DEPARTMENT OF MANAGEMENT SCIENCE

University of Strathclyde Business School

Rolls-Royce Production System: Gate 3 Digital Board

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MSc Data Analytics, 2018

Except where explicitly stated, all the work in this dissertation – including any appendices – is my own and was carried out by me during my MSc course. It has not been submitted for assessment in any other context.

Signed: ________________

Executive Summary

The objective of this project was to digitise the 'Gate 3' visual planning system in the 'Assembly and Test' business unit of the Rolls-Royce Inchinnan plant, which overhauls V2500, BR710 and Tay Aero Engines. This project is part of a wider effort to improve efficiency and effectiveness of information flows associated with planning activities, through the implementation of digital workplace strategies.

Two key research questions were identified for review: "How should data be modelled for planning and scheduling?"; and "How should the chosen models be implemented in an excel-based, VBA environment?". Based on the outcome of this research, a Physical Model, a Process Model, and an Activity Model were developed to explain the operations of Rolls-Royce Inchinnan 'Gate 3'. System requirements were also drawn up and documented to ensure that the final product met the client's expectations.

The 'Gate 3' visual planning system was coded, documenting key elements such as the static data model and critical path algorithm (used to calculate completion dates for assembly operations).

Training was given to users, and a manual drawn up. Following this, the system was implemented by the client, with feedback obtained 1.5 months after the digital tool went live being positive. No bugs were identified, and it was indicated that the tool was working correctly.

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Project Context/ Scene Setting

Section 1: Purpose & Background

This project was undertaken in association with Rolls-Royce Plc, a multinational company focused on the design, manufacture and distribution of power and propulsion systems for the civil aerospace, defence aerospace, marine, and nuclear industries, among others.

Working with members of their Inchinnan site the objective was to digitise a portion of the visual management planning system in the 'Assembly and Test' business unit, which overhauls V2500, BR710 and Tay Aero Engines.

This project is part of a wider initiative that has already seen the digitisation of other portions of the visual management planning system, enabling better control and issue management.

1.1. The Assembly and Test Business Unit

The 'Assembly and Test' business unit oversees the dismantling, inspection, maintenance, and re-assembly of three kinds of civil jet engines:

- The V2500 is the largest of the three, used on short to medium range commercial airliners, primarily the Airbus A320.
- The Tay is the oldest design, in service since 1988, and used on private jets such as the Gulfstream G350 and G450. Given its low volumes it was decided that it would not be in scope of this project.
- The BR710 design is based on the Tay. Conceived as a 'next generation' Tay engine, it is also used on private jets such as the Gulfstream G500 and G550 business jets.

The production operations at the Inchinnan plant are split into three 'Gates', each of which use visual management boards to facilitate oversight. All engines processed follow the same high-level procedure on the shop floor as follows (See Figure 1 for overview):

1. Gate 1 is responsible for induction of the engine into the production system, dismantling of the engine into individual components, inspection of individual components, and determination of conformance of individual components.
2. Gate 2 is responsible for refurbishing or replacing non-conforming parts. This is accomplished in one of three ways:
    a. New Supply (N/S) involves replacing components with new components sourced from suppliers.
    b. Supply Chain (SC) involves refurbishment of components by third party vendors.
    c. Component Repair (CR) involves inhouse refurbishment of components.

3. Gate 3 is responsible for re-assembly of individual components and preparing the engine to be sent for final testing.

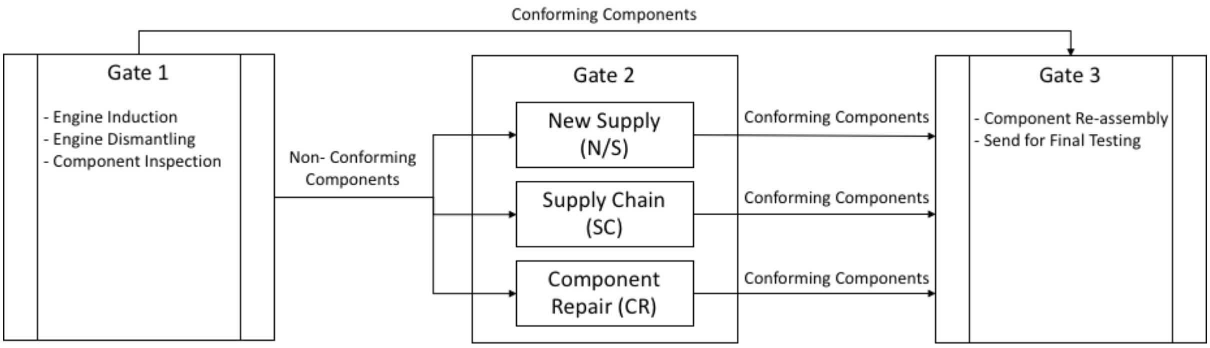


Figure 1 Overview of Assembly and Test Business Unit Shop Floor Operations

Following completion of production operations at the Inchinnan plant, oversight of: third-party testing; return of the engines to the customer; invoicing; and payment collection is also achieved through the visual management planning system, covered by designations 'Gate 4' and 'Gate 5'.

'Gate 1' and 'Gate 2' have already undergone digitisation of the visual management planning system.

1.2. Project Purpose

The purpose of this project is to undertake the digitisation of the 'Gate 3' visual management planning system, improving planning activities through efficient and effective information flows.

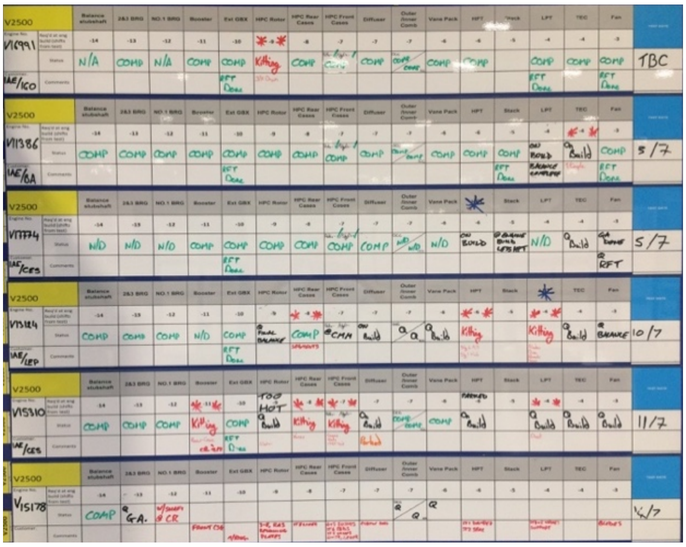
1.3. 'Gate 3'

Re-assembly and preparation for final testing in 'Gate 3' is carried out in the following high-level steps:

1. Module Build involves taking the individual components and assembling them into predefined sub-assemblies.
2. Engine Build is the final build step, where the modules, together with individual components that do not form part of the modules, are assembled in 'Bays' (production cells).
3. Final Testing Preparation involves packing the assembled engine for transport to a third-party test facility.

Planning and scheduling of production operations is overseen as follows:

- At the Unit Supervision Level, information on the build status of each 'Module' is used to determine schedules for 'Engine Build'. This is accomplished through the planning and scheduling visual management boards. As can be seen from the photos in Figure 2, currently these boards are maintained manually. Issues such as material shortages, resource constraints, and equipment outages are discussed at the boards in relation to priorities and work is planned accordingly. The detail of planning required increases from ‘Module Build’ to ‘Engine Build’. 'Module Build' is accomplished through a highly flexible manufacturing setup, where build operations don't need to be carried out sequentially. Therefore, resource constraints tend to have a reduced effect on the ability of ‘Gate 3’ to meet production requirements and can currently be managed through ad-hoc interventions from the unit supervisor without the need for detailed planning. In the case of ‘Engine Build’ the number of ‘Bays’ in-use are both a constraint and an indicator of plant utilisation used by upper management. Therefore, engine build resources in the form of availability/use of ‘Bays’ are tracked.



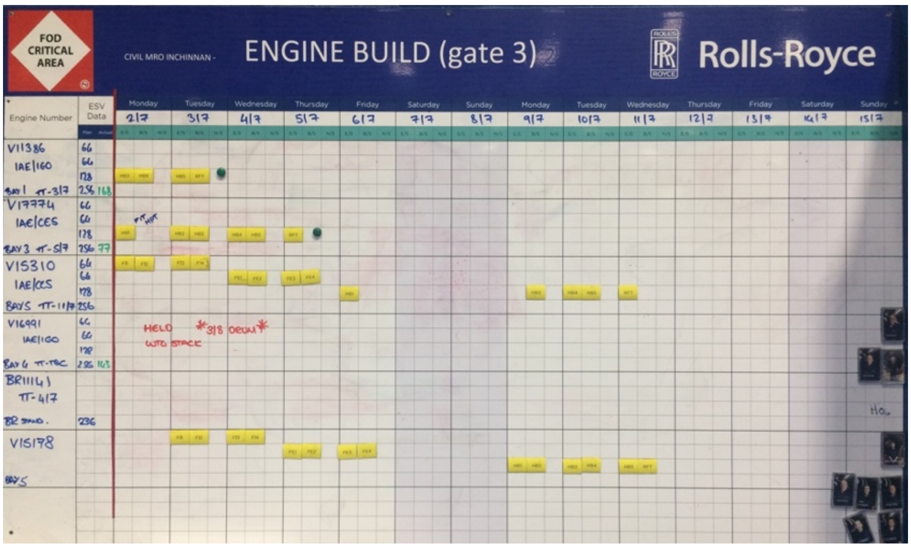


Figure 2 Planning and Scheduling Visual Management Boards (top: Module Build, bottom: Engine Build)

- At the <u>Production Management Level</u>, status of module build and engine build is communicated and discussed for each engine being processed by 'Gate 3'. Issues causing delays are also highlighted and tracked to completion. A separate production management board is used for this, shown in Figure 3.

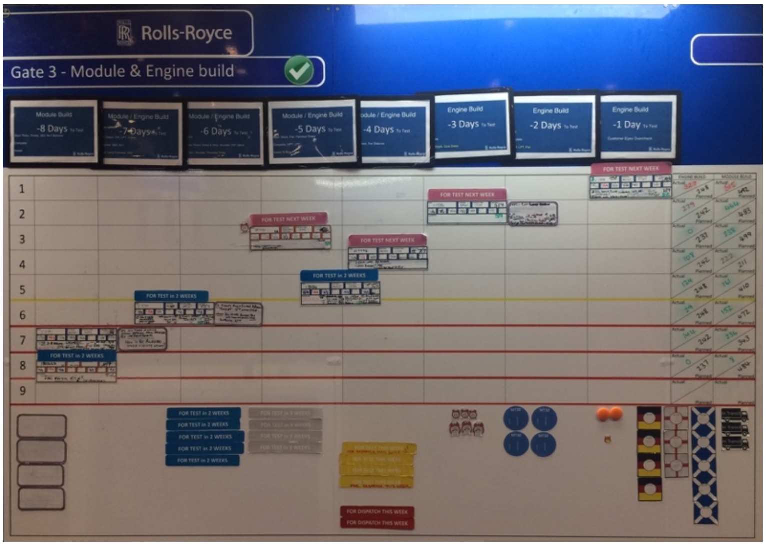


Figure 3 Production Management Board

1.4. Project Plan & Objectives

A project charter was drawn up in order to define objectives, scope, expectations, and timelines of the project. The project charter is a revisable document which helps give direction and sense of purpose to the project from start to end.

Of note with regards to the day-to-day management of the project were:

- The 'Milestone Plan', which was used to track timeline drift against an original plan.
- The 'Version Control', which was used to avoid aimlessness by recording any changes made to objectives, scope, or expectations.

The project charter was reviewed and updated as needed with the client.

1.4.1. Project Charter

Rolls-Royce	Project Charter				**Current Status:**	Completed
					Programme Title:	N/A
Project Title:	Rolls-Royce Production System: Digitalisation of Gate 3				**Workstream**	N/A
Start Date:	***Year***	*2018*	***Week***	*25*	**Facility/Supplier:**	Manufacturing

Current State / Problem
The Rolls-Royce engine overhaul production system at Inchinnan, Renfrew currently uses a third party Enterprise Resource Planning (ERP) software to plan activities. Based on plans modelled in this software, the expected lead time, from when the engine is inducted into Gate 1, until the 'Test Date', should be 55 days. Currently, due to a number of factors, the actual lead time is estimated to be 110 days. Therefore, by the time work is initiated in Gate 3, schedules drawn up on induction of the engine are no longer relevant, creating the following problems: 1. Target completion dates for process operations as per the ERP are unsensible, often in the past. 2. 'Latest Best Estimates' for completion dates must be calculated and tracked manually on a planning board as well as on a visual management board, based on issues encountered during assembly operations. 3. Key contributors towards delays cannot be identified, resulting in a perpetual fire-fighting state.

Future State / Aim
Digitisation of the Gate 3 planning board as well as the Gate 3 management board with the following expectations: 1.1 Wants to generate new target completion dates for each engine once the decision is made by management to commence work in Gate 3. 2.1 Wants to avoid updating the planning board and the visual management board separately with the same information. 2.2 Wants delays in 'Module Build' to be reflected in the plan for 'Engine Build'. 2.3 Wants to be able to change 'Engine Build' plan when issues arise during assembly. 2.4 Wants to identify pre-existing material shortfalls and automatically carry the data over when engines are transferred in. 3.1 Wants to at minimum archive issues for further analysis, if possible creating visualisations on the visual management board. X. Wants to show KPI's for the actual time taken for 'Module Build' and 'Engine Build' for each individual engine. X. Wants to show an overview of engine build status, including issues at 'Module Build' and 'Engine Build' level. X. Wants to be able to assign work to 'Engine Bays' based on manual arbitration during daily management meetings. Note that expectations marked X relate to functionality that already exists on manual boards and needs to be carried forward.

Performance Objectives	Q	C	D	L	P

In	Out
- Use of relevant data from Gate 2/Logistics for Gate 3 shortfall tracking. - Modelling of Gate 3 production system to an adequate level of detail.	- Reducing lead time. - Gate 1, Gate 2, Logistics. - Automated arbitration and scheduling. Work will not be optimised or assigned automatically. - Implementation of the system on the shopfloor. - Tay Engines. - Overtime Allocation. - Handling of parts designated as miscellaneous and non-modular. Thes parts have negligible effect on planning.

Project Leadership	
Sponsor (Rolls-Royce)	**Sponsor (Supplier)**
Scott McManus	*N/A*
Leader	**User**
Marc Rizzo	*Allan Gowans (management representative)*

Comments & Notes

Assumptions/Risks (A/R)
A: Human resources are not viewed as a constraint and therefore can be assumed to be infinite. **A:** 'Module Build' is accomplished through a highly flexible manufacturing setup, where build operations don't need to be carried out sequentially. Therefore it can be assumed that availability of equipment/space required for 'Module Build' has no effect on scheduling.

1.4.2. Milestone Plan

Rolls-Royce **Milestone Plan**

Schedule Issue Date	26/06/2018
Owner	Marc Rizzo

P = Planned Work / **A** = Actual Work / **M** = Planned Milestone / **C** = Completed Milestone / **D** = Delay

Workstream and milestones			2018				2018				2018				2018				2018				2018				End date
			25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	
Project	**Planning & Project Context**	Planned		M																							26
		Actual				C																					28
Project	**Production System Modelling**	Planned			M																						27
		Actual					C																				29
Project	**Programming**	Planned							M																		31
		Actual									C																33
		Planned																									
		Actual																									
Thesis	**Planning & Project Context**	Planned		M																							26
		Actual				C																					28
Thesis	**Introduction**	Planned				M																					28
		Actual																							C		47
Thesis	**Literature Review**	Planned													M												37
		Actual														C											38
Thesis	**Methodology**	Planned															M										39
		Actual																		C							42
Thesis	**Analysis**	Planned																	M								41
		Actual																				C					44
Thesis	**Discussion & Conclusions**	Planned																			M						43
		Actual																					C				45
Thesis	**Corrections & Final Formatting**	Planned																					M				45
		Actual																							C		47

1.4.3. Work Breakdown

Rolls-Royce	Work Breakdown Structure	Project	Rolls-Royce Production System: Digitalisation of Gate 3
		Leader	Marc Rizzo

Planning and Project Context Output 1: Project Charter Output 2: Project Context/Scene Setting Draft	•Formulate project plan/expectations with Client •Drafting of Project Context •Meeting with Superviser to Review
Production System Modelling (ANSI/ISA 88 & ANSI/ISA 95) Output 1: Physical Model Output 2: Process Model Output 3: Activity Model Output 4: System Requirements	•Research production system modelling methodologies •Generate requirements for expectations set out in this project charter
System Design Output 1: Static System Model Output 2: Critical Path Algorithm	•Transform available data on Gate 3 production system into usable formats- object oriented and relational database sructure •Research method to calculated expected completion dates for sequential jobs
Programming Output 1: User Manual	•Iteratively combine Production System Model and User Interface Design into a working system.

1.4.4. Version Control

Version	Date	Updated by	Comments
3.1	26/06/2018	M. Rizzo	New Document
3.2	29/06/2018	M. Rizzo	- Tay engines and overtime allocation specified as out of scope - Addition of comment related to customer target date
3.3	06/07/2018	M. Rizzo	- Handling of parts designated as miscellaneous or non-modular specified as out of scope.

Section 2: Research Objectives

A formal list of client expectations was drawn up during project planning. In order to take those expectations and turn them into suitable outcomes, research was required into three areas:

1. Visual Management principles and best practices on their implementation.
2. Modelling of Production Systems for planning and scheduling.
3. Implementation in Visual Basic of data models.

This section will show how these broad areas were treated in the context of this project and provide questions to be answered in the client report.

2.1. Visual Management

Visual management is a field that has its roots in lean manufacturing. The lean philosophy is concerned with reducing non-value-added activities (also referred to as waste, and motion) throughout the enterprise (Six Sigma Material, 2018). Visual devices support the lean philosophy by improving communication within the business. Visual devices, should answer the questions "What do I need to know?" and "What do I need to share?" (Galsworth, 2017). By tackling these questions transparency within the organisation is increased and time wasted searching for answers to recurrent information deficits is reduced.

One of the foremost experts on visual management, Dr. Gwendolyn Galsworth, in her book, "Visual Workplace: Visual Thinking" (Galsworth, 2017), mentions a 'Ten-Doorway Model' to create a workforce of visual thinkers. Figure 4 gives an overview of each of these doorways, with the category of visual function in red and the individuals responsible in yellow. Of primary importance to this project is doorway 3, which is concerned with visual scheduling and visual displays.

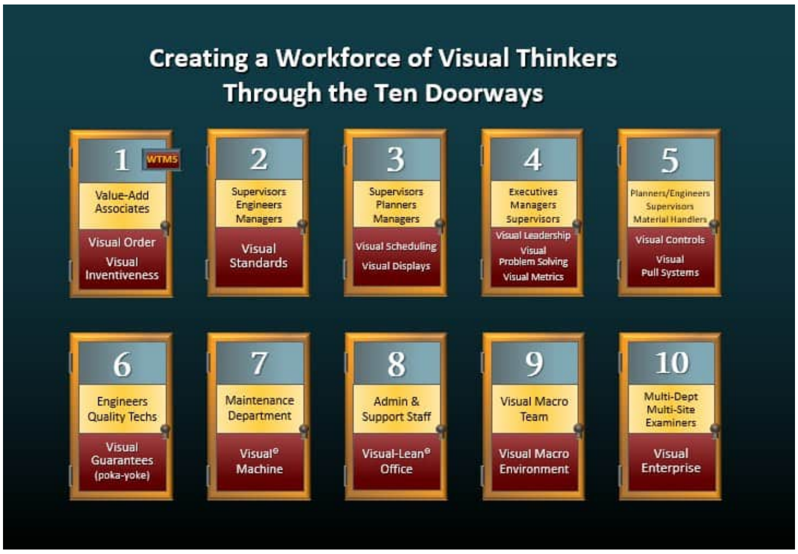


Figure 4 The Ten Doorways into a Visual Workplace (Galsworth, 2017)

Dr. Galsworth also talks about the importance of the "I-Driven approach" (Galsworth, 2017) to workplace visuality. Each individual in the enterprise must understand and drive their own solutions to the information deficits related to the doorways they are responsible for.

This project is being undertaken in an environment with well-developed visual scheduling mechanisms:

- Standards for conveying information digitally have already been established in 'Gate 1' and 'Gate 2'.
- The 'I' in 'Gate 3' is the unit supervisor, who has already developed the need to know and need to share iteratively through the manual boards, with input from managers and value-add staff. Figure 5 gives an overview of the 'need to know' and 'need to share' for 'Gate 3'.

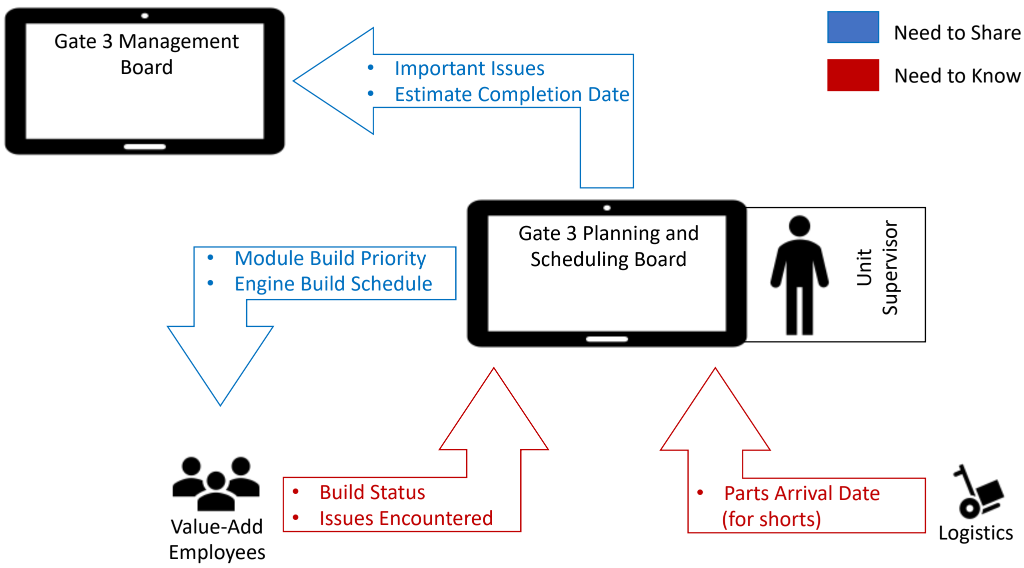


Figure 5 Unit Supervisor Need to Know and Need to Share

The well-developed nature of the visual scheduling mechanisms and associated visual standards at Rolls-Royce Inchinnan mean that no further analysis is required in terms of information deficits and best practices for information portrayal.

2.1.1. Modelling of Production Systems

Rolls-Royce currently utilise a third-party Enterprise Resource Planning (ERP) software provided by 'SAP' (SAP, 2018) in order to model their production system and help in meeting production management challenges. ERP systems are an evolution of Manufacturing Resource Planning (MRP II) systems. The purpose of MRP II systems is to "calculate material requirements precisely with detailed capacity planning, scheduling and shop floor control"

(LaCroix, 2009). ERP builds on this concept by introducing an open, modular approach, where each business function is incorporated for analysis.

As one gets closer to the target completion date for a piece of work, there is an increased need to make corrective decisions faster and as a function of available resources. However, ERP systems require large amounts of data, therefore "they can't meet the need to plan, execute, and redirect manufacturing processes in real time" (Gumaer, 1996). At Rolls-Royce, models developed through ERP are rendered useless due to the unpredictability and dynamism associated with production and distribution activities.

The concept of the Manufacturing Execution Systems (MES) was developed to fill mitigate the shortcomings of ERP systems. Dr. Ing Jurgen Kletti, in his book "Manufacturing Execution Systems- MES" (Kletti, 2007), explains how ERP systems are useful for long-term (weeks/ months) and medium-term (days/weeks) planning associated with corporate management, rough production planning, and load planning. Automation is also implemented at the value-add level of the organisation through standard procedures and machine settings. The MES sits in between these layers, linking them vertically with situation- and technology- oriented aids that support production management decisions at shift intervals (see Figure 6).

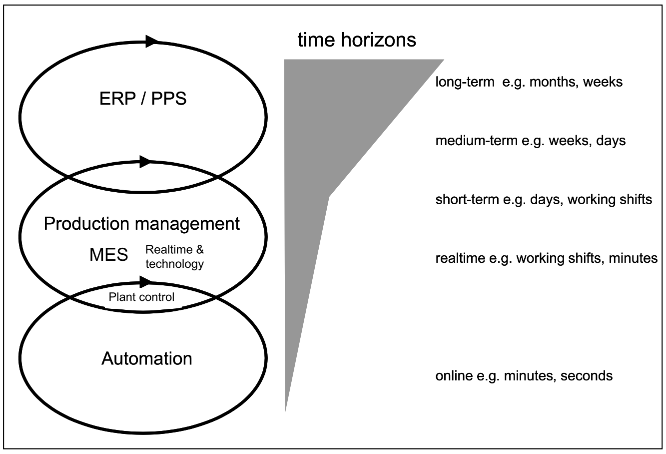


Figure 6 Planning levels and associated length of their Planning Cycles (Kletti, 2007)

Similarly to the ERP model, the MES model is modular in nature. In its latest interpretation of the MES model, the Manufacturing Execution Solutions Association defines a number of functional groups required that should be combined for an effective MES solution at the 'manufacturing/production operations level' of the enterprise (MESA International, 2018). Verein Deutsche Ingenieure (VDI), the association of German engineers, take a slightly different approach in their definition of what makes an effective MES solution. They ask the question 'what should the system do?' rather than the question 'what should it have?'. This results in a list of tasks that is more intuitive and concise (Verein Deutcher Ingenieure, 2007):

- Detailed Scheduling and Process Control
- Equipment Management
- Material Management
- Personnel Management
- Data Acquisition
- Performance Analysis
- Quality Management
- Information Management

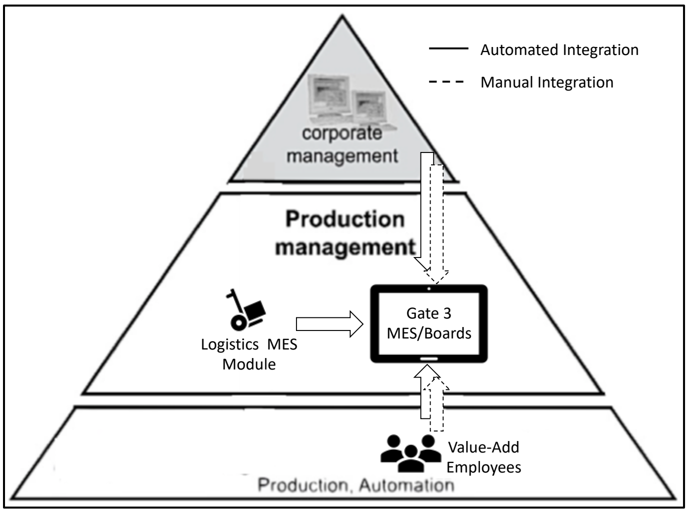


Figure 7 Integration Overview of Gate 3 MES/Boards

The Planning and Scheduling Board, and Management Board for 'Gate 3' are essentially visual implementations of an MES module. As shown in Figure 7, the boards capture data from the Logistics MES, from value-add employees, and from the ERP (Data Acquisition) and use this information (Information Management) to support Detailed Scheduling, and Performance Analysis.

The goal of MES is normally full horizontal and vertical integration, which in terms of Figure 7 would mean two-way automated data flows throughout the organisation levels. However, the expectation of this project was the implementation of an open loop visual planning tool, requiring only a one-way information flow into the 'Gate 3' MES/Board. Note also that some data will be entered manually into the MES/Board by users.

An overview of the data treated across the planning cycle levels is given in Table 1.

Table 1 Treatment of Data for 'Gate 3' MES/Board

Data Description	Planning Level Origin	Method of Integration	Used For
Target KPI's	Corporate Management	Manual- User to populate	Performance Analysis
KPI Actuals	Production, Automation	Manual- User to populate	Performance Analysis
Rough Production Plan	Corporate Management	Manual- To be remodelled in Gate 3 MES based on production plan in ERP	Detailed Scheduling

Data Description	Planning Level Origin	Method of Integration	Used For
Module Build Status	Production, Automation	Manual- User to populate status and issues	Primarily Detailed Scheduling *Note: Archiving of issues will allow for retrospective performance analysis*
Engine Build Status	Production, Automation	Manual- User to populate status and issues	Primarily Detailed Scheduling *Note: Archiving of issues will allow for retrospective performance analysis*
Parts Arrival Date	Production Management	Automated- Pulled from Logistics MES Module	Detailed Scheduling

2.1.1.1. Research Questions

The following research question will be included in the client report:

- Research Question 1: How should data be modelled for planning and scheduling?

This question will be tackled with a focus on MES implementations. The digitisation being undertaken of 'Gate 3' does not qualify as a total implementation of an MES solution since it does not carry out all the tasks required of such a system, and integration will be one-way. However, if viewed from a modular perspective, the data requirements and interfaces involved with the 'Gate 3' board are equivalent to those of the planning and scheduling functional group of an MES. It therefore follows that the project will benefit from implementation of similar models to those used in MES.

2.1.2. Implementation in Visual Basic

An important distinction exists between 'data' and 'information'. The production system model is an alphanumeric representation of the production system, it is data. "When data is process, interpreted, organised, structured or presented so as to make it meaningful or useful" it becomes information (Diffen, 2018). The visual management boards will accomplish this transformation by portraying the production system data in a format that increases cognition. There are various tools used to support data visualisation such as Google Charts, Modest Maps, Visual.ly, Tableau, d3.js, among others (Mcleod, 2014). Further still, open source programming languages such as 'R' and 'Python' have packages offering good data visualisation options.

Rolls-Royce Inchinnan have an ecosystem of excel workbooks which are currently maintained and used by individuals at the production management level. In the case of 'Gate 1' and 'Gate 2' Visual Basic for Applications (VBA) was used in order to turn this data into visual information, which is communicated on digitalised boards. They are expecting a similar solution for 'Gate

3’ and given the experience of the organisation with VBA and excel-based data management they envisage that the implemented solution use the same tools, allowing them to maintain and build on the solution as necessary with their in-house expertise.

2.1.2.1. Research Questions

The following research questions will be included in the client report in order to understand how to effectively implement the production system data model in an excel-based, VBA environment:

- Research Question 2: How should the chosen models be implemented in an excel-based, VBA environment?

Client Report

Section 1: Introduction

Today, adoption of digital workplace strategies to improve business processes is a competitive necessity. Sixty-nine percent of 800 business and IT leaders from fifteen countries surveyed in 2017 confirmed that they implement workplace technology in order to effect business process change (Dimension Data, 2017).

Rolls-Royce Inchinnan have started a process of digitisation of their visual management system with a view to improve production planning and information flows within the 'Assembly and Test' business unit, which overhauls V2500, BR710 and Tay Aero Engines. Having already benefited from the digitisation of 'Gate 1' and 'Gate 2', the project undertaken, and documented in this report, will continue the process of digitisation for 'Gate 3', which handles re-assembly of the engines and preparation for final testing.

The ubiquitous nature of computers and the low-cost of data storage mean that a large amount of digital data is generated and stored within modern organisations. The challenge for most organisations becomes devising ways to integrate these data streams in support of their business processes.

In industrial environments, Enterprise Resource Planning (ERP) systems primarily meet the integration needs of corporate management and rough production planning activities. However, ERP's are not well-equipped to support detailed planning and day-to-day production management. In order to integrate the various data streams required for detailed production planning and scheduling, the concept of the Manufacturing Execution System (MES) was developed. The MES is essentially a modular software designed to collect and interpret live data in support of day-to-day production management.

The digital boards being developed by Rolls-Royce Inchinnan are an implementation of a MES, where data from the Logistics MES, from employees, and from the ERP is captured and used to support Detailed Scheduling, and Performance Analysis.

This report will give an overview of the research carried out and principles used in order to digitise the 'Gate 3 Management Board' and the 'Gate 3 Planning and Scheduling Board' of the Rolls-Royce production system as follows:

- Previous academic work carried out to answer the key research questions identified for this project will be covered in Section 2: Literature Review.
- A description of approaches used to develop the digital boards and associated outcomes will be given in Section 3: Methodology.

- A requirements and traceability matrix, as well as instructions for use are provided in Section 4: Implementation and Testing.
- Critique of the solution implemented and recommendations for further work conclude the report in Section 5: Discussion and Conclusions.

Section 2: Literature Review

2.1. How Should Data be Modelled for Planning and Scheduling?

Price et al. postulated that methodologies for the modelling of computer-based production-planning systems *"cover two different dimensions: (i) determination of the functions to be carried out by the system; (ii) determination of the data and data structures required to support these functions."* (Price, et al., 1992) Although written over twenty-five years ago, their statement is true of all manufacturing decision support literature reviewed as part of this project.

This project involved the digitisation of a manually maintained system. Therefore, the user had a very well-formed idea of the form the system should take and therefore the functions to be carried out could be identified as expectations.

Determination of the data and data structures required is achieved by answering the question 'How should Data be Modelled for Planning and Scheduling?'.

The classification of the boards being digitised as Manufacturing Execution Systems (MES) has been treated in previous sections. Comprehensive standards exist that specify data structures required for Manufacturing Execution System (MES). Use of these standards as reference models is a good starting point for implementation of an MES (Rajesri & Krisna, 2016). As explained in the standards, every enterprise is unique and may exhibit deviations from the models set out. However, they are a good starting point for the establishment of system requirements.

ANSI/ISA-88 (ANSI/ISA, 2010) is a four-part standard that addresses terminology and concepts related to batch control. Industrial processes can be classified as process (of which batch processing is a subcategory) or discrete. Discrete manufacturing involves the physical transformation and/or assembly of distinct units into a final assembly. Process manufacturing involves irreversible transformation of a number of constituents into a final product based on a formula. Although the 'Gate 3' production system is not a batch processing manufacturing setup, the concepts developed for batch control in the ANSI/ISA-88 standard can be used to implement structured methodologies and programming concepts for discrete processes (Zaun & Maki, 2006). The idea of modelling the production system at multiple levels is universal to all manufacturing processes. This is accomplished by considering:

1. What you have in the plant (the physical/ equipment model)

2. What you would like to produce (the recipe)
3. How you will organise yourself to carry out production (the activity model)
4. What records need to be kept (production records).

ANSI/ISA-88 considers system needs related to monitoring, controlling, sensing, and manipulation of the physical process. The expectations set out for this project were more related to the management of workflows, for which ANSI/ISA-95 (ANSI/ISA, 2013) is better suited. Bianca Scholten, in her paper "Integrating ISA-88 and ISA-95" (Scholten, 2007), shows how from an academic standpoint both standards are similar, containing the same four models/concepts listed above. The main differences being that:

- ANSI/ISA-88 uses terminology directed towards batch processes, while ANSI/ISA-95 uses more generic verbiage that can be applied to any type of process.
- The activity model developed in ANSI/ISA-88 focuses on the control of batch processes, without considering production information management, recipe management and production planning/scheduling in detail.

ANSI/ISA-95 and the equivalent ISO 62264 are five-part standards that are more appropriate for use in this project. As seen in Figure 1, they treat the information required in order to implement an effective Manufacturing Execution System (MES) at the production management level of the organisation. Part 3 of these standards clearly sets out the interactions between the various activities associated with manufacturing operations management and what information flows are necessary between the various components. Part 2 of these standards establishes what kind of information is required when modelling the process, the materials, the equipment, and other resources of a production system, as well as understanding how these elements should be linked in the model.

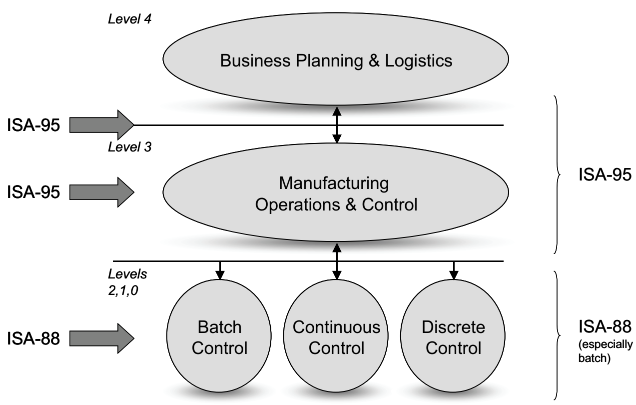


Figure 1 Comparison of Scope and Focus of ISA-88 and ISA-95 (Scholten, 2007)

2.1.1. ANSI/ISA-95.00.03- Activity Models of Manufacturing Operations Management

"Manufacturing operations management is subdivided into four categories: production operations management, maintenance operations management, quality operations management, and inventory operations management, as shown in shaded areas in Figure 2”. (ANSI/ISA, 2013)

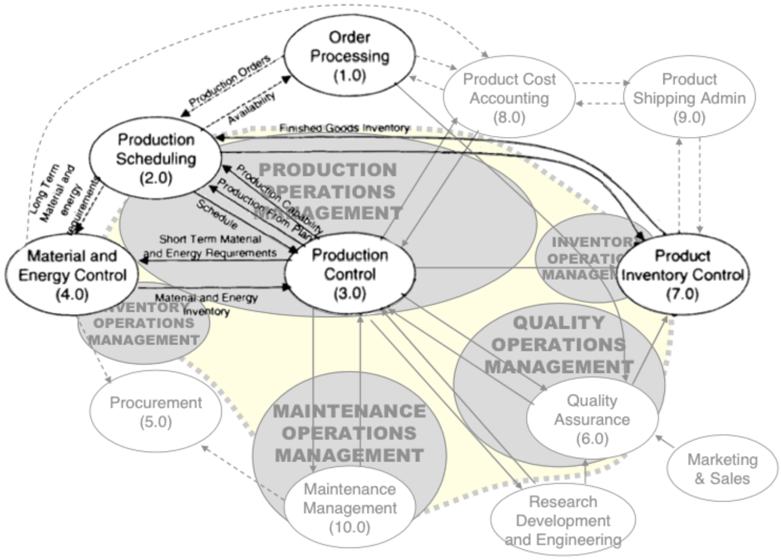


Figure 2 Manufacturing Operations Management Model (functions that are not relevant to this project have been de-emphasised)

The objective of this project is the creation of a digital board to support planning and scheduling. It therefore follows, that as shown diagrammatically in Figure 2, production operations management is the manufacturing operation that must be considered. ANSI/ISA-95.00.03 proposes a generic manufacturing operations model template, which it then applies to the specifics of production operations management (see Figure 3).

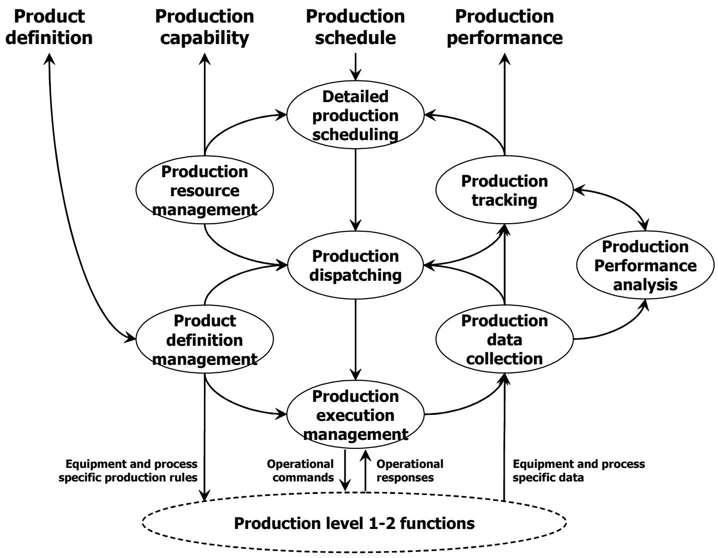


Figure 3 Activity Model of Production Operations Management (ANSI/ISA, 2013)

Product definition management involves the setting up of production rules that instruct the manufacturing operation on how to produce a product. Production resource management involves activities that manage information related to resources such as equipment, people, and materials. Detailed production scheduling involves optimising resources in order to meet the objectives set out by the production schedule, as well as tracking of actual production against targets. Together, information from these three activities are used in order to ascertain which jobs should be prioritised ('dispatched') at a particular moment in time. Finally, production execution management oversees implementation, making corrections to the plan as necessary. There is also a feedback loop in the form of production data collection and production tracking, where among others, data related to process status and unanticipated events is collected so that appropriate responses can be initiated.

The digital board for 'Gate 3' sits within the production execution management activity but provides information to and requires information from other activities as described above.

2.1.2. ANSI/ISA-95.00.02- Object Model Attributes

ANSI/ISA-95.00.02 suggests how data can be modelled to support the needs of production scheduling (see Figure 4). This model was used in order to identify critical data for the implementation of the planning and scheduling visual board. Analysis of how this critical data is treated within the Rolls Royce Production digital ecosystem determined how the data was accessed or generated.

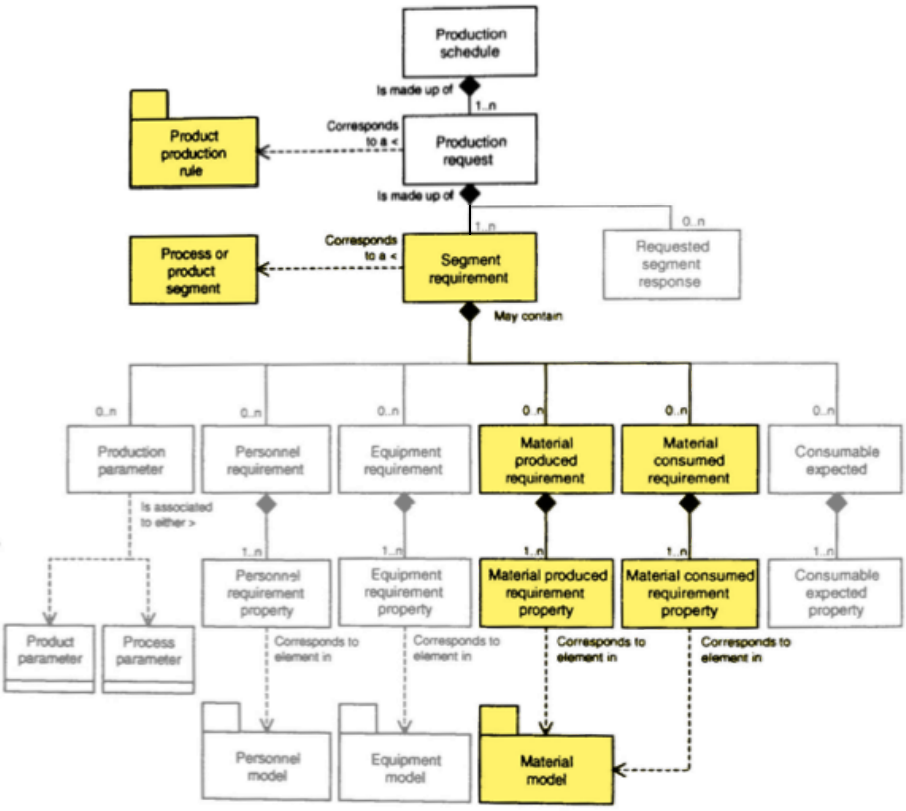


Figure 4 Production Schedule Model (entities that are not relevant to this project have been de-emphasised)

A production schedule is a combination of production requests, which are requests for the production of a product, with associated target dates and identification numbers. The product production rules determine the sequence of process steps (segments) that must be carried out in order to manufacture the product and are used to generate segment requirements that correspond to an identified process segment. The segment requirements can be subdivided into a number of different sub-categories. Given that the expectations for the visual board are that only material availability would be considered when generating the plan, only the material produced requirement and material consumed requirement are relevant, both of which are based on the material model, which is essentially the Bill of Materials (BOM) for the product.

The importance being given to the consideration of materials in the planning functions of the Rolls Royce Production System, rather than other aspects, stems from the fact that material unavailability is viewed as the primary disrupter of production. From an academic standpoint, the importance of linking the BOM and routing information in a single structure to support planning activities is argued by Hastings and Yen in their paper, “Bill of Manufacture” (Hastings & Yen, 1992). The Bill of Manufacture (BOMfr) provides a standard resource for planning, resulting in an integrated production and materials plan. The yellow elements of the production schedule model in Figure 4 make up the BOMfr, with only two additional elements being required in order to accomplish the planning and scheduling function.

However, the iterative nature of the development of manufacturing planning tools usually leads to an evolution over time, brought about by experience of using the system. Therefore, although it is currently the case that only material availability is considered when generating the plan, similar computer-based production planning tools allow for the user to extend the models to support planning of other resources as the need is recognised. (Price, et al., 1992)

2.2. How should the chosen Models be Implemented in an Excel-Based, VBA Environment?

The digitalisation of the planning and scheduling board undertaken in this project involves the use of data as described in section 2.1. Various data management methodologies have been developed to facilitate the storage and retrieval of digital data, each having advantages and disadvantages that make them suited for particular applications.

Halsall and Price suggest a hybrid system involving the use of both a relational database and an object-oriented database to meet the data management requirements of production planning and scheduling (Halsall & Price, 1999). The solution put forward involves a ‘planning by linking’ approach, where resources are matched to process steps to build up object-oriented BOMfr's for each individual engine, when required, from data held in relational databases (see Figure 5).

To accomplish this Halsall and Price suggest the use of data organised into three tables, out of which BOMfr's can be generated for individual products as necessary:

1. Item Table: data on end-items, subassemblies and component parts, and their inter-dependencies.
2. Item_Operation Table: a list of operations required to make each item and items required for each operation
3. Operation Table: a list of operations and sequence information that can be carried out at the plant. Operations can be combined into higher level processes as necessary.

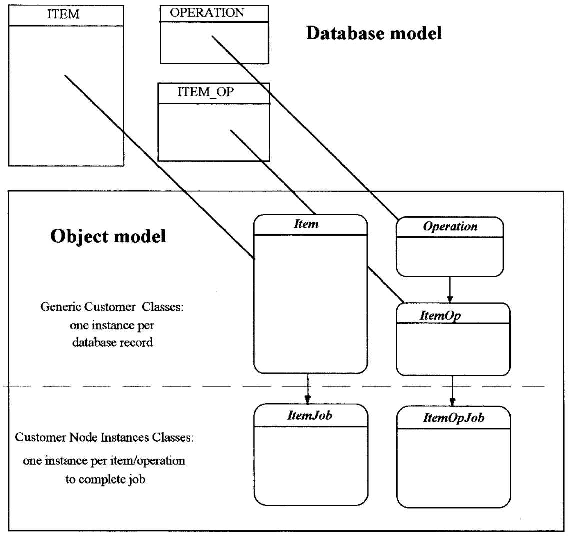


Figure 5 "For each of the operation steps or items identified, a corresponding ItemOpJob or ItemJob instance is created and held in the form of a dictionary or map." (Halsall & Price, 1999)

The BOMfr is made up of a list of materials required to build the item (ItemJob instances) and a list of operations required to build the item with links to material requirements (ItemOpJob instances). It holds information related to processing sequences and resources generated from the above tables, as well as scheduling and manufacturing status information. The parent-child nature with which items and operations are handled make an object-oriented environment simpler since it is possible for lower-level entities to inherit properties from higher-level entities.

During planning and scheduling an 'activity-on-node network' can then be constructed, with items or operations each being assigned a node. Calculations are carried out at the lowest item and operation level but can be aggregated to give higher level overviews as necessary.

2.2.1. The Relational Database

The efficient nature of relational databases in terms of data storage make them an attractive option for handling production management data. They are made up of a set of tables, containing a number of attributes (organised into columns) and instances (placed in rows), with a single value being placed at the intersection between row and column. Each table has a set of values that are unique to the row, known as the primary key. The primary key is used to identify an instance in the table. (Rouse, 2018) Constraints and rules can be placed on the entry and removal of data in order to ensure maintenance of its integrity. A standard programming language, known as Structured Query Language (SQL) can be used to access and manipulate relational databases.

The use of relational database concepts fits well into the requirements of this project. Data presentations in table format are widely used and can therefore be easily understood by any user of the digital board. Moreover, excel stores data in this format.

2.2.2. The Object-Oriented (ANSI/ISA, 2013) Database

“Object-oriented datasets are not necessarily standalone databases or replacements for relational databases. They are database management systems that serve as a complement or enhancement to relational databases.” (Brown, 2018)

The use of sub-classes and the ability of object-oriented databases to handle multi-valued attributes makes them helpful when building a framework to support planning and scheduling. Information is represented as objects in these databases. Each object has a set of properties, to which multiple values can be assigned. Various concepts such as abstraction, polymorphism, encapsulation, reflection, and inheritance are then applied as required to these objects.

Of interest to this project were the concepts of inheritance and reflection. Inheritance enables new objects to take on the properties of existing objects. Therefore, for example, engine number 12345 is an engine of type ‘BR710’, therefore it must inherit the segment requirements of a ‘BR710’ engine. A subclass or derived class (engine number 12345) inherits the properties of the superclass or base class (‘BR710’), creating a hierarchy. (Yaiser, 2012) “Reflection is the ability of a computer program to examine, introspect, and modify its own structure and behaviour at runtime” (Forman & Forman, 2004). Therefore, for example, reflection would allow for the creation of a new plan when a new engine enters the production system, without the need for further coding.

VBA is an object-based language, not an object-oriented language. Therefore, although it supports the creation and handling of objects in its framework, it does not support all of the concepts necessary to achieve object-oriented programming. Both reflection (Graff, 2011) and inheritance (Rubberduck VBA, 2015) are not supported in VBA.

In order to take advantage of object-oriented data structures for planning and scheduling, it is possible to turn spreadsheets into object-oriented models (Boutin & Matta, 2013). Boutin and Matta show how by anchoring each row with what they define as the key, it is possible to store data in an object-like manner. This is accomplished by assigning the first row of the sheet unique class or property names. Each new row after the first row represents a new relationship between the objects in each class. Different excel sheets can be used to store different relationships. If multiple values must be assigned to the same property, a ";" delimiter is used to establish the start/end of each value. See Figure 6 for a visual representation of this.

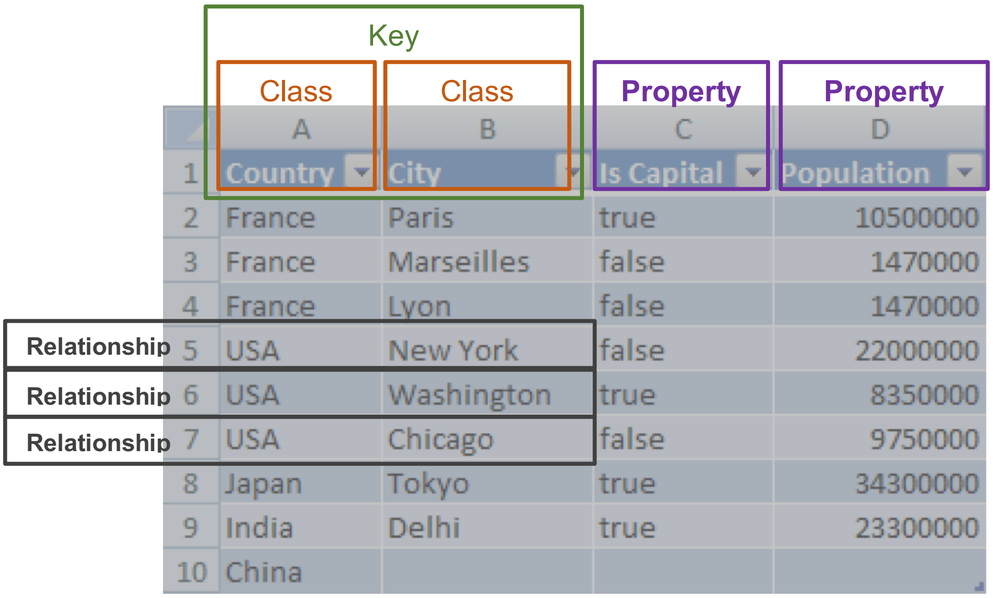


Figure 6 Example of Turning a Spreadsheet into an object-oriented model

The main concepts from Boutin and Matta's work relevant to this project have been described in this report and summarised diagrammatically in Figure 6. For further details on the concepts developed the reader is referred to their paper (Boutin & Matta, 2013).

Section 3: Methodology

3.1. Design and Implementation of Manufacturing Execution Systems (MES)

Rajesri et al. propose a methodology for MES design involving two main steps (Rajesri, et al., 2014):

1. Initial Assessment involves determination of: the implementation scope; analysis of the current system; determination of improvement objectives and system requirements.
2. MES Design involves generating databases, information flows, and programming logic to represent the models and meet the requirements produced during initial assessment.

The above will be discussed further in this section. Following the design phase, implementation of MES should follow a further three steps (Rajesri & Krisna, 2016):

3. Configure, Build and Test involves coding the MES as per the design specifications, and ensuring that the MES performs as expected.
4. Deployment involves training and troubleshooting under the conditions the system is expected to work in.
5. Operation involves putting the system into operation and post-project support to help users work with it.

Testing and deployment will be discussed later in this report. Given that the client did not have the necessary equipment to put the system into operation before the end of the project, step five is out of scope.

3.2. Initial Assessment

Initial assessment involved taking the client's expectations and deriving more specific, measurable requirements. In order to achieve this an understanding of the physical, process, and activity models of the organisation is needed.

3.2.1. Physical Model

The physical model describes how the equipment is organised in order to achieve the enterprise goals. Of particular interest to this project was the modelling of the 'Gate 3' production area. The production area is comprised of six 'Module Build' cells, set up to carry out specific operations as indicated in Figure 7, and six 'Engine Bays', capable of assembling engines as indicated in Figure 7. With the exception of ‘Module Build Cell 2’ and the fact that intermediate assemblies (modules) need to be prepared before being passed on to final engine build, the physical model exhibits very few dependencies. This results in a highly flexible set up, where as long as material is available, operations in one area do not need to wait for operations in another area to be completed.

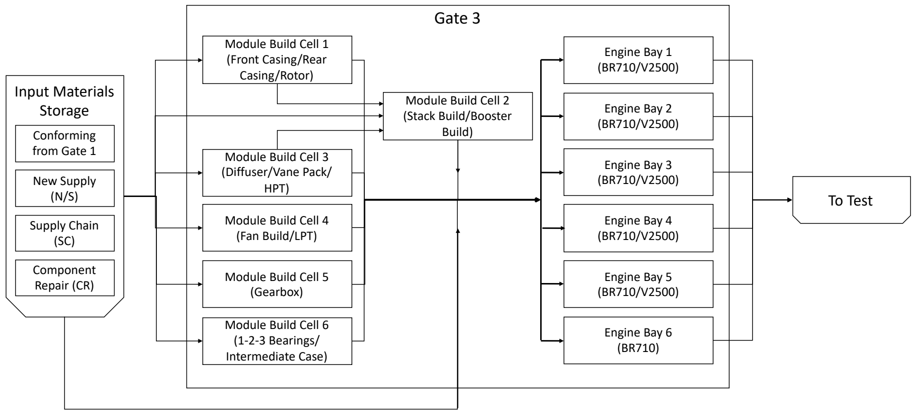


Figure 7 'Gate 3' Physical Model

With input from the client, it was concluded that the physical model afforded sufficient flexibility and capacity so as not to require further consideration in the digital planning tool being developed. It should however be possible to track and record physical resource constraints when they occur to help in identification of bottlenecks if these are present.

3.2.2. Process Model

The process model describes the work that interacts directly with the product, converting it from raw material into finished goods. No consideration is given to other activities undertaken in support of this conversion, such as planning. These support activities are instead considered in the activity model, which will be handled separately in the next section.

Procedure Function Charts (PFC), as described in (ANSI/ISA, 2001), were used in order to represent the process model visually. The fact that the PFC methodology prescribes methods for describing resource elements (such as material) separately from equipment procedural elements means that it is well suited to the needs of representing manufacturing processes. Moreover, it also prescribes methods for visually representing the multiple level structure that exists in a manufacturing environment. For example, the combined processes that occur within ‘Gate 3’ in Figure 7 take all raw materials and output a finished engine for test. However, further detail related to the what occurs within an engine bay may be necessary. PDC allow for this.

This project is concerned with the reassembly of V2500 and BR710 engines at 'Gate 3'. Refer to Figure 8 and Figure 9 for PFC of each of the engines. Process steps marked in grey will be tracked on the planning and scheduling board.

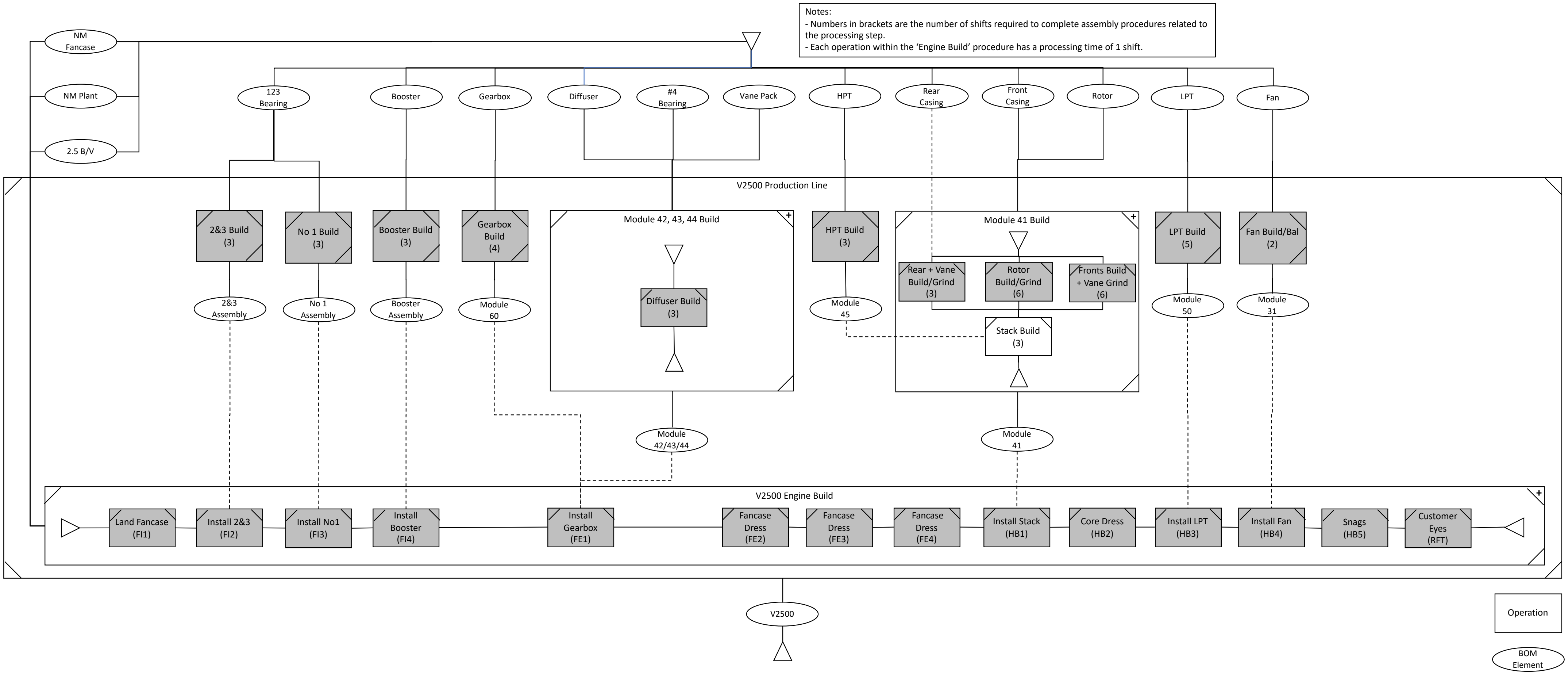


Figure 8 Process Function Chart for V2500

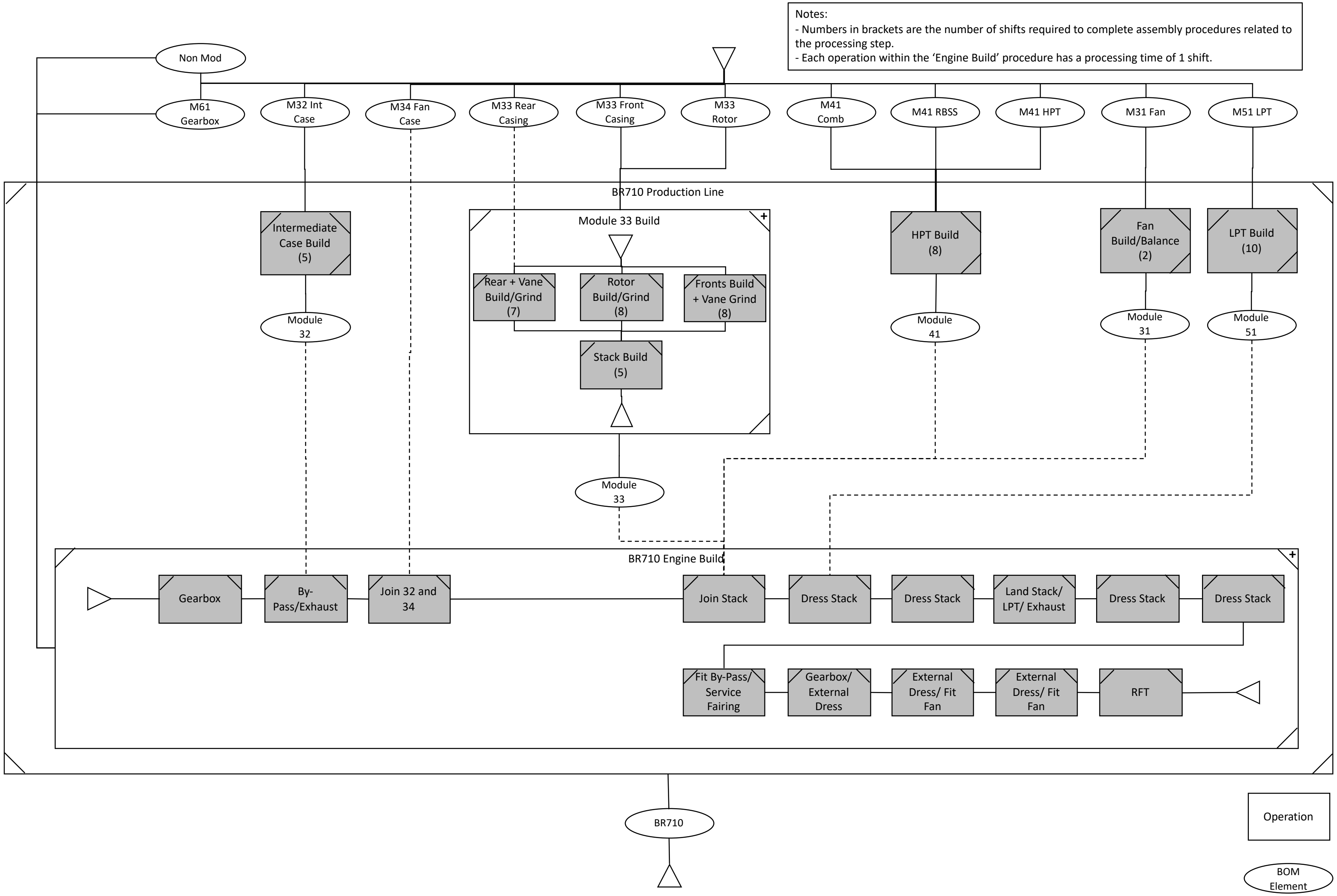


Figure 9 Process Function Chart for BR710

3.2.3. Activity Model

The activity model describes activities associated with manufacturing operations management and was used to identify data exchanges that occur in support of planning and scheduling. A high-level activity model for planning and scheduling was presented in Section 2.1.1, 'Modelling of Production Systems', which is representative of how planning and scheduling at the Rolls Royce Inchinnan plant is handled.

The project requires focus on the detailed production scheduling activity, which is overseen through the use of the planning and scheduling board. Figure 10 shows the activities, represented as ellipses, and data exchanges, represented as arrows, that occur in support of detailed production scheduling at Rolls Royce. It is based on models developed in "ANSI/ISA-95.00.03- Activity Models of Manufacturing Operations Management" (ANSI/ISA, 2013). Data exchanges to and from the detailed production scheduling activity, marked in blue in Figure 10, are of primary interest since they will need to be handled by the planning and scheduling board.

Information is also fed into the management board (represented in green in Figure 10), where: key performance indicators (KPI's) and engine build percentage completion are reviewed (production performance); and key resource constraints such as material shortages and equipment failures are highlighted (production capability). Daily management review of this board results in decisions being taken with regards to the production schedule in the form of prioritisation as well as in communication among various organisation functions on what needs to be done in order to mitigate resource issues.

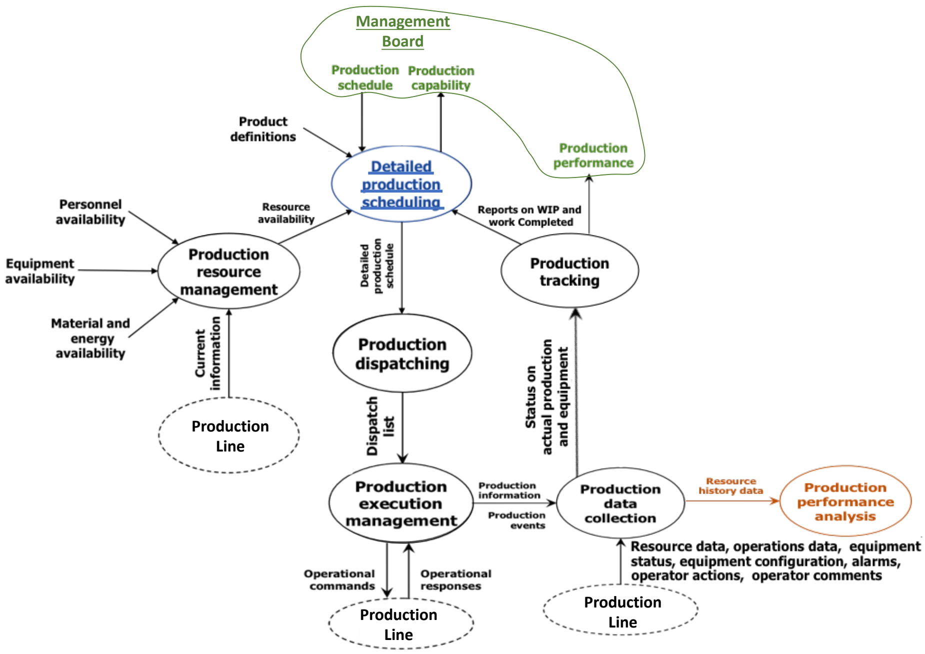


Figure 10 Rolls-Royce Inchinnan Detailed Planning and Scheduling Activity Model

Like the management board, the planning and scheduling board is reviewed by the ‘Gate 3’ production scheduling personnel daily. Discussion on material, personnel, and equipment availability (production resource management) allows decisions to be made on the work that should be carried out (dispatched) based on the processing requirements as set out in the product definitions. Production line supervisory staff then oversee the agreed upon work (production execution management), reporting back on its status and any associated resource issues. In order to aid in the planning and scheduling activity, certain issues (events), and the status of select process steps are recorded and tracked to closure.

The digitisation of the planning and scheduling board, and the management board will allow for automatic handling of some of the information flows. For example: the production schedule and production capability information can be synchronised across the two boards. At the beginning of this project the client set out expectations for the information flows that should be handled automatically. These expectations will be evaluated in the next section.

Comparison of Rolls-Royce Inchinnan operations activities to the models set out in “ANSI/ISA-95.00.03- Activity Models of Manufacturing Operations Management” (ANSI/ISA, 2013) led to the identification of an opportunity for improvement with this project. As shown in orange in Figure 10, the ANSI/ISA model describes how production event data is stored for production performance analysis. Currently, only KPI’s for time spent working on an engine are stored and compared against pre-set targets. These KPI’s are helpful in tracking whether the process is remaining in control but do not shed any light on the factors affecting the ability of the process to meet the targets. Given that data will start being handled digitally, it will be possible to store data related to the occurrence and resolution of production issues/events. The storage and therefore possibility to analyse this data will allow the organisation to better identify causes of underperforming KPI’s.

3.2.4. System Requirements

Expectations were set out by the client at the beginning of this project. Expectations describe the mindset, outcome, or result. It is however necessary to develop these expectations further into requirements. Requirements specify verifiable constraints that the system must meet in order to ensure that the expectations are also met.

Table 1 maps expectations to requirements. Note that expectation numbers are not in ascending order. Expectations have been re-arranged to improve readability.

Table 1 Rolls-Royce Production System Gate 3 Digital Board Requirements

Expectation Number	Expectation Description	Requirement Number	Requirement Description
5.1	Wants to show an overview of engine build status, including issues at 'Module Build' and 'Engine Build' level.	5.1.1	Digital tool shall be used to track BR710 engine.
		5.1.2	Digital tool shall be used to track V2500 engine.
		5.1.3	Digital tool shall have a user interface with a 'Module Build' section.
		5.1.4	Digital tool shall have a user interface with an 'Engine Build' section.
		5.1.5	Digital tool shall have an issue tracking interface.
		5.1.6	Digital tool shall allow user to categorise issues.
		5.1.7	'Module Build' section for BR710 engine shall track the following operations for each individual engine: • Intermediate Case Build • Rear + Vane Build/Grind • Rotor Build/Grind • Fronts Build + Vane Grind • Stack Build • HPT Build • Fan Build/Balance • LPT Build
		5.1.8	'Module Build' section for V2500 engine shall track the following operations for each individual engine: • 2 & 3 Build • No 1 Build • Booster Build • Gearbox Build

Table 1 Rolls-Royce Production System Gate 3 Digital Board Requirements

Expectation Number	Expectation Description	Requirement Number	Requirement Description
			• Diffuser Build • HPT Build • Rear + Vane Build/Grind • Rotor Build/Grind • Fronts Build + Vane Grind • LPT Build • Fan Build/Balance
		5.1.9	'Engine Build' section shall be in the form of calendar.
		5.1.10	'Engine Build' section for BR710 engine shall track the following operations for each individual engine: • Gearbox • By-Pass/Exhaust • Join 32 and 34 • Join Stack • Dress Stack • Land Stack/LPT/Exhaust • Fit By-Pass/Service Fairing • Gearbox/External Dress • External Dress/Fit Fan • RFT
		5.1.11	'Engine Build' section for BR710 engine shall track the following operations for each individual engine: • Land Fancase (FI1) • Install 2&3 (FI2) • Install No 1 (FI3) • Install Booster (FI4)

Table 1 Rolls-Royce Production System Gate 3 Digital Board Requirements

Expectation Number	Expectation Description	Requirement Number	Requirement Description
			• Install Gearbox (FE1) • Fancase Dress (FE2/FE3/FE4) • Install Stack (HB1) • Core Dress (HB2) • Install LPT (HB3) • Install Fan (HB4) • Snags (HB5) • Customer Eyes (RFT)
		5.1.12	Digital tool shall link each issue to a particular 'Module Build' or 'Engine Build' operation.
		5.1.13	Digital tool shall allow user to specify status for 'Module Build' operations.
		5.1.14	Issue tracking interface shall allow for filtering by engine number.
		5.1.15	Issue tracking interface shall hold the following information: • Expected Resolution Date • Category • Description • Resolved (Yes/No)
		5.1.16	Issue tracking interface shall allow for creation of new issues.
		5.1.17	Issue tracking interface shall allow for editing of issues.
		5.1.18	Issue tracking interface shall allow for issues to be marked/unmarked as resolved.

Table 1 Rolls-Royce Production System Gate 3 Digital Board Requirements

Expectation Number	Expectation Description	Requirement Number	Requirement Description
2.1	Wants to avoid updating planning board and visual management board separately with the same information.	2.1.1	Digital tool shall use excel 'shared workbook' functionality to allow for visualisation and interaction on two boards separately.
		2.1.2	'Shared workbook' functionality shall be set up using the following options to avoid loss of data: • On automatic update changes shall only be seen by other users (not saved) • Changes saved must always win
		2.1.3	Digital tool shall be programmed to automatically save at appropriate times.
2.3	Wants to be able to change 'Engine Build' plan when issues arise during assembly.	2.3.1	Digital tool shall record the actual start date and shift for all operations of each individual engine.
		2.3.2	Digital tool shall record the actual finish date and shift for all operations of each individual engine.
		2.3.3	'Engine Build' calendar shall update based on specification of date and shift.
2.2	Wants delays in 'Module Build' to be reflected in the plan for 'Engine Build'.	2.2.1	The data model shall link 'Module Build' operations with 'Engine Build' operations through their respective outflow and inflow materials. (The material produced from 'Module Build' is material consumed in 'Engine Build' operations- see Figure 8 and Figure 9)
		2.2.2	Digital tool shall be capable of calculating a 'Latest Best Estimate' for completion of all operations of each individual engine.

Table 1 Rolls-Royce Production System Gate 3 Digital Board Requirements

Expectation Number	Expectation Description	Requirement Number	Requirement Description
		2.2.3	Latest Best Estimate calculation shall consider duration of operation (in shifts).
		2.2.4	Latest Best Estimate calculation shall consider expected resolution date of issues.
		2.2.5	Latest Best Estimate calculation shall consider the effect of non-working days such as weekends and public holidays.
		2.2.6	Latest Best Estimate calculation shall consider actual start and finish dates of operations.
2.4	Wants to identify pre-existing shortfalls and automatically carry the data over when engines are transferred in.	2.4.1	On engine import the digital tool shall also import data on any existing material shorts from the ‘P&C Kitting Monitor’.
		2.4.2	The digital tool shall periodically automatically sync with the ‘P&C Kitting Monitor’.
		2.4.3	The digital tool shall allow user to trigger syncing with the ‘P&C Kitting Monitor’ manually.
		2.4.4	Shorts shall be handled as specific categories of issues.
		2.4.5	Issues that are shorts shall not be edited by the user (update of the ‘P&C Kitting Monitor’ will drive updates of these types of issues)
1.1	Wants to generate new target completion dates for each engine once the decision is made by management to commence work in Gate 3.	1.1.1	Digital tool shall have an engine import function.
		1.1.2	On engine import user shall be presented with a list of engine number options for import.

Table 1 Rolls-Royce Production System Gate 3 Digital Board Requirements

Expectation Number	Expectation Description	Requirement Number	Requirement Description
		1.1.3	Engine number import list shall not contain engines that are already being tracked in the digital tool (to avoid duplication).
		1.1.4	Digital tool shall be capable of calculating target dates based on operational factors.
		1.1.5	Target date calculation shall consider duration of operation (in shifts).
		1.1.6	Target date calculation shall consider expected resolution date of issues.
		1.1.7	Target date calculation shall consider the effect of non-working days such as weekends and public holidays.
		1.1.8	Target date calculation shall consider actual start and finish dates of operations.
		1.1.9	On engine import, the new target date shall be manipulated by the user
3.1	Wants to at minimum archive issues for further analysis, if possible creating visualisation on the visual management board.	3.1.1	Issues generated during use of the digital tool shall not be deleted.
4.1	Wants to show KPI's for the actual time taken for 'Module Build' and 'Engine Build' for each individual engine.	4.1.1	Digital tool shall allow user to enter times related to 'Module Build' and 'Engine Build' for each engine.
		4.1.2	KPI's shall be presented on the management board.
		4.1.3	KPI's shall be presented on the planning and scheduling board.

Table 1 Rolls-Royce Production System Gate 3 Digital Board Requirements

Expectation Number	**Expectation Description**	**Requirement Number**	**Requirement Description**
6.1	Wants to be able to assign work to ‘Engine Bays’ based on manual arbitration during daily management meetings	6.1.1	Digital tool shall allow assignment of an engine to a particular ‘Engine Bay’ in the ‘Engine Build’ section.

3.3. MES Design

Communicating the design of the software system developed to meet the requirements set out in section 3.2, 'Initial Assessment', is primarily achieved through the use of Unified Modelling Language (UML) for object-oriented architectures (Rajesri, et al., 2014) and Entity Relationship (ER) Diagrams for relational databases (Lucid Chart, 2018). UML and ER diagrams use graphical notations to support the construction and documentation of systems in software projects.

This project involved the use of relational tables in excel to model the product production rules and material model (as described in Figure 4), that together create a Bill of Manufacture (BOMfr). The ER diagram uses symbols to depict relationships between entities and their attributes.

Based on the BOMfr, object-oriented architectures were then used to manage the planning and scheduling of each engine undergoing processing in 'Gate 3'. UML is a suite of methods used in order to effectively communicate the design of object-oriented architectures. Structural diagrams (for example: deployment diagrams, class diagrams, object diagrams) are an element of this suite used to communicate the architecture implemented in this project.

Of particular note in the MES design was also the algorithm used in order to calculate target dates for the completion of each engine (requirements 1.1.4-1.1.8 in section 3.2.4, 'System Requirements') as well as to calculate latest best estimates for completion of each engine (requirements 2.2.2-2.2.6 in section 3.2.4, 'System Requirements'). The algorithm developed was based on the 'Critical Path Method' (Levy, et al., 1963).

3.3.1. Static System Model

The static system model gives a snapshot of the detailed state of the system at a point in time. It essentially describes how data is structured and stored in the system. As suggested by Halsall and Price in their work on hybrid systems for production planning and scheduling (se Section 2.2), the Rolls Royce Production System 'Gate 3' Digital Board was designed to contain product and operational data in relational tables, for which an ER diagram should be used to describe the structure, while the scheduling and manufacturing status information was handled using object-oriented data structures, implemented in excel as set out by Boutin and Matta (see Section 2.2.2) and described in this section using a UML class diagram. Given the hybrid approach used, the two diagrams were combined into Figure 11 to give a full overview of the system.

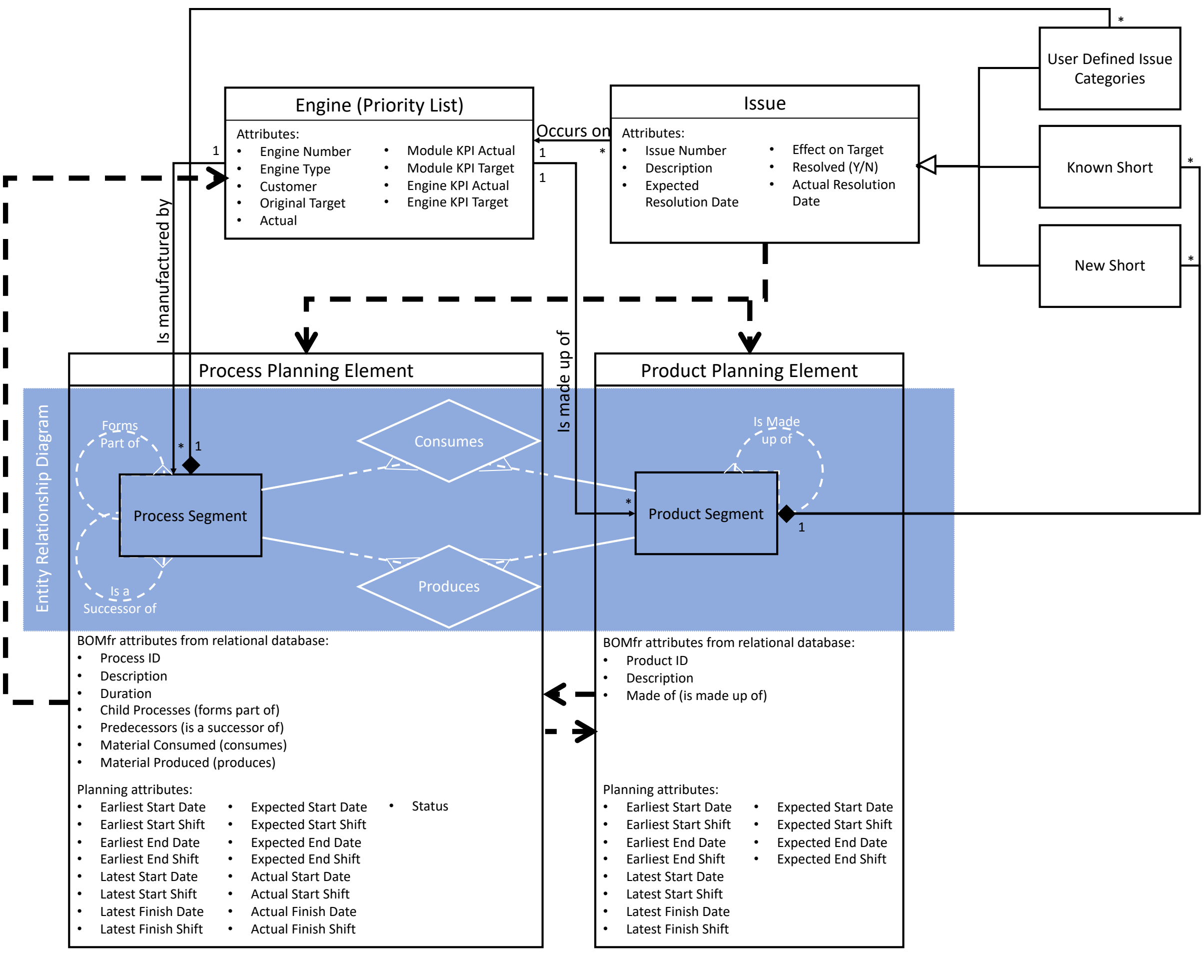


Figure 11 Static Model for Rolls Royce Production System Gate 3 Digital Board

The relational tables (marked in blue in Figure 11) contain two entities: ‘Process Segment’ and ‘Product Segment’, and two associative entities: ‘Consumes’ and ‘Produces’.

The ‘Product Segment’ is a BOM of each of the engines being handled by the digital board, while the ‘Process Segment’ contains information on operations required to complete assembly.

The associative entities are tables used to associate entities that have many to many relationships to each other- a process segment may produce many different BOM elements, and a BOM element may be produced by more than one process running in parallel. In this case two associative entities were used in order to distinguish between the two types of association. A product segment can either be used by (consumed by) a process or can be an output of (produced by) a process.

Recursive relationships also exist within the ‘Process Segment’ and ‘Product Segment’ entities:

- As seen in Figure 8 and Figure 9, operations can be combined into higher level process, for example ‘Rear + Vane Build/Grind’, ‘Rotor Build/Grind’, ‘Front Build +

Vane Grind', and 'Stack Build' are all part of 'Module 41 Build'. Therefore 'Rear + Vane Build/Grind', 'Rotor Build/Grind', 'Front Build + Vane Grind', and 'Stack Build' are part of (child processes) of 'Module 41 Build'.

- Some processes must be done before others (are successors of), for example, 'Stack Build' cannot be started before (are successors of) 'Rear + Vane Build/Grind', 'Rotor Build/Grind', and 'Front Build + Vane Grind'.
- BOM structures have levels, with assemblies being broken down (made up of) other assemblies or components.

Relational data structures follow rules on how they are transformed from the conceptual schema (marked in blue in Figure 11) into the table structures implemented in excel. These rules were followed, with the exception of the 'is a successor of' relationship. Instead of placing the successor as a foreign key in the 'Process Segment' table, a separate table, named 'Process Segment Dependency' was created to handle this relationship in order to facilitate user readability.

The data in the relational model is transformed into an object-oriented architecture for planning and scheduling. The 'Process Planning Element' and 'Product Planning Element' classes contain the data from the 'Process Segment' and 'Product Segment' entities respectively and add further planning-related attributes. Most attributes are self-explanatory. A glossary has been drawn up in Table 2 to establish the meaning of planning related attributes. Moreover, two further classes are used in the model:

- The 'Engine' is a representation of each physical engine undergoing assembly in 'Gate 3'. Each engine is made up of many 'Product Segments' and must undergo many operations ('Process Segments'). The state of the 'Engine' class is dependent on the 'Process Segment', since the 'Actual' attribute is the 'Expected End Date' of the last process segment.
- The 'Issue' is a representation of issues that have an impact on the scheduling of jobs. Therefore, the state of both the 'Product Planning Element' and the 'Process Planning Element' is dependent on 'Issues'. Multiple issues can exist for each engine. There are three kinds of 'Issue':
    - 'Known Shorts' are material shortages that were already being tracked when work on the engine commenced in 'Gate 3'
    - 'New Shorts' are material shortages that were identified after work on the engine commenced in 'Gate 3'
    - 'User Defined Issue Categories' are other process-related issues that can be defined by the user.

The three kinds of ‘Issue’ aggregate into the ‘Process Planning Element’ or the ‘Product Planning Element’ depending on whether they are process related or material related.

Table 2 Glossary for Rolls Royce Production System 'Gate 3' Digital Board Attributes

Term	Description
Earliest	*Start:* This is the earliest date/shift where the process can be started, or material will be available, given process and material constraints that are already known when work on the engine is being started. *End:* The ‘Earliest Start’ plus the duration.
Target	This is the date/shift agreed with management and input by the user for completion of work on an engine. This cannot be earlier than the ‘Earliest End Date’ of the last process segment.
Latest	*End:* This is the latest date/shift where the process can be ended in order to meet the target, given process constraints. *Start:* The ‘Latest End’ minus the duration.
Expected	*Start:* This is the earliest date/shift where the process can be started, or material will be available, given process and material constraints that come up after work on the engine has been started. *End:* The ‘Earliest Start’ plus the duration.
Actual	*In the Engine Class:* The ‘Expected End Date’ of the last process segment. *In Other Classes:* The date/shift where the process was actually start/finished, or the issue resolved.

3.3.2. Critical Path Algorithm

The ‘Critical Path Method’ is used to calculate the ‘Earliest Start’ (ES), ‘Earliest Finish’ (EF), ‘Latest Start’ (LS), and ‘Latest Finish’ (LF) for a collection of ordered jobs that can be started and stopped independently of each other. Each job must have an associated duration and a list of immediate predecessors.

Knowledge of the ES and EF allows for determination of when the process should be expected to finish since they are calculations of the quickest possible path through all the jobs. The LS and LF can be used in one of two ways: if a target date for completion of the process is agreed and set manually, latest starts can be calculated for each job against this target date to support the planner in job prioritisation; or the EF for the process can be made equal to the LF of the final job and an LF for each job calculated accordingly, any jobs where LF is equal to EF are on the critical path which means that any slips will result in the process being completed later (hence the name critical path method).

If the overall start time or date for an engine build is known, the earliest start for a job can be calculated by finding the earliest finish (equal to ES + duration) of all its predecessors and taking the latest of the earliest finish times as the earliest start of the job. The critical path method only considers duration and job sequence. However, this project also considers material availability and operational issues as factors in the calculation of the critical path. In order to account for these additional factors, the algorithm was tweaked so that the ES and EF for a job, calculated using the critical path method, would be overridden by the issue resolution date or the material availability date if these are found to be later.

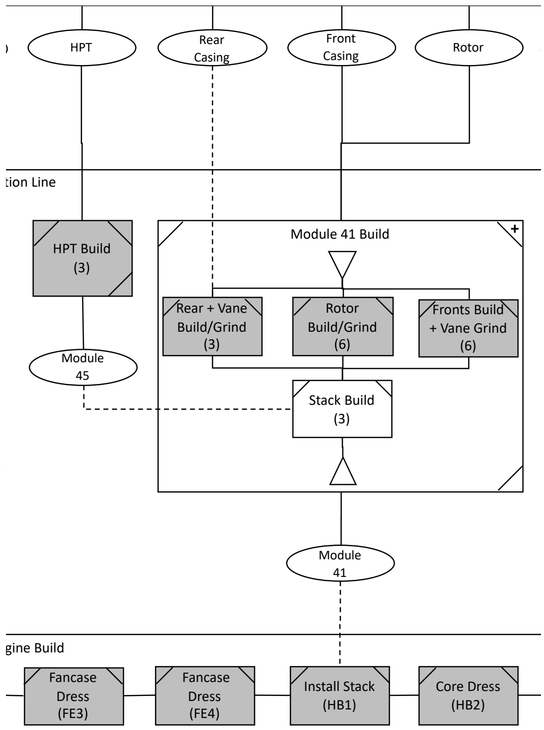


Figure 12 Excerpt of V2500 Production Line

Table 3 gives an overview the algorithm implemented. Further explanation will be provided by taking an excerpt from the V2500 Production Line as an example (refer to Figure 12).

Table 3 Earliest Start and Earliest Finish Algorithm

	Step	Description	Explanation
Initialisation	1	Identify all processes that do not have children (lowest activity planning level) and include these for consideration in the algorithm	In order for this algorithm to work, calculations must be carried out at the lowest activity planning level. Therefore, for example, it is not sufficient to consider the parent process 'Module 41 Build', but it is necessary to consider the individual operations of 'Stack Build', 'Rotor Build/Grind', etc.
	2	Identify materials that are not output by the jobs in the process (these are input materials from processes outside of 'Gate 3')	For example, an availability date can be assigned to materials 'HPT', 'Rear Casing', 'Front Casing', and 'Rotor'. This is done based on predefined logic- if there are no shortages, the availability date is 'today'.
	3	If there are no material shortages associated with the materials identified, then assign a material availability date. Otherwise assign date based on the material availability date.	
	4	Of the lowest level processes (see step 1), identify processes that do not have any predecessors and for which an availability date has been established for all material inputs.	It is necessary to identify the nodes at which the process starts. These are jobs that do not have any predecessors. Moreover, material availability dates must also have been established for all input materials of these jobs.

	Step	Description	Explanation
	5	Assign an earliest start to the processes meeting the criteria in step 4- this is the following day, the issue resolution date, or the material availability date, whichever is later.	Given that material ‘HPT’, ‘Rear Casing’, ‘Front Casing’ and ‘Rotor’ captured in step 2 and step 3, jobs ‘HPT Build’, ‘Rear + Vane Build/Grind’, ‘Rotor Build/Grind’, and ‘Front Build + Vane Grind’ will all meet the criteria of step 4, confirming that these jobs only have dependencies outside of ‘Gate 3’. An earliest start is assigned to the jobs meeting the criteria of step 4 based on predefined logic.
	7	Record jobs which have been assigned an earliest start in Set S.	For example: Set S will include ‘HPT Build’, ‘Rear + Vane Build/Grind’, ‘Rotor Build/Grind’, and ‘Front Build + Vane Grind’ since they meet the criteria of step 4 and would have been assigned a date based on step 5.
	8	For materials that are output by jobs included in Set S, assign a material availability date equal to the latest EF date of the associated jobs.	Given that the earliest start is known, it is possible to calculate the earliest finish of the job based on the duration. Once a job is complete the material it is expected to output will be available. Therefore, for example: the material availability date for ‘Module 45’ can now be defined.
Critical Path Loop	9	For all jobs that have not been assigned an earliest start (complement of Set S), find the jobs for which all the predecessors have been included in Set S and for which an availability date has been established for all material inputs.	If all the predecessors of a job have been assigned an earliest start and a material availability date is established for all material inputs, it is now possible to calculate the earliest start based on predefined logic. Therefore, for example, the earliest start of ‘Stack Build’ can now be calculated since the EF of ‘Rear + Vane Build/Grind’, ‘Rotor Build/Grind’, and ‘Front Build + Vane Grind’ are known and a material availability date has been established for ‘Module 45’. In contrast: - It is not yet possible to calculate an earliest start for ‘Install Stack (HB1)’ because an availability date for ‘Module 41’ has not been defined yet. - It is not yet possible to calculate an earliest start for ‘Core Dress (HB2)’ because it’s predecessor ‘Install Stack (HB1)’ has not been assigned an earliest start.
	10	Assign an earliest start to the processes meeting the criteria in step 9- this is the following day, the issue resolution date, or the material availability date, whichever is later.	
	11	Add jobs which have been assigned an earliest start into Set S.	‘Stack Build’ can be added to Set S since an earliest start has been defined.
	12	For materials that are output by jobs included in Set S, assign a material availability date equal to	Given that the earliest start is now known for ‘Stack Build’, the material availability date for ‘Module 41’ can now be defined.

	Step	Description	Explanation
		the latest EF date of the associated jobs.	
	13	While there are still jobs that have not been assigned an earliest start return to step 9.	Continue looping until an earliest start has been defined for all jobs.

Unlike the ES and EF, calculation of the LS and LF does not require consideration of material availability and operational issues. The LS and LF are used in order to determine the latest a job can be started and finished given a specified target date, thus they are only concerned with how much time is needed to complete the job. Therefore, it is possible to implement the algorithm directly as defined by Levy et al in "The ABCs of the Critical Path Method" (Levy, et al., 1963):

1. Assign a LF target date to the last job. This job is the operation that outputs the assembled engine. (Note: as explained previously, the target date is defined in one of two ways, based on the objective of the calculation)
2. Calculate the LS by subtracting the duration from the LF.
3. Consider any new unmarked job all of whose successors have been assigned a LS/LF and assign the new unmarked job with an LF equal to the smallest LS of all its successors.
4. Calculate the LS of the new unmarked jobs considered in step 3 by subtracting the duration from the LF.
5. Return to Step 3 until all jobs have been assigned a LS and LF.

3.3.3. Critical Path Algorithm- Further Considerations

The implementation of the algorithms based on the critical path method in this project involved consideration of some particular circumstances that needed to be handled.

The first was related to the realisation that although the tool was capable of estimating when a job was expected to be started and when it would end, it is possible for the planner to take extraordinary steps, such as assigning overtime to complete jobs more quickly. The calculations described in the algorithms in section 3.3.1 are estimates based on the standard process, however, as the user inputs information on the actual state of the process, these should supersede any estimates developed by the algorithm. Therefore, rules were implemented where necessary to force the system to consider the most recent information as follows:

1. If an actual finish time has been input, base all calculations on this, else;

2. If an actual start time has been input, base all calculations on this, else;
3. Estimate start and finish times based on standard process, material availability, and operational issue data.

The second was related to the fact that planning is carried out in shifts. Therefore, calculation of ES, EF, LS, and LF based on the duration (in number of shifts) could not be carried out by simple additions and subtractions on a continuous time scale. The consideration of discretised shifts meant that logic had to be added to calculations being made to relate shifts to calendar days. This was accomplished by creating a user input where the number of shifts in a standard working day could be specified. The logic was then developed against this input. This allows the tool to remain relevant even if a decision were made to switch from the current 2-shift-per-day setup currently used at Rolls Royce Inchinnan to another operational setup.

Section 4: Implementation and Testing

4.1. System Testing

Risks are inherently associated with the implementation of any new system. In the case of this project: incorrect calculations by the critical path algorithm could result in late engine builds or suboptimal prioritisation of resources; other programming bugs could mean that an information deficit is created, and key decisions can no longer be taken. System testing allows for mitigation of these risks by ensuring that the system is capable of functioning as required under predetermined use cases.

The rigour of testing usually depends on the severity of the effects of failure. So, for example, the level of testing associated with a software used for air traffic control or to regulate stock market transactions would require higher levels of testing than a software used to automatically issue invoices in a small company. The negative impact of a failure in the former have far greater consequences, even death, and are harder to recover from or correct.

System testing usually takes the form of verification and/or validation testing. Validation answers the question: “Am I building the right product?”, while verification answers the question: “Am I building the product right?”. (Software Testing Fundamentals, 2018)

In this project, testing took the form of verification, undertaken while the system was configured and built.

During the course of the software build, functional tests were run to check that the code was doing what was expected of it. Therefore, for example, when coding the critical path algorithm, the dates output by the algorithm were checked to ensure that they matched manual calculations under various changing conditions, such as: changing material availability dates; addition and resolution of issues; user specifying actual start and end dates.

By verifying the consistency, completeness, and correctness of each part of the software separately, the chances of failures occurring in the final product are greatly reduced.

Verification involves ensuring that all the requirements derived from the user expectations are being met. The ‘Requirement Traceability Matrix’ is a document that maps out user requirements with tests to ensure conformity to the user requirement. Tests can take the form of a predefined functional test method with pass and fail criteria, designed to determine conformity, or a description of how the system meets the requirement. The more scientific approach of the former, involving use of predetermined methods and criteria, is preferable. However, given the low risk and tight timelines, this project took the route of ad-hoc functional testing, with descriptions of how the system meets requirements. The resulting ‘Requirement Traceability Matrix’ is discussed further in section 4.3.

4.2. Training and Troubleshooting

Training and troubleshooting are the final steps before putting the system into operation.

Troubleshooting involved connecting the system to the live material availability data and ensuring that the system continued to work as desired.

Troubleshooting continued during training, where the capabilities of the system were shown to its users using live data. Besides being beneficial to the users, this process was also beneficial in identifying minor improvements that were required based on feedback obtained during these sessions.

4.3. Requirement Traceability Matrix

Table 4 maps requirements to verification. Given that the requirement traceability matrix describes how the system meets requirements, it doubles as a user manual. To facilitate explanation, reference will be made to diagrams of the user interface in Appendix I.

Note that requirement numbers are not in ascending order. Requirements have been re-arranged to improve readability.

Table 4 Rolls-Royce Production System Gate 3 Digital Board Requirements Traceability Matrix

Requirement Number	Requirement Description	Verification
5.1.1	Digital tool shall be used to track BR710 engine.	The digital tool was programmed to handle engines of any type listed in the 'Predefined_Objects' worksheet and for which the necessary material and process information have been added into the 'Process Segment', 'Material_Consumed', 'Process Segment Dependency', 'Material_Produced', and 'Product Segment' worksheets. To access the Module Build and Engine Build User Interfaces for the V2500 engine open worksheet 'V2500' (Item 1 in Appendix I). To access the Module Build and Engine Build User Interfaces for the BR710 engine open worksheet 'BR710' (Item 2 in Appendix I).
5.1.2	Digital tool shall be used to track V2500 engine.	
5.1.3	Digital tool shall have a user interface with a 'Module Build' section.	
5.1.4	Digital tool shall have a user interface with an 'Engine Build' section.	
5.1.5	Digital tool shall have an issue tracking interface.	Issue tracking interface can be accessed by double clicking items marked with 5 in Appendix I.
5.1.6	Digital tool shall allow user to categorise issues.	Issue Categories are user defined through the worksheet 'Predefined_Objects'. *Note: The Categories 'Known Short' and 'New Short' are system defined to handle material shorts.*
5.1.7	'Module Build' section for BR710 engine shall track the following operations for each individual engine: • Intermediate Case Build • Rear + Vane Build/Grind	The Module Build User Interface for the BR710 engine considers the operations listed.

Table 4 Rolls-Royce Production System Gate 3 Digital Board Requirements Traceability Matrix

Requirement Number	Requirement Description	Verification
	• Rotor Build/Grind • Fronts Build + Vane Grind • Stack Build • HPT Build • Fan Build/Balance • LPT Build	Each operation listed in this requirement is linked to an operation defined in the 'Process Segment' worksheet. Calculations are carried out based on information in the 'Process Segment', 'Material_Consumed', 'Process Segment Dependency', 'Material_Produced', and 'Product Segment' worksheets and output to the user as needed.
5.1.8	'Module Build' section for V2500 engine shall track the following operations for each individual engine: • 2 & 3 Build • No 1 Build • Booster Build • Gearbox Build • Diffuser Build • HPT Build • Rear + Vane Build/Grind • Rotor Build/Grind • Fronts Build + Vane Grind • LPT Build • Fan Build/Balance	The Module Build User Interface for the V2500 engine considers the operations listed. Each operation listed in this requirement is linked to an operation defined in the 'Process Segment' worksheet. Calculations are carried out based on information in the 'Process Segment', 'Material_Consumed', 'Process Segment Dependency', 'Material_Produced', and 'Product Segment' worksheets and output to the user as needed.
5.1.9	'Engine Build' section shall be in the form of calendar.	Engine Build User Interface is in calendar form, with information being showed for 7 days into the future, and 2 days into the past. As demonstrated in Appendix I, the calendar dates can be toggled manually, allowing the user to view the information they need. The date is automatically reset to 'today': at midnight; on engine import (Item 3); and when an update is run manually (Item 4).

Table 4 Rolls-Royce Production System Gate 3 Digital Board Requirements Traceability Matrix

Requirement Number	Requirement Description	Verification
5.1.10	'Engine Build' section for BR710 engine shall track the following operations for each individual engine: • Gearbox • By-Pass/Exhaust • Join 32 and 34 • Join Stack • Dress Stack • Land Stack/LPT/Exhaust • Fit By-Pass/Service Fairing • Gearbox/External Dress • External Dress/Fit Fan • RFT	The Engine Build User Interface for the BR710 engine considers the operations listed. Each operation listed in this requirement is linked to an operation defined in the 'Process Segment' worksheet. Calculations are carried out based on information in the 'Process Segment', 'Material_Consumed', 'Process Segment Dependency', 'Material_Produced', and 'Product Segment' worksheets and output to the user as needed.
5.1.11	'Engine Build' section for BR710 engine shall track the following operations for each individual engine: • Land Fancase (FI1) • Install 2&3 (FI2) • Install No 1 (FI3) • Install Booster (FI4) • Install Gearbox (FE1) • Fancase Dress (FE2/FE3/FE4) • Install Stack (HB1) • Core Dress (HB2) • Install LPT (HB3) • Install Fan (HB4) • Snags (HB5) • Customer Eyes (RFT)	The Engine Build User Interface for the V2500 engine considers the operations listed. Each operation listed in this requirement is linked to an operation defined in the 'Process Segment' worksheet. Calculations are carried out based on information in the 'Process Segment', 'Material_Consumed', 'Process Segment Dependency', 'Material_Produced', and 'Product Segment' worksheets and output to the user as needed.

Table 4 Rolls-Royce Production System Gate 3 Digital Board Requirements Traceability Matrix

Requirement Number	Requirement Description	Verification
5.1.12	Digital tool shall link each issue to a particular 'Module Build' or 'Engine Build' operation.	As seen in the 'Edit Issue' dialogue box in Appendix I, the user must specify a 'Process Step' for each issue. *Note:* in the case of material shortages, information in the 'Material_Consumed' worksheet is used to automatically link material shortage issues to the process step.
5.1.13	Digital tool shall allow user to specify status for 'Module Build' operations.	A maximum of 11 statuses are user defined through the worksheet 'Predefined_Objects'. The statuses 'On Build' and 'Complete' are system defined and automatically generated when a start date or a completion date are entered respectively.
5.1.14	Issue tracking interface shall allow for filtering by engine number.	Double clicking on a cell containing an engine number will filter out any issues related to that particular engine in the 'Issues' dialogue box shown in Appendix I. Further filtering functionality, in the form of 'Show Unresolved', 'Show Past Due', and 'Show All Engines' options was also added to make information extraction efficient (See Appendix I).
5.1.15	Issue tracking interface shall hold the following information: • Expected Resolution Date • Category • Description • Resolved (Yes/No)	'Issues' dialogue box is set up to present this information to the user as necessary (Item 5 in Appendix I). The 'Issue Log' worksheet stores this information.
5.1.16	Issue tracking interface shall allow for creation of new issues.	An 'Add Issue' button was added to the 'Issues' dialogue box to allow for this functionality. Refer to Item 5 in Appendix I. Estimated completion dates for processes related to the issue are re-calculated and updated accordingly.

Table 4 Rolls-Royce Production System Gate 3 Digital Board Requirements Traceability Matrix

<table>
<tr><th>Requirement Number</th><th>Requirement Description</th><th>Verification</th></tr>
<tr><td>5.1.17</td><td>Issue tracking interface shall allow for editing of issues.</td><td>An ‘Edit Issue’ button was added to the ‘Issues’ dialogue box to allow for this functionality. Refer to Item 5 in Appendix I.

To edit an issue, select it in the ‘Issues’ dialogue box and click the ‘Edit Issue’ button. If the resolution date is changed, affected processes are re-calculated and updated accordingly.

Note: issues related to material shortages cannot be edited. The system is designed to automatically handle this information based on entries made to the ‘Kitting Monitor’ for ‘Gate 2’.</td></tr>
<tr><td>5.1.18</td><td>Issue tracking interface shall allow for issues to be marked/unmarked as resolved.</td><td>‘Mark As Resolved’ and ‘Mark As Unresolved’ buttons were added to the ‘Issues’ dialogue box to allow for this functionality. Refer to Item 5 in Appendix I.

To mark issues as un/resolved, select the issues in the ‘Issues’ dialogue box and click the appropriate button. Affected processes are re-calculated and updated accordingly.</td></tr>
<tr><td>2.1.1</td><td>Digital tool shall use excel ‘shared workbook’ functionality to allow for visualisation and interaction on two boards separately.</td><td rowspan="2">The tool could not be set up in place since necessary screens were not purchased. These requirements were communicated to the client, to be implemented during setup.</td></tr>
<tr><td>2.1.2</td><td>‘Shared workbook’ functionality shall be set up using the following options to avoid loss of data:
• On automatic update changes shall only be seen by other users (not saved)
• Changes saved must always win</td></tr>
<tr><td>2.1.3</td><td>Digital tool shall be programmed to automatically save at appropriate times.</td><td>The tool automatically saves when a new engine is imported; when the excel file is closed; and once a day during an automatically run system update at midnight.</td></tr>
</table>

Table 4 Rolls-Royce Production System Gate 3 Digital Board Requirements Traceability Matrix

<table>
<tr><th>Requirement Number</th><th>Requirement Description</th><th>Verification</th></tr>
<tr><td></td><td></td><td>Manually saving the sheet is not advisable since it may result in a loss of data.</td></tr>
<tr><td>2.3.1</td><td>Digital tool shall record the actual start date and shift for all operations of each individual engine.</td><td>This is carried out in the worksheet ‘Process_Planning_Element’. Information is held until the engine is deleted from the tool (delete engine functionality accessed through Item 3 in Appendix I).</td></tr>
<tr><td>2.3.2</td><td>Digital tool shall record the actual finish date and shift for all operations of each individual engine.</td><td rowspan="9">Information is held in the ‘Process_Planning_Element’ and ‘Product_Planning_Element’ worksheets. It is held until the engine is deleted from the tool (delete engine functionality is accessed through Item 3 in Appendix I).

On engine import; following any new or edits to issues; or following any changes to module build status, recalculation of dates and shifts for all process operations is automatically retrigger.

Calculation is carried out using the critical path algorithm described in Section 3.3.2, ‘Critical Path Algorithm’. Calculations are automatically programmed to exclude weekends as non-work days. The user can also include a list of ‘Bank Holidays and Shutdown’ days in the ‘Predefined_Objects’ worksheet that will also be excluded as non-work days.

The ‘Module Build’ and ‘Engine Build’ sections of the planning and scheduling sheets of the BR710 and V2500 are updated as needed. And the ‘Management Board’ sheet is also updated.</td></tr>
<tr><td>2.3.3</td><td>‘Engine Build’ calendar shall update based on specification of date and shift.</td></tr>
<tr><td>2.2.1</td><td>The data model shall link ‘Module Build’ operations with ‘Engine Build’ operations through their respective outflow and inflow materials. (The material produced from ‘Module Build’ is material consumed in ‘Engine Build’ operations)</td></tr>
<tr><td>2.2.2</td><td>Digital tool shall be capable of calculating a ‘Latest Best Estimate’ for completion of all operations of each individual engine.</td></tr>
<tr><td>2.2.3</td><td>Latest Best Estimate calculation shall consider duration of operation (in shifts).</td></tr>
<tr><td>2.2.4</td><td>Latest Best Estimate calculation shall consider expected resolution date of issues.</td></tr>
<tr><td>2.2.5</td><td>Latest Best Estimate calculation shall consider the effect of non-working days such as weekends and public holidays.</td></tr>
<tr><td>2.2.6</td><td>Latest Best Estimate calculation shall consider actual start and finish dates of operations.</td></tr>
</table>

Table 4 Rolls-Royce Production System Gate 3 Digital Board Requirements Traceability Matrix

Requirement Number	Requirement Description	Verification
2.4.1	On engine import the digital tool shall also import data on any existing material shorts from the 'P&C Kitting Monitor'.	Data on material shorts is pulled for an engine on import (import engine functionality is accessed through Item 3 in Appendix I).
2.4.2	The digital tool shall periodically automatically sync with the 'P&C Kitting Monitor'.	The tool is set to sync automatically on a daily basis at midnight.
2.4.3	The digital tool shall allow user to trigger syncing with the 'P&C Kitting Monitor' manually.	To trigger syncing manually click Item 4 in Appendix I.
2.4.4	Shorts shall be handled as specific categories of issues.	The Categories 'Known Short' and 'New Short' are system defined to handle material shorts.
2.4.5	Issues that are shorts shall not be edited by the user (update of the 'P&C Kitting Monitor' will drive updates of these types of issues)	Issues related to material shortages cannot be edited. The system is designed to automatically handle this information based on entries made to the 'Kitting Monitor' for 'Gate 2'.
1.1.1	Digital tool shall have an engine import function.	Engine import functionality can be accessed through Item 3 in Appendix I.
1.1.2	On engine import user shall be presented with a list of engine number options for import.	Engine numbers presented to the user for import are generated by considering all BR710 and V2500 engines being tracked in the 'Kitting Monitor' for 'Gate 2' and removing any engines that have already been imported into the tool.
1.1.3	Engine number import list shall not contain engines that are already being tracked in the digital tool (to avoid duplication).	
1.1.4	Digital tool shall be capable of calculating target dates based on operational factors.	On engine import; following any new or edits to issues; or following any changes to module build status, recalculation of dates and shifts for all process operations is automatically retrigger. Calculation is carried out using the critical path algorithm described in Section 3.3.2, 'Critical Path Algorithm'. Calculations are automatically programmed to exclude weekends as non-work days. The user can include a list of 'Bank Holidays and Shutdown' days in the
1.1.5	Target date calculation shall consider duration of operation (in shifts).	
1.1.6	Target date calculation shall consider expected resolution date of issues.	

Table 4 Rolls-Royce Production System Gate 3 Digital Board Requirements Traceability Matrix

Requirement Number	Requirement Description	Verification
1.1.7	Target date calculation shall consider the effect of non-working days such as weekends and public holidays.	'Predefined_Objects' worksheet that will also be excluded as non-work days. The 'Module Build' and 'Engine Build' sections of the planning and scheduling sheets of the BR710 and V2500 are updated as needed. And the 'Management Board' sheet is also updated.
1.1.8	Target date calculation shall consider actual start and finish dates of operations.	
1.1.9	On engine import, the target date shall be manipulated by the user	Target date can be manipulated by the user inside the 'Engine Import Overview' dialogue box as per Appendix I. *Note: target date entry is constrained by the material shortage data. Entry of a target completion date earlier than would be possible given the material shortages is not allowed.*
3.1.1	Issues generated during use of the digital tool shall not be deleted.	Issues are not removed from the 'Issues Log' when an engine is deleted (delete engine functionality is accessed through Item 3 in Appendix I). They are kept for use in future analysis.
4.1.1	Digital tool shall allow user to enter times related to 'Module Build' and 'Engine Build' for each engine.	Start dates and completion dates for process operations can be input by the user into the tool by double clicking Items 6 & 8 in Appendix I.
4.1.2	KPI's shall be presented on the management board.	'Module ESV' and 'Engine ESV' are shown on the management board. These values are updated manually by the user in the 'Priority List' worksheet.
4.1.3	KPI's shall be presented on the planning and scheduling board.	'Module ESV' and 'Engine ESV' are shown in the 'Engine Build' section of the planning and scheduling board. These values are updated manually by the user in the 'Priority List' worksheet.
6.1.1	Digital tool shall allow assignment of an engine to a particular 'Engine Bay' in the 'Engine Build' section.	'Engine Bay' can be assigned by inserting the number manually into Item 9 in Appendix I.

Section 5: Discussion and Conclusions

5.1. Reflection

The objective of this project, to undertake the digitisation of the ‘Gate 3’ visual management planning system, improving planning activities through efficient and effective information flows, was met.

The client was given and trained on a Visual Basic (VBA) Excel tool that automatically connects to material information from upstream processes and allows for tracking of process status and issues. Moreover, the tool is capable of using the data provided to it to estimate completion dates at an individual process operation level, returning this information to the client, in a format similar to that originally used in the manual version of the ‘Gate 3’ boards.

Although the objective of this project was met, the use of Excel combined with VBA for data storage and as a user interface posed challenges that could have been avoided had another programming language been chosen. The fact that VBA is not an object-oriented programming language, and is not equipped with a comprehensive, flexible array of user interface elements meant that a lot of time was spent programming loops to make up for the lack of inheritance and reflection capabilities, as well as turning spreadsheets into user interfaces. Inherent to the creation of programming loops is an increase in processing requirements and run time.

The use of excel spreadsheets to implement the relational database model should also have been implemented in a Standard Query Language (SQL) database. SQL offers in-built consistency, availability, and maintainability features ensuring that relationships across the various data tables implemented are not broken and that future data entry follows a predefined set of rules, protecting against entry errors.

In hindsight, time may have been better spent convincing Rolls-Royce management to undertake the digitisation with the correct tools and programming languages, rather than developing work-arounds for the challenges posed by the Excel-VBA combination.

The time constraints of the project also meant that adequate commenting to explain what is happening inside the code was not completed. The code does what it is supposed to and the documentation inside this report is thorough, however, it may be difficult for another individual to connect the concepts explained inside this report with portions of code. A potential hurdle to further development of the digital tool.

Despite the challenges described, feedback obtained 1.5 months after the digital tool went live was positive. No bugs were identified, and it was indicated that the tool was working correctly.

5.2. Future Work

The digital tool will give the client better insight and control over the assembly operations occurring in 'Gate 3'. Further work can be carried out on and around the tool to enhance its use, ensure its accuracy, and drive operational excellence:

1. By request, the tool only considers material resource constraints when calculating completion dates. Other resources, such as equipment and people are not considered. This is because lack of material availability is viewed as the key contributor of process delays. The digital tool now allows for formal tracking and archiving of different kinds of issues. This data can be used to confirm the supposition that it is in fact material related issues that contribute most to process delays. It can also be used to identify other resources that may need to be tracked for effective planning and scheduling. Using similar concepts to those defined in this report the tool can be enhanced to consider other resources, such as equipment or people, when determining completion dates.
2. Through verification, it was confirmed that the critical path algorithms developed work well. However, since the focus of this project was not on optimisation of these algorithms, further work can be carried out to reduce processing requirements. A key shortcoming identified in this respect was the fact that it was decided to calculate the earliest possible completion date (calculated during engine import) and the latest best estimate (used to track the completion date during assembly) with the same algorithm. Although very similar, the logic involved in the two scenarios is slightly different, complicating the resultant algorithm. Optimisation of the algorithm is a research project in its own right.
3. As explained in previous sections of this report, ad-hoc verification was carried out to ensure a conforming final product. However, given the large number of factors affecting the calculation of dates, it would be highly advisable to carry out some form of validation on the results being generated by the critical path algorithm. This can be done by developing an additional excel sheet that tests the conformity of results in the original tool. At a predetermined frequency, a copy can be made of the original tool. This can then be checked against the additional excel sheet. If no problems are found after a sufficient number of checks, the algorithm can be considered to be validated.

As is the case in most circumstances, the key to operational excellence is continuous improvement. It is for this reason that the tool should always be considered a work in progress, constantly tweaked to provide better information, functionality, and response times, in line with the prevailing needs of the organisation.

Bibliography

ANSI/ISA, 2001. *Batch Control Part 2: Data Structures and Guidelines for Languages.* North Carolina: ISA- The Insturmentation, Systems, and Automation Society.

ANSI/ISA, 2010. *Batch Control.* North Carolina: ISA- The Insturmentation, Systems, and Automation Society.

ANSI/ISA, 2013. *Enterprise-Control System Integration.* North Carolina: ISA- The Insturmentation, Systems, and Automation Society.

ANSI/ISA, 2013. *Enterprise-Control System Integration Part 3: Activity Models of Manufacturing Operations Managment.* North Carolina: American National Standard.

Boutin, S. & Matta, J., 2013. *K-Inside: How to turn Spreadsheets into Object Oriented Models.* [Online]
Available at: http://www.k-inside.com/web/wp-content/uploads/2013/05/CSDM2012-KI-paper49.pdf
[Accessed 17 September 2018].

Brown, M. S., 2018. *Forbes Get The Basics On NoSQL Databases: Object-Oriented Databases.* [Online]
Available at: https://www.forbes.com/sites/metabrown/2018/03/31/get-the-basics-on-nosql-databases-object-oriented-databases/#3b7cb9d52b2d
[Accessed 18 September 2018].

Diffen, 2018. *Data vs. Information.* [Online]
Available at: https://www.diffen.com/difference/Data_vs_Information
[Accessed 13 07 2018].

Dimension Data, 2017. *The Digital Workplace Report: Transforming Your Business.* [Online]
Available at: https://www.dimensiondata.com/microsites/-/media/95C5923C59FD4437B870929D3396F891.ashx
[Accessed 7 1 2019].

Forman, I. R. & Forman, N., 2004. *Java Reflection in Action.* 1st Edition ed. s.l.:Manning.

Galsworth, G. D., 2017. *Visual Workplace: Visual Thinking.* 2nd Edition ed. Florida: CRC Press.

Graff, J. C., 2011. *Code Project: Reflection in VBA.* [Online]
Available at: https://www.codeproject.com/Articles/164036/Reflection-in-VBA-a-CreateObject-function-for-VBA
[Accessed 17 September 2018].

Gumaer, R., 1996. Beyond ERP and MRP II. *IIE Solutions,* 28(9), p. 32.

Halsall, D. N. & Price, D. R., 1999. A DSS approach to Devloping Systems to Support Production Planning and Control in Smaller Companies. *International Journal of Production Research,* 27(7), pp. 1645-1660.

Hastings, H. A. J. & Yen, C. H., 1992. Bill of Manufacture. *Production and Inventory Management Journal,* 33 (4), pp. 27-33.

Kletti, J., 2007. *Manufacturing Execution Systems- MES.* 1st Edition ed. Berlin: Springer.

LaCroix, C., 2009. *Understanding the difference between MRP and ERP systems.* [Online]
Available at: https://searcherp.techtarget.com/news/991375236/Understanding-the-difference-between-MRP-and-ERP-systems
[Accessed 11 07 2018].

Levy, F. K., Thompson, G. L. & Wiest, J. D., 1963. The ABCs of the Critical Path Method. *Harvard Business Review*, September.

Lucid Chart, 2018. *What is an Entity Relationship Diagram.* [Online]
Available at: https://www.lucidchart.com/pages/er-diagrams
[Accessed 11 10 2018].

Mcleod, G., 2014. *30 Simple Tools for Data Visualisation.* [Online]
Available at: https://www.fastcompany.com/3029239/30-simple-tools-for-data-visualization
[Accessed 13 07 2018].

MESA International, 2018. *MESA Model.* [Online]
Available at: http://www.mesa.org/en/modelstrategicinitiatives/MESAModel.asp
[Accessed 12 07 2018].

Price, D. H., Sharp, J. A. & Muhlemann, A. P., 1992. A taxonomy for supporting the development of computer-based production planning and control systems. *European Journal of Operational Research,* 61(1-2), pp. 41-47.

Rajesri, G. & Krisna, P., 2016. *A methodology for Manufacturing Execution Systems (MES) implementation.* s.l., IOP Conference Series: Materials Science and Engineering.

Rajesri, G., Kristianto, L. & Dissa, C. R., 2014. Manufacturing Execution System Design using ISA-95. *Advanced Material Research,* Volume 980, pp. 248-252.

Rouse, M., 2018. *Search Data Management.* [Online]
Available at: https://searchdatamanagement.techtarget.com/definition/relational-database
[Accessed 17 9 2018].

Rubberduck VBA, 2015. *OOP in VBA?.* [Online]
Available at: https://rubberduckvba.wordpress.com/2015/12/24/oop-in-vba/
[Accessed 17 September 2018].

SAP, 2018. *SAP.* [Online]
Available at: https://www.sap.com
[Accessed 11 07 2018].

Scholten, B., 2007. *Integrating ISA-88 and ISA-95.* Houston, Texas, ISA EXPO.

Six Sigma Material, 2018. *Six Sigma Material.* [Online]
Available at: http://www.six-sigma-material.com/Visual-Management.html
[Accessed 09 07 2018].

Software Testing Fundamentals, 2018. *Verification vs Validation.* [Online]
Available at: http://softwaretestingfundamentals.com/verification-vs-validation/
[Accessed 7 1 2019].

Verein Deutcher Ingenieure, 2007. *VDI 5600-1-2007 Manufacturing Execution Systems (MES).* s.l.:s.n.

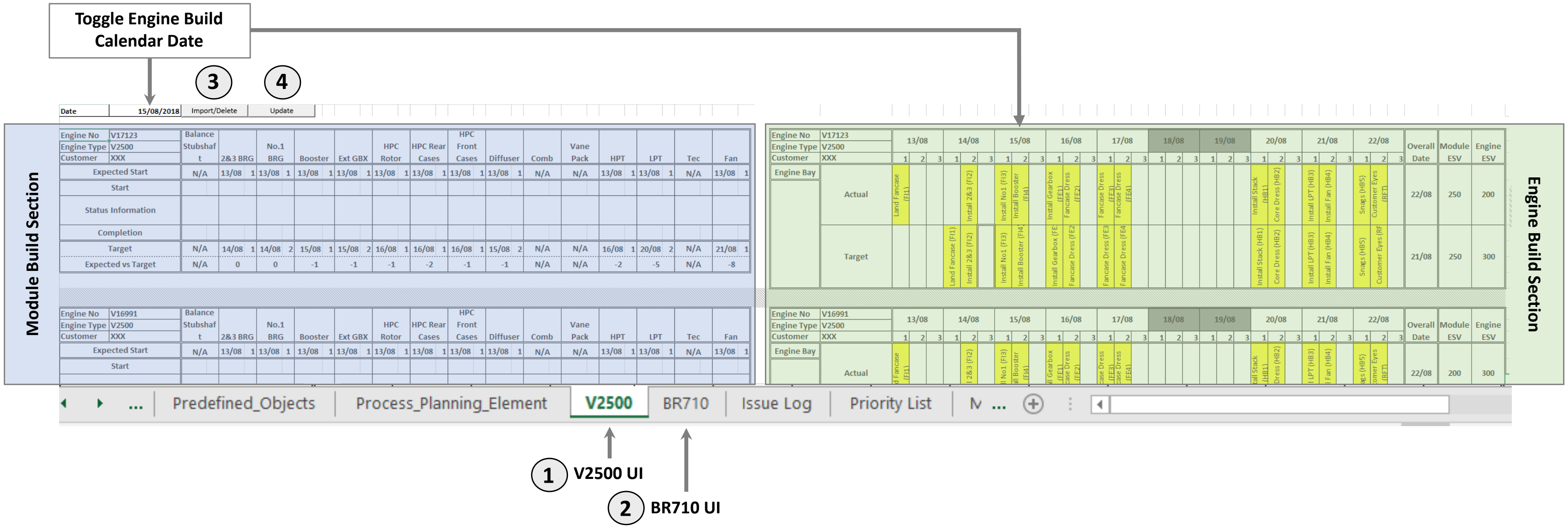
Yaiser, M., 2012. *Adobe Object-Oriented Programming Concepts: Inheritance.* [Online]
Available at: https://www.adobe.com/devnet/actionscript/learning/oop-concepts/inheritance.html
[Accessed 17 9 2018].

Zaun, R. & Maki, A., 2006. S88 Isn't Just For Batches Anymore. *World Batch Forum*, 5-8 March.

Appendix I

I.1. Planning and Scheduling Board User Interface (UI)

Note: Numbered items are cross-referenced in Section 4.3, ‘Requirement Traceability Matrix’. Functionality of items numbered ‘○’ is accessed by a single left-click, while functionality of items numbered ‘XX’ is accessed by double-clicking. In most cases this results in a window being opened to allow for manipulation of the schedule or to provide further information that may be required by the user. Refer to section I.3, ‘Supplementary User Interface (UI) Elements’, for an overview of the windows opened when clicking numbered items.



Module Build Functionality

Engine No V 5 23 Engine Type V 0 Customer X	Balance Stubshaft		2&3 BRG		No.1 BRG		Booster		Ext GBX		HPC Rotor		HPC Rear Cases		HPC Front Cases		Diffuser		Comb	Vane Pack	HPT		LPT		Tec	Fan	
Expected Start	N/A		13/08	1	13/08	1	13/08	1	13/08	1	13/08	1	13/08	1	13/08	1	13/08	1	N/A	N/A	13/08	1	13/08	1	N/A	13/08	1
Start															6												
Status Information															7												
Completion															6												
Target	N/A		14/08	1	14/08	2	15/08	1	15/08	2	16/08	1	16/08	1	16/08	1	15/08	2	N/A	N/A	16/08	1	20/08	2	N/A	21/08	1
Expected vs Target	N/A		0		0		-1		-1		-1		-2		-1		-1		N/A	N/A	-2		-5		N/A	-8	

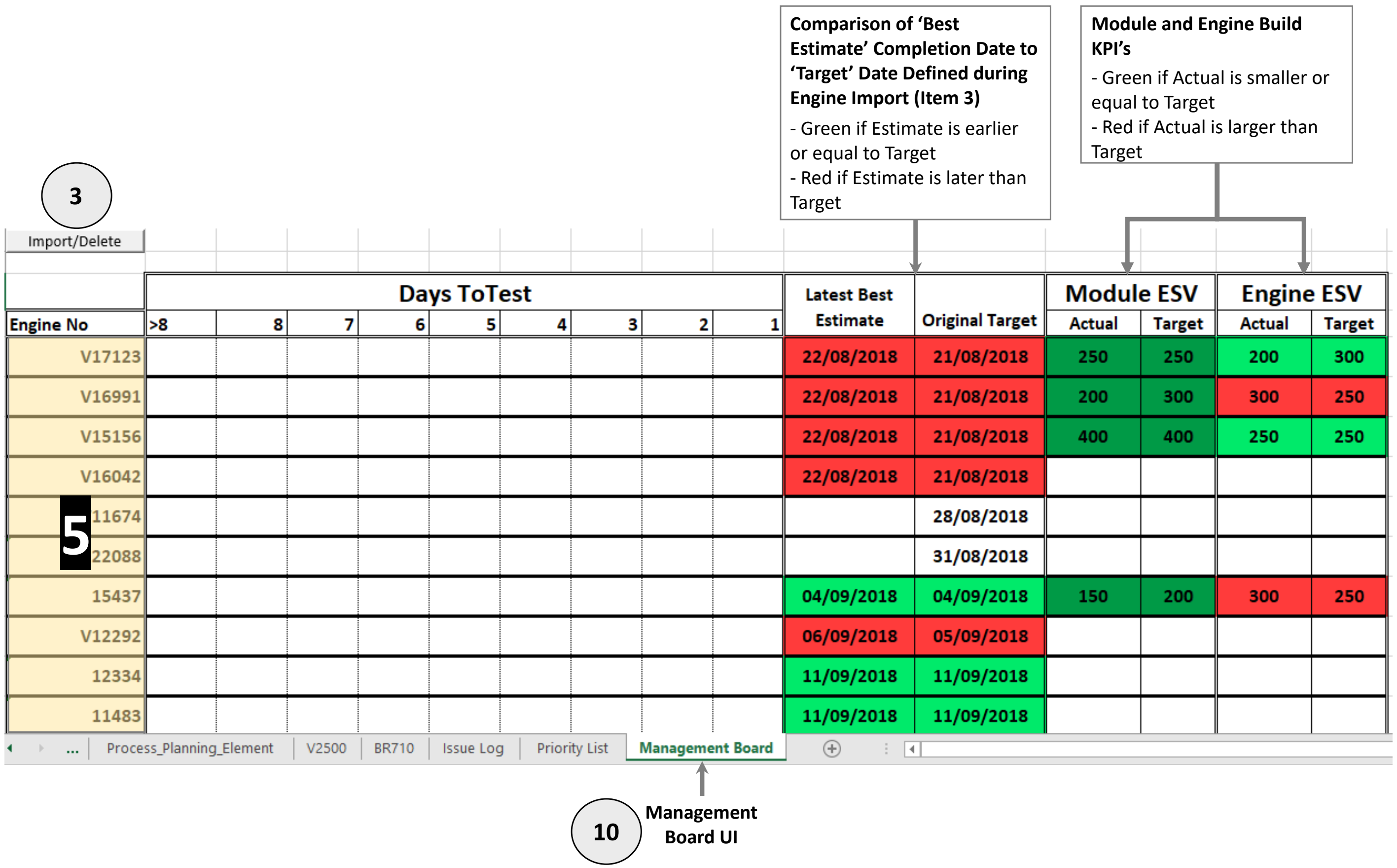
Engine Build Functionality

Engine No 5 23 Engine Type 0 Customer		13/08			14/08			15/08			16/08			17/08			18/08			19/08			20/08			21/08			22/08			Overall Date	Module ESV	Engine ESV
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3			
Engine Bay	Actual	Land Fancase (FI1)				Install 2&3 (FI2)		Install No1 (FI3)	Install Booster (FI4)		Install Gearbox (FE1)	Fancase Dress (FE2)		Fancase Dress (FE3)	Fancase Dress (FE4)	8							Install Stack (HB1)	Core Dress (HB2)		Install LPT (HB3)	Install Fan (HB4)		Snags (HB5)	Customer Eyes (RFT)		22/08	250	200
	Target				Land Fancase (FI1)	Install 2&3 (FI2)		Install No1 (FI3)	Install Booster (FI4		Install Gearbox (FE	Fancase Dress (FE2		Fancase Dress (FE3	Fancase Dress (FE4								Install Stack (HB1)	Core Dress (HB2)		Install LPT (HB3)	Install Fan (HB4)		Snags (HB5)	Customer Eyes (RF		21/08	250	300

9 Insert Engine Bay Directly

I.2. Management Board User Interface (UI)

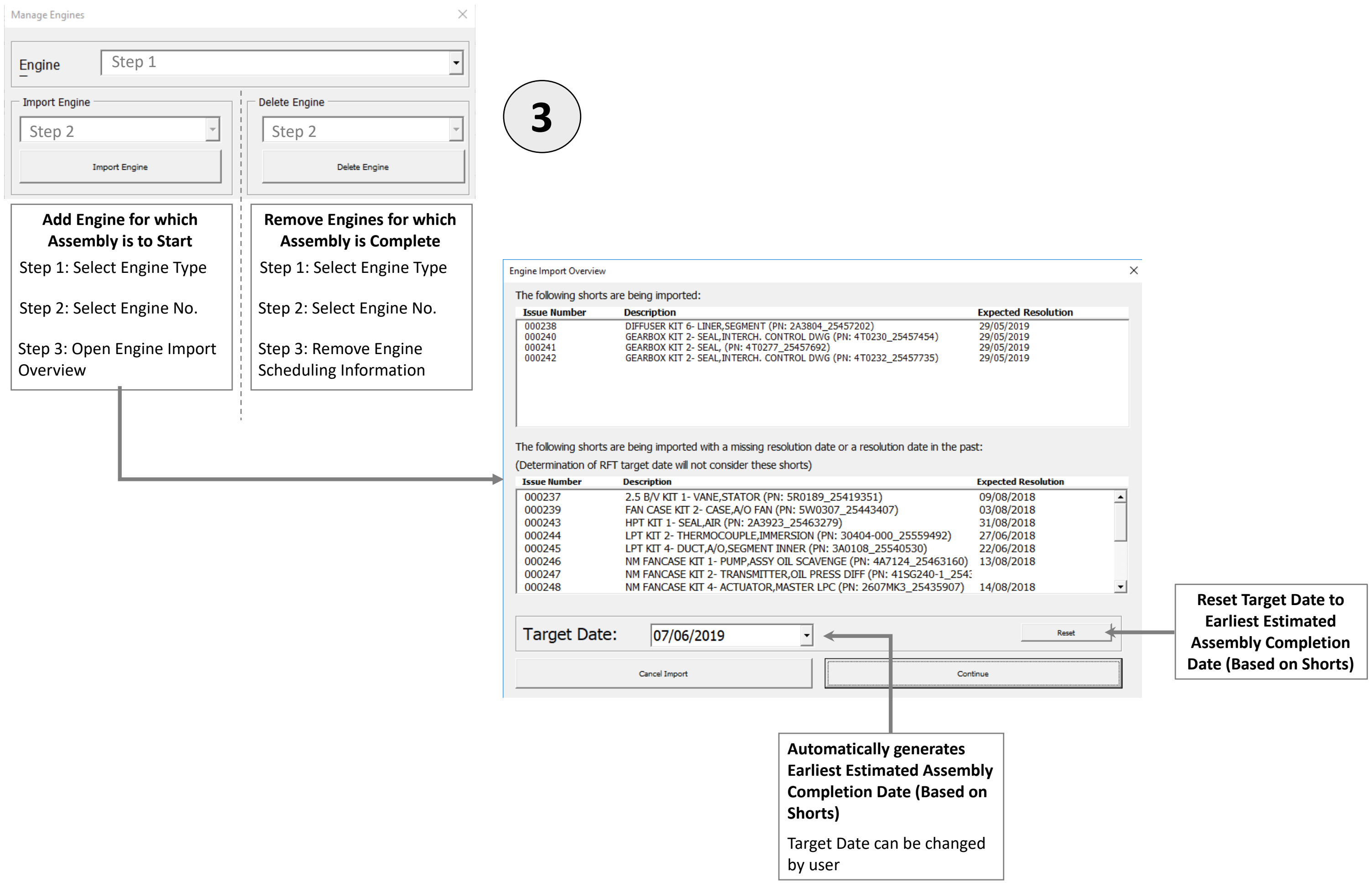
Note: Numbered items are cross-referenced in Section 4.3, ‘Requirement Traceability Matrix’. Functionality of items numbered ‘○’ is accessed by a single left-click, while functionality of items numbered ‘XX’ is accessed by double-clicking. In most cases this results in a window being opened to allow for manipulation of the schedule or to provide further information that may be required by the user. Refer to section I.3, ‘Supplementary User Interface (UI) Elements’, for an overview of the windows opened when clicking numbered items.



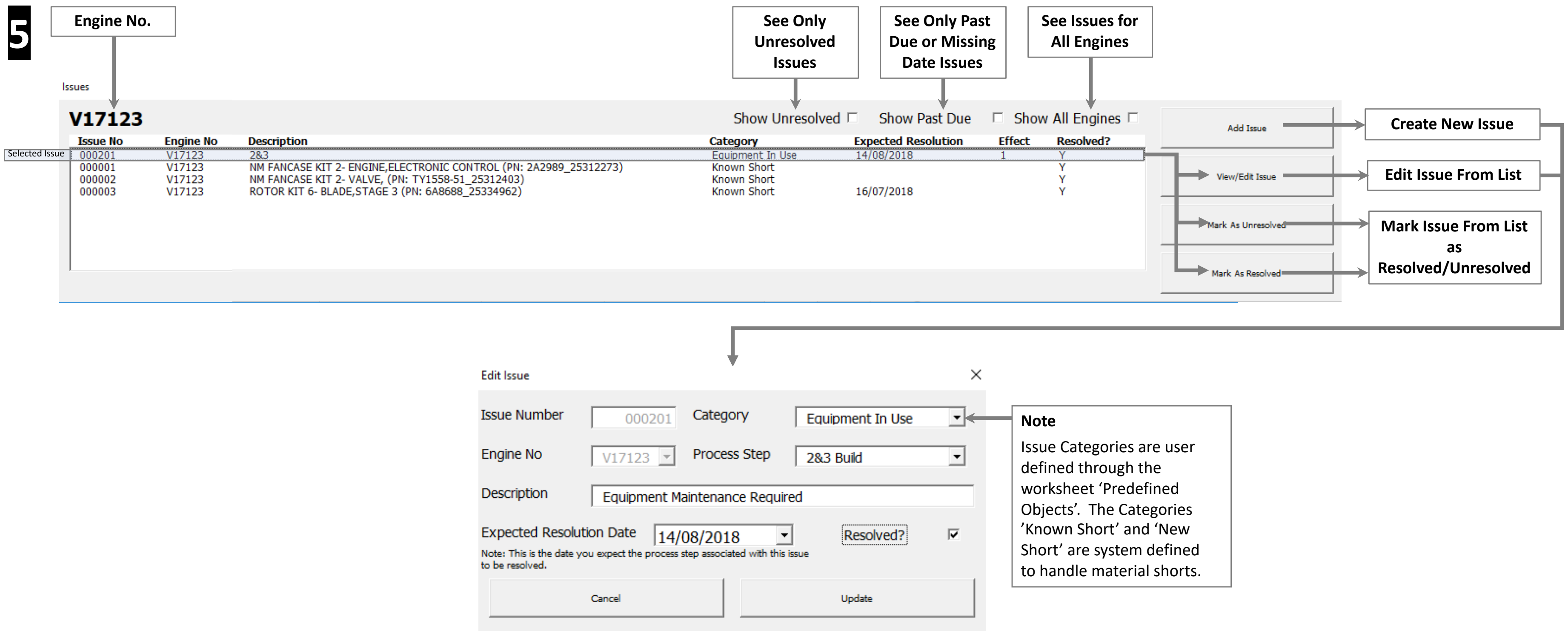
I.3. Supplementary User Interface (UI) Elements

Note: Numbered items are cross-referenced in Section 4.3, ‘Requirement Traceability Matrix’.

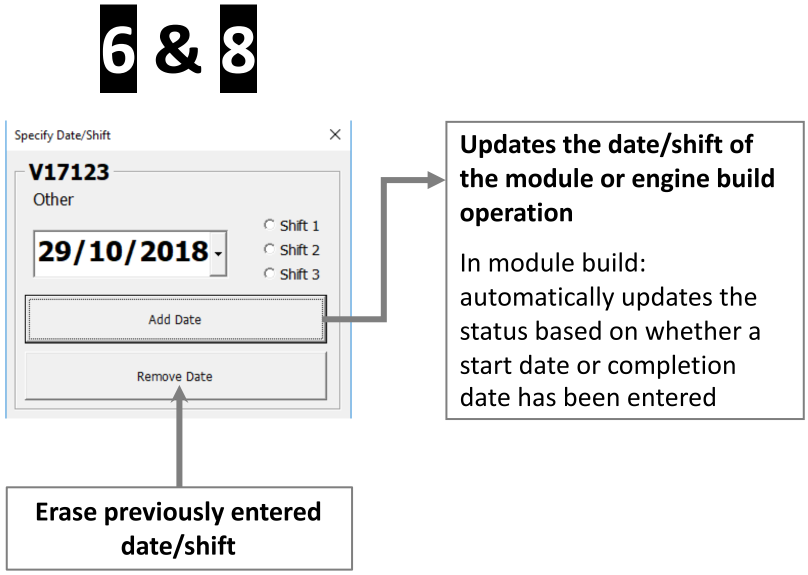
I.3.1. Import/Delete Engine UI (Item 3)



I.3.2. Issue Handling UI (Item 5)



I.3.3. Inputting Start Dates and Completion Dates (Items 6 and 8)



I.3.4. Inputting Module Build Status (Item 7)