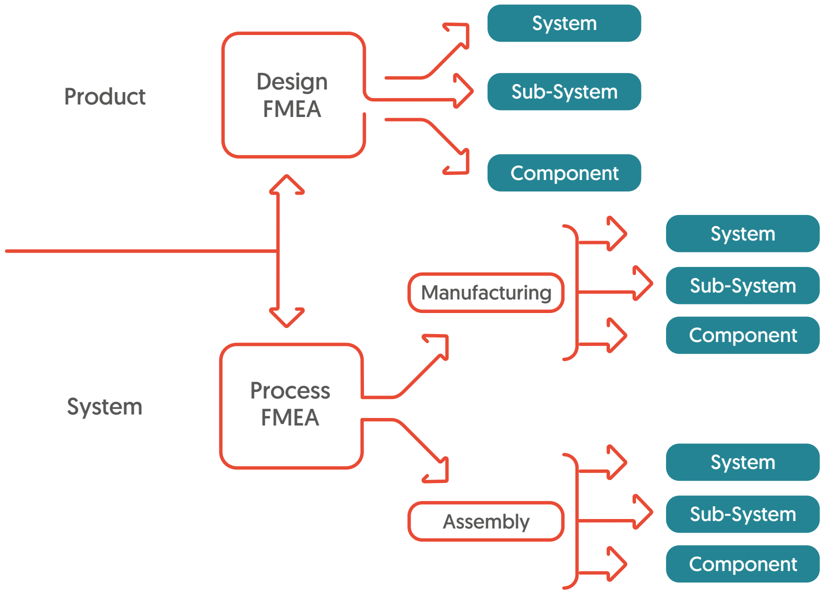

Figure 15. Relationship between some types of FMEA

A brief description of the above FMEA is shown below:-.

Design FMEA (DFMEA) focuses on a product, typically at the subsystem or component level. The focus is on design-related deficiencies, with emphasis on improving the design and ensuring product operation is safe and reliable during the useful life of the equipment.

Process FMEA (PFMEA) focuses on the manufacturing or assembly process, emphasising how the manufacturing process can be improved to ensure that a product is built to design requirements in a safe manner, with minimal downtime, scrap and rework.

For each FMEA, the step-by-step process of identifying potential failure modes, quantifying the Severity (SEV), Occurrence (OCC) likelihood, and chances of Detection (DET) before failure, as well as mitigation strategies, is the same. Once quantified the resultant product of Severity, Occurrence, and Detection, known as the Risk Priority Number (RPN), is used to rank the potential failure modes and prioritise them.

To assist in the priorisation and scoring of the above process, DFMEA and PFMEA guidelines and rankings can be found at Press, Dyadem. Guidelines for Failure Mode and Effects Analysis (FMEA), for Automotive, Aerospace, and General Manufacturing Industries. Baton Rouge US: CRC Press, 2003.

An extract from the guidelines and rankings are shown in Figure 16 below:-

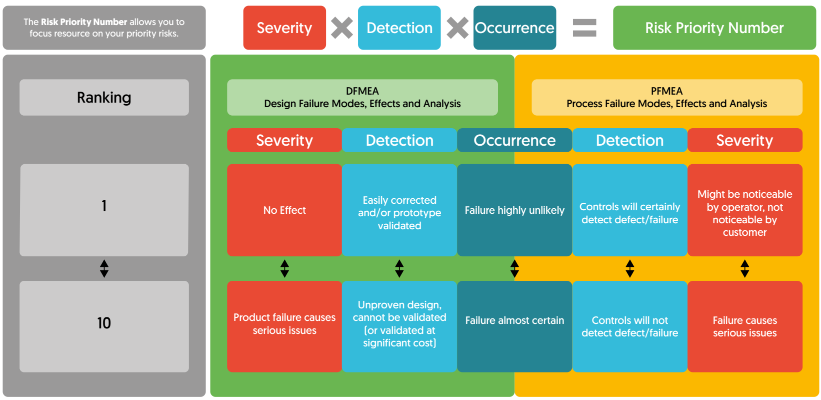

Figure 16. Extract from DFMEA and PFMEA guidelines and rankings

The FMEA process is carried out with all stakeholders and the information is captured. There are software packages with FMEA templates that may be used.

2.5.2 MOJ Project – Failure Mode and Effects Analysis

FMEA workshops were carried out with the MOJ project team for each subsystem – portal frame, superblock, market stall, windows and partitions and the outputs reviewed with the broader team, scored and submitted for Gateway 1 review.

Detailed output from the MOJ Project FMEA workshops is shown in Chapter 3 – Design for Manufacture and Assembly.

2.6 Preliminary Process Flows

2.6.1 Preliminary Process Flows (Generic Approach)

Process flows provide a graphical representation of the current or proposed sequences of manufacturing processes. The purpose of developing process flows is to ensure that the process definition, PFMEA and control plans can be created and analysed in the appropriate sequence, and it enables bottlenecks or duplication of effort to be identified and improvements in the process to be made. It is also a visual confirmation that all stakeholders understand the proposed sequence of the manufacturing processes.

2.6.2 MOJ Project – Preliminary Process Flows

A workshop was held with the MOJ Project team to develop preliminary process flows for the components to be manufactured. Design data was shared for each part and assembly and the team mapped out process steps. Manufacturing process flow charts were then developed to pictorially represent the manufacturing process steps for Gateway 1 submission. The resulting process steps were reviewed and agreed.

Figure 17 shows an example of the manufacturing process steps for superblocks:-

PROCESS FLOW DIAGRAM		
Part Number	Unknown	Date Completed...
Part Description	Superblock to Megablock	Review Date...
Part Number	Unknown	Prepared by...
Synonyms (This part is also known as)		

Step	Fabrication	Move/Lift	Store	Inspect	Operation Description	Item	Product and Process Characteristics	SC/CC	Control Methods
1	X				Rebar cut to length and placed in custom mould		Customised mould/ tooling required (1 week)		
2	X				Concrete batched				
3	X				Pour concrete into mould		How many moulds are needed?		
4	X				Turn out and cure for 2 days		Turntable mould		
5		X			Stack with spacers and store at concrete factory		Machine Stacking		
6		X			Ship to brick slip manufacturer		TBC – transport costs, sustainability?		
7	X				Brick slip manufacturer fixes brick slips to gravel boards		TBC		
8		X			Phenolic insulation milled at Insulation Manufacturer and shipped to Consolidation Centre		TBC – transport costs? Channel for strap, proximity of brick slip manufacturer to concrete manufacturer		
9	X				Steel bands cut to correct length shipped to Consolidation Centre				
10	X				Two pieces of insulation put between two gravel boards by hand				
11	X				Four steel bands wrapped around by hand and crimped		Use crimping machine. Standard tooling		
12				X	Superblock QA checked				
13	X				Superblocks assembled on a toaster (10) and made into a megablock		Car lifting machine for toaster.Custom Tooling		
14				X	Megablock inspected				
15			X		Megablock stored and shipped to site				

Figure 17. Example of the manufacturing process steps for superblocks

2.7 Preliminary Bill of Materials

2.7.1 Preliminary Bill of Materials (Generic Approach)

A BOM or product structure is a list of the raw materials, sub-assemblies, intermediate assemblies, sub-components, parts, and the quantities of each needed, to manufacture an end product. A BOM may be used for communication between manufacturing partners or confined to a single manufacturing plant. A BOM is linked to Enterprise Resource Planning manufacturing and procurement systems.

A structured, pictorial BOM is created and owned by the responsible engineer for each system and is a business critical reference document used across all functions in manufacturing.

A BOM provides:-

- clarity on all the elements that make up a component
- clarity on volumes
- assurance that everyone is on the same page and has a consistent understanding

The BOM is used for:-

- planning volumes
- costing
- calculating weight
- discussions with suppliers
- managing complexity and kitting
- identifying service parts
- storage and freight requirements
- communicating latest design intent to team
- tracking timely release of CAD data
- purchase and works orders
- quality deliverables

It enables everyone to visualise all the elements that go into the end product.

2 – Planning for Manufacturing Quality

Without a complete and accurate BOM, decisions regarding material planning and replenishment are often made in a vacuum, resulting in excess inventory, stock shortages, expediting charges and delays to manufacturing.

The BOM is a critical tool for manufacturing success and the development of a BOM is a QA gateway element which has to be satisfied before the gateway can be passed.

2.7.2 MOJ Project – Preliminary Bill of Materials

A BOM workshop was held for the superblock component and the MOJ Project team developed and agreed a preliminary structured BOM.

Figure 18 below shows a sample BOM for a superblock:-

Part No	Custom or Proprietary	Supplier	Tooling	Purchasing Decision	Description	Quantity Per Assembly	Quantity Per building
SB01	Custom			Assy	Superblock Façade Panel Assy 1125mm	1	5,400
GB01	Custom	Supplier 1	Not required	BF	Gravel Boards	2	10,800
W101	Custom	Supplier 2	Not required	BF	Wool Insulation	1	5,400
ST01	Proprietary	Supplier 3	Not required	BF	Stainless Steel Band Strap	4	21,600
SS01	Custom		Not required	BF	Steel Spacers	8	43,200
BS01	Custom	Supplier 4	Not required	BF	Brick Slips Mats	1	5,400
SB02	Custom			Assy	Superblock Façade Panel Assy 1125mm	1	585

Figure 18. Sample bill of material for superblock

2 – Planning for Manufacturing Quality

At the superblock BOM workshop, the MOJ Project team identified four potential variants of superblock along with their estimated planning volumes, they were:-

- façade Panel Assy 1125cm
- façade Panel Assy 675cm
- façade Panel Assy Internal Corner
- façade Panel Assy External Corners

The BOM developed for the superblock provided greater clarity with regard to where improvements could be made.

The BOM was also used to consider different approaches to component supply for the market stall component. The preferred approach, from a quality assurance perspective, was 'kitting'. In this instance the market stall was divided into sub-assemblies or kits, similar to a flat-pack kitchen, and delivered as needed Just in Time (JIT).

The kitting approach improved on the traditional method of supplying components in bulk to site, this is where one bulk delivery is made and may incur significant waste.

The structured BOM allowed the MOJ Project team to visualise and understand the kitting process, the different kitting possibilities and assembly process ramifications.

2 – Planning for Manufacturing Quality

Figure 19 below shows a potential kitting solution, identified by the MOJ Project team for the market stall:-

Part No	Custom or Proprietary	Supplier	Tooling	Purchasing Decision	Description	Quantity Per Assembly	Quantity Per building
MS01	Custom	Supplier 5		Assy	Market Stall Assy (Big)	1	12
SA01	Custom		Not required	Assy	Market Stall Assy (3 side)	5	60
SA02	Custom		Not required	Assy	Market Stall Assy (4side complete tray)	1	12
MS01	Proprietary	Supplier 5		Assy	Market Stall Assy (Medium)	1	12
SA01	Custom		Not required	Assy	Market Stall Assy (3side)	3	36
SA01	Custom		Not required	Assy	Market Stall Assy (4side complete tray)	1	12

Figure 19. Example of kitting solution for market stall

2 – Planning for Manufacturing Quality

Overall, the structured BOM element for APQP delivered much needed clarity to the MOJ Project and provided the following benefits:-

- a shared insight into part complexity
- a common understanding of planning volumes
- an understanding of potential kitting options
- assisted in the early identification of issues around storage capacity
- identified potential cost savings

For Gateway 2, the MOJ Project team were briefed on the QA process and deliverables for Gateway 2 and ownership of the deliverables was agreed.

"The APQP pilot challenged the conventional construction approach to design and showed the benefits of applying a completely different mind-set when investing in manufacturing tools and processes".

Rochelle Thompson, MOJ Project team member

2.8 Tools used in the APQP process but not demonstrated in the MOJ Project.

As mentioned in paragraph 2.2.2 Measurement Systems Analysis, Statistical Process Control and Pre-Production Part Approval Process was not demonstrated in the MOJ Project, however a brief description of each is shown below.

2.8.1 Measurement Systems Analysis

Measurement Systems Analysis is an experimental and mathematical method of determining how much the variation within the measurement process contributes to overall process variability emphasising repeatability and reproducibility of the measurements. The method considers equipment, human factors, process, samples, environment and management – and ensures different people using the same device achieve the same average result.

2.8.2 Statistical Process Control

Statistical Process Control (SPC) is a tool for quality control employing statistical methods to monitor and control a process using real-time data during manufacturing.

Developed during the 1920's by Walter Shewart, SPC provides the statistical tools to track, manage and control a process to ensure that products meet requirements.

2.8.3 Production Part Approval Process

Production Part Approval Process is a tool used to confirm adherence to QA standards and processes.

PPAP occurs at the end of the validation process and will include all the specifications, test results, validation certifications and lab certifications for the final product.

If you want to get started and/or want further information on the systems, tools and approaches described in this publication, visit the construction website at www.the-mtc.org/construction

3

DESIGN FOR MANUFACTURE AND ASSEMBLY

1. Introduction and Overview

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1 – Introduction and Overview

1.1 Introduction

In line with its commitment to the Transforming Infrastructure Performance Programme, the MOJ is committed to procure, by preference, requirements for new buildings off-site. As part of this approach the application of DfMA, a methodology which has been widely used in the manufacturing sector for many years, was demonstrated in the MOJ project, described in Chapter 1 – Overview.

DfMA stands for Design for Manufacture and Assembly and is the combination of two methodologies, Design for Manufacture, which means the design for ease of manufacture of the parts that will form a product, and Design for Assembly, which means the design of the product for ease of assembly.

DfMA is used to provide guidance to design teams to simplify the product structure, to reduce manufacturing and assembly costs, and to quantify improvements. The purpose of applying DfMA is to identify, quantify and eliminate waste or inefficiency in a product design.

The MTC has extensive knowledge and expertise of applying DfMA in the manufacturing sector to support designs that will be easy to manufacture and assemble, at full scale production.

Quote:-

"The MTC has opened our eyes further to the wider benefits that production manufacturing approaches can bring to the construction industry and have set the stakeholders on a collaborative path that we believe will see the construction industry's can-do attitude harnessed to reap the benefits of DfMA".

Bryden Wood
MOJ project team member

1.2 Overview

The government has challenged the UK Construction and Infrastructure sector to become more cost and time efficient. The Construction 2025 Report sets out challenging targets and some of these are described in Chapter 1 – Overview, paragraph 1.1 of this book. Some of the challenges that the construction sector must address include:-

- poor productivity and profitability
- the need to improve project performance
- skilled labour shortages
- sustainability concerns

Against this background the construction sector has recently embraced the concepts of Design for Manufacture and Assembly and is applying it to off-site manufacture and on-site assembly. It provides a systematic approach for buildings to be constructed more quickly, safely and cost-effectively.

The Design for Manufacturing and Assembly overlay to the RIBA Plan of work was published in 2016. It acknowledges the importance of DfMA in contributing to the mass production of construction solutions. It also reinforces the importance of collaborative working when designing processes and components along the whole value chain embracing design teams, clients, contractors and off-site manufacturers.

1 – Introduction and Overview

DfMA encourages a mindset to be used throughout all stages of a construction project, as shown in Figure 1 below:-

RIBA Plan of work 2013 – Designing for Manufacture and Assembly

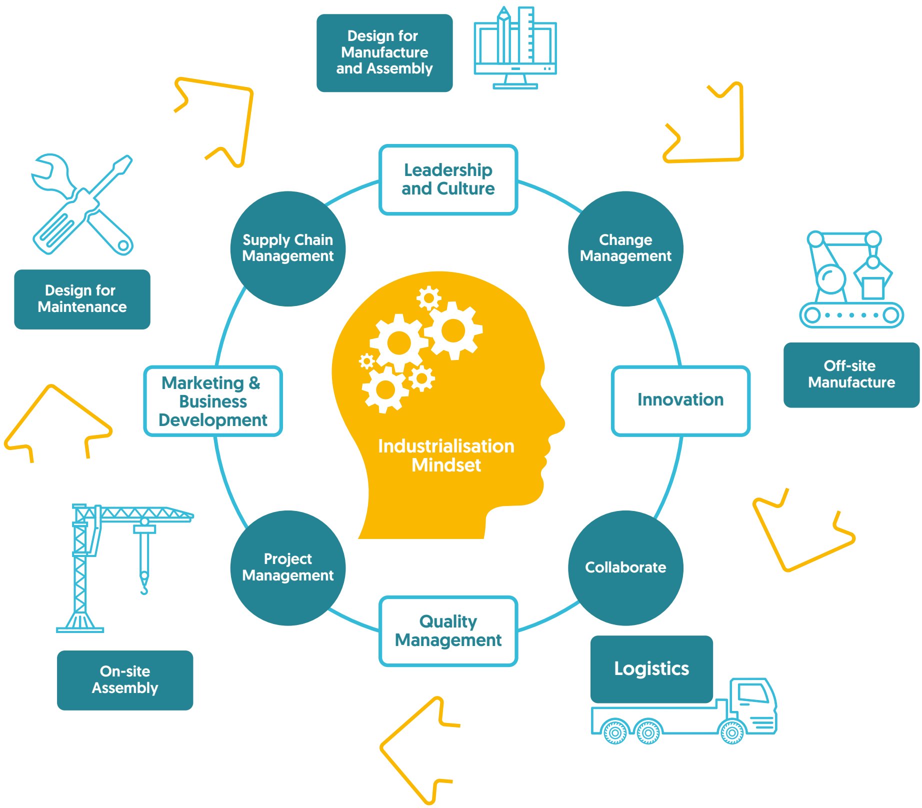

Figure 1. DfMA mindset through the stages of construction

The DfMA approach used by the MTC on the MOJ project was based on a manufacturing orientated approach and was tailored for the specific requirements of this project. The MTC team believe that the application of the DfMA approach to construction projects will shorten the new product development cycle, improve productivity and overall efficiency in the construction sector.

1.3 Where have the systems and tools been used?

Design for Manufacture (DfM) and Design for Assembly (DfA) or combined as DfMA are systematic disciplines focusing on the optimisation of design for manufacturing and assembly. The use of these methodologies can be traced back to the late 1950s and they remained in development throughout the 1970s, with significant benefits being realised across manufacturing industries.

The main players in the development of these systems and tools were:-

- Lucas DFA * 1981
- Boothroyd-Dewhurst DFA * 1983
- The Hitachi Assemblability Evaluation Method (Hitachi AEM) 1990
- British Standard BS8887-1 (2006) Design for Manufacture, Assembly, Disassembly and End of life processing (MADE)

(* both arising from collaborative work between researchers based at Salford University in the UK and Massachusetts University in the USA)

The DfMA systems and tools are part of, what is termed, concurrent engineering which is a method by which several teams, within an organisation, work simultaneously to develop new products and services. By engaging in multiple aspects of development concurrently, the amount of elapsed time, involved in getting a new product to market, is reduced significantly.

The DfMA systems and tools have been used extensively across all sectors of industry but particularly in aerospace, automotive, pharmaceutical and defence

1.4 Why these systems and tools for the Construction Sector?

DfMA and the supporting systems and tools described in this chapter, have been selected as they are recognised throughout industry as helping to reduce time taken to bring a new product to market and reduce risk by bringing together the various disciplines across a business or industry. They do this by encouraging the sharing of knowledge across the product lifecycle from concept, design and manufacture through to its use by the consumer.

1 – Introduction and Overview

The MTC are of the view that up front design for manufacturing and assembly activities will make a significant impact on the risk and cost profile of a project. With a traditional design effort the concept is considered in outline only and the feasibility of manufacture, assembly and buildability are not detailed until the technical design phase. This means that changes incur greater cost and cause delays to projects. Traditional design effort also means that the risk is high and protracted across the concept, development and technical stages of the project, as shown in Figure 2 below :-

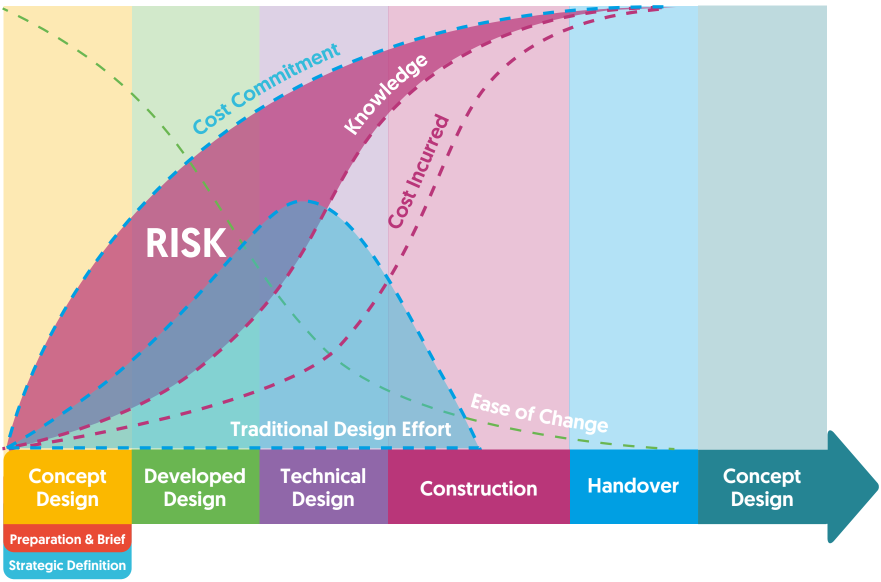

Figure 2. Traditional design effort and its impact on risk and cost

1 – Introduction and Overview

Using DfMA encourages a collaborative design approach where more effort is put in at the concept stage and the design is developed concurrently with manufacturing, assembly and buildability processes. DfMA also enables prototypes to be developed digitally, which:-

- provides opportunity to make changes at an earlier stage
- enables digital prototypes to be developed reducing the cost of physical prototypes
- minimises the impact of risk on overall project performance, as shown in the Figure 3 below:-

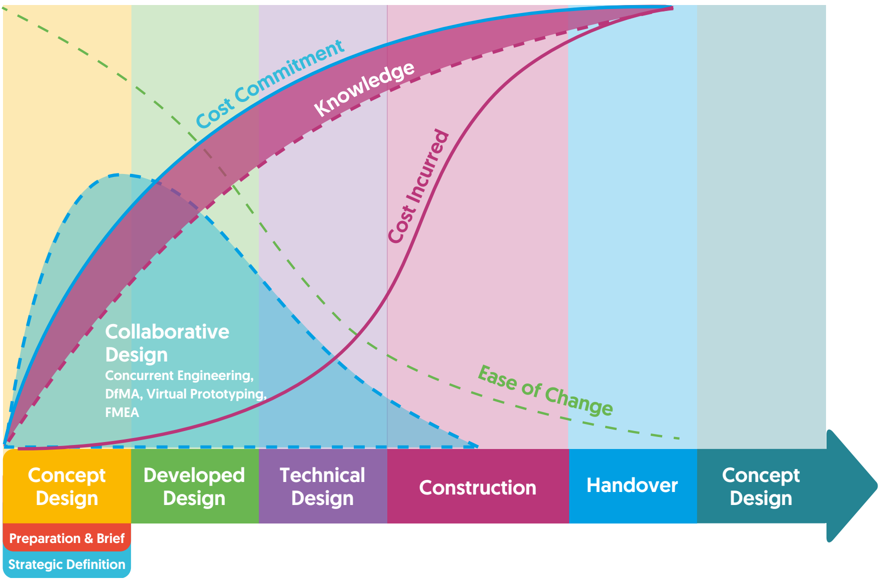

Figure 3. Collaborative design approach showing reduction in risk and cost

DfMA can contribute to the growing application of modular design thinking and pre-assembly of construction components. It can be used to support designers, creating elements that are easier to manufacture and assemble at full scale production. The use of DfMA will provide a much deeper understanding of component specification and the detailed material and technical requirements that are required from the supply chain to contribute to the manufacture.

1.5 Benefits

DfMA has the potential to shorten the new product introduction cycle and improve productivity and contribute to overall efficiency in the construction sector as it has proven in manufacturing environments. Its use can:-

- reduce costs relating to the design of components and systems by carefully considering the manufacturing and assembly processes
- reduce manufacturing costs (by reducing non-essential part count) and selecting most efficient manufacturing methods and materials
- reduce the cost of the Bill of Materials (BOM)
- reduce overhead cost of production in managing, stocking and dispensing parts to production
- reduce assembly time and complexity
- improve design efficiency and productivity
- help shorten assembly lines resulting in a reduction in the cost of logistics and work in progress
- help balance manufacturing investment with long term assembly costs

1.6 The MOJ Project

The MTC supported the MOJ project team in the manufacturing design of the elements that would form some of the key components of a new build system. In particular, the MOJ wanted to utilise the MTC's knowledge and expertise in manufacturing to support designers creating "elements" that will be easier to manufacture and assemble at full scale production.

The MTC support involved the assessment of 5 key components of the proposed build system from a manufacturing and assembly feasibility perspective. The MTC provided its knowledge and expertise in the assessment of the 5 key components using appropriate design review tools and techniques, with a view to identifying improvement opportunities in design, methods of manufacture, and methods of assembly. The components that were assessed are described later in this chapter, in paragraph 2.2.2 – MOJ Project Cross Functional Design Review Workshop.

2. Design for Manufacture and Assembly

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2 – Design for Manufacture and Assembly

2.1 MTC's approach to Design for Manufacture and Assembly

The MTC's approach to Design for Manufacture and Assembly uses a set of systems and tools that have been used in a variety of industry sectors. This paragraph describes the four main systems and tools that the MTC use when carrying out DfMA projects. They are used in combination with one another and are:-

- Cross Functional Design Review Workshops (see paragraph 2.2.1)
- Failure Mode and Effects Analysis (FMEA), Design Failure Mode and Effects Analysis (DFMEA), Process Failure and Mode Effects Analysis (PFMEA) (see paragraph 2.3.1)
- Design for Manufacture and Design for Assembly (DfMA – see paragraph 2.4.1)
- Virtual Prototyping (see paragraph 2.5.1)

These systems and tools are consistent with the RIBA Plan of Work and are used to support Stage 2 – Concept Design. An illustration of how the systems and tools are positioned in the Concept Design stage of the RIBA Plan of Work is shown in Figure 4 below:-

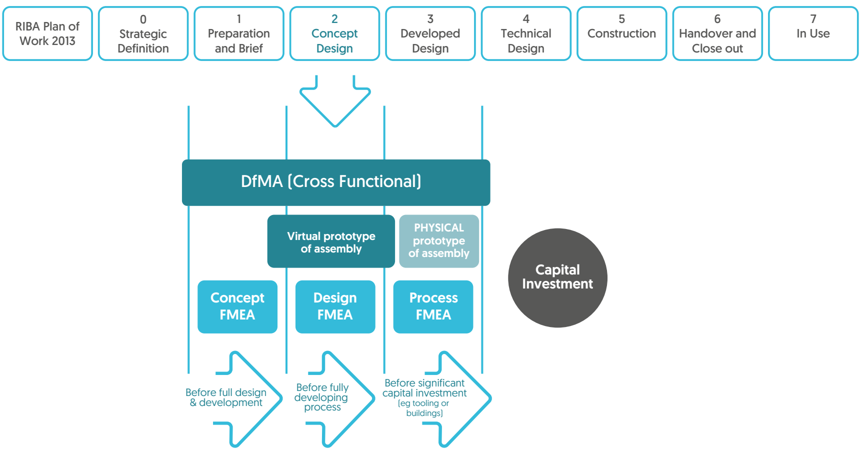


Figure 4. Application of MTC DfMA systems and tools during the concept stage of the RIBA Plan of Work

2 – Design for Manufacture and Assembly

Figure 5 below shows, the DfMA systems and tools and their relationship with the key stages of the RIBA Plan of Work, it describes the key stages that should be followed from design assessment to virtual prototyping of the assembly sequence.

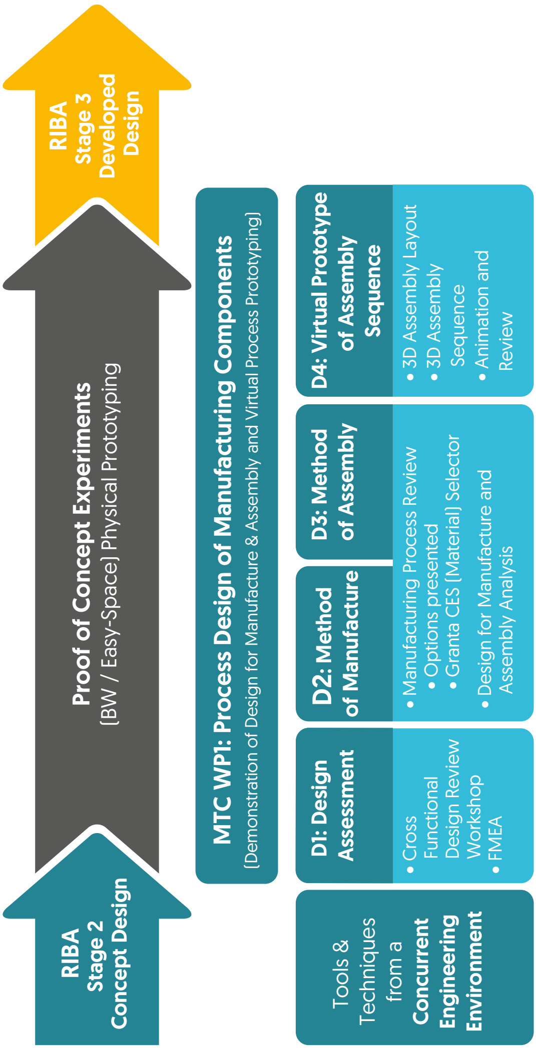


Figure 5. DfMA process and its relationship with RIBA Plan of Work

2.2 Cross Functional Design Review Workshop

2.2.1 Cross Functional Design Review Workshop (Generic Approach)

A Cross Functional Design Review Workshop is a collaborative approach to a design review, widely used across many industries. It can be used to rapidly gain understanding of the project design and encourage engagement with cross functional stakeholders.

The workshop is an ideal environment to identify risks associated with the proposed design and for developing mitigation strategies. Stakeholders from all functional areas should be represented from the beginning of the process to gain understanding of the concept, its implications and the potential impact for the business and project.

A typical Design Review workshop requires:-

- a nominated facilitator
- a cross functional representative group able to contribute to the design being considered
- appropriate environment for the size of the group carrying out the review
- the latest edition of materials relative to the subject being considered and may include drawings, CAD data, DfMA analysis, FMEAs, Animations, VR environments (virtual prototypes), physical models and prototypes
- a method of capturing and describing the ideas and concepts being considered e.g. whiteboards, post-it notes
- a method of recording review comments and agreeing subsequent actions e.g. risk or FMEA register to show progress at the next design iteration

2 – Design for Manufacture and Assembly

Due to the separation of disciplines and companies by trades and contracts in a project, it can be difficult to form a cross-functional review workshop, however, due to the range of knowledge of the team, it is this type of workshop that generates the most value. The cross functional workshop encourages the review team to behave as a single entity and tackle complex problems early and reduces the need to add contingency costs to each contractual relationship.

A cross functional review workshop delivers many benefits including:-

- feedback and learning from across the project
- flagging up potential pitfalls and problems
- shorter development cycle
- buy-in to new ideas across disciplines
- sharing knowledge across 'silos' of activity
- shortening the feedback loop
- reducing the learning curve
- encouraging the adoption of disruptive technology

2.2.2 MOJ Project – Cross Functional Design Review Workshop

The cross functional design review team involved representatives from the MOJ project team who were able to contribute, both generally and technically, to the design being considered. The workshops were facilitated by the MTC team DfMA experts.

The reviews helped to bring the MOJ project team up-to-speed on the key elements of the RIBA Stage 2 concept, which in turn helped to identify technical, structural, and practical requirements, not considered in the RIBA Stage 2 Concept Report.

As a result, some risks and opportunities identified during the review process were able to be mitigated, either whole or in part, and issues experienced during the ongoing physical proof of concept prototype work, were resolved.

2 – Design for Manufacture and Assembly

The Cross Functional Design Review Workshop reviewed all the components under consideration using the FMEA process described in paragraph 2.3.1. The components considered were:

- façade system, containing, superblocks and megablocks (a megablock is an assembly of 10 superblocks)
- cell windows (as contained within the façade system)
- portal frame, including the riser
- partition wall
- "market stall" frames

Figure 6. A superblock under construction

Quote:-

"The MTC team facilitated and stimulated our design workshop events, which were a great way of flushing out concerns and issues with the current design concepts and leveraging the knowledge of the cross functional teams assembled to provide new direction for future development'".

Peter Wilson, Project Manager, Bryden Wood

2 – Design for Manufacture and Assembly

At the workshop the cross functional review team were divided into sub groups to consider the design of the 5 components and how they could be made. The review team used brainstorming, post-it notes and theming to discuss, shape and agree improvement opportunities, see Figure 7 below:-

Figure 7. A cross functional design review team considering design options in a workshop environment

In addition the group identified risks, associated with the design, which were classified into Design FMEA or Process FMEA risks and captured on the relevant MTC templates.

2.3 Failure Mode and Effects Analysis

2.3.1 Failure Mode and Effects Analysis (Generic Approach)

Failure Mode and Effect(s) Analysis (FMEA) has its roots in US Military standard MIL-STD-1629 (1949). The primary function of the standard was to determine the effect of system or equipment failures in terms of their impact on mission success, personnel safety or equipment damage. It was later developed in the aerospace industry and adopted by the automotive industry by the late 1970s, as a method of reducing costs and risks related to poor quality. It remains the basis of formal risk identification and mitigation in many industries worldwide.

In manufacturing industries that support the automotive and aerospace industries, the formal practice of DFMEA and PFMEA is a due-diligence requirement in adherence to quality systems like Advanced Product Quality Planning (APQP). APQP is described in detail in Chapter 2 – Planning for Manufacturing Quality.

Failure Mode and Effects Analysis (FMEA) is a step by step analytical technique for identifying possible failures in a design, manufacturing or assembly process, for a service or a product. 'Failure Mode' means the ways, or modes in which something might fail.

The FMEA process is designed to reduce the time to identify failure modes and increase the opportunity to mitigate against or ideally avoid them before capital expenditure is committed. The later in a project that a failure mode is identified, the more expensive and difficult it may be to develop and execute mitigating actions.

FMEA is designed to:-

- identify potential failure modes
- understand the direct causes and effects of such failure
- assess the risks associated with the failure mode and prioritise them for corrective action
- identify and carry out appropriate corrective actions to address the most serious concerns

FMEA is carried out in a Design Review Workshop by a cross functional team of subject matter experts and stakeholders, to identify weaknesses in a system or a product and mitigate against failure before the system or product starts manufacture and assembly.

2 – Design for Manufacture and Assembly

There are many applications of FMEA with Design and Process being the most common in manufacturing industries. The relationship between, design and process FMEA is shown in Figure 8 below:-

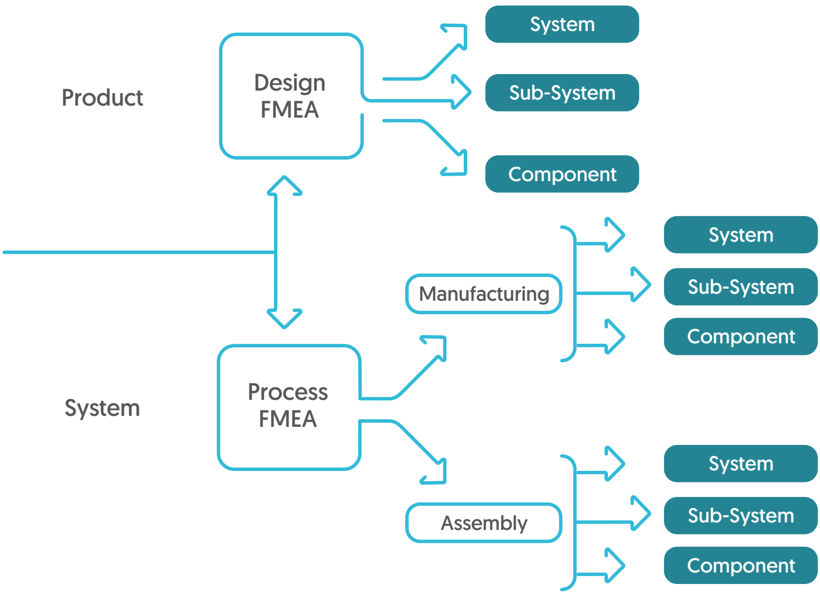


Figure 8. Relationship between some types of FMEA

Design FMEA (DFMEA) focuses on product design, typically at the subsystem or component level. The focus is on design-related deficiencies, with emphasis on improving the design and ensuring product operation is safe and reliable during the useful life of the equipment.

Process FMEA (PFMEA) focuses on the manufacturing or assembly process, emphasising how the process can be improved to ensure that a product is built to design requirements in a safe manner, with minimal downtime, scrap and rework.

2 – Design for Manufacture and Assembly

For each FMEA, the step-by-step process of identifying potential failure modes, quantifying the Severity (SEV), Occurrence (OCC) likelihood, and chances of Detection (DET) before failure, as well as mitigation strategies, is the same. Once quantified the resultant product of Severity, Occurrence, and Detection, known as the Risk Priority Number (RPN), is used to rank the potential failure modes and prioritise them.

To assist in the prioritisation and scoring of the above process, DFMEA and PFMEA guidelines and rankings can be found at Press, Dyadem. Guidelines for Failure Mode and Effects Analysis (FMEA), for Automotive, Aerospace, and General Manufacturing Industries. Baton Rouge US: CRC Press, 2003.

An extract from the guidelines and rankings are shown in Figure 9 below:-

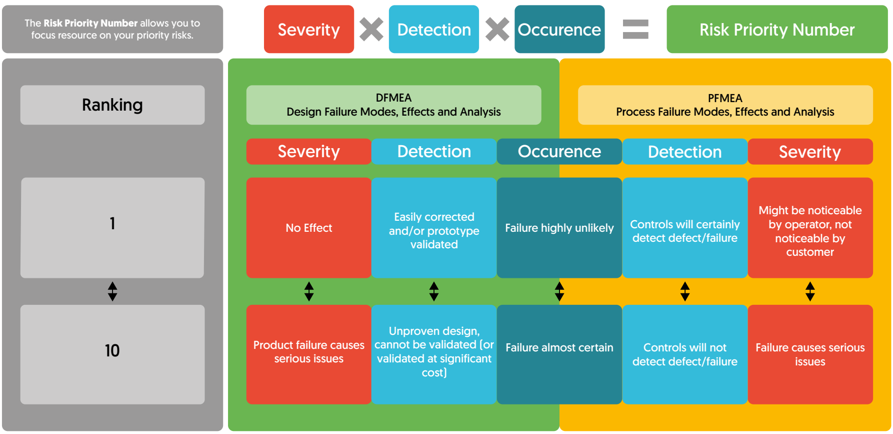


Figure 9. Extract from DfMEA and PFMEA guidelines

The FMEA process is carried out with all stakeholdes and the information is captured. There are software packages available with FMEA templates that may be used.

2.3.2 MOJ Project – Failure Mode and Effects Analysis

The MTC team undertook a number of Design Review Workshops with the MOJ project team, using Failure Mode and Effect(s) Analysis (FMEA). To ensure the review group had a common understanding of FMEA and could contribute effectively in group discussions and when working in separate groups, the MTC provided FMEA training.

The MTC facilitated the workshops which reviewed the 5 components being considered. The 5 components are listed in paragraph 2.2.2 MOJ Project – Cross Functional Design Review Workshop.

A standard MTC FMEA template, was used to capture risks for each of the 5 components. The review team identified more than 80 FMEA risks across the 5 components which led to the redesign of a number of elements. The potential risks, failure modes, and opportunities to improve the design or mitigate the risks identified were captured on the Failure Mode Effect Analysis register. These risks were then classified as DFMEA or PFMEA.

Shown in Figure 10 below is an extract from the Design Failure Mode Effects Analysis and shows an example of the highest scoring risk priority items identified that required immediate attention:-

Design Failure Mode Effects Analysis Register – Superblock

FMEA TYPE	ID	Process Details/ Function	Potential Failure Mode (what could go wrong?)	Potential Failure Mode Effect (why is this bad?)	SEVERITY	Potential Failure Mode Cause (how could it happen?)	FREQUENCY OF OCCURANCE	Prevention of potential Failure Mode Cause (what stops this currently?)	PROBABILITY OF DETECTION OF CAUSE	RISK PRIORITY NUMBER	Recommended Improvement Corrective Actions (what are we going to do to mitigate against this?)	Acton Owner
D	1	Corner block - Strapping corner block stability	Corner block unstable, difficult to move	Causes complexity in the process and could cause non-conformance	9	Strapping not sufficient to support corner block assembly	8	Additonal support to be used	3	216	Strap configuration revised to eliminate instability	
D	2	Gravel board Superblock life	Gravel boards not durable	Maintenance Required	10	Incorrect coverage of the rebar by the concrete for required 60 years lifecycle	10	Design Guidelines	2	200	Increase the thickness of the gravel board Alternative options for rebar	

Figure 10. Extract from a Design Failure Mode and Effect Analysis

2.4 Design for Manufacture and Assembly

2.4.1 Design for Manufacture and Assembly (Generic Approach)

Design for Manufacture (DfM) and Design for Assembly (DfA) are combined as DfMA. DfMA is carried out in a Design Review Worksop where it is used to concurrently optimise product design for manufacture and assembly. Benefits of this approach include:-

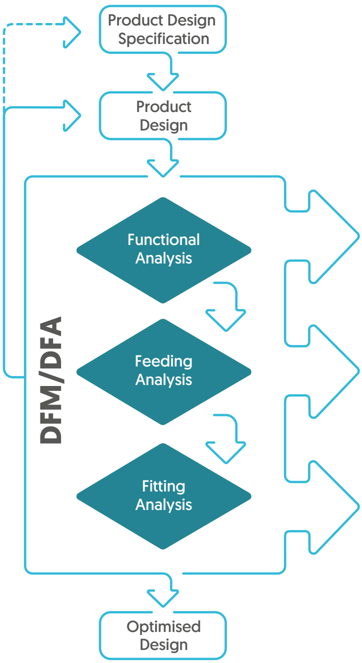
- improved product quality
- reduced product cost
- reduced time to market
- increased productivity and profitability

DfMA sets out to standardise component design, production methods and assembly processes, and promotes Modular Product Design Systems featuring optimised bills of material, making the components easier to manufacture and assemble.

DfMA does this by quantifying the design efficiency through systematic analysis of the function of each component within an assembly or system. It informs the selection of appropriate materials and manufacturing processes and reduces the number of "non-essential parts".

2 – Design for Manufacture and Assembly

A DfMA 3 stage review process can be seen at Figure 11 below: -



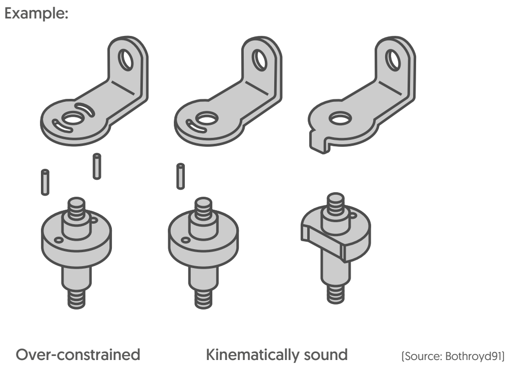


Figure 2: Different components have diffrerent production costs

Functional Design Efficiency	50%	66%	100%
Feeding/handling ratio	[7.6/2]=3.8	[5.2/2]=2.6	[2.4/2]=1.2
Fitting Ratio	[11.1/2]=5.55	[7.1/2]=3.55	[4/2]=2

Figure 11. DfMA Work flow with typical example [from Boothroyd] and DFA scoring summary

This example shows how, by using DfMA, the original design of the component is systematically considered and improved by considering its handling and feeding attributes which are scored using a DfMA scoring summary. As can be seen on the above table, the improvements in the functional design efficiency result in a reduction in feeding and fitting ratios, an increase in the percentage of functional design efficiency and a reduction of 4 to 2 manufacturing parts.

2.4.2 MOJ Project – Design for Manufacture and Assembly

The MTC team, working with the MOJ project team in the Design Review Workshop, used the DfMA approach to analyse the 5 key components to:-

- analyse and assess the design and process flow of the 5 key components to make recommendations to improve manufacture and assembly of the components
- develop a method of manufacture or manufacturing assembly sequence of the key components
- create a list of components, which would deliver the most benefit and could be developed into virtual processes

The MTC team and the MOJ project team evaluated each design using the DfMA assessment criteria defined in the K G Swift and J D Booker (1997) Process Selection from Design to Manufacture, see figure 12 below:-

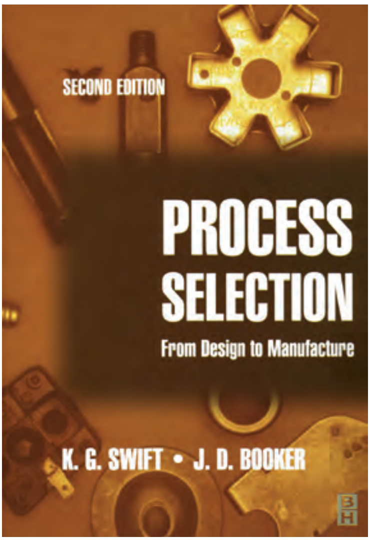


Figure 12. Process Selection from Design to Manufacture

2 – Design for Manufacture and Assembly

The output from the DfMA exercise was captured on a MTC DfMA template, an extract of which is shown in Figure 13 below:-

mtc Manufacturing Technology Centre

Assy. No.	0_TLA
Assy. Name	Top level Assembly
Parts	19

A Parts	2
B Parts	17
Secondary Ops	0

Design Efficiency	10.53%
Feeding Ratio	23.25
Fitting Ratio	25.35

				Handling Index								
Type	Part No.	Part Name	Function	Size & Weight	A	Handle	B	Orient.	B	Rational Orient.	B	Total
-	1	Superblock	A	Large/Heavy hoist/ 2 people	3	No difficulties	0	Easy to see	0.1	Easy to see	0.2	3.3
-	2	Adhesive	A	Convenient - hands only	1	Sticky	0.5	Symmetrical	0.5	Symmetrical	0	1.5
-	3	Superblock	B	Large/Heavy hoist/ 2 people	3	No difficulties	0	Easy to see	0.1	Easy to see	0.2	3.3

Figure 13. Extract from the MTC DfMA spreadsheet

The MOJ project team, supported by the MTC team, identified more than 20 alternative manufacturing methods, alternative design considerations and improvements in the manufacturing process across the 5 components.

One of the alternative manufacturing methods that was developed was the use of stackable concrete moulds to replace the “sand castle” method currently used for gravel-boards. Using a stackable mould, the “SLUMP” effect was eliminated by creating groove features on the reverse side of the part and by holding the concrete in the moulds for the complete curing cycle, their dimensional stability was also improved.

2 – Design for Manufacture and Assembly

Figure 14 below shows the original gravel board manufacturing method:-

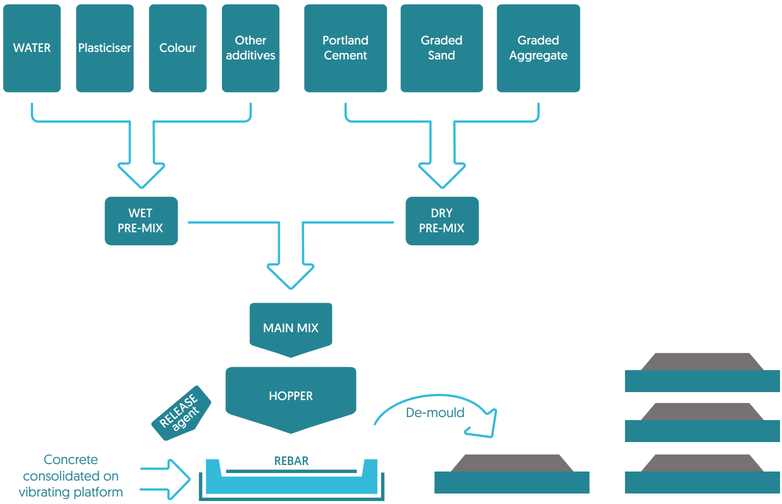


Figure 14. Gravel board design for manufacturing material and process flow – original manufacturing method

2 – Design for Manufacture and Assembly

Figure 15 below shows the revised gravel board manufacturing method:-

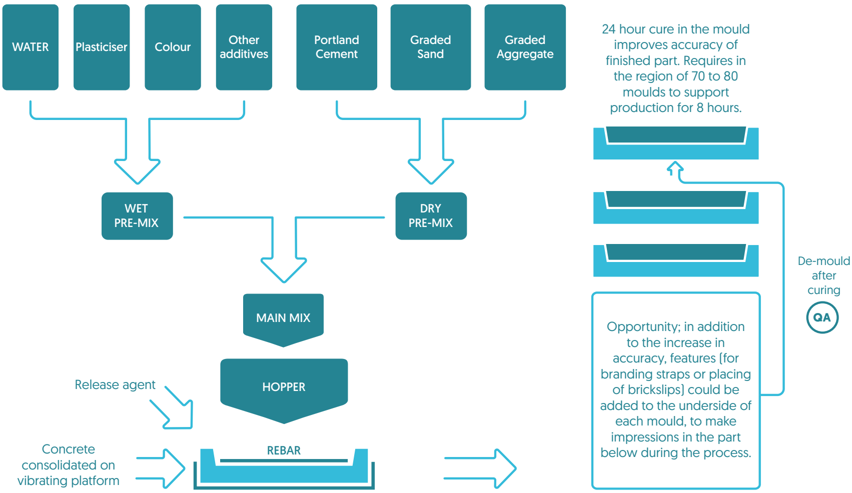


Figure 15. Gravel board design for manufacturing material and process flow – revised manufacturing method

Potential and example manufacturing processes suggested for the 5 Key components were then mapped according to process type:-

- stock / material identification
- shaping – either by machine or manually
- joining
- finishing
- quality assurance
- dispatch – which includes packing or kitting, if required

2 – Design for Manufacture and Assembly

An example of a potential superblock process routing is shown below in Figure 16:-

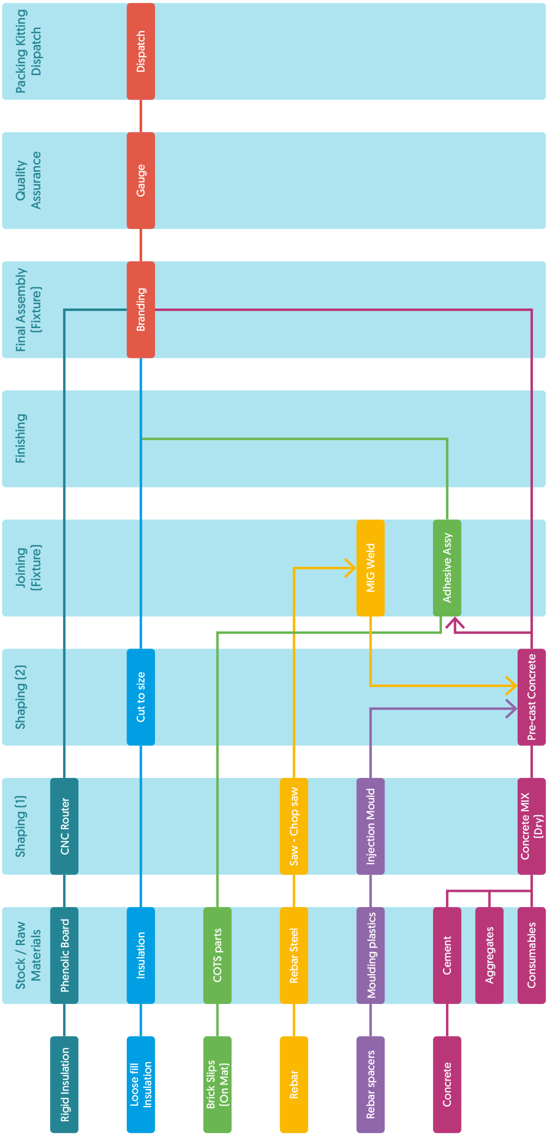


Figure 16. Potential process routing for superblock

2 – Design for Manufacture and Assembly

The use of DfMA, identified further superblock and megablock improvement opportunities including:-

- superblock and megablock manufacturing efficiency, improved by 6% overall compared to the initial design assembly (RIBA 2)
- megablock shims eliminated and incorporated in superblock spacers
- 4 pick and place operations removed from each megablock assembly step
- improved repeatability and consistency of the assembly of each megablock
- 1 part number deleted, along with the stores requirement
- cycle time improved by up to 2 minutes per megablock
- amount of handling reduced
- number of non-essential parts reduced

The proposed manufacturing and assembly changes were further discussed and agreed with the MOJ project team and these were used as the basis for creating the Virtual Prototyping, see paragraph 2.5 in this chapter.

2.5 Virtual Prototyping

2.5.1 Virtual Prototyping (Generic Approach)

Virtual prototyping enables different manufacturing processes and improvements identified by the DfMA process to be visualised and it also allows multiple options to be trialled more quickly with less investment in resources compared to physical prototyping. It provides the opportunity to take an overall view of the process and to identify any potential problems.

Virtual prototyping of products is normally carried out using computer-aided-design (CAD) and computer-aided-engineering (CAE) to validate a product before developing it and committing to a physical prototype. The MTC has taken this process further and has developed Virtual Prototyping of the manufacturing and assembly process using Computer Aided Manufacturing (CAM) tools such as CNC machines and simulation tools which allows visualisation of manufacture and assembly processes.

Virtual prototyping of the manufacturing and assembly process, contributes to the construction sector's growing requirement for digitising the process of construction and applying it to off-site manufacturing and the preparation of key components.

Virtual process prototyping provides a way to reduce the cost and risks associated with new product introduction and also:-

- validates mitigation measures identified in FMEA
- advances DfMA activity in a virtual environment by simplifying complex processes in a cost effective way
- provides a visual way for cross functional teams to review the processes and provide feedback

2.5.2 MOJ Project – Virtual Prototyping

The MOJ project team requested that the superblock/ megablock component be developed as a virtual prototype. It was agreed that the MTC and a small group of MOJ project team members would generate initial key guidelines from the DfMA activity, these included:-

- minimal manual lifting
- minimal raw material handling
- smooth transitions between work stations
- minimal opportunity to damage work in progress
- consistent working height
- fewer and simpler assembly operations
- vertical (gravity assisted) assembly
- manage WIP (curing zones)
- jigs and fixtures for improved assembly processes

The joint working group agreed a general layout that suited the physical size and shape of the superblock components being assembled and, using CAD data, a number of layout options were identified including the nagare, (horseshoe cell design). However, using virtual prototyping it was agreed that a linear based assembly line was most suitable and this was designed, clearly identifying the steps and potential sequence of steps, along with known 'care-points. A potential superblock linear flow schematic was produced as shown in Figure 17 on the next page.

2 – Design for Manufacture and Assembly

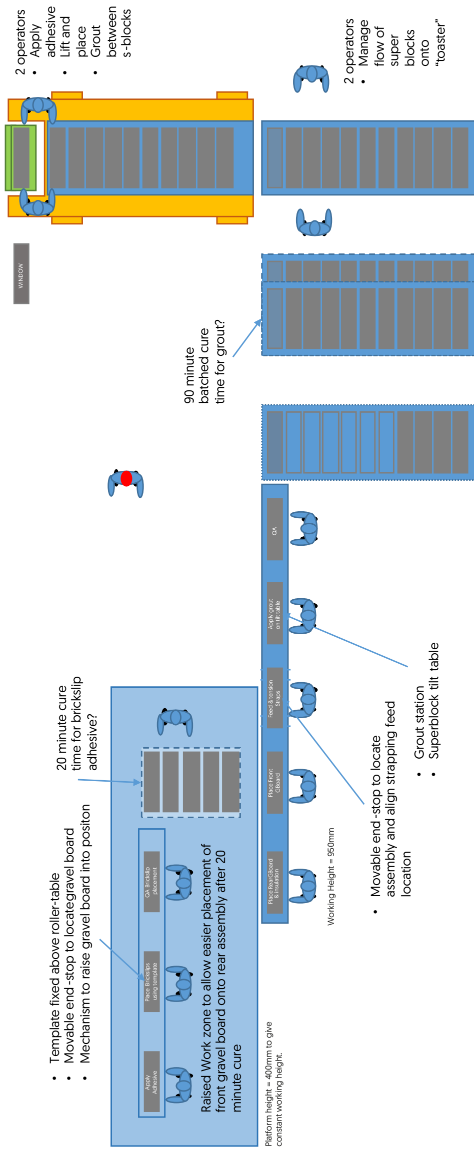


Figure 17. Superblock linear flow schematic

2 – Design for Manufacture and Assembly

Using the superblock schematic as a starting point, the CAD data was re-configured taking into account:-

- the assembly process sequence, showing the assembly stage for each work station
- the need to minimise material movement
- the need to minimise handling and lifting

The assembly line was also modelled to facilitate controlled material movement between stations including:-

- provision of adhesive curing zones
- line-side material storage

As a result of reconfiguring the CAD data, a revised assembly line was created and this is shown in Figure 18 below:-

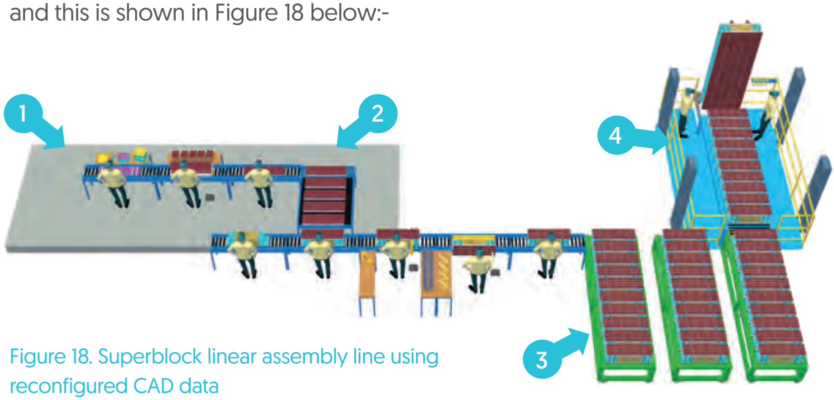


Figure 18. Superblock linear assembly line using reconfigured CAD data

The modelled assembly line also included (as denoted by numbers 1-4 above):-

1. a raised area to minimise the change in working height between major process steps
2. adhesive curing buffer so that work in progress stays within the manufacturing system
3. provision for batching products into the required quantities for megablock assembly
4. concept model of the megablock assembly platform

The creation of the modelled assembly line, using virtual prototyping, was reviewed and agreed by the MOJ project team who recognised the benefits that this approach delivered including less time to design the layout, opportunity for visual assessment and significantly less cost than producing a physical prototype.

2.5.3 MOJ Project – Assembly Animation

The output from the virtual prototyping also formed the basis for the creation of a 3D animation. The screenshots shown at Figure 19 below are some examples of the 3D animation that was created showing the material movement and assembly steps.

Figure 19. Screenshots from superblock assembly animation

A review of the animation process showed that the material movement to create the superblock had been fully considered and the team were able to identify, and agree, the type of movement required and the handling material equipment that would be required for that movement.

The 3D animation was reviewed by the cross functional design review team and helped to identify additional requirements i.e.:-

- where material handling would be required
- what type of handling equipment would be required
- what kind of adhesive dispensing and metering would be required (to ensure the correct amount was used and to prevent operator injury).

2 – Design for Manufacture and Assembly

Quote:-

'The workshops MTC led, aided in the development of production lines suitable for the assembly of superblocks and megablocks and demonstrated the benefit of applying the experience from complimentary industries.

The assembly processes were modelled in 3D CAD and animated to show individual process steps, which allowed the whole team to come together and and agree step change improvements in the development of the assembly processes including removing production rate limiting factors from the physical prototype process'.

Dries Hagen, Head of Property, Bryden Wood

The output from the Virtual Prototyping approach formed the basis for the creation of the Production Facility Design layout, which is described in detail in Chapter 5 – Production Facility Design.

If you want to get started and/or want further information on the systems, tools and approaches described in this publication, visit the construction website at www.the-mtc.org/construction

4

PROCESS LIFECYCLE COST MODELLING

1. Introduction and Overview

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1 – Introduction and Overview

1.1 Introduction

Process lifecycle cost modelling has been used extensively in a wide range of industries including automotive, aerospace and construction where it has demonstrated that redesigned processes can be compared without any disruption to production lines or investiment in expensive equipment or materials.

The Manufacturing Technology Centre (MTC) has broad ranging experience of process lifecycle cost modelling in industries including food, automotive and construction. The MTC believes that process lifecycle cost modelling can make a significant contribution to transforming performance and productivity in the construction sector.

The MTC has been working with a major Ministry of Justice (MOJ) Project to demonstrate the approach and benefits of process lifecycle cost modelling at the early stages of construction project planning where novel materials and processes were being considered.

The MOJ Project is using a construction methodology referred to as Design for Manufacture and Assembly (DfMA). This methodology revolves around the design of standard component parts that can be mass produced and then delivered to the construction site where, due to the simplicity of component connections it can be assembled by a lower than normal skilled work force. The approach and application of DfMA is described in more detail in Chapter 3 of this book.

The MTC approach to cost modelling enables evaluation of investment requirements, as well as providing financial information to assess the financial viability of the new processes.

This chapter describes the generic approach that MTC takes to modelling projects and the systems and tools used for the specific requirements of the MOJ Project. It also describes the benefits that process lifecycle cost modelling can bring to the construction sector and the benefits delivered for the MOJ Project.

Quote:-

"The Process Lifecycle Cost Model supported our costing methods and also provided a novel and more detailed approach to assessing the cost of the whole process life cycle".

David Kendall, Project and Cost Management for Property and Construction, WT Partnership.

1.2 Overview

Process lifecycle cost modelling is concerned with evaluating the cost of manufacturing processes and provides information to inform the selection of suppliers and manufacturing processes for novel products. A Process Lifecyle Model describes the whole lifecycle of a manufacturing process from development through to decommissioning.

The key steps within a Process Lifecycle Model are shown in Figure 1 below:-

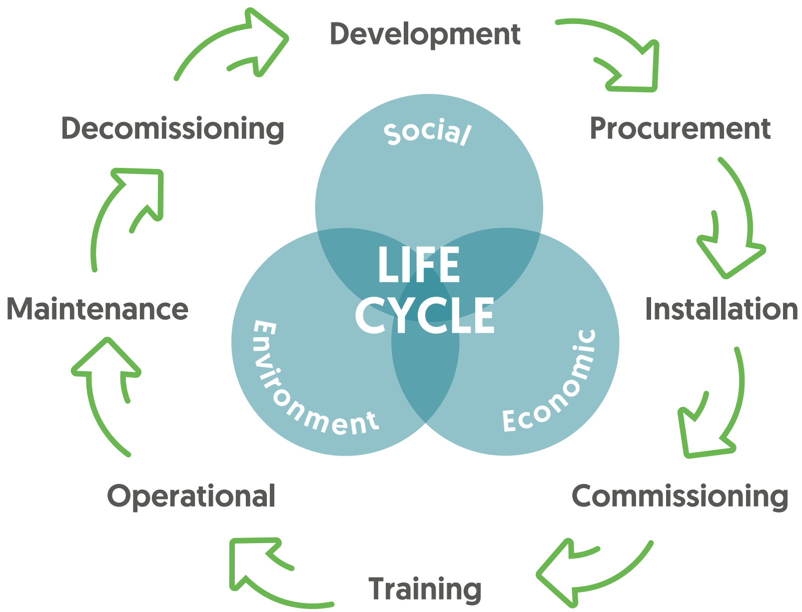

Figure 1. An example of a Process Lifecycle Model

The construction sector has extensive experience of costing construction projects where materials and processes are known, however the manufacture of novel components and their assembly off-site, being adopted by the MOJ Project, is new and the costs associated with the manufacturing lifecycle and the supporting processes are not so well known.

The MTC team believe process lifecycle cost modelling provides a more informed calculation of uncertainty and risk through early engagement of stakeholders and a deeper understanding of key cost drivers, which allows mitigation strategies to be developed and tested earlier in the construction planning process.

Process lifecycle cost modelling also enables:-

- estimation of costs to be quickly carried out
- identification of key cost drivers and a better view of how costs are split across different processes
- a more informed view of whole life costing compared to traditional steady state costing
- greater granularity of cost factors compared to current industry practice

1.3 Where have the systems and tools been used?

Process lifecycle cost modelling has been used extensively in many industries that require product or service transformation. It can help determine resource requirements for manufacturing processes as well as compare different options for production and assist in the selection of the most appropriate process and supplier. Some applications where the tools have been used include:-

- Cost modelling for combined process and material part design with use of composites (Schubel, 2012)
- Return on investment analysis of BIM in construction (Giel, 2010)
- Reduction of manufacturing cost per part in automotive industry (Chiron Global Systems Group)

1.4 Why these systems and tools for the Construction Sector?

The systems and tools selected by the MTC for the MOJ Project, allow accessibility to widely available software without the need to procure a licence and were considered to be the most appropriate, as they addressed the changing outlook to project costing in the construction sector including:-

- moving from a cost estimating mind set to one of using cost drivers to support decision making
- the need for a better understanding of the costs involved in the process of manufacturing building components and materials by all stakeholders at the early stages of the project
- the need for a better understanding of the cost of different process options
- the need to understand the environmental effects of a process and demonstrate compliance with industry regulations and standards

1.5 Benefits

Process lifecycle cost modelling provides a detailed view of how the cost to produce a component is distributed across different cost categories and supports more informed process and supplier selection. The benefits that can be realised from undertaking process lifecycle cost modelling include:-

- providing an assessment of the lifecycle of the component from development, procurement, installation, commissioning, training, operational, maintenance and decommissioning
- enabling alternative approaches and variations to be considered in a non-risk environment
- enabling novel component manufacture options to be assessed which provide more informed decision making in the component design stage
- engaging the manufacturer or supplier earlier in the project to provide a more realistic outlook on cost as well as improved transition between design to manufacture
- providing a better understanding of the level of investment necessary to develop on-site and off-site component manufacture
- understanding the financial benefits of alternative manpower resourcing strategies
- more informed and robust supplier selection criteria

- providing a more detailed view of how the cost to produce a component is distributed across different cost categories
- identifying key cost drivers enabling more specific cost comparisons to be made
- informing continuous improvement activities by identifying where to focus effort in order to reduce costs

1.6 The MOJ Project

The MTC used process lifecycle cost modelling in the MOJ Project to provide an insight into the impact of selecting different processes and suppliers for the manufacture and assembly of novel components. The modelling:-

- provided a manufacturing lifecycle assessment for the components
- contributed to the selection of components and suppliers
- informed the development of a procurement sourcing strategy

The MOJ Project Process Lifecycle Cost Model was developed working closely with key stakeholders throughout the process. Design and outputs were shared and agreed as they were developed in order to ensure the final output met stakeholder requirements.

The MOJ project team recognised the valuable contribution that process lifecycle cost modelling can make to improve productivity and efficiency of construction projects.

Quote:-

"MTC provided a better understanding of the requirements of process flows and time management for setting up workshops which is key to our public sector industry business with the complicated skilled workforce we have".

MOJ project team member

2. Process Lifecycle Cost Modelling

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2 – Process Lifecycle Cost Modelling

2.1 MTC's approach to Process Lifecycle Cost Modelling

The MTC's approach to process lifecycle cost modelling uses a set of generic systems and tools and these have been used for both process lifecycle cost modelling, as described in this chapter and Supply Chain Modelling, as described in Chapter 6.

There are 4 main systems and tools that are used in a systematic way to create Process Lifecycle Cost Models, they are:-

- Business Questions Workshop
- Concept Model
- Model Specification Document
- Process Lifecycle Cost Model

Note:
These systems and tools are also described in Chapter 6 – Supply Chain Modelling

In creating a Process Lifecycle Cost Model, the MTC follows a three step methodology, as shown in Figure 2 below:-

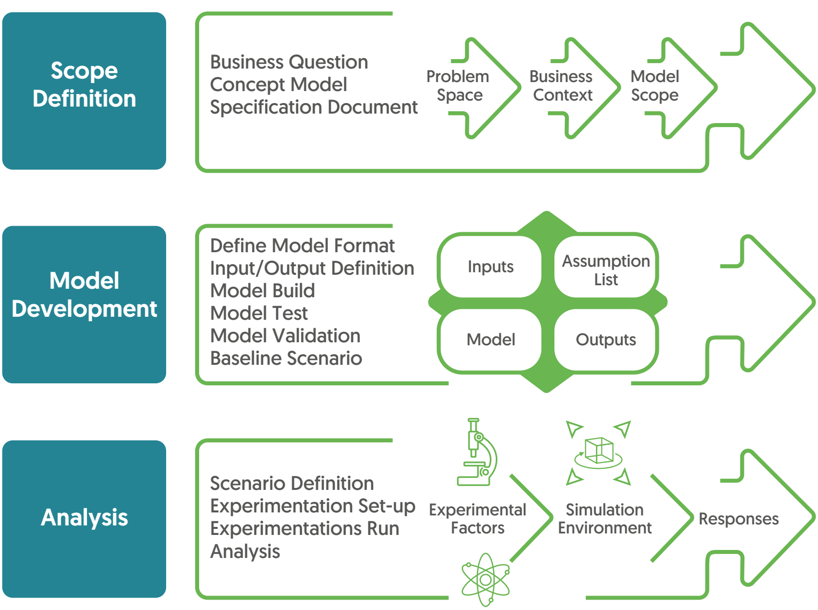

Figure 2. Process Lifecycle Cost Model Methodology

2 – Process Lifecycle Cost Modelling

The methodology shown in Figure 2 describes the stages of model development and the elements considered in each stage and is informed by the model objectives agreed with stakeholders data collection, model development and analysis.

Note:

Scope Definition is further explained in paragraph 2.3, 2.4, 2.5

Model Development is further explained in paragraph 2.6

Analysis is further explained in paragraph 2.7

2.2 Process Lifecycle Cost Model Development Process

The MTC has developed a seven step Model Development Process to ensure consistency of approach. It is important that development of a model and the associated analysis are carried out in a systematic way.

The Model Development Process is shown in Figure 3 on the next page and ensures that all the business requirements are captured, to inform the design of the Process Lifecycle Cost Model. Validation is carried out throughout the process with key stakeholders and ensures that they are engaged, bought into the process and that the modelling and analysis are fit for purpose.

2 – Process Lifecycle Cost Modelling

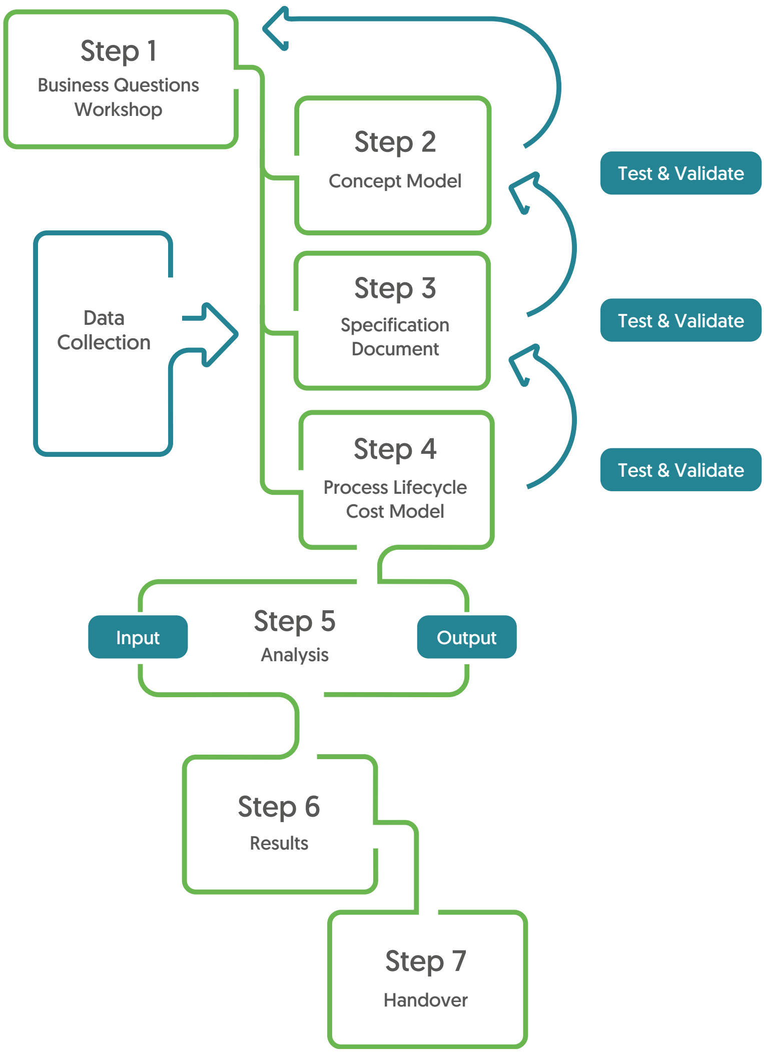

Figure 3 Process Lifecycle Cost Model Development Process

[Steps 1 - 7, shown in the above process are described in more detail in paragraphs 2.3 to 2.9]

2.3 Business Questions Workshop – Step 1 of the Process Lifecycle Cost Model Development Process

2.3.1 Business Questions Workshop (Generic Approach)

The business questions workshop is the first step in the development of a Process Lifecycle Cost Model. Its purpose is to bring together, at any early stage, the stakeholders from the partner organisations to discuss and agree issues, challenges and their relative importance. These are known as the business questions and provide the basis for the structure of the Process Lifecycle Cost Model so that it is able to provide answers to the agreed questions.

The business questions workshop is facilitated and follows a pre-determined structure. Ideally the stakeholders who attend the workshop should have a strategic knowledge of what they want to achieve and what they see as the key measures of success.

The workshop encourages in-depth discussions on the significant requirements of the Process Lifecycle Cost Model. The output from the workshop provides the input for the design of the options to be considered by the model.

Typically the workshop involves:-

- identifying the business questions
- structuring the business questions into themes
- prioritising the business questions

Examples of typical business questions are:-

- what is the cost impact of procuring, commissioning, maintaining and disposing of new machinery required for a novel process?
- what is the impact of various levels of production?
- what is the impact of manufacturing component off-site?
- how does the operational cost associated with the use of a process compare to its lifecycle cost?
- what are the environmental impacts of alternative processes?

2 – Process Lifecycle Cost Modelling

Participating in a business questions workshop provides many benefits to stakeholders including:-

- providing the opportunity for stakeholders to be involved much earlier than normal in project planning, to gain an overall project view and reach consensus on priorities for the project
- gaining a deeper understanding of the project challenges and opportunities
- gaining common agreement on what the Process Lifecycle Cost Model must address
- achieving collective buy-in to the modelling approach being taken

2.3.2 MOJ Project – Business Questions Workshop

The MOJ business questions workshop involved representatives from the project team and was facilitated by the MTC process lifecycle cost modelling experts. The workshop discussed the key challenges that the project was facing and as a result, key areas were identified for consideration, these included:-

- end to end manufacturing process options, see Figure 4 on the next page
- the manufacturing processes needed to produce a novel component
- the ability to compare different processes using the same or different suppliers
- the maximum number of processes to be evaluated
- the complexity of the key processes and the key drivers to be modelled e.g. resources, tooling
- out of scope elements e.g. raw material of the manufactured process and the post completion of the component manufacture

2 – Process Lifecycle Cost Modelling

The main focus of the MOJ project was evaluating the cost of the manufacturing process, of the novel components within the component lifecycle, of novel components, shown in green in figure 4 below:-

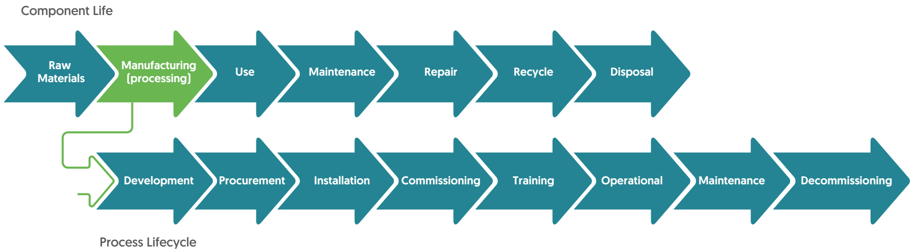

Figure 4. A flowchart showing the scope of the Process Lifecycle Cost Model

The whole process lifecycle was then considered for the manufacturing process, as shown in the lower flow diagram, from development through procurement, installation, commissioning, training, operational, maintenance and finally, decommissioning.

The MOJ project team workshop, through discussion, identified a key business question and further secondary questions that needed to be considered by the model and these are shown below:-

Key question:

What is the most cost effective and beneficial way to produce key components?

Secondary questions:

- which components should be produced on-site?
- is the process compatible with environmental standards?
- what is the trade-off between automation vs manual processes?
- what should the target defect rate be for the various suppliers?

The output from the workshop was:-

- an agreed project scope for the manufacture of the key components
- a defined and agreed set of business questions which were then used to structure and build the Process Lifecycle Cost Model, see paragraph 2.6, supported by a Specification Document, see paragraph 2.5

A number of benefits from undertaking the business questions workshop were identified and these included:-

- an opportunity for the MOJ project team to meet much earlier than normal in the project, to gain an overall project view and reach consensus on priorities for the project
- an opportunity to explore costing issues and challenges associated with the off-site manufacture and assembly of construction components
- collective buy-in to the modelling approach being taken and a common agreement on what the model must address

2.4 Concept Model – Step 2 of the Process Lifecycle Cost Model Development Process

2.4.1 Concept Model (Generic Approach)

Creating a Concept Model is the second step in the development process and is essential for visualising a Process Lifecycle Cost Model. A well designed Concept Model significantly enhances the likelihood of a successful outcome from a modelling study and reduces re-work of the model build. It also enables the model scope to be clearly communicated to stakeholders.

A Concept Model is created in order to define the scope and content of a Process Lifecycle Cost Model and is a useful and powerful tool to support communication during the process of developing models. A number of facilitated workshops are held with stakeholders to discuss, validate and gain agreement to the content of the model including the business questions, discussed earlier in paragraph 2.3 of this chapter, the model structure, key model logic, scope and KPI.

2 – Process Lifecycle Cost Modelling

In building a Concept Model a methodology defined by Robinson (2004) was used. The methodology outlines 5 key activities, and is shown in Figure 5 below:-

1. understanding the problem situation
2 determining the modelling and general project objectives
3. identifying the model outputs (responses)
4. identifying model inputs (experimental factors)
5. determining the model content (scope and level of detail), identifying any assumptions and simplifications

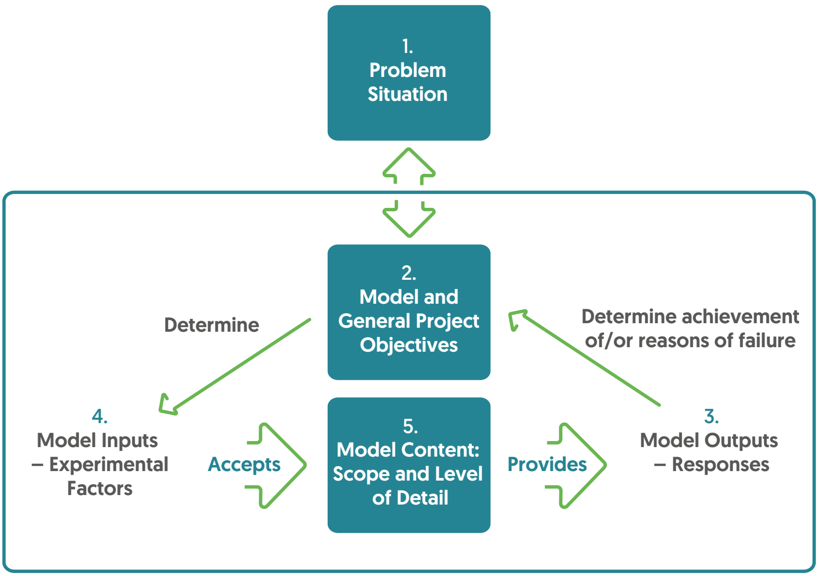

Figure 5. Concept Model Methodology – (Robinson 2004)

2 – Process Lifecycle Cost Modelling

The development of a Concept Model provides further insight into the operation of the Process Lifecycle Cost Model and:-

- provides a visualisation of the modelling framework including its scope and content
- validates the approach to be taken before model build commences
- helps to identify data required to populate the Process Lifecycle Cost Model
- provides information to populate the Specification Document, described in paragraph 2.5, which is used to inform the development of the Process Lifecycle Cost Model

2.4.2 MOJ Project – Concept Model

In building the Concept Model for the MOJ Project, the MTC team followed the process (Robinson – 2004) described above in paragraph 2.4.1, Figure 5.

The MTC team held a number of workshops with the MOJ project team and the Concept Model which included the questions that were developed at the business questions workshop, the model structure, model logic, scope and KPI, was discussed and agreed. It was also agreed that environmental factors should be considered in the selection of processes and therefore it was agreed to undertake an evironmental impact assessment of each process modelled.

2 – Process Lifecycle Cost Modelling

The MOJ Project Concept Model has four elements, see Figure 6 below:-

- business questions
- manufacturing generic process flow for the component assembly process
- manufacturing process options for different assembly operations
- cost inputs and the KPI that will represent model outputs

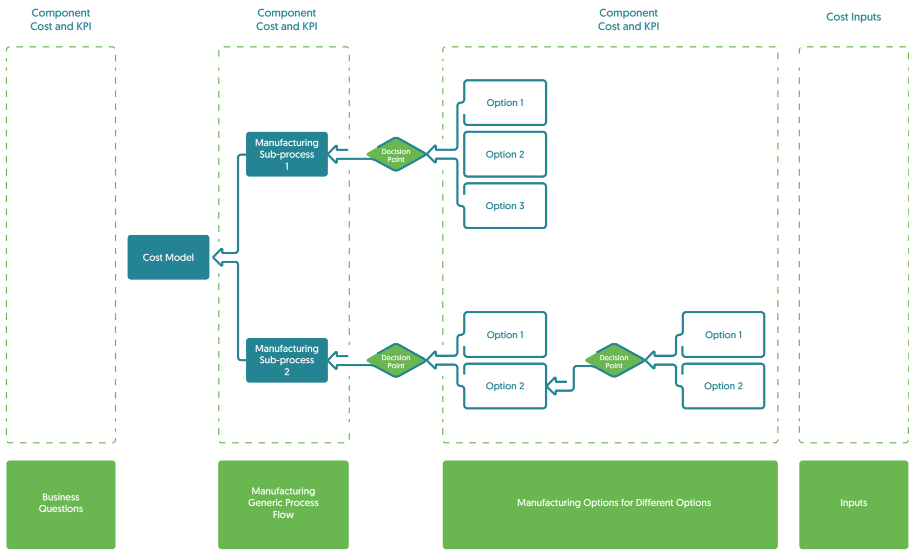

Figure 6. Example of a Concept Model Template

2 – Process Lifecycle Cost Modelling

The Concept Model structure is based on the process flow that reflects the component manufacture and assembly process. It represents the steps in the production process without specifying how, and with what equipment, an operation is performed.

The Concept Model developed for the MOJ Project was informed by the existing superblock manufacturing and assembly process, see Figure 7 below. The superblock design and assembly process is described in more detail in Chapter 3 – Design for Manufacture and Assembly.

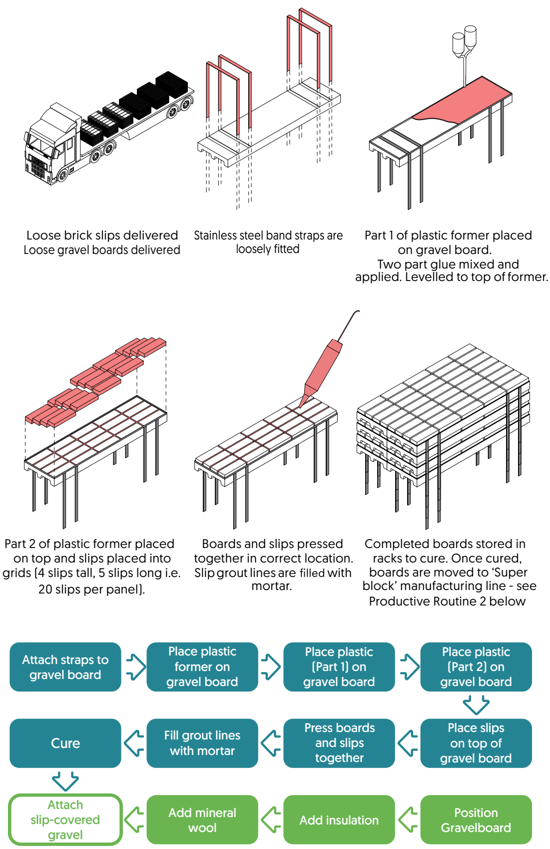

Figure 7. Example of a superblock manufacturing and assembly process

2 – Process Lifecycle Cost Modelling

The model considered different options for each of the steps in the manufacturing process, as shown in Figure 8 below e.g. automated and manual. Within the manual option 2 different suppliers were considered:-

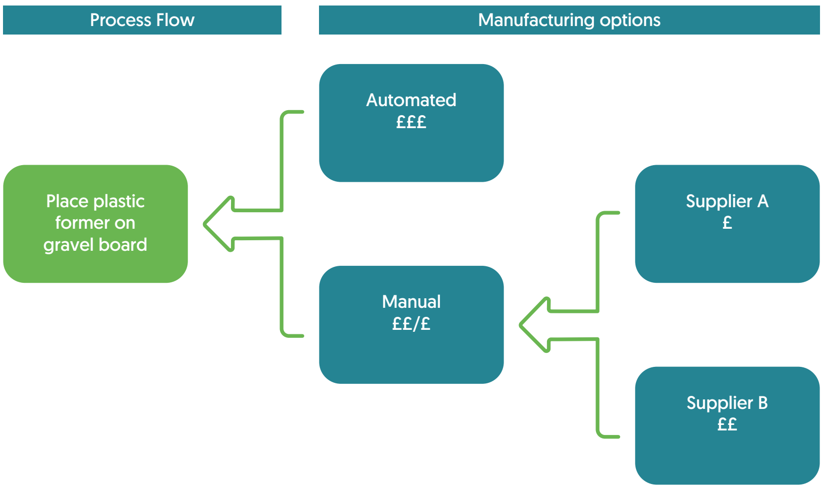

Figure 8. Process and manufacturing options

2.5 Model Specification Document – Step 3 of the Process Lifecycle Cost Model Development Process

2.5.1 Model Specification Document (Generic Approach)

Creation of the Specification Document is the next step in developing a Process Lifecycle Cost Model. It is an evolving working document which outlines the scope of the model. The Specification Document is populated using input from all key stakeholders and is then discussed and agreed.

There are 2 types of Specification Document, a Requirements Specification Document which defines what the model is required to address, including functionality, usability, performance and a Design Specification Document which outlines how the model has been built to meet the requirements.

Both Specification Documents are reviewed and updated throughout the life of the project. Typical content includes:-

- business questions
- model requirements
- scope
- model structure
- general modelling assumptions
- key performance indicator(s) (KPI)
- experimental factors
- glossary of terminology

A completed Requirements and Design Specification Document:-

- provides a record of the agreed scope, capability, functionality and requirements of the model to be developed
- provides documentation to support the development and understanding of the models capabilities and purpose
- gives a focus for ongoing modelling activity
- reduces model development time
- minimises re-work of templates
- enables the management of stakeholder expectations
- enables the validation of the model in respect of design vs requirements

2.5.2 MOJ Project – Model Specification Document

The MTC scoped the requirements specification and design specification using input from the MOJ project team workshops. The completed specifications were then shared, reviewed and amended. Changes were managed using a change management process and appropriate configuration control.

The model specification template developed for the MOJ Project team combined the content of both the requirements and design specification.

2 – Process Lifecycle Cost Modelling

The combined content of the MOJ requirements specification and design specification template is shown in Figure 9 below:-

Contents

Executive Summary		2
1.	Introduction	5
2.	Objectives	6
3.	Business Questions	7
4.	Model Requirements	9
	4.1 Functionality	*9*
	4.2 Usability	*9*
	4.3 Reliability	*9*
	4.4 Performance	*10*
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	4.7 Change Management	*10*
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10.	Glossary of Terminology	24

Figure 9. MTC combined specification document template

Following discussion, a fully populated Specification Document for input to the Process Lifecycle Cost Model was agreed. It set clear expectations on what the model was going to deliver as well as allowing validation of whether the delivered model met the stated requirements.

2.6 Process Lifecycle Cost Model - Step 4 of the Process Lifecycle Cost Model Development Process

2.6.1 Process Lifecycle Cost Model (Generic Approach)

Step 4 in the Process Lifecycle Cost Model Development Process, described in paragraph 2.2, Figure 3, is where the Process Lifecycle Cost Model is built. Once the model is developed, it provides the capability to visualise and understand the potential Process Lifecycle Cost Model configuration. Through experimentation, the model will allow the evaluation of different options of the lifecycle process.

In building a Process Lifecycle Cost Model, it is beneficial to build in modules e.g process, labour, equipment, relative to the requirements that have been built into the model. This allows concurrent development of the modules, resulting in a reduction in model development lead times. For each module, there are three phases of development:-

- model build
- model test
- model validation

Each module is validated and verified, then all of the modules are integrated into one model and a final validation and verification is carried out. The methodology used to build the model is shown in Figure 10 below:-

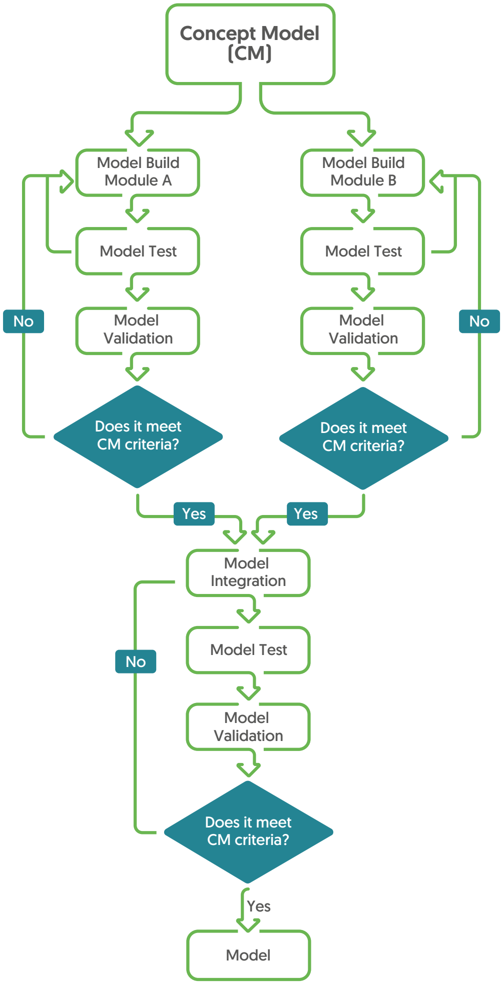

Figure 10. Model building methodology

2.6.2 MOJ Project – Process Lifecycle Cost Model

To build the MOJ Project Process Lifecyle Cost Model the Concept Model, see paragraph 2.4.1, was used as a framework to identify further data required. On-site visits were undertaken to observe and document the manufacturing processes required and to collect further data. On-site reviews were then held to verify and validate the documented process flows and the data collected.

The data collection sheet in Figure 11 below was used to collect data for the components over their lifecycle for an automated process and 2 manual processes with different suppliers:-

Place plastic former on gravel board	Automated £££	Manual S1 £	Manual S2 ££
Development			
Placement			
Installation			
Comissioning			
Training			
Operational			
Maintenance			
Decomissioning			

Figure 11. Example data collection sheet

2 – Process Lifecycle Cost Modelling

In some instances data was not available, so assumptions were made and documented and then agreed with the MOJ project team. Validating assumptions is as important as validating data supplied, as the maturity and accuracy of each has an impact on the output from a model and hence the confidence in the resulting analysis. An example of some of the assumptions made are shown in Figure 12 below:-

Data Requirements	Assumption
General Assumption	This example is based on production of a superblock using manual labour. The difference in the process is the use of an adhesive process for gluing the gravel boards, which can be manual, pneumatic or automated
Operation list	The operation list is based on a developed process flow: BIM planner SW. Additional information provided is that there is now an adhesive gluing process within the process flow that takes 140 minutes in total (curing)
Equipment Catalogue	Tooling and equipment requirements are defined. Assumed 1 month for installation (20 Working days). Assumed commissioning rates for machines to be long, based on size and integration complexity assessment (non-experienced)
General Assumption	The cost model is based on production of one component, therefore assume one machine can cope with the capability
Worker Catalogue	Worker rates determined are based on the data collected during site visits
Equipment Catalogue	The equipment list is provided but pricing is estimated
Consumable Catalogue	If the consumable becomes part of the product it is not considered in the model
Non Op	Assumed 3 month of development time (45 days)
Non Op – Development costs	Assumed overall staff hourly rate for planning team is £200/based on having 10 members of staff being paid £20/h
Non Op – Decommissioning	Based on the assumption that the decomissioning team is based on 1 facility manager and a team of 5 workers based on 37hrs per week

Figure 12. Example of model assumptions

2 – Process Lifecycle Cost Modelling

In building the MOJ Project Process Lifecycle Cost Model templates were created. In addition, the MOJ project team also wanted to understand the environmental impacts and so both Process Lifecycle Cost Model and Environmental Impact Assessment templates were developed.

The Process Lifecycle Cost Model and Environmental Impact Assessment templates developed are shown at Figure 13 below:-

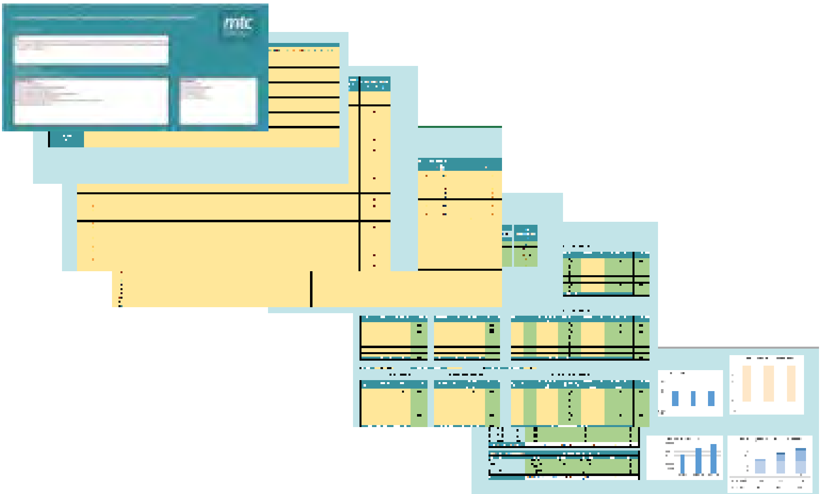

Figure 13. Integrated Process Lifecycle Cost Model and Environmental Impact Assessment Template

The templates were populated with all the data and assumptions relevant to the components and reviews were held to validate the data and assumptions in the templates before modelling went ahead.

To support the validation of the cost model output, it is good practice to establish an information trail. To assist in this, a Master Data Assumptions List (MDAL) was developed for the MOJ Project which detailed the concept model element, data requirements for each element and the data provider. An example of the MDAL developed for the MOJ Project is shown in Figure 14 below:-

Concept Model Element	Data Requirements	Data Requirements
KPI	Specific Environment Impact KPI	MOJ project team
	Scope defined by business questions	MOJ project team
	Specific KPI on cost	Contractors
Manufacturing and assembly generic process flow	Generic Stems for manufacture of a component	DFMA Lead
Manufacturing and assembly options	Potential different options in the assembly process	DFMA Lead
	Operations cycle times	
	Specific equipment list dedicated to operations	
	Equipment chracateristics (energy usage per time unit, etc)	
Inputs	Specification of input categories	PLCM Lead
	List of detailed inputs	PLCM Lead
	Input definitions and equations	PLCM Lead

Figure 14. Example of a master data assumptions list (MDAL)

2.7 Analysis – Step 5 of the Process Lifecycle Cost Model Development Process

2.7.1 Analysis (Generic Approach)

Analysis is a phase of the development process where the simulated model is used to run experiments that enable stakeholders to explore the business questions. There are different types of analysis that the Process Lifecycle Cost Model can undertake e.g. Sensitivity and Scenario 'What if' analysis.

i) Sensitivity analysis is a technique used to determine how different values of an independent variable impact a particular dependent variable i.e. KPI, under a given set of assumptions.

ii) Scenario 'What if' analysis measures how changes in a set of independent variables impact a set of dependent variables.

Sensitivity analysis and scenario 'What if' analysis both involve experimentation. Experiments are conducted by selecting and varying experimental factors (input variables) in the model, then measuring the model response (outputs).

2 – Process Lifecycle Cost Modelling

The flowchart shown below in Figure 15, describes the key steps of the experimentation process.

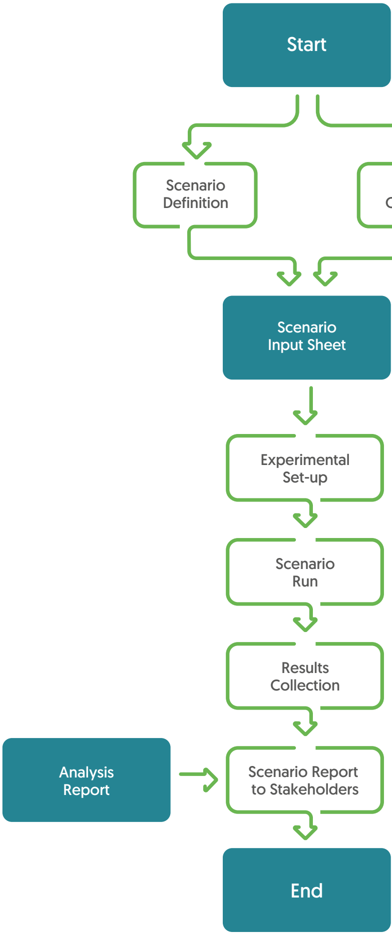

Figure 15. Key steps in the experimentation process

One the model is created, multiple experiments can be undertaken to test different scenarios and they are normally measured against defined key performance indicators, for example, price per hour is a key KPI for construction projects.

2.7.2 MOJ Project – Process Lifecycle Cost Model Analysis

Output from the Process Lifecycle Cost Model provided valuable information to the MOJ project team helping them to better understand the impacts of the various activities on costs and environmental factors and examples of these are given in Figures 16 and 7 below:-

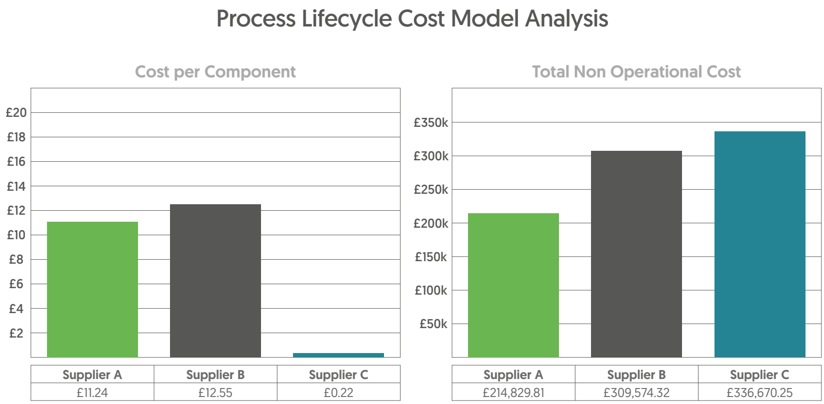

Figure 16. Example of output from Process Lifecycle Cost Model

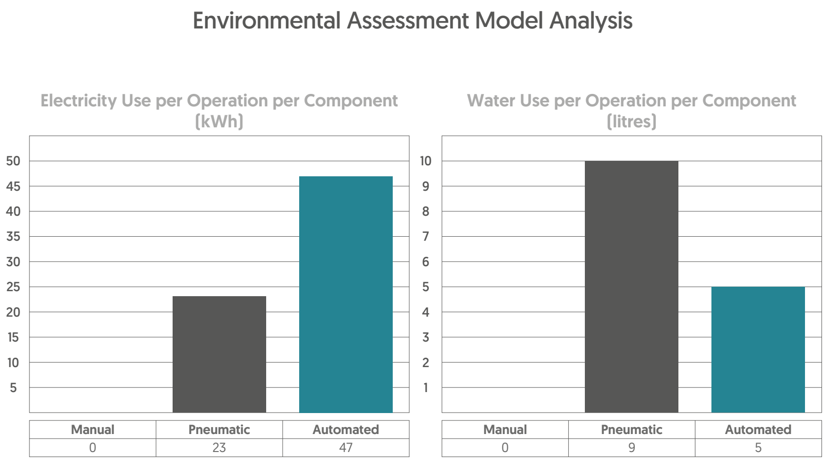

Figure 17. Example of output from the Environmental Impact Assessment Model

2.8 Results – Step 6 of the Process Lifecycle Cost Model Development Process

2.8.1 Results (Generic Approach)

The Process Lifecycle Cost Model provides results on the agreed KPI and the results are presented and explained to stakeholders in a numerical and visual way. Examples of results that modelling can provide include:-

- operational cost per unit
- lifecycle cost of the process
- waste generated
- water consumed
- energy consumed

2.8.2 MOJ Project – Process Lifecycle Cost Model Results

The results of the process lifecycle cost modelling undertaken for the MOJ Project were shared and reviewed as they were developed. A final presentation was given to the MOJ project team and all the results and KPI produced by the model, were presented and explained.

The key outputs from the models were:-

- the Process Lifecycle Cost Model enabled the calculation of cost of the process required to build the components over the lifecycle of the component. The model enabled cost comparison of different process options and different suppliers.
- the Environmental Impact Assessment enabled evaluation of the impact that processes and different suppliers may have on the environment over the lifecycle of the component.

2.9 Handover – Step 7 of the Process Lifecycle Cost Model

2.9.1 Handover (Generic)

Once the Process Lifecycle Cost Model has been developed and the results shared, it is handed over to stakeholders and this is normally carried out face to face. Typically the handover ensures that:-

- input and results interfaces are usable to non-simulation experts
- the stakeholder is able to easily visualise results
- there is a user guide on how to run scenarios
- there is good understanding of what the model should be used for and what it should not be used for

2.9.2 MOJ Project – Handover of Process Lifecycle Cost Model

A formal handover of the Process Lifecycle Cost Model and Environmental Impact Assessment to the MOJ project team was carried out and this involved a presentation which explained the features and operations of the models and also ensured that all requirements of the handover described above were met, see paragraph 2.9.1 above.

Sharing and involving the MOJ project team during model development, helped them understand the Process Lifecycle Cost Model as it developed, how they could align to current processes and also helped them to appreciate how modelling can inform strategic decision making about costing and environmental impacts, early in the planning process.

The output provided by MTC to the MOJ project team, was a Process Lifecycle Cost Model which can be used to define specific scenarios related to the manufacture of components for their projects. MTC also provided the MOJ project team with the knowledge and understanding to enable them to run their own scenario experiments.

If you want to get started and/or want further information on the systems, tools and approaches described in this publication, visit the construction website at www.the-mtc.org/construction

5
PRODUCTION FACILITY DESIGN

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1 – Introduction and Overview

1.1 Introduction

The Ministry of Justice is embracing new methods of construction building. These include using a construction methodology referred to as Design for Manufacture and Assembly (DfMA). This methodology revolves around the design of standard component parts that can be mass produced and then delivered to the construction site, where, due to the simplicity of component connections, it can be assembled by a, lower than normal, skilled workforce.

Using DfMA and off-site manufactured components allows local labour to be involved in the construction of buildings and reduces the need for skilled labour. It ensures a 'right first time' approach, prevents the need for rework and the discovery of problems later in the build life. (The approach and application of DfMA in the MOJ Project is described in more detail in Chapter 3, Design for Manufacture and Assembly).

The MTC was asked to support the MOJ Project in designing manufacturing and assembly processes for the production of key components of the building. In particular, the MOJ project team wanted to bring the MTC's knowledge and expertise in manufacturing to support designers creating "elements" that would be easy to manufacture and assemble at full scale production.

The MTC approach to Production Facility Design, through the use of simulation, adds a visualisation dimension to DfMA without the requirement for physical prototypes or mock-ups. It uses the latest advanced systems and tools to create simulated assembly lines, work stations, material flows and equipment positioning in virtual reality (VR). VR provides an insight into the ergonomic and environmental impact of any design concept. It allows 'What if' scenarios to be considered, reduces risk and ensures that the design concept developed by the DfMA approach has the capability to deliver the requirements that have been specified.

MTC's powerful set of VR systems and tools have been used extensively to create virtual manufacturing and assembly environments in different industries including food, automotive and aerospace. The MTC believes that Production Facility Design can make a significant contribution to transforming performance and reducing costs in the construction sector.

1 – Introduction and Overview

The MTC's VR systems and tools enable a wide range of simulation and visualisation opportunities for product and production line designs to be considered in a virtual reality environment, see Figure 1 below:-

Figure 1. Example of MTC virtual reality visualisation

Quote:-

"Just a quick note to express my sincere gratitude for your contribution this week. Between last week and this week we managed to reach a crescendo on Wednesday whereby the visualisation of, and immersion into, the VR prototypes, assembly sequences and methods of manufacture had the contractors "dancing in the aisles."

The way the material was prepared and presented suddenly brought the art of the possible to life. As you know we at Bryden Wood often struggle to singularly get the industry to engage with new methodologies. Having you guys alongside us has been a great help."

Dries Hagen,
Head of Property, Bryden Wood

This chapter describes the generic approach that MTC takes to Production Facility Design and the systems and tools used for the specific requirements of the MOJ Project. It also describes the benefits that Production Facility Design can bring to the construction sector and the specific benefits delivered for the MOJ Project.

1.2 Overview

The construction sector has challenging targets as contained in the Construction 2025 Report and the Transforming Infrastructure Report (2017) and described in Chapter 1 – Overview – paragraph 1.1, of this book.

The construction sector is beginning to recognise that Production Facility Design can make a major contribution to delivering improvement and efficiencies in the manufacture and assembly of construction components. MTC's knowledge and approach to Production Facility Design, tailored for construction, was used to support the MOJ Project.

MTC's approach to Production Facility Design, provides the capability to understand the production facility and machine layout configuration and, through experimentation, allows evaluation of potential throughput performance.

This capability minimises the risks associated with Production Facility Design and provides value-added decision support for complex Production Facility Design problems. The key areas of evaluation for production facility modelling are:-

- the layout design of production areas
- the throughput (volume) that is achievable for a production facility
- the number of production assets and labour required to achieve the targeted throughout

This chapter also describes MTC's use of Discrete Event Simulation (DES) modelling to support decision making on Production Facility Design configuration options.

1.3 Where have the systems and tools been used?

Simulation modelling, including DES, has been extensively used in automotive, aerospace and other environments where the creation of a physical prototype can be very costly and time consuming and requires high levels of rework, until the designs and layouts are optimised.

Simulation modelling is also used in a variety of other industries such as logistics, food, rail transport, to identify bottlenecks, areas of potential people congestion or process overlap and helps understanding of the interactions and impacts of processes, equipment and layout design before investing capital.

The MTC has extensive experience of using these tools with industry. A major aerospace OEM, provided the following feedback:-

The MTC's approach enabled us to gain insight into the proposed concepts and:-

- identified production facility infrastructure and service clashes before installation
- identified the risk of lack of access for the maintenance team
- allowed a clear view of the insufficient crane height available to move products through the production facility

The aerospace OEM further stated that potential issues were identified early in the design of the production facility which led to a major redesign of the cell layout before investment in a costly physical prototype was made.

1.4 Why these systems and tools for the Construction Sector?

The MTC, based on their experience of Production Facility Design in a number of different industry sectors, selected a suite of systems and tools that have a proven track record of helping industry design production facility layouts and assembly processes. The MTC believed that these systems and tools were the most appropriate to be used in simulating the manufacture and assembly of the components to the required quality, production rate and target time.

VR technology studies have shown the use of VR by employees can increase efficiency in manufacturing assembly and decrease error rates, eliminating the need for re-work and reducing waste.

A study conducted by Boeing measured 25% improved efficiency and a reduction in first time errors in participants using VR technology compared to 2D instructions on a fixed monitor or mobile screen (Richardson, 2014). A study carried out by GE demonstrated 34% improvement in efficiency when wiring a wind turbine's control box (Michael E Porter, 2017) using VR smart glasses compared to a paper based manual.

1.5 Benefits

The use of Production Facility Design simulation systems and tools delivers many benefits, these include:-

- early communication and co-ordination between project stakeholders to gain ownership and buy-in to the design of a production facility
- provides an opportunity to engage operational staff in scenario planning and layout design to gain ownership and buy-in
- virtual validation in the early phases of the design of the production facility, identifying improvement opportunities and verifying suitable manufacturing and assembly processes
- virtual "try-out" of layout and assembly processes early in the project
- enables the virtual design of production facility layouts and manufacturing and assembly processes without the use of physical prototypes
- reduces cost, risk and time in building physical prototypes
- reduces the amount of floor space required, distance travelled by operatives between work stations and handover points, within the work area
- contributes to 'good architecture' including building design, usability, ambience

1.6 The MOJ Project

As mentioned in paragraph 1.1, the MTC were asked to support the MOJ Project in designing manufacturing and assembly processes for the production of key components of the building. The output from the simulation systems and tools:-

- informed the design of the manufacturing and assembly processes required to produce the components e.g. footprint, number of resources, work in progress
- enabled assessment of the variability of the achievable production rates required and high level design requirements of the production facility
- aided communication of the design and operational processes to project team members and operational staff
- supported the MOJ project team in determining which components could be produced on-site and which needed to be produced off-site

2. Production Facility Design

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2 – Production Facility Design

2.1 MTC's Approach to Production Facility Design

MTC has a well proven approach to Production Facility Design that has been used in a variety of industry sectors and manufacturing environments. This section describes the main systems and tools and how they are used:-

- Model Specification Document
- Capacity Model
- Dynamic Simulation Modelling – Discrete Event Simulation (DES)
- 3D Production Facility Design Model
- Virtual Design Review

Figure 2 below shows the sequence of steps followed to create a simulated Production Facility Design:-

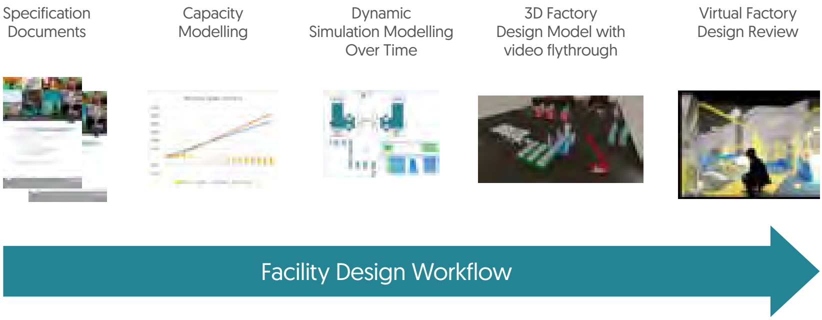

Figure 2. Sequence of steps to create a simulated Production Facility Design

A brief description of each of the steps is given below.

The **Model Specification Document** (see paragraph 2.2) captures the requirements for the different models and also documents the design as they are developed during the project.

The **Capacity Model** (see paragraph 2.3) assesses the component production rate required to achieve the construction programme. It also enables analysis of footprint requirements for buffer stock.

Dynamic Simulation Modelling – DES (see paragraph 2.4) is used to gain understanding of the performance of different processes in order to identify the optimum process.

A **3D Production Facility Design Model** (see paragraph 2.5) is created incorporating assembly lines, operator positions, storage requirements and workflows which demonstrate the concept production facility layout. A video flythrough of the production facility is created in order to allow the concept model to be viewed and shared across stakeholders to gain feedback on the model and suggestions for improvement.

A **Virtual Design Review** (see paragraph 2.6) of the concept model is undertaken, using a suite of virtual reality tools and facilities to immerse stakeholders into the virtual model, which allows them to view the layout from different viewpoints and angles and provide feedback on issues and improvements.

The MTC used the approach described above to support the MOJ Project in the design of a production facility, see paragraphs 2.2 to 2.6 for a detailed description of each system and tool.

2.2 Model Specification Document

2.2.1 Model Specification Document (Generic Approach)

Creation of the Specification Document is a key step in developing simulation models. It is an evolving working document which outlines the scope of the model. The Specification Document is populated using input from all key stakeholders and is then discussed and agreed.

There are 2 types of Specification Document used when developing simulation models, a Requirements Specification Document which defines what the model is required to address, including functionality, usability, performance and a Design Specification Document which outlines how the model has been built. Often these documents are combined into one.

Both Specification Documents are reviewed and updated throughout the life of the project. Typical contents include:-

- business questions
- model requirements
- scope
- model structure
- assumptions
- key performance indicator(s) (KPI)
- experimental factors
- glossary of terminology

2 – Production Facility Design

The completed combined Requirements and Design Specification Document:-

- provides a record of the agreed scope, capability, functionality and requirements of the models being developed
- provides documentation to support the development and understanding of the models capabilities and purpose
- gives a focus for ongoing modelling activity

The benefits included:-

- reduced model development time
- minimised re-work of templates
- management of stakeholder expectations
- validation of the model in respect of design vs requirements

2.2.2 MOJ Project – Model Specification Document

The MTC team scoped the requirements specification and design specification using input from the MOJ project team workshops and the completed specifications were then shared, reviewed and amended. Changes were managed using a change management process and appropriate configuration control.

The Model Specification Document for the MOJ Project combined the content of both the requirements and design specification.

Throughout each stage of the development of the simulated Production Facility Design, see Figure 3 below, the Model Specification Document was updated with changes agreed by the project team and provided traceable documentation throughout the development cycle.

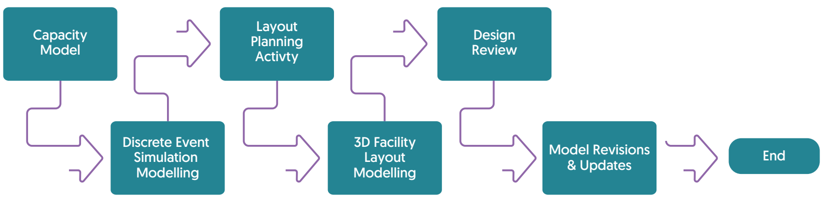

Figure 3. Stages in the development of the simulated Production Facility Design

2 – Production Facility Design

The Model Specification Document developed for the MOJ Project outlined the scope of the Production Facility Design, and included:-

- the content of the DES model to support the design of the manufacturing and assembly areas of the key components of the building e.g:-
  - superblocks and potentially megablocks
  - partition walls
  - market stall
- assessment of the component throughput potential of the various manufacturing and assembly areas
- assessment of the variability of the manufacturing and assembly areas to produce the components to the target volume
- understanding the requirements for storage, goods in, work in progress and finished components
- providing understanding of how process flows and the impact of variable performance, affect the system's ability to deliver a target throughput

2 – Production Facility Design

2.3 Capacity Model

2.3.1 Capacity Model (Generic Approach)

Delivery delays, storage and damage of materials are significant factors which cause building delays, it is estimated that damage to materials can be as high as 30%. Capacity modelling mitigates these issues by increasing understanding of the capacity and volume requirements that a production facility will need. It also increases understanding of whether supply rates are adequate to meet demand rate, enabling a just in time approach to be successfully adopted and a reduction in stock levels.

A Capacity Model is a mathematical model, based in MS Excel, and contains key customer inputs and assumptions and helps understanding of the key factors that affect a Production Facility Design such as product cycle times, labour shift patterns, product footprint.

This is often the first step to understanding the requirements and business case justification behind the development and investment in a production facility.

The following is a list of typical key data inputs required to populate a Capacity Model:-

- working day durations
- number of teams
- team utilisation
- production durations
- component footprint
- start date
- production timeframe
- floor space available
- daily rate of consumption
- duration of consumption

2 – Production Facility Design

An extract from a Capacity Model showing the types of numerical data it contains, is shown below in Figure 4:-

M1.1 Production Team Size	
Team size	Number of teams
2	7

M2.1 Working Day Durations	
Shift Duration (hours)	Shift Duration (mins)
8.5	510

M3.1 Calendar Assumptions	
Days per Week	Days per Month
5	4.3

M4.1 Average Team Utilisation
Utilisation
81%

M5.1 Production Durations			
Set Up Time	Op Time (mins)	Move to Storage	Total Time per Unit
0	15	0	15

M6.1 Capacity Requirements per Team		
Total Storage Required per Team (1 day)	Total Storage Required per Team (1 week)	Total Storage Required per Team (1 month)
17	84	365

M7.1 Capacity Requirements per Site		
Total Storage Required all Teams (1 day)	Total Storage Required all Teams (1 week)	Total Storage Required all Teams (1 month)
116	582	2529

M8.1 Capacity Availability per Facility			
Floor Space Facility	% Floor Space Availability for Storage	Floor Space Available for Storage per Facility	Number of Days Worth Storage of Components
280	70%	196	11.7

M9.1 Capacity Availability per Site			
Floor Space Storage Area	% Floor Space Available for Storage	Floor Space Available for Storage in Storage Area	Number of Days Worth Storage of Components
200	70%	140	1.2

Figure 4. An extract of numerical data contained in a Capacity Model

There are a number of benefits of using a Capacity Model including:-

- reducing financial risk
- enabling informed decisions to be made about design options
- ensuring the production facility has the capability and capacity to meet required demand
- identifying requirements for storing buffer stock and work in progress

2.3.2 MOJ Project-Capacity Model

The MOJ Project Capacity Model was created in MS Excel and was used to calculate the physical dimensions for storing the key components to ensure the production facility had the capacity for the required storage space and to explore and answer two main questions that the project team wanted to consider:-

Question 1.
What are the space requirements for the storage of superblocks on-site? Within this question two scenarios were modelled:-

- the ability to store assembled superblocks within each on-site workshop
- the ability to store assembled superblocks within a defined storage area

The output from the Capacity Model provided the dimensions of the required space for storage of the superblocks and identified that there was insufficient space for the storage of the superblocks on-site.

Question 2.
Will superblock assembly rates support building construction demand rates? Within this question two scenarios were modelled:-

- initial data assumption to confirm and validate concept
- the effect of adding a small amount of variance to the assembly time for each superblock

2 – Production Facility Design

The output from the Capacity Model is shown below in Figures 5 and 6. Figure 5 shows the initial assumed supply and demand rates and Figure 6 shows the effect of adding additional assembly time.

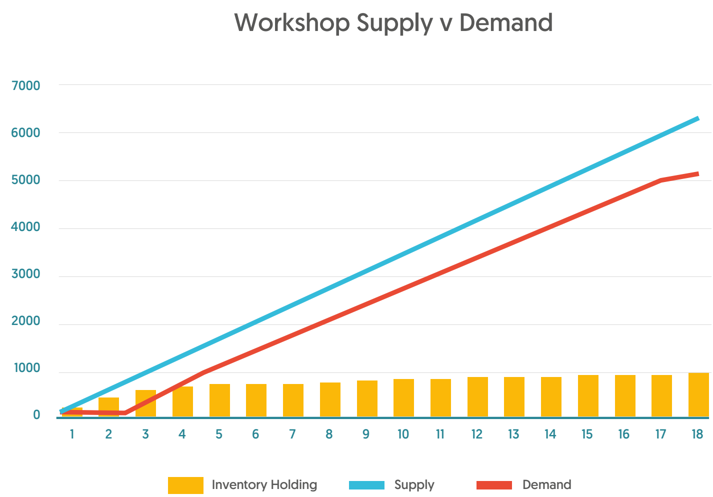

Figure 5. Output from the Capacity Model using the initial assumed supply and demand rates

The chart above shows that:-

- the workshops can support the assumed demand rate
- there is sufficient time allowed between the workshop operational date and the commencement of the build
- the workshop assembly rate is sufficient to support the build throughout the construction programme

As can be seen in Figure 6 on the next page, adding additional assembly time to the duration of the superblock assembly has significant impact on the workshops ability to support the construction demands. In this scenario, 2 minutes were added for the collection of components, plus 4 minutes to move the completed assembly to a line side storage area.

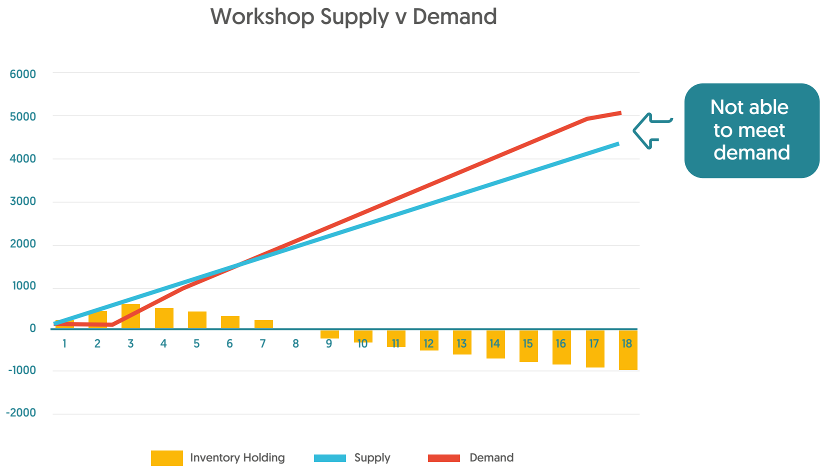

Figure 6. Output from the Capacity Model showing the effect of adding additional assembly time

The chart above shows that:-

- supply from the workshops is initially sufficient to support demand from the construction site
- by month 8, the demand rate is higher than the rate of supply and there is a shortfall of inventory
- the workshop assembly rate is not sufficient to support the build throughout the construction programme

The output from the modelling provided the MOJ project team with an insight into the capability of the proposed production facility, e.g:-

- the original plan of producing on-site during construction, was not viable due to storage space requirements
- it provided the project team with an understanding of the implications of supply and space variability and how this could affect their potential suppliers
- it enabled the project team to have a better understanding of what they required from their suppliers, which helped to inform decision making during supplier selection

2.4 Discrete Event Simulation

2.4.1 Discrete Event Simulation (Generic Approach)

Production facilities are complex systems that require many variables and their associated variance to be taken into account in designing a suitable production facility layout. Discrete Event Simulation (DES) is a capability used in simulation that represents the relevant aspects of real-world processes and systems over time. It is able to address complex problems such as in Production Facility Design simulation and it allows the exploration of multiple scenarios within that environment. (Banks et al.2005).

DES enables different scenarios to be tested and evaluated when factors which contribute to the output of the operation are changed e.g. number of process assets, number of operators, volume requirements and supply of material. The appropriate use of DES reduces the risk and probability of making costly mistakes when changing production facility layouts. DES can be used to inform understanding and decisions around:-

- additional facilities to meet customer needs
- limitations of existing facilities
- capacity and process capability of new or existing facilities
- identifying and mitigating bottlenecks
- production planning verification

The benefits of using DES for Production Facility Design simulation in the construction sector are that it:-

- helps stakeholders visualise and reach consensus of understanding of the overall production facility layout using graphics and animation
- empowers frontline staff or the building occupants to positively influence the building design
- can model unexpected events to understand their impact on manufacturing, assembly and the overall construction programme
- uses 'What if' scenarios which enable the user to test various layouts, manufacturing and assembly alternatives, before committing to a plan
- provides value-added decision support for complex production facility layout problems
- reduces the risk of delivering a system that can't achieve capacity requirements

- helps determine the number of assets that will be required to operate the production facility
- helps mitigate the likelihood of building a large component in a space from which it cannot subsequently be moved
- can be used to evaluate the next best steps when a change to a building or layout is proposed

DES is the simulation tool used by MTC for Production Facility Design. The MTC also uses DES in Supply Chain Modelling, see Chapter 6 in this book, and many other business applications.

2.4.2 MOJ Project – Discrete Event Simulation

DES was used in the MOJ Project to create a simulation model of the proposed superblock assembly process to test various assembly line scenarios and ultimately verify that the assembly process selected could deliver the required production rate.

The DES model was built to address the business questions identified in previous stages of the model development cycle. The business questions were:-

- how many resources (long lead time and high investment items only) are required to achieve the production volume required?
- what WIP and storage requirements are needed to support production?
- what is the throughput potential of the system and where are the constraints?
- what impact does the time required for system ramp up and down, have on the ability to meet the required production volumes?

As is typical at the early stages of a programme, not all data is available, so assumptions are used in the creation of the DES Model. A benefit of modelling is that it helps the understanding of what data is required and its significance, providing a focus for the collection of the key data and reducing the time spent on data collection.

The assumptions used to populate the MOJ DES model included:-

- pallets are required for transportation within the workshop and also to and from the consolidation area
- one pallet uses approximately 1.2m^2 of floor space

2 – Production Facility Design

- 6 teams, each consisting of 2 people will work (8.5 hours per work day)
- each team requires an assembly station
- workstations have adjacent storage that holds the required number of components to produce one day's worth of superblocks
- storage is one unit high (superblocks will not be stored stacked on each other)
- storage floor space is limited to 30% of the production facility footprint
- demand rate is 156 superblocks per day per site
- demand rate is consistent with no peaks and troughs

It was agreed with the MOJ project team that the following three components would be modelled in order to assess various manufacture and assembly process flows and whether they could be produced at the required volume on-site:-

- superblock
- partition walls
- market stall

A schematic of the manufacture and assembly process flow was created for the superblock and this is shown in Figure 7 below:-

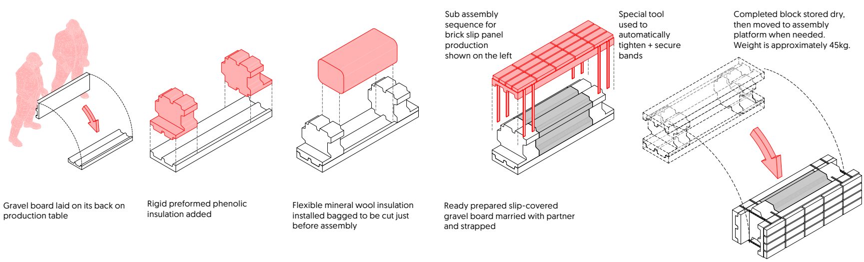

Figure 7. Superblock manufacture and assembly process flow

Using the DES process, the MTC, created a number of baseline designs for consideration by the MOJ project team, one of these is shown in Figure 8 below:-

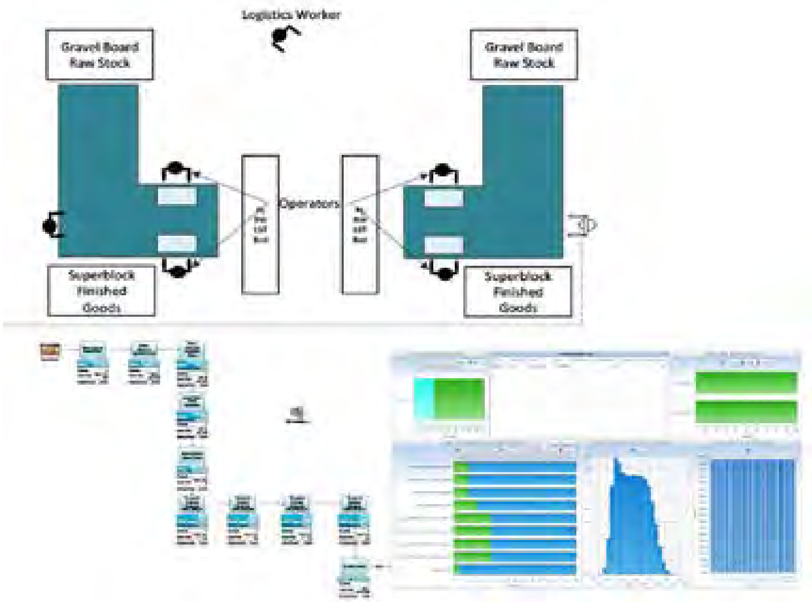

Figure 8. Example of a baseline design for the superblock

The image at the top of Figure 8 shows a schematic of the assembly workstation layout for the superblock with two separate cells and illustrates the layout that was flowcharted and analysed.

The image on the bottom left shows the assembly sequence and process flows of key tasks to be undertaken and the minimum and maximum time it will take. The image on the bottom right shows numerical results from the DES model including:-

- total time needed to create the assembly
- % of time the operator is utilised
- time taken to assemble the components

2 – Production Facility Design

Based on the results from the DES study and the MTC's experience of designing layouts, the advantages and limitations to the proposed layout design were identified. The issues around the limitations, together with alternative negare (horseshoe) and linear cell solutions were presented to the MOJ project team and it was agreed that a linear cell solution would be adopted.

The DES modelling identified:-

- the level of key resources that would be required
- WIP and storage requirements needed for production
- throughput potential of the system and related constraints
- required production volumes and production facility start dates of the programme
- an indication of stock holding requirements

It also produced:-

- savings in development time to bring the system into operation
- reduced physical prototyping by 3-4 months and avoided wasted time and money
- a faster and more iterative process design
- a more robust system design and easier implementation

2.5 3D Production Facility CAD Model

2.5.1 3D Production Facility CAD Model (Generic Approach)

The DES model, described in the previous paragraphs, considers various production facility layout options and provides the optimum layout within the constraints of the production facility. The layout can then be conceptualised using 3D CAD models enabling the production facility to be viewed by stakeholders in a virtual environment. One of the ways this can be done is by the use of a video "flythrough" which gives an elevated view of the production facility and allows different parts of the assembly to be viewed to understand the relationships between manufacturing cells. It allows stakeholders to view the layout and assembly processes in a virtual reality environment and give feedback to identify risks, problems and suitability of the layout.

Modelling facilities in 3D has become a valuable tool for mitigating risk in setting up a new production line in a production facility. The MTC experts have created many 3D CAD production facility layouts to provide customers with a deeper insight and greater awareness of the production facility being modelled. The ability to rearrange the production facility in a virtual environment e.g. machinery, doors, window frames, walkways etc. allows an optimum production facility design to be visualised. This is even more beneficial when using a DES model to calculate the quantity of assets and footprint based on work in progress and stock levels to deliver the product at the rate specified.

Figure 9 below is an example of a 3D simulated production facility:-

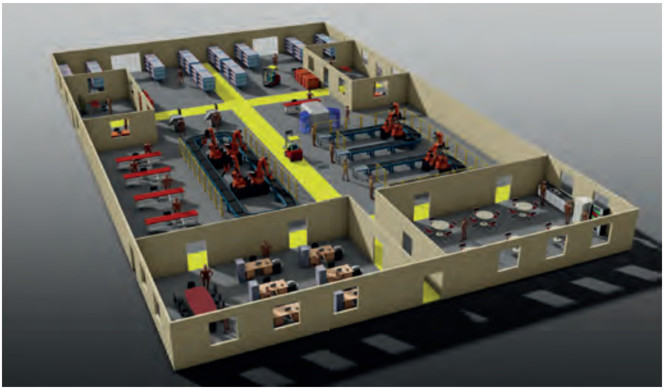

Figure 9. Example of a 3D simulated production facility

2 – Production Facility Design

3D production facility CAD modelling is used extensively to problem solve at an early stage in the concept design process. It enables:-

- customers and stakeholders to view the production facility in a virtual environment and see the relationship between the various elements of the layout
- different scenarios to be trialled
- fixturing designs to be considered
- ideas to be discussed and feedback to be given on different layouts
- operational experts to input their ideas about the production facility and layout
- lessons learned to be captured and taken into account in future builds

2.5.2 MOJ Project – Production Facility CAD Model

The MOJ Project production facility was modelled and a video "flythrough" was created to ensure stakeholders could assess initial concepts and the potential size and scale of the production facility. These concepts were determined by the capacity modelling and DES work described in paragraphs 2.3 and 2.4. Aspects that the MOJ project team wanted to consider were:-

- what are the footprint requirements for the production areas of the three components to be produced in the production facility?
- what design layout is required to enable the production of the components to be carried out in any equivalent production facility, irrespective of location?
- what is the most efficient layout that reduces movement of parts to minimise potential damage?

2 – Production Facility Design

A 3D model was created to demonstrate a concept production facility that incorporated the assembly lines for the superblock, partition wall and market stall frame components and a video flythrough of the production facility was shared with the stakeholders to gain feedback on the proposed production facility layout.

The MTC produced the 3D CAD model and used Revit to create the walkthrough and recorded it using Camtasia software. The following three illustrations, Figures 10, 11 and 12, are screen shots of the superblock assembly line, from the flythrough video which was shared with the MOJ project team:-

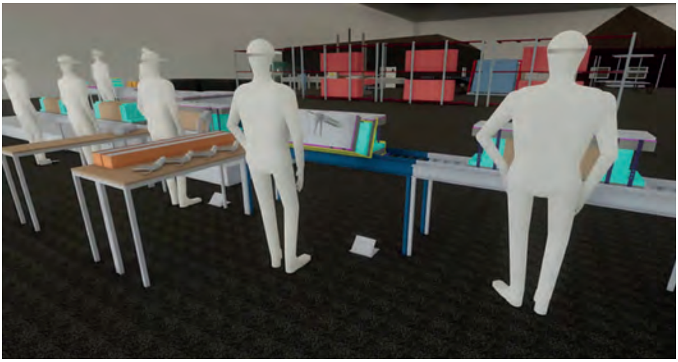

Figure 10. View of virtual optimised superblock assembly line

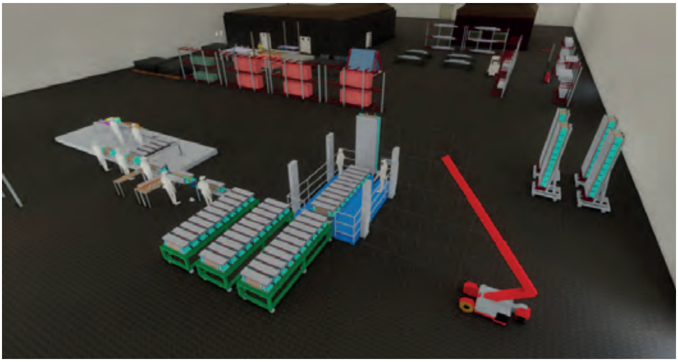

Figure 11. View of virtual factory facility incorporating superblock assembly line

2 – Production Facility Design

Figure 12. View of virtual partition wall assembly line

The above illustration, Figure 12, shows the partition wall assembly line, which is a particularly important aspect of the Production Facility Design.

Visualising the assembly line enabled the MOJ project team to understand the size and weight of the partition wall relative to the size of the operatives and the space requirements needed. It also highlighted the challenge of getting the partition wall from the assembly line onto a lorry. It showed that, due to the size of the partition wall it would have to be loaded onto the lorry in a tilted position and so a tilted 'A' frame would need to be used for this operation. This challenge was identified from the 3D CAD modelling which, through discussion, enabled a solution to be found.

An animated sequence of the superblock assembly line can be viewed at www.the-mtc.org/facilitylayout

The video "flythrough" showing the optimised 3D CAD model was shared with the MOJ project team who identified the following benefits from the model, it:-

- allowed reviews and collaboration to take place early on in the project lifecycle
- identified risks at an early stage of the programme which enabled mitigation plans to be put in place thereby reducing costs and avoiding delays in the programme
- allowed the MOJ project team to review the production facility and provide feedback from a customer perspective
- enabled a common understanding amongst the MOJ project team of an initial concept of the production facility layout

2.6 Virtual Design Review

2.6.1 Virtual Design Review (Generic Approach)

A Virtual Design Review utilises the 3D production facility and ensures all stakeholders can undertake an immersive review of the production facility before any prototyping has occurred.

The MTC uses state-of-the-art virtual reality equipment in order for stakeholders to review and discuss the design of a proposed production facility in a virtual environment. It allows changes to be made to the layout in a risk free environment and is a more immersive experience than the video flythrough, allowing the user a more in-depth view of the production facility and layout.

The MTC has undertaken many Virtual Design Reviews across a variety of industries and the feedback is always positive, some examples include:-

- generating a lot of enthusiasm from stakeholder and customers
- helping drive the meeting and making discussion more dynamic
- allowing all interested stakeholders to view the production facility or manufacturing line without investing money in a prototype
- enthusing customers and allowing them to give feedback on their production facility before any investment in capital or equipment
- identifying potential issues early in the design of the manufacturing production facility

2.6.2 MOJ Project – Virtual Design Review

The MOJ Project production facility was modelled in 3D and a virtual "walkthrough" was created to ensure the project team could assess initial concepts and were aware of the size and scale of the production facility that would be required. These concepts were informed by the capacity and DES modelling.

The virtual walkthrough was presented to the MOJ project team who were "immersed" in the model using an 'HTC Vive' in the MTC state-of-the-art VR suite. This allowed the MOJ project team to see workstations, operatives, walkways and to walk around the assembly cells and experience the spatial context of the layout in virtual reality. This enabled feedback to be gained on the proposed layouts, risks to be identified and mitigated before any investments in physical prototypes or capital were committed.

2 – Production Facility Design

Figure 13 below shows a walkthrough Virtual Reality Design Review at the MTC:-

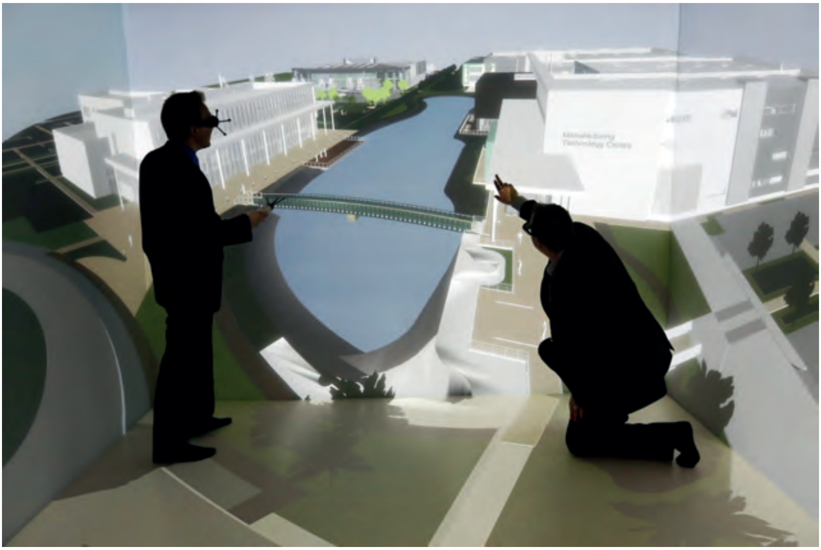

Figure 13. Virtual Reality Design Review at the MTC

The MOJ project team identified the following benefits from the Virtual Design Review, it:-

- informed the design of the production facility
- allowed manufacturing processes to be considered before money was invested
- allowed detail design reviews to be undertaken and feedback to be captured from all stakeholders
- enabled the MOJ project team to alter the layout before physically assembling it
- helped reduce cost and downtime due to issues being identified at the start and not the end of the project

If you want to get started and/or want further information on the systems, tools and approaches described in this publication, visit the construction website at www.the-mtc.org/construction

6

SUPPLY CHAIN MODELLING

1. Introduction and Overview

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1 – Introduction and Overview

1.1 Introduction

The MTC has extensive experience of carrying out supply chain modelling in a wide range of industries including manufacturing, automotive, aerospace and construction. The MTC believe that supply chain modelling can make a significant contribution to transforming performance and productivity in the construction sector.

The MTC was asked to demonstrate to the MOJ project team, the approach and benefits of supply chain modelling at the early stages of construction project planning where novel materials and processes were being considered and where no supply chain existed. The project involved the manufacture of standard component parts that could be mass produced and then delivered to the construction site for assembly by a lower than normal skilled workforce due to the simplicity of component connections.

This chapter describes the generic approach that MTC takes to modelling projects and the approach, systems and tools used for the specific requirements of the MOJ project. It also describes the benefits that supply chain modelling can bring to the construction sector and the specific benefits delivered for the MOJ project.

The MOJ project team recognised the valuable contribution that supply chain modelling can make to improve productivity and efficiency of construction projects.

Quote:-

"I'd like to thank the team at the MTC for leading the work we have been undertaking on supply chain modelling. The MTC team's level of knowledge, professionalism and insight has being very impressive. But the greatest skill the team has shown is the ability to listen and learn about why construction is or can be different to other industries. The approach to supply chain modelling has opened my eyes to dynamic modelling and its ability to simulate the many variables of construction such as weather, labour output and supplier failure. This has provided us with a great level of insight and surety on the supply chain modelling. I can see dynamic modelling having a much wider application in construction and could have great impact on areas such as logistics mapping, crane usage, line of balance planning and failure assessments."

John Handscomb
Pre-Construction Procurement Lead, Kier Construction

1.2 Overview

The construction sector has supply chain capability and where there is data available or sources of data are known, estimating and planning methods are in place. However, the construction sector has limited experience of planning when novel materials or processes are proposed and when information is not known or is limited. The complexity of the supply chain means that the impact of any changes needs to be carefully considered and fully understood before being implemented.

Supply chain modelling provides a way in which different scenarios and impacts on supply chain performance can be understood and evaluated before finalising the supply chain structure. It provides the capability to engage with different delivery teams and collaborators and to test different supplier and supply chain variants. With the use of supply chain simulation models, the construction sector can become smarter and can build evidence-based understanding of the uncertainty and risk associated with different supply chain strategies and configurations.

Supply chain modelling can also transform the way that procurement for construction projects is carried out, allowing greater control of supply chain variants and more control over cost and on-time delivery.

1.3 Where have the systems and tools been used?

The supply chain modelling tools, including Discrete Event Simulation (DES), have a well proven track record in a variety of industries including:-

- Logistics
- Pharmaceutical
- Paper
- Textiles
- Aerospace
- Automotive
- Fast moving consumer goods e.g. food

1.4 Why these systems and tools for the Construction Sector?

The construction sector has a supply chain planning capability at both operational and tactical levels where historical and source data is available. However, the industry recognises that disruption in the supply chain, late delivery and over-ordering, with the consequent creation of up to 30% scrap, is quite common.

The construction sector has limited experience with planning where novel materials and processes are involved and when data and information is not known or is limited. Dealing with this uncertainty and building understanding of new supply chain strategies are areas where modelling and simulation can provide high impact support.

Decisions about supply chain configurations are key as they affect construction build delivery, costing and efficiency. The modelling simulation tools, allow novel ways of managing procurement to be explored including:-

- supply chain configuration to support multiple build sites
- supplier capability
- comparison with traditional procurement methods

1.5 Benefits

The approach to supply chain modelling described in this chapter can ensure that the construction sector becomes smarter, by building evidence-based understanding around the risks and uncertainty associated with different supply chain strategies. This can transform the way that procurement of construction projects is carried out, allow greater control of supply chain impact and provide more control over cost and on-time delivery.

The benefits that can be realised from undertaking supply chain modelling include:-

- enabling the testing of different supply infrastructure variants and evaluating the impact on construction key performance indicators
- enabling clear objectives for supply chain delivery to be identified
- improved construction schedule planning, supplier selection and identification of transport requirements
- involvement of multiple stakeholders which encourages stronger relationships to be built early in the programme
- building smarter commercial relationships within the supply chain
- building evidence-based understanding around the risks associated with different supply chain strategies
- enabling greater control of supply chain impact and more control over cost and on-time delivery

1.6 The MOJ Project

The MTC used supply chain simulation to understand the MOJ Project supply chain configuration for the novel approach to component construction and, through experimentation, evaluated impacts on supply chain performance. Simulation minimises risks associated with new supply chain development and provides value-added decision support for complex supply chain problems.

The MOJ Project Supply Chain Model was developed working closely with key stakeholders throughout the process. Design and outputs were shared and agreed as they were developed in order to ensure the final output met stakeholder requirements.

2. Supply Chain Model Development

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2 – Supply Chain Development

2.1 MTC's approach to Supply Chain Modelling

The MTC's approach to supply chain modelling uses a set of generic systems and tools that have been used in a variety of industry sectors and supply chain environments. The following paragraphs describe the systems, tools and approaches that have been used in these environments. There are four main systems and tools that are used in a systematic way to create Supply Chain Models which enable evaluation of different options. They are:-

- Business Questions Workshop
- Concept Model
- Model Specification Document
- Supply Chain Model

In creating a Supply Chain Model, the MTC uses these systems and tools and follows a three step methodology as shown in Figure 1 below:-

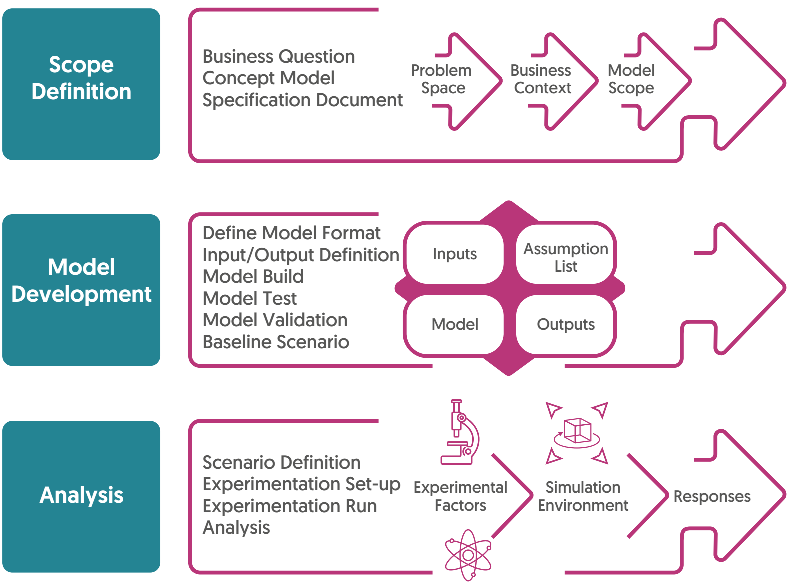

Figure 1. Supply Chain Model Development Methodology

The above methodology demonstrates the stages of model development, the elements considered in each step and is informed by the model objectives agreed with stakeholders, data collection, model development and analysis.

Note:
Scope Definition is further explained in paragraph 2.4, 2.5 and 2.6
Model Development is further explained in paragraph 2.7
Analysis is further explained in paragraph 2.8

To simulate the Supply Chain Model, the MTC uses Discrete Event Simulation (DES) and this is described in more detail in paragraph 2.2.

2.2 Developing a Generic Supply Chain Model

2.2.1 Discrete Event Simulation (DES)

Supply chains are complex systems that require many variables, and their associated variance to be taken into account in order to represent real-world system behaviour. DES is an approach used in simulation that has the capability to represent different aspects of the real-world processes and systems over time. It is able to address complex problems such as in the supply chain and allows the exploration of multiple scenarios within that environment (Banks *et al.2005*).

It allows different scenarios to be tested and evaluated i.e. when factors which contribute to the output of the operation are changed e.g. number of suppliers, supplier location, supplier production rates, lorry capacity. The appropriate use of DES reduces the risk and probability of making costly mistakes when changing supply chain design and allows informed decisions regarding alternatives to be made.

The benefits of using DES for supply chain simulation in the construction sector are that it:-

- helps stakeholders visualise and reach consensus of understanding of the overall supply chain processes using graphics and animation
- is able to capture supply chain uncertainty using probability distributions
- can model unexpected events e.g. risks, to understand their impact on the supply chain and the construction programme
- uses 'What if' scenarios which enable the user to test various supply chain alternatives before committing to a plan which can dramatically minimise the probability of rework within the planning process
- provides value-added decision support for complex supply chain problems

DES is the simulation tool used by MTC for supply chain modelling and for many other business applications.

2.3 Supply Chain Development Process

The MTC has created a seven step Model Development Process to ensure consistency of approach, as it is important that development of a model and the associated analysis are carried out in a systematic way.

2 – Supply Chain Development

The process shown in Figure 2 below ensures that all the business requirements are captured to inform the design of the Supply Chain Model. Validation is carried out throughout the process with the key stakeholders and ensures that they are engaged, bought into the process and that the modelling and analysis is fit for purpose.

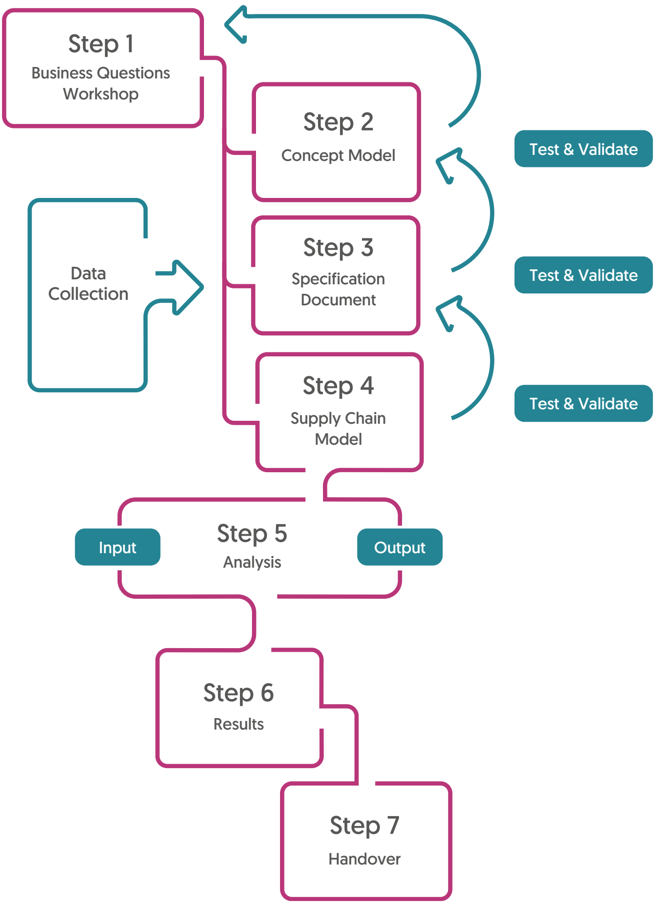

Figure 2. Supply Chain Development Process

Steps 1-7, shown in the above process are described in more detail in paragraphs 2.4 to 2.10.

2.4 Business Questions Workshop – Step 1 of the Supply Chain Development Process

2.4.1 Business Questions Workshop (Generic Approach)

The business questions workshop is the first step in the development of a Supply Chain Model. Its purpose is to bring together, at an early stage, the stakeholders from the partner organisations to discuss and agree issues, challenges and their relative importance to the supply chain.

These are known as the 'business questions' and provide the basis for the structure of the Supply Chain Model so that it is able to provide answers to the defined and agreed business questions.

The business questions workshop is facilitated and follows a pre-determined structure. Ideally the stakeholders who attend the workshop should have strategic and operational knowledge of what they want to achieve and what they see as the key measures of success.

The workshop encourages in-depth discussions on the significant features of the Supply Chain Model.

The output from the workshop provides the input for the design of the options to be considered by the model.

Typically the workshop involves:-

- identifying the business questions
- structuring the business questions into themes
- prioritising the business questions

Examples of typical business questions are:-

- what kind of physical logistics approaches are under consideration? – e.g. the use of a distribution hub only, or the use of a distribution hub and storage at the point of use?
- what is meant by supply chain? does it start when the goods leave the supplier and end when they arrive at the construction site?
- what is the model going to be used for? – e.g. indication of potential or to support business case?
- how is option success measured? – e.g. what are the Key Performance Indicator(s)?
- how much stock should be held in the supply chain and on site?
- how many deliveries are needed?
- where should the central hub be located?

Participating in a business questions workshop provides many benefits to stakeholders including:-

- providing opportunity for stakeholders to be involved much earlier than normal in project planning to gain an overall project view and reach consensus on priorities for the project
- gaining a deeper understanding of the project challenges and opportunities
- gaining a common agreement on what the Supply Chain Model must address
- achieving collective buy-in to the modelling approach being taken

2.4.2 MOJ Project – Business Questions Workshop

The MOJ project business questions workshop involved representatives from the project team and was facilitated by the MTC team supply chain modelling experts. The workshop discussed the key challenges that the project was facing and as a result key areas to address were identified for consideration, see Figure 3 below:-

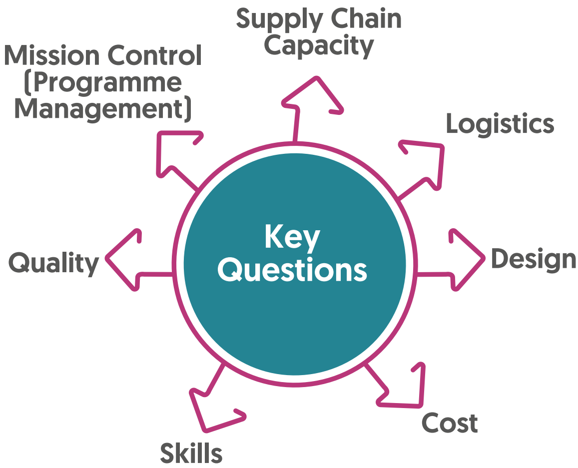

Figure 3. Business questions workshop key areas considered

The workshop discussed and explored the key areas shown in the above diagram and through brainstorming and theming identified a number of business questions.

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These questions formed the basis for the development of the model requirements and scope which then informed the next steps (Specification Document and Concept Model). The key business questions developed included:-

- can different supply configurations improve the end of build programme?
- what is the optimum level of holding stock in the supply chain?
- how much stock on site is required to maintain work?
- how frequent should deliveries happen?
- what should a procurement strategy be?

The MOJ were of the view that a number of benefits came from the workshop and these included:-

- an opportunity for the project team to meet much earlier than normal in the project, to gain an overall project view and reach consensus on priorities for the project
- an opportunity to explore supply chain issues and challenges associated with the manufacture and assembly of construction components
- collective buy-in to the modelling approach being taken and a common agreement on what the models must address

2.5 Concept Model – Step 2 of the Supply Chain Development Process

2.5.1 Concept Model (Generic Approach)

Creating a Concept Model is the second step in the development process and is essential for visualising a Supply Chain Model. A well designed Concept Model significantly enhances the likelihood of a successful outcome to a simulation study and reduces re-work of the model build. It also enables the model scope to be clearly communicated to stakeholders.

A Concept Model is created in order to define the scope and content of a Supply Chain Model and is a useful and powerful tool to support communication during the process of developing simulation models. A number of facilitated workshops are held with stakeholders to discuss, validate and gain agreement to the content of the model including the business questions discussed earlier in paragraph 2.4 of this chapter, the model structure, key model logic, scope and KPI.

In building a Concept Model a methodology to define key activities that need to be addressed is useful. A methodology defined by (Robinson, 2004) outlined 5 key activities, see Figure 4 below, that need to be addressed to build a Concept Model, they are:-

1. understanding the problem situation
2. determining the modelling and general project objectives
3. identifying the model outputs (responses)
4. identifying model inputs (experimental factors)
5. determining the model content (scope and level of detail) identifying any assumptions and simplifications

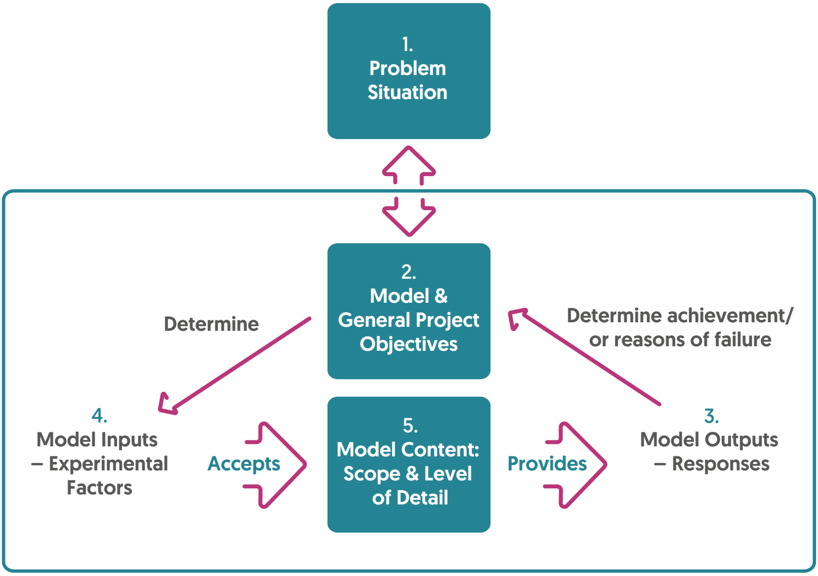

Figure 4. Concept Model Methodology – (Robinson, 2004)

The development of a Concept Model provides further insight and:-

- provides a visualisation of the modelling framework including its scope and content
- validates the approach to be taken before model build commences
- helps to identify data required to populate the Supply Chain Model
- provides information to populate the model Specification Document, described in paragraph 2.6 of this chapter, which is used to inform the development of the Supply Chain Model

2.5.2 MOJ Project – Concept Model

In building the Concept Model for the MOJ project, the MTC team followed the process (Robinson, 2004) described above in paragraph 2.5.1, Figure 4.

The MTC team held a number of workshops with the MOJ project team to create the Concept Model, which included the questions that were developed at the business questions workshop, the model structure, model logic, scope and KPI. An example of some the the detail used to build the Concept Model is shown in Figure 5 below:-

Inputs	Experimental Factors	Outputs (KPI)	Scope	Structure
Construction site schedule Number of suppliers Location of suppliers Lorry load Build start date	Supplier production rate Start stock at site Number of lorries	Number of build days Transport lead time CO2 emissions Overtime Stock level profile	Up to 3 construction sites Up to 20 suppliers Central transportation system	Consumption Module Supply Module Transportation Module

Figure 5. Example of detail contained in Concept Model

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After a number of discussions with the MOJ project team, the Concept Model shown in Figure 6 below was developed and agreed:-

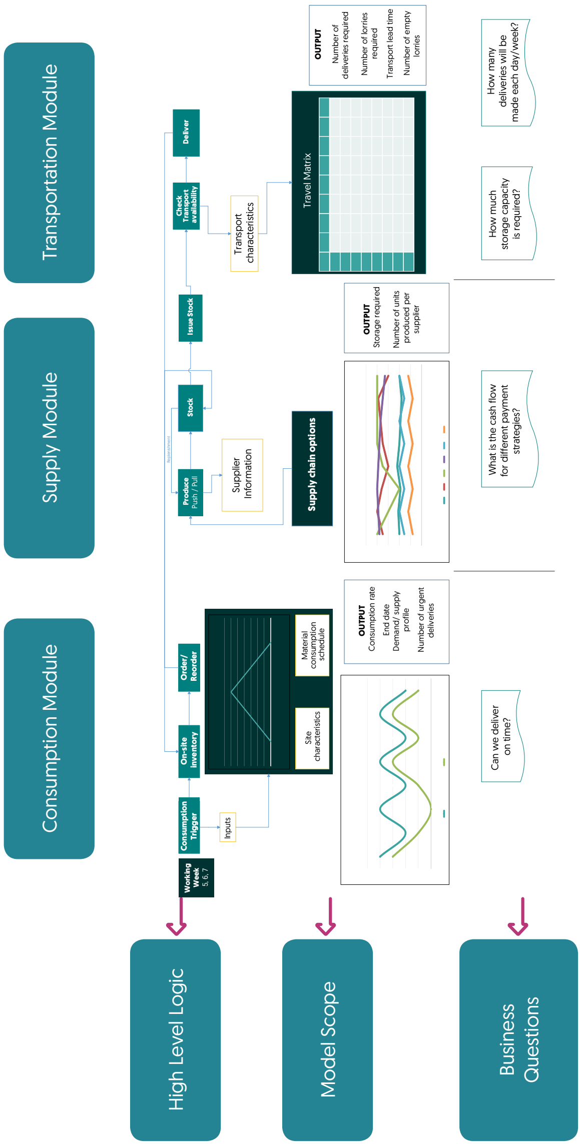

Figure 6. Supply Chain Concept Model

The development of the Concept Model enabled:-

- the business questions to be linked to the specific sections of the Supply Chain Model i.e. consumption module, supply module, transportation module
- the creation of a visualisation of the modelling framework including its scope and content
- confirmation and validation of the approach that was going to be taken to build the simulated Supply Chain Model

2.6 Model Specification Document – Step 3 of the Supply Chain Development Process

2.6.1 Model Specification Document (Generic Approach)

The Specification Document is the next step in developing a Supply Chain Model. It is an evolving working document which outlines the scope of the DES model. The Specification Document is populated using input from key stakeholders and is then discussed and agreed.

There are 2 types of Specification Document, a Requirements Specification Document which defines what the model is required to address, including functionality, usability, performance and the Design Specification Document which outlines how the model is built to meet the requirements.

Both Specification Documents are reviewed and updated throughout the life of the project. Typical content includes:-

- business questions
- model requirements
- scope
- model structure
- general modelling assumptions
- key performance indicator(s) (KPI)
- experimental factors
- glossary of terminology

A completed Requirements and Design Specification Document:-

- provides a record of the agreed scope, capability, functionality and requirements of the models to be developed
- gives a focus for ongoing modelling activity
- reduces model development time
- minimises re-work of templates
- enables the management of stakeholder expectations
- enables the validation of the model in respect of design vs requirements

2.6.2 MOJ project – Model Specification Document

The MTC scoped the requirements specification and design specification using input from the MOJ project team workshops. The completed specifications were then shared, reviewed and amended. Changes were managed using a change management process and appropriate configuration control.

The Model Specification Document template developed for the MOJ project, combined both the Requirements and Design Specification shown in Figure 7 below:-

Contents

Executive Summary 2
1. Introduction 5
2. Objectives 6
3. Business Questions 7
4. Model Requirements 9
4.1 Functionality 9
4.2 Usability 9
4.3 Reliability 9
4.4 Performance 10
4.5 Supportability 10
4.6 Configuration Control 10
4.7 Change Management 10
4.8 Constraints 11
4.9 Security 11
5. Scope 12
5.1 In Scope 12
5.2 Out of Scope 12
6. Model Structure 13
6.1 Overview 13
6.2 Consumption Module 14
6.2.1 High Level Logic 14
6.3 Supply Module 16
6.3.1 High Level Logic 16
6.4 Transportation Module 18
6.4.1 High Level Logic 18
7. General Modelling Assumptions 21
8. Key Performance Indicators (KPI) 22
9. Experimental Factors 23
10. Glossary of Terminology 24

Figure 7. MTC combined specification document template

Following discussion, a fully populated Specification Document for input to the Supply Chain Model was agreed. It set clear expectations on what the model was going to deliver as well as allowing validation of whether the model delivered and met the stated requirements.

2.7 Supply Chain Model – Step 4 of the Supply Chain Development Process

2.7.1 Supply Chain Model (Generic Approach)

Step 4 in the Supply Chain Development Process, described in paragraph 2.3, Figure 2, is where the supply chain is simulated using DES. Once the simulation model is developed using software and programming, it provides the capability to visualise and understand the potential supply chain configuration. Through experimentation, the simulation model allows the evaluation of different options on supply chain performance and its influence on the performance of the construction programme.

In building a simulated Supply Chain Model, it is beneficial to build in modules e.g. consumption, supply, transportation. This allows concurrent development of the modules resulting in a reduction in model development lead times. For each module, there are three phases of development:-

- model build
- model test
- model validation

Each module is validated and verified, then all of the modules are integrated into one simulation model and a final validation and verification is carried out.

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MTC uses a defined methodology to build the simulation model and this is shown in Figure 8 below:-

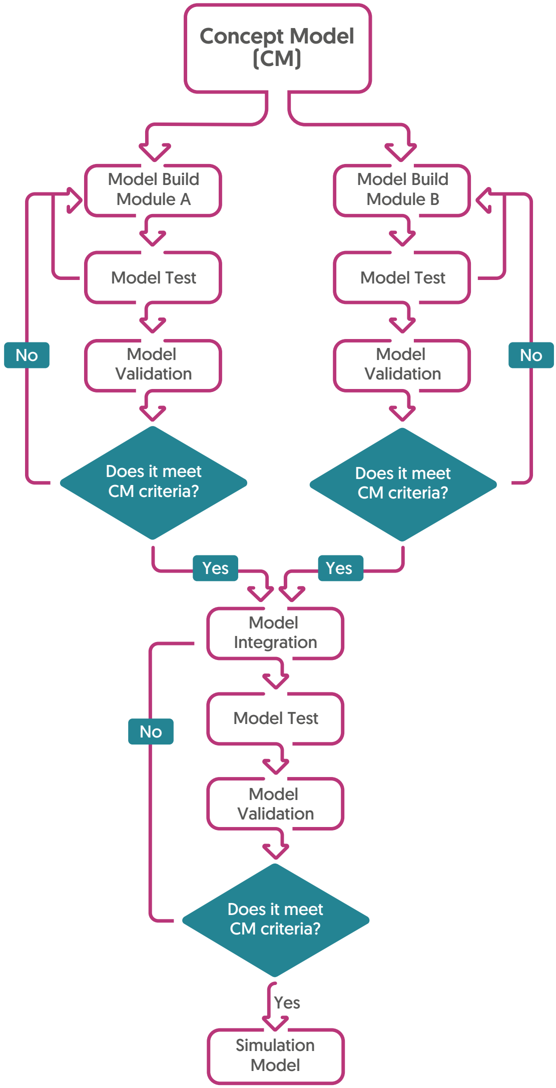

Figure 8. Simulation model building methodology

2.7.2 MOJ Project – Supply Chain Model

To build the simulated Supply Chain Model the Concept Model was used as a framework to identify the scope and level of detail required for the model and a number of workshops were undertaken with the MOJ project team to further define the 3 modules – the Consumption Module, the Supply Module and the Transportation Module as shown in Figure 9 below.

Consumption Module	Supply Module	Transportation Module
Represents the consumption rate of the construction site	Represents the supply chain producing components for the construction site	Represents the transportation system that moves components from supply to construction site

Figure 9. High level description of the contents of each module

The image in Figure 10 below shows how the Consumption Module was further developed, i.e. data inputs, simulation model and logic assumptions.

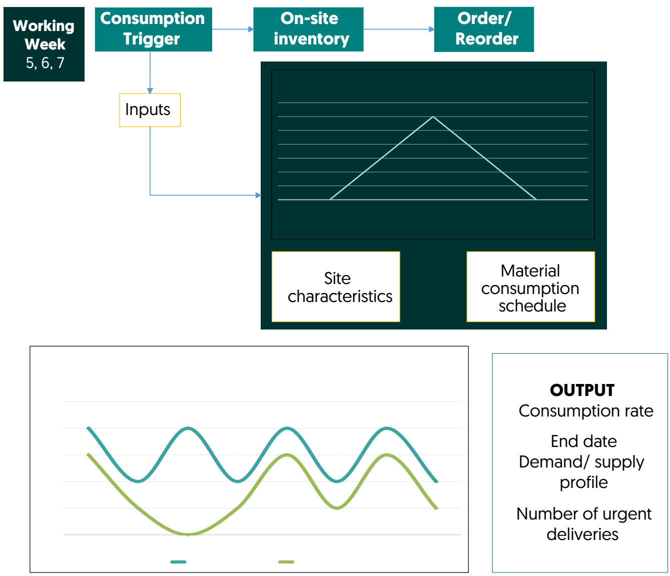

Figure 10. Model development and validation of Consumption Module

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At the review workshops, feedback gained from the MOJ project team was incorporated to improve the model and confirmation was obtained that the model would deliver what was specified in the Model Specification Document. The same approach was followed for the Supply Module and the Transportation Module.

Using the output from the workshops the simulated Supply Chain Model was created and a model integration workshop was held to share the full model content with the MOJ project team.

The integration workshop demonstrated the full Supply Chain Model showing the key modules linked together. Independent testing was also undertaken to verify that the model logic was correct. The MTC team and MOJ project team then validated the model assumptions, inputs, outputs and logic and to confirm that they met the previously agreed criteria.

In addition further workshops were held to validate the model in terms of results of the trial runs and to confirm that the model met the requirements of the MOJ project team. Independent testing was also undertaken to verify that the model logic was. Once the model was validated and verified, experimentation was undertaken to ascertain the sensitivity of the model output to variance of the model inputs.

2.8 Analysis – Step 5 of the Supply Chain Development Process

2.8.1 Analysis (Generic Approach)

Analysis is a phase of the development process where the simulated model is used to run experiments that enable stakeholders to explore the business questions. There are different types of analysis that the Supply Chain Model can undertake e.g. Sensitivity and Scenario 'What if' analysis.

i) Sensitivity analysis is a technique used to determine how different values of an independent variable impact a particular dependent variable i.e. KPI, under a given set of assumptions.

ii) Scenario 'What if' analysis measures how changes in a set of independent variables impact a set of dependent variables.

As the simulation model handles variability, 'What If' analysis is always run multiple times. Each time is referred to as an iteration and the results of each scenario are collated and looked at together. It allows consideration of different supply chain configurations and, it enables stakeholders to quickly see what the impact of a change or a decision has on supply chain performance and therefore the construction programme.

Sensitivity analysis and scenario 'What if' analysis both involve experimentation. Experiments are conducted by selecting and varying experimental factors (input variables) in the model, then measuring the model response (outputs).

Figure 11 below shows a high level experimentation process:-

Figure 11. High level experimentation process

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The flowchart shown below, Figure 12, describes the key steps in the experimentation process:-

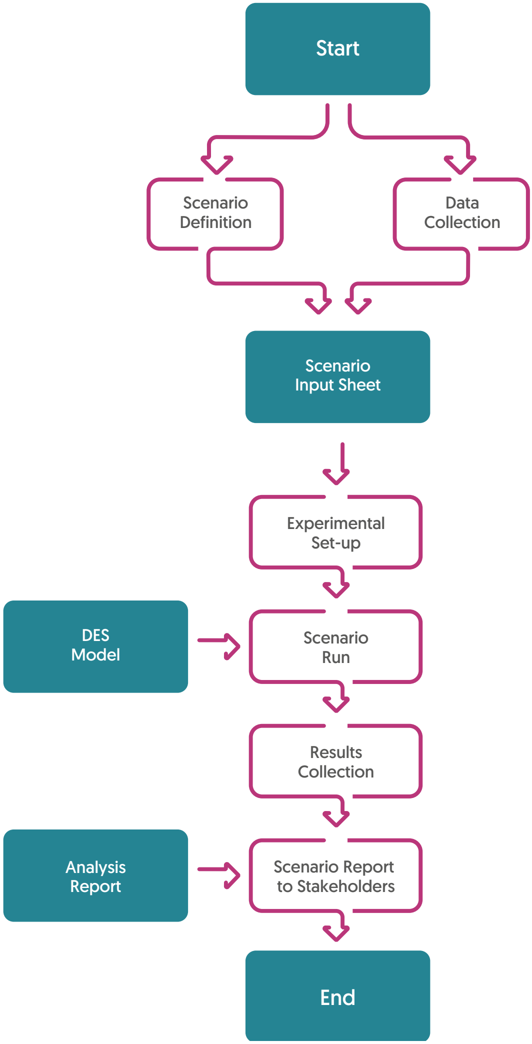

Figure 12. Key steps in the experimentation process

2 – Supply Chain Development

Multiple experiments can be undertaken to test different scenarios and they are normally measured against defined key performance indicators. For example, the end of build date is one of the main KPI for construction projects that is frequently tested, as delays may have legal and financial repercussions.

Each experiment can be further analysed in depth by looking at performance measures of the construction project for each scenario such as:-

- levels of stock required
- consumption profile of components throughout the build
- transport lead times
- predicted build period

2.8.2 MOJ Project – Supply Chain Model Analysis

Once the simulated Supply Chain Model was validated and verified a series of experiments was undertaken using Sensitivity Analysis and 'What If' Analysis to demonstrate the model capability. A number of scenarios were defined that addressed different business questions, and different supply chain configurations that the MOJ project team wanted to explore.

Figure 13 below is a summary of the scenarios considered:-

Scenario No.	Component	Hubs	Suppliers
1	Component A	A	1
2	Component A	0	1
3	Component A	A	1 2 3
4	Component A	0	1 2 3
5	Component B	B	4
6	Component B	B	4 5
7	Component C	0	4 5
8	Component D	A	1
9	Component E	0	1
10	Component E	B	1
11	Component F	C (used as assembly point)	4 5
12	Component F	A (fixed location)	1 2
13	Component A	A (different locations)	1
14	Component A	B	1 2 6
15	Component A	B	1 2 7
16	Component A	B	1 2 8

Figure 13. Scenarios considered

Note:
Component is a type of part supplied to a construction site, **hub** is a central point to which goods are delivered to and supplied from, **supplier** is a person, company or organisation that supplies goods to a construction site.

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In addition The Supply Chain Model experimentation was structured to enable the MOJ project team to define specific scenarios related to their live project and enable them, going forward, to run their own experiments to answer defined business questions. Experimentation consisted of:-

i) Sensitivity Analysis

The simulated Supply Chain Model enabled sensitivity analysis experimentation on the MOJ project supply chain. Sensitivity analysis was conducted to see how changes in the production rate of a key building component, affected the end of build date.

One of the scenarios selected for experimentation involved assessment of construction component production rates of between 50 and 350 per day and the number of days required to finish the build, as shown in Figure 14 below.

Experiment	Production Rate	Days to Finish Build
1	50	300
2	100	282
3	150	265
4	200	252
5	250	250
6	300	250
7	350	250

Figure 14. Example of one of the scenarios used in the sensitivity analysis

The results of the sensitivity analysis experimentation shown in the graph below, indicates that the optimum component production rate of 250 per day is required to achieve the minimum build time of 250 days. The chart shows that the impact of changing the rate between 50 and 200 is significant in relation to the build time, for example increasing the rate from 50 to 100 reduces the build time by approximately 20 days. Increasing the rate above 200 has some impact on the build time but this is insignificant. For a production rate higher than 250 there is no change to the build time.

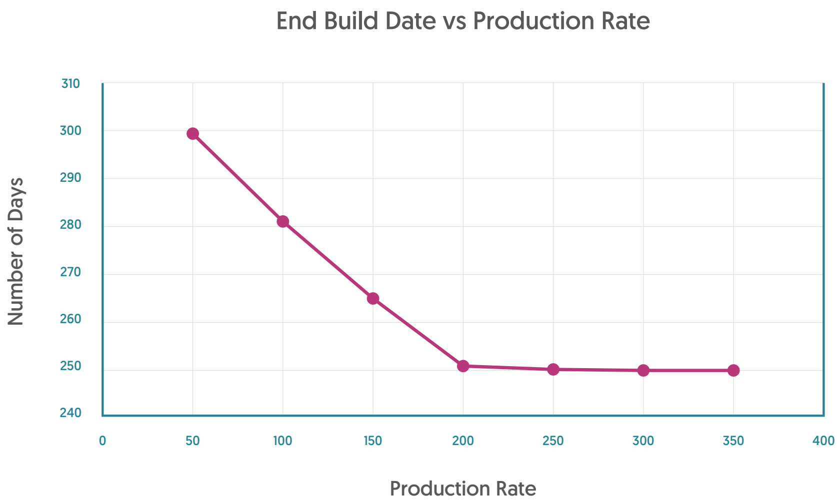

Figure 15. Example of sensitivity analysis-results

ii) Scenario 'What if' analysis

'What if' analysis was carried out for the MOJ project to determine the probability of meeting the target build date using an optimal component production rate of 250 per day.

'What if' analysis allows the impact of changes on the process or scenario to be assessed. It enables models to be run with different data and to compare different scenario results to the baseline. In order to represent uncertainty, a sampling technique such as Monte Carlo can be used and the simulation is repeated a number of times, e.g. 100 replications. The results of all the replications are collated into an 'S' curve as shown in Figure 16.

As can be seen, 55% of the 100 replications resulted in a build completion date of no more than 250 days. Therefore the probability of achieving 250 days is said to be 55% i.e. that there is a 55% chance of achieving 250 days. Figure 16 also shows 90% of the 100 replications resulted in a build completion date of no more than 255 days i.e. that there is a 90% chance of achieving 255 days.

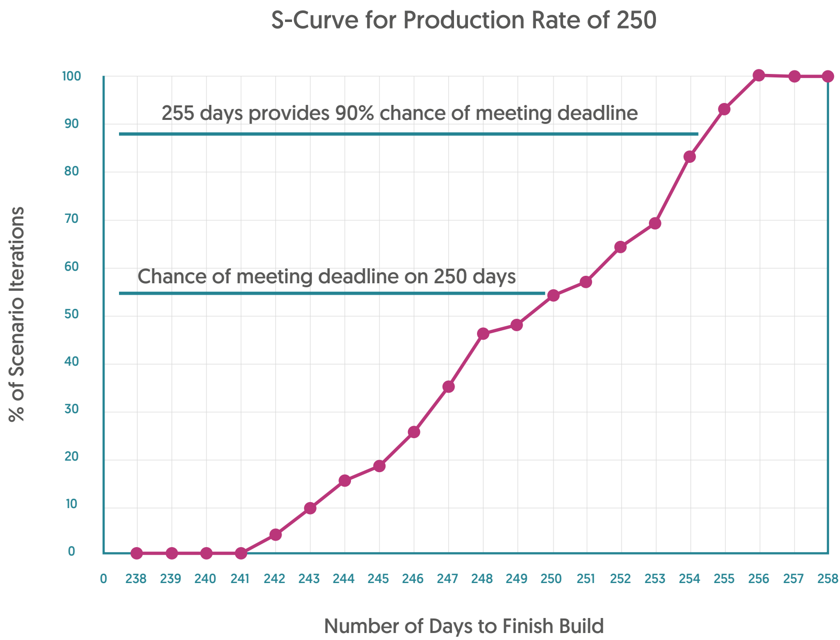

Figure 16. Example of 'What if' analysis assuming a production rate of 250

2.9 Results – Step 6 of the Supply Chain Development Process

2.9.1 Results (Generic Approach)

The simulation model provides results on the agreed KPI and the results are presented and explained to stakeholders in a numerical and visual way. Examples of results that can be provided include:-

- the number of days to complete the build
- the number of occasions when overtime is required on site
- number of deliveries
- transport lead time
- CO2 emissions
- amount and range of stock at different suppliers.

2.9.2 MOJ Project – Supply Chain Model Results

The results of the simulated Supply Chain Model were shared and reviewed as they were developed. The MTC gave a final presentation to the MOJ project team and all the results and KPI that were produced by the model were presented and explained.

2.10 Handover – Step 7 of the Supply Chain Development Process

2.10.1 Handover (Generic)

Once the Supply Chain Model has been developed it is handed over to the stakeholders and this is normally carried out face to face. Typically the handover ensures that:-

- input and results interfaces are usable to non-simulation experts
- the stakeholder is able to easily visualise results
- there is a user guide on how to run scenarios
- there is good understanding of what the model should be used for and what it should not be used for

2.10.2 MOJ Project – Handover of Supply Chain Model

A formal handover of the Supply Chain Model from the MTC to the MOJ project team was carried out and this involved a presentation which explained the features and operations of the model and also ensured that all requirements of the handover described above were met (see previous paragraph 2.10.1).

The simulated Supply Chain Model created, allowed multiple scenarios to be considered in support of strategic decision making and took into account variables with regard to the construction site, supply chain and transportation.

Sharing and involving the MOJ project team in developing the DES model during model development, helped them understand the Supply Chain Model as it developed, how it could align to current processes and also helped them to appreciate how modelling can inform strategic decision making about the supply chain early in the planning process.

The output provided by MTC to the MOJ project team was a simulated Supply Chain Model which can be used to define specific scenarios related to their live project and will enable them, going forward, to run their own experiments. It also provided:-

- an understanding of different supply chain configurations
- evaluation of impacts on supply chain performance
- minimisation of risks associated with new supply chain development
- value-added decision support for complex supply chain problems

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