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Systems Engineering Approach to the Automated Manufacture of Static Tool-Holding

Systems Engineering Approach to the Automated Manufacture of Static Tool-Holding

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Copyright Statement

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Abstract

Investigation of the 'design to delivery' phase is critical for establishing the productivity of a small manufacturing enterprise producing small, variable product batches. Previous research indicates how productivity of small manufacturing enterprises is subject to multiple challenges including reduced utilisation of advanced technology, having limited resources and needing the correct culture. Existing studies of productivity problem-solving have used a typical structure of: 1) problem definition through existing practice analysis, 2) identification of areas to improve and 3) use of analytical tools to rank productivity losses or 'bottlenecks'. Stakeholder input (often through interviews or group exercise) and quantitative analysis tools are key aspects of most studies, with them used in combination to determine the largest bottlenecks. While existing works have successfully identified key bottlenecks within organisations there are a lack of case studies which present the process of solution implementation and subsequent data analysis to document a full implementation cycle of changes. The implementation stage of introducing process improvements is critical in ensuring a system improvement is made and justifying the initial need for change. This research details a full implementation cycle of defining a problem through observation, identifying areas to change, selecting solutions to integrate and documenting implementation of solutions. This allows for benefits analysis over an extended time period to be conducted. A case study small manufacturing enterprise is used with a large reduction in their 'design to delivery' phase being the problem to address. Considerable analysis of key business functions has been completed through stakeholder input and time studies to identify all process bottlenecks. All bottlenecks identified have been scored based upon their impact to both the 'design to delivery' process time as well as to the stakeholder business plan. Comprehensive research was conducted on possible solutions to the key bottlenecks identified, with the most suitable solutions selected based upon a determined set of criteria unique to the company and the 'design to delivery' phase. In total 6 key bottlenecks were selected with 6 solutions chosen using the described methods. Significant benefits have been introduced to the case study company of a near 60% reduction in 'design to delivery' phase time, a new manufacturing process halving manufacturing costs and the introduction of automation. Introduction of new software packages have provided scope for further work opportunities to implement these elsewhere in the company. The research conducted has provided a unique study of implementing system improvements, building upon existing literature that typically concludes at the pre-implementation stage. Additionally, the combination of time study analysis and stakeholder input has allowed a company utilising traditional processes and typical characteristics of a small manufacturing enterprise to introduce considerable process changes, by removing any uncertainties or reluctance to do so. It is anticipated that the processes of the case study company are relatable to other small manufacturing enterprises looking to implement similar changes.

Chapter 1 Introduction

Chapter 1.1 Background on SMfE

The UK government identifies small and medium-sized enterprises as those with 0 to 250 employees (Rhodes et al, 2020). 5.9 million enterprises existed in 2019, accounting for over 99% of UK businesses. Small enterprises are defined as containing up to 49 employees (OECD, 2020). Typical characteristics of Small Manufacturing Enterprises (SMfE) can include:

- Entering a market place promoting a single product (Laforet et al, 2006)
- Using limited resources for product manufacture (Kim et al, 2008)
- High engagement and 'partner-like' relationships with customers during product development as opposed to 'acquaintance' approach of large organisations (National Academies Press, 2000)
- Less complex and informal organisational structure (Mittal et al, 2018)
- Lower use of advanced technologies or research and development (Mittal et al, 2018)
- Variable products are produced in small batch quantities meaning manual or 'handwork' techniques are utilised (Zheng et al, 2019)

The above characteristics indicate that successful SMfE: sustain a market position in single product markets, select suitable equipment for product manufacture and achieve a good reputation amongst customers. Additionally, they will overcome a less formalised management structure by instilling the correct culture.

One challenge for SMfE is maintaining market position by adapting to market condition changes from competition both inside and outside of their chosen industry (Laforet et al, 2006). Competition increases the need for SMfE to innovate new products. Laforet et al studied 1000 UK SMfE by identifying requirements for successful product innovation, with findings indicating that CEO buy-in, employee empowerment, continuous market analysis and utilisation of computer-aided design/manufacturing systems were commonplace in the 'most innovative' SMfE. Similarly Bigliardi et al (2011) studied 285 Italian SMfE with 'highly innovative' examples utilising these practices whilst also training staff internally and collaborating with research institutes and universities.

As SMfE typically have limited manufacturing resource, suitable equipment selection is critical for increasing productivity. The UK House of Commons (2018) described productivity as 'total output produced per input' and identified the importance for SMfE to maximise process efficiency. One approach is utilising automation by taking mechanical tasks and designing a system to perform them in a fully automatic way (Gordon, 2018). Gordon identified three leading benefits of process automation:

1) Increased mechanical precision of parts (accuracy)
2) Reduced operating costs
3) Increased consistency of parts (repeatability)

Despite the above benefits, there are many risks and challenges associated with adopting automation.

Immediate capital investment is required for automation with Almannai et al (2008) highlighting how the interaction of man and machine can require in-depth studies to prevent process 'over-automation'. Xue (2018) discusses the importance of linking design and manufacture via computer-aided process planning for successful data exchange during automation adoption. This prevents systems from becoming separate 'automation islands'. An example of data exchange is the correct exchange of a Computer Aided Design (CAD) model to a Computer Aided Manufacturing (CAM) software for programming (Xue, 2018).

Another possible automation challenge is adhering to health and safety regulations where robotic loading is utilised. As MTDCNC (2020) state, robotic loading equipment selection involves choosing between industrial robots or collaborative robots (cobots). Industrial robots require increased safety systems such as protective caging due to being high power systems, therefore increasing the financial resource requirements. Cobots are emerging as a cheaper alternative with reduced regulations and the capability to operate within a human-occupied workspace.

Maintaining a good customer reputation requires a SMfE to continue supplying quality products. Sahoo et al (2017) studied the use of Total Quality Management (TQM) systems in Indian SMfE. They found a reluctance to adopt TQM in multiple cases due to it being a 'daunting' concept needing expertise and high operational costs to implement. TQM consists of 8 principles using internal data to drive improvements including customer focus, continuous improvement and fact-based decision making (ASQ, unknown). Eriksson (2015) studied TQM across different sized organisations and concluded that its use within manufacturing has been left behind by the likes of the service industry. A possible reason is TQM complexity preventing SMfE implementing it effectively (Eriksson, 2015) which was also found by Sahoo et al.

A final challenge for SMfE relates to personnel and culture. Lestari et al (2014) studied organisational culture within a group of SMfE and determined that SMfE culture is not man-made. The culture is a direct effect of the values and decisions made by management which impact all employees. Lestari et al also identified that negative cultures contained a lack of quality control, standard operating procedures and future strategy.

The challenges presented highlight how SMfE can experience great success or difficulty through decision-making. Correct decisions are critical in ensuring the right SMfE culture is developed and allowing the SMfE to overcome challenges associated with: introducing processes and systems for maintaining product quality, manufacturing productivity and achieving market potential.

Chapter 1.2 Case Study Company Background

A case study analysis of a UK-based SMfE has allowed this research to be completed. The SMfE provides manufactured solutions for cutting tool-holding and component work-holding in the Computer Numerical Control (CNC) machine tool industry. The focus of this research will be on the tool-holder products discussed within chapter 1.3.

Key details about the SMfE include:

- Approximately 40 staff
- Products are designed, manufactured, inspected and assembled in-house
- Utilisation of CNC, CAD and IT equipment for the 4 processes described above
- 2 production shifts run Monday to Thursday and 1 shift on Friday

Additional detail on products, existing equipment and the various manufacturing processes available with the existing equipment are detailed in Appendix 1.

Initial observations identified common SMfE characteristics for the case study in line with chapter 1.1 including a defined culture, product innovation and partnerships with academic institutes. Additionally, the SMfE has close customer collaboration to maintain a good reputation. Ongoing research and development in certain areas is minimal, possibly due to prioritising day-to-day operations.

A large reliance on skilled operators and manual 'handwork' techniques was observed as proposed by Zheng et al (2019) with minimal automation utilised. The existing practices will be discussed in further detail in chapter 3. An industry standard accredited quality management system exists within the company.

The above details were beneficial in providing an early indication of the potential challenges ahead and allowed for definition of the research problem in chapters 1.3 and 1.4.

Chapter 1.3 Research Problem Definition

For the SMfE this research was deemed essential due to their requirement to shorten the 'design to delivery' process time for tool-holder manufacture. Currently tool-holder sales contribute over 50% of combined annual turnover with the belief that turnover could be increased through productivity improvements. The 'Design to Delivery' (DTD) process time (from designing a tool-holder to the assembled tool-holder being delivered) was estimated at 6 weeks (30 working days) by the SMfE management. The long-term requirement is to reduce the DTD process time to 2 weeks (10 working days), therefore allowing 'catalogue status' to be achieved.

Addressing the problem of reducing the DTD process time requires a suitable methodology considering existing studies on engineering problem-solving and problem-solving within SMfE. The defined methodology will provide an underlying framework to investigate and address the leading causes for the 30 days' time estimate, therefore allowing for identification of possible solutions to implement and reduce this.

The managing director of the SMfE has approved the use of all images and data presented within this research, with any confidential data masked and/or renamed generically to prevent disclosure. From chapter 3 onwards the term SMfE refers directly to the case study company unless otherwise specified.

Chapter 1.4 Research Aim & Research Objectives

The detail from chapters 1.1 to 1.3 allowed a defined research aim to be created:

To produce a case study for improving the 'Design to Delivery' (DTD) process lead time of a Small Manufacturing Enterprise (SMfE) through a suitable engineering problem-solving approach which allows implementation of new technologies to improve process productivity and equipment utilisation

The aim encapsulates the requirement to continuously consider the impact on the DTD process time throughout the research and ensures a logical methodology is utilised. A selection of key business functions associated with tool-holder DTD are to be analysed, correlating with the below research objectives:

- To familiarise with key business functions within the existing tool-holder DTD process and collate data on process timings
- To identify a group of key 'bottlenecks' in the existing DTD process and investigate appropriate solutions to remove or reduce these
- To review new technologies associated with the manufacturing and inspection bottlenecks identified
- To investigate the existing CAD software and parametric design tools to determine the applicability of parametric design in tool-holder design
- To implement a solution allowing for automated, 'lights-out' manufacture of tool-holders
- To introduce a method of stocking common material utilised in manufacturing key tool-holder products
- To utilise existing data and introduce a system for identification and management of current fixture equipment used in tool-holder manufacture
- To investigate and implement a CAM solution following software investigation, whilst capturing the challenges of implementation into the SMfE
- To investigate industry 4.0 solutions for measuring Overall Equipment Effectiveness (OEE), machine utilisation and establishing the benefits and IT requirements to collect live manufacturing data, before identifying an opportunity for future implementation

Initial SMfE stakeholder input helped determine these objectives by considering the long-term business strategy for the tool-holder DTD process.

Chapter 1.5 Thesis Outline

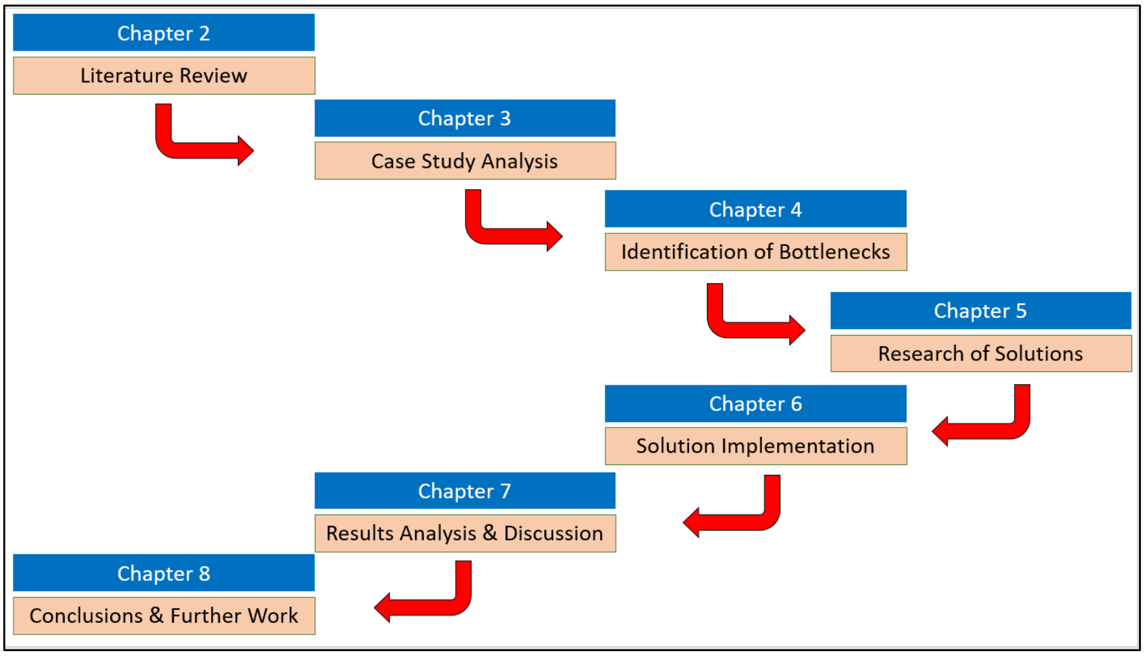


Figure 1.5-1 – Flowchart of thesis outline

This chapter introduces a summary of the content covered within chapters 2 to 8 as documented in figure 1.5-1.

Chapter 2 contains a review of existing methodologies utilised in engineering problem-solving as well as individual analytical tools. The review then proceeds to analysing example case studies using these methodologies and analytical tools within SMfE where possible. The findings are discussed for both general and SMfE specific use, with identification of the positive and negative aspects of existing research helping to define the intentions of this work. Chapter 2.4 sees selection of both an applicable methodology and analytical tools which are documented in a flowchart plan for chapters 3 to 7.

Chapter 3 studies the DTD process in the key business functions allowing for capture of positive and negative observations as well as process time study data. The reader is provided with an in-depth understanding of these business functions in terms of how they fit into the DTD process as well as detail on the existing technologies used.

Chapter 4 collates the process bottlenecks from chapter 3's negative observations with focus placed on the impact of each on the overall DTD process time. Additionally, input is used from the case study company to compare and rank the leading bottlenecks to implement process improvements against.

Chapter 5 investigates available technologies and possible solutions to reduce the process lead time of the key bottlenecks identified within chapter 4. This analysis considers the research problem defined within chapter 1.3 and the relevance of solutions to answering the research problem. In chapter 5.3 multiple possible solutions are proposed for each key bottleneck with comparisons of these made against defined criteria. Solutions are chosen for each bottleneck based upon the defined criteria before a justification of how each solution addresses the research problem.

Chapter 6 details a flowchart of milestones for implementing the chosen process improvement solutions. This chapter documents the full implementation of all process improvements with the key implementation milestones documented in chapter 6.2 and additional implementation milestones documented in chapter 6.3.

Chapter 7 uses performance metrics collated throughout chapters 3 to 6 to provide a numerical analysis of the DTD process before and after solutions are implemented. This includes determining a new DTD process lead time as well as financial analysis of the cost of manufacturing and the productivity gains increased as a result of the work completed. A discussion is made on the research as a whole and how it can be applied as a useful case study within the engineering problem-solving subject for others.

Chapter 8 details how the research has met the aim and objectives defined within chapter 1 as well as documenting specific challenges experienced and lessons learned by the case study company. Opportunities for further work are also discussed.

Chapter 2 Literature Review

Chapter 2.1 General Engineering Problem-Solving Approaches

Prior to studying SMfE cases general engineering problem-solving methodologies are introduced with consideration of their applicability to the research problem.

Reverse engineering (RE) is defined as a method of 'invention based on knowledge and data acquired from earlier work' (Wang, 2010). RE starts at the end product/goal/system and works backwards to determine the key milestones in reaching the start point. Wang refers to RE as the 'technology of reinvention'. An example discussed by Bell (2006) relates to software developers reverse engineering software code to identify potential software bugs.

The '5 whys' technique (see figure 2.1-1) is a root-cause analysis problem-solving tool popularised by Toyota in Japan (Card, 2016). Card states that asking why upon problem identification and continuing to do so for each answer leads to a clear solution as figure 2.1-1 illustrates. Despite this Card argues that narrowing problems to a single root-cause is not always suitable for 'driving improvement', referring to its unsuitability for their case study of complex health care systems.

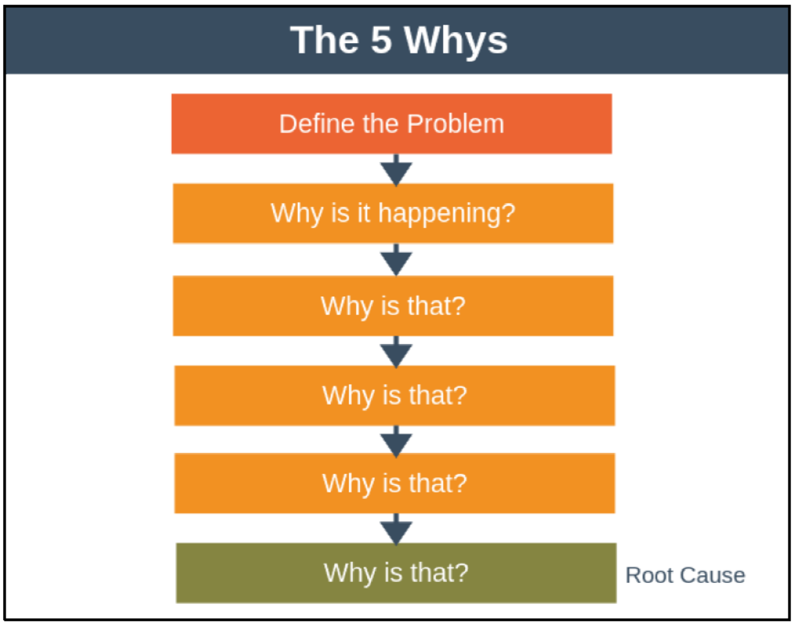


Figure 2.1-1 - Example workflow which a 5 whys process takes – (Anonymous, 2020)

Sharp (1991) introduces a methodical framework to engineering problem-solving through chronological process tasks in figure 2.1-2. This problem-solving methodology was utilised by Sharp in design engineering subject teaching. A key aspect is 'recognising a need' where it must be ensured the problem identified is the fundamental issue and not a symptom of a different problem. Incorrectly recognising the need can potentially lead to 'inadequate designs' (Sharp, 1991).

1) **Recognizing a need**
2) **Defining the problem, the objectives and the constraints**
3) **Collecting information and data**
4) **Generating alternative solutions**
5) **Evaluating the consequence of different solutions**
6) **Deciding and specifying the final 'best' solution.**

Figure 2.1-2 - Problem-solving framework tasks as detailed by Sharp (1991)

Sharp discusses that the increasing complexity of modern engineering systems established a need for systemic engineering approaches to design. Wasson (2015) describes an engineering system as containing integrated interoperable elements configured to allow users to achieve 'performance-based mission outcomes' with a probability of success. Potential causes which risk system failure must be prevented to maximise a system's success. A systems engineering approach is defined as an 'interdisciplinary approach and means to enable the realisation of successful systems' by The International Council of Systems Engineering (INCOSE) (Caillaud, 2016).

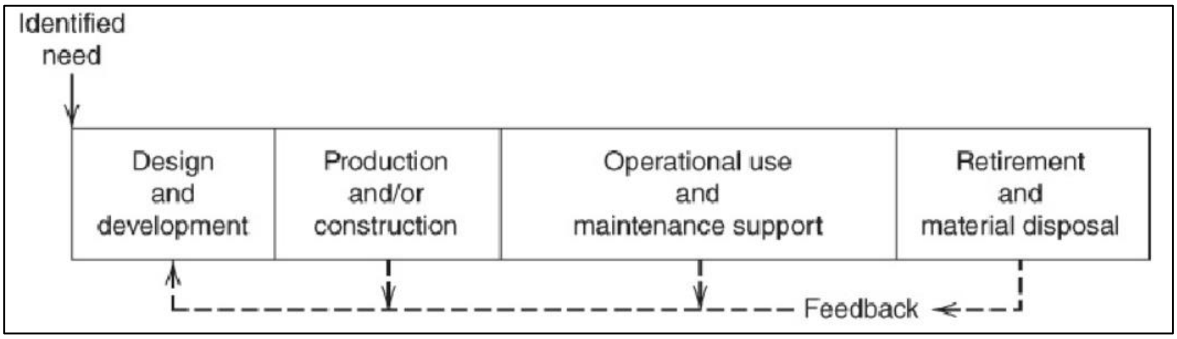


Figure 2.1-3 – System life cycle as defined by Blanchard et al (2016)

Figure 2.1-3 illustrates an engineering system life-cycle where a systems engineering approach is used to identify system problems. This is an essential requirement in allowing continuous improvement (Blanchard et al, 2016). Blanchard et al (2016) agree with the common SMfE challenges identified in chapter 1.1 and suggest that overcoming these establishes the need for systems engineering. Their work suggests a successful systems engineering approach utilises suitable analysis tools including top-down/bottom up analysis and the life-cycle analysis. A more detailed life-cycle analysis is seen in appendix 2 for further reference. Both Blanchard et al and Sharp's research highlight the need for good problem definition.

Kamrani et al (2010) also agree that a good systems engineering approach within manufacturing companies helps 'define a problem'. They state that a systems engineer adds value by measuring and reducing system risks. Trainor et al (2007) proposed that including stakeholders (anyone impacted by a system) in systems engineering problem definition is essential to 'completely define a problem'. Kamrani et al agree with this by stating that addressing stakeholders' concerns is a 'key objective'. Stakeholder analysis helps in defining:

1) Stakeholders requirements/wants/needs of a system
2) The functions, objectives, measures and constraints of a system
3) The Political, Economic, Social and Technological (PEST) factors which aid problem research and development (Economic Times, Unknown)

Environmental factors / **Enter-prise factors**	**Opportunities**	**Threats**
Strengths (Stärken)	**SO strategies** Use internal strengths to develop external opportunities (best case)	**ST strategies** Use own strengths to reduce external threats or to avoid
Weaknesses (Schwächen)	**WO strategies** Reduce internal weaknesses or build-up of absent strengths to perceive external opportunities	**WT strategies** Reduce internal weaknesses and simultaneously avoid threats (numerous WT combinations) -> critical situation -> defensive strategies (disposal, liquidation, turnaround)

Figure 2.1-4 – Diagram of Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis – (Team Schönsleben, 2014)

SWOT analysis (see figure 2.1-4) can assist in collating stakeholder input by identifying the positives (strengths and opportunities) and the negatives (weaknesses and threats) of a process. Categorising SWOT observations allows the user to collect internal and external (PEST) considerations into a tangible output to aid decision-making and engineering problem definition.

This chapter has introduced some problem-solving methodologies which could be utilised within the case study SMfE in different ways. For example:

- Reverse Engineering – starting at a finished tool-holder and reverse engineering to determine requirements for successful manufacture
- 5 Whys – identifying problems in the DTD process and their associated root causes
- Systems Engineering – collating data on existing systems and adding value by reducing risks through proposing solutions for system improvement
- Stakeholder Analysis – collating stakeholder requirements and external factors to help in problem definition

Chapter 2.2 Review of Industry Example Engineering Problem-Solving Literature

In this chapter examples of engineering problem-solving methodologies utilised in case studies are provided, with a focus on SMfE where possible to aid with research methodology selection.

Vosniakos et al (2006) investigated the re-engineering of a SMfE security door production process using multiple analysis tools to document the 'as-is' scenario of the SMfE. It was determined that analysis tools were critical in identifying weaknesses in the 'as-is' scenario, with the Failure Mode & Effects Analysis (FMEA) determining the need for new machinery due to long cycle times being a leading 'failure mode'. Other tools utilised included Quality Function Deployment (QFD), Activity-On-Node (AON) [see figure 2.2-1], Work in Progress (WIP) analysis and cost/cycle time studies.

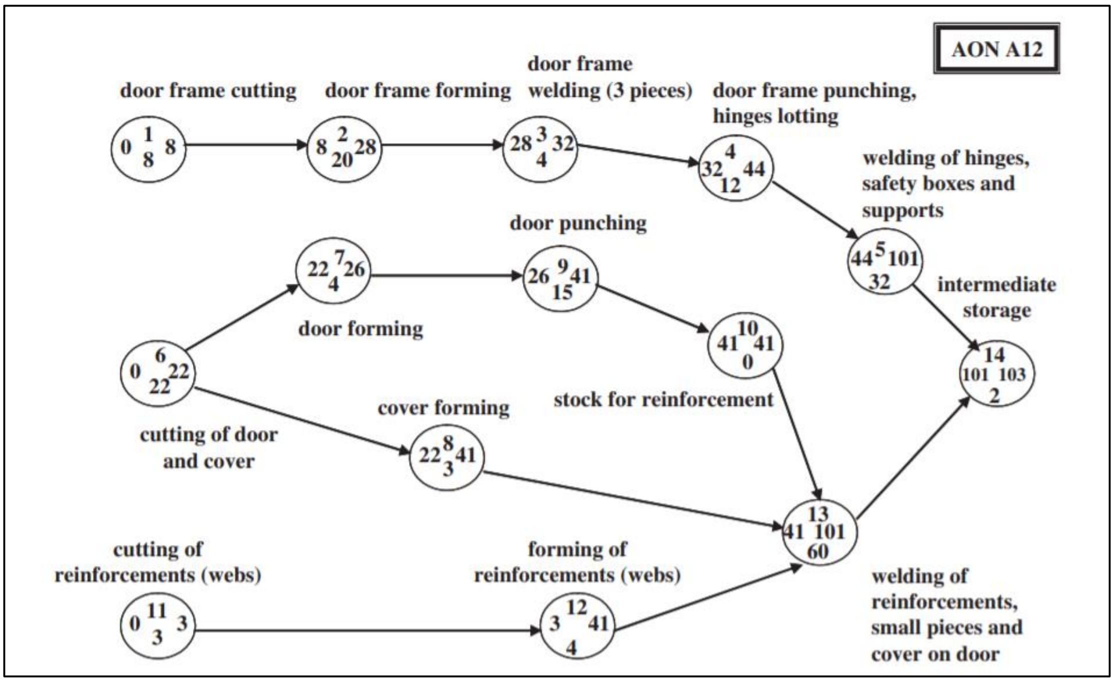


Figure 2.2-1 – Activity-On-Node analysis of security door manufacture – Vosniakos et al (2006)

The AON tool provides a simple process flow detailing important timings for every process (earliest start date, latest finish date and process duration) in addition to identifying concurrent processes.

Buczacki et al (2018) utilised a systems engineering approach within a SMfE producing radio frequency identification technologies. A typical process flow is discussed for projects with each project providing unique challenges. One finding suggested that the SMfE partially utilised systems engineering principles, however a lack of focus on using internal procedures was also identified. The SMfE determined that achieving growth through winning larger projects required internal procedure creation in order to minimise risks and costs, improve project delivery times and improve customer satisfaction.

Buczacki et al discuss the use of a 7-step systems engineering methodology as documented below. They state that larger organisations are more likely to adopt this than SMfE:

1) State the problem
2) Investigate alternatives
3) Model the system
4) Integrate the system
5) Launch the system
6) Assess performance of the system
7) Re-evaluate the system

Figure 2.2-2 illustrates the 7-step methodology as a V diagram with the 7 steps not always happening chronologically due to system developments impacting the previously defined specifications. The V diagram demonstrates these feedback loops by connecting steps with two-way arrows.

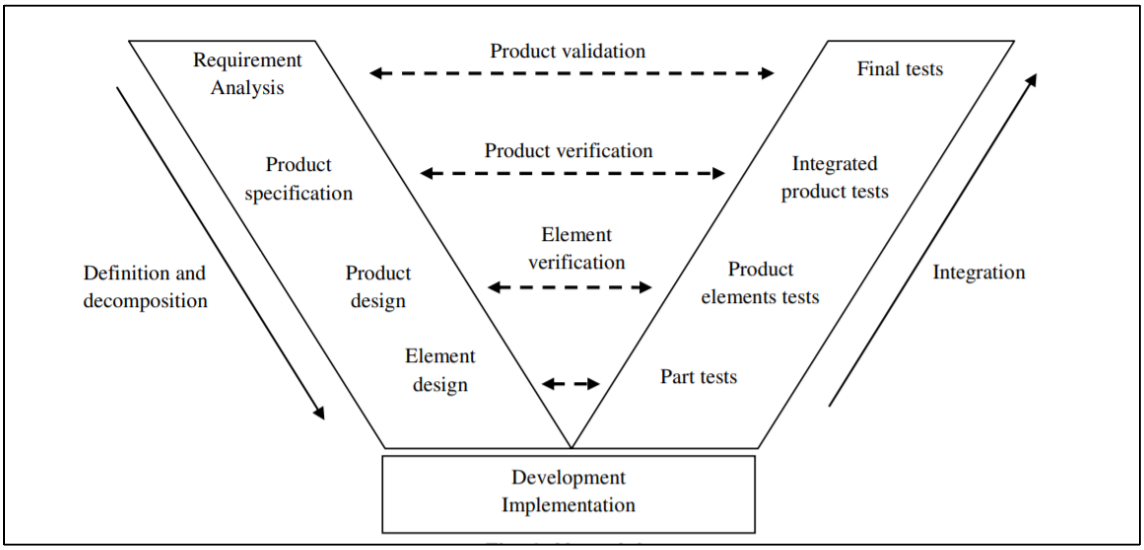


Figure 2.2-2 - V type diagram systems engineering approach defined by Buczacki et al (2018)

Gräßler et al (2018) reviewed systems engineering opportunities for specific SMfE use due to present approaches being "not appropriate". They refer to systems engineering as a 'holistic' approach covering a full system life-cycle and suggest that the variable internal procedures of SMfE make adaptation of large enterprise approaches impractical. Gräßler et al refer to 6 principles for a SMfE implementing systems engineering (see figure 2.2-3).

One conclusion implied that SMfE and larger enterprises benefit and suffer in different areas when utilising the figure 2.2-3 methodology. In SMfE project experts' communication and collaboration is simple due to having a limited number of personnel. SMfE issues occur when extra workload is required for frequent stakeholder communication, division of larger projects and determining the amount of data to use for decision-making. It was discussed that good internal communication must prevent generation of partial solutions only suiting certain requirements.

Figure 2.2-3 - Six systems engineering principles for a SMfE to consider - Gräßler et al (2018)

The figure 2.2-3 methodology was applied to a SMfE producing unique and complex automated equipment for construction applications. Leading issues found included overrunning projects and a lack of collaboration between specific stakeholders. Gräßler et al determined that requirements engineering and IV&V had limited potential due to limited stakeholder knowledge and IV&V not improving the stated issues. Although new process implementation would create extra work, improved IC&C, documentation, project phase implementation and an iterative approach were identified as improvement opportunities.

Mason-Jones et al (1998) presented a case study for redesign of a manufacturing system in the logistics industry. Their methodology focused on systematic thinking or seeing problems as a 'complex of interacting parts' where system success 'cannot be replicated by the simple addition of its parts'. The UDSO approach in figure 2.2-4 was discussed.

Understand – problem definition, systems boundaries and performance metrics

Document – Modelling a system to set benchmarks using tools such as process mapping

Simplify – utilising the modelled system to identify 'waste' or inefficiencies

Optimise – introducing methods of control e.g. statistical process control

Figure 2.2-4 - UDSO approach used by Mason-Jones et al (1998)

The case study analysis focused on establishing the 'Understand' and 'Document' phases through market analysis, process mapping and data collection. Three tools are utilised: Input/Output Analysis (IOA), Process Flow Analysis (PFA) and Zoom and Focus Analysis (ZFA).

The observations suggested that isolated operations were disconnected from production scheduling with different departments working to different production targets (i.e. number of components produced per shift, number of orders completed per shift etc.). This disconnect negatively impacted order delivery performance. Stakeholder input was captured from interviews in addition to studies and historical data analysis.

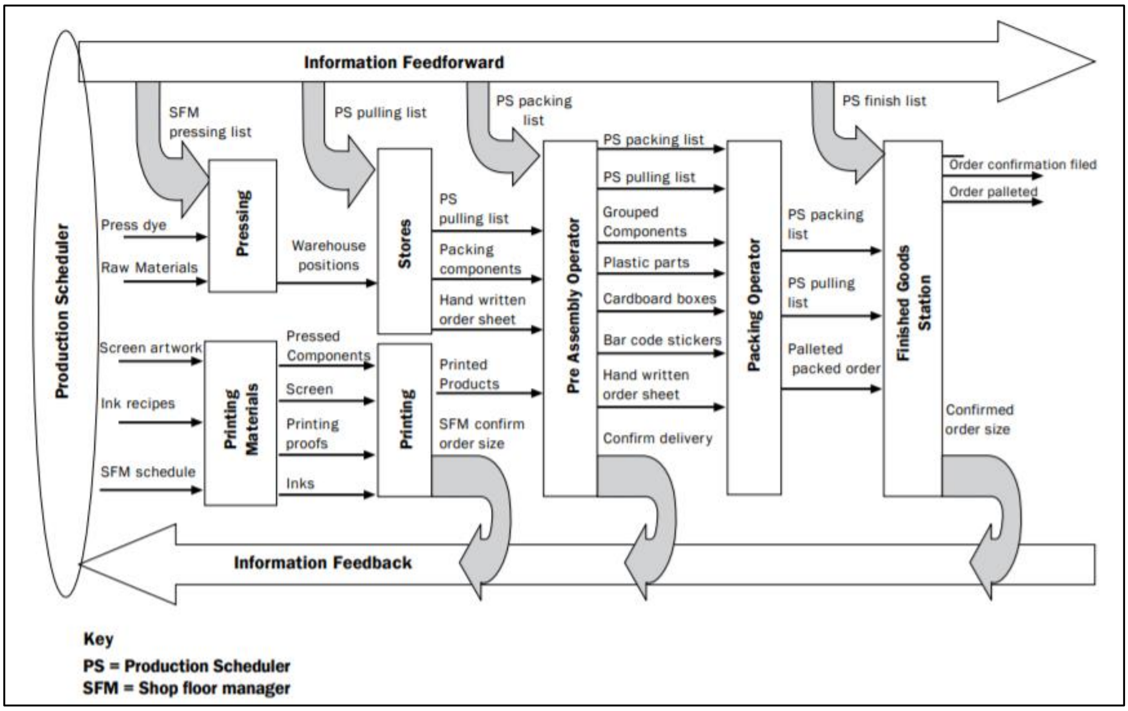


Figure 2.2-5 - Case study company IOA – Mason Jones et al (1998)

The figure 2.2-5 IOA contains multiple processes and systems highlighting all production planning inputs and outputs prior to goods shipment. Individual PFA flowcharts illustrated specific processes such as material movement through the shop floor. Figure 2.2-6 illustrates a partial ZFA conducted on a 'symptom', with the analysis reflecting a 5 whys style approach to identify root causes. Mason-Jones et al (1998) conclude by developing 'as-is' and 'as-it-should-be' process flowcharts thus commencing the 'Simplify' UDSO phase as a further work opportunity.

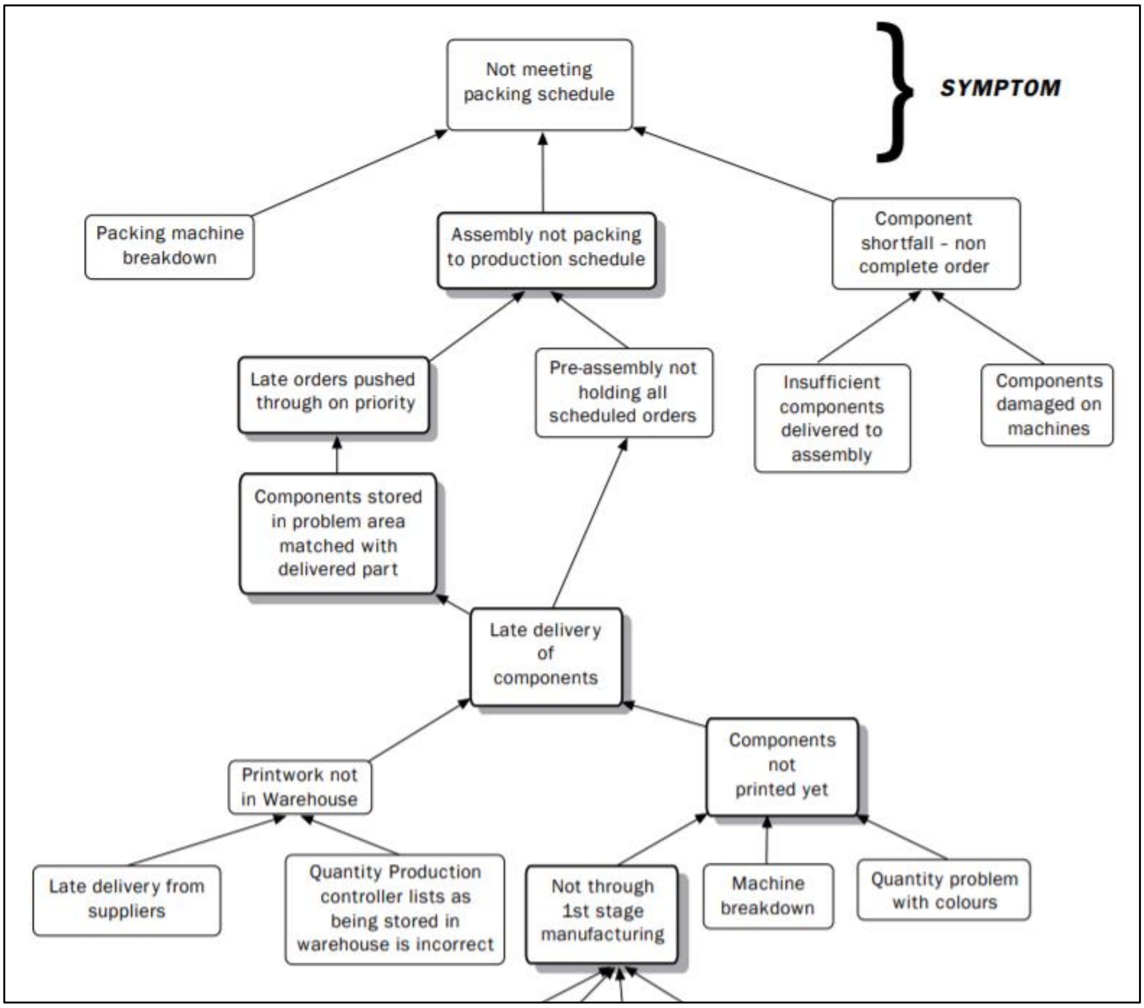


Figure 2.2-6 - Section of a ZFA within the Mason-Jones et al case study (1998)

Tagliaferri et al (2016) utilised a systems engineering approach in assessing Electric Vehicle (EV) and Internal Combustion Engine Vehicle (ICEV) life cycles. The approach analysed environmental impacts for each vehicle type associated with their manufacture, usage and disposal. Analysis tools utilised included process flow charts and hot-spot analysis with the example in figure 2.2-7 providing a visual aid of the global warming contributions of each component during Lithium ion battery manufacture. Comprehensive data is used in analysing the environmental impacts of each vehicle during use, with conclusions indicating that ICEV contribute more to global warming during use whilst EV contribute more to global warming during manufacture.

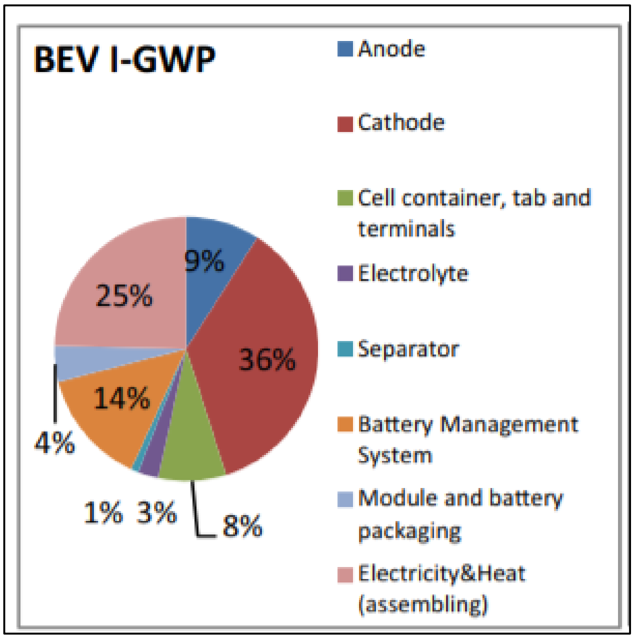


Figure 2.2-7 - Hot Spot Analysis of Global Warming Potential during EV battery manufacture - Tagliaferri et al (2016)

Holgado (2019) investigated systems engineering within Performance Based Maintenance Service (PBMS) systems by utilising a case study to determine a systems-based approach. PBMS systems are utilised when manufacturers outsource activities to companies to complete with an agreed performance requirement. A system life-cycle approach consisting of identification, concept, requirements, design, implementation, re-engineering and end-of-life phases is introduced with Holgado's research analysing the identification to design phases.

Integrated Definition for Function Modelling (IDEF0) and Unified Modelling Language (UML) analysis tools are utilised in figures 2.2-8 to 2.2-9. The IDEF0 diagram in figure 2.2-8 indicates the Inputs (I), Outputs (O), Control measures (C) and Resources required (R) to meet the central function with I1 to I3 determined through stakeholder analysis. Holgado discusses how IDEF0 can also be used for sub-system analysis through additional IDEF diagrams. The IDEF0 in figure 2.2-8 was used to generate sub-system requirements in the case study. UML is utilised in the design life-cycle phase with processes and physical items being assigned attributes. Figure 2.2-9 details the UML associated with information the PBMS system requires for supplying spare parts.

Holgado concludes by establishing that further work is needed to increase the level of detail within the IDEF0 for the case study. It is also determined that a generic systems-based approach requires defining for the life-cycle phases of implementation, re-engineering and end-of-life for PBMS systems.

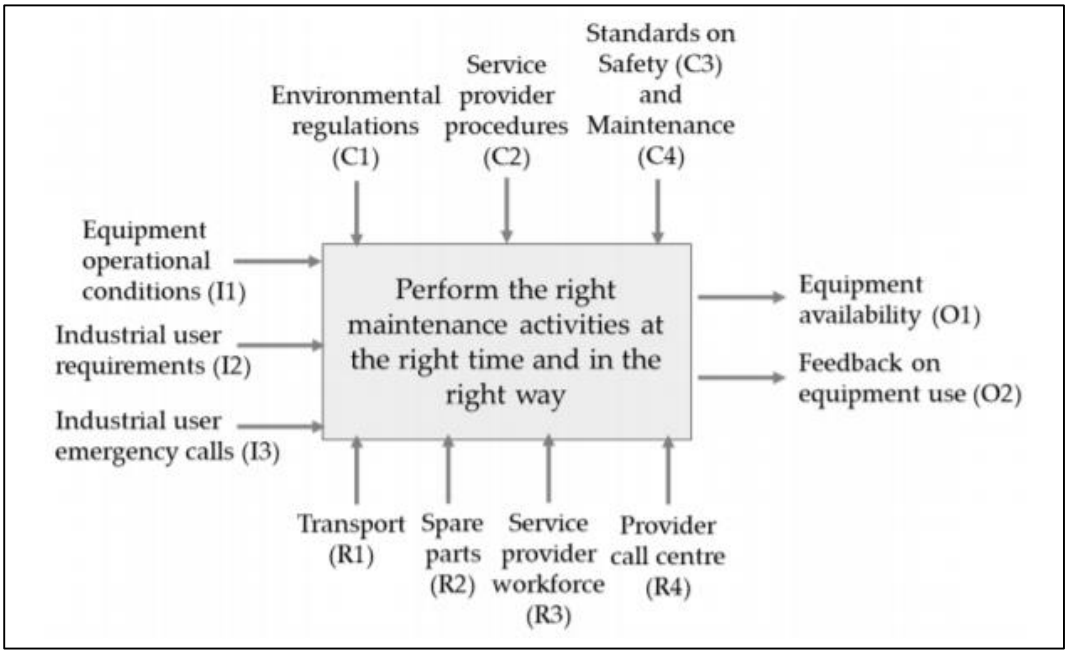


Figure 2.2-8 – IDEF0 diagram for a generic PBMS system – Holgado (2019)

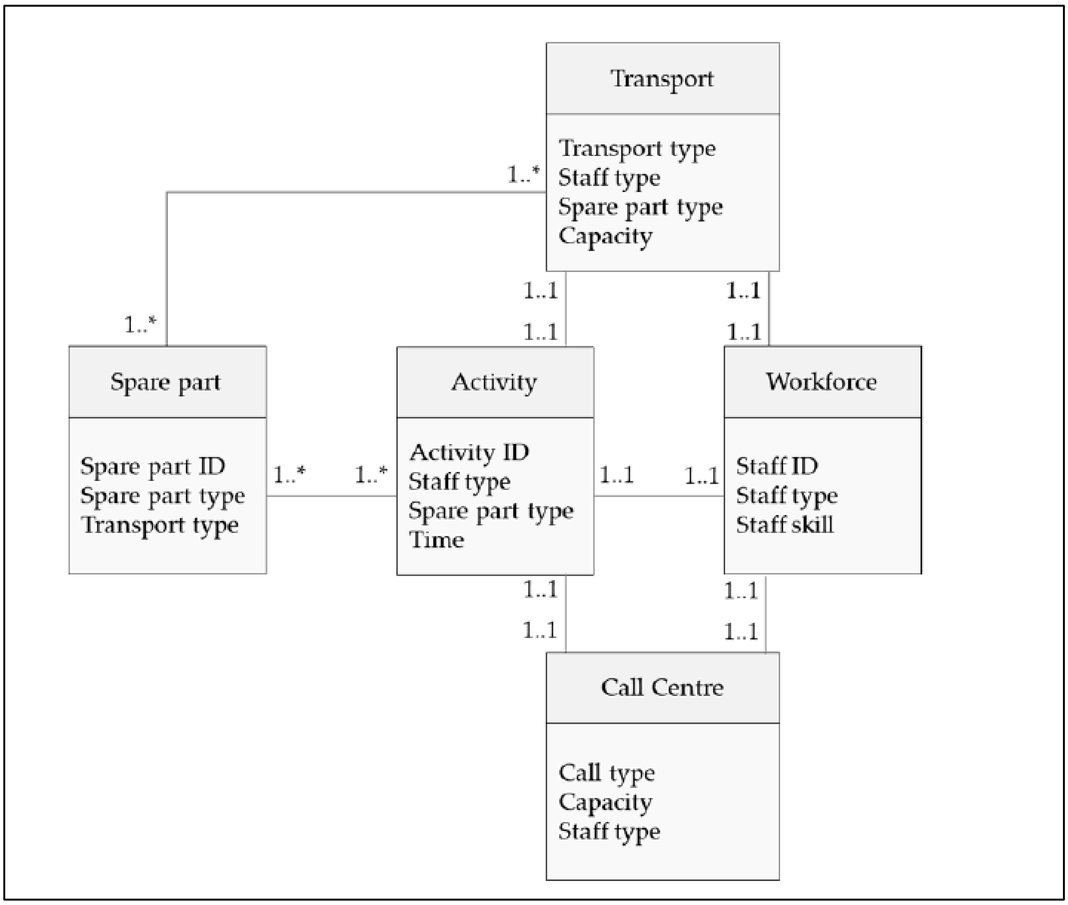


Figure 2.2-9 – UML diagram for a generic PBMS system – Holgado (2019)

Khatri et al (2016) investigated SWOT analysis in an Indian SMfE within the automotive industry. They proposed a combined SWOT and Analytical Hierarchy Process (AHP) analysis to rank the importance of SWOT observations. The SWOT-AHP method assisted the SMfE in selecting one of three lean manufacturing methodologies to implement.

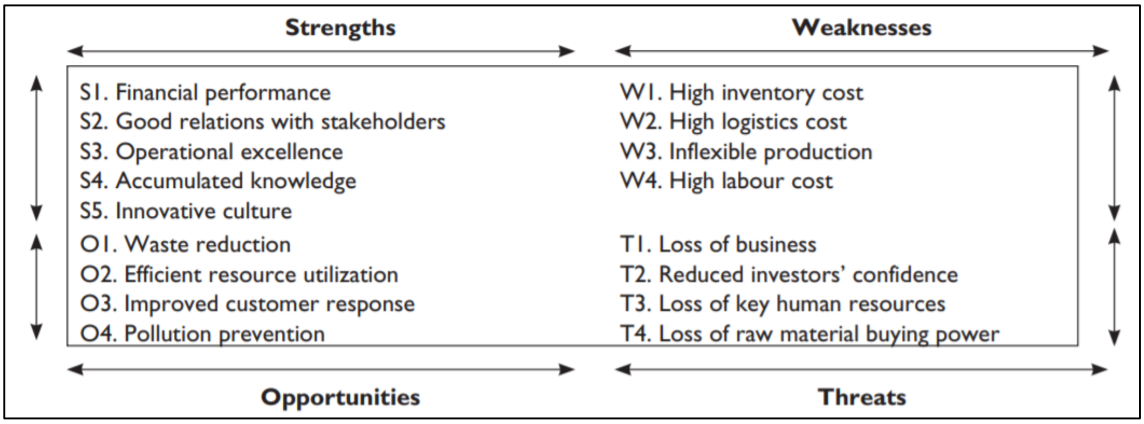


Figure 2.2-10 - SWOT analysis for Indian Automotive SMfE - Khatri et al (2016)

Figure 2.2-10 was collated from multiple stakeholder groups providing input through a steering committee who composed the SWOT matrix. Khatri et al (2016) state that the 4 SWOT categories should be limited to 10 observations each to prevent problem complexity. The AHP tool utilised the figure 2.2-10 SWOT observations through pairwise comparison to mathematically compare individual observations against each other. SWOT observations were also ranked in terms of their importance against a Noble Goal detailed in figure 2.2-11. The leading scorers from pairwise comparison were used to numerically rank the three lean methodologies in terms of their importance to the SMfE, with AHP determining that the lean and green methodology was most suitable.

The new methodology allowed for system implementations to address the leading observations including 'achieving operational excellence' and 'improving resource utilisation'. Khatri et al (2016) conclude by stating how the SMfE experienced reduced costs, reduced emissions and improved customer satisfaction.

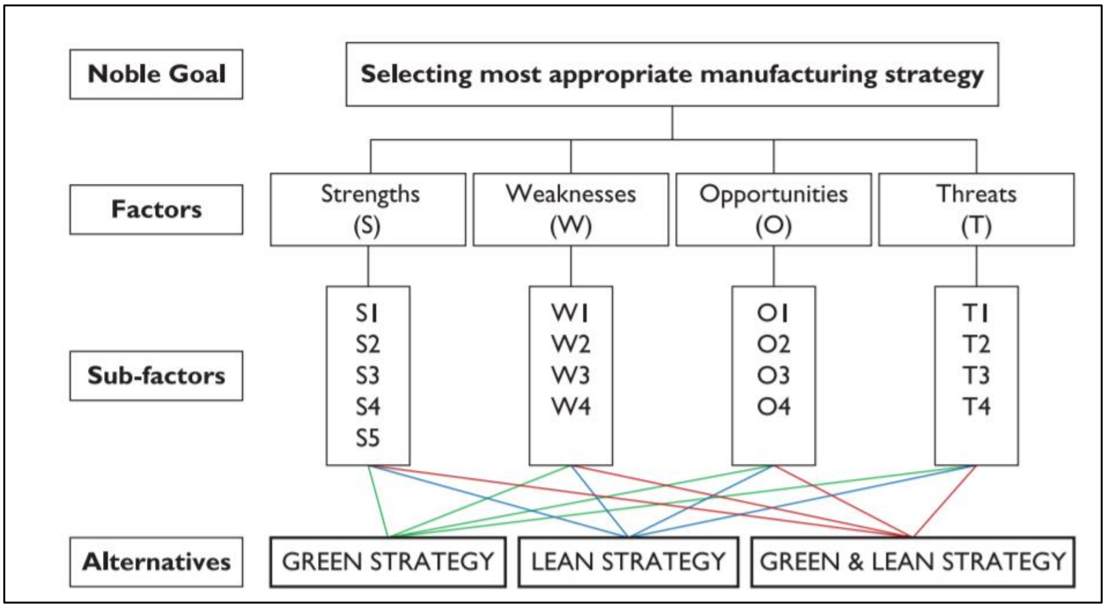


Figure 2.2-11 - AHP diagram for the Indian SMfE - Khatri et al (2016)

Toklu et al (2016) also utilised a SWOT and AHP combination as well as Root-Cause Analysis (RCA) and Taxonomy tools to propose a strategic planning model for a SMfE producing band saw machines. Figure 2.2-12 illustrates the fuzzy sequential model methodology with an Ishikawa (fishbone) diagram used for RCA. The taxonomy tool helped with 'the identification of inter-relationships between practices in a clear manner' through completion of a matrix documented in figure 2.2-13.

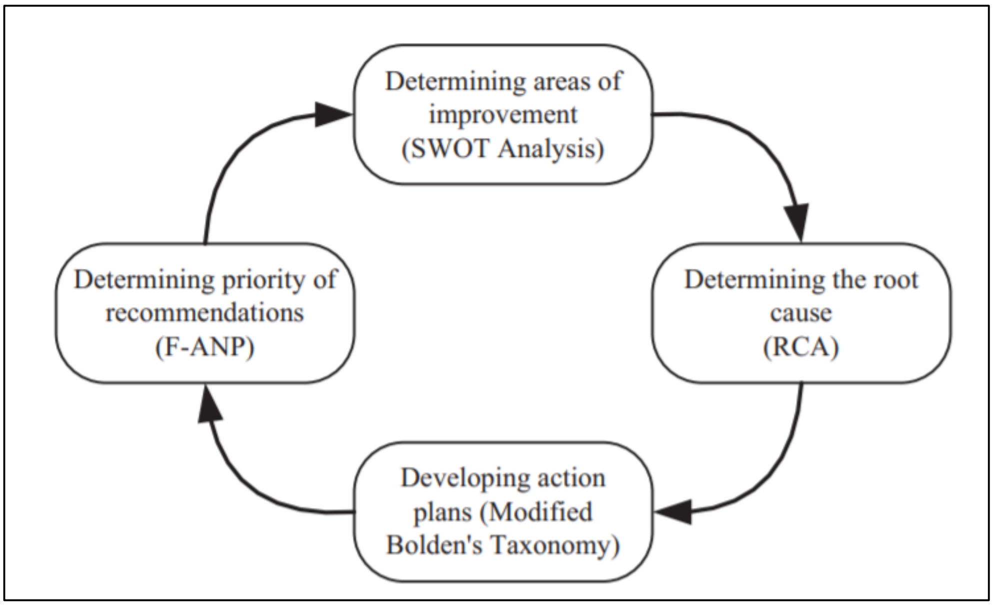


Figure 2.2-12 - Overview of Fuzzy Sequential Model (FSM) utilised by Toklu et al (2016)

	Business Focus			Organisation Focus	
Business Characteristic	A – Improved Quality	B – Reduced Cost	C – Customer Responsiveness	D – Improved Technology	E – Employee Development
1 - Design & Production					
2 – Inventory & Stock					
3 - Work Organisation					
4 – Wider Organisation of Manufacturing					
5 – Social Impact					

Figure 2.2-13 - Blank Bolden's Taxonomy Matrix Utilised by Toklu et al (2016)

The taxonomy matrix requires users to input business characteristic requirements in the red cells to achieve the business and organisation focus principles in columns A-E. Toklu et al provide an example for column A, row 1 with design and production requiring quality standards, statistical process control and total productive maintenance to achieve improved quality.

8 SMfE functions were investigated including manufacturing, product development and sales and marketing with SWOT observations collated through meetings with all employees. Open to Improvement Areas (OIAs) and subsequent Ishikawa diagrams (see figure 2.2-14) were created with the assistance of relevant stakeholders and use of the SWOT observations. Figure 2.2-14 details an OIA of 'lesser market share' with the Ishikawa diagram determining ineffective use of new media as a possible contributing factor. Toklu et al related all OIAs to the relevant cell within the taxonomy matrix with the example 'lesser market share' falling under cell 5C. The recommended solutions for this OIA determined were new media, branding and marketing.

AHP and a fuzzy number methodology were used to rank OIA importance and use the recommendations found from the Ishikawa and taxonomy diagrams. This prioritised focus on the leading OIAs with the study concluding on three immediate OIAs to address.

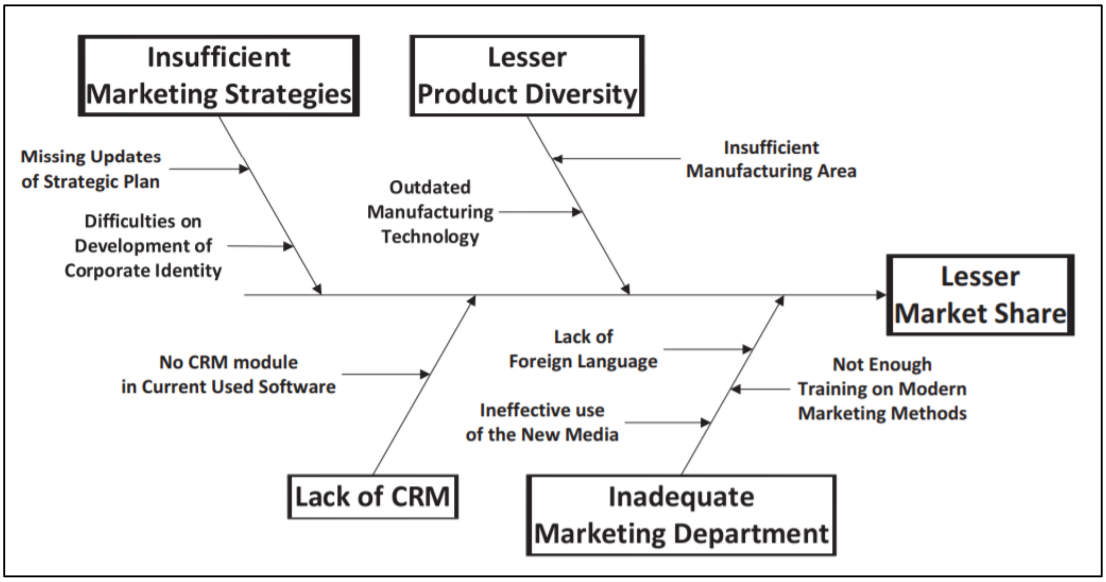


Figure 2.2-14 - Ishikawa Diagram utilised by Toklu et al (2016)

Sluismans et al (2010) researched the use of SWOT within 1200 SMfE to investigate introducing a standardised SWOT observation collection procedure. Their approach was focused on helping SMfE hold 'strategic conversations' through SWOT utilisation whilst aiming to overcome common process criticisms including a lack of thoroughness, a lack of a structured method and the limited timeframe available to perform an analysis. The procedure also aimed to prevent SMfE from capturing multiple, ambiguous SWOT observations.

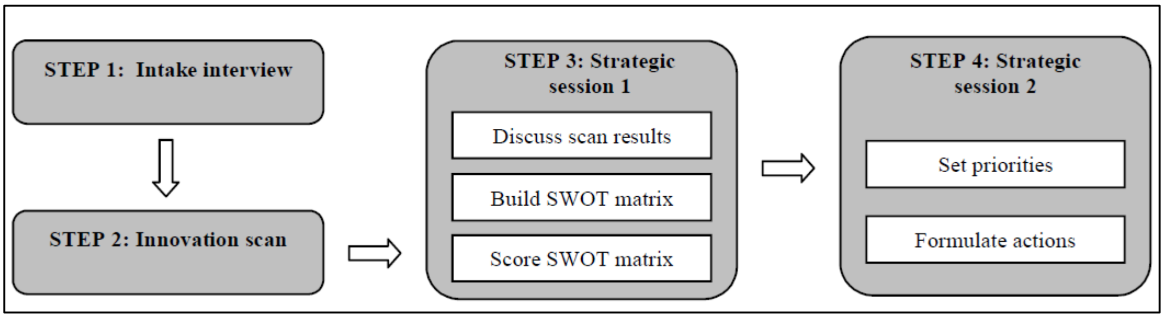


Figure 2.2-15 - The 'intervention' process utilised in SMfE by Sluismans et al (2010)

The figure 2.2-15 procedure highlights four steps to complete a SWOT analysis with step 3 being critical. Sluismans et al developed two protocols for the critical step 3: 1) building the SWOT matrix and 2) scoring the matrix. Extended group sessions with company-wide stakeholders and a facilitator to steer discussions ensured the matrix was built and scored. This ensured the sessions had a purpose, a procedure and a deliverable (see appendix 3 for further detail on the protocol methodology).

		O						T						
		trend kitchens central role in house	new materials for kitchen tops	technology - energy saving kitchen	selling kitchen plans as a separate service	sales of kitchenware by website		high costs to (re-)build houses	fierce competition - numerous kitchen chains enter the market	fierce competition - carpenters	dealers of kitchenware want to open own stores	difficulties in filling vacancies carpenters		
S	kitchens as product	6	6	4	2	0	18	1	6	6	5	5	23	41
	exclusive kitchenware	2	1	4	0	6	13	3	5	0	0	0	8	21
	kitchen designers (sales people are interior designers)	5	6	6	6	0	23	6	6	6	4	0	22	45
	location of kitchen-shops	6	0	0	6	0	12	0	6	2	6	3	17	29
	strong relationships with top architects	4	6	6	2	1	19	5	6	3	1	1	16	35
	Subtotaal A	23	19	20	16	7		15	29	17	16	9		
W	no use of computer programs to draw/ design kitchens	4	0	1	6	0	11	2	1	1	1	5	10	21
	insufficient communications between sales and installation	1	4	6	0	0	11	1	5	6	0	0	12	23
	follow up of marketing actions	4	5	4	5	0	18	1	6	6	5	0	18	36
	conditions and terms of payments	1	1	1	0	0	3	2	1	3	0	0	6	9
	lost margins due to numerous changes in projects	1	2	2	0	0	5	0	6	4	0	0	10	15
	Subtotal B	11	12	14	11	0		6	19	20	6	5		
	Eindtotaal	12	7	6	5	7		9	10	-3	10	4		

Figure 2.2-16 – Confrontation matrix example for SWOT analysis – Sluismans et al (2010)

One conclusion from participants determined that the most successful aspect of the process was achieving ‘focus’ and ‘priority’ from SWOT analysis, as ‘focusing leads to priorities and by setting priorities focus is achieved’ (Sluismans et al, 2010). The confrontation matrix in figure 2.2-16 formulated in the group sessions was praised as its scoring system allowed identification of the most beneficial strengths and weaknesses which maximise opportunities and minimise threats.

Buchmayr et al (2014) also utilised SWOT analysis during study of selective laser melting (SLM) additive manufacture. The strengths and weaknesses of SLM were listed to identify related opportunities and threats. Buchmayr et al categorised three types of SWOT strategy as:

Strategies to match Strengths with Opportunities – **Matching**

Converting Weaknesses & Threats into Strengths & Opportunities - **Conversion**

Elimination of Weaknesses & Threats – **Neutralisation**

Strengths (S)	**Weaknesses (W)**
1 Representation of complex geometries (cavities, undercuts, free-form surfaces)	1 High production costs (investment and metal powder costs)
2 Increased component complexity is achieved at no additional cost	2 Low production speed
3 Tool-free production	3 Limited component size
4 Unmanned production (overnight)	4 Good surface quality requires post-processing (blasting)
5 High material efficiency	5 Internal stress / warpage / tolerances
6 Rapid prototype production	6 Missing process monitoring (QA)
7 Direct production of tools	7 Limited metal powder availability
8 Suitable for small series	8 Great effort to optimize the process parameters for new powders
9 Suitable for many alloys	9 SLM-compatible design and adapted support structures
10 Fineness of the microstructure and good mechanical properties	10 types of process-related defects (binding defects, balling and porosity)
11 Metal structure on the base body (hybrid construction, layer composite)	11 anisotropy of properties
12 Saving of manufacturing steps	12 Uneconomical large-scale production
13 Several system providers in the EU	13 Independent system maintenance hardly possible
14 Good process controllability	
Opportunities (O)	*Dangers (T)*
1 Lower powder costs through multiple powder manufacturers	1 Lack of good designers
2 New application potential when new powder materials are available	2 Inadequate training on additive manufacturing
3 trend towards "customization"	3 Economical printing through more cost-effective manufacturing processes

Figure 2.2-17 – Part of the SWOT matrix from Buchmayr et al (2014)

The partial SWOT matrix in figure 2.2-17 allowed Buchmayr et al to associate observations to one of the three strategies. An example conversion strategy contained W1 and O1 as reducing production costs increases industry competition therefore leading to overall material cost reductions. The main conclusion suggested that detailed discussions of the SWOT strategies recorded are required, with a need for research and development activities to 'accelerate' in line with component improvements.

Benjamin et al (2009) investigated 5 whys use in reducing the scrap of a barrel manufacturing company in South-East Asia. Figures 2.2-18 and 2.2-19 highlight the use of a root-cause problem-solving (RCPS) methodology utilising Pareto analysis (2.2-18) and 5 whys (2.2-19). Pareto analysis determined that material scratching within the manufacturing processes was the leading cause of scrap when quantified by weight.

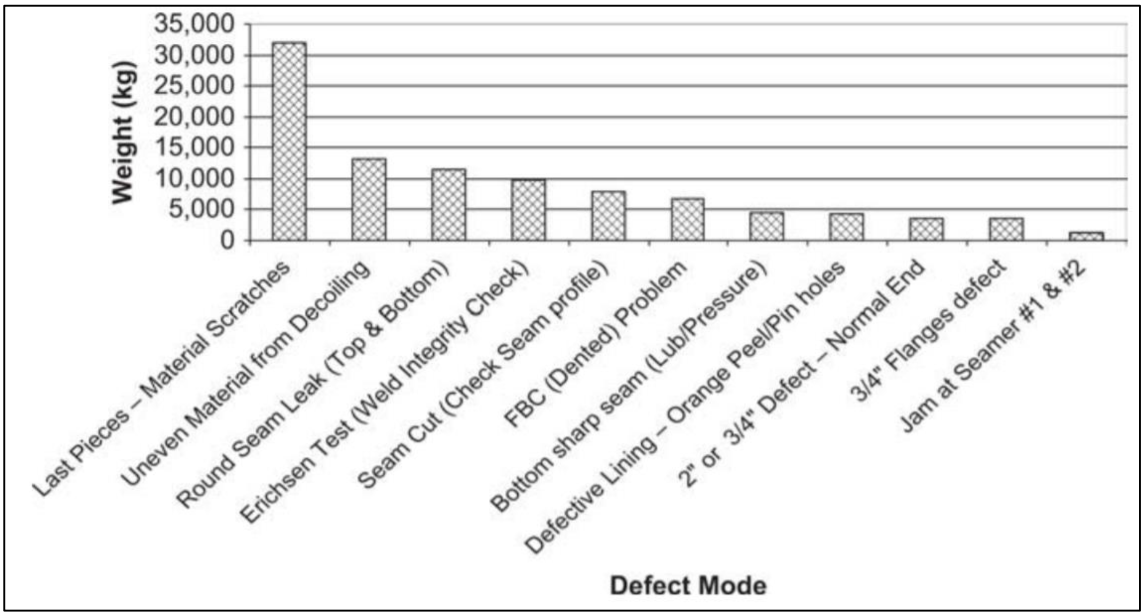


Figure 2.2-18 – Pareto analysis of leading scrap causes by Benjamin et al (2009)

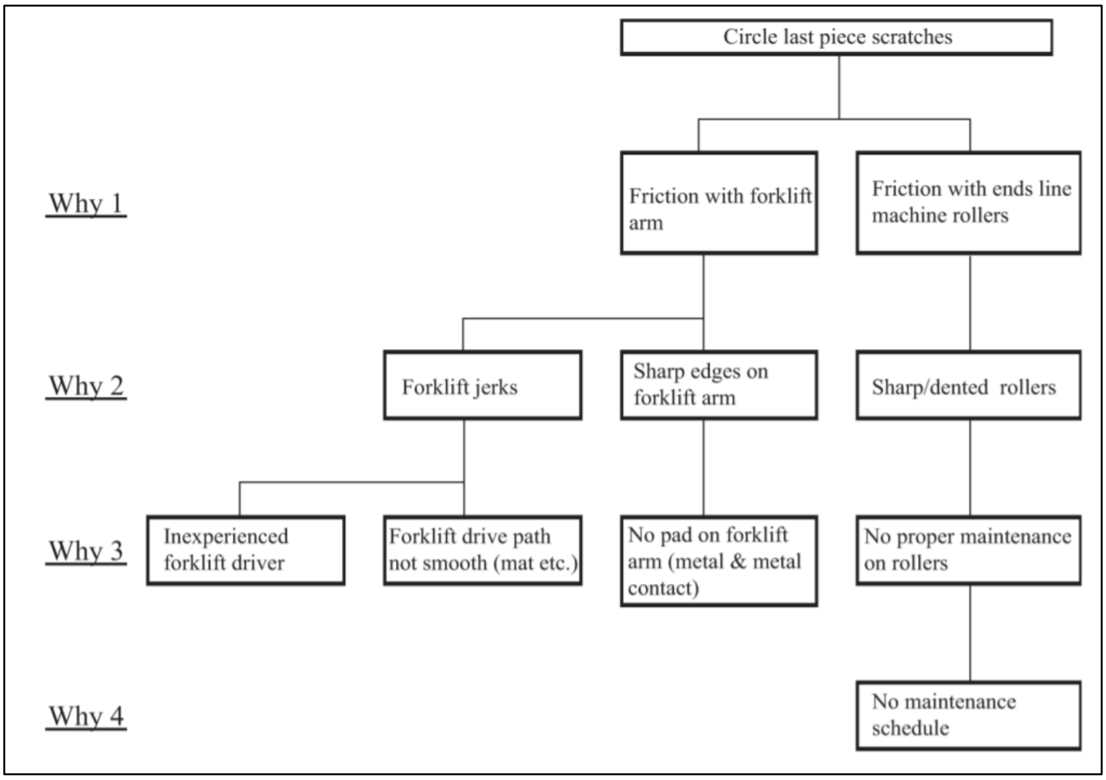


Figure 2.2-19 – 5 whys analysis for material scratching root-cause by Benjamin et al (2009)

The 5 whys analysis on material scratching identified root causes within 4 'whys' in figure 2.2-19 which highlights the effectiveness of the process. Large investment solutions including robotic loading were proposed to improve material transportation, however the company selected leaner solutions including maintenance of forklifts and 'dummy' material to minimise barrel material contact friction during transport. These solutions saw a 100% reduction in scrap from material scratching and led to significant cost savings.

Chapter 2.3 Summary of Reviewed Literature

Analysis of the chapter 2.2 literature on SMfE problem-solving approaches found that:

1) There are a limited number of beneficial SMfE examples for reference
2) The majority of examples utilised a systematic or systems engineering based approach to SMfE problem-solving
3) There are a variety of analytical tools which highlights the need for correct identification of suitable tools for use
4) SWOT analysis is beneficial when combined with a method to rank observations
5) A structured methodology or framework must be defined to govern the whole process

The reviewed literature covered various manufacturing processes with most studies using SMfE examples which are relevant to the chosen case study. All studies utilised analysis tools even within less relevant industries such as those covered by Buchmayr and Tagliaferri. The applicable SMfE case studies typically required production process improvements similar to the DTD process requirements defined in the chosen case study. Most studies oversaw either successful system implementations (Khatri, Vosniakos, Mason-Jones studies) or identification of further work opportunities (Toklu, Gräßler, Holgado studies).

Point 2) was determined from multiple works directly referring to a systems-based approach during problem definition, with the Buczacki, Gräßler and Mason-Jones works detailing comprehensive multi-step methodologies. Literature by Khatri and Toklu focused heavily on SWOT analysis but also referred to systems-based approaches. Most literature utilised multiple tools to identify, rank and implement changes. Minimal resource on SMfE use of reverse engineering and 5 whys was observed other than the Benjamin et al literature, further supporting the case for a systems-based approach to the chosen research problem.

Points 3) and 5) highlight the importance of methodology definition and tool selection. This suggests that comprehensive analysis of the methodologies presented within figures 2.2-2 to 2.2-4 and the individual tools (i.e. FMEA, IDEF0, SWOT, AHP etc.) was required to establish the contribution each would provide to this case study and the requirements for successfully utilising them.

The reviewed works indicate that correct use of a methodology and/or analytical tools can fully define a research problem by being able to offer suggestions on the business function or process to make improvements in. Additionally, the wide range of industries utilising similar methodologies and/or analytical tools validates the use of these, with each author being able to utilise them to solve their research problem effectively. Industries studied ranged from the service industry to general manufacturing to automotive with each having unique challenges to address by the author.

Despite studying a range of successful systems engineering examples the majority provide only introductory analysis of case studies through definition of a framework and study of the 'as-is' scenario. The reviewed works generally conclude by proposing the most beneficial changes for an SMfE to make but only as further work opportunities. In the select few identified where solutions are implemented the benefits seen are only summarised briefly with a lack of thorough analysis. Through concluding research at the solution identification stage it is unclear whether significant long-term improvements were gained in the case studies reviewed. This provides a possible knowledge gap in the SMfE problem-solving field because it could be argued that there is a lack of sufficient evidence to validate that the systems engineering approaches used truly work.

Within the reviewed literature minimal time study data was observed excluding the Activity on Node (AON) analysis conducted by Vosniakos. It is unclear from their research how Vosniakos determined the AON values and whether they used stakeholder observations, time studies of specific components going through production or another method. The very limited resource from the existing literature on time studies does not help address the requirement of the chosen case study in applying times to multiple processes in a DTD phase.

This research aims to conduct a systems engineering approach on a SMfE through identifying the leading 'bottlenecks' in the DTD process. In order to meet the aim and objectives this research aims to build upon the previously studied literature by fully documenting the implementation stage of system improvements, subsequently reviewing the long-term impacts and detailing challenges experienced. With the capture of the implementation and results phases a full system improvement life-cycle is studied, unlike the partial cycles studied.

This research also aims to provide a suitable method for capturing relevant and usable time study data throughout a DTD process, detail which was lacking in the reviewed literature. A method combining stakeholder observations and using physical time studies of parts going through a process step will be used to ensure that the data captured is reliable for use in determining the key bottlenecks of the case study SMfE.

Chapter 2.4 Methodology Definition & Analysis Tool Selection

The methodology framework for the chosen case study was defined first through comparison of the approaches in figures 2.2-2 to 2.2-4. These approaches all contained a start point (problem definition), a mid-point (requirements definition) and an end point (integration), with the Buczacki and Mason-Jones research additionally including system re-evaluation and optimisation as a necessity. Considerable overlap was observed between the three approaches with each containing a differing number of steps to all achieve the same critical end point of system integration.

It was determined that the 7-step approach utilised by Buczacki et al (see figure 2.4-1) provided the best methodology for use in this research with clear tangible milestones to achieve. Tasks 1) to 5) aim to address the research aim and objectives. It was determined that the other two approaches provided less clarity and more ambiguity for each process step.

1) State the problem
2) Investigate alternatives
3) Model the system
4) Integrate the system
5) Launch the system
6) Assess Performance of the system
7) Re-evaluate the system

Figure 2.4-1 – 7-step methodology to be used in this research as presented by Buczacki et al (2018)

With the methodology defined suitable analysis tools required selection. The selected analysis tools are discussed below with reasoning as to how they are applicable to the DTD process problem. Additional analysis and comparison of all tools from chapter 2.2 is accessible within appendix 4 for further reading along with diagrams in appendix 5 for tools not illustrated (QFD, clustering etc.).

Activity-On-Node (AON) / Timeline Analysis

AON was used successfully by Vosniakos et al to map the manufacturing process timeline in figure 2.2-1 by providing a visual aid of process steps, their estimated duration and their required start and end dates. Additionally, AON indicates where concurrent processes occur. Its applicable to the DTD process by assisting in identifying the above detail for the defined 30-day process and helping to establish which processes contribute the most time. A process timeline was also chosen for creation to solely display the DTD process function time contributions without start and end dates.

Stakeholder Analysis via SWOT

SWOT analysis was utilised effectively in various studies in chapter 2.2 due to it allowing stakeholder input within SMfE as discussed by Toklu, Sluismans and Khatri. Stakeholder analysis can greatly assist in making observations for the DTD process as well as considering external factors by utilising the knowledge and experience of those involved in day-to-day operations in the SMfE case study. SWOT analysis will allow stakeholder input on multiple business functions within the SMfE.

Scoring SWOT Matrix Approach

The reviewed literature suggested that SWOT analysis requires an observation ranking method. Toklu and Khatri's studies utilised complex AHP approaches while Sluismans and Buchmayr presented simpler scoring and categorisation methods. The Sluismans confrontation matrix from figure 2.2-16 was selected as it ensured stakeholder involvement in ranking the observations they determined. The positive feedback on the matrix method discussed in chapter 2.2 aided its selection. The method will allow stakeholders across the DTD process to reach agreement on the leading strengths and weaknesses of the case study SMfE.

Bottleneck Identification & Selection - FMEA

The AON/timeline and SWOT studies will provide two DTD process data sources consisting of observations to address from process time and stakeholder viewpoints. Combining these findings into a group of process 'bottlenecks' which can be ranked by their process impact will require an additional tool. An FMEA-based tool was selected as it will provide a scoring system to rank 'bottlenecks' which accounts for their impact on both the process time and stakeholders. The total scores will highlight the leading bottlenecks to address through solutions research. The FMEA scoring system aims to keep the process simple. Vosniakos et al achieved success through FMEA use in their research by identifying manufacturing cycle time as a leading bottleneck.

Bottleneck RCA – ZFA Tool

To determine the root causes of the identified bottlenecks suitable analysis is required. Mason-Jones utilised ZFA (see figure 2.2-6) to determine root causes for a symptom through visual aids. Its use for the DTD process will allow in-depth study of each bottleneck to determine all possible root causes.

Research of Possible Solutions

The root causes identified by ZFA for each bottleneck could potentially require multiple solutions to research. Each bottleneck will therefore be assigned a defined problem to allow for focused research on appropriate solutions. Solution comparison will be performed using a set of criteria considering the impact to current process time, financial requirements and impact on process stakeholders to allow selection of suitable solutions.

With the analysis tools and methodology defined, figures 2.4-2 to 2.4-3 illustrate the systems engineering framework to be employed which will:

1) Utilise stakeholder input
2) Collate data on the existing practices
3) Use an 'inter-disciplinary approach for realisation of successful systems' (INCOSE definition)

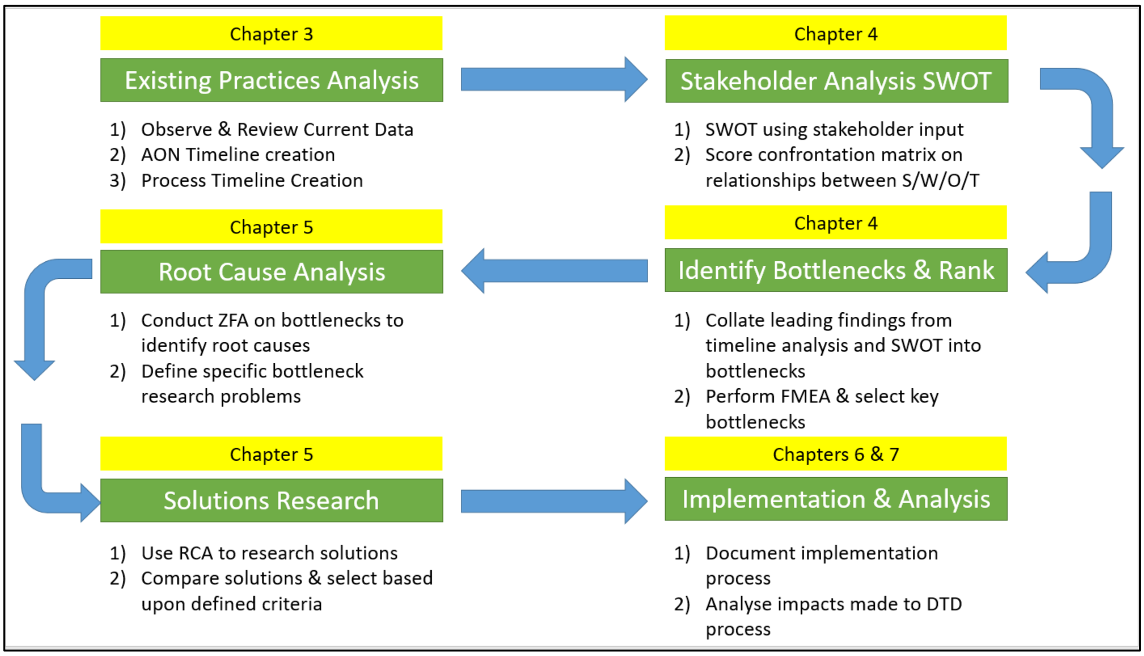


Figure 2.4-2 – Defined Systems Engineering Methodology

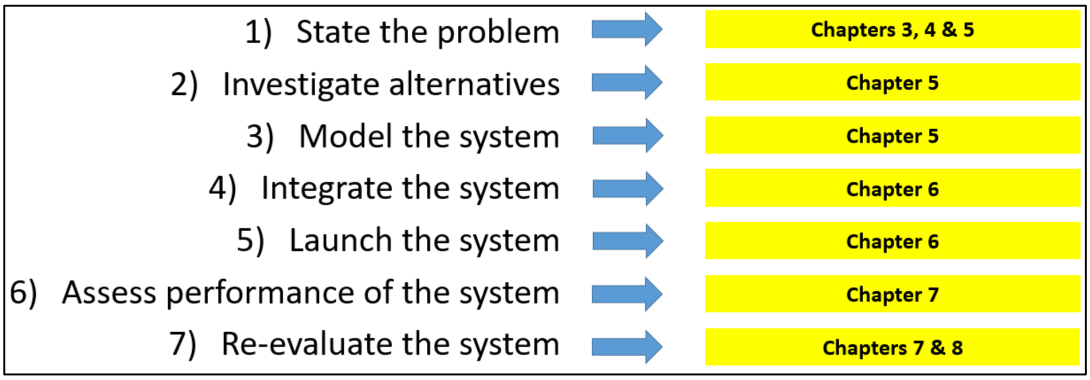


Figure 2.4-3 – Selected Analysis Methodology by Buczacki et al with Associated Chapters

Chapter 3 Existing Practices Analysis in DTD Process

Chapter 3.1 Introduction to Key Business Functions

Creation of the AON and process timeline diagrams relied upon individual analysis of the DTD process functions. Figure 3.1-1 details an existing flowchart of process steps and the staff involved. For the purposes of defining the AON and process timeline diagrams a modified version of this flowchart was created in figure 3.1-2 which groups process steps into business functions.

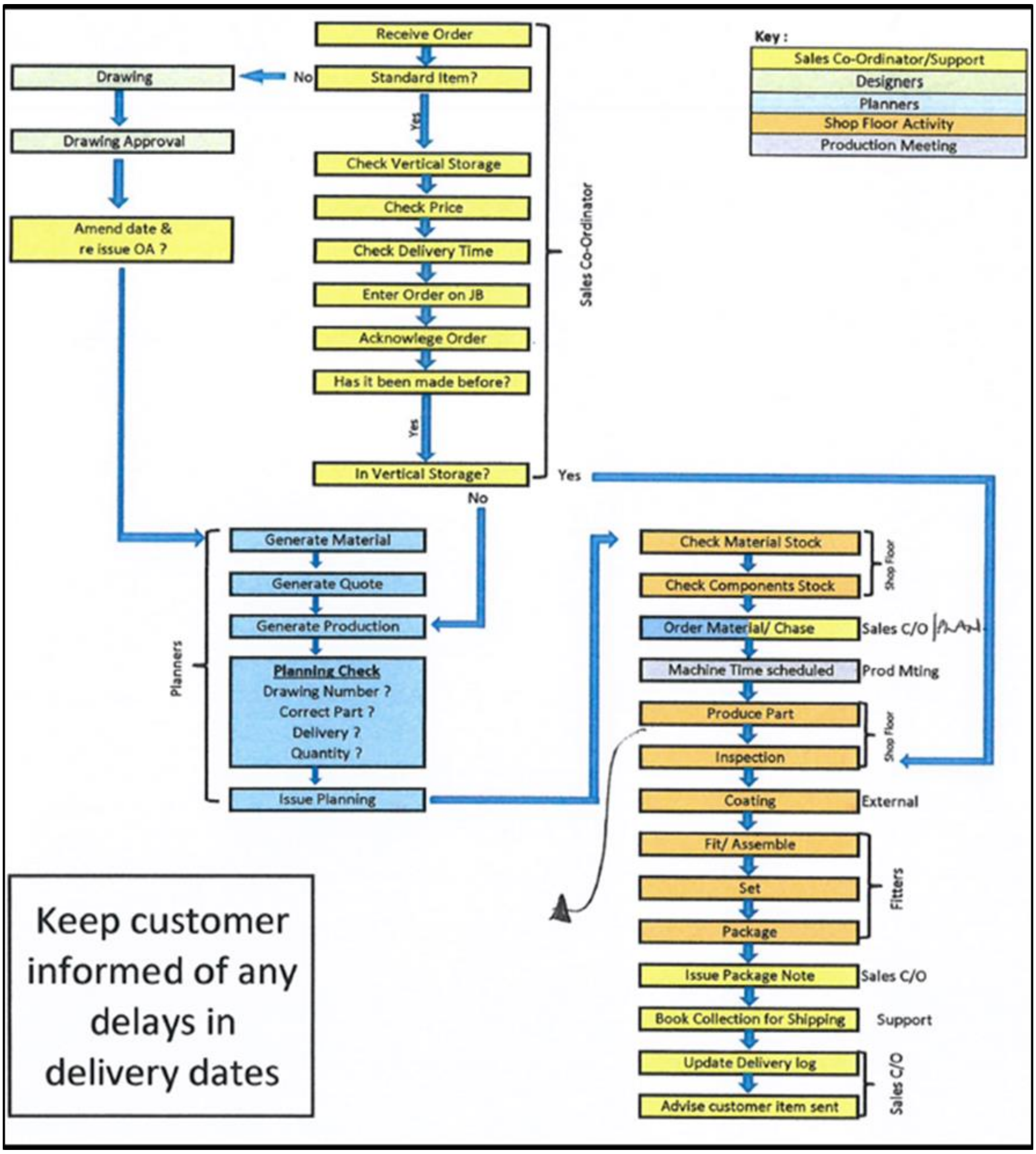


Figure 3.1-1 – Existing SMfE flowchart for 'Design to Delivery' (DTD) process for tool-holders

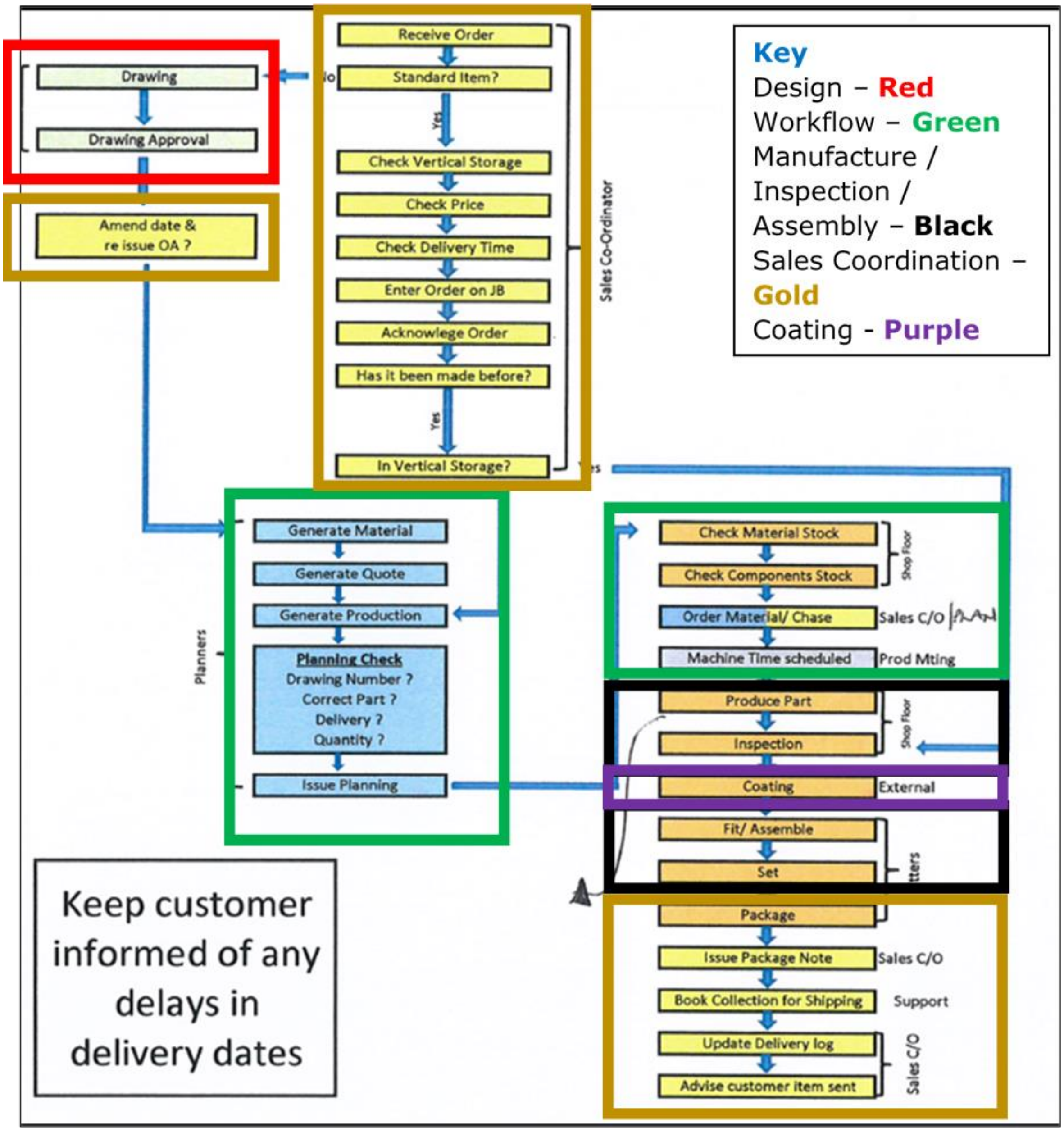


Figure 3.1-2 – Updated SMfE flowchart of DTD process featuring key business functions

5 colour-coded function groups are defined in figure 3.1-2. The manufacture, inspection and assembly processes are grouped due to an overlap in the inspection processes as discussed in chapters 3.5 and 3.6. Existing practices for each function were determined through time studies where possible in addition to making independent observations and gaining stakeholder input. The data collected will supply estimated timings for the AON and timeline diagrams. Chapters 3.2 to 3.6 investigate the color-coded functions to achieve process time estimates.

Figures 3.1-3 and 3.1-4 illustrate the AON and timeline diagram templates which will be populated throughout chapter 3. Process time estimates will be made in the unit of days. In both diagrams the sales coordination and workflow functions are divided into sub-functions based on the multiple green and gold boxes within figure 3.1-2.

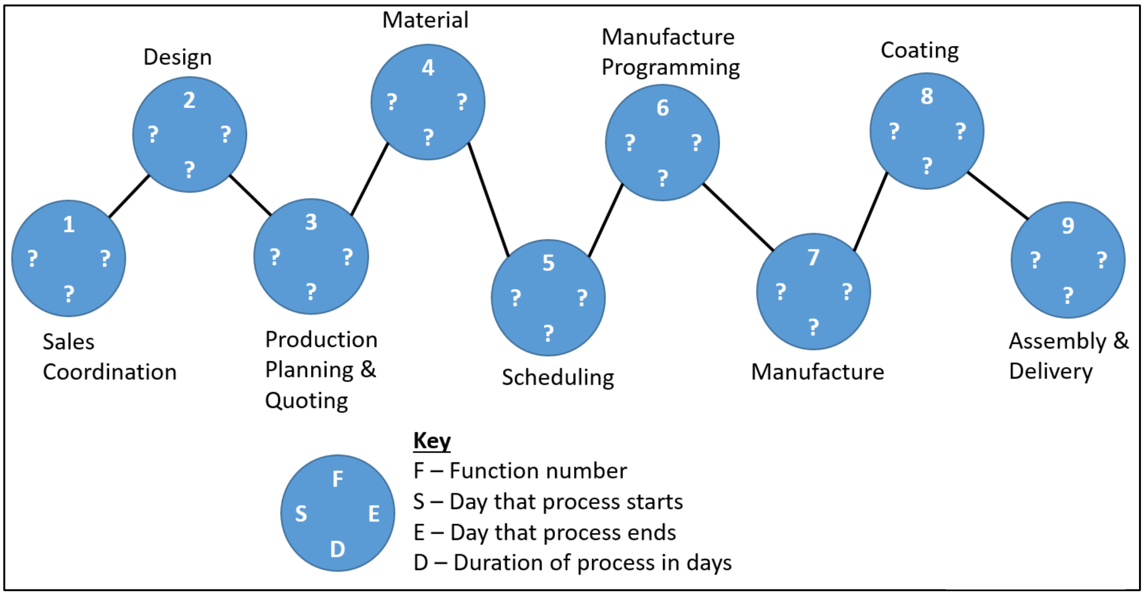


Figure 3.1-3 - Blank AON diagram and key to populate with process times

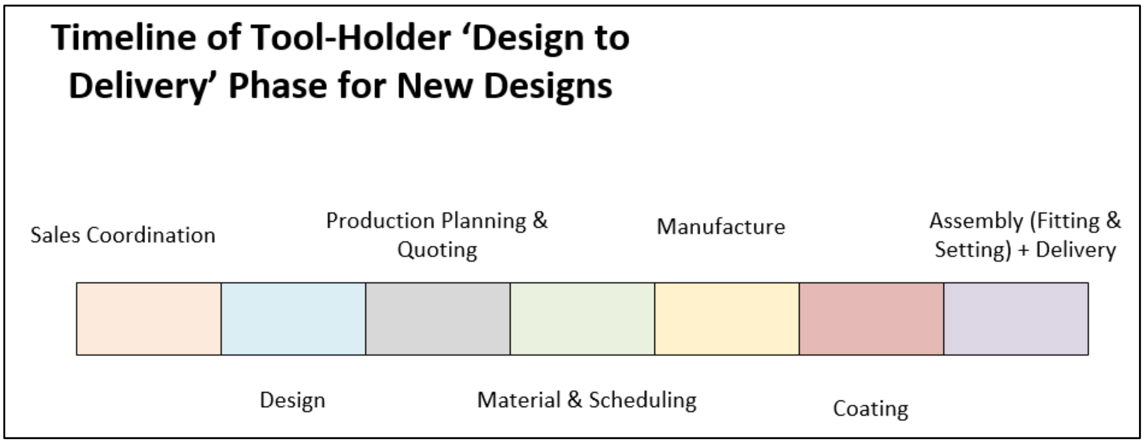


Figure 3.1-4 - Blank DTD process timeline to populate with process times

Populating figures 3.1-3 and 3.1-4 requires the study of process flow for a new design and must include the design function process steps in figure 3.1-2. The process steps for existing designs of 'Check Vertical Storage' through to 'In Vertical Storage' are therefore not considered for this study. The DTD process times will be based on the leading tool-holder product type which allows for quick tool changeover and accounts for 75% of annual SMfE tool-holder sales. The phrase 'tool-holder' in the following chapters refers to this product type.

Chapter 3.2 Existing Practices Analysis – Sales Coordination & Coating

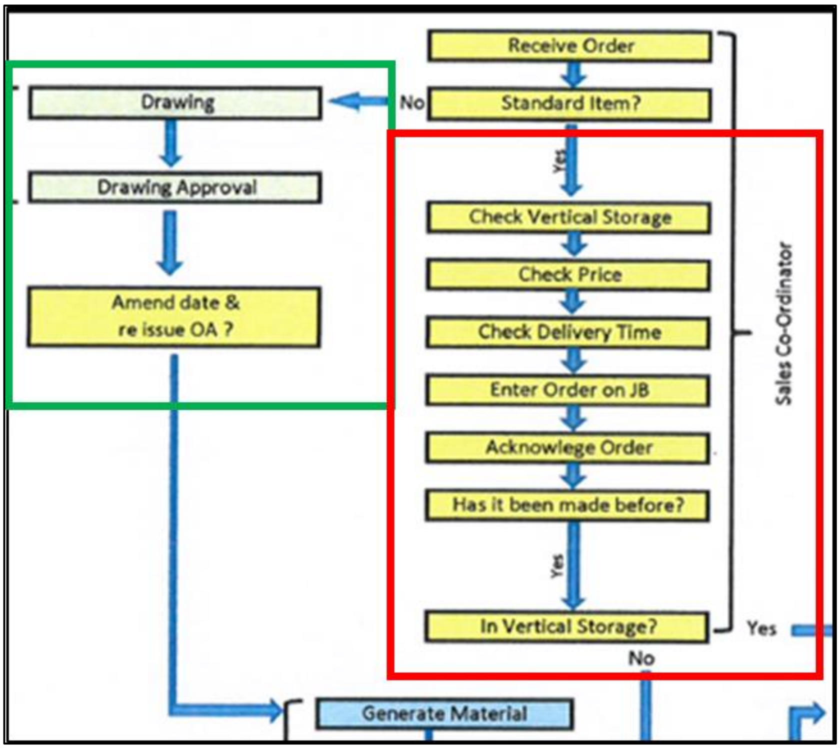
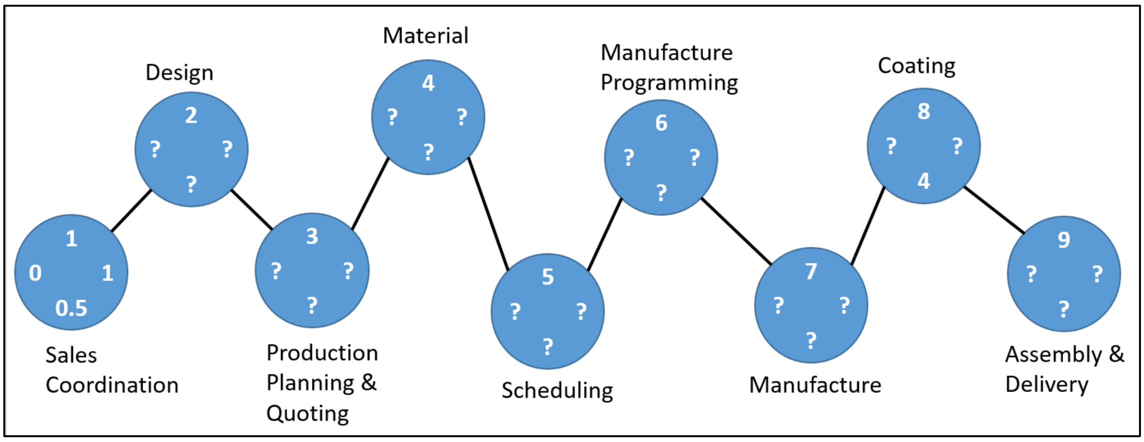


Figure 3.2-1 - Partial flowchart indicating process flow for new tool-holder designs (green box) and for existing designs (red box)

New tool-holder designs have requirements passed onto design by sales coordination after establishing the order is not standard (an existing design). Sales coordination staff are then only required following customer drawing approval (see figure 3.2-1) to issue an updated order acknowledgement (OA) and delivery date to the customer. To do this the staff use Enterprise Resource Planning (ERP) software to produce the OA documentation. The standard item investigation and re-issued OA steps should provide a negligible contribution (a few minutes) to total DTD process time, however a conservative 0.5 sales coordination day (4 hours) contribution has been applied as a 'worst-case' scenario.

Tool-holders are treated to prevent external rusting and corrosion. They are coated with a black coating for aesthetic purposes. These processes are outsourced by the SMfE as the requirements to perform these internally are outweighed by the cost of outsourcing. The coating process contributes 4 days to DTD process time which cannot be reduced.

With the time contributions determined for Sales Coordination and Coating, the AON and timeline diagrams were updated in figure 3.2-2 below.



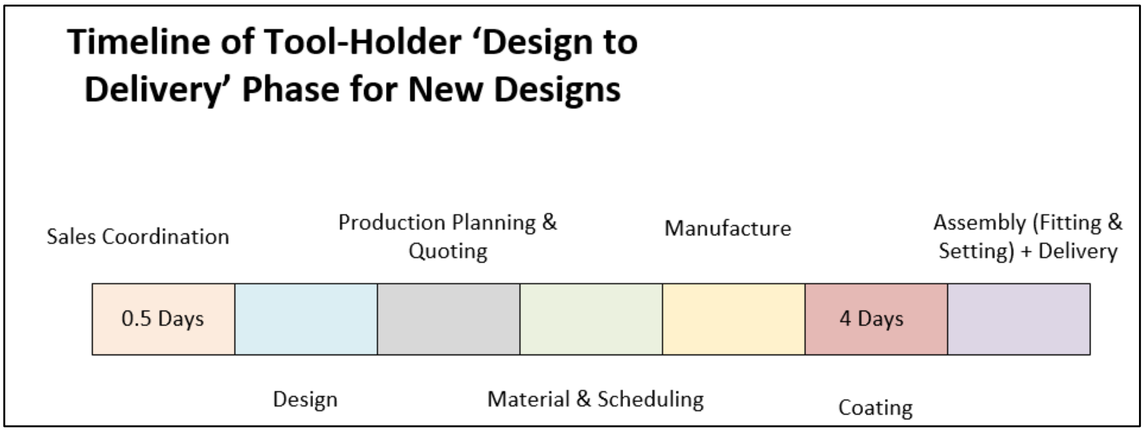


Figure 3.2-2 - Updated AON diagram and DTD process timeline with Sales Coordination & Coating Timings

In figure 3.2-3 the sales coordination steps associated with delivery are detailed. Although shop floor staff 'Package' items the sales coordination staff provide guidance on order priority. The sales coordination tasks following packaging are completed using the ERP software and IT resources. The contribution of these are negligible to the DTD process time therefore no time is assigned for delivery within the figure 3.2-2 diagrams.

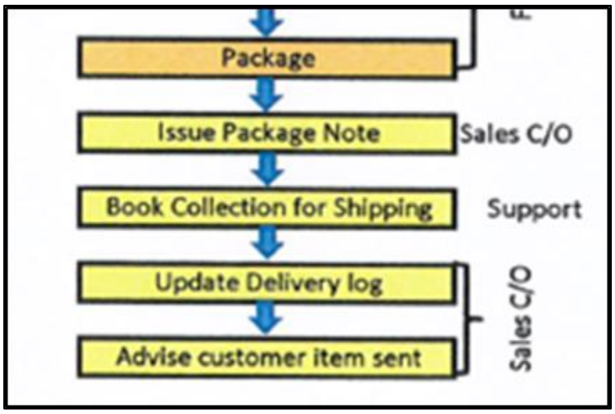


Figure 3.2-3 - Partial flowchart indicating post-assembly processes in DTD timeline for tool-holders

The sales coordination and coating processes have been grouped together due to the minimal time reductions achievable. These are due to having small time contributions and uncontrollable contributions (coating process time). Due to these factors these functions were not analysed further within chapter 4.

Chapter 3.3 Existing Practices Analysis – Design

For new tool-holder designs the design function will produce CAD models and drawings for customer approval using dedicated software. Figure 3.3-1 presents schematics of the two tool-holder types manufactured using the DTD process.

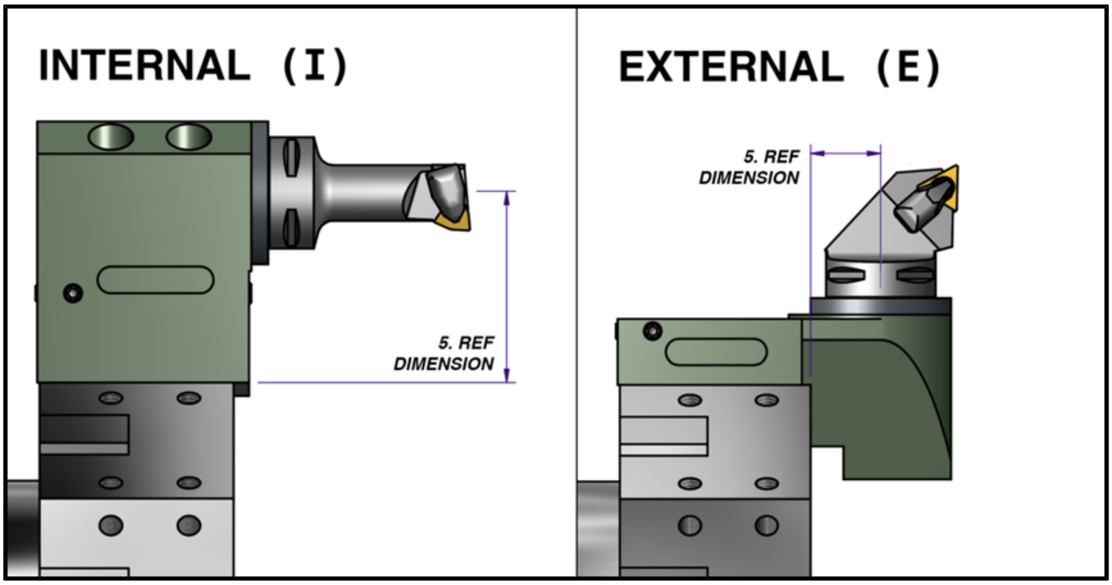


Figure 3.3-1 – Tool-Holder Reference Dimension Schematics taken from the SMfE Website

Tool-holders are designed for use on specific CNC machines with each machine containing unique turret geometrical designs onto which the tool-holder mounts (see grey turret in figure 3.3-1). New design considerations include:

1) Turret mounting geometry (bolt-hole patterns and geometrical features for accurate tool-holder location)
2) Overall tool-holder dimensions
3) The cutting tool diameter the holder can hold
4) The position of the cutting tool centre line horizontally and vertically (see 5. Ref dimension in figure 3.3-1 example)

The SMfE contains comprehensive detail for multiple CNC machines allowing the design engineers to establish points 1) to 4) for new designs. When point 3) is established the full assembly can be modelled as standardised bore details are associated with standardised sub-assembly components. The designers will produce CAD models and associated drawings for all new designs.

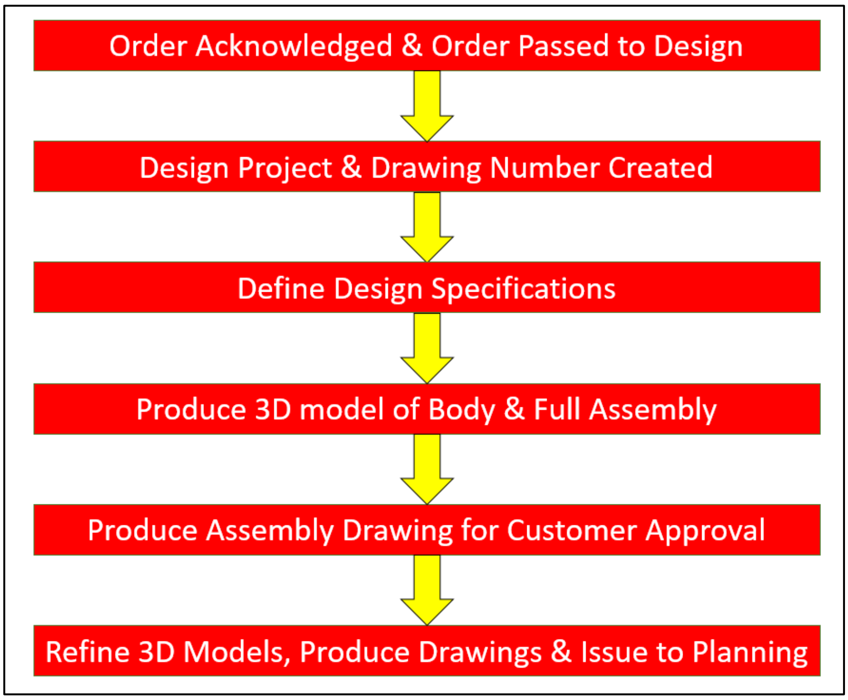


Figure 3.3-2 - Flowchart of design function processes in new tool-holder design

Figure 3.3-2 documents the process steps to allow new design manufacture. Designs projects are assigned numbers and manually managed through hard copy storage and spreadsheets. Every tool-holder is assigned a unique drawing number for future reference.

A commercial CAD package is utilised for 3D modelling and drawing production. Due to the SMfE containing an extensive drawing portfolio current drawings exist in scanned hand-written, 2D model and 3D model formats with the current CAD package providing access to 3D and 2D files. The existing CAD software is the 2011 edition which initially appeared outdated.

The drawing produced for customer approval is a simple assembly schematic highlighting essential dimensions for the customer. Following customer approval detailed production drawings are created in conjunction with sales coordination providing the updated OA for the customer. All drawings are checked by senior staff prior to sending for customer approval and prior to being passed onto production planning to ensure any change requirements are captured. All drawings and CAD models are stored on the SMfE IT network.

The parametric design capabilities of the existing CAD software were investigated. Parametric modelling techniques were currently accessible as figures 3.3-3 to 3.3-4 demonstrate from a user guide developed by Shih (2010). Model dimensions can be related through equations, whereby one dimension change can automatically update multiple dimensions.

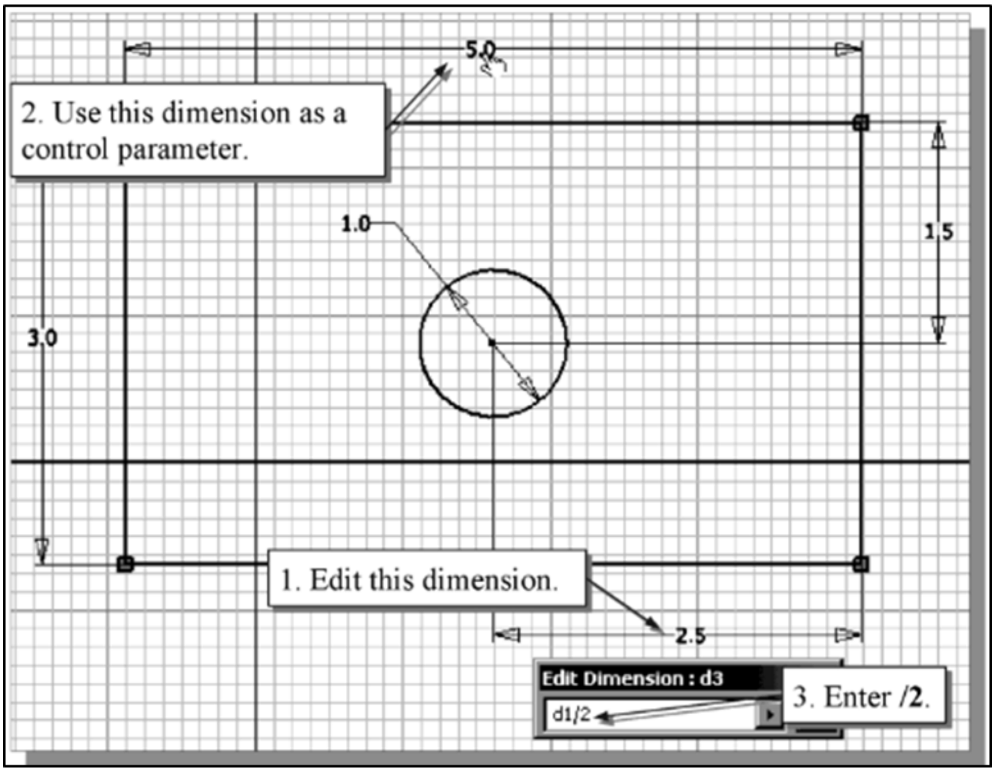


Figure 3.3-3 – 2011 CAD parametric design example image 1 – Shih (2010)

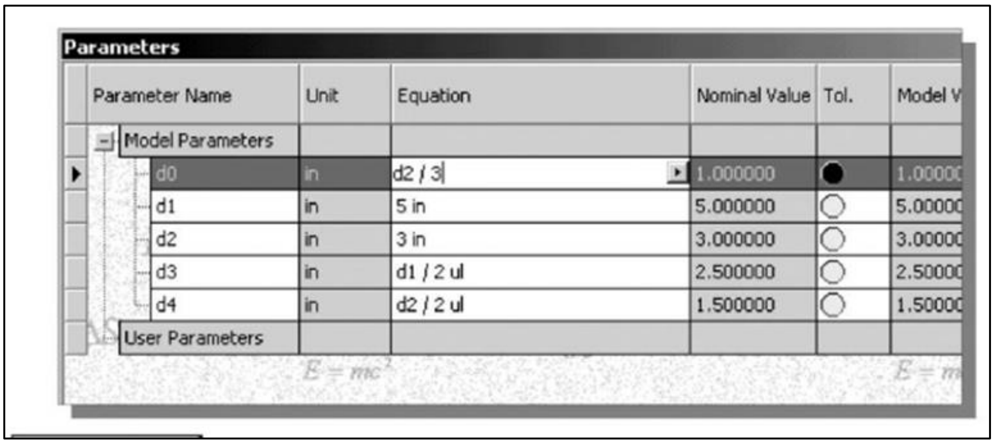


Figure 3.3-4 – 2011 CAD parametric design example image 2 – Shih (2010)

It was observed that an alternative approach using model templates was utilised for new designs, with each template containing the different standardised bore geometry associated with design consideration point 3). Designers utilise these templates such as the one in figure 3.3-5 by adding in the required detail for design considerations 1), 2) and 4) discussed previously.

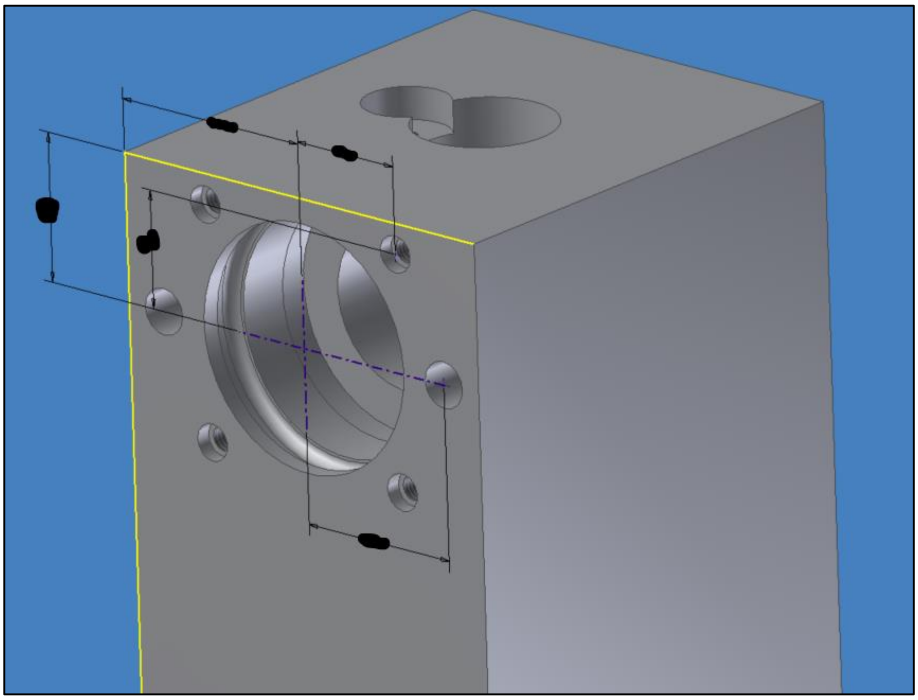


Figure 3.3-5 - Example CAD model template used for new designs

The template model method is a beneficial practice as it reduces modelling time by preventing having to remodel existing complex bore geometry for all new designs. The added detail by a designer varies for different CNC machines which suggests that parametric modelling implementation would be difficult to standardise for multiple new designs to further reduce process time.

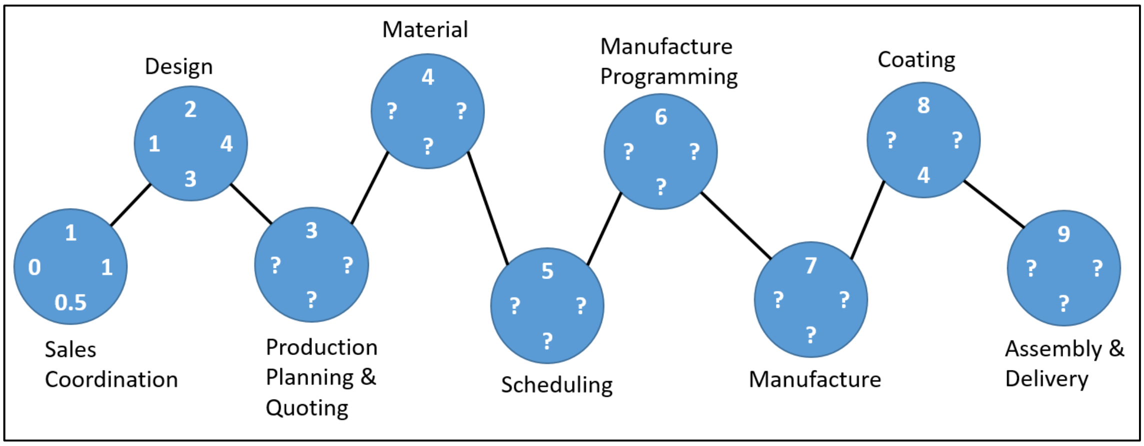
A time study was conducted to determine an average new design time contribution. Table 3.3-1 highlights how manufacturing drawings were generated within 6 days, however this is an inaccurate estimate as the 6 days will have also included:

1) The time elapsed waiting for customer approval
2) Other projects the design engineer worked on in addition to the time study new design

When taking these factors into account the design staff agreed that an estimated 3 days was spent solely working on the new design. This revised estimate was believed to be more realistic and was added to the AON and timeline diagrams in figure 3.3-6.

Total Time Since Order Date (in Working Days)	Status Update
0 Days	Details passed to design allowing project creation
3 Days	Customer approves drawing
4 Days	Detailed drawings started
6 Days	Detailed drawings approved for planning

Table 3.3-1 - Time study of a new design progressing through design function



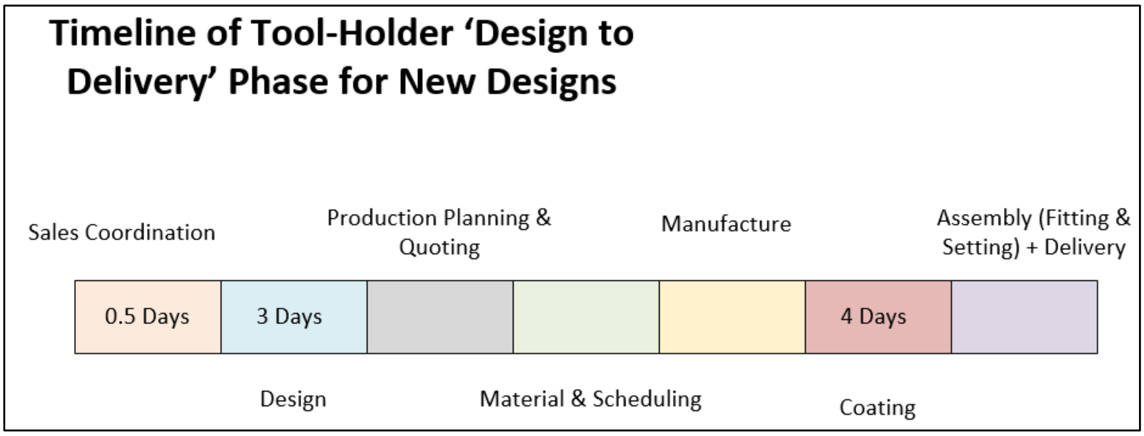


Figure 3.3-6 - Updated AON diagram and DTD Process Timeline With Design Timings

Figure 3.3-7 details design function observations where good practices were utilised and where potential issues exist. For chapters 3.3 to 3.6 this format is used in summarising each function group. Lack of parametric design was not included based upon the findings discussed previously.

Positive Observations	Negative Observations
Utilisation of CAD 3D and 2D software for producing designs & accessing existing files stored on IT network	CAD software version in use is 2011 – Possibility of equipment performance issues as time progresses, newer files may not be accessible and new features being missed out on
Design projects and drawing records kept via spreadsheet means for future references	Existing records for design projects and drawings all manually updated – time-consuming to keep accurate
Use of template models to design tool-holders – time-saving exists in process currently	Drawing revisions and change records not currently documented – only drawings contain individual revision changes
All drawing approvals by customer received and captured as a record	

Figure 3.3-7 - Observations Summary of Design Practices in DTD Process

Software data management and change history data capture were identified as negative observations as manual management provides difficulty in capturing all data without significant time input. In chapter 4 all negative observations will be considered to determine whether they are leading bottlenecks. Further detail on existing design practices is found within appendix 6.

Chapter 3.4 Existing Practices Analysis – Workflow Management

Chapter 3.4.1 Production Planning & Quoting Existing Practices

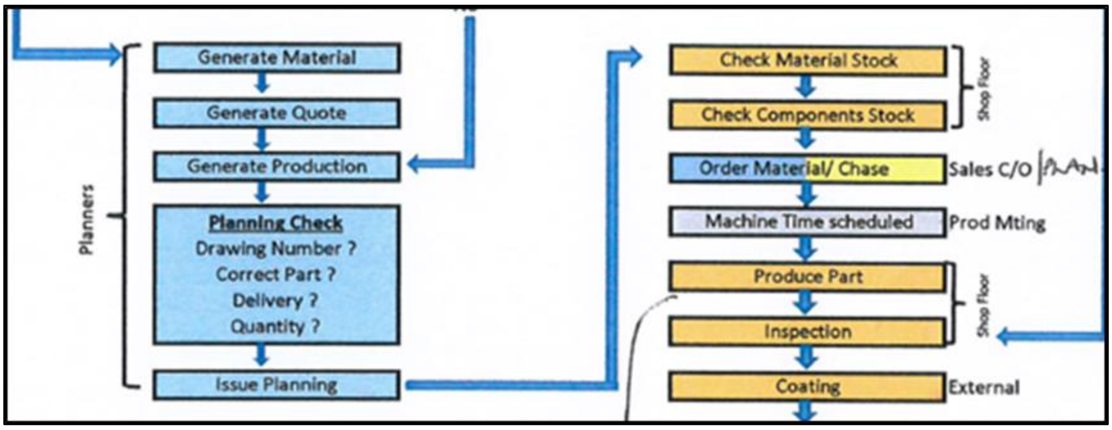


Figure 3.4-1 - Partial flowchart focusing on workflow management processes in DTD process

This chapter focuses on existing practices following the OA customer update prior to the 'produce part' step in figure 3.4-1. The ERP software is heavily utilised in the production planning and quoting steps (blue boxes) with table 3.4-1 discussing these further.

Process Step	**Summary of Process Step**
Generate Material	New product entry into ERP system as assembly, consisting of tool-holder body and sub-assembly components
Generate Quote	An ERP system quote contains: 1) Costs of bought-out accessories/material 2) Job routing for manufactured components including part setup and machine run times (using production drawings) The quote provides a template for use with any order entered into the system for a specific tool-holder
Generate Production	The quote detail is transferred into the specific order entered into the ERP system previously to give related costing and job routing detail
Planning Check	The planning paperwork is reviewed prior to issuing to production Correct planning contains drawing number, product code detail, quantity, delivery date, material, job routing etc.
Issue Planning	The planning paperwork is printed in hard copy form and issued along with drawings to production

Table 3.4-1 - Table of Production Planning & Quoting Processes for Tool-holders

The table 3.4-1 processes provide negligible contributions individually to the DTD process as the ERP system assists in providing semi-automation of the planning process. A conservative contribution of 0.5 planning days to the DTD process was determined and added to the AON and timeline diagrams in figure 3.4-2.

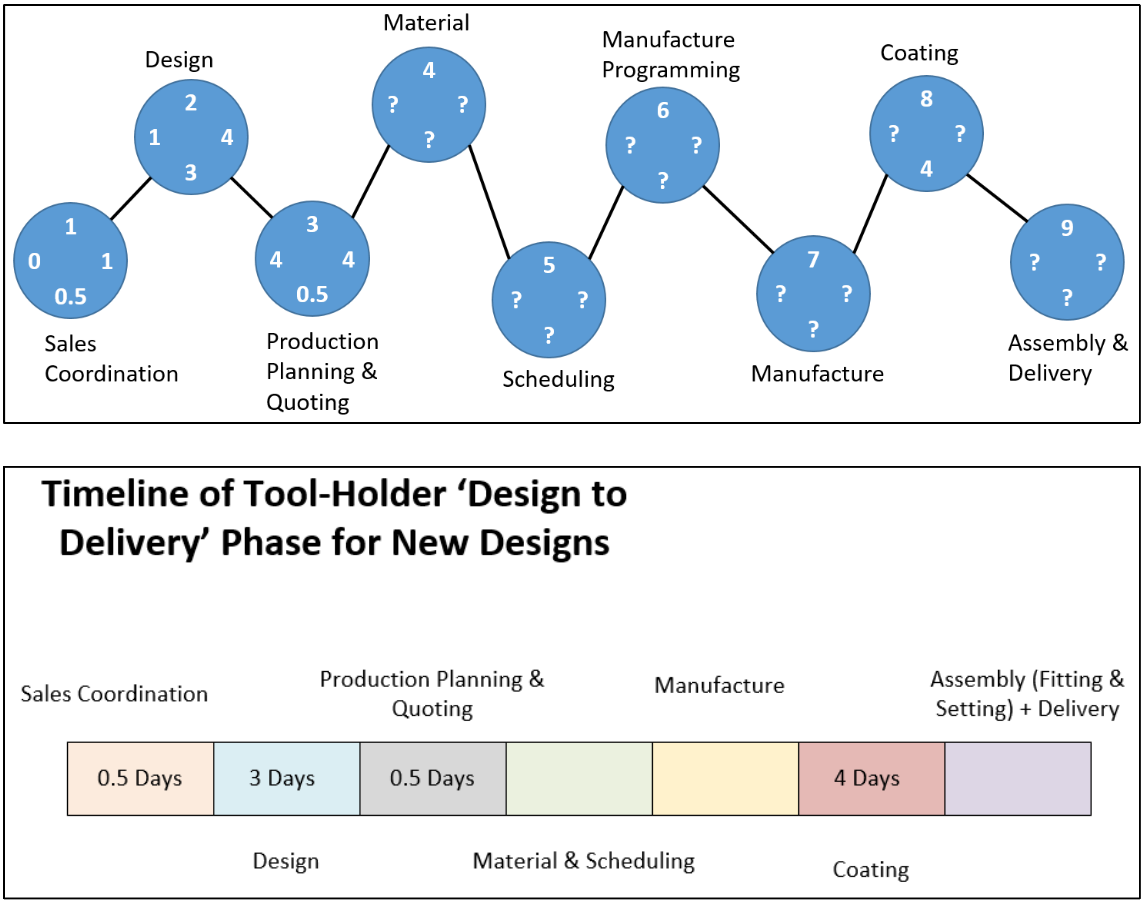


Figure 3.4-2 - Updated AON Diagram and DTD Process Timeline With Production Planning & Quoting Timings

Chapter 3.4.2 Material Existing Practices

Most tool-holders are manufactured from cast iron which provides:

1) Good machinability for accurate machining
2) Vibration resistance properties
3) Ability to be treated for removing distortion/warping

Stocked Material Sizes
110mm x 110mm x 3m long bar
130mm x 130mm x 3m long bar
150mm x 150mm x 3m long bar
180mm x 180mm x 3m long bar

Table 3.4-2 - Stocked Cast Iron Bar Sizes

The SMfE stocked a selection of material sizes seen in table 3.4-2. The bar lengths are utilised where possible with different length billets sawn in relation to the tool-holder dimension requirements. Chapter 3.5 discusses the relationship between billet size and tool-holder dimensions in determining the ideal material size used in the ERP system quote. The 'Check Material Stock' step in figure 3.4-1 determines whether any available stock is usable for an order or whether specific size billets are required. Figure 3.4-3 illustrates different material process time scenarios.

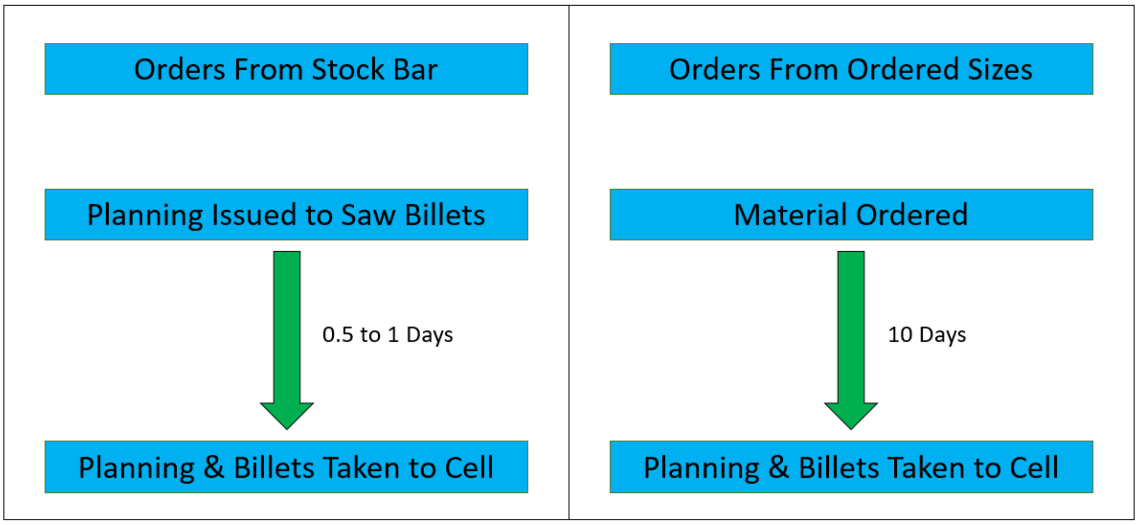


Figure 3.4-3 – Material scenario time contribution diagrams based upon using stock material and ordered material cut to size

Using stock bar lengths provides a considerably smaller time contribution compared with ordered billets. A single supplier provides all purchased cast iron sizes with a 10-day delivery time for specific billets and a 2-3 days' delivery time for 3m bar lengths.

The 'Check Components Stock' process step relates to ensuring available stock exists for sub-assembly components, fasteners and seals. To simplify DTD process analysis it is assumed these components are available, therefore allowing sole focus on tool-holder body manufacture. Additional detail on sub-assembly components is provided within appendix 6. 'Order Material/Chase' relates to any purchasing required for these extra components. This process provides a negligible contribution to the DTD process time.

Chapter 3.4.3 Scheduling Existing Practices

The 'Machine Time Scheduled' process step relates to scheduling orders for machining in the tool-holder production cell. Most tool-holders are produced on the Horizontal Milling (HM) machine or Vertical Milling (VM) machines with the HM machine reserved for larger, specialist designs (see figure 3.4-4). The remaining tool-holders are produced on the VM machines. VM machine production is reviewed in chapter 3.5 due to the majority of tool-holders being manufactured on these machines.

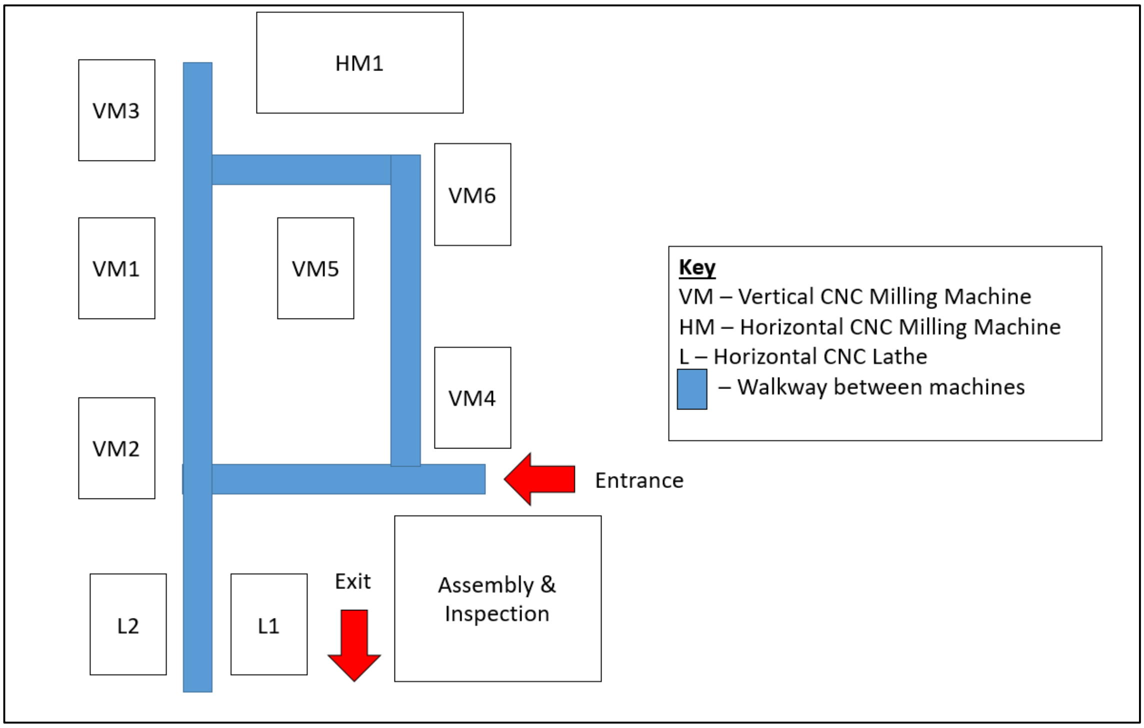


Figure 3.4-4 - Layout of existing tool-holder production cell

The 6 VM machines are different versions of the same model with the oldest (VM1) being 10 years older than the youngest (VM6). Specific orders were previously allocated to specific machines based upon the customer or product type, however this practice was phased out. Orders are currently scheduled in twice-weekly meetings between key cell staff using production data extrapolated from the ERP software into a spreadsheet.

Scheduling decisions for each VM machine are relayed to cell staff through daily shift changeover meetings with factors dictating scheduling including operator selection based on ability and job complexity. The 6 VM machines are similar in terms of operational requirements with all operators capable of running all machines. Additionally, the cell production manager provides work-to-lists for each machine to detail the order priority for operators.

Chapter 3.4.4 Summary

Material and scheduling times required assigning to the AON and timeline diagrams. A 0.5 day scheduling contribution was determined based upon the twice-weekly reviews. For material the worst case of 10 days' delivery was determined for the DTD process in order to account for new designs requiring specific billet sizes. Figure 3.4-5 illustrates the updated diagrams with these times whilst figure 3.4-6 summarises the positive and negative workflow management observations.

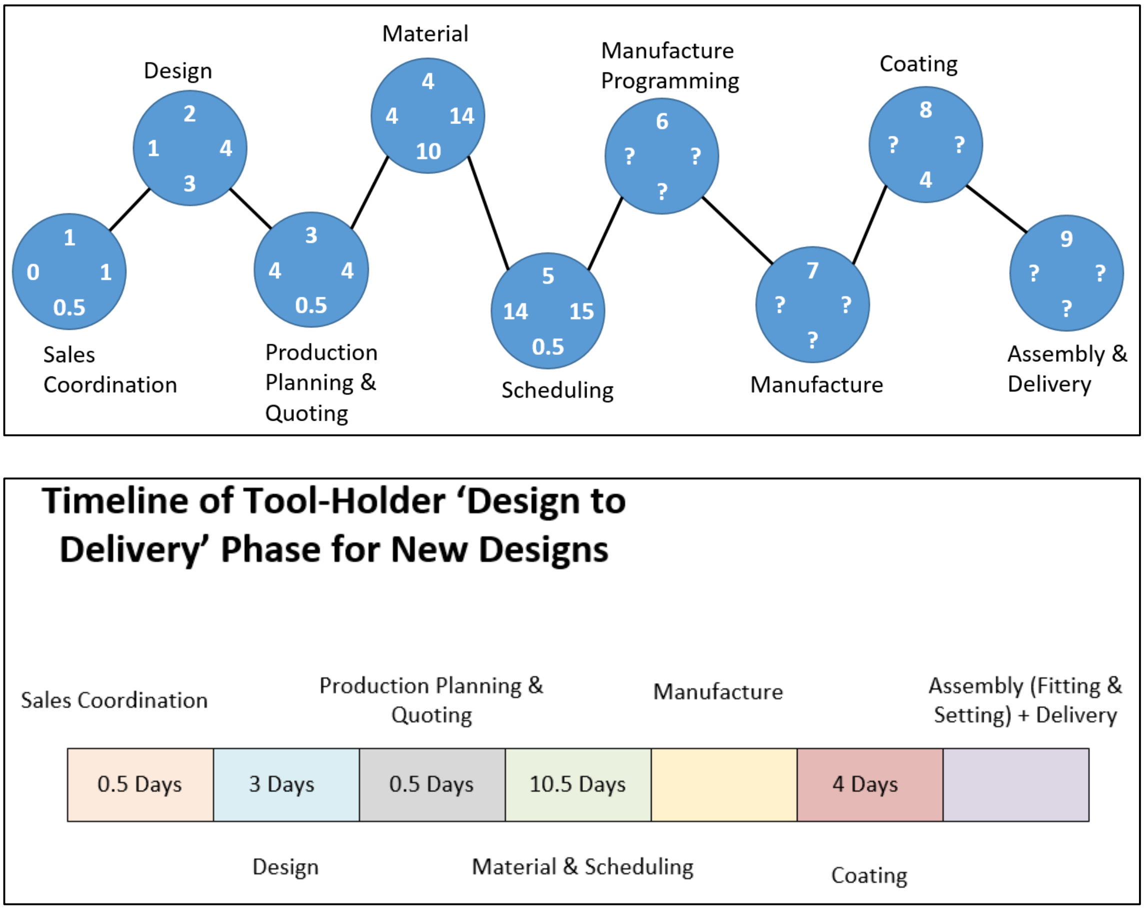


Figure 3.4-5 - Updated AON Diagram and DTD Process Timeline With Material & Scheduling Timings

Positive Observations	Negative Observations
Production Planning – ERP system stores historical order and quote data for future reference	Large lead time on material billets cut to size
Use of IT resources to assist with production schedule – use of database and spreadsheet combination	Order schedule requires manual input to keep updated despite use of IT resource
Stock cast iron bar is stocked for use on suitable orders	Orders allocated to machines 'ad-hoc', short term scheduling
Popular sub-assembly components are stocked for use on new orders	

Figure 3.4-6 - Observations Summary of Production Planning & Quoting, Material & Scheduling Functions

Chapter 3.5 Existing Practices Analysis – Manufacturing

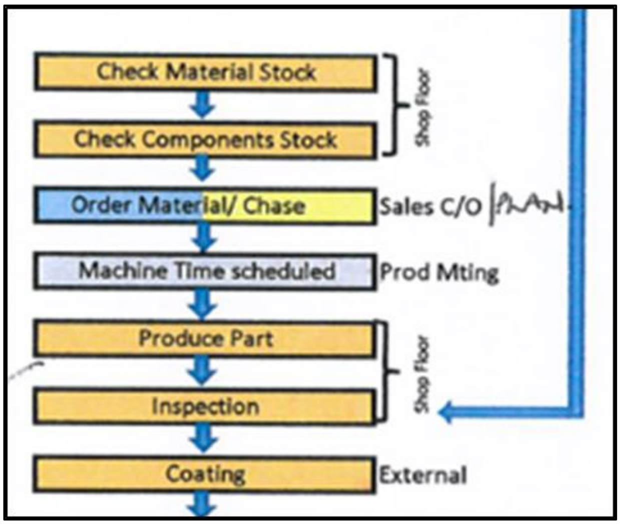


Figure 3.5-1 - Partial flowchart focusing on manufacturing processes in DTD process

This chapter analyses the 'produce part' and 'inspection' figure 3.5-1 process steps.

Chapter 3.5.1 Material Billet Definition, Time Study & Manufacturing Themes Introduction

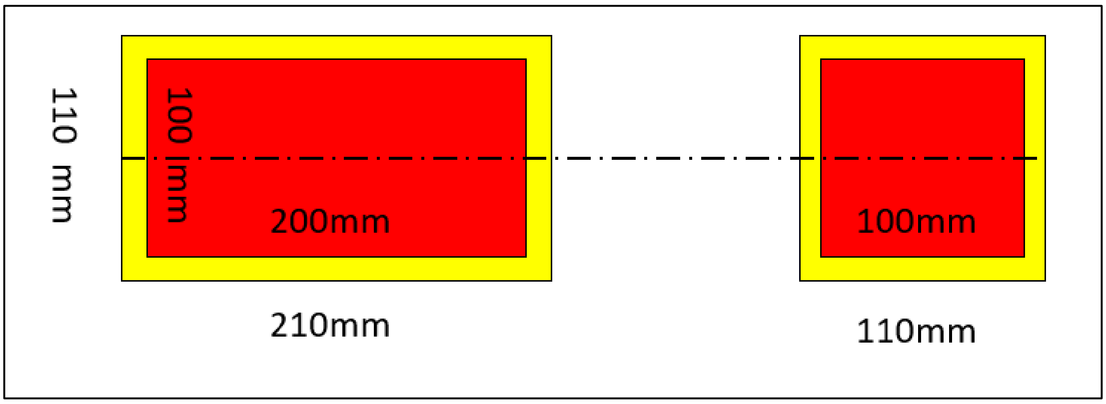


Figure 3.5-2 – Diagram of material billet sizes (yellow block) in comparison to finish sizes of a tool-holder (red block)

Figure 3.5-2's diagram illustrates the relationship between tool-holder finish dimensions and material billet dimensions. The billet size compromises the amount of material to remove against job complexity to optimise the machining cycle time. Appendix 6 details further reading on this process. Material ready for machining is placed into the cell along with its planning paperwork for use.

Prior to investigating the individual processes a time study was conducted on two typical existing design batches due to a lack of new design batches being available for study. Batches 1 and 2 were for 14-off and 6-off quantities respectively, with timings estimated from daily manual progress monitoring. Figures 3.5-3 to 3.5-4 detail the batch timelines.

Task Name	Duration
Setups 1 & 2 - Billet in Vice for Profile Machining	4 days
Setup 3- Machining Front Bore in 1st Part	0.5 days
Setup 3 - Remainder of Batch Front Bore Machining	1.5 days
Setup 4 - Actuation Bore Machined on Top Face Using Indexer	1.5 days
Setup 5 - Remaining Features Machined on Indexer	1.5 days

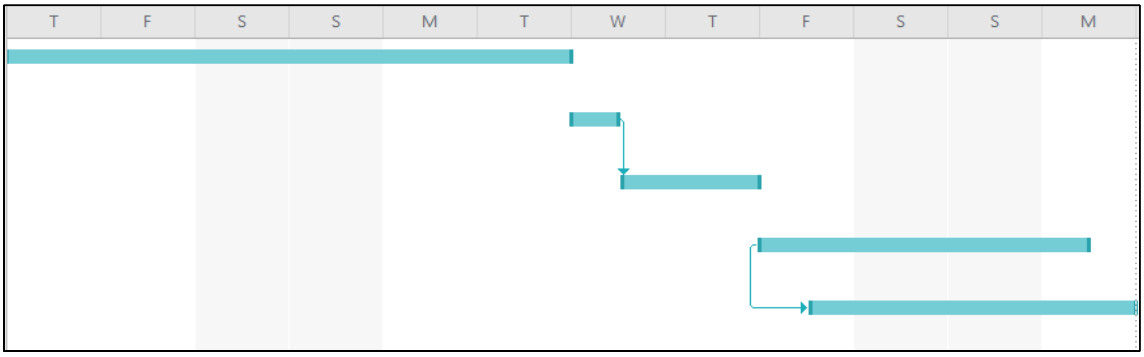


Figure 3.5-3 - Timeline of 14-off Holder Batch Manufacture

Task Name	Duration
Setups 1 & 2 - Billet in Vice for Profile Machining	1 day
Setup 3- Machining Front Bore in 1st Part	0.5 days
Setup 3 - Remainder of Batch Front Bore Machining	1.5 days
Setup 4 - Actuation Bore Machined on Top Face Using Indexer	0.5 days
Setup 5 - Remaining Features Machined on Indexer	0.5 days

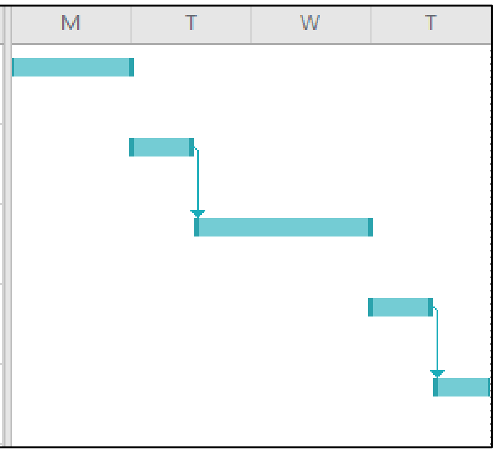


Figure 3.5-4 - Timeline of 6-off Holder Batch Manufacture

The setups defined within figures 3.5-3 to 3.5-4 will be introduced in chapter 3.5.4. The studies suggest that first-off holders in a batch consume a considerable period of total batch time. Batch 1's 14 tool-holders were produced in 8 working days and batch 2's 6 tool-holders were produced in 4 working days. These findings suggest that:

1) The 14-off batch was slightly more productive (1.75 tool-holders/day average) than the 6-off batch (1.5 tool-holders/day average)
2) The ratio of machining time to setup time increases for larger batches

These findings suggest the process is better suited to larger batch quantities. Individual manufacturing themes were investigated to understand the time study results further and are illustrated in figure 3.5-5.

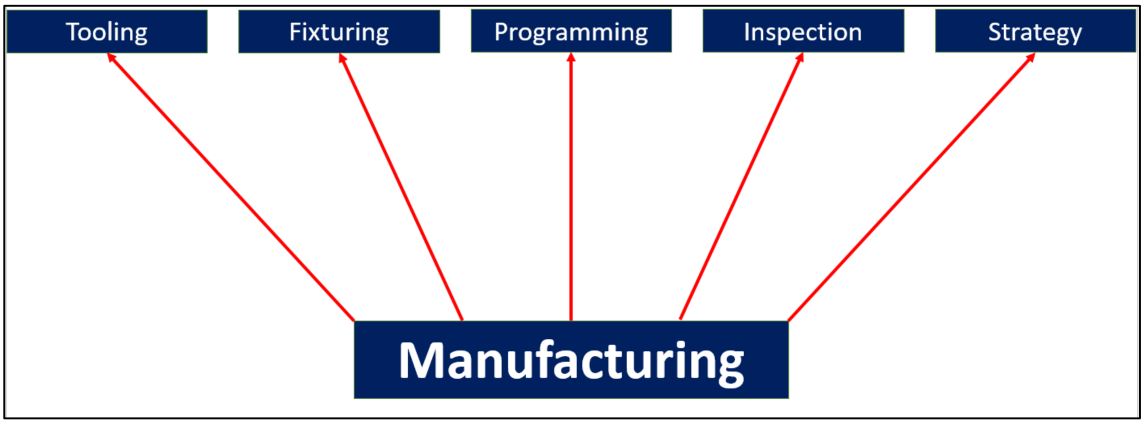


Figure 3.5-5 – Diagram of manufacturing themes to be discussed in detail

Chapter 3.5.2 Programming Existing Practices

For received orders the machine operators check whether machining programs exist. Table 3.5-1 provides features of the 6 VM machines and their CNC controlling PCs. The programming on each machine controller is similar due to the similarity of all 6 machines.

Features of VM machine CNC controllers
1) Conversational programming as opposed to conventional G&M codes 2) Machine programs stored in control memory, not on network 3) Programs transferrable between machines 4) File transfer ports vary – (VM1 uses floppy disk, VM6 uses USB) 5) Programs only have forwards transfer compatibility

Table 3.5-1 - Table of features for VM machine CNC controllers

For existing designs operators are able to transfer existing program files as per point 3) in table 3.5-1, however for new designs programs require writing using conversational programming. All operators are trained in conversational programming. Estimating programming time is difficult as each design provides different challenges, but observation and collaboration with stakeholders determined a 0.5 production day contribution (9 hours in an 18-hour working day) for this process.

Operators utilise the manufacturing drawing for writing program NC code with no CAD model usage. Limited program simulation capability existed on the CNC controllers which increased the likelihood of human error through being less able to detect programming errors. Programming errors can lead to undesirable part reworking costs.

Chapter 3.5.3 Tooling Existing Practices

The VM machines can hold 29 tools each plus an inspection probe. It has been determined from historical data that each machine should always contain 20 essential tools for machining standard features. The remaining tool pockets are utilised for part specific tooling with additional tooling stored in multiple storage units inside the cell. For new designs the operators determine the required tooling during the conversational programming phase.

Observations and discussions with cell stakeholders found that suitable tool identification can be difficult and leads to unplanned downtime. Figure 3.5-6 illustrates a brief analysis on availability of the 20 essential tools during a particular shift. The analysis indicated limited tool availability with the conclusion that some tooling was shared between machines. Further investigation identified a difficult balancing act between tool management for the cell and the available finances for all SMfE tooling.

Tool No.	VM1	VM2	VM3	VM4
1	1	1	1	1
2	1	1	1	1
3	1	1	1	1
4				1
5				
6	1		1	1
7	1	1	1	1
8				1
9				
10				1
11	1			1
12		1	1	1
13				
14				1
15		1	1	1
16				
17		1		1
18				
19				1
20	1			

Figure 3.5-6 - An example study of 'essential tooling' in some of the VM machines (Green - available, Red - not available)

A contribution due to sharing essential tooling between machines was approximated at 0.25 to 0.5 production hours after stakeholder consultation. Frequency of occurrence however was unable to be measured without additional investigation.

Chapter 3.5.4 Strategy Existing Practices

Strategy refers to the manufacturing setups used for tool-holder production on the VM machines. These machines have a 3+1 axis milling capability (see chapter 3.5.5). The strategy also defines the fixturing and inspection equipment used. Figure 3.5-7 illustrates a tool-holder and the features machined within each machining setup:

1) The standardised bore detail for sub-assembly components (setup 3)
2) The bore detail into which the sub-assembly mechanism components fit for unit actuation (setup 4)
3) The features allowing holder mounting onto a CNC machine (setups 1 & 2)
4) Remaining features (setup 5)

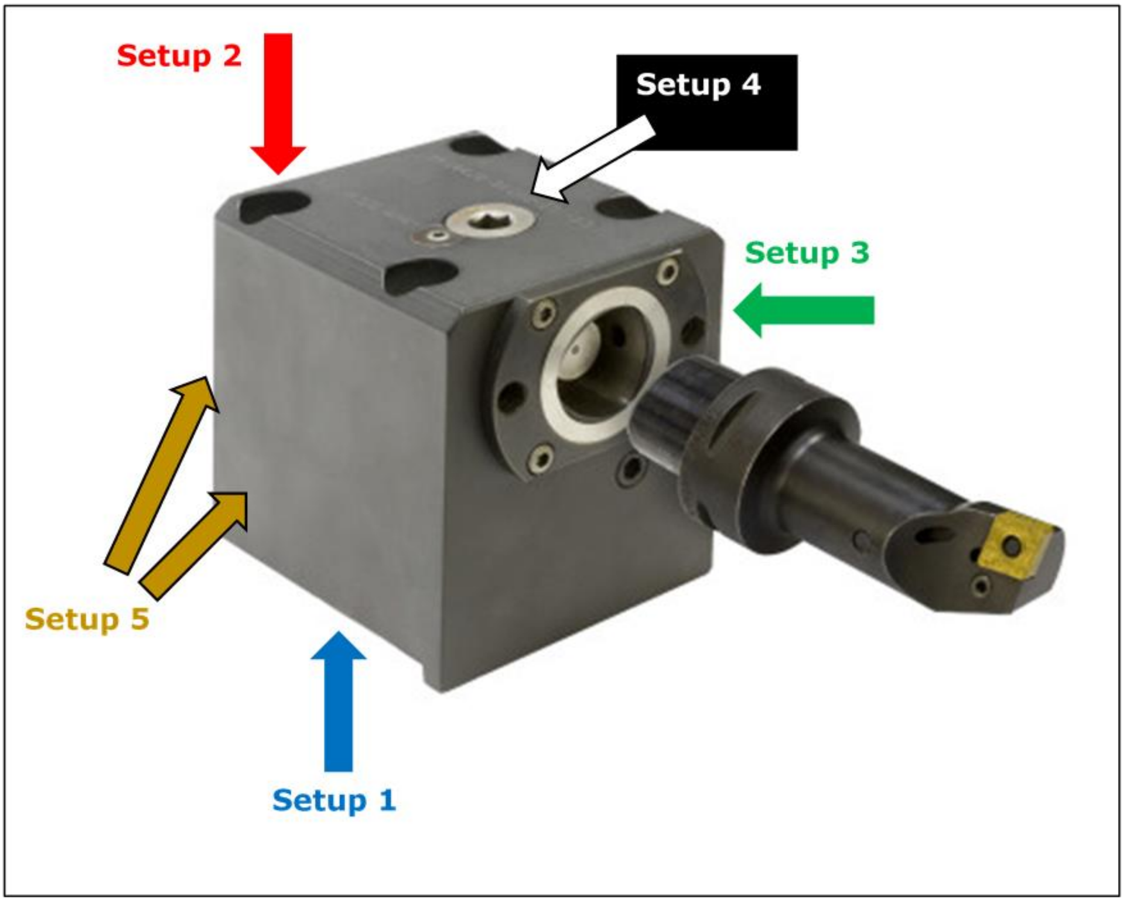


Figure 3.5-7 - Tool-holder image with arrows added related to the features machined in each setup – image taken from SMfE website

The figure 3.5-8 flowchart relates the machining requirements to figure 3.5-7. This generic strategy is utilised for most tool-holders with specific variations occurring between each design. Figure 3.5-8 also details the fixture equipment for each setup. The machined features in setup 1 establish the primary datum for: 1) mounting the finished holder to the CNC machine and 2) locating on fixtures used during setups 3, 4 and 5 to machine critical features. All holders are machined one at a time in a particular setup prior to moving onto the next machining setup.

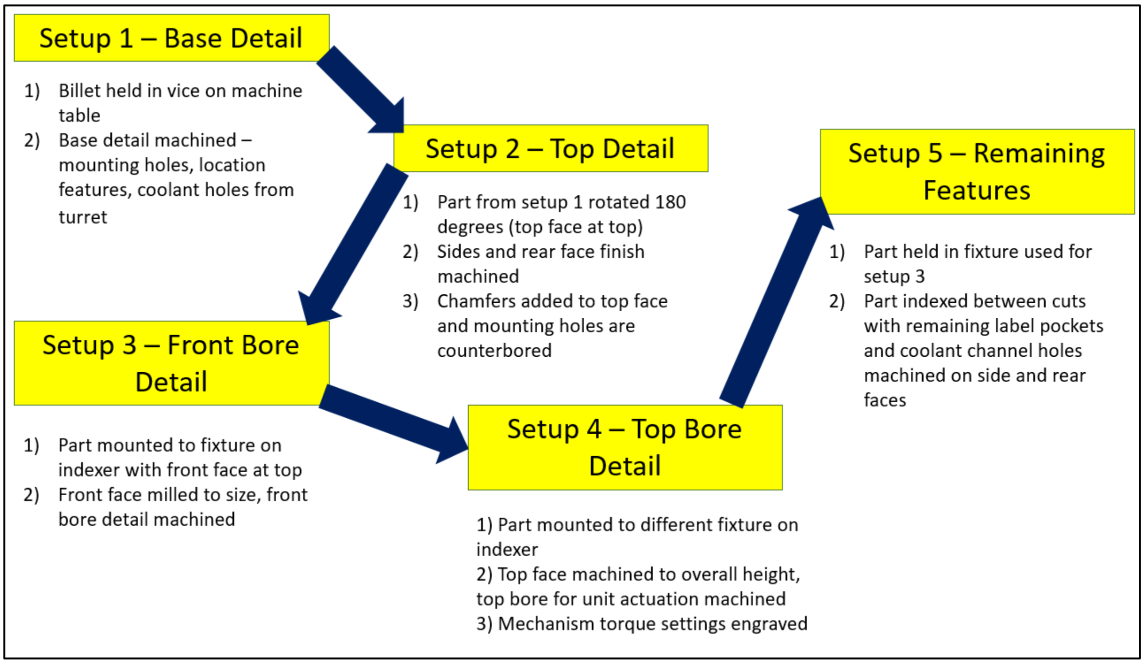


Figure 3.5-8 – Flowchart of the 5 setup processes for the tool-holder in figure 3.5-7

Figures 3.5-7 to 3.5-8 suggest the strategy limits the machining of different faces and features to separate machining setups. The rotary indexer (introduced in chapter 3.5.5) is only fully utilised for less critical features in setup 5. The full strategy initially appears manually intensive with considerable time needed for producing the multiple machining setups. A manually intensive approach was observed as a typical SMfE characteristic in chapter 1.1. Manual machine loading contributes significantly to setup time and highlights a possible need for automation. In chapter 3.5.7 time contributions are estimated using figure 3.5-8 and the two time studies from chapter 3.5.1.

Chapter 3.5.5 Fixturing Existing Practices

Figure 3.5-9 introduces the VM machine axes [3 translational (X/Y/Z) and one rotational (A)]. The A axis is only usable for indexing between machining passes making the process a 3+1 machining process. Setups 1 and 2 require most material removal with table vices used for part work-holding during machining of the primary datum face. Fixtures suiting the datum face machined in setup 1 are used for setups 3 to 5, with an example in figure 3.5-9 mounted to the indexer. Creation of specific fixturing internally for use on different tool-holders has overseen approximately 150 fixtures produced. Minimal calibration of these appeared to exist. Additional detail on the use of fixtures for machining each setup is detailed within appendix 6.

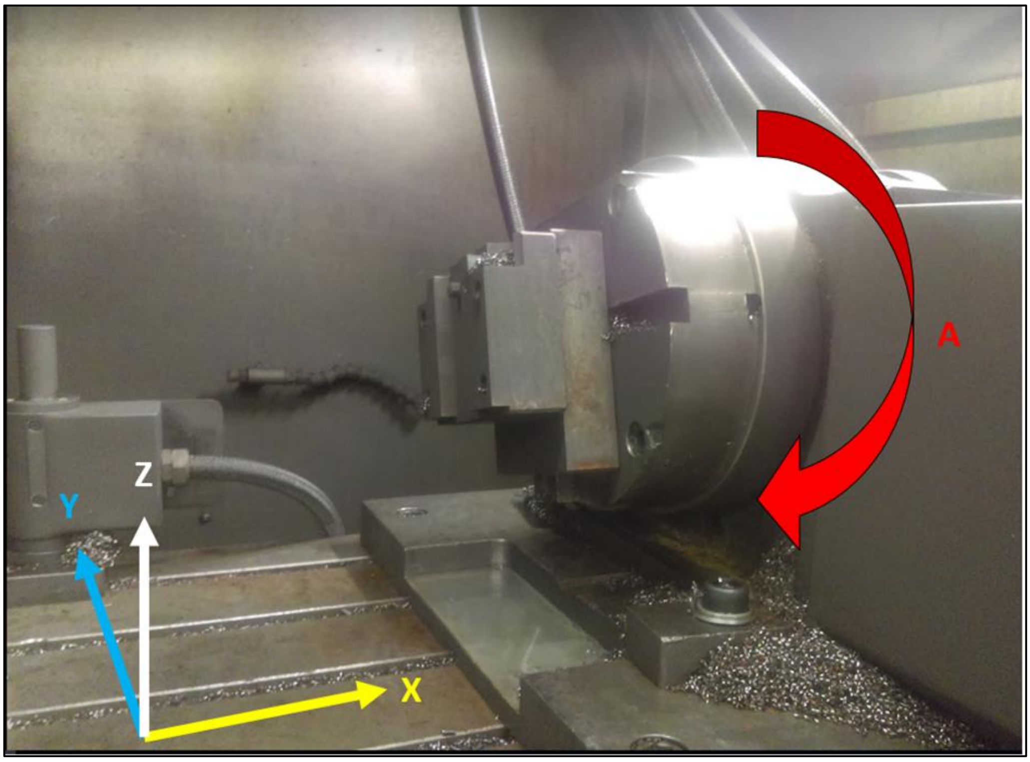


Figure 3.5-9 – Photo inside existing VM machines including axes labels

The 150+ fixtures are stored on racks and pallets in the cell with minimal organisation (see figure 3.5-10). Fixtures are numbered and associated to specific drawing numbers to aid operator identification. A single fixture may be potentially suitable for multiple tool-holder designs all containing the same setup 1 datum face, however relating fixtures to a single drawing number does not communicate this fact. Correct fixture identification during setup appears to cause unplanned downtime due to the lack of organisation. An estimated 0.25 to 0.5 production hours' contribution was determined for identification.

Figure 3.5-10 – Photograph of some of the fixtures utilised in setups 3 to 5

Chapter 3.5.6 Inspection Existing Practices

Manufactured tool-holders are inspected for geometrical and dimensional tolerances specified in drawings. The geometrical tolerances include feature sizes (i.e. bore diameters) and the dimensional tolerances measure positional relationships. The inspection approach is introduced from a manufacturing viewpoint in this chapter covering:

1) The manual measurement equipment
2) The process associated with setup 3 for off-machine inspection

Manual measurement equipment (micrometers etc.) and internally produced calibrated gauges are utilised for geometrical tolerance inspection. Figure 3.5-11 illustrates a go/no-go bore gauge for checking bore diameters with in-tolerance diameters seeing the go gauge fit and the no-go gauge not fitting. Geometrical features can be inspected whilst a part is on-machine. The VM machines contain machine tool probes allowing for on-machine inspection but are not currently utilised.

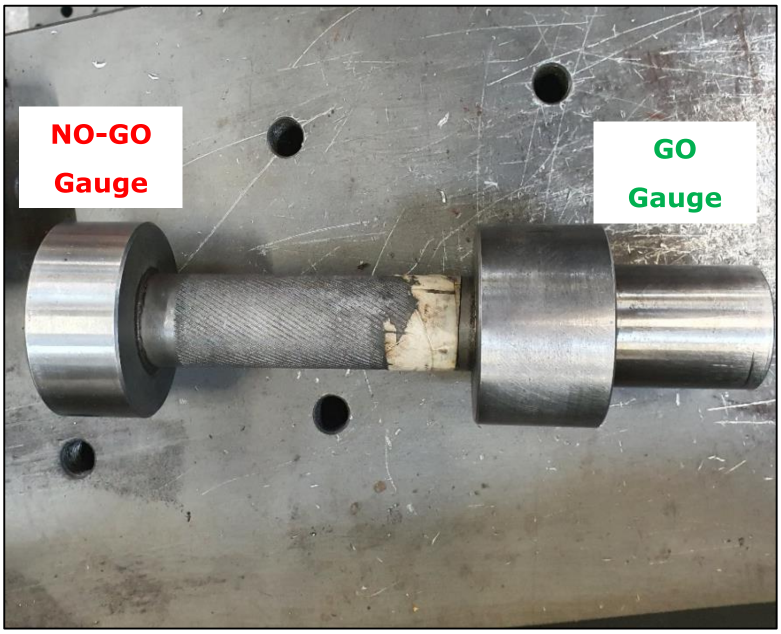


Figure 3.5-11 - Example Bore Go/No-Go Gauge to Check Bore Diameter on a Tool-Holder

For setup 3 the key positional tolerances inspected are the horizontal and vertical positions of the bore machined into the front face. With no on-machine probing an off-machine inspection process is therefore used which is discussed further in chapter 3.6. The bore centre position approximates the cutting tool centre position once assembled which is demonstrated in the figure 3.3-1 schematic.

The bore inspection process requires part unloading from setup 3 to inspect the part off-machine. The 1st-off part in a batch requires multiple bore position inspections. The operator will machine a test hole which is inspected prior to reloading the part and machining the full bore detail with programming adjustments made. The finished bore is then also inspected for position to ensure that positional tolerances are achieved. Once achieved the remaining batch bores can be machined without test holes.

Process Steps & Time Estimates for Bore Inspection
Removal of tool-holder from setup 3 for inspection (max 0.25hrs)
Inspection of bore detail using off-machine process (0.25 to 0.5hrs)
Replacement of tool-holder onto setup 3 for machining (max 0.25hrs)

Table 3.5-2 – Process steps for inspecting bore position using off-machine process

Table 3.5-2 estimates a minimum one-hour requirement for a single off-machine bore inspection. First-offs contribute additional inspection time due to the multiple inspections made. The findings associated with setup, machining and inspection time support the 0.5 days' setup 3 first-off production time determined in the chapter 3.5.1 time studies. The existing inspection time requirements mean that larger batches (10+) are unable to have 100% bore position inspection, with approximately 1 in 3 holders inspected.

Chapter 3.5.7 Summary

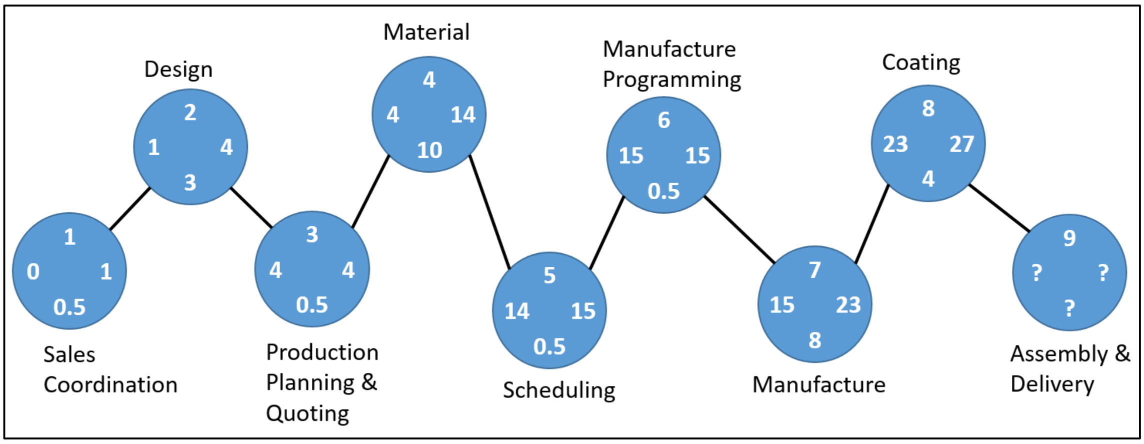
Setup	Setup Time	Machining Time
1 & 2	15 to 30 mins - 1st off 15 mins each for batch remainder	1.5 to 2 hrs -1st off 1 to 1.5 hrs each for batch remainder
3	2 to 3hrs - 1st off 30 mins to 1hr each for batch remainder	1.5 to 2hrs - 1st off 1 to 1.5hrs each for batch remainder
4	30 mins - 1st off 15 mins each for batch remainder	30 mins - 1st off 15 to 30 mins each for batch remainder
5	15 mins - 1st off 15 mins each for batch remainder	15 to 30 mins - 1st off 15 to 30 mins each for batch remainder

Figure 3.5-12 - Setup and machining time estimates based upon time study & stakeholder input

Figure 3.5-12 collates all the data from chapters 3.5.1 to 3.5.6 to estimate strategy setup and machining times. 1st-off parts have increased setup and machining time with the time estimates per part reducing for subsequent parts. This highlights how larger batches improve productivity. Prior to adding times to the AON and timeline diagrams the key points were collated:

1) Time studies showed 14 holders = 8 days' machining & 6 holders = 4 days' machining
2) Typical batch quantity ranges from 1-off to 20-off
3) Programming time estimated at 0.5 days for new designs
4) Tooling & fixturing downtime losses included within setup time

A medium size batch quantity of 11-off was considered for the DTD process time, with a conservative 8 days' contribution estimated to incorporate unplanned downtime losses. This combined with 0.5 days' programming time provides a total manufacture function contribution of 8.5 days. Figure 3.5-13 illustrates the updated AON and timeline diagrams with the manufacturing function observations summarised in figure 3.5-14.



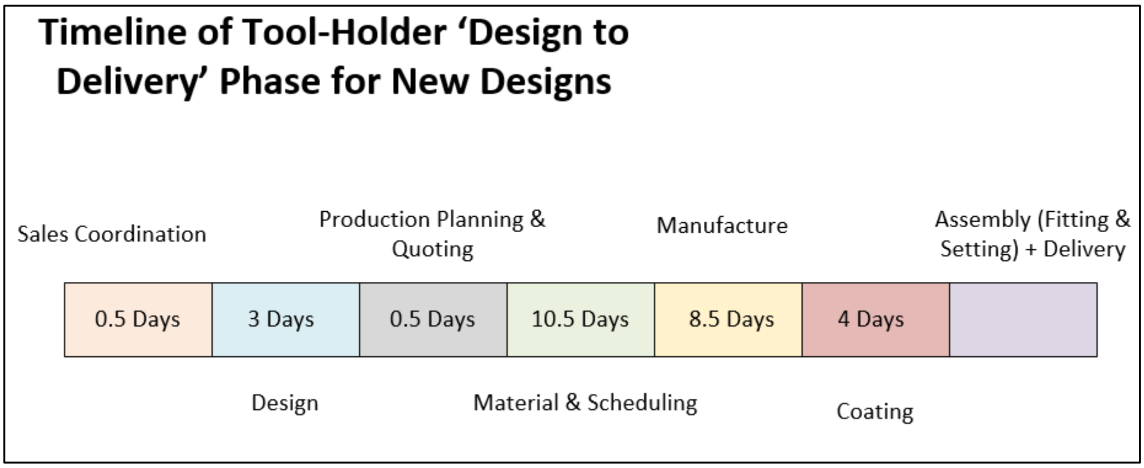


Figure 3.5-13 - Updated AON Diagram and DTD Process Timeline With Manufacture Timings

Positive Observations	Negative Observations
Multiple similar VM machines provide flexibility to machine holders on various machines	Process is manually intensive, multiple setups required – no automation use
Products to be manufactured are very similar in general shape and geometrical features – allows common strategy use	Machine programs all written using drawing as reference, no CAD model use – opportunities for human error to exist
Range of fixturing and tooling recorded and documented for holder manufacture	Tooling – exists but time losses possible from machines not being fully stocked
Operators skilled at setup and writing programs	Fixturing – Multiple fixtures exist, but organisation and current system usability is difficult
Existing programs can be transferred from old VM machines to newer ones (forward compatibility)	Machine programs - Not stored on network, only on the machines (limited memory) and no transfer backwards compatibility exists

Figure 3.5-14 - Observations Summary of Manufacture Function

Chapter 3.6 Existing Practices Analysis – Inspection & Assembly

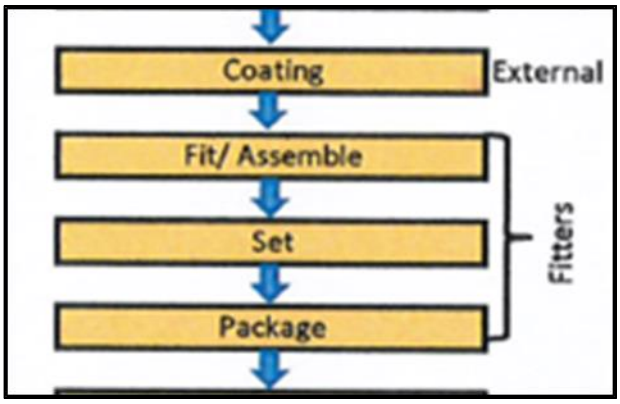


Figure 3.6-1 - Partial flowchart focusing on inspection and assembly DTD process steps

Figure 3.6-1 details the remaining DTD process steps. The SMfE utilises the terms fit/fitting and set/setting for assembly and post-assembly inspection respectively. Fitting and setting occur following coating. Fitting sees the assembly of the sleeve sub-assembly pieces, fasteners and seals to the manufactured body to produce the finished product. Setting involves inspecting the front bore position on the fully assembled unit. The off-machine manufacturing inspection process defined in chapter 3.5.6 is discussed in conjunction with the setting process due to process similarity.

Chapter 3.6.1 Fitting Existing Practices

The sub-assembly components are assembled to the tool-holder body with the front sleeve sub-assembly manually checked to ensure it has been assembled flat to the holder's front face. Fitting is assigned a standard 0.25 hrs time per tool-holder with minimal productivity losses in the process and a lack of improvement opportunities observed. Fitting was therefore not investigated further in chapter 4.

Chapter 3.6.2 Setting Existing Practices & Manufacturing Inspection Off-Machine

Figure 3.6-2 illustrates the calibrated equipment used for bore position checking:

1) A one-dimensional height gauge
2) A granite inspection table
3) Specific inspection fixturing

The height gauge uses a metal ball probe for touching onto part features as opposed to the indicator seen in figure 3.6-2. The inspection fixturing is similar to the machine fixturing discussed in chapter 3.5.5 in terms of datum detail, however the inspection fixtures are large, dense cubes containing multiple mounting features on different faces. This minimises the quantity of fixtures required. The dense cubes also provide a stable surface for part inspection.

Figure 3.6-2 - One dimensional height gauge, granite table and fixture example used for inspection

Bore positions are inspected by mounting the holder onto the fixture and measuring bore position horizontally and vertically from reference features on the fixture. The reference features provide a zero value from which the bore positions are measured. The position value measured is shown on the gauge's digital readout. Appendix 6 provides further detail on the exact processes for measurement. The one-dimensional aspect of the height gauge means horizontal positions are measured by placing the fixture and tool-holder at 90 degrees to allow for measurement of horizontal features in the vertical plane.

For off-machine bore inspection the metal probe touches onto the bore feature directly, whereas for setting this is not possible due to the unit being assembled. During setting a cylindrical bar insert piece is used which attaches to the tool-holder's clamping mechanism. The setting process sees the inspector touch onto the cylindrical bar at multiple points along its length to measure bore position in relation to the fixture reference features. The cylindrical bar simulates a cutting tool being inserted into the holder during product usage. The dimensional report in figure 3.6-3 presents a schematic of the described process.

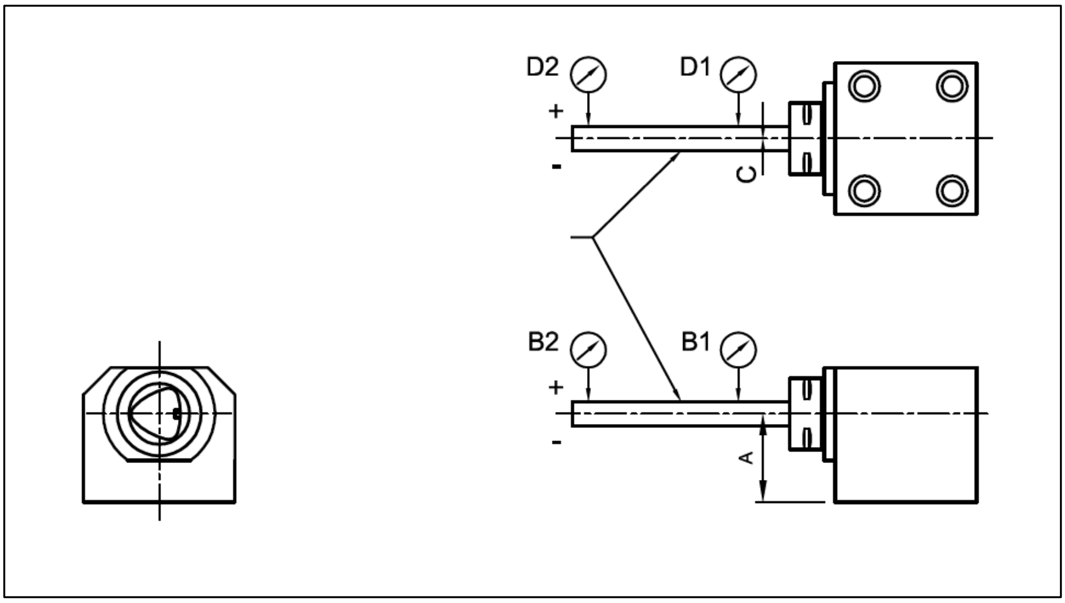


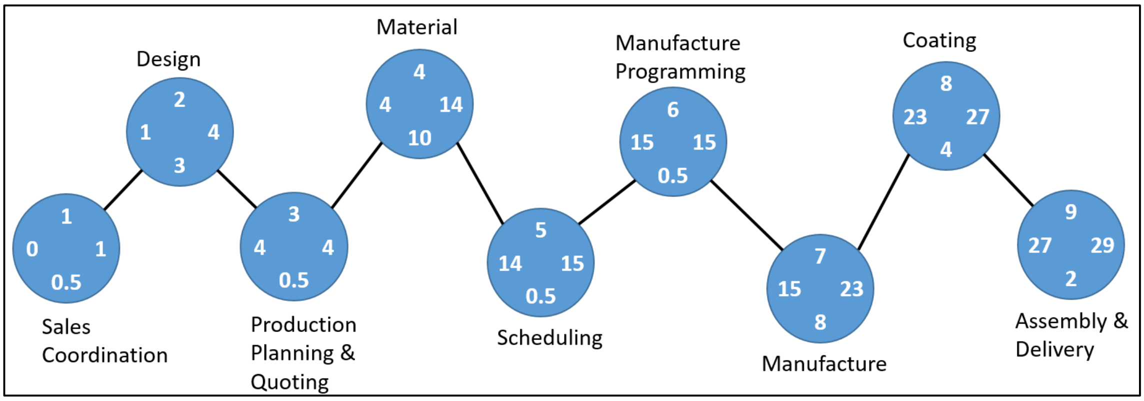
Figure 3.6-3 – SMfE report template section highlighting setting process checks to perform using insert piece

In figure 3.6-3, Dimensions A, B1 and B2 measure bore position vertically with C, D1 and D2 measuring position horizontally (in the 90-degree setup). A and C relate to specified drawing tolerances whilst B1-B2 and D1-D2 measure runout of the cylindrical bar, based on the readings taken from touching the bar along its length. 100% capture of these values for tool-holders is achieved via an inspection record spreadsheet with each tool-holder assigned a unique number for traceability. It is assumed the estimated time for both off-machine inspection and setting processes are equal, therefore ranging from 0.25hrs to 0.5hrs as detailed previously in table 3.5-2.

Chapter 3.6.3 Leakage Testing & Packaging Existing Practices

Prior to packaging tool-holders are tested for leakage to ensure through-coolant capability of high pressure coolant. Appendix 6 details this process along with packaging details as both processes provide negligible contributions to the DTD timeline.

Chapter 3.6.4 Summary



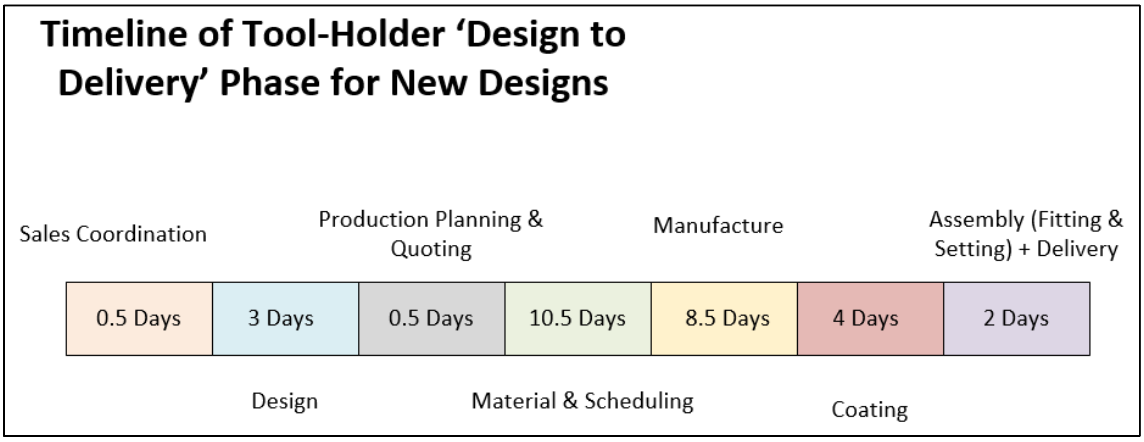


Figure 3.6-4 - Updated AON Diagram and DTD Process Timeline with Assembly, Inspection & Delivery Timings

Figure 3.6-4 illustrates the finalised AON and DTD timeline diagrams. 2 days' assembly and delivery was estimated as one tool-holder requires approximately 1 hour of fitting, setting, testing and packaging in an 8-hour working day. For the 11-off batch approximately 1.5 days would be required, however a conservative 2 days has been given factoring in any unplanned downtime. The positive and negative observations are detailed within figure 3.6-5.

Positive Observations	Negative Observations
Range of internal inspection equipment available and calibrated	Setting and off-machine inspection process can be time consuming to setup – compared to manual gauge checks, or if on-machine checks were used with probing
Large range of product variations can be inspected through use of cube-type fixturing	Large range of inspection fixtures to maintain to provide reliable inspection data
Use of height gauge – straightforward and multiple staff trained in for inspection	Setting process using height gauge is heavily manual – individuals have different 'feel', different results can be achieved by different personnel on same setup
Inspection spreadsheet record of position results completed on all tool-holders – providing future traceability	Fixtures have minimal organisation in terms of identification, storage is more organised than for manufacturing equivalent
Defined fitting and setting processes applicable for most tool-holders	100% inspection not feasible on larger batches during manufacture due to time constraints – also off-machine inspection results not recorded for process analysis

Figure 3.6-5 -Observations Summary of Assembly, Inspection & Delivery Functions

Chapter 4 Selection of Productivity Bottlenecks

Chapter 4.1 Analysis of DTD Process Diagrams & Observations

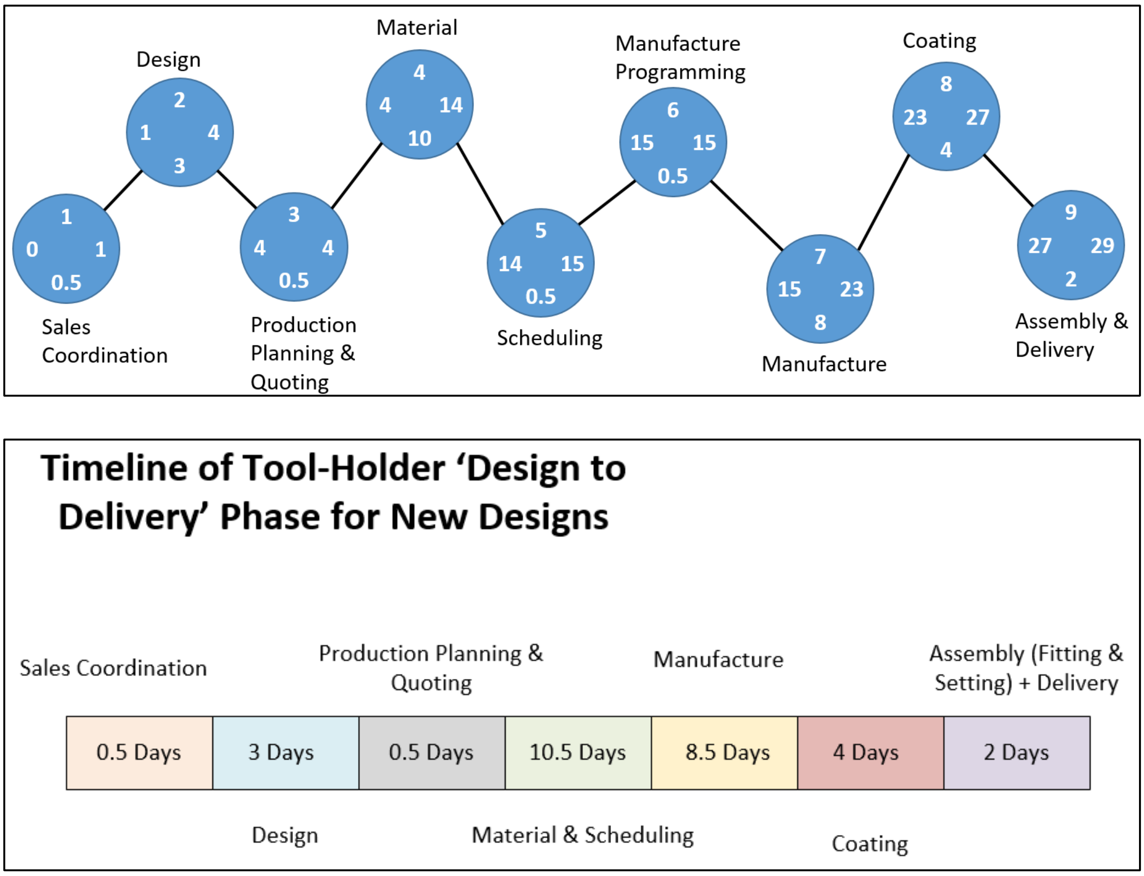


Figure 4.1-1 – Finalised AON and DTD Process Timeline Diagrams

The completed diagrams in figure 4.1-1 determined a 29-day DTD process time which is similar to the 30-day estimate from chapter 1.3. Approximately 75% of the total time is attributed to design, material/scheduling and manufacture. The AON diagram illustrates the significant delay in starting manufacture caused by long material delivery times (start on day 15). One process delay impacts the whole flow significantly due to there being no concurrent processes. Figures 4.1-2 to 4.1-3 collate the negative observations from chapters 3.2 to 3.6 contributing to the current DTD process time.

Figure 4.1-3 considers the current manufacturing data capture approach despite it not directly impacting DTD process time as data capture can play a significant role in manufacturing decision-making. Current data collection is a manual process relying on obtaining accurate job times from machine operators. No separation of actual setup and actual machining times for jobs exists which provides no feedback on the accuracy of the estimated setup and machining times assigned during planning. For this reason investigation of machine monitoring technologies will be considered.

Business Function	Negative Observations
Design	CAD software is 2011 version – Possible performance and file compatibility issues over time + newer features not accessible
	Existing records for design projects and drawings all manually updated – time-consuming to keep accurate
	Drawing revisions and change records not currently documented – only drawings contain individual revision changes
Workflow Management (Planning, Quoting, Material, Scheduling)	Large lead times on specific material sizes
	Order schedule requires manual input to keep updated despite use of IT resource
	Orders allocated to machines 'ad-hoc', short-term scheduling
Manufacture	Process is manually intensive, multiple setups required – no automation use
	Machine programs all written using drawing as reference, no CAD model use – opportunities for human error to exist
	Tooling – exists but time losses possible from machines not being fully stocked
	Fixturing – Multiple fixtures exist, but organisation and current system usability is difficult
	Machine programs - Not stored on network, only on the machines (limited memory) and no transfer backwards compatibility exists

Figure 4.1-2 – Negative observations identified for the design, workflow management and manufacturing business functions

Business Function	Negative Observations
Inspection & Assembly (Assembly + Delivery)	Setting and off-machine inspection process can be time consuming to setup – compared to manual gauge checks, or if on-machine checks were used with probing
	Large range of inspection fixtures to maintain to provide reliable inspection data
	Setting process using height gauge is heavily manual – individuals have different 'feel', different results can be achieved by different personnel on same setup
	Fixtures have minimal organisation in terms of identification, storage is more organised than for manufacturing equivalent
	100% inspection not feasible on larger batches during manufacture due to time constraints
	Off-machine inspection results not recorded for process analysis
Data Capture on Manufacturing	Setup and Run times in production planning differ to actual times collected – operators record single time figure against an order – no knowledge of actual setup / machine run time ratio from actual data

Figure 4.1-3 - Negative observations identified for the assembly, inspection & delivery business functions as well as data capture from manufacturing

Approximated DTD process time contributions for all negative observations are detailed in figures 4.1-4 to 4.1-5 where possible for comparison.

Business Function	Negative Observations	Time Estimate (Where Possible)
Design	Out of date CAD software	Not possible
	Manual design projects management	Approx. 0.5 to 1hr per day for design manager
	Part history / change record management not fully recorded	Could prevent wrong drawing being issued to production – quality cost savings
Workflow Management	Large lead times on specific material sizes	10 days
	Manual input required to update machine schedule	0.5 to 1hr per day for cell production manager
	Orders allocated to machines 'ad-hoc', short-term scheduling	Orders could be delayed approx. 1-2 days if priorities change
Manufacture	Process highly manually (minimal automation or 'lights-out' manufacture)	Typical 1st-off tool-holder could take 10hrs (setup + run time) – and no 'lights-out' run time currently
	Machine programs written using conversational programming	0.5 days approx.
	Tooling time losses from finding appropriate tooling	0.25 to 0.5 hrs per job to find tooling
	Fixturing system - lack of thorough management	0.25 to 0.5 hrs per job identifying fixtures
	Machine programs management	Potential time losses for program transfer, rewriting etc.

Figure 4.1-4 - Negative observations identified for the design, workflow management and manufacturing business functions with time estimates where applicable

Business Function	Negative Observations	Time Estimate (Where Possible)
Inspection	Setting process with fixturing setup time	0.25 to 0.5hrs per part
	Large quantity of inspection fixtures to manage	Not possible
	Manual inspection – individuals have different 'feel'	Time losses from inspection discrepancies possible
	Fixture organisation and identification minimal	0.25 to 0.5hrs identification
	100% manufacturing inspection not possible on larger batches	Possible quality issues at setting stage
	Off-machine inspection results not recorded for process analysis	Possible quality issues at setting stage
Data Capture on Manufacturing	No accurate capture on individual actual setup and actual run times using current approach	No capture of potential issues associated with setup of jobs – no improvements made and time reductions not seen

Figure 4.1-5 - Negative observations identified for the assembly, inspection & delivery business functions as well as data capture from manufacturing with time estimates where applicable

From a DTD process time viewpoint figures 4.1-4 to 4.1-5 identify leading process time contributors including:

1) Material delivery time – (1/3 of the total process time)
2) Manual machining setup process – large time consumption to produce 1st-off holder with no automation and 'lights-out' machining
3) Manual program writing – timely process and contains potential for errors and associated costs
4) Inspection off-machine is time-consuming in terms of setup and part inspection
5) Downtime during setup attributed to tooling and fixturing identification

Those not listed above were seen as insignificant in reducing the DTD process time. Examples include design management and machine scheduling which despite being manual were successful practices. The CAD software age and inspection equipment use by different personnel are possible losses in specific scenarios. The time impact of the setting process was not seen as critical unlike the off-machine manufacturing inspection process which also includes part loading and unloading time.

The practices analysed above agreed with chapter 1.1 challenges found including:

- Limited resources for product manufacture (Kim et al, 2008)
- Less complex and informal organisational structure (Mittal et al, 2018)
- Lower use of advanced technologies, research and development (Mittal et al, 2018)
- The required batch quantities are small and variable with manual techniques utilised (Zheng et al, 2019)

The current practices are well-defined and highlight partial success in managing with limited resources, however there may be potential cost reduction opportunities through automation. Recent lack of investment in CAD and CAM software further support maximised use of limited resources.

The culture focuses on 'day-to-day' or 'ad-hoc' management (see chapter 3.4) which is typical of an SMfE producing variable batch products. Good quality management exists through data capture in the setting process, however the manufacturing inspection process is less controlled.

The leading contributors identified above will be analysed in further detail within chapter 4.3 to aid bottleneck identification.

Chapter 4.2 SWOT Analysis of Tool-Holder DTD Process

Stakeholders contributed significantly to the chapter 3 study. Despite this full stakeholder analysis was essential in identifying their requirements and the external factors impacting the DTD process. A SWOT analysis was conducted using focused group sessions with stakeholders across all functions. SWOT observations were limited to 10 for each category where required to focus discussions. The observations are listed in figures 4.2-1 to 4.2-4.

Strengths	S1	Broad Product Offering - 100s of existing designs
	S2	Skilled Machine Operators
	S3	Multiple Similar Machines - Flexibility in Scheduling & Assigning Programs
	S4	Large amount of useful resource - existing designs/programs/fixturing
	S5	Simple final inspection process
	S6	Utilisation of CAD to produce drawings
	S7	Single system for purchasing, planning, shipment control
	S8	Stock-holding of finished assemblies and stock material
	S9	Similar process for 100s of product types - assembly components, material used
	S10	Long term agreements in place with key customers

Figure 4.2-1 - Identified Strengths from Stakeholder Analysis

Weaknesses	W1	100s of designs - part history, change record not collated
	W2	Order equipment requirements (fixturing, tooling) not defined until operator receives order
	W3	Multiple machines - larger batch quantities required to achieve high utilisation
	W4	Existing programs & fixturing - lack of organisation
	W5	Manufacturing inspection process - time consuming and 100% inspection not possible
	W6	Machine programming done manually - no CAD model use
	W7	Manufacturing setup - time consuming & manual, specifically for 1st-offs
	W8	Existing resources not utilised to full capacity (machine tool probes, CMM)
	W9	Long material delivery time for specific sizes
	W10	Long term agreements restrict sales to certain customers

Figure 4.2-2 - Identified Weaknesses from Stakeholder Analysis

Opportunities	O1	Tool-holder products sold to customers globally
	O2	Tool-holder products suitable for all manufacturing industries (i.e. automotive, aerospace, general manufacturing)
	O3	Existing long-term agreements - more order opportunities with improved delivery time
	O4	Increased adoption of automation in SMEs (robotic loading, multi-axis machining)
	O5	Material supplier can supply specified sizes in large quantities
	O6	Stock-holding of most popular sellers capable with reduced delivery time

Figure 4.2-3 - Identified Opportunities from Stakeholder Analysis

Threats	T1	Over-reliance on aging equipment - higher maintenance costs
	T2	Reduced machine cutting time - longer setups - less cost effective
	T3	'Lights-out' machining not practiced - less available cutting time
	T4	Increased adoption of automation in SMEs (robotic loading, multi-axis machining)
	T5	CAM not utilised - commonplace within manufacturing
	T6	Long term agreements reliant on meeting certain % on-time delivery requirements

Figure 4.2-4 - Identified Threats from Stakeholder Analysis

The discussions led to a reduced list of opportunities and threats in comparison to strengths and weaknesses. The strengths and weaknesses related to various chapter 3 findings whilst also considering the impact of tool-holder supply agreements with key customers. The most lucrative existing supply agreement is with a market leader which contains an agreed list of key tool-holders to supply. This agreement also restricts the sales opportunities to certain customers for the SMfE.

Figure 4.2-3 highlights how DTD process improvements could lead to increased business with new and existing customers through increased production capacity and an improved delivery performance. Threats found in figure 4.2-4 consider the impact of maintaining the existing practices identified and not adopting new approaches. Reduction of these threats will also maximise the sales opportunities. Competitors could capitalise on a lack of new technology adoption by the SMfE.

To rank the importance of the observations from figures 4.2-1 to 4.2-4 the confrontation matrix was utilised. The same stakeholder groups scored observations based on the following relationships:

1) Each strength optimising each opportunity
2) Each strength reducing each threat
3) Each weakness reducing each opportunity
4) Each weakness increasing each threat

A relationship score between 1 (weak) and 5 (strong) was determined for each observation pair to indicate the influence strengths and weaknesses had on opportunities and threats. For each individual strength/weakness their scores for all opportunities and threats were totalled in order to identify the strengths and weaknesses of greatest combined influence. An example of a strong relationship sees:

W7 / T2 – relationship score **5 –** The manual setup process exposes the SMfE to the long setup time threat, with reduced utilisation and increased downtime costs

In the figure 4.2-6 confrontation matrix the total scores for all 20 strengths and weaknesses are seen in the bottom row with scores ranging from 21 to 50. Only strengths and weaknesses scoring above 40 were investigated further due to their greater influence. Those investigated are listed in figure 4.2-5 below.

Strengths	S2	Skilled Machine Operators
	S3	Multiple Similar Machines - Flexibility in Scheduling & Assigning Programs
	S8	Stock-holding of finished assemblies and stock material
	S9	Similar process for 100s of product types - assembly components, material used
	S10	Long term agreements in place with key customers
Weaknesses	W3	Multiple machines - larger batch quantities required to achieve high utilisation
	W4	Existing programs & fixturing - lack of organisation
	W5	Manufacturing inspection process - time consuming and 100% inspection not possible
	W6	Machine programming done manually - no CAD model use
	W7	Manufacturing setup - time consuming & manual, specifically for 1st-offs
	W9	Long material delivery time for specific sizes
	W10	Long term agreements restrict sales to certain customers

Figure 4.2-5 - Strengths and Weaknesses identified for further investigation with total scores of 40+ in the figure 4.2-6 confrontation matrix

The figure 4.2-5 observation scores ranged from 41 to 50 suggesting a similar level of influence from all observations. The specific business function or theme associated for each observation was determined and categorised through colour coding of the total scores in figure 4.2-6. An example theme contains S10 and W10 as both observations are associated with the existing SMfE tool-holder customer agreements. The colour coded functions or themes used for categorisation were:

Green – The existing manufacturing process (equipment, personnel, utilisation)

Dark Blue – Popular tool-holders (tool-holder supply agreements, associated material delivery times)

Grey – Tool-holder product similarity in terms of DTD process requirements

Red – Inefficiencies in existing equipment and management processes (fixtures, inspection, programs)

Light Blue – Machine programming (manual programming process)

		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10
		Broad Product Offering	Skilled Machine Operators	Multiple Similar Machines	Variety of equipment available	Simple final inspection process	Utilisation of CAD for drawings	ERP Single system used	Stock-holding of finished parts and material	Similar process for 100s of product types	Long term agreements in place	Part design change record management	Fixturing, tooling not defined until production issued	Multiple machines - utilisation varies	Lack of organisation programs & fixturing	Manufacturing inspection inefficient & not 100% complete	Manual machine programming	Manufacturing setup process inefficient	Existing resources not utilised fully (probes, CMM)	Material delivery time for specific sizes	Long term agreements sales restrictions
O1	Tool-holder products sold globally	5	1	1	3	1	4	5	5	5	4	5	1	1	1	3	1	3	1	4	5
O2	Tool-holder products wide-ranging applications	4	1	1	1	1	4	1	5	5	4	1	1	1	1	3	1	3	1	1	5
O3	Increased opportunities with current agreements	2	4	3	4	3	1	1	5	3	5	1	3	5	3	5	3	5	2	5	5
O4	Increased adoption of automation in SMEs	3	5	5	3	2	4	2	3	5	5	3	1	5	3	3	4	4	3	3	2
O5	Material supplier can supply large quantities of cut sizes	2	1	1	1	1	1	4	5	4	4	1	1	4	4	1	4	2	1	5	3
O6	Stock-holding most popular tool-holders	3	1	2	1	1	3	2	5	1	5	1	1	4	5	1	2	4	1	5	3
T1	Over-reliance on aging equipment	1	5	5	3	3	5	1	1	4	5	2	1	2	5	5	5	5	5	1	4
T2	Long setup times & reduced utilisation	1	5	5	5	1	1	1	2	5	1	1	5	5	5	5	5	5	5	4	4
T3	Lights-out' machining not practiced	1	4	5	1	1	1	1	3	5	3	1	1	5	3	4	5	5	3	5	2
T4	Increased adoption of automation in SMEs	3	5	5	3	2	4	2	3	5	5	3	1	5	3	3	4	4	3	3	2
T5	CAM not utilised	1	5	5	2	1	5	1	2	5	3	5	1	5	5	5	5	5	1	1	2
T6	Long term agreements require certain % on-time delivery	1	4	3	1	4	1	1	5	3	5	1	5	5	5	5	3	5	3	5	5
	TOTAL	**27**	**41**	**41**	**28**	**21**	**34**	**22**	**44**	**50**	**49**	**25**	**22**	**47**	**43**	**43**	**42**	**50**	**29**	**42**	**42**

Figure 4.2-6 – SWOT confrontation matrix for Tool-Holder DTD process

Figure 4.2-6 identifies successful stakeholder input in determining influential strengths and weaknesses based on external opportunities and threats. Through categorisation these influential strengths and weaknesses can be compared with the leading contributors from chapter 4.1 to determine the key DTD process bottlenecks.

Chapter 4.3 Comparison of Productivity Bottlenecks Observed

The outputs from chapters 4.1 and 4.2 were compared to determine the DTD process bottlenecks.

Timeline Analysis	Stakeholder SWOT Analysis
1) 10 days material delivery time	A) Theme: Existing manufacturing process
2) Manual machine process (inefficient and no 'lights-out' machining)	B) Theme: Group of popular tool-holder sellers & their material requirements
3) Manual machine programming	C) Similarity across full process for large range of tool-holders
4) Inspection off-machine inefficient	D) Inefficiencies in equipment
5) Tooling time losses	E) Lack of organisation and data capture
6) Fixturing time losses	F) Machine programming

Table 4.3-1 - Comparison of outputs from chapters 4.1 to 4.2

Table 4.3-1 lists the findings. Clear overlap is seen between chapter 4.1 and 4.2 in the topics mentioned. Table 4.3-2 details the bottlenecks created through combining similar table 4.3-1 findings.

Bottleneck	Timeline & Stakeholder Output Theme
Long Material Delivery Time	Timeline point 1), stakeholder theme B)
Manual Machine Setup	Timeline point 2), stakeholder theme A)
No 'Lights-Out' Machining & Reduced Utilisation	Timeline point 2), stakeholder theme A)
Manual Machine Programming	Timeline point 3), stakeholder theme F)
Off-Machine Inspection Process	Timeline point 4), stakeholder theme E)
Tooling	Timeline point 5) stakeholder theme D)
Fixturing	Timeline point 6) stakeholder theme D)
Non-Stock Holding of Popular Sellers	Timeline point 1), stakeholder theme B)
Management of existing machine programs	Timeline point 3), stakeholder themes C)

Table 4.3-2 - Identified list of bottlenecks using chapters 4.1 to 4.2 data

The bottlenecks in table 4.3-2 highlight consistent themes within both data sets. Work was now required to rank and identify the key bottlenecks. An FMEA-based approach was utilised containing different scoring parameters to a generic FMEA (see template in figure 4.3-1):

1) RPN renamed Bottleneck Impact
2) SEV renamed Stakeholder Impact
3) OCC renamed Timeline Impact
4) DET was insignificant as all bottlenecks were detected. Each bottleneck was assigned a DET score of 1

Process Step	Potential Failure Mode	Potential Failure Effect	SEV[1]	Potential Causes	OCC[2]
What is the step?	In what ways can the step go wrong?	What is the impact on the customer if the failure mode is not prevented or corrected?	How severe is the effect on the customer?	What causes the step to go wrong (i.e., how could the failure mode occur)?	How frequently is the cause likely to occur?
ATM Pin Authentication	Unauthorized access	• Unauthorized cash withdrawal • Very dissatisfied customer	8	Lost or stolen ATM card	3
	Authentication failure	Annoyed customer	3	Network failure	5

Current Process Controls	DET[3]	RPN[4]	Action Recommended
What are the existing controls that either prevent the failure mode from occurring or detect it should it occur?	How probable is detection of the failure mode or its cause?	Risk priority number calculated as SEV x OCC x DET	What are the actions for reducing the occurrence of the cause or for improving its detection? Provide actions on all high RPNs and on severity ratings of 9 or 10.
Block ATM card after three failed authentication attempts	3	72	
Install load balancer to distribute workload across network links	5	75	

Figure 4.3-1 – Example of an FMEA conducted on an ATM – I Six Sigma (2020)

Using the defined methodology:

Bottleneck Impact = Stakeholder Impact * Timeline Impact * Detectability

Timeline Impact and Stakeholder Impact scores were based upon the contributions in figures 4.1-4 to 4.1-5 and the total scores for related observations in the figure 4.2-6 matrix respectively. For the long material delivery time bottleneck:

Timeline Impact = 10 [10 days' contribution to DTD process in figure 4.1-4]

Stakeholder Impact = 43 [the average of S8 (44) & W9 (42) observations associated with tool-holder material in figure 4.2-6]

Where required the stakeholder impact used an average score of all related strengths and weaknesses of a bottleneck from table 4.3-2 as seen in the above example. Timeline impact scores used the maximum contribution in days from figures 4.1-4 and 4.1-5. For manufacturing bottlenecks an 18-hour day equalled 1 DTD process day, so contributions of <1 day were calculated based on this (i.e. a 0.5hrs contribution timeline impact equalled 0.5/18, or 0.03 days).

Figures 4.3-2 to 4.3-3 contain the FMEA matrix. The 10-day material time scored the highest BI due to its significant TI value. The remaining BI scores are much closer and range from 0 to 21, with high scorers including the manual manufacturing approach and lack of 'lights-out' manufacture. Low BI scorers were associated to small TI contributors associated with tooling, fixturing and the choice not to stock popular tool-holders.

Key: Stakeholder Impact (SI), Timeline Impact (TI), Detectability (D), Bottleneck Impact (BI)

Bottleneck / Failure Mode	Potential Effect	SI	Potential Cause	TI	Current Controls	D	BI = SI* TI * D
Long Material Delivery Time	Reduced time to manufacture tool-holders to meet current 30 day lead time	43.0	Ordering special size material after an order is placed	10.00	Stocked bar lengths of square material size to reduce special size orders	1	430.00
Manual Machine Setup	Reliance on skilled operator, fine adjustment required to maximise accuracy, but still possibility for errors	45.5	Reliance on traditional process using existing equipment, minimal adoption of automation	0.22	Setup equipment such as DTIs, fixtures etc. to ensure accurate positioning and work holding	1	10.01
No 'Lights-out' Machining & Reduced Utilisation	Maximum 80hrs machining time per machine available in week, no overnight / weekend running	44.0	Use of multiple 3+1 axis VM machines requiring manual setup and loading / unloading	0.33	Operators encouraged to run multiple machines through company bonus system to improve utilisation	1	14.52
Manual Machine Programming	Potential for programming errors as written in full conversational programming language	42.0	Continued use of machining drawings, but not utilising CAD models or CAM programming	0.50	Toolpath simulation within VM machine controller, fully toleranced drawings and staff available to assist with program issues	1	21.00

Figure 4.3-2 – FMEA matrix on 4 of the 9 DTD process bottlenecks identified in table 4.3-2

Key: Stakeholder Impact (SI), Timeline Impact (TI), Detectability (D), Bottleneck Impact (BI)

Bottleneck / Failure Mode	Potential Effect	SI	Potential Cause	TI	Current Controls	D	BI = SI* TI * D
Off-Machine Inspection Process	Unable to achieve 100% inspection on full tool-holder batches, potential errors assembling / disassembling setups to inspect parts	43.0	No part inspection on machines for position	0.06	Calibrated off-machine fixtures used for inspection, full inspection performed where possible, 1st off parts are checked multiple times to make in-process adjustments prior to batch running	1	2.58
Tooling	Time spent looking for tools, multiple machines can be affected by sharing tooling	43.0	Not stocking spare tooling of essential tools frequently enough	0.03	Required tooling communicated to purchasing via required tooling board in cell	1	1.29
Fixturing	Time spent identifying suitable fixturing for job	43.0	Lack of organisation, fixtures are only related to single drawing numbers	0.03	Fixtures stored in single location, marked up where possible	1	1.29
Non-Stock Holding of Popular Sellers	Delivery performance relies on meeting 30-day delivery	43.0	Special size material used for orders, only material for customer orders purchased	0.00	Recorded list of popular sellers within existing agreements accessible, material sizes stored in ERP system	1	0.00
Management of existing machine programs	Time spent finding / transferring programs	43.0	Knowledge of programs on each machine not known at planning stage	0.03	Equipment to transfer programs between machines available	1	1.29

Figure 4.3-3 – FMEA matrix on 5 of the 9 DTD process bottlenecks identified in table 4.3-2

Chapter 4.4 Selection of Key Productivity Bottlenecks

The BI scores in figures 4.3-2 to 4.3-3 allowed selection of the leading 5 bottlenecks for solutions research (see table 4.4-1). A 6th bottleneck was added following stakeholder FMEA feedback on the desire for a 'quick-win' solution due to bottlenecks 1 to 5 potentially requiring long-term solutions.

Bottleneck	**Description**
Bottleneck 1	Long Material Delivery Time
Bottleneck 2	Manual Machine Setup
Bottleneck 3	No 'Lights-Out' Machining & Reduced Utilisation
Bottleneck 4	Manual Machine Programming
Bottleneck 5	Off-Machine Inspection Process
Bottleneck 6	Fixturing

Table 4.4-1 - List of bottlenecks to implement system improvements on

The 6th bottleneck of fixturing was selected as stakeholders agreed this would prove the most beneficial from the three options in figure 4.3-3 with BI scores of 1.29 each.

Chapter 5 Research of Solutions

Chapter 5.1 Problem Definition for Key Bottlenecks

The bottlenecks defined in table 4.4-1 were reviewed using the ZFA tool for root-cause analysis. The bottleneck 1 ZFA is illustrated in figure 5.1-1.

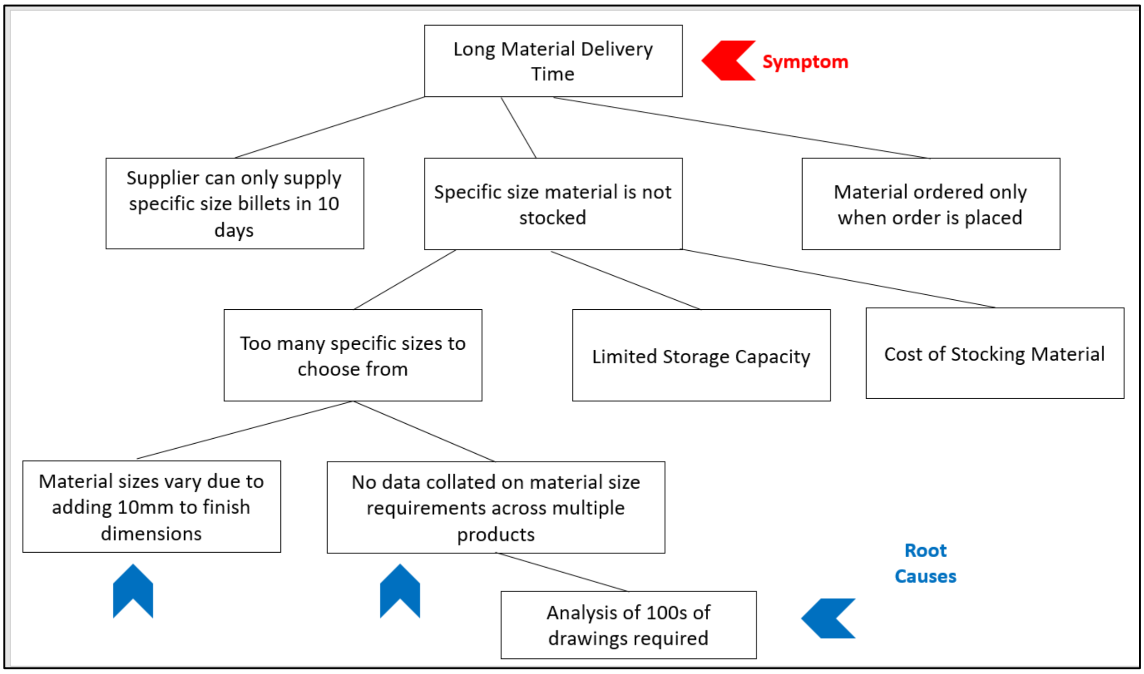


Figure 5.1-1 - Zoom & Focus Analysis (ZFA) on Bottleneck 1 highlighting the symptom and root causes

Figure 5.1-1 identifies 3 root causes of the long material delivery time 'symptom' which are large variation in material sizes, a lack of collated data on multiple tool-holders and no previous analysis of drawings. These root-causes allowed a tangible bottleneck research problem to be defined:

Reducing the 10-day delivery time on material through a method of categorising tool-holders into a set of specific material sizes, allowing for common stock-holding

ZFA was conducted on bottlenecks 2 to 6 with the diagrams detailing the root causes available in appendix 7. The root causes and defined problem for each bottleneck are illustrated in figures 5.1-2 to 5.1-3. The defined problems focus on addressing the majority of root causes associated with each bottleneck and allowed for focused research.

Symptom Long Material Delivery Time **Root Causes**

1) Material sizes vary due to adding 10mm to finish dimensions
2) No data collated on material size requirements across multiple products
3) Analysis of 100s of drawings required

Problem Definition: Reducing the 10-day delivery time on material through a method of categorising tool-holders into a set of specific material sizes, allowing for common stock-holding

Symptom Manual Machine Setup **Root Causes**

1) Tool-holder mounting interface detail on each fixture – various interfaces required
2) Fixtures are not maintained / calibrated
3) VM machines are 3+1 axes
4) Process is not currently repeatable
5) No automated loading

Problem Definition: Reducing setup time through a system(s) providing setup repeatability and optimising machining setups through simplifying equipment and manual requirements (via full or semi-automation)

Symptom No 'Lights-Out' Machining and Reduced Utilisation **Root Causes**

1) No data capture on utilisation
2) 'Ad-hoc' machine scheduling process – open to daily amendments
3) No method of automated loading and unloading of parts
4) More machines than operators
5) Reliance on multiple batches in production simultaneously (shorter changeover times)

Problem Definition: Introducing a method for 'lights-out' manufacture via automated loading in addition to commencing data capture of machine utilisation, to improve workflow management

Figure 5.1-2 – Diagram of the symptom, root causes and defined problem for bottlenecks 1 to 3

Symptom Manual Machine Programming **Root Causes**

1) Programs written in full code at the machine
2) Limited program simulation capabilities
3) Manual programs written using conversational software
4) No use of CAD models for programming
5) Use of machining drawings to program
6) Tooling to be determined manually by operator

Problem Definition: Reducing manual requirements within programming of machine tools through system improvements, utilising available commercial solutions

Symptom Off-Machine Inspection Process **Root Causes**

1) Inspection process is manual – reliance on skilled inspector
2) Taking parts on and off machine mid-setup – open to slight positional changes on machine
3) Accurate part setup required on fixture
4) Required identification of appropriate inspection fixture
5) Machine tools not currently calibrated

Problem Definition: Reducing the manufacturing inspection process time to allow for 100% inspection of tool-holders, utilising on-machine inspection capabilities if possible

Symptom Fixturing **Root Causes**

1) Fixtures are numbered based off previous drawings
2) No collated database of turret interface detail exists for multiple interfaces
3) No visible fixture indication system in cell

Problem Definition: Utilising existing data to introduce an organised machining fixture system allowing for ease of identification and relation of fixtures to production orders

Figure 5.1-3 - Diagram of the symptom, root causes and defined problem for bottlenecks 4 to 6

Chapter 5.2 Research of Possible Solutions for Key Bottlenecks

This chapter introduces potential solutions for the bottlenecks with consideration of how they address the root causes established for each bottleneck. Additional detail on the potential solutions discussed is available within appendix 8.

Chapter 5.2.1 Bottleneck 1: Long Material Delivery Time

The research problem in figure 5.1-2 implies common stock-holding of material is possible through categorisation into a set of different sized material groups. Two approaches to defining the material groups were considered:

1) Defining the groups through existing tool-holder design dimensional data
2) Defining material sizes for each group and modifying existing tool-holder designs through optimisation to fit these size groups

Both approaches would reduce the variety of material sizes created by the existing material sizing strategy through grouping similar sizes to use standard size billets.

Approach 1) contained limited reference material but increases the use of existing design dimensional data through collation. This would allow for dimensional commonality across multiple designs to be identified. Additionally, use of this data would allow a set of governing rules to be created which define the material groups including:

1) Material limits – defining the minimum and maximum excess material to machine to achieve the finished tool-holder dimensions (ensuring machining cycle times are efficient)
2) Material size requirements for selected work-holding method
3) Quantity of billets to stock for each material group size
4) Ensuring key tool-holders fit the material size groups

Approach 2) would require selection of suitable design analysis tools to optimise existing designs to suit a set of pre-defined material groups. Design tools could include parametric design as discussed within chapter 3.3 (and illustrated again within figure 5.2-1) or alternative tools such as topology optimisation (see figure 5.2-2).

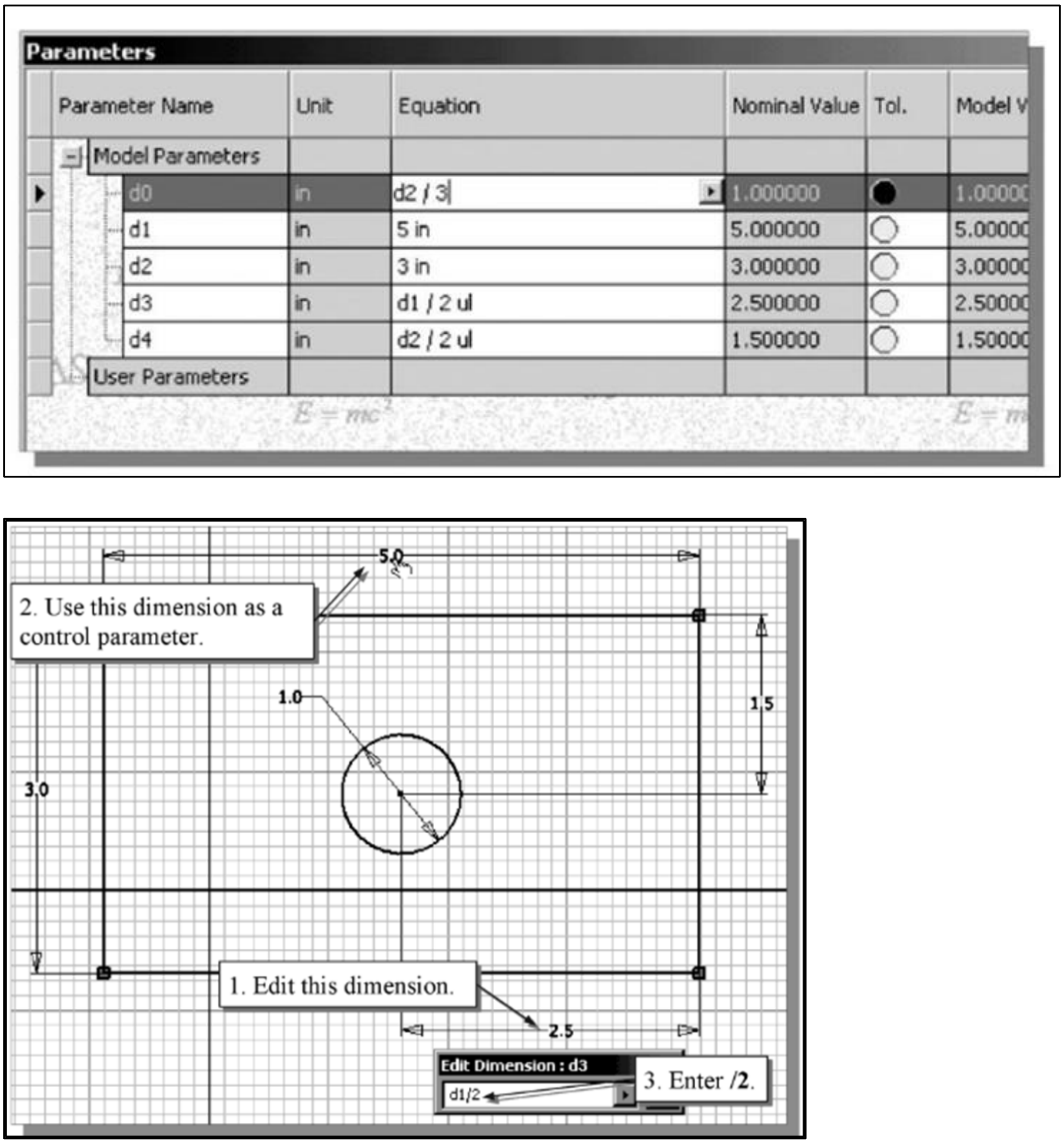


Figure 5.2-1 - Examples of parametric design capability within current CAD package - (Shih, 2010)

Topology optimisation provides a CAD-driven process used in feature-driven optimisation with Figure 5.2-2 presenting an optimisation methodology utilised by Jiu et al (2020). For tool-holder design optimisation a methodology and list of governing rules would ensure successful process implementation. Design optimisation must not compromise key tool-holder properties including accurate cutting tool positioning, through-coolant capability and vibration dampening. Categorising tool-holders would require similar rules to those discussed for approach 1).

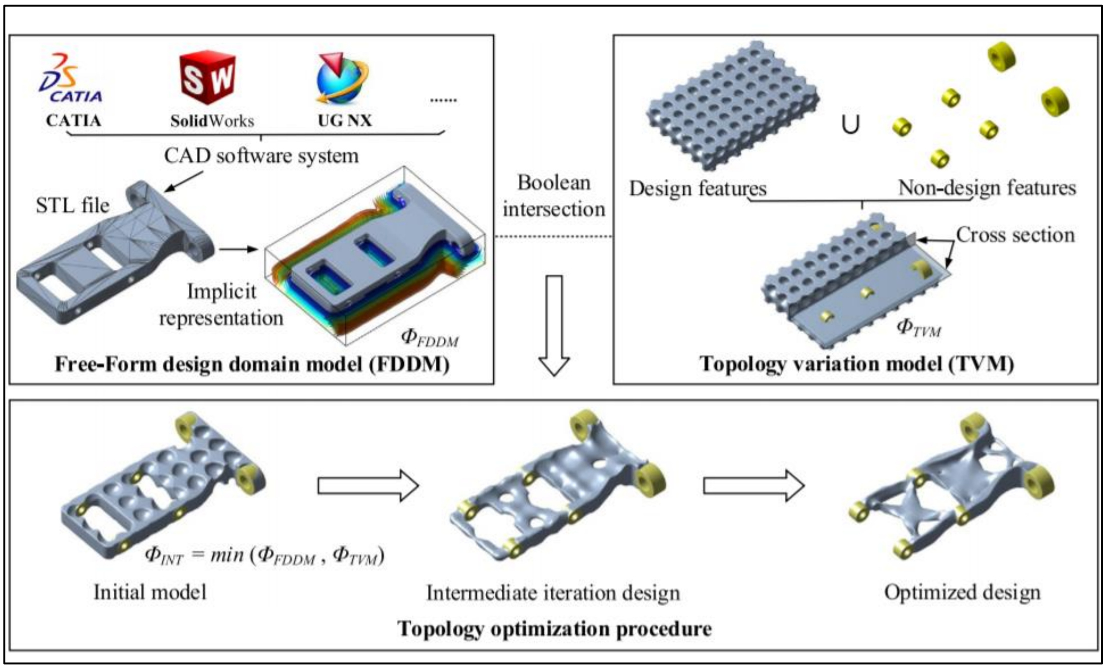


Figure 5.2-2 - Topology optimisation example - Jiu et al (2020)

Both approaches would require comprehensive analysis of existing design data and need to factor in the level of personnel and resource utilisation required.

Chapter 5.2.2 Bottleneck 2: Manual Machine Setup

This bottleneck was divided into two groups of possible solutions:

1) Work-holding solutions providing repeatability and optimised machining
2) Part loading solutions providing repeatability and efficient loading

Work-holding solutions were investigated first with the following paragraphs determining alternatives to the existing 3+1 axis setup strategy.

Increasing use of existing machine tool probes

This approach would maintain the current setup strategy whilst utilising existing machine tool probes more effectively. There are existing programs and knowledge within the manufacture function to increase probe utilisation during machine setups which would allow for time reductions, immediate savings and increased setup repeatability between parts. Due to the knowledge and equipment already available this approach could be implemented effectively.

5-axis machining

One approach is to reduce the number of setups required as the existing process utilises 5 separate setups for machining different features. Being able to machine the primary datum detail from the current setup 1 in a single setup together with other features could provide two benefits:

1) Reducing total number of setups
2) Removing need for the fixtures used in setups 3/4/5

Figure 5.2-3 illustrates a 5-axis add-on trunnion system for 3-axis VM machines containing two rotary axes and allowing for 5 faces to be machined in 1 setup. This system could replace the rotary indexers on the existing VM machines and provide 3+2 or full 5-axis machining capability. Integration of this system with the existing VM machine systems could be difficult with some potential difficulties discussed further in appendix 8.

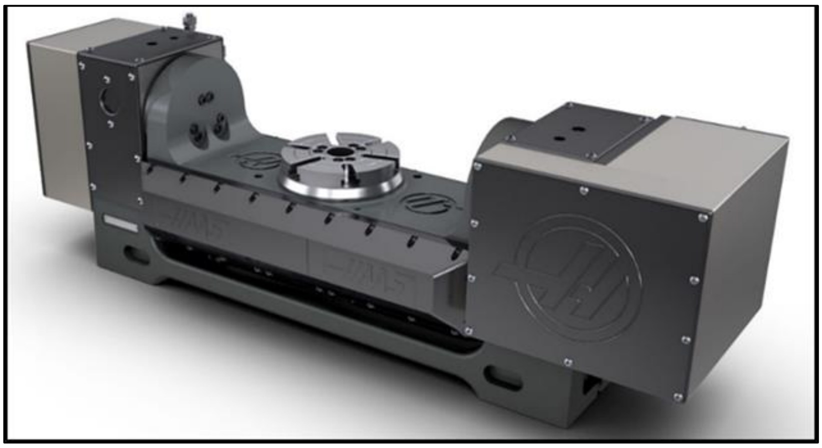


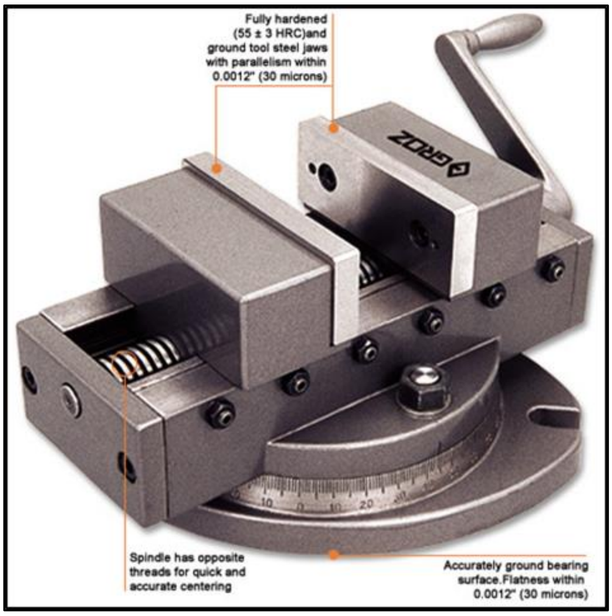
Figure 5.2-3 - Example of a 5-axis trunnion add-on solution for machine tools – (Haas, 2020)

Figure 5.2-4 - Example of a 5-axis milling machine – (Haas, 2020)

Figure 5.2-4 demonstrates an alternative approach, a 5-axis milling machine tool. This removes potential integration challenges associated with the trunnion add-on but would likely require increased financial resource. A new machine provides a ready-made system allowing 5 faces to be machined in 1 setup and reduce the number of setups required.

Alternative work-holding methods

Figure 5.2-5 details different work-holding methods for improving repeatability and reducing setup time with all 3 suitable for multi-axis machining applications.



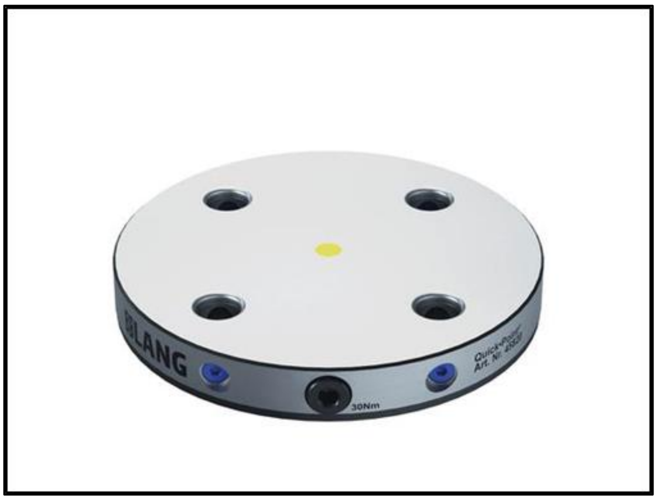


Figure 5.2-5 - Examples of current work-holding solutions to suit 5-axis applications [top - self centring vices (Groz Tools, 2020) , middle - dovetail vices (GrabCAD, 2020), bottom – zero point fixture plates (Lang Technik, 2020)]

Each fixture type utilises different approaches for achieving repeatability and setup modularity (see appendix 8 for further detail). The key benefits of each system are the reduced setup time contribution they provide and capability for use with automated loading systems. The dovetail and zero-point solutions provide large clearance around the work piece, allowing for optimised machining in one setup when used with a 5-axis approach.

Part loading solutions which could improve efficiency and repeatability during machine loading were also investigated as per Point 2) at the beginning of this chapter.

Robotic arms for machine tool loading

Industrial robots and cobots were introduced in chapter 1.1 as possible automation solutions. Figure 5.2-6 illustrates both systems with large industrial robots used in a sealed production line environment and smaller cobots 'collaborating' alongside humans in an open environment.

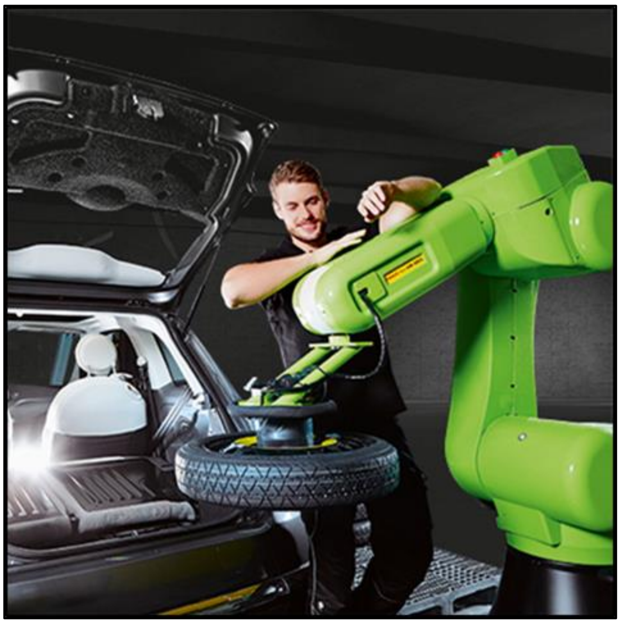


Figure 5.2-6 - Examples of Cobots [Top – (Fanuc, 2020)] and Industrial Robots [Bottom – (Francis, 2018)]

Analysis of a leading robotics supplier identified key variables for successful robot selection including the robot's load capacity, reach and axes of movement. Figure 5.2-7 provides a diagram containing terminology associated with robotic arms. End effectors link a robot to its local environment and provide an 'effect' (Nof, 1999) through transferring of loads. Different end-effector types are pictured in figure 5.2-8.

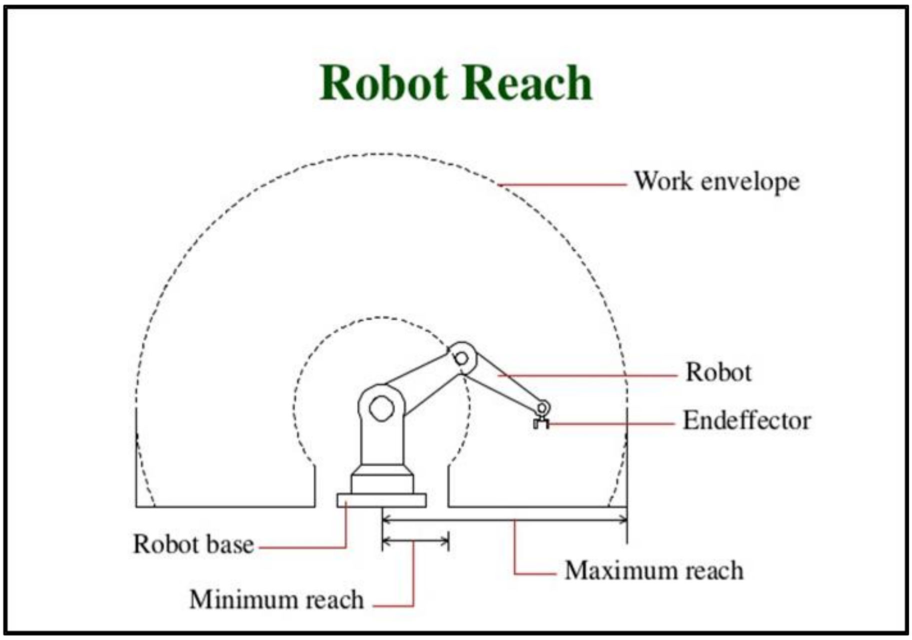


Figure 5.2-7 - Diagram defining robot reach and work envelope – Murugan (2018)

For loading rectangular billets into the existing VM machines a magnetic end effector on a robotic arm appears the most suitable solution.

Figure 5.2-8 - End effector gripping methods for part work-holding [jaws – left (Maw, 2017), magnet – right, (Bernier, 2014)]

For successful robotic loading on the VM machines some additional considerations independent of the robot's specifications include:

- Integration of robot with the machine tool software
- Identifying setups where the greatest benefits would be achieved
- Integration of robot with machine operators
- How the robot accurately locates and secures parts during loading

Robotic arms provide suitable process repeatability and increased loading efficiency as required. A large return on investment is needed however indicating that any robot chosen must provide 'lights-out machining' capability to justify its implementation.

5-axis machining utilising robotic loading

Figure 5.2-9 - Example of a 5-axis milling machine with palletised loading – Matsuura (2020)

Figure 5.2-9 presents a 5-axis machine with integrated robotic pallet loading which combines previously discussed solutions. Parts are loaded into a loading station pallet manually by an operator with a robotic arm placing pallets either into a storage system or onto the machine table. This approach allows machining of one part and loading of another simultaneously, improving productivity and providing a 'lights-out' manufacturing solution through the use of robotic loading.

Chapter 5.2.3 Bottleneck 3: No 'Lights-Out' Machining and Reduced Utilisation

The lack of 'lights-out' machining was identified as a threat in chapter 4.2 with reduced utilisation a result of the existing manufacturing practices. This chapter focuses on capturing data to improve machine utilisation through machine monitoring packages having identified robotic solutions for achieving 'lights-out' machining previously. An example monitoring package is illustrated in figure 5.2-10.

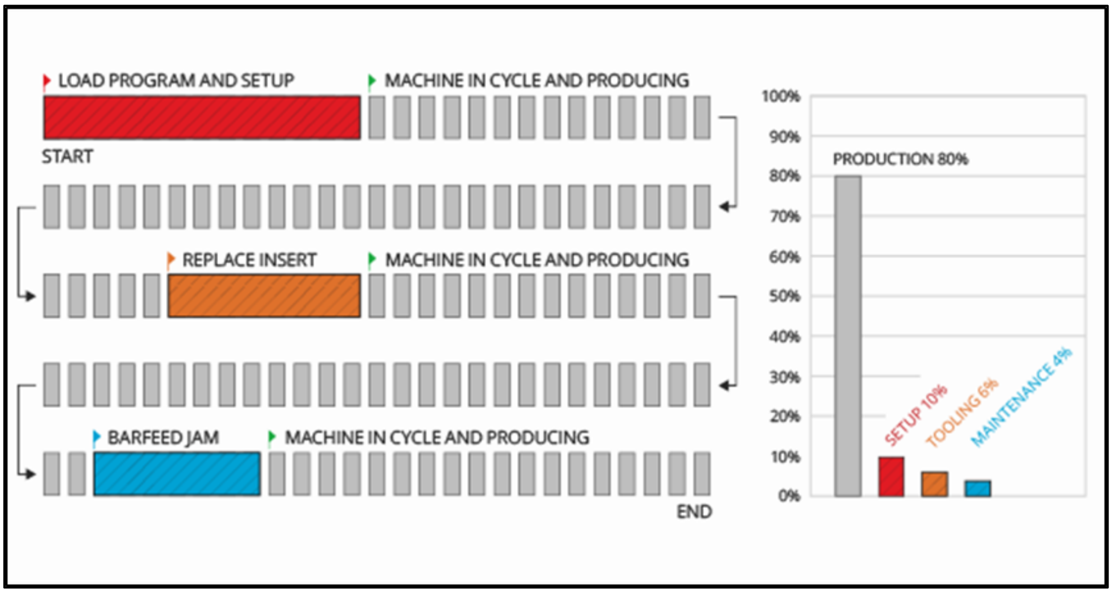


Figure 5.2-10 - Example of Production Data Collection From a Machine Tool via Monitoring Software – CIMCO (2020)

Figure 5.2-10 illustrates monitoring software that captures useful data on machining cycle times and downtime with 80% utilisation or 'production' achieved. Downtime is divided into planned (setup) and unplanned (tooling and maintenance) categories. Downtime analysis could be beneficial for the SMfE by identifying the leading downtime causes and allowing for process improvements to be introduced through accurate data use.

The monitoring packages investigated were capable of measuring key performance indicators including machine tool Overall Equipment Effectiveness (OEE) (see figure 5.2-11). OEE determines machine tool effectiveness as a percentage for a user-defined time period by multiplying the characteristics in figure 5.2-11.

For data collection a machine monitoring package requires:

1) An Ethernet connection between the machine and IT network
2) A software agent for extracting machine parameters to illustrate within the software (Sandvik Coromant, 2018)
3) Software installed on the IT network for data analysis (Sandvik Coromant, 2018)

See appendix 8 for additional detail on the above requirements. Monitoring software is usable with any machine meeting the above requirements with it being usable on the existing VM machines for removing downtime contributors. It could also be used for monitoring a 'lights-out' process on a new machine.

‘Lights-out’ manufacturing has the potential to increase SMfE tool-holder production time from 80 hours to 168 hours per week (24/7) which would assist in reducing production costs through unmanned manufacture.

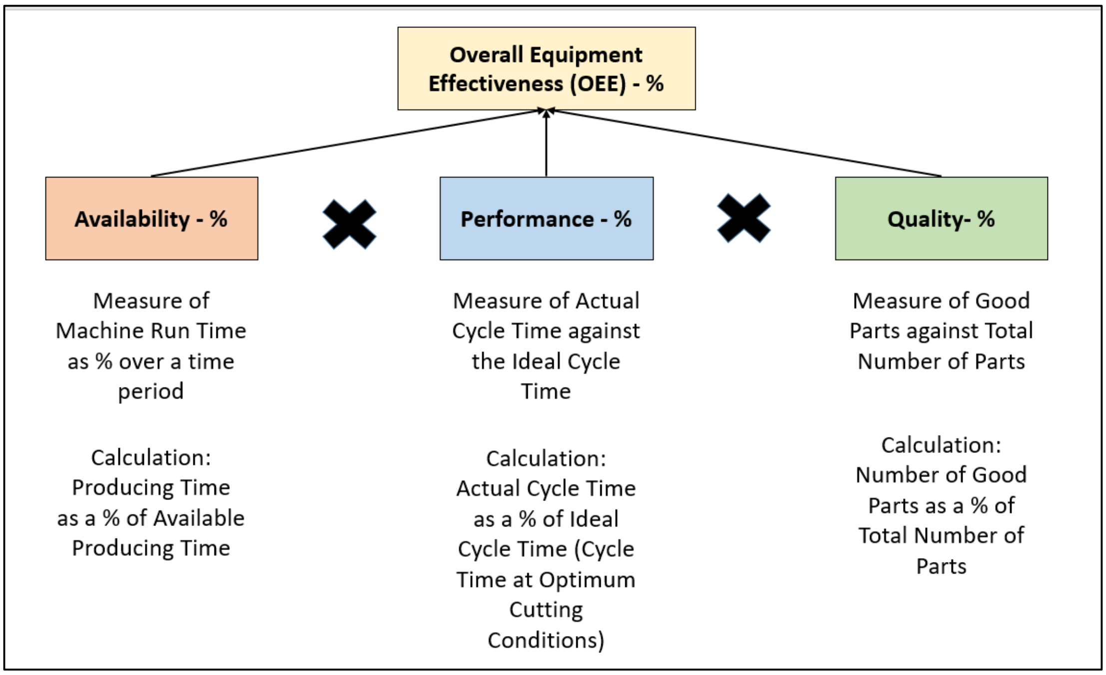
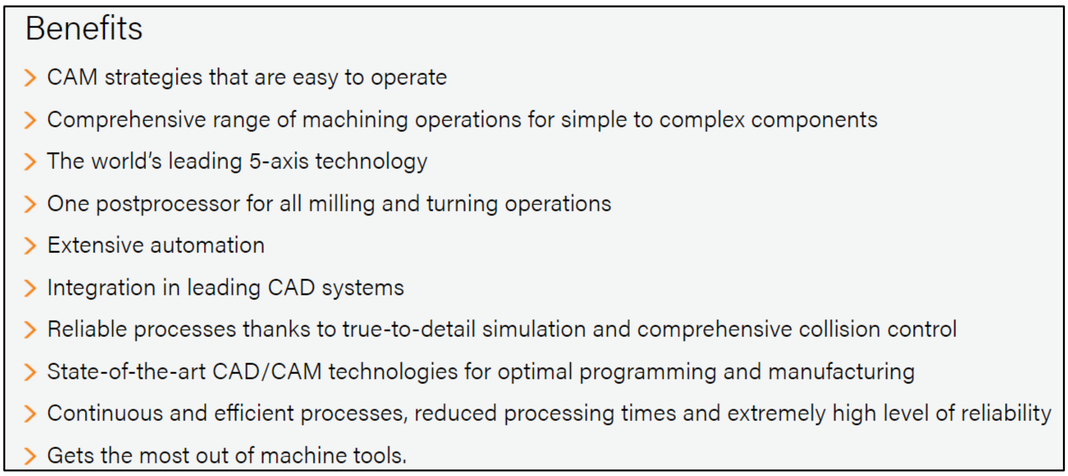


Figure 5.2-11 - Diagram Defining Overall Equipment Effectiveness (OEE) Parameter

Chapter 5.2.4 Bottleneck 4: Manual Machine Programming

CAM software was investigated based upon the root causes in figure 5.1-3 and to introduce programming improvements while reducing the existing manual requirements of programming. Radhakrishnan et al (2008) identified how CAD/CAM created a ‘paradigm shift’ in CNC programming through computer simulation and CAM utilising post-processor software to generate NC program code immediately. This code is currently written manually and in full by operators on the VM machines.



Benefits

- CAM strategies that are easy to operate
- Comprehensive range of machining operations for simple to complex components
- The world’s leading 5-axis technology
- One postprocessor for all milling and turning operations
- Extensive automation
- Integration in leading CAD systems
- Reliable processes thanks to true-to-detail simulation and comprehensive collision control
- State-of-the-art CAD/CAM technologies for optimal programming and manufacturing
- Continuous and efficient processes, reduced processing times and extremely high level of reliability
- Gets the most out of machine tools.

Figure 5.2-12 - List of benefits CAM offers from a leading UK supplier – (OpenMind, 2020)

Figure 5.2-12 highlights the key benefits of CAM from a leading supplier. Additional considerations for CAM implementation in the SMfE related to CAD integration, tooling and personnel with these discussed further in appendix 8.

With simulation in CAM capable of identifying potential collisions an important process control can be introduced which is not currently available. This could assist with cost reductions related to 1) machine tool damage, 2) tooling damage and 3) part reworking or replacements caused by programming errors. CAM-based solutions were only considered due to the multiple benefits discussed. Leading commercial packages were reviewed as well as an additional specialist package detailed in figure 5.2-13.

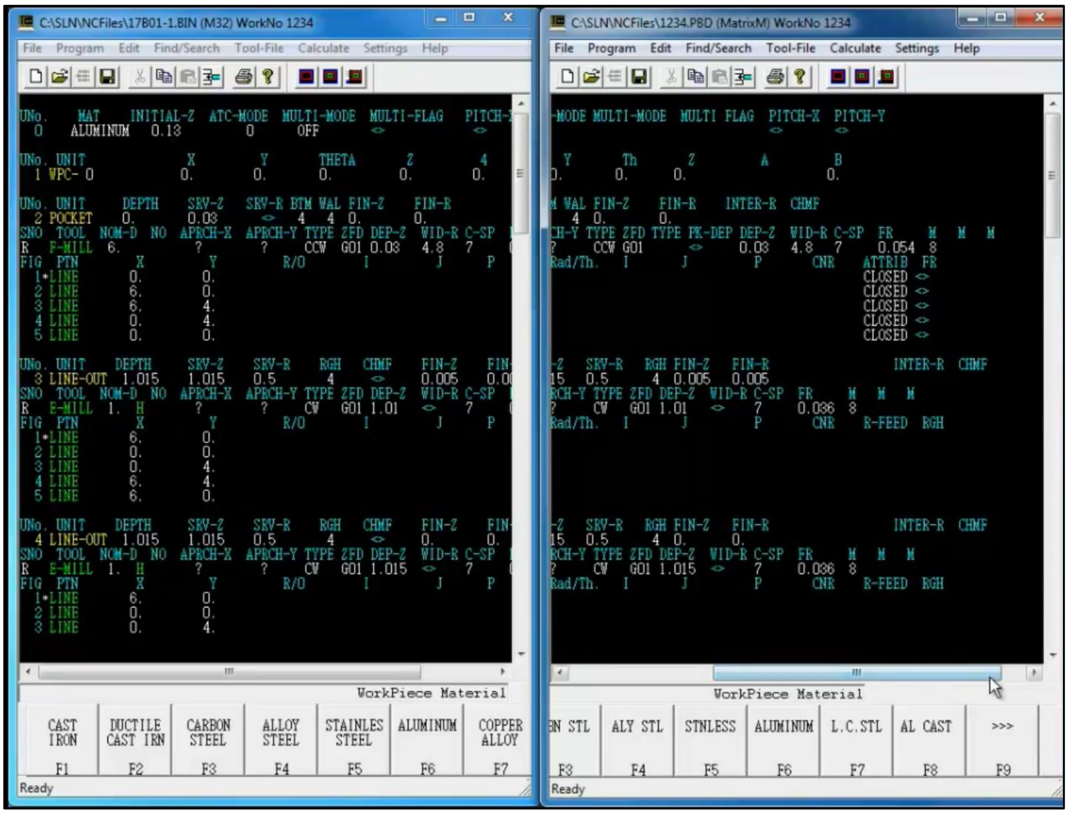


Figure 5.2-13 – CAM software which also offers program file transfer between VM machines – (Phoenix CNC Support Ltd, 2020)

The software package in figure 5.2-13 provided 2 key features:

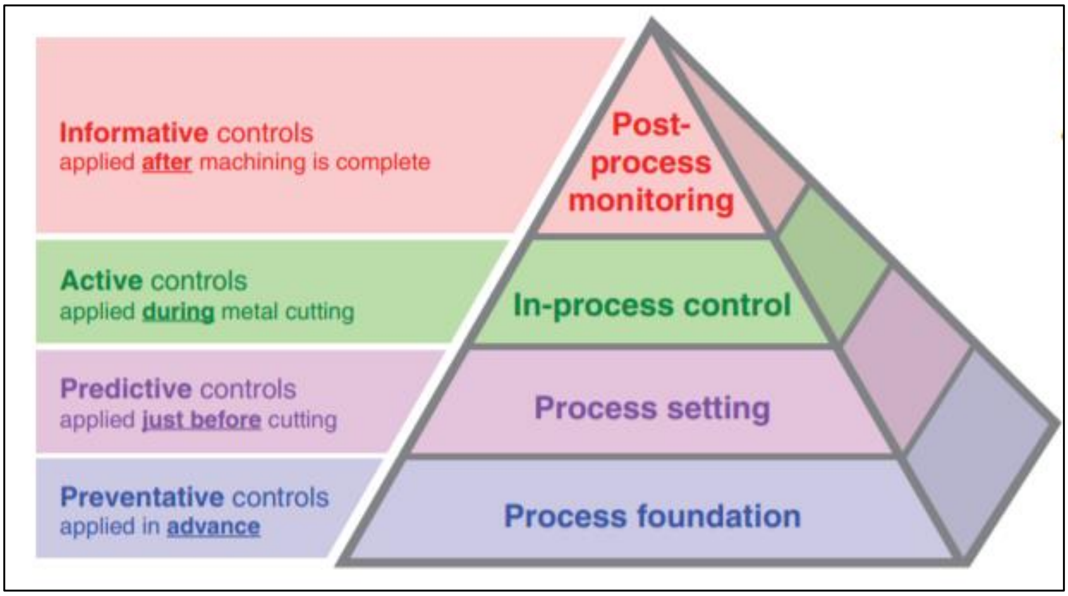
1) Industry standard CAM programming capability
2) Program file transfer between the existing VM machines through relevant NC code transfer allowing for forward and backwards compatibility

Backwards program transferring from new to old VM machines is not currently possible (see table 3.5-1). Figure 5.2-13 illustrates code transfer and comparison between two machine languages during the transfer process. This solution would provide considerable benefit for the existing VM machines but is only usable for machine tools made by one supplier.

Chapter 5.2.5 Bottleneck 5: Off-Machine Inspection Process

In this chapter on-machine and alternative off-machine inspection solutions were investigated with the key requirements being to reduce process time and provide 100% tool-holder manufacturing inspection capability.

On-machine inspection using probing



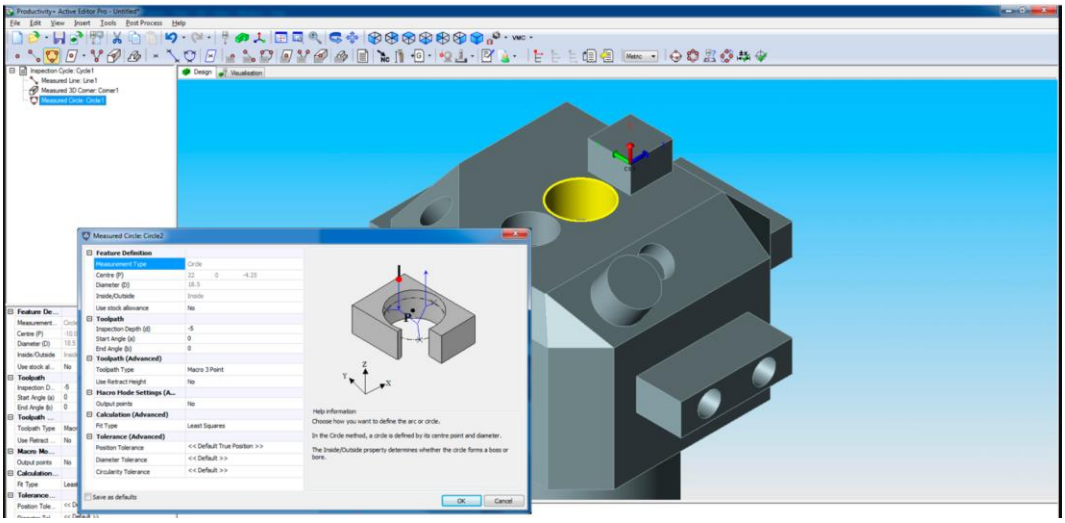


Figure 5.2-14 - Leading UK supplier's definition of the building blocks for on-machine inspection through probing [top – (Renishaw® plc, 2011)] and their associated on-machine inspection software [bottom – (Renishaw® plc, 2020)]

Figure 5.2-14 illustrates key principles and equipment associated with on-machine inspection through probing which require suitable measures to adequately control sources of process variation (Renishaw® plc, 2011). Examples of process variation can include:

- Machine tool condition monitoring and maintenance
- Temperature variations during machining
- Local environment conditions to process (fixtures, tooling etc.)
- Setup (part, tooling, probe)

Further detail is provided for the above in appendix 8. Figure 5.2-14 introduces associated software for integrating on-machine inspection probing cycles into NC programs. The above findings and process pyramid in figure 5.2-14 suggest this method requires comprehensive analysis for successful implementation. Despite this it provides the capability to inspect features within seconds and provide a large time reduction if correctly implemented.

On-machine inspection using an inspection arm

Figure 5.2-15 illustrates a user-controlled measurement arm to manually touch onto parts using a probe. A leading UK supplier highlights their suitability for use in shop floor environments through using temperature compensation features to maintain results accuracy (FARO®, 2020). The arm provides a transportable solution allowing it to be shared between multiple machines and for features to be checked on-machine. Partnering inspection software is supplied to produce the inspection data.

Figure 5.2-15 - Example of a 3D measuring arm – (FARO®, 2020)

Off-machine inspection – CMM & Gauging Systems

Off-machine solutions were investigated as an alternative to on-machine inspection with figure 5.2-16 presenting two commercial solutions.

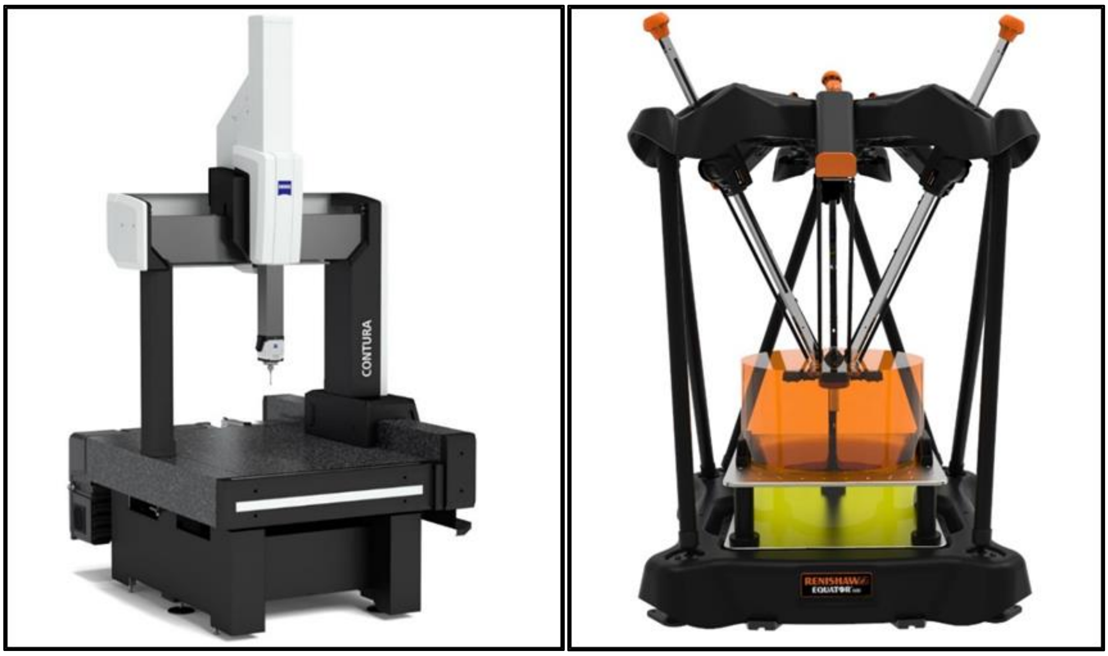


Figure 5.2-16 - Examples of industry standard off-machine inspection processes: a Coordinate Measurement Machine (CMM) [left – (Zeiss, 2019)] and a comparator gauging system [right – (Renishaw® plc, 2018)]

A CMM uses a CNC system to probe parts placed on a granite table with dedicated software for CNC programming through manual probing or CAD model utilisation. The equipment specialises in providing accurate and repeatable results with frequent calibration capable through supplied gauging equipment. The system requires a temperature controlled environment away from shop floors. The SMfE has an existing CMM used on other products with more complex features.

A gauging system provides an off-machine system for location near CNC machines on a shop floor which uses temperature compensation features. The system also runs CNC inspection programs which checks parts against a 'master part'. This provides a method of measuring process variation through inspection data. The system provides fast, repeatable inspection and can 'cope with thermal variation by re-zeroing' (Renishaw® plc, 2018). Compatible PC software for programming and results access is provided along with modular fixturing kits for part setup.

Both systems should provide inspection time reductions through part inspection taking a few minutes. This is a large reduction on the near 30 minutes currently required for off-machine inspection.

Chapter 5.2.6 Bottleneck 6: Fixturing

For this bottleneck the solution should focus on addressing the identification and organisation issues identified within chapter 3. Within the SMfE there is:

1) Sufficient information to categorise fixtures by machine suitability as opposed to drawing number
2) Sufficient storage space to organise the fixtures for easy identification

For point 1) the information within the SMfE is readily accessible (current fixture list, related drawings and CNC machine interface detail). Figure 5.2-17 presents a methodology for implementing an improved system using points 1) and 2) which builds upon the existing good practices. The improvements should aid communication between the manufacturing and design functions through use of design data for manufacturing purposes. Figure 5.2-18 illustrates a tool-holder drawing containing relevant machine interface data behind the blue box.

It is assumed that unidentified fixtures will exist if the figure 5.2-17 methodology is used. For unidentified fixtures collation of existing machine interface data in conjunction with manual fixture feature measurement should allow for categorisation of these.

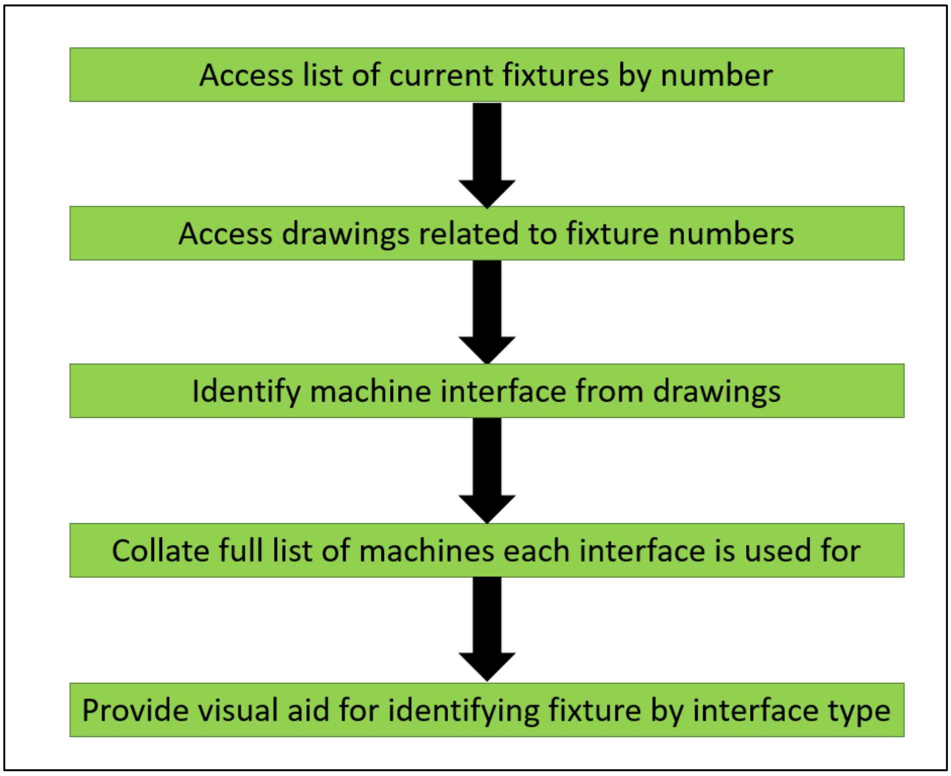


Figure 5.2-17 - Flowchart of processes for implementing fixture system improvements

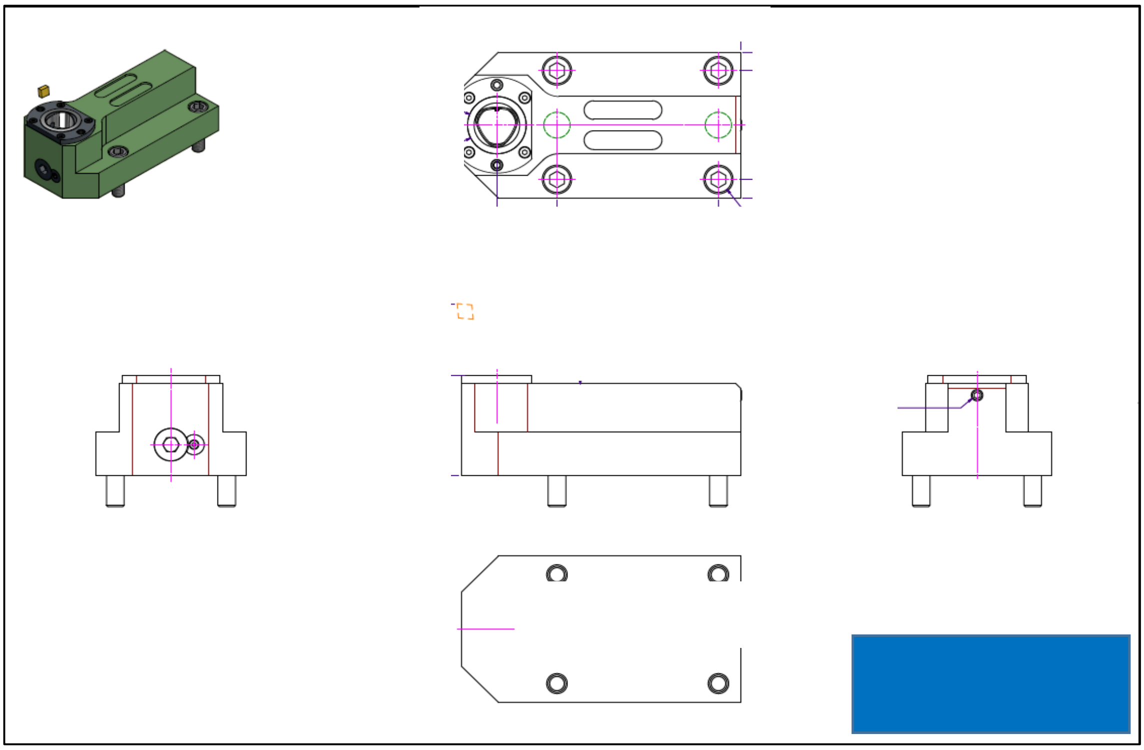


Figure 5.2-18 - Example assembly drawing for a tool-holder with dimensions masked

Chapter 5.3 Comparison of Solutions for Key Bottlenecks

For comparison of the chapter 5.2 solutions for each bottleneck a set of selection criteria were defined:

- Benefits of the Solution (BOS)
- Process Time Impact (PTI)
- Impact on Process, Equipment and the Whole Cell (IPEC)
- Impact on Personnel (IP)
- Financial Requirements (FR) (with a rating between 1 and 5 on the perceived investment and personnel / resource requirements)

Comparison matrices were created for the 6 bottlenecks with each containing comprehensive solutions analysis using the defined criteria. The matrices are illustrated in figures 5.3-1 to 5.3-8, with bottlenecks 2 and 5 requiring 2 matrices each due to having an increased number of solutions. Summaries of each matrix and their key points are provided within the following sub-chapters.

Chapter 5.3.1 Bottleneck 1: Long Material Delivery Time Solutions Comparison

The key findings from figure 5.3-1 for both solutions include:

- Both solutions providing similar outputs for multiple selection criteria (the first 3 criteria contain the same observations for each solution)
- The optimisation method has a substantially higher impact on design function personnel (see IP criteria observations)
- The optimisation method design resource requirements caused this solution to have an increased FR rating of 2
- The existing design categorisation method has a reduced FR rating, however it still requires large production staff resource for data collation

Solution	Determining material groups based upon various existing tool-holder dimensions	Defining material groups by size and amending designs through optimisation
Benefits of Solution (BOS)	1) Existing tool-holder designs are categorised with dedicated material billet sizes and not varying sizes 2) Allows common material stock-holding, with more orders progressing to production quicker following planning	1) Existing tool-holder designs are categorised with dedicated material billet sizes and not varying sizes 2) Allows common material stock-holding, with more orders progressing to production quicker following planning
Process Time Impact (PTI)	Potential reduction of 10 days on 'design to delivery' lead time	Potential reduction of 10 days on 'design to delivery' lead time
Impact on Process / Equipment / Cell (IPEC)	1) Larger material storage space required for stock-holding 2) Possible adjustments to existing machine programs, to account for new material sizes if existing machine programs are utilised 3) Improved workflow and job scheduling possible through increased amount of available material 4) Machine and operator scheduling importance will increase, due to reduced lead time in getting jobs on machine	1) Larger material storage space required for stock-holding 2) Possible adjustments to existing machine programs, to account for new material sizes if existing machine programs are utilised 3) Improved workflow and job scheduling possible through increased amount of available material 4) Machine and operator scheduling importance will increase, due to reduced lead time in getting jobs on machine
Impact on Personnel (IP)	1) Potential difficulty for machine and personnel scheduling to maintain performance, scheduling approach may require improvements 2) Potential workload increase placed on operators with more jobs available to machine in shorter timeframe 3) Analysing 100s of drawings required – time-consuming exercise to categorise material groups for production management staff	1) Potential difficulty for machine and personnel scheduling to maintain performance, scheduling approach may require improvements 2) Potential workload increase placed on operators with more jobs available to machine in shorter timeframe 3) Intense workload requirements for design team (3-4 people) to review and implement new design processes on 100s of designs using new CAD tools
Financial Requirements (FR)	Increased material stocking costs FR rating: 1 / 5 – (1 Low, 5 High)	Increased material stocking costs FR rating: 2 / 5 - (1 Low, 5 High)

Figure 5.3-1 – Comparison matrix for Bottleneck 1 solutions

Chapter 5.3.2 Bottleneck 2: Manual Machine Setup Solutions Comparison

The solutions in figures 5.3-2 to 5.3-3 contain differing criteria observations. A summary of the key findings indicate that:

- Maintaining the existing setup strategy with probing improvements would provide the cheapest, quickest and easiest solution implementation
- The 5-axis work-holding and machining methodology would reduce number of setups and provide the greatest time reductions
- A 5-axis machine with robotic loading provides the greatest financial requirement, but provides a full solution to implement 'lights-out' machining
- Any solutions for the existing machines require a single machine trial period to prove the concept and minimise the impact on current production
- Solutions rolled-out on multiple VM machines could become costly (5-axis trunnions or robots for example)
- Defining training requirements for operators is critical for all solutions

Solution	Utilising probes more for setup on existing processes	5-axis add-on trunnion solution to current machines	New 5-axis machine implementation
BOS	1) Improves use of existing equipment and process 2) Should require minimal integration 3) Provides minimal disruption to production and personnel 4) Knowledge exists in company already to use	1) Increased number of faces machined in a setup 2) Will reduce the number of setups from 5 to 2/3 3) Provides 2 rotary axes for positioning 4) Removes need for existing fixturing 5) 5-axis process without needing a new machine	1) Increased number of faces machined in a setup 2) Will reduce the number of setups from 5 to 2/3 3) Provides 2 rotary axes for positioning 4) Removes need for existing fixturing 5) Ready-made 5-axis solution
PTI	4 hrs time for 5 setups currently 5 setups still required but saving of at least 1 hr possible with probes	With modular work-holding and reduced setups – setup time could reduce by 75% to 1hr maximum	With modular work-holding and reduced setups – setup time could reduce by 75% to 1hr maximum
IPEC	1) No new equipment to integrate, previous work conducted on probing routines to utilise 2) Existing processes allow for immediate implementation and procedure development 3) Multiple machines allow trial on one machine to reduce production disruption	1) Integration of system with existing CNC hardware and software required 2) Integration with work-holding needed 3) A single machine trial required to minimise production downtime 4) External assistance may be required for trialling	1) Integration of new machine into cell – location, space requirements etc. 2) Integration with new work-holding approach needed 3) Programming software requirements – New programming approach, CAM? 4) Machine loading, manual or automated?
IP	1) No change to fundamental setup approach 2) Minimal training required 3) Not all personnel require immediate training, key personnel only during implementation	1) Operator training on new work-holding and 5-axis programming approaches (possibly complex) 2) Suitable operators need involvement from outset	1) Key personnel need involving for integration and training from outset 2) Training required: loading, programming, setup 3) Impact on existing cell in terms of operators available
FR	No new equipment requirements and quick implementation FR rating – 1/5 - (1 Low, 5 High)	New equipment, external resource, complexity and time requirements FR rating – 4/5 - (1 Low, 5 High)	New equipment, external resource, complexity and time requirements FR rating – 5/5 – (1 Low, 5 High)

Figure 5.3-2 - Comparison matrix (1 of 2) for Bottleneck 2 solutions

Solution	Implementing 5-axis work-holding equipment	Robotic Automation implementation on existing VM machines	5-axis machine implementation with automated pallet loading
BOS	1) Equipment can reduce number of setups with a suitable 5-axis process 2) Modular equipment – reduced manual alignment of each part following loading 3) Modularity should improve loading repeatability	1) Introduces repeatability into part loading process 2) Reduced loading and unloading time of parts 3) Capability to run 'lights-out' and improve machine utilisation	1) Increased number of faces machined in a setup 2) Will reduce the number of setups from 5 to 2/3 3) Introduces repeatability into part loading process 4) Capability to run 'lights-out' and improve machine utilisation
PTI	With 5-axis approach and reduced setups – setup time could reduce by 75% to 1hr maximum	With right fixturing approach, setup could reduce considerably to 1 to 2hrs per part, depending on no. of setups	Combination of other technologies – setup time could be reduced to 0.5 to 1hr
IPEC	1) Possible new machining strategy based upon the equipment selected 2) Integration required with a 5-axis approach 3) Existing machine programs need adjustment to incorporate new approach if existing programs used	1) Robot location in cell, will protective caging be required? Industrial or cobot? 2) Location suitable for operator machine access 3) Defined fixturing approach, to allow robot to load, locate and secure parts accurately 4) Integration with existing CNC control for 'lights-out' manufacture	1) Location of machine – space requirements greater than existing machines 2) Integration with new work-holding process 3) Programming must be defined – manual or CAM? 4) Requirements defined for 'lights-out' manufacture
IP	1) Personnel training on using new approach 2) Decision on whether to use for all machines, from single machine trial, impacts training requirements 3) Production downtime must be minimised	1) Key personnel need identifying from outset 2) Personnel need training on robot collaboration, programming and part loading process 3) New fixturing approach could require training 4) Robotics safety training required for all staff	1) Key personnel need identifying from outset 2) Training required on: work-holding, loading/unloading parts, programming, machine operation 3) Strategy defined for 'lights-out' personnel roles
FR	New equipment and process definition as well as training FR Rating – 2/5 – (1 Low, 5 High)	New equipment and process definition as well as training – prior to full roll-out FR Rating – 5/5 – (1 Low, 5 High)	Entire new group of systems integrated into company FR Rating – 5/5 – (1 Low, 5 High)

Figure 5.3-3 - Comparison matrix (2 of 2) for Bottleneck 2 solutions

Chapter 5.3.3 Bottleneck 3: No 'Lights-Out' Machining & Reduced Utilisation Solutions Comparison

The 2 'lights-out' machining solutions from bottleneck 2 are included in figure 5.3-4 in addition to machine monitoring software. The key findings indicate that:

- 'Lights-out' machining is only achievable through robotic loading on the existing VM machines or a new 5-axis machine
- Other bottleneck 2 solutions do not support 'lights-out' machining
- Both automation solutions provide 168 hours machining time capability in a week, but require considerable investment and personnel resource initially
- The 5-axis machine with palletised loading guarantees a reduced number of setups
- The robotic loading on existing VM machines approach would require integration with the chosen work-holding strategy
- The monitoring software has reduced investment costs but requires IT expertise and suitable infrastructure for implementation
- Monitoring software process savings will occur over time and not immediately
- Monitoring software can be applied to the existing VM machines or a new machine

Solution	Robotic Automation implementation on existing VM machines	5-axis machine implementation with automated pallet loading	Machine Monitoring Software to measure productivity, utilisation and OEE
BOS	1) Introduces repeatability into part loading process 2) Reduced loading and unloading time of parts 3) Capability to run 'lights-out' and improve machine utilisation	1) Increased number of faces machined in a setup 2) Will reduce the number of setups from 5 to 2/3 3) Introduces repeatability into part loading process 4) Capability to run 'lights-out' and improve machine utilisation	1) Automatically collects data on machine producing time and % utilisation 2) Breakdown on unplanned downtime and sources of productivity loss provided 3) Allows key decisions to be made using data
PTI	1) Increases machining hours in a week from 80 to 168 (over double) 2) Utilisation increases as operators can run multiple machines	1) Increases machining hours in a week from 80 to 168 (over double) 2) Utilisation should increase as parts can be loaded while also machining	Indirectly can improve machine utilisation by providing benchmark data and justifying productivity improvement decisions
IPEC	1) Robot location in cell, will protective caging be required? Industrial or cobot? 2) Location suitable for operator machine access 3) Defined fixturing approach, to allow robot to load, locate and secure parts accurately 4) Integration with existing CNC control for 'lights-out' manufacture	1) Location of machine – space requirements greater than existing machines 2) Integration with new work-holding process 3) Programming must be defined – manual or CAM? 4) Requirements defined for 'lights-out' manufacture	1) Established IT data capturing system through connection of resources 2) Machines need to have established connection to network 3) A data collection adaptor to collect data and a data aggregator to connect to software required
IP	1) Key personnel need identifying from outset 2) Personnel need training on robot collaboration, programming and part loading process 3) New fixturing approach could require training 4) Robotics safety training required for all staff	1) Key personnel need identifying from outset 2) Training required on: work-holding, loading/unloading parts, programming, machine operation 3) Strategy defined for 'lights-out' personnel roles	1) Personnel inclusion from outset to achieve their 'buy-in' 2) Operator buy-in helps capture and record issues, to assist in productivity loss identification
FR	New equipment and process definition as well as training – prior to full roll-out FR Rating – 5/5 – (1 Low, 5 High)	Entire new group of systems integrated into company FR Rating – 5/5 – (1 Low, 5 High)	Software implementation and IT installations needed FR Rating – 1/5 – (1 Low, 5 High)

Figure 5.3-4 - Comparison matrix for Bottleneck 3 solutions

Chapter 5.3.4 Bottleneck 4: Manual Machine Programming Solutions Comparison

The two solutions in figure 5.3-5 are 1) a commercial CAM package and 2) the specialist software from figure 5.2-13. Key findings indicated that:

- Both solutions require similar investment and contain similar features for CAM programming
- Involvement of key personnel from the outset is critical to ensure training requirements are fulfilled
- An immediate return on investment may not be experienced during process familiarisation, with process time reductions of 50% estimated long-term
- The backwards compatibility of the specialist software could prevent time contributions of unnecessary new program creation on older VM machines
- The transfer software is only suited to one brand of machine tools which are those currently utilised within the cell
- If a new machine was to be implemented its supplier and model could dictate which software is selected

Solution	CAM implementation	Software for CAM and converting NC programs between existing VM machines
BOS	1) Programming using CAD models, reduces human error opportunities 2) Simulation capability improves capture of potential collisions 3) Software will utilise improved cutting strategies to optimise cutting time, not possible through manual programming	1) Programming using CAD models, reduces human error opportunities 2) Program transfer capability between any two existing VM machines (forward and backwards transfer) 3) Software is suited to brand of existing VM machines in terms of programming language NC code
PTI	Process time improvement will be minimal during familiarisation, as competency increases programming time could be reduced from 0.5 days (9hrs) to 4-5 hrs	Process time improvement will be same as for alternative solution Additional savings could be made on transferring programs instead of writing new – <0.5hr transfer vs 9hrs writing new
IPEC	1) Determining 3D model files to use for programming 2) Collaborating with design to produce and maintain CAD files 3) Ensuring relevant post-processor is identified and implemented for the machine(s) to be used for CAM programming 4) To consider the tooling required for achieving CAM optimisation strategies	1) Determining 3D model files to use for programming 2) Collaborating with design to produce and maintain CAD files 3) Collating detail on VM machine controlling PCs to trial program transfer and machine using transferred programs 4) Local network storage of existing machine programs required to access during software use
IP	1) Operator training on basics of CAM software and use of CAM for tool-holder specific programming 2) Correct program generation, storage location and file revision management philosophy embedded with personnel	1) Operator training on using software for program file transfer as opposed to current direct machine transfer method 2) Operator training on basics of CAM software and use of CAM for tool-holder specific programming
FR	Software implementation, introduced process changes within company and personnel training FR Rating – 3/5 – (1 Low, 5 High)	Software implementation, introduced process changes within company and personnel training FR Rating – 3/5 – (1 Low, 5 High)

Figure 5.3-5 - Comparison matrix for Bottleneck 4 solutions

Chapter 5.3.5 Bottleneck 5: Off-Machine Inspection Process Solutions Comparison

Figures 5.3-6 to 5.3-7 detail the four solutions introduced with key findings indicating that:

- The CMM process contains the smallest financial requirement due to being an existing resource with trained personnel, allowing for immediate implementation
- On-machine inspection with probing provides the smallest inspection cycle time, allowing inspection on-machine within seconds
- On-machine inspection would require concept prove out on a single machine prior to roll-out onto multiple machines
- The measurement arm and gauging system location within the cell could allow for one system to cover multiple machines
- All processes except for the CMM need training requirements establishing prior to implementation
- On-machine probing requires a comprehensive analysis of all process variation sources and identified control measures for these. There are uncertainties associated with the required resource and implementation difficulty
- The measurement arm is a manual process whilst the remaining solutions all run automated programs
- The CMM and gauging solutions could still suffer from long process times if the existing setup approach is maintained for part loading and unloading

Solution	On-Machine inspection - fully utilising machine tool probes	On-Machine inspection – inspection arm implementation
BOS	1) Utilises existing probe equipment available on VM machines 2) Identifies and introduces controls on variation sources, related to both the part and local environment 3) Improved knowledge of machine tool accuracy defined during process foundation stage (see process pyramid) 4) Capability to inspect all parts on-machine, in same environment, allowing 100% inspection and process variation monitoring	1) Parts inspected on-machine in existing setup and under machine conditions 2) Arm is portable, can be mounted on machine with ease 3) One arm could work for multiple machines 4) Temperature compensation is accounted for, shop floor suitability 5) Pickup and play functionality, simple training requirements
PTI	Inspection time per part (including part loading/unloading) reduced from 1hr to seconds	Inspection time per part (including part loading/unloading) reduced from 1hr to 5-10 mins
IPEC	1) Process foundation – benchmarking machine tool accuracy and optimising, controlling machining variation sources – tooling, fixturing, temperature 2) Process Setting – Improving setting for tooling, probes, work piece processes on existing equipment 3) In-Process Control – introducing inspection into NC programs, and through monitoring variation sources allow for in-program adjustments	1) Defined requirements for measurement working envelope and best setup for measurement accuracy and repeatability 2) Determine strategy for measuring specific features and arm location in relation to the work piece during inspection defined 3) Schedule use of arm if shared between machines to prevent bottlenecks 4) The safe storage of the arm when not in use on any of the machines
IP	1) Operator involvement on new processes related to tooling, probes, fixturing, setting and programming as part of methodology 2) For senior operators training on probing routines and any results capture software needed	1) Operator training on arm operation for safe use and accurate inspection 2) Standard inspection procedure to ensure that repeatability is seen across multiple measurements for multiple parts by all operators
FR	Difficult to understand full value because of multiple sources of variation to minimise FR Rating – 3/5 – (1 Low, 5 High)	Initially one arm and training are the requirements, potentially further arms depending on utilisation FR Rating – 2/5 – (1 Low, 5 High)

Figure 5.3-6 - Comparison matrix (1 of 2) for Bottleneck 5 solutions

Solution	Off-Machine inspection – CMM embedding into process	Off-Machine inspection – Comparator gauging system implementation
BOS	1) High accuracy process with traceable and frequent calibration 2) Temperature variation accounted for through controlled space 3) Repeatable process with part alignment defined by user 4) Programs run using CNC control to generate immediate results data	1) Temperature variation accounted for through re-zeroing of the standard 2) Can be used in shop floor environment 3) Automated inspection programs used, while operators run machines 4) Instant results generation and feedback provided 5) Software capable of integrating with CNC machines for in-process adjustments
PTI	Inspection time per part (not including part loading/unloading) reduced from 30 mins to 5-10 mins	Inspection time per part (not including part loading/unloading) reduced from 30 mins to 5-10 mins
IPEC	1) Workload management for tool-holder inspection against other CMM requirements to ensure process is not a bottleneck 2) Standard process requires defining for critical tool-holder features to inspect across multiple parts 3) Program creation requirements prior to part inspection 4) Setup approach on table requires defining for validating results	1) Identification of suitable equipment location – shared between machines? 1 device would be trialled initially to prove concept 2) Determine method for re-zeroing, CAD model or physical part can be used 3) Integration of device for in-process adjustments with CNC machines for achieving full feedback loop 4) Determine key features to inspect and program for inspection
IP	1) Involvement of inspectors from outset to embed process, write programs, process inspection data and determine standards 2) Potential for increasing trained personnel to provide support and cover for current inspectors and prevent workload build-up	1) Involvement of machine operators and inspectors from outset to trial device (writing and accessing programs, generating results, re-zeroing, part setup) 2) Operators to be trained on using results software to provide feedback loop through CNC machines to make in-process program adjustments
FR	Existing resource within company, embedding new system process to improve inspection time FR Rating – 1/5 – (1 Low, 5 High)	System purchase, training and accessories (fixturing, software) as well as external resource for VM integration FR Rating – 3/5 – (1 Low, 5 High)

Figure 5.3-7 - Comparison matrix (2 of 2) for Bottleneck 5 solutions

Chapter 5.3.6 Bottleneck 6: Fixturing Solutions Comparison

The chosen methodology (see figure 3.5-8) for fixture system improvements will:

- Provide a considerable time saving for fixture identification
- Be implemented in a short timeframe with minimal resource requirement
- Assist the communication between the design and manufacture functions

Solution	Introduction of fixture management and visual identification system
BOS	1) Uses existing knowledge to accurately define fixtures by interface and not by single drawing number 2) Allows fixture detail to be implemented into production planning to assist operators upon receiving planning 3) Allows for future fixture quantity reduction in case unnecessary duplicates exist 4) Every fixture will be numbered and identified with appropriate dimensional detail 5) Storage area will be more organised
PTI	Fixture identification time currently ranges between 15 to 30 mins Visible system would allow identification within seconds
IPEC	1) Access required to machine interface details for multiple machines 2) Access required to manual measurement equipment for measuring interface geometry whilst not disrupting production 3) Capacity to separate fixtures out whilst being fully categorised 4) Access required to marking equipment for fixture marking / engraving used during final assembly
IP	1) Operator buy-in through demonstration of system to ensure it is utilised and maintained 2) Buy-in from production planning personnel to use detail within production planning for operator benefit 3) Support from management involved in creation of initial system to build-upon
FR	Building upon existing system in place to assist operators FR Rating – 1/5 – (1 Low, 5 High)

Figure 5.3-8 - Comparison matrix for Bottleneck 6 solution

Chapter 5.4 Selection of Solutions for Key Bottlenecks

The comparison matrices within chapter 5.3 were utilised for solution selection. The relationships between different bottlenecks were studied. It was identified through the figure 5.4-1 spider diagram how significant the selection of the bottleneck 2 solution was on all other bottlenecks.

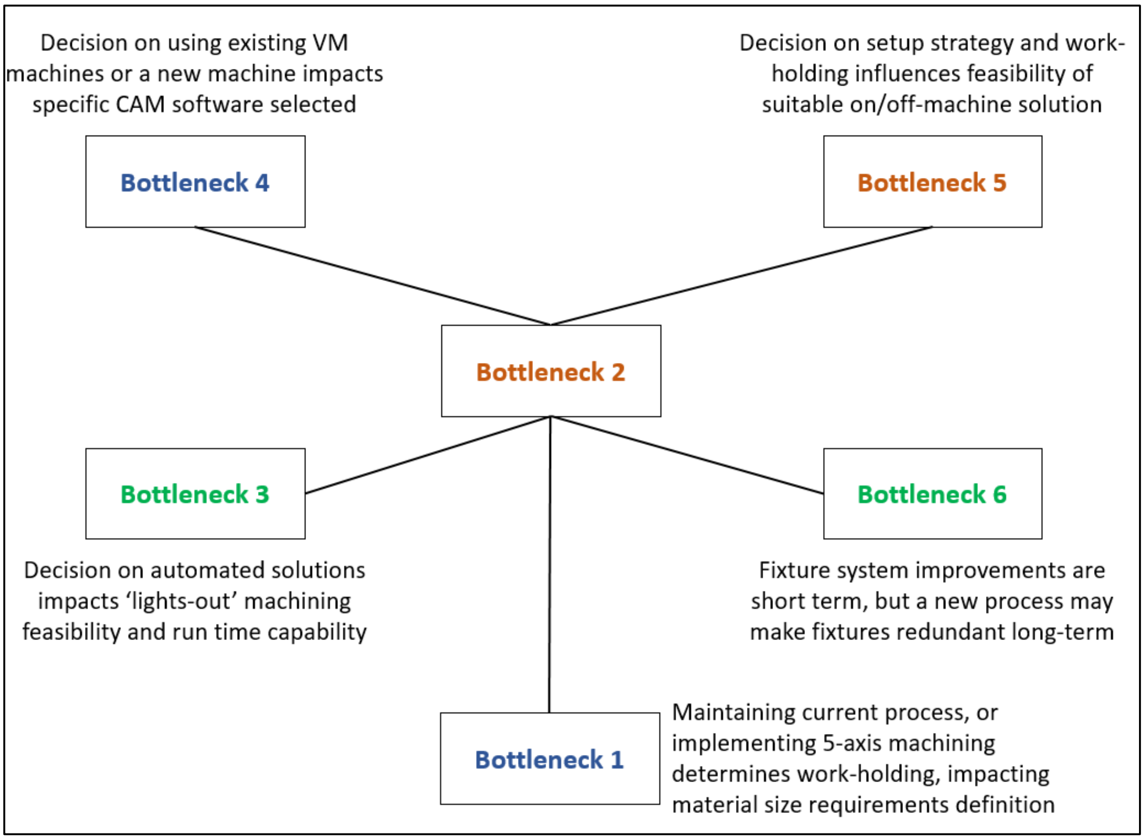


Figure 5.4-1 - Spider diagram indicating the impact bottleneck 2's solution choice has on other bottleneck solution choices

Due to its considerable impact bottleneck 2's solution was selected first to provide clarity for subsequent solution choices. Figure 5.4-2 details the chosen solutions with reasoning whilst highlighting reasons for not selecting other solutions. All selection decisions were made through matrix analysis and agreement between key stakeholders.

A 5-axis machine with palletised loading was chosen for its combined machine tool and robotic loading system despite the large financial requirement. This system would also include dedicated training to cover essential training requirements. The perceived difficulty of integrating add-on solutions with the existing equipment did not outweigh the benefits, with immediate savings not achievable until a concept was proven.

Manual Machine Setup - Chosen Solutions	Reasoning for Selection
5-axis machine implementation with automated pallet loading	1) Number of setups reduced to a maximum of 3 2) Part loading via automation, reducing manual requirements and improving repeatability 3) Allows modular fixturing to be used (removing need for 100s of fixtures) 4) New equipment containing the latest CNC technologies 5) Standalone process not requiring retrofitting or linking of new and aging equipment 6) 'Lights-out' machining capability
Implementing 5-axis work-holding equipment	1) Necessity for use with 5-axis machining and automated loading 2) Equipment can be used on wide variety of parts through modular method

Reasons for Not Selecting Other Solutions
1) Utilising probes for setup – 5 setups still utilised as well as manual part loading, some savings made, but use of high quantity of fixtures still required
2) 5-axis add-on trunnion – retrofitting could create difficulty in: 1) identifying perfect solution for existing machines, 2) integration with existing machines and 3) large investment to implement on multiple machines equivalent to a new machine tool investment
3) New 5-axis machine – standalone machine doesn't guarantee 'lights-out' machining without automated loading, return on investment is harder to justify without guaranteed 'lights-out' machining
4) Robotic Loading Arm – large investment and potentially difficult integration in a compact cell with aging equipment and with manual setup fixturing, Mass of billets may also require an industrial robot which increases installation challenges

Figure 5.4-2 - Chosen Solutions & Not Chosen Solutions for Bottleneck 2 With Reasoning

Palletised loading was chosen over VM machine robotic loading. Specifications implied that only segregated industrial robots were suitable for the required application due to large tool-holder billet masses (FANUC, 2020). 5-axis work-holding was identified as essential for the selected machine, with the specific equipment chosen within chapter 6.2.1.

The bottleneck 2 solution allowed for other bottleneck solution choices beginning with bottleneck 1 (see figure 5.4-3). The chosen solution could provide a 10 day DTD process time reduction through utilisation of existing data to define material groups. The 5-axis work-holding process will assist in defining the material requirements for manufacture on the new machine.

Long Material Delivery Chosen Solution	Reasoning for Selection
Determining material groups based upon various existing tool-holder dimensions	1) Allows stock-holding of common material sizes and same-day machining of new orders for existing designs 2) Reduces the number of special material sizes required with 10 days delivery 3) Improves knowledge of common dimensions across 100s of holders through categorisation 4) Uses existing data from design drawings without having to redesign tool-holders 5) Categorisation of the key holders contained in supply agreements will allow for improved delivery performance of these

Reasons for Not Selecting Other Solution - Defining material groups by size and amending designs through optimisation
1) Time required for training and implementation of new CAD tools needed
2) Some tool-holders unable to be optimised without reducing functionality
3) Design optimisation time required prior to categorisation being possible
4) Existing designs would require re-approval from customers for changes
5) Appears to be considerably more work for no additional time gain on the chosen solution

Figure 5.4-3 - Chosen Solution & Not Chosen Solution for Bottleneck 1 With Reasoning

Figure 5.4-4 details the bottleneck 3 solutions. Machine monitoring of the new 5-axis machining process will ensure essential 'lights-out machining is fully achieved and potentially justify roll-out of monitoring software onto the existing VM machines.

No 'Lights-Out' Machining & Reduced Utilisation Chosen Solutions	Reasoning for Selection
5-axis machine implementation with automated pallet loading	1) Part loading via automation, reducing manual requirements and improving repeatability 2) New equipment containing the latest CNC technologies 3) 'Lights-out' machining capability, increasing number of available weekly machining hours from 80 hrs to 168 hrs 4) Utilisation should increase as operators can load parts whilst the machine is also running 5) Once loaded the machine can be unmanned and fully operational, allowing the operator to run a second machine and increase utilisation elsewhere
Machine Monitoring Software to measure productivity and utilisation	1) To justify above process investment, monitoring of producing time required to maximise utilisation and achieve quicker return on investment 2) Accurate actual cycle times can be captured and compared to estimated machining times, improving the accuracy of future production planning 3) Machine scheduling and utilisation targets can be set through use of data 4) Leading sources of downtime can be identified and reduced through knowledge of when machine is producing

Reasons for Not Selecting Other Solution - Robotic Automation implementation on existing VM machines
1) Large investment and potentially difficult integration in a compact cell with aging equipment and with manual setup fixturing 2) Mass of billets may also require an industrial robot which increases installation challenges 3) Long cycle times mean a robotic arm may be idle for long periods if not used on multiple machines, suggesting it will have a slow return on investment 4) Roll-out of multiple arms for multiple machines could be costly in comparison to the single palletised loading 5-axis machine to achieve same performance levels

Figure 5.4-4 - Chosen Solutions & Not Chosen Solution for Bottleneck 3 With Reasoning

Figure 5.4-5 details bottleneck 4's solution. A commercial CAM package was selected which was capable of integrating with any 5-axis machine tool chosen for implementation. Immediate focus was placed on the 5-axis process with the specialist software not selected being a future consideration for the existing VM machines.

Manual Machine Programming Chosen Solution	Reasoning for Selection
CAM implementation	1) Programming for a 5-axis machine not achievable by manual approach without great difficulty, an improved programming approach is needed 2) New 5-axis process must optimise manufacturing cycle time, CAM allows for improved cutting strategies and tool paths to achieve this 3) Software compatible for multiple machine tool brands and models through supply of dedicated post-processors for the specific CNC controller model 4) Reduced human error in process through use of simulation during programming 5) In-process adjustments can be made and updated in programs within seconds through post-processor use 6) Improved use of CAD data, linking design and manufacturing functions

Reasons for Not Selecting Other Solution - Software for CAM and converting NC programs between different controlling PCs
1) Software is only dedicated to machines made by one supplier, limiting the choice of 5-axis machine solutions if this CAM package was to be used 2) The new 5-axis machine process will be independent of the existing VM machines, without the need for program transfer capability 3) Management of existing programs was not identified as a leading bottleneck previously to implement immediate system improvements on

Figure 5.4-5 - Chosen Solution & Not Chosen Solution for Bottleneck 4 With Reasoning

Figure 5.4-6 details the bottleneck 5 solution with the CMM providing a guaranteed inspection process time reduction through utilising an existing resource. This selection allowed extra focus to be placed on implementing other new technologies elsewhere as the CMM was already established within the SMfE. It provides a short-term solution which can be used long-term, or be replaced by an on-machine approach such as probing to provide further time reductions. The CMM approach minimises the example process variation sources discussed within chapter 5.2.5.

Off-Machine Inspection Process Chosen Solution	Reasoning for Selection
Off-Machine inspection – CMM embedding into process	1) Makes use of an existing resource to inspect parts efficiently 2) The equipment is already established, reduced time required for process implementation and integration with new machine 3) Allows focus to be placed on implementing new technologies for other bottlenecks whilst utilising a validated inspection process 4) Equipment accuracy and repeatability already established 5) Process guarantees 100% part inspection capability 6) Can be used as a short-term or long-term solution, depending on whether on-machine inspection is a future requirement

Reasons for Not Selecting Other Solutions
1) On-Machine inspection - fully utilising machine tool probes: A) Considerable analysis required to find process variation sources and introduce suitable control measures B) For use on existing machines multiple control measures not practiced would require introduction for system success C) Unknown investment requirements to achieve full on-machine inspection of parts 2) On-Machine inspection – inspection arm implementation & Off-Machine inspection – comparator gauging system implementation: A) New 5-axis process requires considerable resources (financial and personnel time) to implement other solution technologies, limited time to embed additional new system B) Both approaches require considerable work on standardising: the process for achieving repeatability, training, program creation and results generation C) Additional work would be required in integrating these systems with the existing machine tools and associated equipment as well as with the new machine

Figure 5.4-6 - Chosen Solution & Not Chosen Solutions for Bottleneck 5 With Reasoning

Fixturing Chosen Solution	Reasoning for Selection
Introduction of improved fixture management and visual identification system	1) Immediate time savings should be achieved on identifying fixtures in seconds and not minutes 2) Improves communication between design, production planning and manufacture 3) Utilises existing data to improve an existing system

Figure 5.4-7 - Chosen Solution for Bottleneck 6 With Reasoning

Figure 5.4-7 summarises the reasoning for improving the current fixturing system to ensure a short-term solution or 'quick-win' is achieved.

Figure 5.4-8 illustrates how the majority of chosen solutions formulate an entirely new manufacturing process (excluding the fixturing system improvements). The independence of the new 5-axis process allows this to be implemented and proven out separately from production in the cell on the existing VM machines.

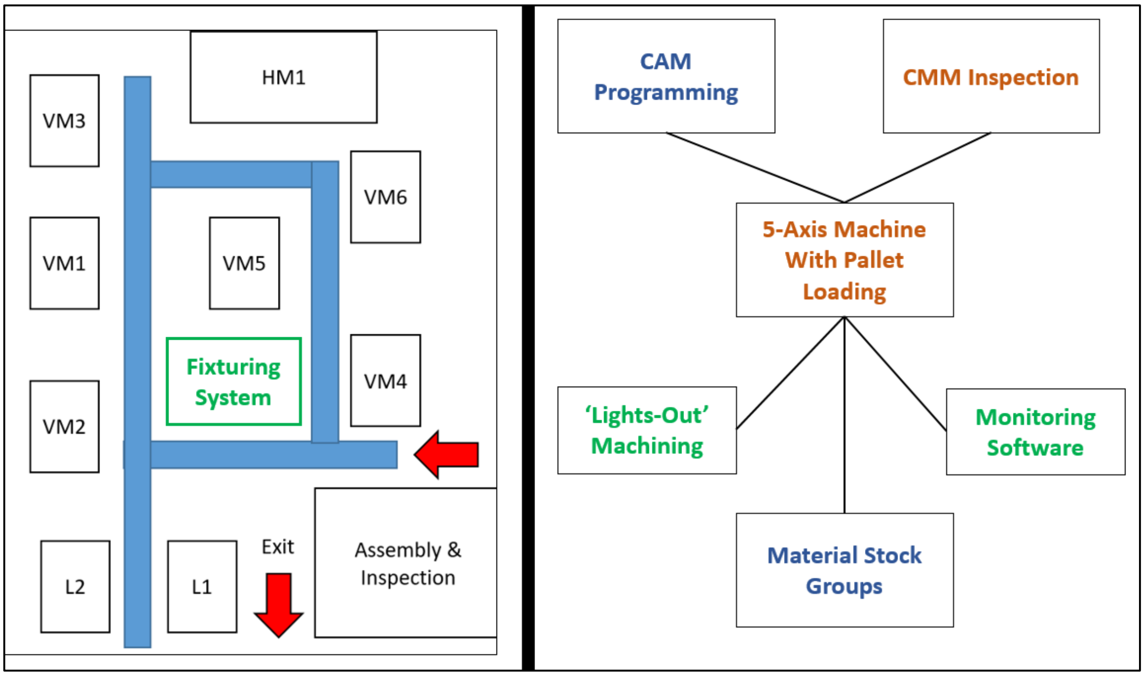


Figure 5.4-8 - Diagram indicating the chosen solutions and where they will impact (existing process left & new process right of the black line)

Chapter 5.5 Chosen Solutions Suitability to Problem & Root Causes Defined

The diagrams for each bottleneck detailing the problem definitions and root causes in figures 5.1-2 to 5.1-3 were updated to include the chosen solutions. Figures 5.5-1 and 5.5-2 illustrate these updates with the root causes addressed by the chosen solutions coloured in green and the root causes not addressed coloured in red. The majority of root causes are addressed by the chosen solutions with those not addressed typically being factors beyond the solution's capability. Examples of root causes not addressed include 'ad-hoc' scheduling, a need for large batch orders and the tooling used. All solutions appear to suitably address the defined problems for each bottleneck.

Symptom Long Material Delivery Time **Root Causes**

1) Material sizes vary due to adding 10mm to finish dimensions
2) No data collated on material size requirements across multiple products
3) Analysis of 100s of drawings required

Problem Definition: Reducing the 10-day delivery time on material through a method of categorising tool-holders into a set of specific material sizes, allowing for common stock-holding

Solution: Introducing material groups based upon existing tool-holder dimensions which will be stocked

Symptom Manual Machine Setup **Root Causes**

1) Tool-holder mounting interface detail on each fixture – various interfaces required
2) Fixtures are not maintained / calibrated
3) VM machines are 3+1 axes
4) Process is not currently repeatable
5) No automated loading

Problem Definition: Reducing setup time through a system(s) providing setup repeatability and optimising machining setups through simplifying equipment and manual requirements (via full or semi-automation)

Solution: Implementation of a 5-axis machine and work-holding with palletised robot loading

Symptom No 'Lights-Out' Machining and Reduced Utilisation **Root Causes**

1) No data capture on utilisation
2) 'Ad-hoc' machine scheduling process – open to daily amendments
3) No method of automated loading and unloading of parts
4) More machines than operators
5) Reliance on multiple batches in production simultaneously (shorter changeover times)

Problem Definition: Introducing a method for 'lights-out' manufacture via automated loading in addition to commencing data capture of machine utilisation, to improve workflow management

Solution: Automated robot loading and implementation of machine monitoring software

Figure 5.5-1 - Diagram of the symptom, root causes and defined problem for bottlenecks 1 to 3 with solutions added

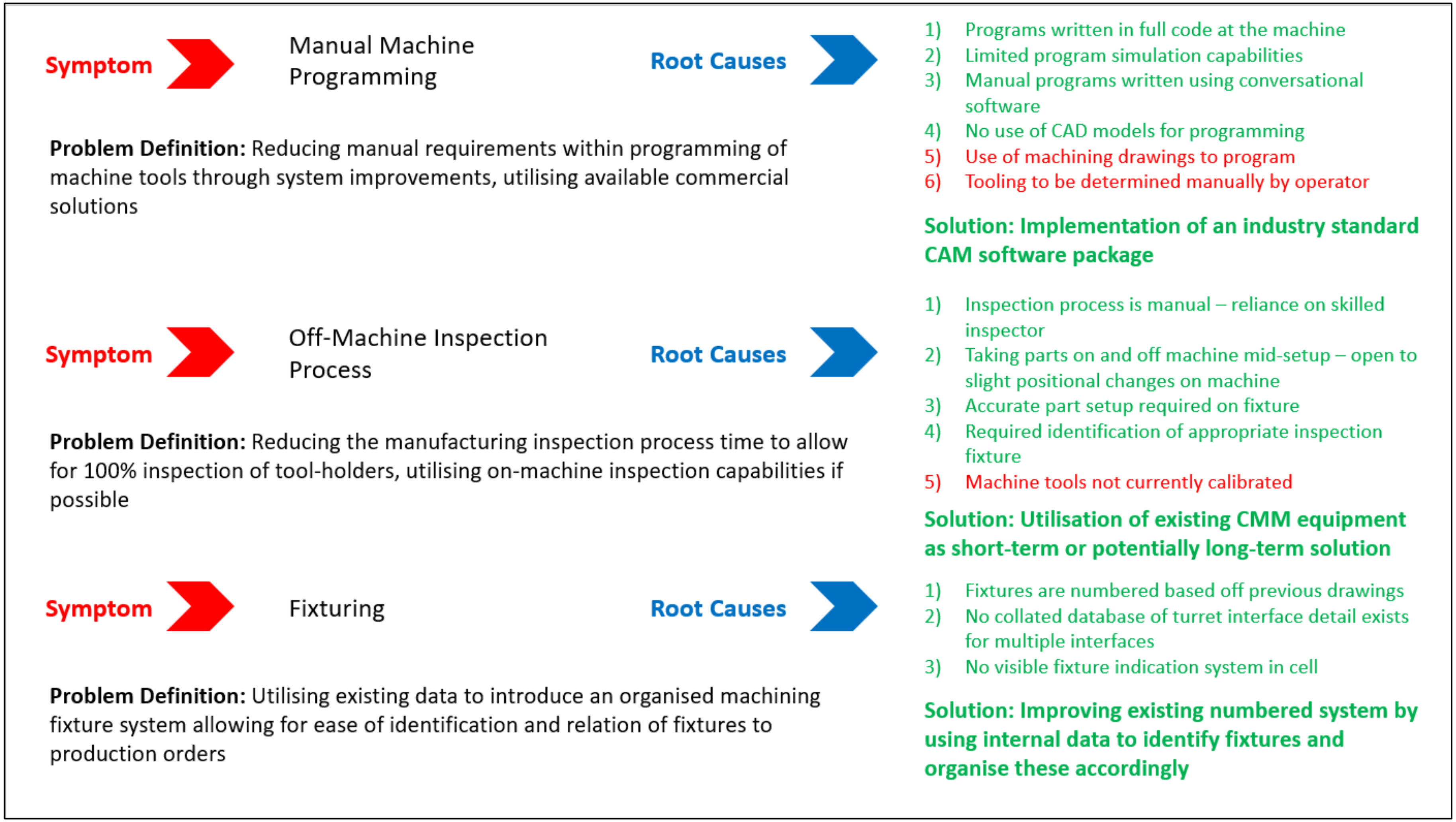


Figure 5.5-2 - Diagram of the symptom, root causes and defined problem for bottlenecks 4 to 6 with solutions added

Chapter 6 Implementation of Chosen Solutions

Chapter 6.1 Requirements for Implementing Each Solution

The specific requirements for each solution were defined through flowcharts containing milestones and related tasks. A reverse engineering approach starting at the implemented solution was used to determine the milestones and tasks for each solution. Figure 6.1-1 details the bottleneck 1 flowchart with milestones in the white boxes and the related tasks in the gold boxes. The tasks indicate the specific personnel to be involved (for example design are required to supply drawings).

The flowcharts for bottlenecks 2 to 5 are contained in appendix 9 for further reading. The flowchart process identified how certain solutions were dependent on others, i.e. ‘lights-out’ machining requiring 5-axis machine and CAM implementation first. A master flowchart was created in figure 6.1-2 to map these dependencies.

In figure 6.1-2 a main workflow of milestones connected by red arrows details the path to achieve ‘lights-out’ machining. Certain solutions such as material group definition and CMM inspection strategy were dependent on other milestones, with blue arrows branching off from the main workflow to indicate these. The fixturing system improvements and monitoring software selection milestones were identified as independent milestones.

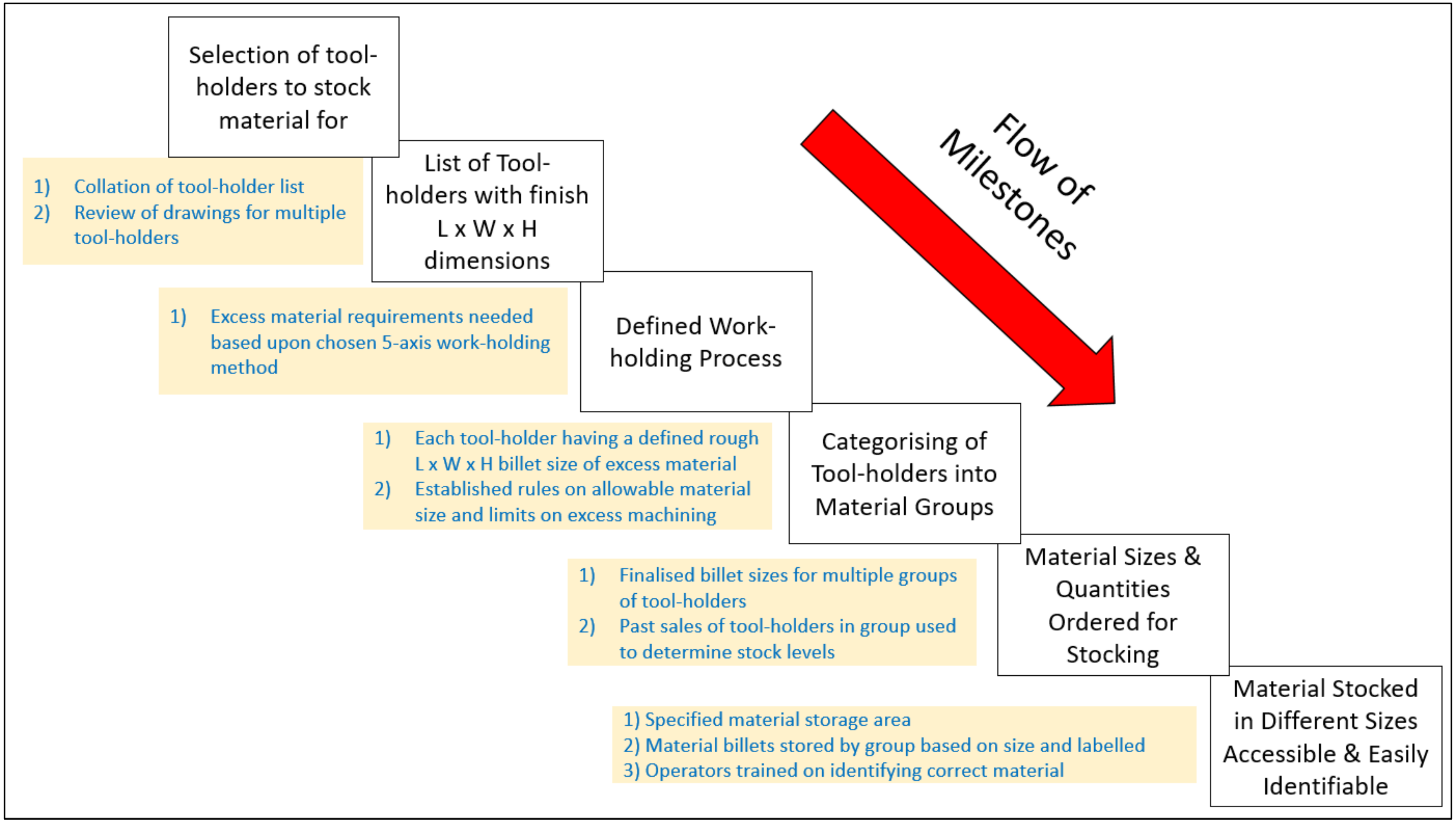


Figure 6.1-1 - Flowchart of milestones and tasks for implementing the Bottleneck 1 solution

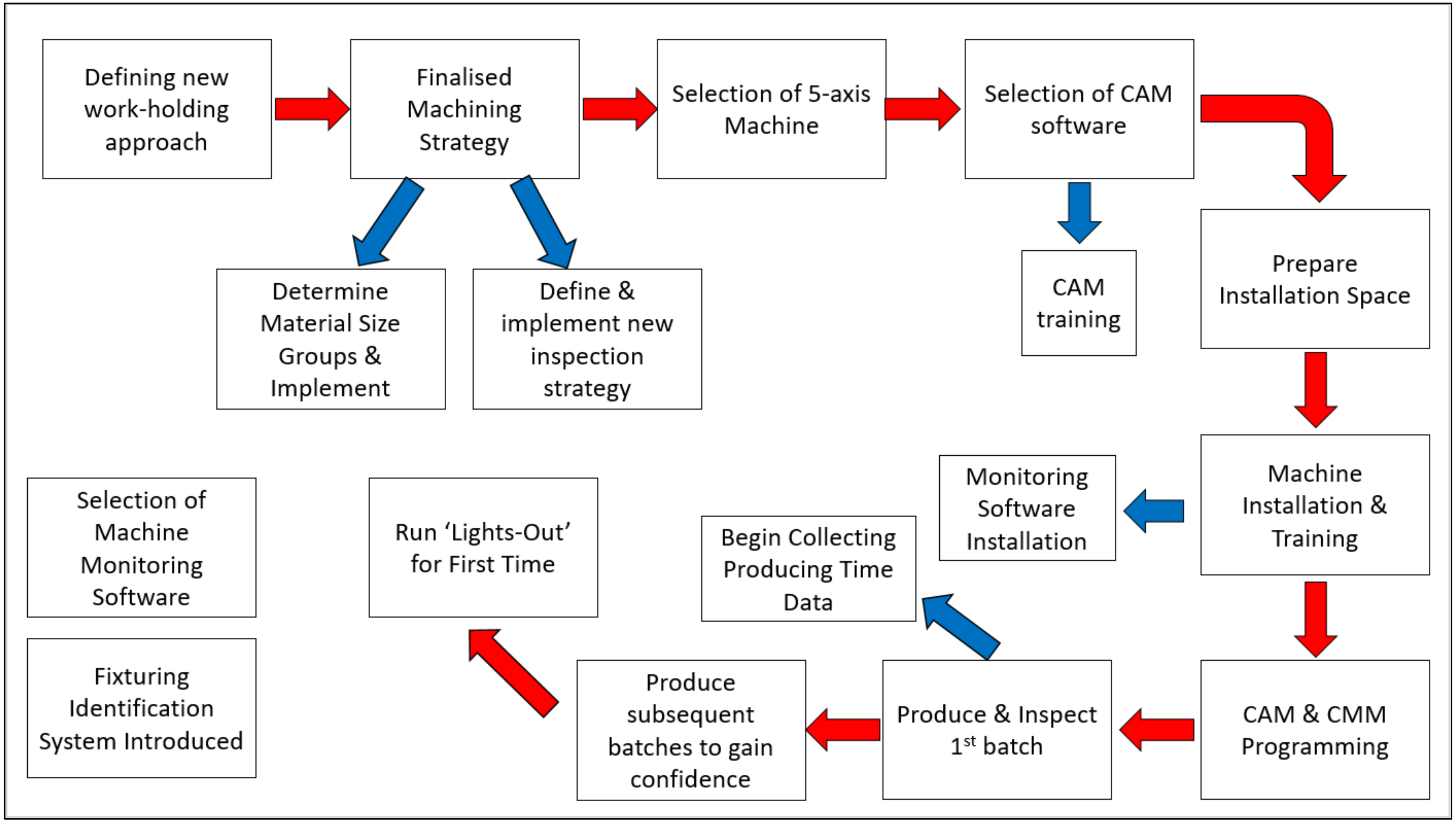


Figure 6.1-2 - Flowchart indicating main process workflow for solutions (red arrows) with branches indicated (blue arrows)

Chapter 6.2 Summary of Main Workflow Solutions Implementation

This chapter summarises the implementation milestones of the main workflow to achieve 'lights-out' machining (see figure 6.1-2). Further detail is available in appendix 10 on the implemented solutions.

Chapter 6.2.1 Main Workflow Milestones – Defining Work-Holding Approach & Machining Strategy

Using 5-axis work-holding required strategy definition to optimise the new machining setups. 5-axis work-holding solutions provide the capability to allow machining of 5 billet faces in 1 setup. Figure 6.2-1 represents the defined generic 5-axis setup approach with setup 1 machining 5 billet faces and setup 2 machining the remaining face.

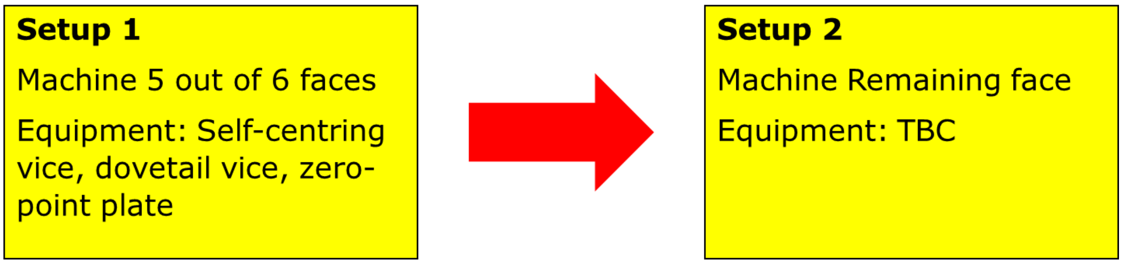


Figure 6.2-1 - Process diagram for 5-axis machining setups considering equipment to be used

This approach was considered for all tool-holders including the one in figure 6.2-2 to help determine the faces to machine in setup 1. It was found that the holder's rear face provided the best face for work-holding during setup 1 as it optimised the tool-holder features machined, highlighted by the blue, green, red and white arrows within figure 6.2-2. The rear face typically contains simple features to machine during setup 2.

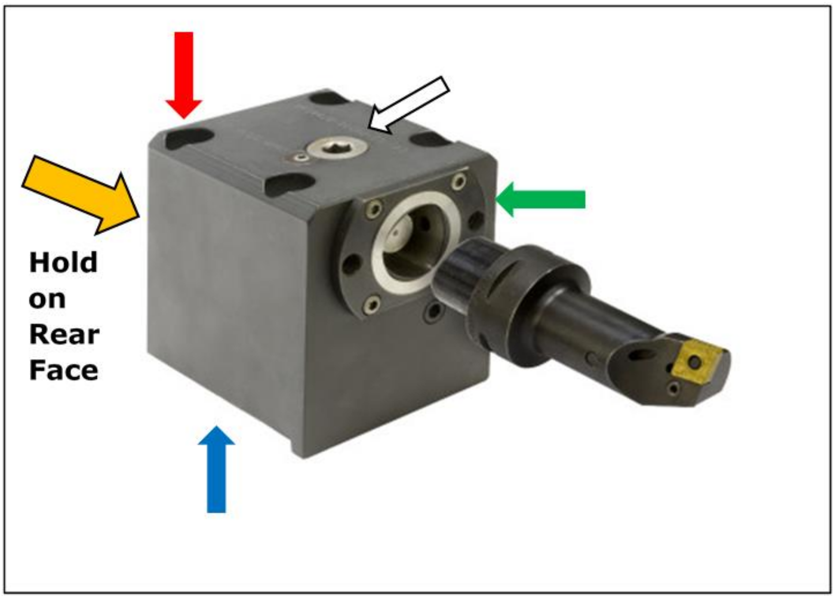


Figure 6.2-2 – Tool-holder image from SMfE website with arrows indicating setup features to machine

This approach was chosen through utilising support from CAM suppliers investigating tool-holder manufacturing optimisation methods. With the setup strategy defined the work-holding equipment to use for setups 1 and 2 now required selecting. Figure 6.2-3 illustrates a diagram of the setup 1 process.

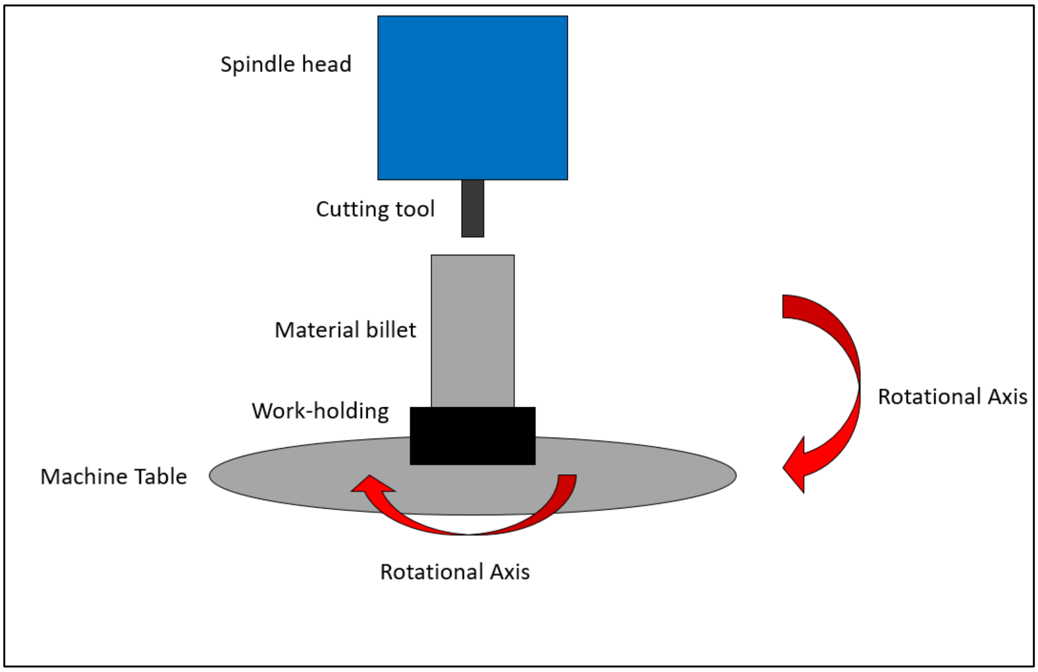


Figure 6.2-3 - Diagram of Setup 1 Process

3 key requirements for the chosen equipment were defined:

1) Provide secure clamping to minimise vibration
2) Overcome moment forces applied during cutting at an indexed position
3) Provide sufficient clearance for indexing by clamping at a reduced height

The zero-point plate in figure 6.2-4 was selected for use with setup 1 for multiple reasons including:

- A low clamping height as the plates are 27mm thick (Lang Technik, 2020)
- Reduced preparation work required on billets prior to setup 1
- The plate is modular allowing any attachment with 4 pull studs to be clamped and allows for future fixturing flexibility
- The 4 pull stud location holes are modular regardless of the billet size to be held

Figure 6.2-4 - The zero-point fixture plate used for setup 1 – Lang Technik (2020)

The setup 1 approach was not usable for setup 2 as the four modular location holes in the billet required removal. A methodology was defined to locate on standardised features of a tool-holder machined in setup 1 (see red area in figure 6.2-5). These standardised bore/hole features had 5 product size variations, allowing 5 groups of duplicate fixture plates to be produced for use in setup 2. These plates clamped the tool-holder using the figure 6.2-5 bore/hole detail on one side and mounted to the zero-point plate on the opposite side.

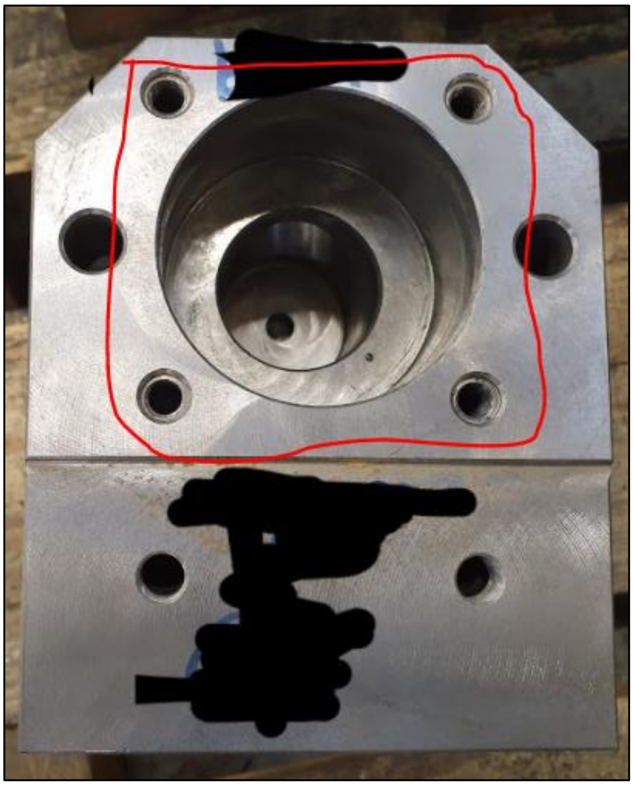


Figure 6.2-5 - Example Tool-Holder highlighting bore and mounting holes for setup 2 location

Figure 6.2-6 contains an updated setup diagram containing the equipment used for each setup. The material preparation process for setup 1 is discussed in chapter 6.2.2.

Figure 6.2-6 - Process diagram for 5-axis machining setups with defined work-holding

Chapter 6.2.2 Main Workflow Milestones – Selection of 5-Axis Machine

The 5-axis machine selected must:

1) Utilise the chapter 6.2.1 setup approach
2) Allow for 'lights-out' machining through palletised loading
3) Machine 'key' tool-holders

SMfE management selected the machine in figure 6.2-7 using the above criteria and supplier demonstrations, meetings etc. This machine best suited the requirements despite being from a new supplier not previously used. The chosen machine contained a B-axis rotary table and C-axis trunnion in addition to the X/Y/Z translational axes.

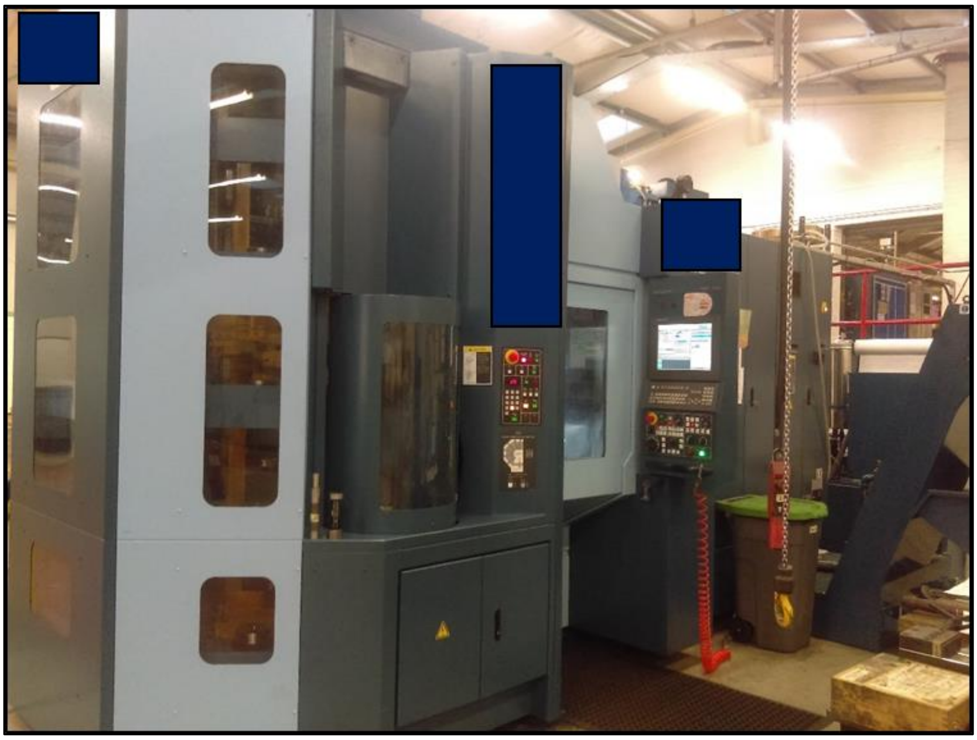


Figure 6.2-7 - Photograph of the 5-axis machine installed

The palletised loading system on the left of figure 6.2-7 contains 32 pallets and allows for 32 consecutive machining cycles. Figure 6.2-8 provides labelled illustration of the loading station used and the equipment from chapter 6.2.1. Pallets are moved by the robotic arm attached to the orange beam.

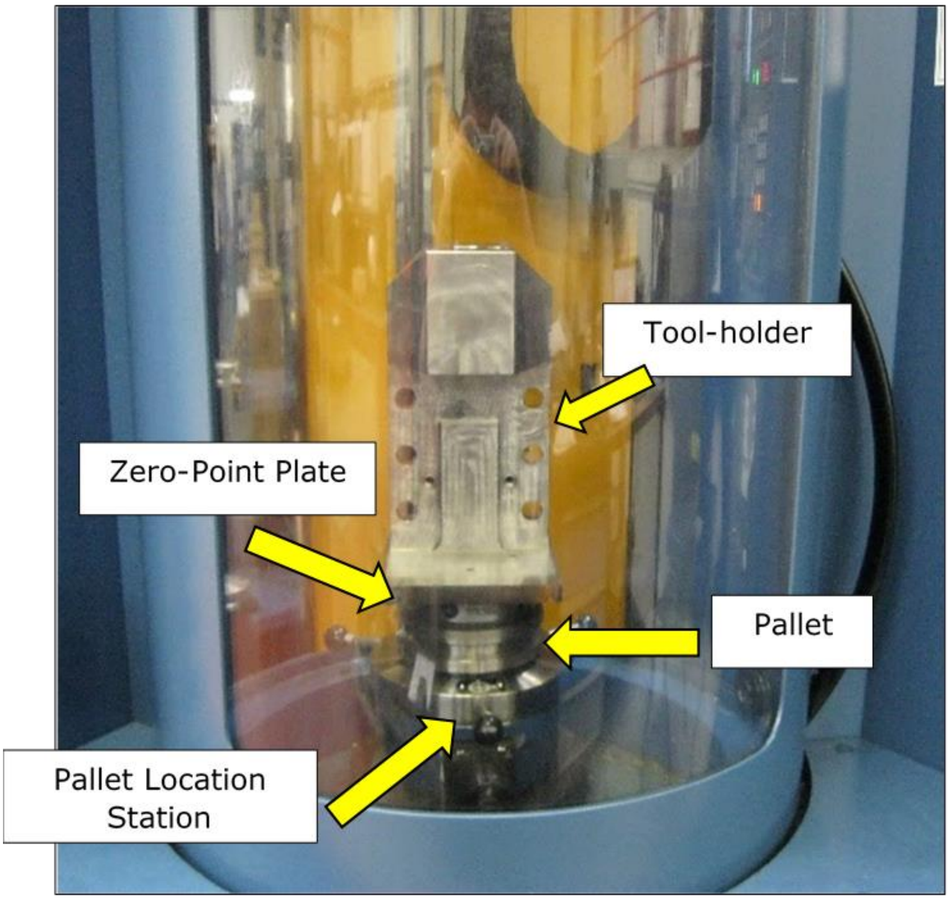


Figure 6.2-8 – Labelled diagram of the part loading station

The pallets are modular allowing repeatable location in the machine storage system and on the machine table by the robotic arm, which moves the pallets within seconds.

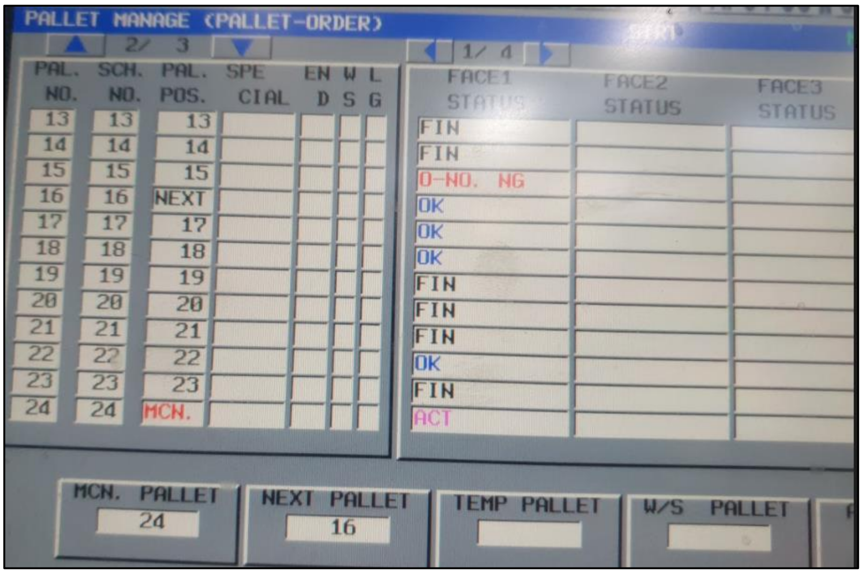


Figure 6.2-9 - Pallet management screen with pallet 24 on machine and 16-18 and 22 set to run

'Lights-out' machining is achievable through loading billets into the 32 pallets and assigning each of these an NC program on the PC controller. Pallets are set to run or 'OK' as seen in figure 6.2-9. When set to 'OK' the robotic arm loads each pallet onto the machine table sequentially after completion of the previous pallet's machining cycle. Completed pallets are placed back in the storage area.

For machining the 'pre-op' (4 location holes in billets for plate location in setup 1) a decision was required on where to machine these. 'Pre-ops' required machining either on the 5-axis machine with additional work-holding equipment or on a dedicated VM machine.

A 5-axis 'pre-op' process was selected using a modular vice mounted to the zero-point plates (see figure 6.2-10). This would further assist in successfully implementing the new machine whilst minimising production downtime on the existing VM machines. The vice is self-centring with a stamping system for marking serrations into the billet for clamping (Lang Technik, 2020). The stamping system requires minimal setup (a few minutes) and is usable on different billet sizes.

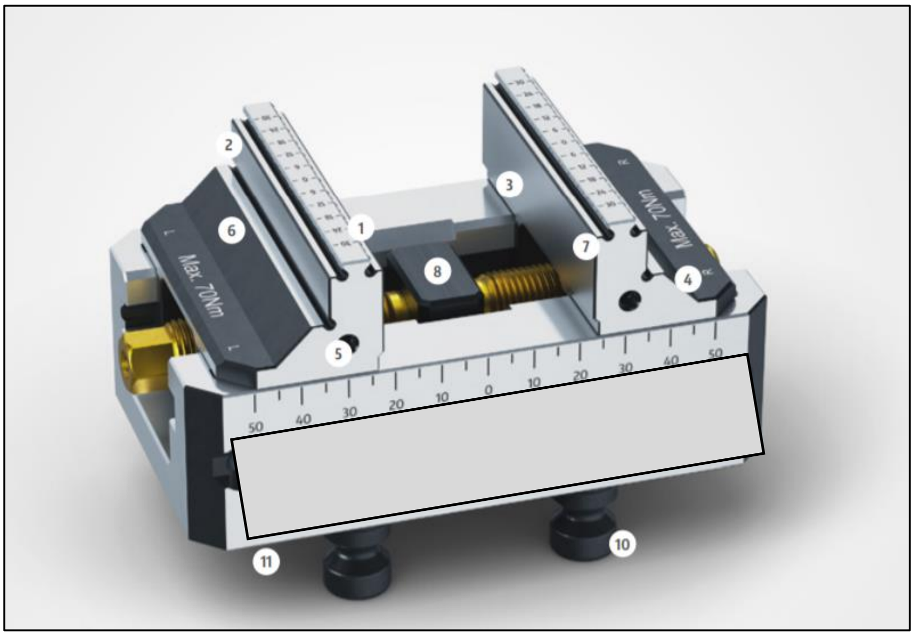


Figure 6.2-10 - Selected self-centring vice for pre-op machining – Lang Technik (2020)

Figure 6.2-11 details the 3 machining setups for tool-holder manufacture using the 5-axis process. Palletised loading allows setup and loading tasks to be performed simultaneously to machining.

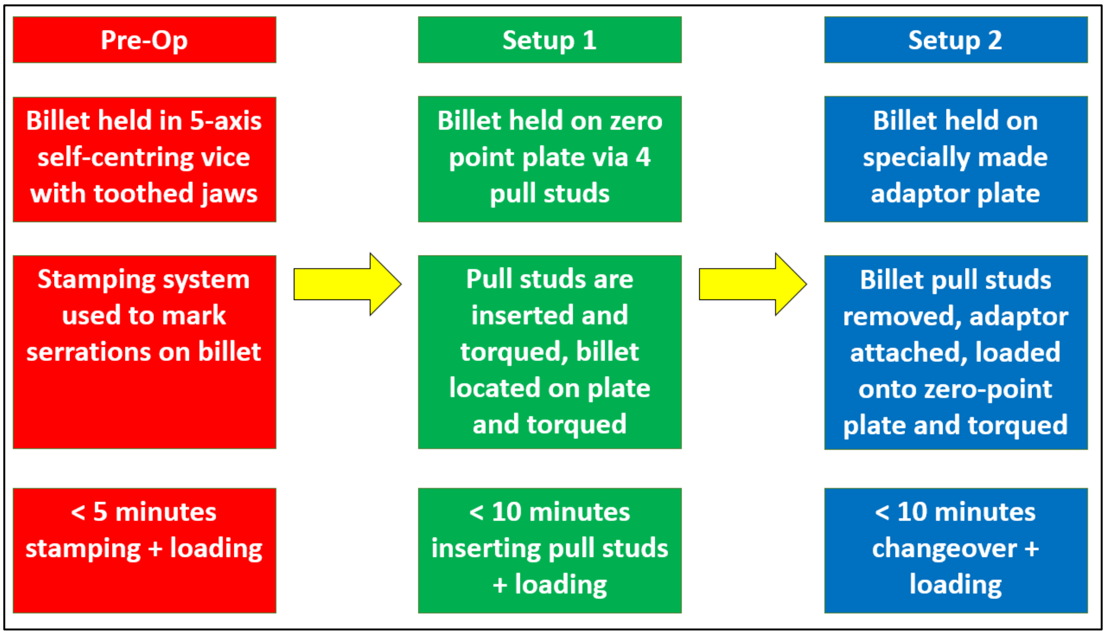


Figure 6.2-11 - Summary of the setups used for 5-axis machining including process times

Chapter 6.2.3 Main Workflow Milestones – Selection of CAM Software

Following machining strategy definition CAM supplier demonstrations were conducted in conjunction to the chapter 6.2.2 tasks. 3 different demonstrations utilised an example tool-holder to demonstrate software features and define the exact package specifications required. Each supplier defined the required process as 3+2 axis machining as opposed to simultaneous 5-axis machining. Each software package contained 3+2 axis programming capability as a standard feature, with simultaneous 5-axis milling capability requiring additional, unnecessary costs.

Each package was compared for features, training, add-ons and price (see comparison matrix in appendix 10). Minimal difference existed between them meaning that the deciding factor in choosing package B from appendix 10 was software usability. SMfE Production stakeholders agreed that this package was most the most user-friendly. Training, support and the 5-axis machine post-processor were included within the purchase.

Key elements for successful CAM implementation included:

1) CAD file usage and access
2) CAM Program file data: naming convention, management and revision control
3) Program process definition for 'pre-op' programs
4) Identifying personnel for programming and loading

For point 1), 3D generic CAD files were already utilised for CMM programming and therefore could be used for CAM. Files were made accessible on the IT network and were used for both the CAM and CMM processes being implemented. This improved communication between design, manufacture and inspection.

For point 2), a new program file naming convention was utilised to identify programs by product code as opposed to the drawing numbers used on VM machine programs. Controlling program revisions was immediately embedded as a necessity through the practice of 're-posting' amended CAM programs into the machine via the post-processor. This ensured outdated program files were not accessible for use.

For point 3), a set of standard 'pre-op' programs based upon the defined material sizes were created. For easy identification the program file names were saved by billet group number (see chapter 6.3.1). All program files associated with points 2) and 3) were provided with a specified network storage location.

For point 4), management reviews identified two operators for running the machine, with one focusing on writing CAM programs on one shift and one focusing on loading and running proven programs on the opposite shift. This maximised machine utilisation by ensuring a sensible balance of machine running and 'prove-out', with 'prove-out' of new programs referring to the 1st tool-holder of a new program run carefully through to 'prove' it runs successfully.

Chapter 6.2.4 Main Workflow Milestones – Machine Installation & Completion of First Batch

The machine installation and training of staff in both CAM and machine operation goes beyond the scope of this work. The first tool-holder batch was produced successfully with supplier support. CAM allowed use of optimisation tools to reduce machining cycle time on the first tool-holder batch considerably. Further details on CAM software optimisation tools are available in appendix 10.

Subsequent 'prove-out' of multiple tool-holder batches following the first batch increased confidence in the process to allow for trialling 'lights-out' machining.

Chapter 6.2.5 Main Workflow Milestones – Run 'Lights-Out' for the First Time

After successful 'prove-out' of approximately 10 different tool-holder programs 'lights-out' machining was trialled. This increased the available time during the week for manufacture. A suitable, proven program was selected for use on a large customer batch order of 80 tool-holders with the trial completed overnight during the week (6 hours 'lights-out' manufacture).

Successful 'lights-out' manufacture required:

1) A proven program
2) Loaded material billets
3) Available tooling for manufacture

The chosen program provided a long setup 1 cycle time (3 hours) due to its 'L' shape machined from a rectangular billet (see figure 6.2-12). This order utilised the machine's sister tooling capability whereby key tool duplicates were stocked, allowing for new tools to replace expired ones after extended use during unmanned machining.

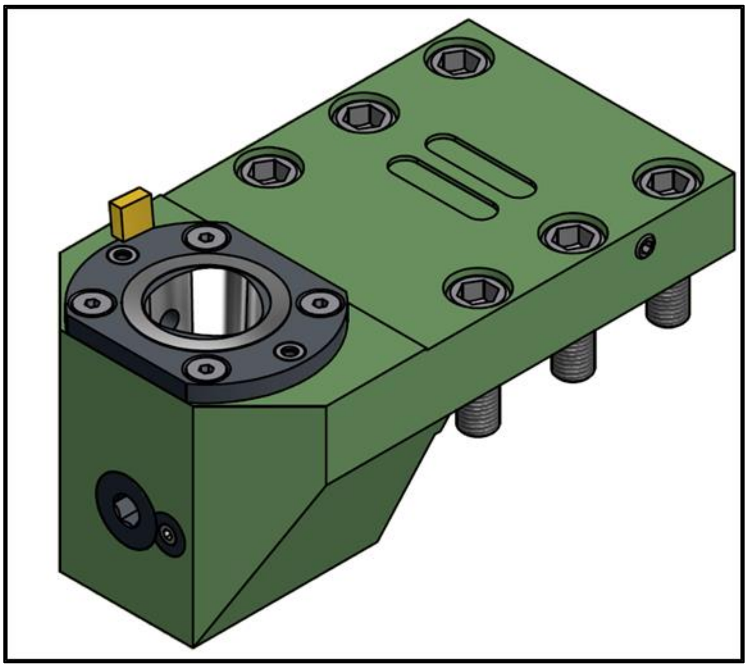


Figure 6.2-12 - CAD model image of the holder chosen for 'lights-out' machining

The trial was run with immediate review indicating complete and successful machining for the full 6-hour ‘lights-out’ period. This allowed successful weekend running to be introduced on the 80-off order and increased utilisation further, whilst ensuring the main flowchart from figure 6.1-2 had reached its conclusion.

Chapter 6.3 Summary of Other Solutions Implementation

This chapter focuses on the additional solution implementations not within the main workflow in figure 6.1-2.

Chapter 6.3.1 Other Solution Milestones – Determining Material Size Groups

To implement the categorised material groups identification of key tool-holders to manufacture using the 5-axis process was completed, through collating a database similar to figure 6.3-1. Leading tool-holder sellers within the previous year were generally also holders contained in the existing supply agreements. This allowed for prioritisation of these holders for CAM programming and 'prove-out'.

Product Code	Past Sales	Drawing N°	Key Agreement Holder? (Y/N)	Priority No.
Holder 1	155	XX	Y	1
Holder 2	105	XX	Y	2
Holder 3	99	XX	Y	3
Holder 4	67	XX	Y	4
Holder 5	62	XX	Y	5
Holder 6	50	XX	Y	
Holder 7	35	XX	N	
Holder 8	34	XX	Y	
Holder 9	32	XX	N	
Holder 10	28	XX	Y	
Holder 11	26	XX	N	
Holder 12	25	XX	Y	
Holder 13	24	XX	Y	
Holder 14	24	XX	N	
Holder 15	22	XX	Y	
Holder 16	20	XX	Y	
Holder 17	20	XX	Y	
Holder 18	20	XX	Y	

Figure 6.3-1 – Example layout of tool-holder database used for material groups definition

Drawings of all tool-holders collated in the database were reviewed to identify their finish size dimensions and required material billet dimensions. The methodology used is presented in figures 6.3-2 to 6.3-3. The key difference to the previous approach sees a requirement for 30mm excess material on one of the dimensions to account for the setup 1 pull studs.

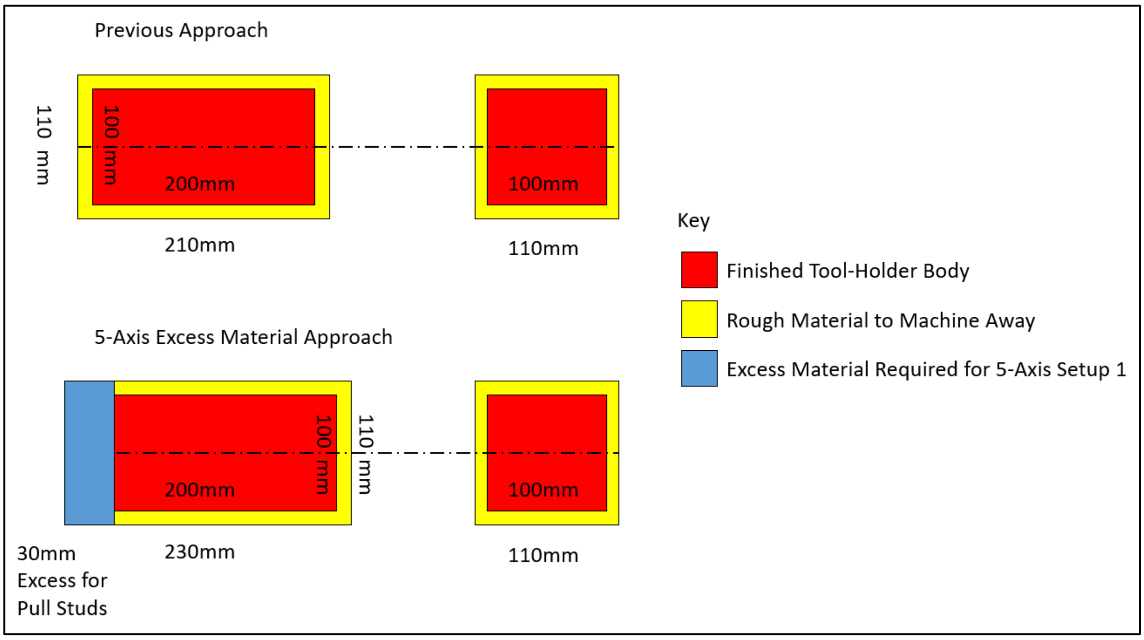
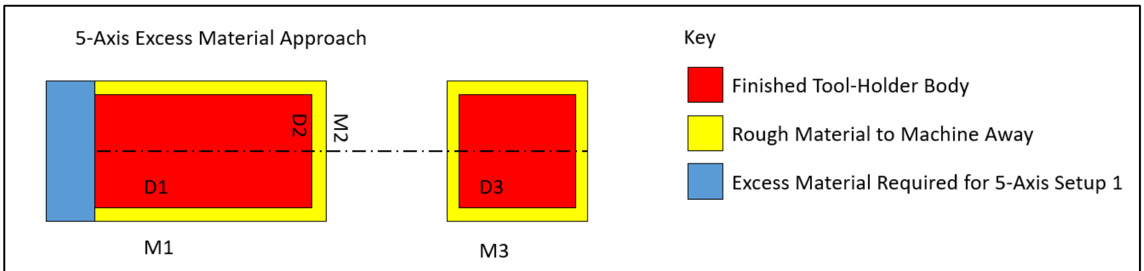


Figure 6.3-2 - Diagram comparing existing material size definition approach against new approach for 5-axis process



Rules on Sizing Material for 5-axis approach

If D1 / D2 / D3 refer to tool-holder finishes sizes and M1 / M2 / M3 refer to rough material sizes needed:

1) If D1 ends in a 0 digit – M1 = D1 + 30mm
2) If D1 ends in a digit from 1 to 9 – M1 = D1 rounded to next 10 + 30mm, i.e. D1 = 201mm, M1 = D1 rounded to 210 + 30 = 240mm

3) If D2 ends in a digit from 0 to 5 – M2 = D2 rounded to next 10, i.e. D2 = 111mm, M2 = 120mm
4) If D2 ends in digit from 6 to 9, M2 = D2 rounded to next 10 + 10mm, i.e. D2 = 106mm, M2 = D2 rounded to 110mm + 10mm = 120mm

5) Same rules for D3 / M3 apply as for D2 / M2

Figure 6.3-3 - Diagram defining rules for determining material size for tool-holders made using the 5-axis process

The governing rules used in figure 6.3-3 were determined by production staff involved in embedding CAM with a minimum of 5mm rough material required for the M2 and M3 dimensions. Most tool-holder M1 dimensions correlated with billet length due to the 30mm excess material making billets longer, as seen in the example in figure 6.3-4.

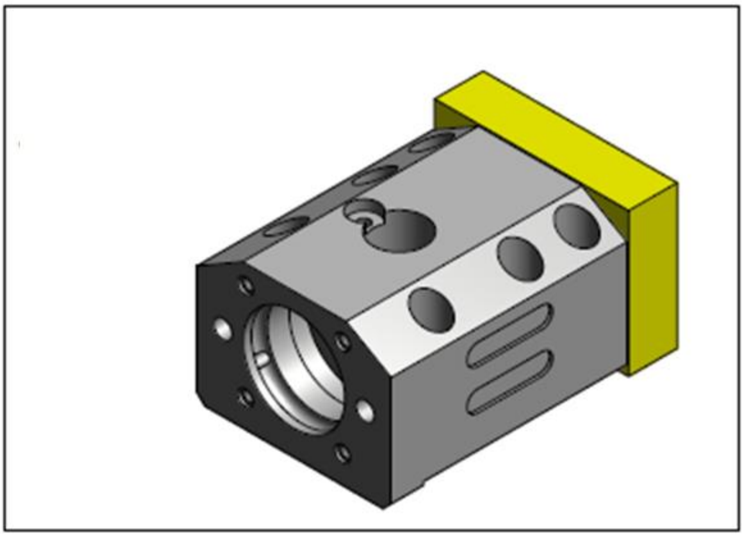


Figure 6.3-4 - Tool-holder CAD model with yellow section representing excess material where pull studs are contained during machining setup 1

With M1 to M3 determined for all holders categorisation of similar sizes was performed, with the stocked bar square sizes of 110mm, 130mm, 150mm etc. used for initial categorisation. Figure 6.3-5 highlights holders categorised with a maximum size of 110mm x 110mm for dimensions M2 and M3. Limits were applied on the required material to machine away for the M2 and M3 dimensions, with a limit of 30mm maximum applied to achieve D2 and D3 where possible.

Figure 6.3-5 indicates how holders fitting the 110mm square size required separation into two groups due to the variance in M1 values, as the M1 values contained the 30mm excess material (yellow cells). Holders with sales above 10 were highlighted to ensure these were prioritised during categorisation as they were most likely to be programmed and ‘proven-out’ first. The two groups created for 110mm square billets provided an equal number of categorised holders for each.

Billet Size	1)		L	W x H	
			220	110 Sq	
Long Product Code	Dwg	Sales Qty	M1	M2	M3
		99	220	110	70
		16	180	110	90
		10	170	100	100
		8	180	110	90
		6	180	110	110
		5	180	100	90
		5	190	90	90
		4	210	100	80
		4	210	110	80
		3	190	110	90
		3	180	110	70
		2	200	100	90
		2	210	100	90
		2	180	100	80
		1	180	110	110
		1	210	100	90
		1	170	80	80
		5 (2013)	170	110	70
		10 (2014)	170	100	90

Billet Size	2)		L	W x H	
			140	110 Sq	
Long Product Code	Dwg	Sales Qty	M1	M2	M3
		35	120	110	70
		26	120	100	80
		12	130	110	80
		10	120	100	100
		10	130	110	90
		7	130	110	100
		6	130	110	80
		4	130	60	90
		4	110	90	60
		3	140	110	90
		2	130	100	80
		2	130	110	90
		2	140	110	90
		2	130	110	90
		1	120	100	80
		1	120	100	80
		1	130	110	100
		1	140	110	90

Figure 6.3-5 - Images of the first 2 billet groups created with product code and drawing detail covered by white boxes

This methodology was utilised to determine all material groups with a final list of groups detailed in figure 6.3-6. Billet groups 1 to 9 were immediately determined whilst sizes 10 to 12 were added later on for other tool-holder product types. Billet 8 was split into two sizes (8 and 13) following a secondary review.

Billet No.	W x H	L	Reorder Point
1	110 Sq	220	10
2	110 Sq	140	5
3	130 Sq	250	10
4	130 Sq	190	25
5	150 Sq	200	20
6	150 x 110	250	15
7	150 x 110	190	20
8	150 x 130	285	10
9	180 Sq	285	3
10	180 x 150	200	15
11	180 x 93	200	5
12	200 x 130	270	10
13	150 x 130	250	10

Figure 6.3-6 - List of material groups created for common stock-holding

A storage area was identified for all material groups with each assigned dedicated, labelled pallets containing visual aids for loading and unloading of material (see figure 6.3-7). Numbered slots for every billet to be stored allowed for quick stock level analysis using the reorder point quantities in figure 6.3-6 as a guide. Reorder point quantities were determined using past sales quantities for each group's set of holders.

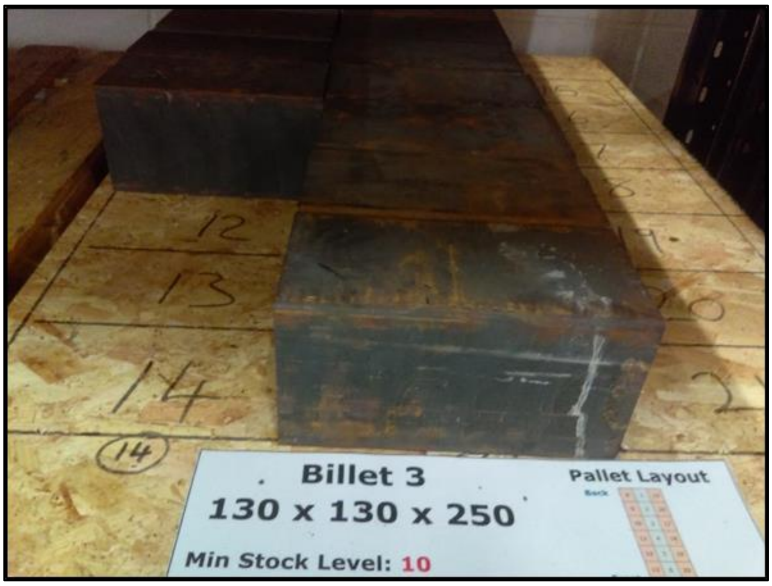


Figure 6.3-7 - Example billet group storage pallet containing identification label

Material 'pre-ops' were machined only when required initially, with a future aim being to 'pre-op' all material upon receiving it to make it readily available for new orders. Operators were provided with detailed guides on the material groups system introduced.

Chapter 6.3.2 Other Solution Milestones – CMM Inspection Implementation

The use of zero-point fixture plates allowed definition of the CMM inspection process. After the critical tool-holder features were machined during setup 1 off-machine inspection was required. The tool-holders contained the setup 1 excess material and four pull studs which allowed for inspection using zero-point fixture plates as seen in figure 6.3-8.

Figure 6.3-8 - Photograph of a tool-holder on the CMM table utilising the zero-point plate setup

3D CAD models allowed for off-machine inspection program creation. The programs measured all critical geometrical and dimensional tolerances in a single setup. The key bore positions discussed in chapters 3.5.6 and 3.6.2 could be measured quicker and without the need for specialist fixturing. Additionally, bore positions could be directly measured in relation to the primary datum as opposed to reference points on a cube fixture.

Figure 6.3-8 indicates how the CMM uses an indexing head to measure all features in a single setup. Off-machine program creation allowed for CMM and CAM programming to occur concurrently. During prove-out and batch production all tool-holders were inspected to embed process confidence and meet the requirement for 100% manufacturing inspection.

Inspection following setup 1 allowed in-process adjustments to be made for the next part and the inspected part (if required), with the 5-axis machine's modular fixturing allowing for quick part reloading and re-machining.

Chapter 6.3.3 Other Solution Milestones – Machine Monitoring Software Selection & Implementation

A commercial machine monitoring package was initially required for implementing 5-axis machine monitoring, however the 5-axis machine purchased contained dedicated monitoring and data collection software. The decision was made to use this over investing in a standalone package. The dedicated software is illustrated in figure 6.3-9 with green highlighting producing time and orange highlighting machine downtime periods.

Mins	LogNo	LogID	Macid	PalletNo	ToolNO	Programme	BatchNo
1.28	-1	1	1001	28	0		-1
2.38	-1	2	1001	28	96		0
20.92	-1	2	1001	28	103		0
0.72	-1	2	1001	28	69		0
0.70	-1	2	1001	28	74		0
0.63	-1	2	1001	28	78		0
1.33	-1	2	1001	28	6		0
1.97	-1	2	1001	28	2		0
0.90	-1	2	1001	28	101		0
2.85	-1	2	1001	28	11		0
0.65	-1	2	1001	28	14		0
0.67	-1	2	1001	28	16		0
0.72	-1	2	1001	28	24		0

Figure 6.3-9 - Example screenshot of the dedicated machine monitoring software provided by the 5-axis machine supplier (Program file name masked)

The software detailed specific tooling and pallet data including the required tooling for all NC programs saved on the machine. These features were in addition to the software monitoring and collecting run time data. The software was not capable of measuring machine OEE, however the capability to capture critical run time data was prioritised at this early stage. Successful software utilisation would justify specific OEE software as a future opportunity elsewhere.

The machine monitoring software appendix 9 flowchart lists the requirements for successful monitoring and data as:

1) Setup of network connection port near the machine and plugging the machine in
2) Software agent for data format transfer and collection
3) Installation of the software on the IT network

Point 2 was built-in to the machine as a standard feature whilst points 1) and 3) were completed during installation. The figure 6.3-9 data from the monitoring software was made accessible through a dedicated spreadsheet measuring the producing time for a user-defined time period (see figure 6.3-10). The monitoring software and associated spreadsheet were made accessible through PC installation to relevant stakeholders. Figure 6.3-10 details the various times in minutes, with conversions into hours needing to be done manually.

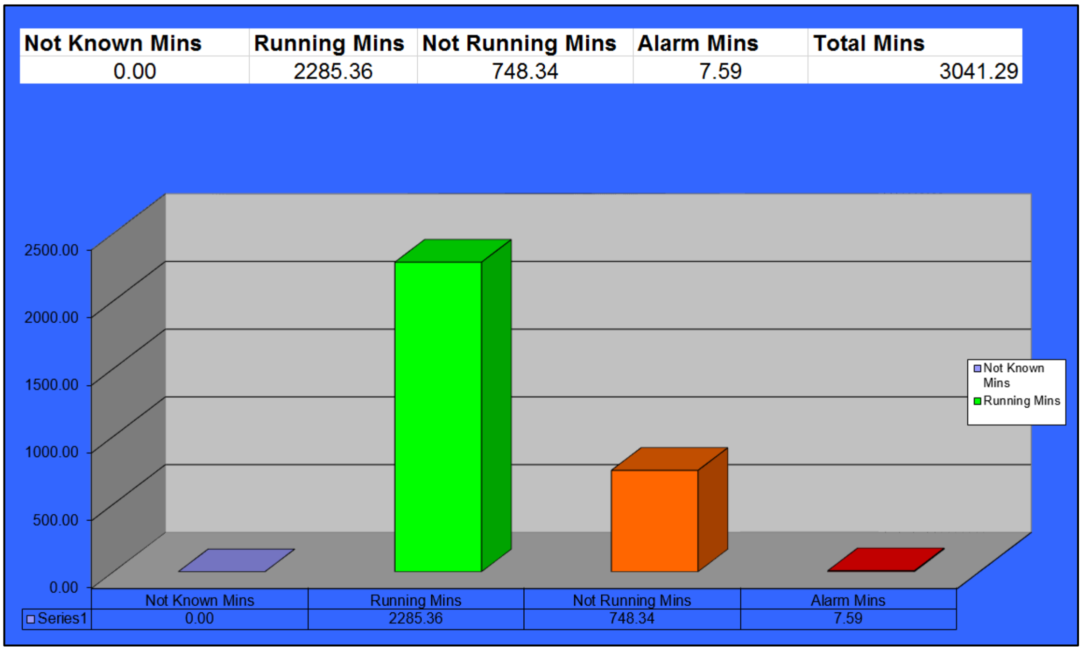


Figure 6.3-10 - Screenshot of spreadsheet data collected on production uptime, downtime and alarm time for a defined time period

Chapter 6.3.4 Other Solution Milestones – Fixturing System Improvements

The fixturing system was completed independently of the other solutions discussed. The flowchart defined in figure 5.2-17 was utilised for identification and categorisation using available data. Example data from the design function included machine interface details as seen within figure 6.3-11.

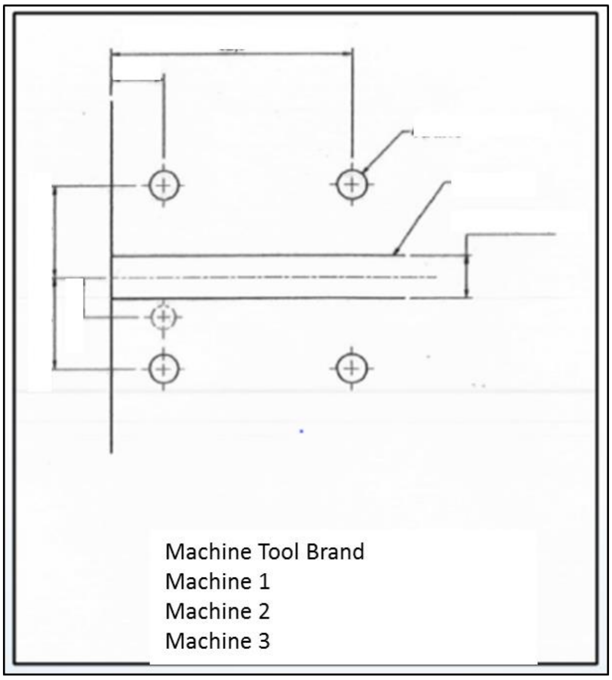


Figure 6.3-11 - Example machine interface detail reference used during fixture categorisation (dimensions masked)

Measurement of all 150+ fixtures allowed relation of these to specific interfaces such as the figure 6.3-11 example. This related fixture features to suitable machines and machine brands. A set of reference sheets were created for location within the tool-holder production cell as visual aids (see figure 6.3-12). These reference sheets highlighted common interfaces and their associated fixtures through categorisation into tables separated by machine brand. Each table row relates to a different machine model and interface.

Introducing the reference sheets was simplified through organisation of the storage area (see figure 6.3-13). During identification any fixtures that were previously unidentified were assigned numbers to build upon the existing numbered system. All numbered fixtures were stored chronologically (see figure 6.3-13).

The system was introduced to operators through demonstration with the reference sheets providing additional guidance on related actions for making new fixtures. Immediate feedback saw reduced identification time and operators buying-in to the system as well as suggesting additional improvements for consideration.

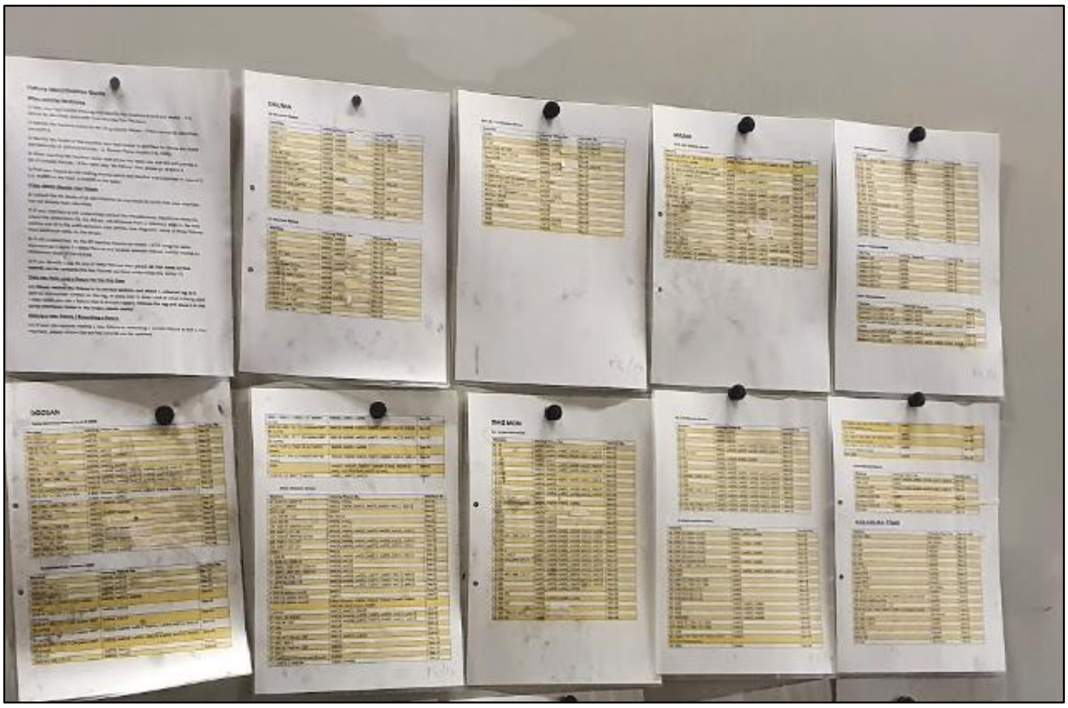


Figure 6.3-12 – Photograph of visual reference sheets used in the fixture system

Figure 6.3-13 – Organised fixtures on the storage racking for use with the reference sheets

Chapter 7 Analysis of Implemented Solutions & Discussion

Following implementation the practices and the DTD process timelines before and after the implemented changes were compared. Additionally, an analysis of performance following implementation was conducted over 12 months after the solutions were implemented.

Chapter 7.1 Comparison of Previous Process V New Process

Bottleneck	Existing Practice Process Time Contribution	New Process Time Contribution
Bottleneck 1 – Long Material Delivery Time	10 days delivery for specific material sizes	0 days delivery time – material stocked
Bottleneck 2 – Manual Machine Setup	5hrs for 5 machining setups	0.5hrs maximum total for 3 setups (can be done during machine run time however)
Bottleneck 3 – No 'Lights-Out' Machining & Reduced Utilisation	80 hrs per machine run time available per week with no monitoring	168 hrs run time on machine with % utilisation monitoring
Bottleneck 4 – Manual Machine Programming	0.5 days (9hrs manual programming time)	0.5 days (9hrs CAM programming time – reduce to 4/5hrs over time) + machining optimisation
Bottleneck 5 – Off-Machine Inspection Process	1hr unloading, inspection (0.5hrs) and reloading time	0.25hrs unloading, inspection (0.1 to 0.2hrs) and reloading time
Bottleneck 6 - Fixturing	Max. 0.5hrs identification time	Identification in seconds

Figure 7.1-1 - Comparison of bottleneck process time contributions for the existing practice processes and new processes implemented

Figure 7.1-1 identifies the tangible improvements each solution provided for the key bottlenecks. As these bottlenecks were common throughout tool-holder manufacture the time contribution savings over a prolonged period will be significant, with savings ranging from 100% for bottlenecks 1 and 6 to 50% minimum for bottleneck 4. Bottleneck 3 doubles the weekly available tool-holder machining time.

The solutions in figure 7.1-1 have provided considerable manufacturing process optimisation with figure 7.1-2 highlighting the impact the 5-axis process made on tool-holder manufacturing time. For a 1-off holder the manufacture time was halved as total process time reduced by 67% from 10 hours to 3 hours. Additionally, manufacturing time estimates are provided for the 11-off batch size selected for the DTD process timeline in chapter 3. Concurrent part loading and machining, 'lights-out' machining and CMM inspection should reduce the manufacturing time for an 11-off by over 80% from 8 days to 1.5 days.

Existing VM Process	5-Axis Process
1-off tool-holder time estimates: 5 hours setup time (5 setups) 5 hours manufacture time	1-off tool-holder time estimates: 0.5 hours setup time (3 setups) 2.5 hours manufacture time (including pre-op)
Manufacturing Time Estimate for 11-off: 8 days	Manufacturing Time Estimate for 11-off: 1.5 days

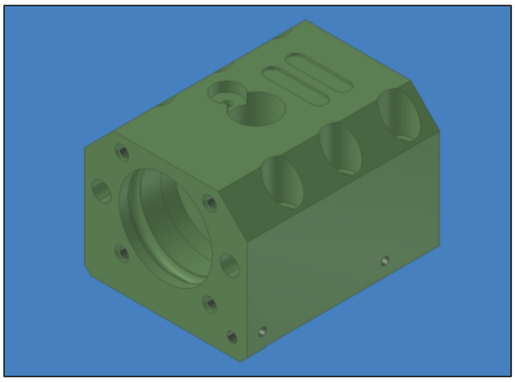


Figure 7.1-2 - Comparison of setup and manufacture time estimates for existing VM and 5-axis processes for typical tool-holder represented by CAD model

Chapter 7.2 Comparison of DTD Process Timelines

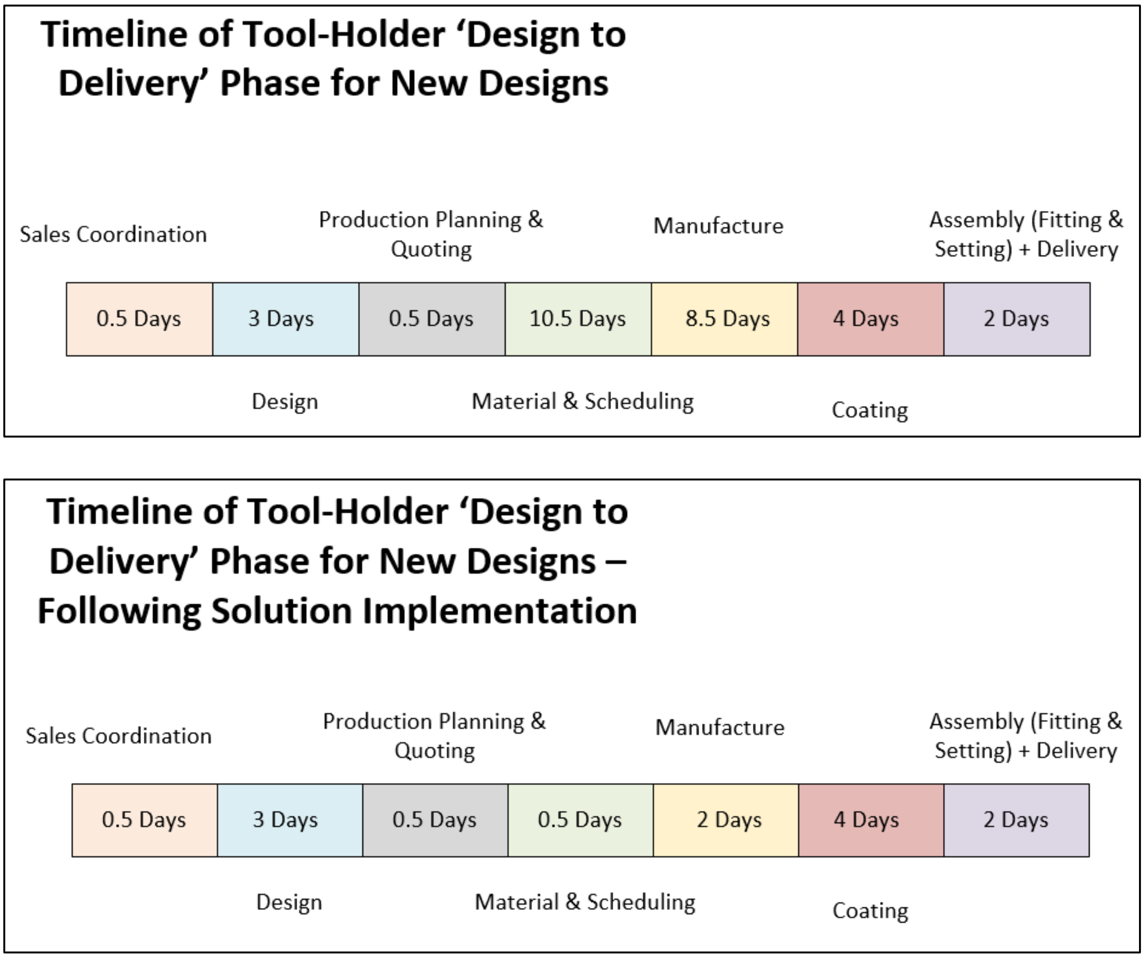


Figure 7.2-1 – DTD process timelines for the processes observed in chapter 3 (top) and with the implemented solutions (bottom)

Comparison of the figure 7.2-1 timelines indicate significant savings as full process time reduced by nearly 50% from 29 days to 12.5 days. Common stock-holding of popular material groups and the 5-axis manufacturing process provide the leading savings of 10 and 6.5 process days respectively. Additionally:

1) Existing designs require no design time contributions, reducing their total process time to 9.5 days and allowing them to achieve catalogue status
2) The 0.5 days' estimates for Sales Coordination and Production Planning were conservative and therefore may reduce process time further
3) Further manufacturing reductions are possible as the 2 days' includes 0.5 days' assigned to CAM programming which could reduce long-term

Chapter 7.3 Analysis of Performance

'Lights-out' machining was introduced in month 4 of 5-axis machine operation, with a significant increase in the quantity of tool-holders produced and machine hours run experienced as a result (see figure 7.3-1). This capability requires sustained large batch quantities to maintain this increased utilisation.

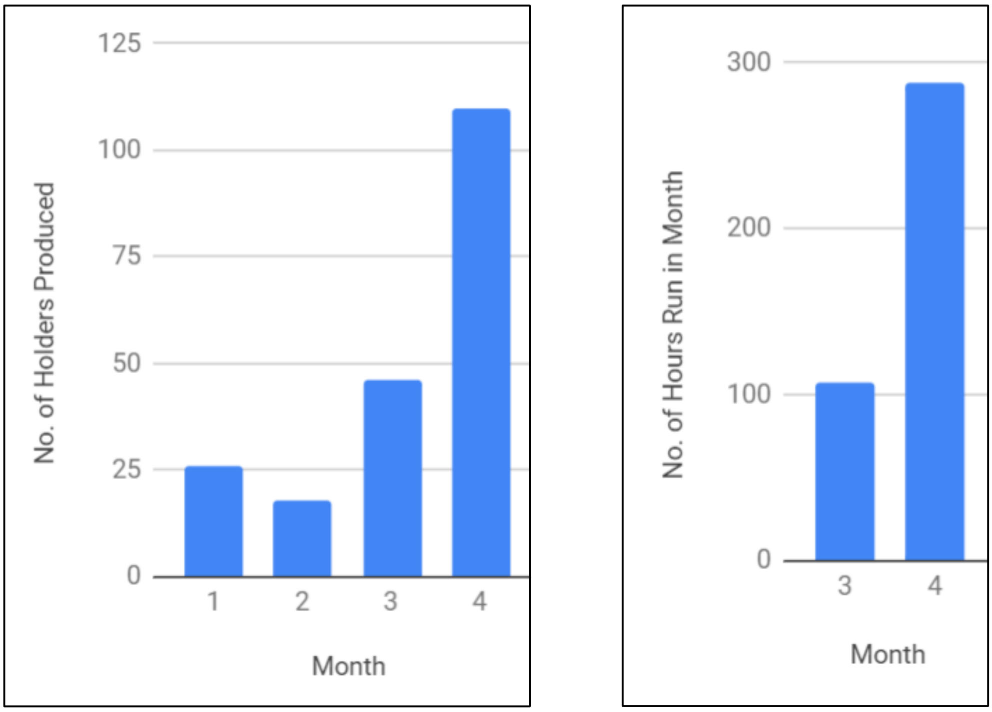
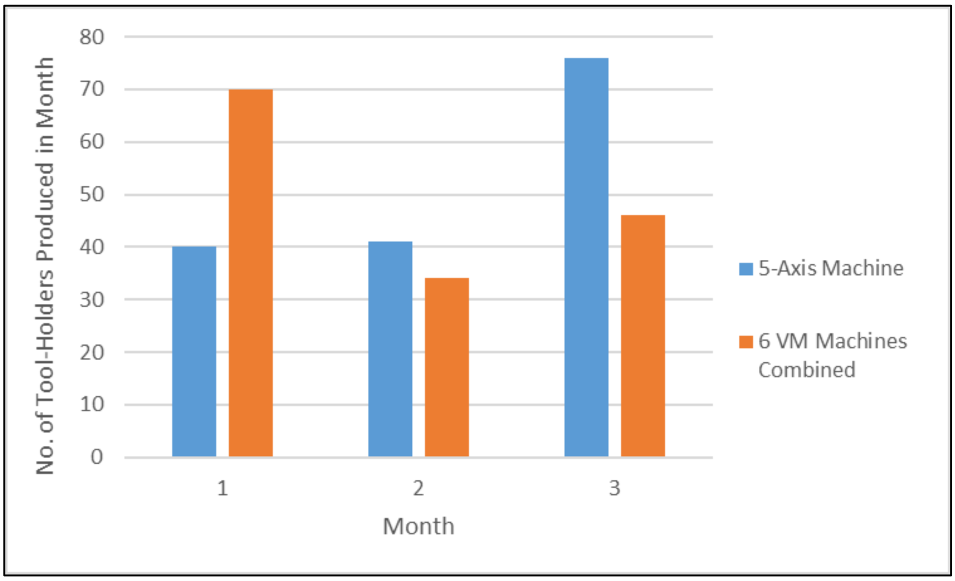


Figure 7.3-1 - Extracts from 5-axis machine monthly graphs analysing quantity produced and run hours, with 'lights-out' machining introduced in month 4 and the monitoring software collecting run hours from month 3 after implementation

The graphs in Figures 7.3-2 compare the sole performance of the 5-axis machine against the 6 VM machines combined over a 3-month period. The 5-axis machine single-handedly produced more tool-holders than the 6 VM machines combined by month 3 of the study despite only producing for half of the combined VM machines time. This indicated a large productivity gain.



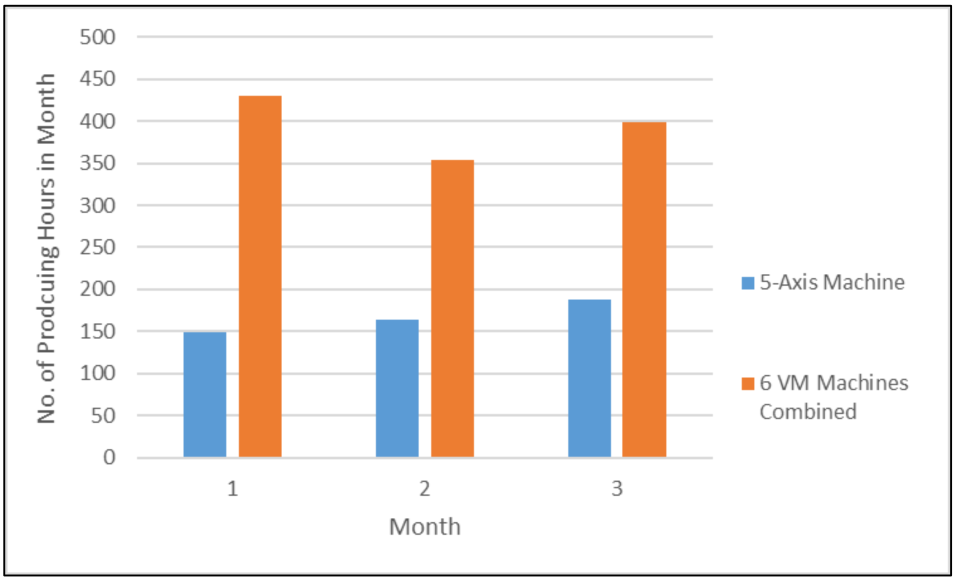


Figure 7.3-2 – Two graphs comparing number of holders produced (top) and number of producing hours (bottom) by month for the 5-axis machine and 6 VM machines combined during a 3-month study

Figure 7.3-3 details 5-axis machine performance during a period of sustained large batch quantities during months 16 to 19 after installation. The monthly tool-holder quantity produced approached 150 (37.5 per week) and 400 hours producing time (100 hours per week) by month 19. Using month 19's performance levels for a full year:

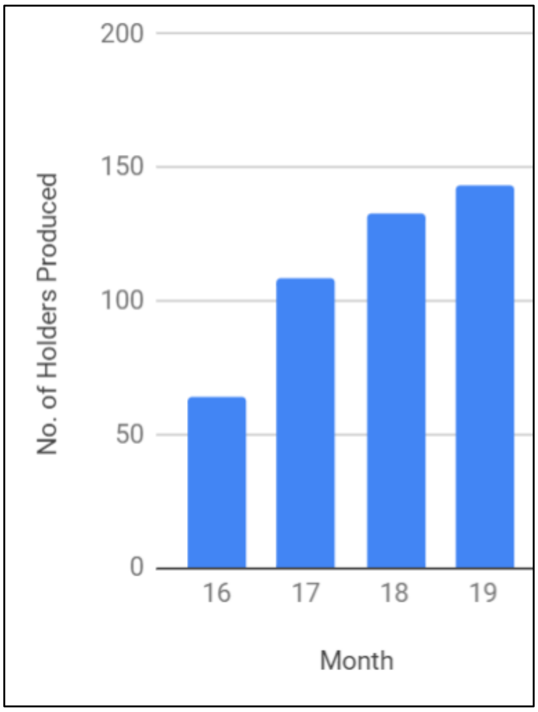
Tool-holder quantity produced = 12 x 150 = 1800 tool-holders

Machine Producing Time = 100 hrs x 52 weeks = 5200 hours

Using figure 7.3-2's data, 6 VM machines combined averaged 400 hours per month:

400 x 12 = 4800 producing hours

The above calculations highlight how the 5-axis machine will produce for more hours than the 6 VM machines combined if sustained over a period of 12 months.



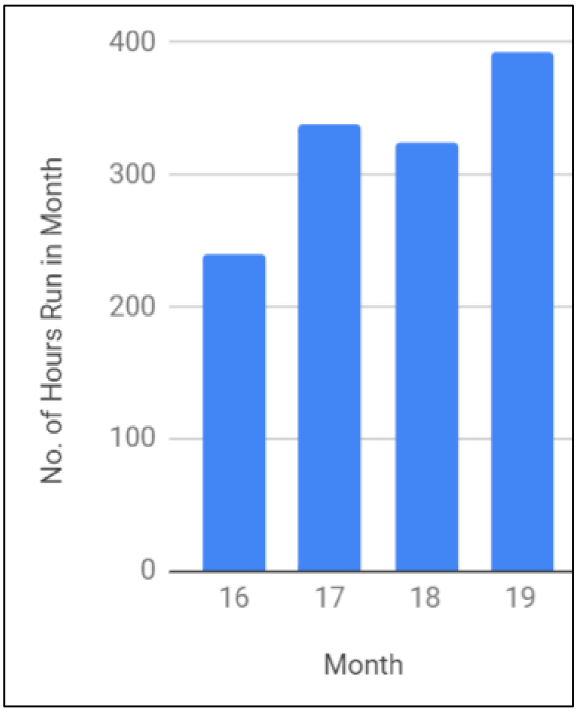


Figure 7.3-3 – Graph extracts indicating the number of tool-holders produced per month and run time hours per month for months 16 to 19 after installation

In the 12 months before implementation the 6 VM machines combined produced 1600 tool-holders. The 1800 quantity estimated above for the 5-axis machine highlights increased SMfE machining capacity and allows for increased sales. Additionally, the capability to manufacture tool-holders more efficiently allows larger batches to be managed more effectively. There is potential for further performance increases on the peak weekly output of 37.5 tool-holders and 100 hours weekly producing time determined from figure 7.3-3, particularly if annual sales quantities surpass 2000+ tool-holders.

The manufacturing costs associated with the 5-axis and VM machine processes were compared. The SMfE defines machine costs by an hourly rate (cost of labour, overheads etc.), with these detailed below for the processes using an algebra value '*x*':

Single VM machine hourly rate = *x*

5-axis machine hourly rate = *1.5x*

Utilising the 1-off hourly process times (setup + machining) from figure 7.1-2, the approximated costs for 1-off tool-holder manufacture for each process are:

VM machine 1-off cost = (5+5) * *x* = *10x*

5-axis machine 1-off cost = (0.5+2.5) * *1.5x* = *4.5x*

It is seen that the cost of 1-off production using the 5-axis process provides a 50%+ cost reduction over the VM machine process.

10-Off Batch Cost Approximations

Process	Process Hourly Rate in terms of '*x*'	10-off Setup Costs (Approximated)	10-off Machining Costs (Approximated)
1 VM Machine	*x*	1st-off = 5hrs Remainder = 1.5hrs each average (using figure 3.5-12 estimates)	1st-off = 5hrs Remainder = 4hrs each (using figure 3.5-12 estimates)
5-Axis Machine	*1.5x*	1st-off = 0.5hrs Remainder = 0.5hrs each (but can be done whilst machining incurring no setup costs, equal 0 hrs)	1st-off = 2.5hrs Remainder = 2.5hrs each

VM Machine 10-off Cost	5-Axis Machine 10-off Costs
Setup: 5 + (9*1.5) = 18.5 hrs Machining: 5 + (9*4) = 41hrs Cost: (18.5 + 41) * *x* = ***59.5x***	Setup: 0.5 + (9*0) = 0.5 hrs Machining: 10*2.5 = 25 hrs Cost: (0.5 + 25) = ***25.5x***

Figure 7.3-4 - Cost approximations comparison for VM machine and 5-axis machine for 10-off batch production

Figure 7.3-4 further highlights the cost reductions achieved from the 5-axis machine thanks to reduced process times and the ability to incur no setup costs for batches. With increased 'lights-out' machining utilised the hourly rate for this machine may also decrease from *1.5x,* allowing for additional cost savings over a longer time period of 12 months. The data above further emphasises the impact the chosen process has made with 50% financial cost reductions achieved on different batch sizes, in addition to the DTD process savings made.

Chapter 7.4 Discussion on Research Methodology & Contribution to SMfE Problem-Solving

A single case study SMfE has been used as the basis for this research. The significant savings made as discussed within chapters 7.1 to 7.3 suggest that the methodology chosen was suitable. Careful consideration of the different systems engineering frameworks and analytical tools presented in chapters 2.1 to 2.2 allowed selection of a logical workflow of tasks. This workflow provided a clear start, middle and end for the research:

- Start – SMfE study and data collection (stakeholder input and time-studies)
- Middle – Data analysis, selection of key bottlenecks, solutions research and selection
- End – Solution implementation and subsequent data analysis

A key component in the success of the systems engineering approach was the constant consideration of any observation or proposed solution against the fundamental key performance indicator, the DTD process time. The reduction in DTD process lead time did not quite achieve the SMfE case study's long term goal of a 10-day process time for new designs (see chapter 8.1). Despite this the initial 30-day process time has been drastically reduced.

Another key component of the success of the methodology presented has been the use of quantitative analysis throughout to justify any significant decisions. Despite the significant use of data, the combination of data analysis with stakeholder input ensured that the implemented changes had the best possible chance of succeeding. This was due to having company-wide involvement in the full 7-step methodology framework used from figure 2.4-3.

The above points suggest that the research provides a successful application of systems engineering to problem-solving within SMfE, however consideration must be given on the contribution of this research to the subject of SMfE problem-solving. In order to do this the case study SMfE utilised must be analysed in terms of the wider industry of general manufacturing.

From in-depth study within chapter 3 it was established that the SMfE contains a sequenced order of processes for tool-holder manufacture. From study of these processes within chapters 3.2 to 3.6 it was determined that the SMfE contains multiple business functions including design, manufacturing, assembly and inspection. With inspection processes checking manufactured parts and allowing for in-process adjustments it is evident that the case study SMfE contains a quality control process. This quality control process has been added to with the use of the CMM in checking tool-holders manufactured using the new 5-axis process.

One benefit of already having the defined business functions discussed is that the case study SMfE has been able to achieve an internationally recognised quality management system accreditation. This accreditation is a fundamental requirement for manufacturing companies regardless of size, meaning that the case study SMfE contains quality management processes which can translate to any other general manufacturing company. Additionally, the observed case studies within the literature review saw the real life companies contain similar key business functions such as manufacturing and quality control.

Based upon the above findings it is believed that this specific research can be applied to other SMfE due to the belief that other SMfE would contain a similar flow of processes or business functions, even though they may manufacture products for a completely different industry. If other SMfE must hold the same internationally recognised quality management system accreditation, then they will have to contain relatable processes to the case study SMfE. This implies that similar process steps to those from the DTD process timeline would exist within these companies.

Having established the relatability of the case study SMfE to other companies, it must now be defined exactly what benefits this research can provide to them. The case study SMfE contained three typical characteristics of a SMfE at the outset of this research, as discussed in chapter 1.1:

- Traditional or manual approach to manufacture
- Small batches of variable products
- Limited resource

Due to these three characteristics, the research immediately contained a challenge of needing to convince key stakeholders of the need for change. It is believed overcoming this challenge was possible through presenting substantial time study data and involving stakeholders in the process of collating and selecting the key bottlenecks. For this reason, it is believed that this research provides a significant contribution to any company unsure of how to begin the productivity improvement journey due to stakeholder uncertainty or resistance.

By providing a full implementation cycle study this research is useful for not only SMfE, but for any manufacturing company. This is due to the belief that the documentation of implementation and subsequent data analysis is not commonplace within the subject, supported by a lack of examples within chapter 2. This is critical given that the physical act of implementation could be argued to be just as difficult if not more so than identifying the problem and proposing solutions. Significant challenges and lessons learned were determined within this research with these discussed further in chapter 8.2. It is hoped that any SMfE aiming to make similar changes can anticipate possible challenges in the process and learn from the experiences gained within the implementation phase in this work.

Chapter 8 Conclusions

Chapter 8.1 Comparison of Outcomes Against Objectives and Aim

The chapter 7 data findings highlight how the research aim provided in chapter 1.4 has been addressed through:

1) DTD process time reduced to 12.5 days from 29 days (over 50% reduction)
2) Utilising a systems engineering methodology and suitable analysis tools for problem identification and solutions implementation
3) Focused research of suitable technologies to reduce production bottlenecks
4) Implementation of automation allowing 'lights-out' manufacture, improved machine utilisation and a significant increase in the available time for tool-holder manufacture

It must be noted that the aim of achieving a 10 day DTD process lead time to allow catalogue status has not been fully achieved within this work. Despite this it is hoped that the SMfE is capable of reducing the lead time to 10 days with further work on improving productivity of the processes introduced. An example of this would be increasing the proficiency of CAM programming. This combined with the potential to increase the quantities of tool-holders sold with an increase in sales provides a positive future for the SMfE.

Analysis of the completed work implies successful mechanical engineering problem-solving and analysis of a relevant SMfE case study. The research objectives have been achieved through:

1) Full process workflow analysis including detailed study of individual processes and business functions, allowing identification of good and bad practices in addition to potential sources of inefficiency
2) Categorising the sources of reduced productivity through utilising stakeholder input to methodically rank these
3) Utilising root-cause analysis to determine research problems allowing for focused solutions research
4) Review and discussion of multiple applicable technologies and systems associated with the design, manufacturing, inspection and workflow management functions such as CAD tools, CAM, automation, monitoring software and semi-automated inspection systems
5) Using a defined set of criteria to aid selection of researched solutions for implementing 'lights-out' manufacturing, common material stock-holding, manufacturing equipment management, CAM and machine monitoring

6) Successfully implementing solutions through effective planning and identification of tasks and key milestones
7) Utilising relevant data throughout the research allowing for analysis of the 'before' and 'after' scenarios for the SMfE

Chapter 8.2 Challenges Experienced & Lessons Learned

The completed research tasks provided various management and technical challenges including:

1) Implementation of multiple engineering process solutions simultaneously
2) Balancing process implementation against existing production
3) Embedding the CAM solution into tool-holder manufacture
4) Collection and condensing of accessible data during the analysis phase
5) Dealing with non-conformities during introduction of standardised systems

Challenge 1) relates to the requirements of key production staff to simultaneously implement 5-axis manufacture, 5-axis work-holding and CAM programming. Considerable time contributions were required for training staff in these various disciplines within a short timeframe. In retrospect this posed a potential risk through increasing the difficulty of capturing all applicable knowledge needed for successful implementation. This oversight arguably contributed to the time required to confidently machine 'lights-out'. This experience should aid the SMfE in adequately managing personnel resources during future process improvement projects.

Challenge 2) relates to the requirement of senior production staff to balance new process implementation and manage existing production. Whilst the new processes did not prevent existing VM machine production, the reduced involvement of senior production staff increased the difficulty in successfully managing this. The SMfE attempted to mitigate this challenge by involving senior staff not involved in day-to-day VM machine production within the implementation of the new processes. The experience highlighted how future implementation processes should utilise additional staff in order to simultaneously maintain existing processes.

Challenge 3) was caused by simultaneously learning a new work-holding strategy for 5-axis machining in addition to the new programming methodology. The software contained comprehensive programming feature options to learn which were not previously available in the established NC programming process. Additionally, the use of a CAD-driven approach required a period of trial and error to understand how to successfully adjust and improve programs during the 1st-off proving out process. The successful integration of CAM within a new manufacturing strategy should allow for smoother implementation of CAM in existing processes elsewhere in the SMfE. This is due to gaining an increased understanding of the software.

Challenge 4) relates to both chapters 3 and 4. Certain practices could only capture stakeholder observations as opposed to time estimate data. Chapter 4 required considerable stakeholder time input which was initially difficult to organise, but proved ultimately successful in determining tangible outputs for bottleneck identification. From a research viewpoint the experiences gained highlight the importance of identifying areas at the outset where quantitative data capture is difficult. This allows an approach to be defined as part of the methodology framework for collecting other forms of usable data.

Challenge 5) considers the difficulties in introducing the material and fixturing systems where governing rules applied to 150+ unique cases. Exceptions to the rules occurred through difficulty in standardising all tool-holder designs, leading to focus being placed on ensuring the majority of cases suited the systems. The material billet groups for example focused on categorising leading tool-holder sellers into different sizes. This experience highlighted how variable product manufacture is likely to produce anomalies whose criticality must be factored in to any standardised system introduction.

Chapter 8.3 Potential Opportunities for Further Work

Potential opportunities for further work exist to build on the implemented systems documented in this research. These opportunities would see roll out of improvements elsewhere in the SMfE. Some of these are briefly discussed below.

During bottleneck 5 solution implementation the possibility of on-machine inspection was identified as a potential long-term solution. The 5-axis machine installed contains a machine tool probe allowing for on-machine inspection with use of a suitable approach. Using the probe would prevent off-machine inspection unloading requirements and could further reduce manufacturing process time through obtaining critical inspection data on-machine.

Difficulty of implementing on-machine inspection on the existing VM machines was discussed. A gauging method was initially researched which provides an alternative approach for part inspection. This could be applied on-machine via a 'master part' allowing for 're-zeroing'. Figure 8.3-1 presents a preliminary setup investigation utilising a tool-holder, a clamped 'master part' and a machine tool from the university with on-machine probing capability. The tool-holder's critical features are inspected by the probe with the equivalent features on the machined 'master part' also inspected. This allows for results comparison within the same environment and could ensure inspection result repeatability between parts, as the master part's inspection data is traced back to frequent inspections on calibrated equipment (i.e. a CMM). The variation in the master part's CMM and machine tool inspection data helps determine the machine tool's accuracy and subsequently the machined part's inspection data accuracy also.

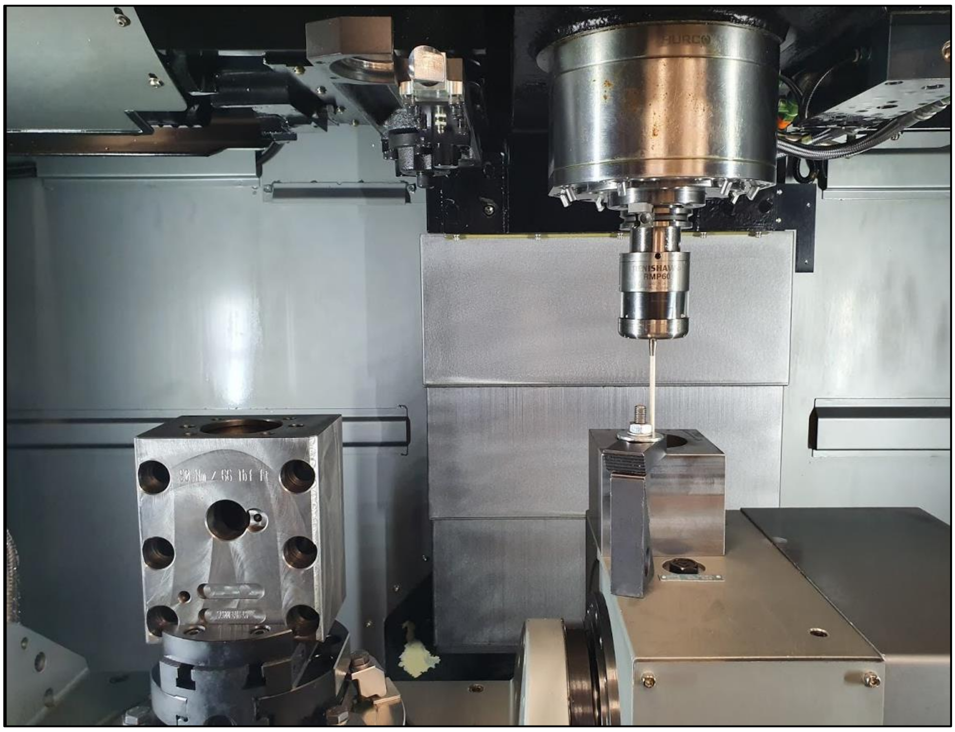
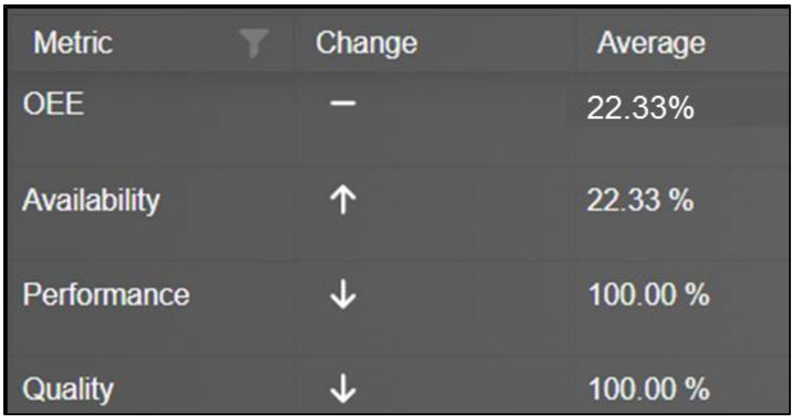


Figure 8.3-1 - Example of on-machine inspection conducted through gauging process from trial conducted at the university

Further use of CAM on other machines within the SMfE is an opportunity to consider. For the tool-holder cell one consideration relates to whether to implement the existing CAM software on the VM machines, or the alternative software from chapter 5 allowing for program transfer between all machines.

Finally the monitoring software for the 5-axis machine proved successful but prevented automated collection of machine OEE data. A trial package measuring OEE was investigated for use on one of the VM machines as seen in figure 8.3-2. This measured availability, performance and quality which could be of benefit to the SMfE.



Metric	Change	Average
OEE	–	22.33%
Availability	↑	22.33 %
Performance	↓	100.00 %
Quality	↓	100.00 %

Figure 8.3-2 - Example of commercially available OEE machine monitoring software trialled on a SMfE VM machine

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Appendix

Appendix 1 – Additional Background Detail on the SMfE

The SMfE products are supplied to various customers within multiple manufacturing industries utilising CNC machine tools. Additionally, the SMfE provides a supply chain management production cell for companies wishing to outsource manufacturing.

The tool-holder products manufactured are suitable for static turning applications on CNC lathes, where a static cutting tool tip is fed into a rotating work piece. The product range offered includes solutions for machining internal features such as bores, machining features through external turning and holders specifically designed for deep-boring applications. Each product provides different benefits to the end user, with these benefits ranging from allowing for quick changeover of tools to minimising vibration during machining to providing coolant directly to the cutting tip (through-coolant).

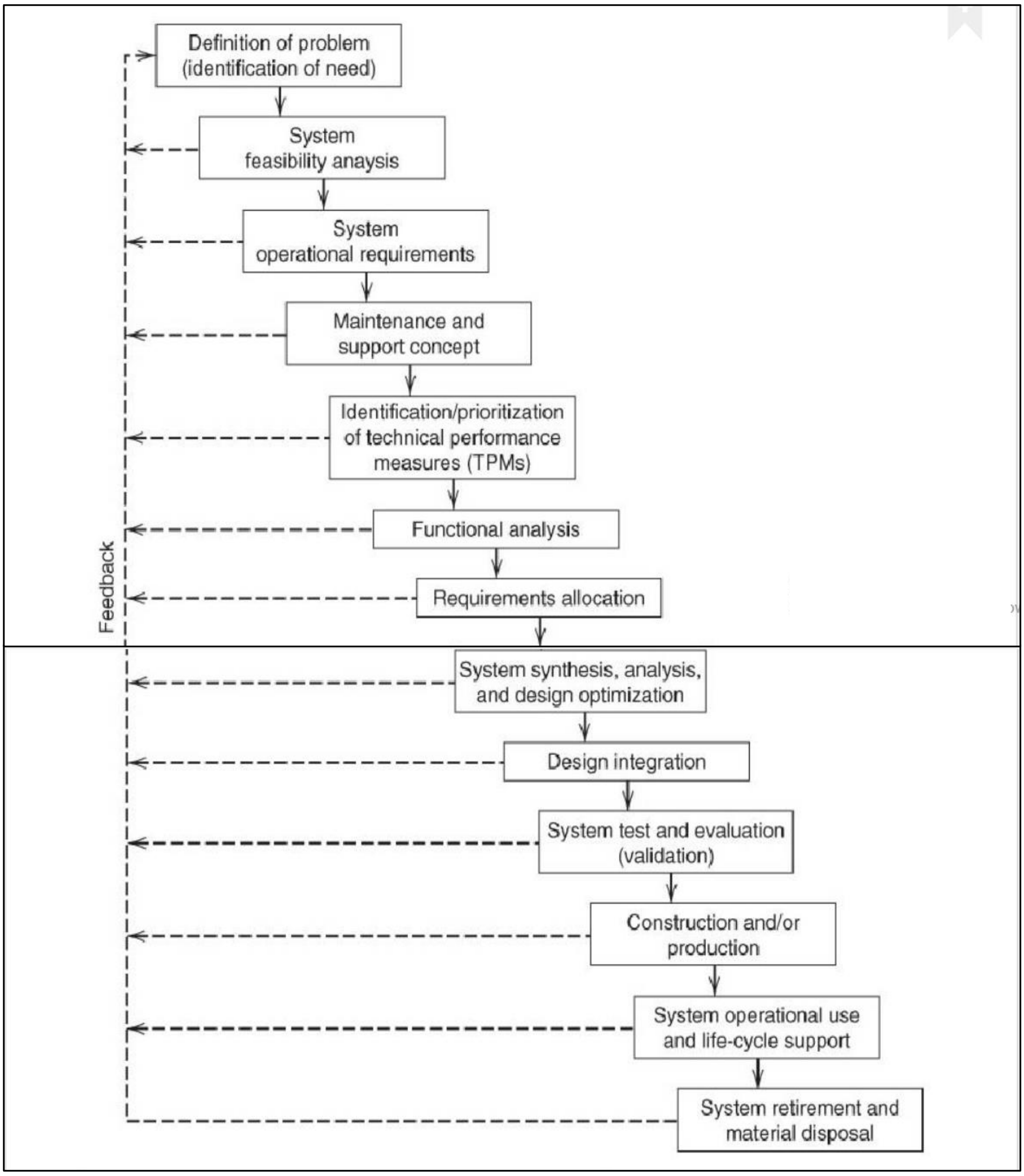
The work-holding products are designed to satisfy various CNC applications:

- Collets and expanding mandrels securely clamp round work pieces on internal surfaces (mandrels) and external surfaces (collets) respectively for turning and grinding processes
- Centres precisely locate and support work pieces at the tailstock end of a lathe during turning operations
- Various tombstone style fixturing solutions allow for clamping of large work pieces or multiple, small work pieces in a single setup, for use on larger machines
- Bespoke fixturing solutions are available upon customer request

The SMfE has a global market presence within the CNC machine tool industry, selling into multiple continents in addition to domestic (UK) sales. As part of its global outreach, a sister distribution company was formed for North American sales with products supplied from the UK site. The SMfE has been able to procure large contracts with leading suppliers particularly within the cutting tool industry.

As discussed, the company employs approximately 40 staff, with an approximated 50/50 split between shop floor staff and office staff. Products are designed, modelled and drawn utilising 2D and 3D CAD software. Various CNC machinery is utilised within the company to manufacture products including equipment for milling, turning, grinding and wire erosion processes, with roughly 20 machines used on the shop floor. Dedicated inspection equipment used includes a Co-ordinate Measurement Machine (CMM), various 1-Dimensional height gauges, granite inspection tables and specially made fixturing in addition to various manual inspection equipment (slip gauges, micrometers, Vernier calipers etc.).

Appendix 2 – Detailed Systems Engineering Life Cycle Analysis (Blanchard et al, 2016)



Appendix 3 – SWOT Analysis Protocol (Sluismans et al, 2010)

	Protocol 4: Building SWOT matrix	Protocol 5: Scoring SWOT matrix
Purpose	The main goal of this session is to get a common group insight into the various elements that typify the internal and external environment in which the company acts. To put it differently, a prioritized list of at most 5 strengths (S), 5 weaknesses (W), 5 opportunities (O) and 5 threats (T) has to be identified and described.	The main goal of this session is that the participants have to relate the strengths and weaknesses to the opportunities and threats. As such, the participants have to indicate the importance of the interrelations between the elements. Patterns are made visible and priorities have to be set to benefit from the strengths or to eliminate the weaknesses.
Procedure	Group discussion of approx. 5 hours	Group discussion of approx. 5 hours
☐ Practical set up	▪ 2 consultants need to be involved in this session: a facilitator & a reporter. ▪ The standard questions have to be used but can be clarified with examples. ▪ The facilitator starts by addressing the questions one by one. ▪ The poster can be used to highlight the differences between the internal and external environment. ▪ The participants are asked to write down their answers using a separate post-it note for each answer. ▪ The second consultant collects the answers and clusters them into different groups by posting them on the wall or anywhere else possible. ▪ The clusters represent a particular S,W,O or T. ▪ The consultants discuss each cluster of answers with the participants and jointly decide on the formulation and meaning of each of the S,W, O &T. ▪ One consultant writes these formulations down and as such summarizes all the identified S, W, O and T. ▪ The next step is to select the 5 most important elements in each SWOT category. ▪ The participants are asked to vote for their top 5 items in each of the four SWOT categories – by means of stickers or other. ▪ The top 5 items with the most votes are written down in the matrix. These items will be further scrutinized in the intervention processes.	▪ Each participant in the session receives a printed version of the confrontation matrix. On an individual basis the explicit relations between each of the elements are marked. ▪ To define whether there exists a specific relation, standard questions have to be used. ▪ The next step is to augment the individual answers and plot them in the common matrix. This is executed by the consultants: one calculates the number of relations; the other plots them in the matrix. ▪ The interrelations between S, W, O and T will be discussed for their viability. After the group has reached consensus on which factors are at stake, they can discuss which challenges to emphasize. ▪ As soon as these choices have been made, the matrix helps in gaining insight in which elements need to be worked on to be able to achieve the selected challenges.
☐ Standard questions to choose from	Standard questions have to be used from a list containing 18 questions (5 about strengths, 5 about weaknesses, 4 about opportunities and 4 about threats). At least one question for each SWOT category has to be selected by the head of the participating team (owner/CEO/etc.) before the session takes place. The consultants choose the other relevant question to stimulate the group to list all crucial environmental factors.	Standard questions have to be used to relate the strengths and weaknesses to the opportunities and threats. The questions are the following four: a. Does strength A help in taking opportunity Y? b. Can strength A be used to defeat threat Z? c. Does weakness B hinder taking opportunity Y? d. Does weakness B worsen threat Z?
☐ Supporting materials	Toolbox, including for example, a tenfold of the 18 questions printed on plastic measuring rods, post-its, markers, stickers, illustrative posters of a company's internal and external environments, etc.	Excel and powerpoint files that allow a uniform presentation of the SWOT-elements, the discussion about their interrelations and the final judgments by the group.

Appendix 4 – Chapter 2.2 Analysis Tool Comparison Table

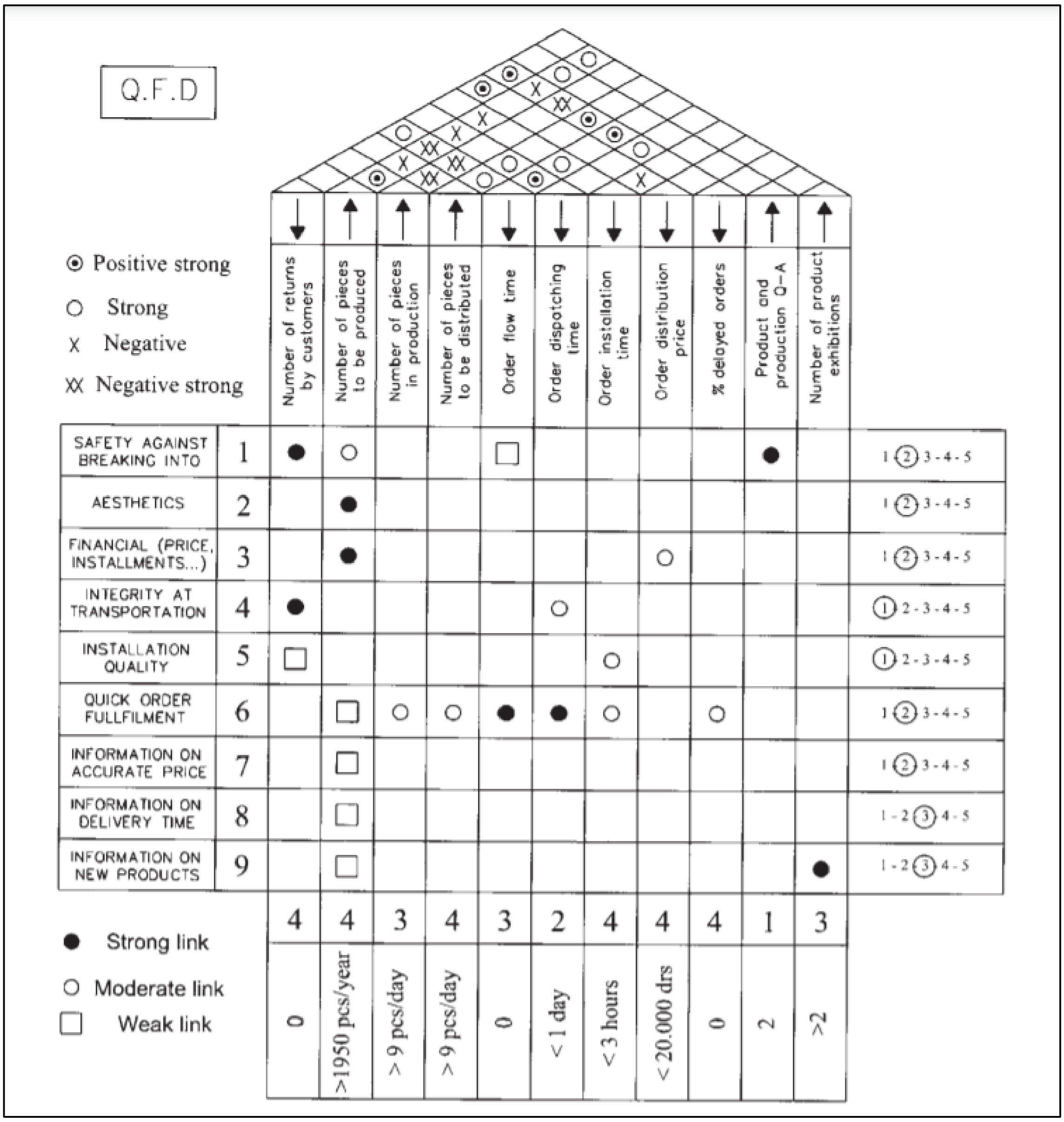
Analysis Tool	Observations
Activity-On-Node (AON) [*Vosniakos et al]*	1) Illustrates a series of processes well by highlighting of process length to overall time frame 2) Provides additional information to a standard timeline by highlighting the required start date for a process 3) **Requirements to Use:** Knowledge of process times gained through existing practices analysis means
Quality Function Deployment (QFD) [See Appendix 5 – *Vosniakos et al*]	1) Establishes relationships between external customer requirements and internal quality requirements 2) Detailed diagram focusing on overall product improvement **3) Requirements to Use:** detailed knowledge on external requirements, internal requirements, targets to achieve **4) Requirements to Use:** Based on 3), extensive time with staff company-wide, through means of a group exercise to create diagram
Clustering (See Appendix 5) – [*Vosniakos et al*]	1) Matrix used to represent AON findings as distinct groups of processes 2) A matrix algorithm is used to determine row and column values in the matrix, not covered by Vosniakos et al **3) Requirements to Use:** Knowledge of processes within a process flow as well as the matrix mathematical algorithm to utilise correctly
Cost Analysis (See Appendix 5) [*Vosniakos et al*]	1) Pie chart breaking down processes into individual cost contributors for manufacturing a component 2) Findings in pie chart were based upon on an Ishikawa diagram not illustrated within the work **3) Requirements to Use**: Defined method for capturing process costs requiring access to financial and process details related to material costs, process timings etc.
Failure Mode & Effects Analysis (FMEA)	1) Method of recording and ranking problems by scoring frequency, severity and detectability of a problem 2) Indicates largest problems via simple scoring method

[*Vosniakos et al]*	**3) Requirements to Use:** A list of problems or bottlenecks to score through involvement of multiple stakeholders
Input/Output Analysis (IOA) [*Mason-Jones et al*]	1) Diagram of information transfer through all processes in a single function or full process within a SMfE 2) Functions/processes listed as blocks with information transferred described above flow arrows 3) Allows information transferred forwards and backwards to be displayed 4) **Requirements to Use**: knowledge of all information transferred through all processes within a focused process whether this be a sole function or company-wide
Process Flow Analysis (PFA) (See appendix 5) [*Mason-Jones et al*]	1) Diagram demonstrating material flow through company as a sequence of operations 2) **Requirements to Use**: knowledge of a full sequence of operations for a sole product process or company-wide
Zoom and Focus Analysis (ZFA) [*Mason-Jones et al*]	1) Root-cause analysis diagram, starting with a symptom and investigating causes until a root-cause(s) for the symptom is/are established 2) Diagram provides alternative causes for each symptom with level of detail dependent on root-cause depth 3) **Requirements to Use**: an in-depth knowledge of a process obtained through observations and possible stakeholder input
Hot-Spot Analysis [*Tagliaferri et al*]	1) Pie chart detailing contribution of different factors to chosen parameter 2) Very similar to cost analysis chart described previously 3) **Requirements to Use:** An application of it needs to be found, the parameter used in the observed paper was not relevant to this research
Integrated Definition for Function Modelling (IDEF0)	1) Diagram defining the inputs, outputs, controls and requirements to meet a central requirement for a system or function 2) Allows tasks to be generated based upon the 4 variables detailed in the diagram

[*Holgado*]	3) **Requirements to Use:** In-depth knowledge of the system/function of interest to generate inputs/outputs/controls/requirements and the central objective, achievable by stakeholder analysis and/or observations
Unified Modelling Language (UML) [*Holgado*]	1) Diagram breaking down a process into constituent parts i.e personnel, equipment, material etc. 2) Attributes are assigned to constituent parts, which are required for these to operate successfully **3) Requirements to Use:** knowledge of system requirements and constituent parts to build the diagram
SWOT & Analytical Hierarchy Process (AHP) [*Khatri et al*]	1) Steering committee and groups of company-wide stakeholders determined S/W/O/T & AHP 2) SWOT limited to 10 observations per category & reduced to 5 following further review 3) SWOT observations related to alternatives in AHP model & ranked mathematically using Eigenvalues **4) Requirements to Use:** Involvement of stakeholders' company-wide to determine S/W/O/T and AHP diagram structure, understanding of Eigenvalues method for ranking SWOT observations
SWOT, Ishikawa, Taxonomy & Fuzzy Sequential Model [*Toklu et al*]	1) SWOT conducted through meetings with department managers to develop open to improvement areas (OIA) 2) Ishikawa root-cause analysis conducted with staff company-wide on OIAs, root cause of OIAs linked to action plans defined in taxonomy matrix 3) OIAs categorised into strategic, tactical and operational, compared against each other using pairwise mathematical modelling to rank OIAs **4) Requirements to Use:** Involvement of stakeholders' company-wide to determine S/W/O/T and perform root-cause analysis if taxonomy is used. Mathematical understanding of pairwise method required

SWOT [*Sluismans et al*]	1) Protocol method – 2 main sessions with stakeholders' company-wide to 1) build a SWOT matrix and 2) score SWOT matrix 2) S/W/O/T limited to 5 observations per category 3) S/W scored on impact they would have on O/T to determine the biggest changes in developing a strategy 4) **Requirements to Use:** Involvement of company-wide stakeholders to determine S/W/O/T in 2 sessions and score the confrontation matrix
SWOT [*Buchmayr et al*]	1) SWOT conducted on a subject and not a case study 2) S/W/O/T not limited to number of observations for each category & no method of ranking 3) S/W/O/T observations categorised by Matching, Conversion & Neutralisation groupings 4) **Requirements to Use:** Once S/W/O/T identified, categorise them by what type of observation they are
Pareto Analysis [Benjamin et al]	1) Graphical method comparing defect modes by quantity of a chosen variable, with weight in kg of scrapped material used in the literature example 2) Leading defect modes identified based upon the chosen variable using actual data, as opposed to judgements used by stakeholder analysis 3) Chosen defect modes can be then analysed by other means **4) Requirements to Use:** Defect modes identified through observation and a variable chosen for comparison through graphical representation
5 Whys Analysis [Benjamin et al]	1) Uses tree diagram like ZFA to identify root causes from leading symptom or 'defect' in reviewed literature 2) Why analysis and causes continue being identified until underlying root causes are found, typically identified by the 5th why analysis process step **3) Requirements to Use:** Identified leading issues/ 'defects' for a process using tools such as Pareto analysis

Appendix 5 – Examples of Tools Compared in Appendix 4 Not Previously Illustrated in Chapter 2.2

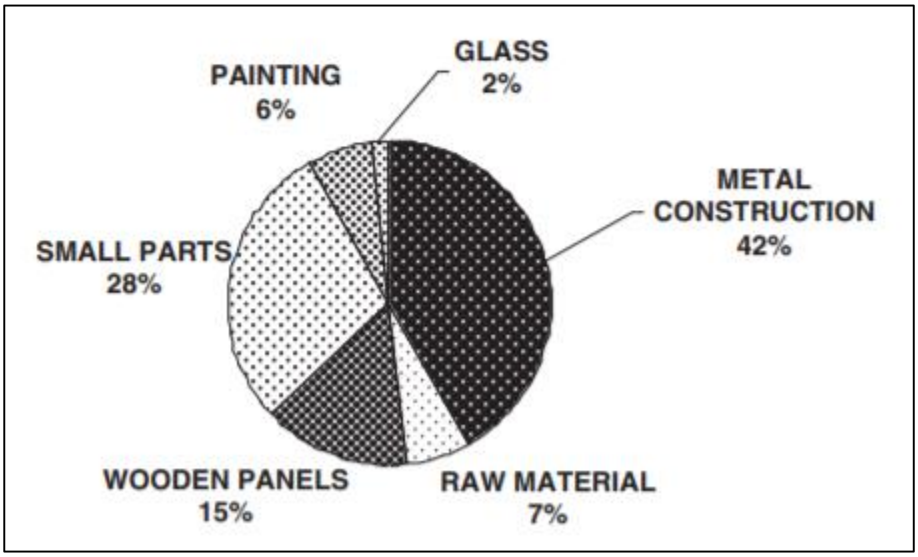


QFD analysis matrix tool utilised by Vosniakos et al (2006)

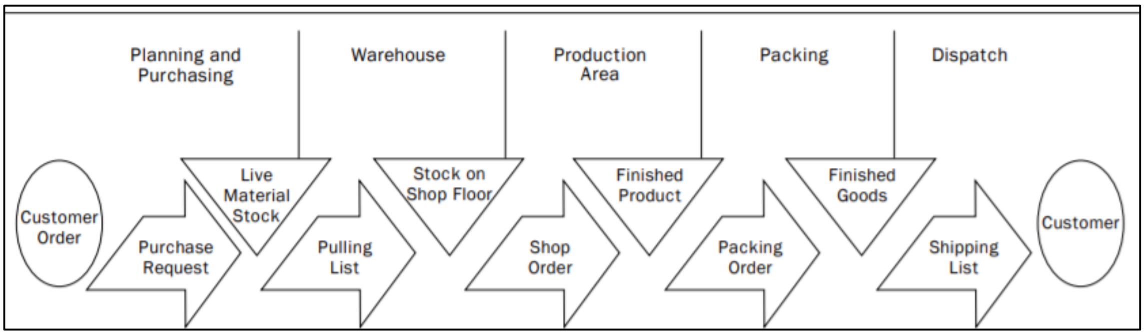
Table 1. Cluster analysis at A12 IDEF level.

	1	2	3	4	5	13	14	6	7	8	9	10	12	11
2	1	1	0	0	0	0	0	0	0	0	0	0	0	0
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	1	1	0	0	0	0	0	0	0	0	0	0	0
4	0	0	1	1	0	0	0	0	0	0	0	0	0	0
5	0	0	0	1	1	0	0	0	0	0	0	0	0	0
14	0	0	0	0	1	1	1	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	1	1	0	0	0	0	0
8	0	0	0	0	0	0	0	1	0	1	0	0	0	0
6	0	0	0	0	0	0	0	1	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	1	0	1	0	0	0
13	0	0	0	0	0	1	0	0	0	1	0	1	1	0
10	0	0	0	0	0	0	0	0	0	0	1	1	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	1	1
11	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Clustering tool utilised by Vosniakos et al (2006)



Cost analysis breakdown tool utilised by Vosniakos et al (2006)



PFA tool utilised by Mason-Jones et al (1998)

Appendix 6 – Additional Detail on Existing Practices

Design

Design projects are stored in paper copy form with spreadsheets utilised to manage design drawing numbers, with these containing a description of the item for future identification. Whenever existing designs are ordered, the designers can access these files to identify the relevant drawings to be printed and passed onto the production planning function. Tool-holder product description and drawing number spreadsheet data is utilised in managing the website catalogue of existing designs, which users can access and refer to when making enquiries.

As discussed design and sales coordination personnel share approval drawings with customers to receive signed approval for manufacture. Generally tool-holder drawing approval is received first time, or received after minor change requests provided by the customer are made to the design which is sent for re-approval.

Assembly drawings created are given an 00 drawing number suffix with tool-holder body manufacturing drawings having an 01 suffix and any additional manufactured sub-assembly components given drawing suffixes starting with 02, 03, 04 etc. as required. The prefix drawing number to these different suffixes is determined from the spreadsheet data described above and is used on all assembly and manufacturing drawings for a design.

Workflow Management

Sub-assembly components can include location parts produced internally such as round bungs, rectangular tenon pieces or bolt-on location shanks fitted to the base of the tool-holder body. These sub-assembly components are designed in accordance with standards and interface tolerances.

A large range of fasteners and seals (bolts, O-rings, sealing plugs etc.) are stocked for use during fitting and to allow high pressure through-coolant tool-holder capability. This provides coolant directly to the cutting tool tip to assist with improving cutting conditions. Any sub-assembly components requiring manufacture are raised as separate planning to the tool-holder body and assembly planning discussed within chapter 3.4.1. Any specialist components to be bought-out for the order are identified during the planning stage for purchasing.

Manufacturing

When defining material size the general practice is to minimise the material removal required, to reduce machining time and consumables wear. Figure 3.5-2's illustration implies that where possible 10mm material is added to the finish sizes, giving 5mm per side of the billet to machine. Generally 10mm is always added to the length of the billet. Sometimes more material may require removing on the width or height dimensions of the billet to achieve the finish size, particularly in cases where the stocked square bar sizes are utilised and not specially ordered sizes.

In order to machine setups 3 to 5 on the indexer two types of fixture are required as the front face bore and top face bore details are at 90 degrees to each other. The second fixture with the same interface as the fixture in figure 3.5-9 will have this mounting interface parallel to the axis of rotation, at 90 degrees to the detail on the figure 3.5-9 fixture. This suggests that for each interface two fixtures are required, however as multiple tool-holders use the same interface with different offset requirements there may be additional fixtures needed for a single interface.

Inspection

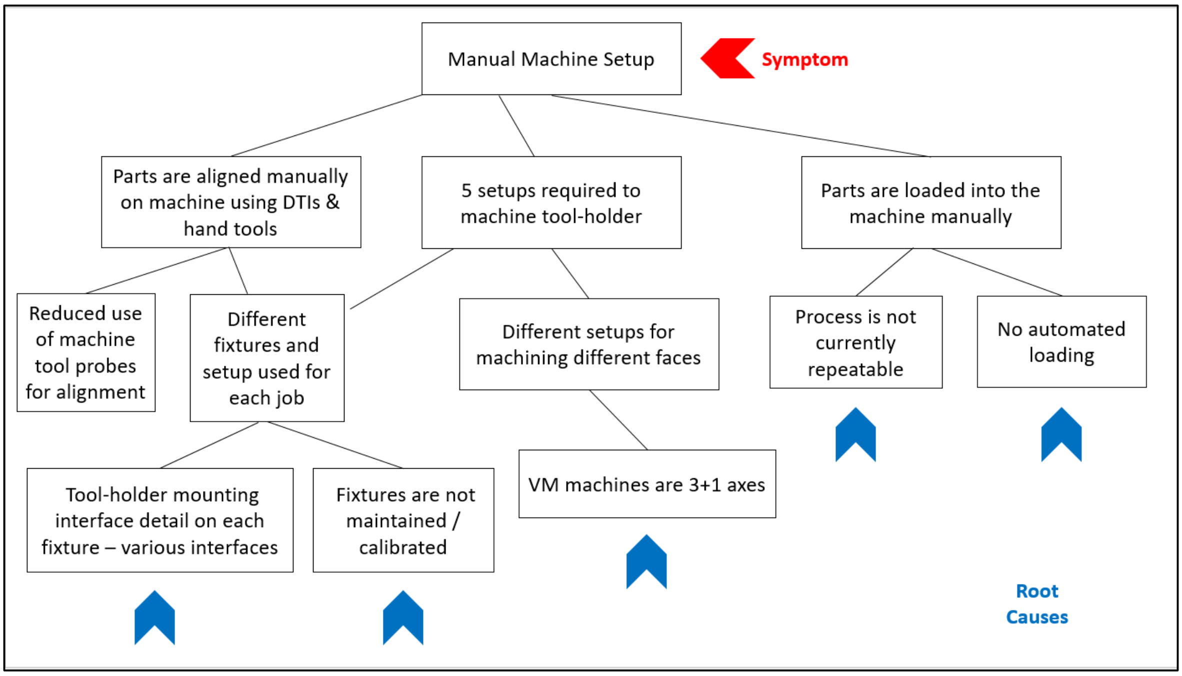
The reference features used for measuring bore position with the height gauges off-machine as discussed in chapter 3.6.3 are touched onto and zeroed. Once zeroed the bore feature is touched onto by the gauge's ball probe and its centre position is measured by sweeping the bore surface above and below the centre position. The height gauge determines the centre position value based upon averaging the dimensions measured during sweeping above and below the centre point. Due to zeroing from the reference features, the centre position value provided highlights the bore position in relation to the primary datum feature. This process is completed on the tool-holder in both vertical and horizontal axes by adjusting the fixture setup as required to measure in the vertical plane.

For the setting process the results measured indicate where the tool centre line is and the runout achieved over its length by measuring the B and D dimension pairs from figure 3.6-3. Tolerances are specified for the position and runout based upon the standardised size of the front face bore, with bigger tolerances provided for bigger bore diameters. These tolerances are determined by the SMfE as part of their product specification using the sub-assembly clamping mechanism assembled to the holder.

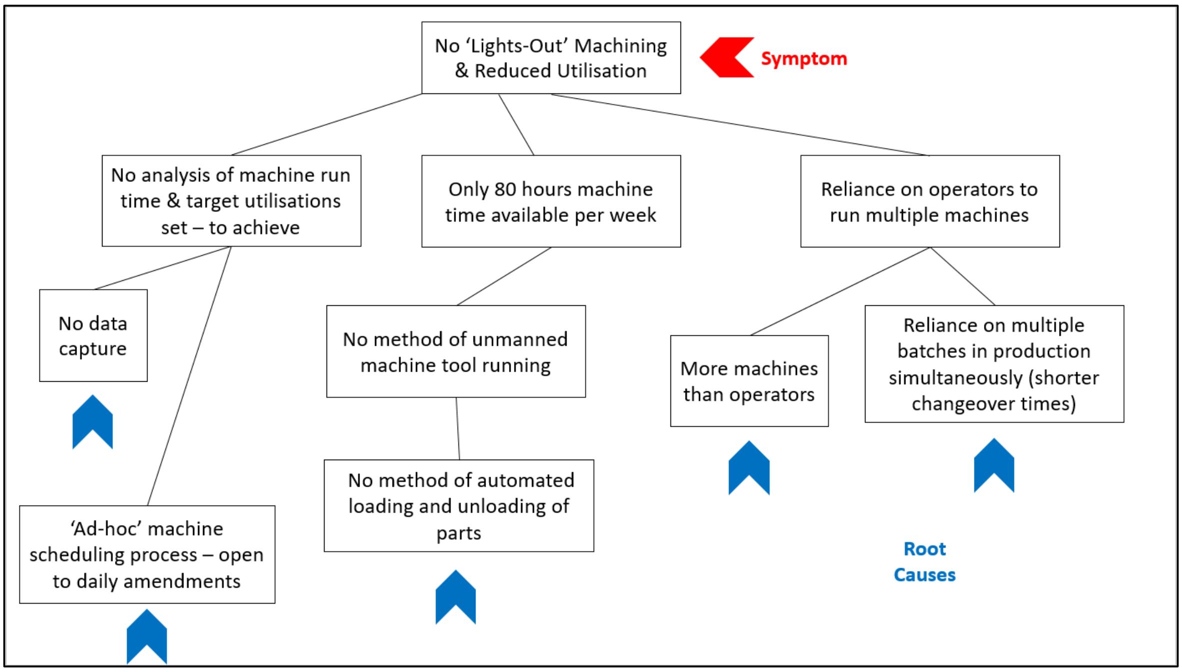
Leakage Testing & Packaging

Leakage testing simulates high pressure coolant travelling through the holder body. The test checks all seals on the assembled part underwater by inserting compressed air through coolant inlets. Any leaks are identified through visible air bubbles on any seals. These are then addressed prior to passing the final assembly and allowing for product packaging. Finished holders are packaged in cardboard boxes and wooden crates for shipment depending upon their specific sizes.

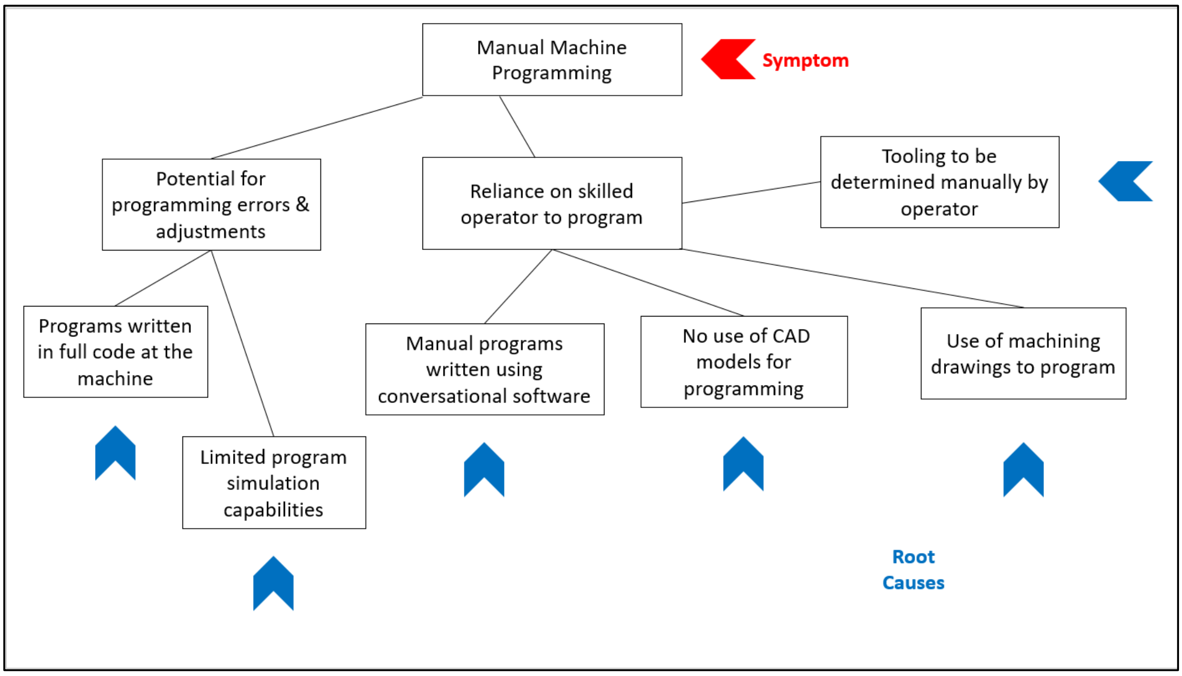
Appendix 7 – ZFA Diagrams for Bottlenecks 2 to 6



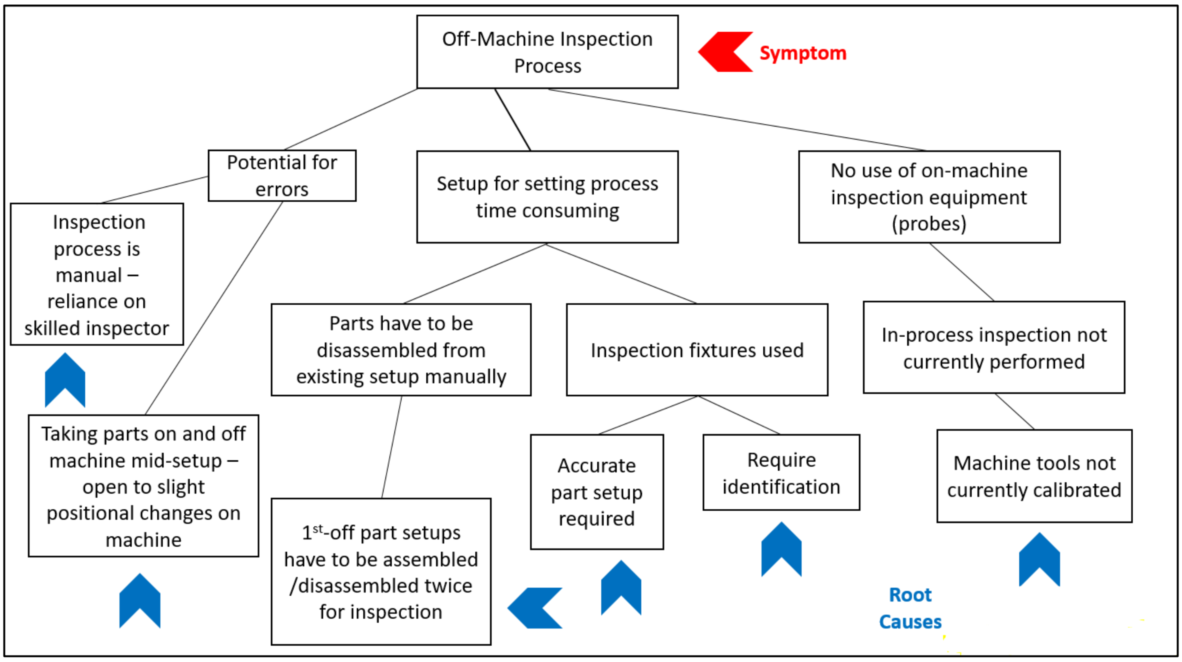
ZFA diagram for bottleneck 2



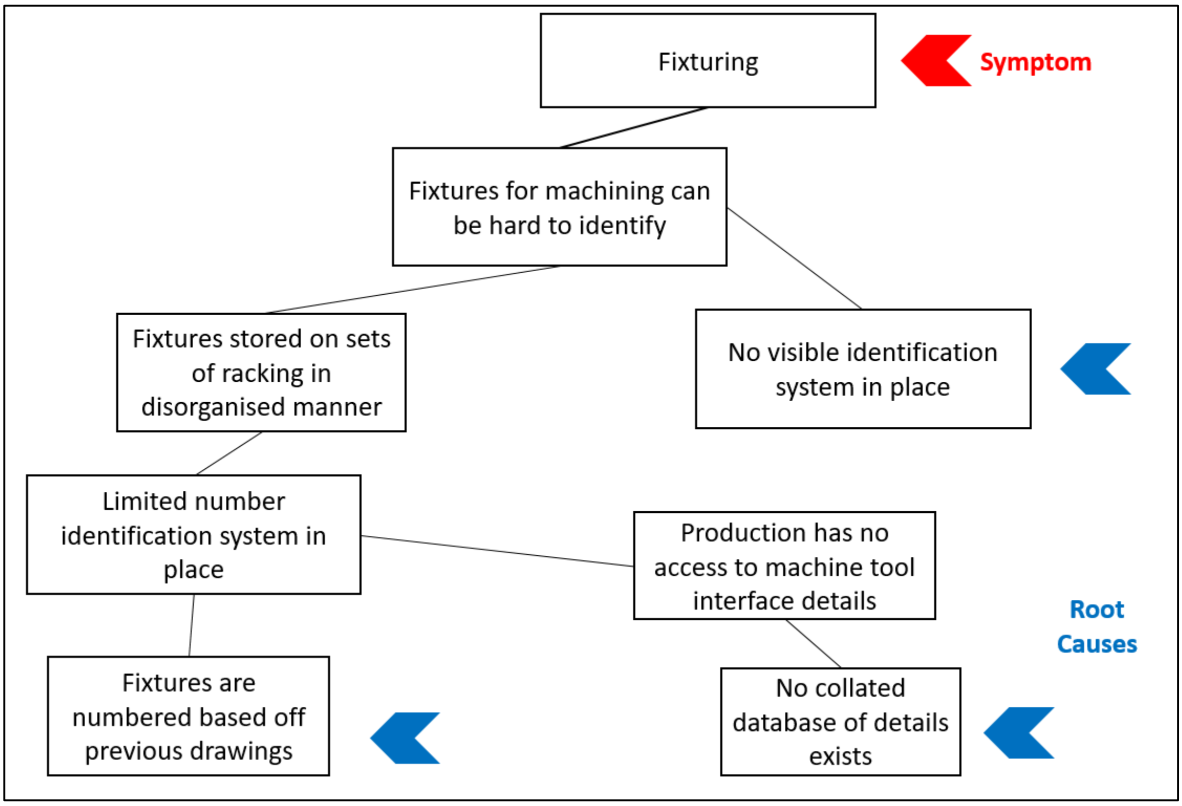
ZFA diagram for bottleneck 3



ZFA diagram for bottleneck 4



ZFA diagram for bottleneck 5



ZFA diagram for bottleneck 6

Appendix 8 – Additional Solutions Research Detail

Bottleneck 1 – Long Material Delivery Time

Parametric design would provide a method of designing tool-holders via a defined mathematical method, as opposed to the existing process of creating designs to solely suit 1) the standardised bore size, 2) turret interface detail and 3) the L x W x H dimension limits governed by the machine tool the holder is used on. The parametric approach would utilise relationships to optimise the finish dimensions in addition to ensuring the tool-holders incorporated the three key requirements discussed above.

If a parametric approach was to be utilised to fit new tool-holder dimensions to a defined material system, the potential of creating parts which do not meet the required product specifications must be avoided. Additionally, creation of designs which contain an inefficient level of material to machine just to fit the defined material groups must be avoided.

Bottleneck 2 – Manual Machine Setup

Potential challenges an add-on 5-axis trunnion system could create on the existing VM machines include:

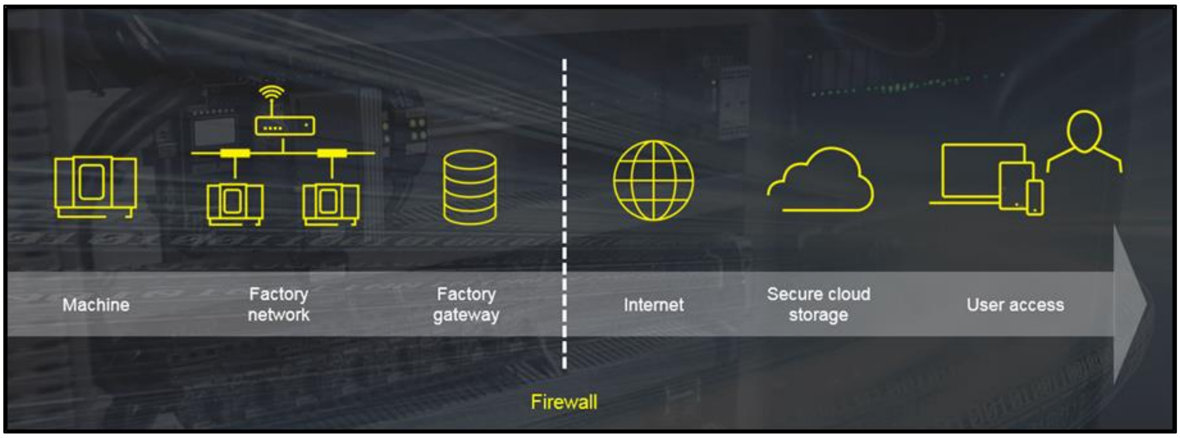
1) Integrating it with the current hardware/software on the machines
2) The working envelope requirements for the trunnion add-on in relation to machine tool working envelope
3) The 5-axis work-holding method used on the rotary table and integration of this with the machine tools
4) Ensuring repeatability is achieved during indexing / table rotation
5) The complexities associated with programming on the existing machines using this new approach

The below summarises the 5-axis work-holding equipment alternatives investigated in chapter 5.2.2:

- Self-centring vices allow for reduced changeover time of material blocks due to the mechanism in place, which as its name suggests centres billets without operator manual alignment requirements
- The dovetail style vice appears to grip onto components through gripping onto matching bands which must be machined into the material billets prior to part clamping using this method
- The zero-point fixture plate introduces the use of pull studs, which fit into the four holes of the plate and lock in place through a mechanical operation utilising an Allen key to operate a set of pistons (Lang Technik, 2020)

- The pull studs are inserted into four matching holes machined into a billet prior to being able to use the zero-point fixture plate for machining, as the four pull studs provide the link between the billet and fixture plate

Bottleneck 3 – Machine Monitoring Software



The diagram above is from marketing material for the OEE software trialled within chapter 8.3 and illustrated in figure 8.3-2 (Sandvik Coromant, 2018). It illustrates the connectivity requirements to achieve live data from machines for analysis as briefly introduced in chapters 5.2.3 and 6.3.3. The machine with a suitable adaptor to convert data is connected through the factory network to the internet. The factory gateway is the data aggregator software, collating machine data and providing this to the data monitoring software stored on the cloud and accessible for users through the internet (Sandvik Coromant, 2018).

Bottleneck 4 – Manual Machine Programming

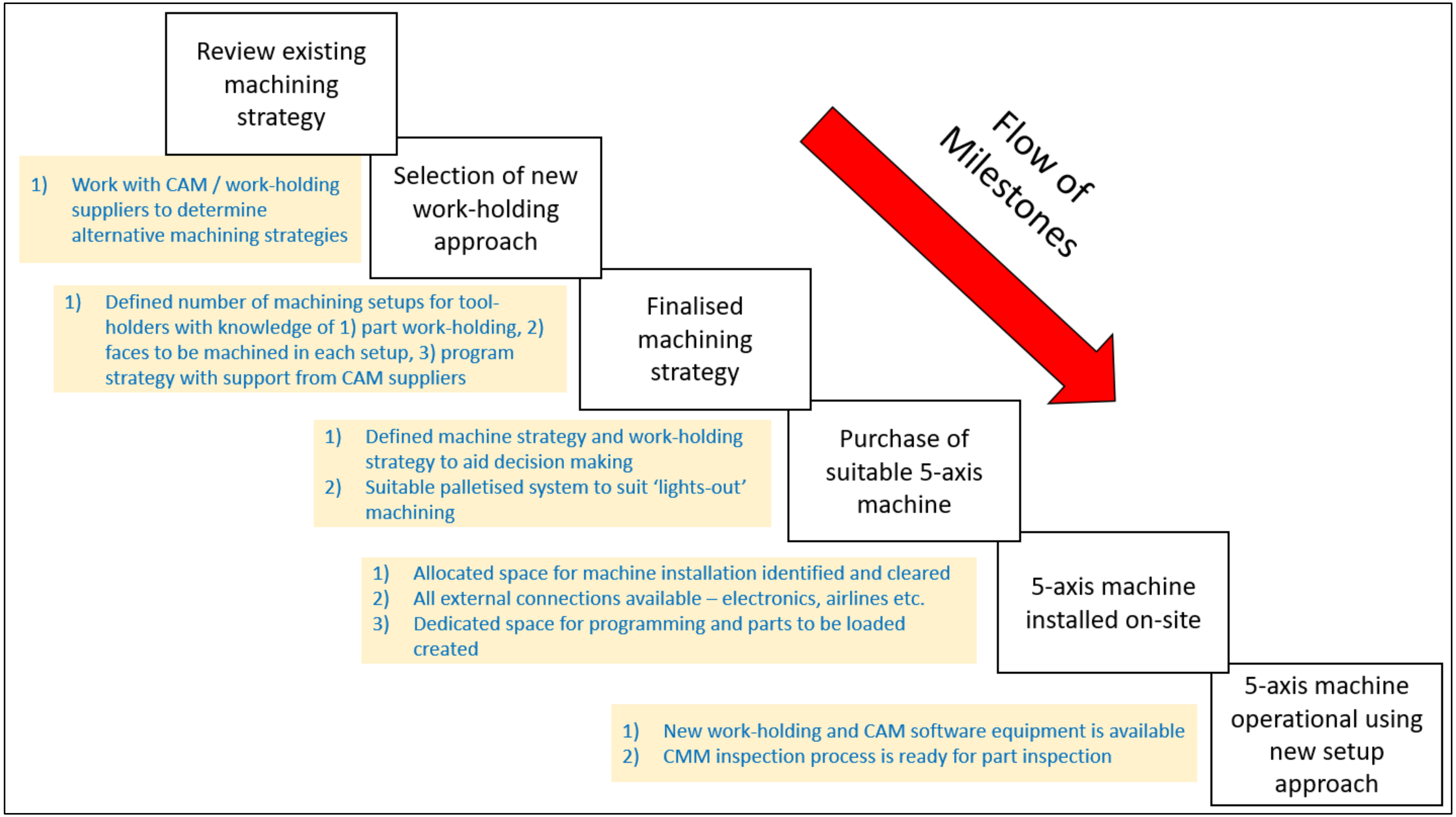
Some of the key considerations required for CAM software implementation with the existing tool-holder production process could be:

1) Integration with current CAD software (file transfer format)
2) Tooling – (Can current tooling be optimised with CAM strategies? Is new tooling required?)
3) Integration with hardware – (post-processor requirements, would CAM be used with current 3+1 process, or a new process?)
4) Integration with personnel – (training required, utilising collision control and simulation features)
5) Program & model control – (program naming conventions and storage, detailing revision changes)

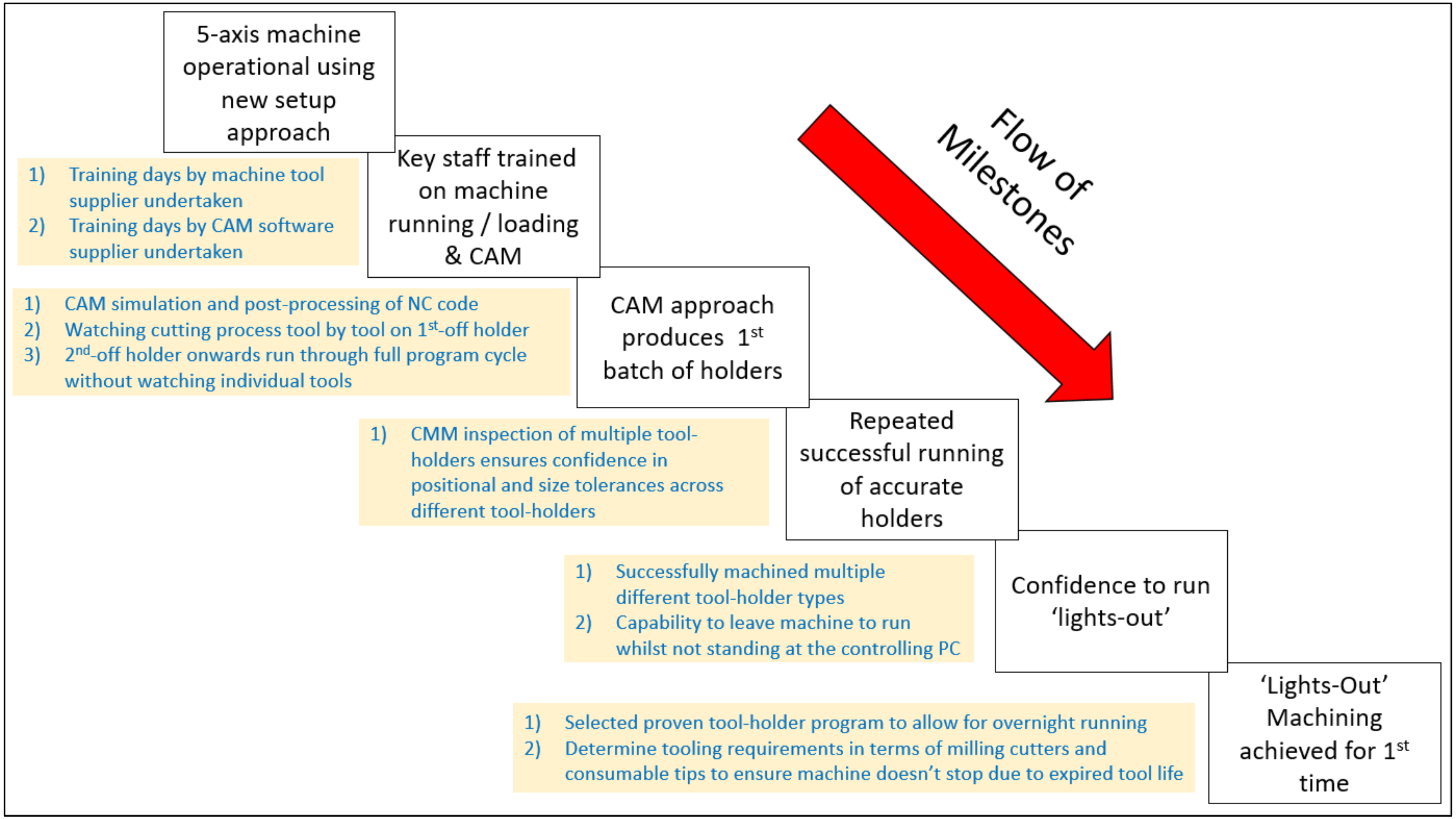
Bottleneck 5 – Off-Machine Inspection

For probing for on-machine inspection, some sources of process variation controls are more easily introduced than others. In the SMfE temperature within the cell is not controlled currently, but part setup is controlled more easily through the current setup process, even if this is currently an inefficient process.

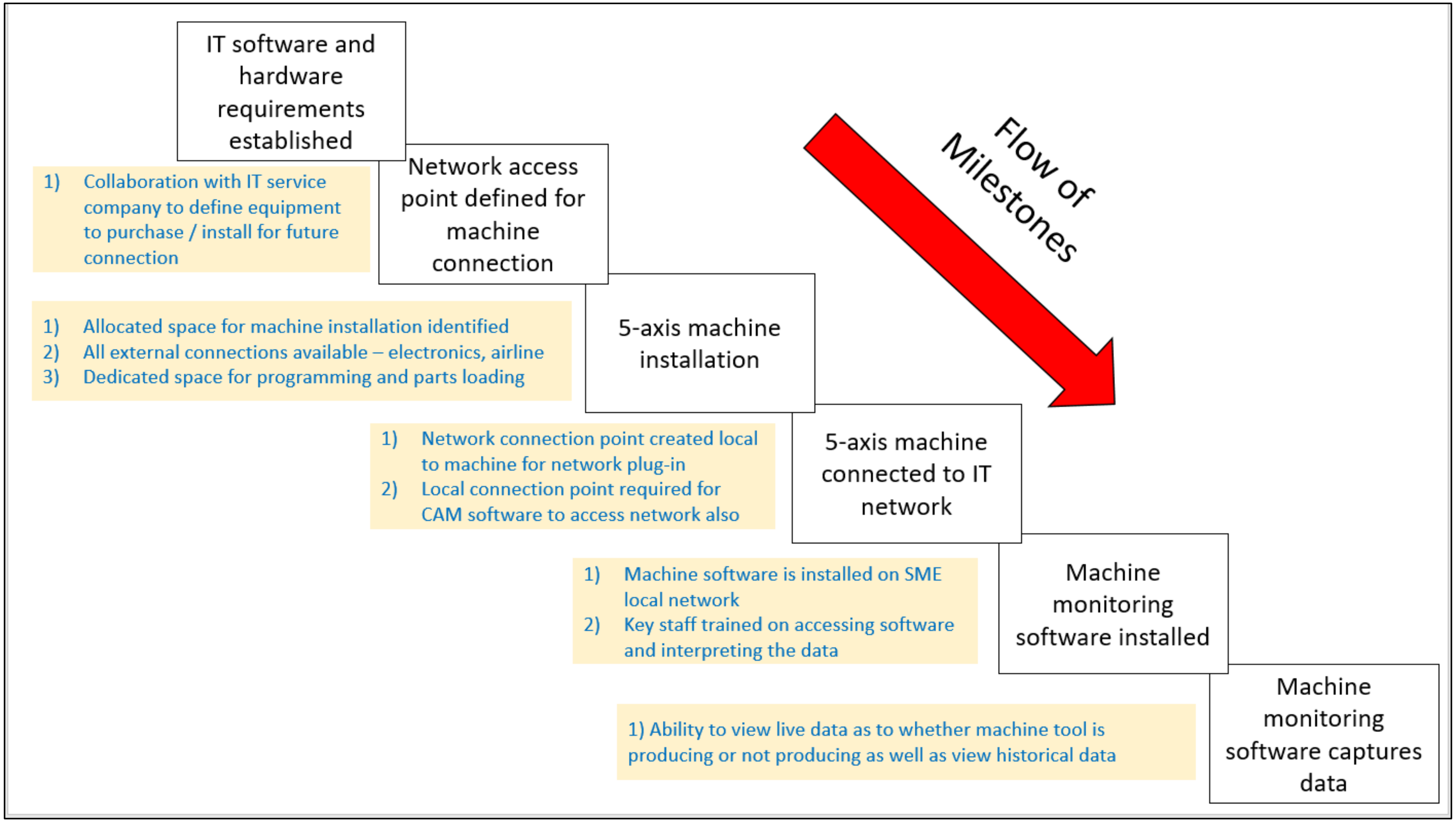
Appendix 9 – Implementation Flowcharts for Bottlenecks 2 to 6 Solutions



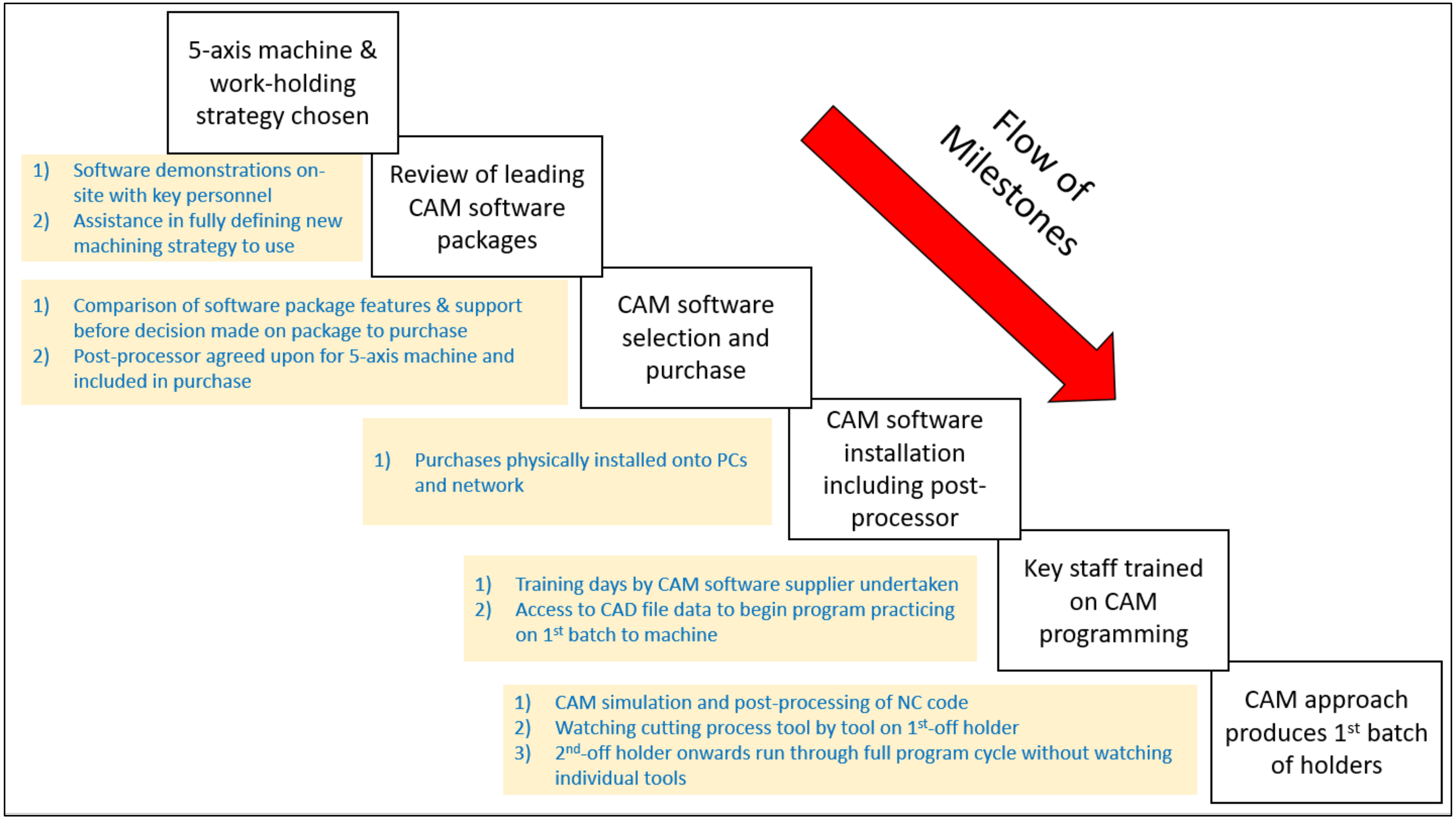
Flowchart for Bottleneck 2 5-Axis Machine and Work-Holding Solution Implementations



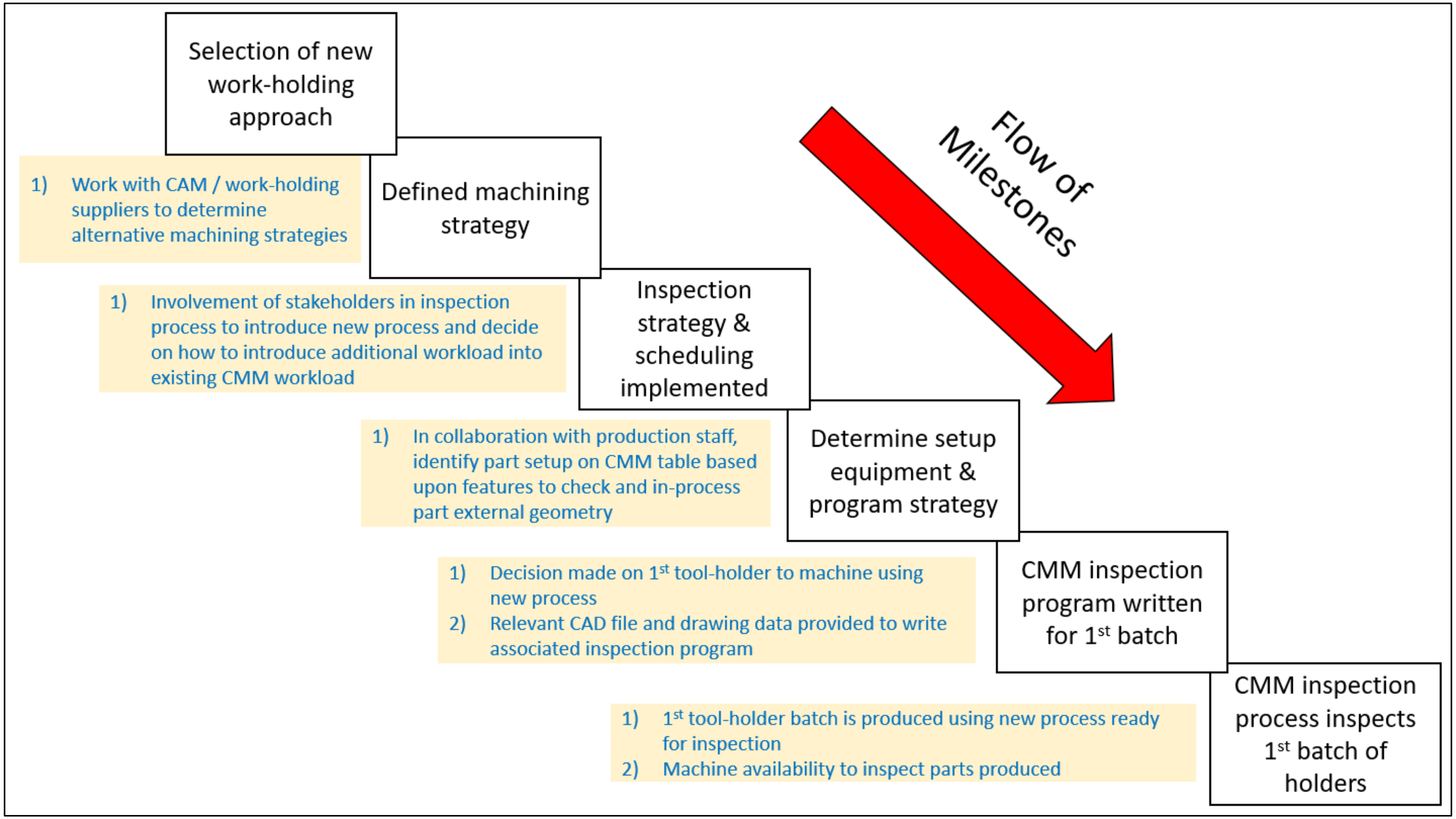
Flowchart for Bottleneck 3 'Lights-Out' Solution Implementation



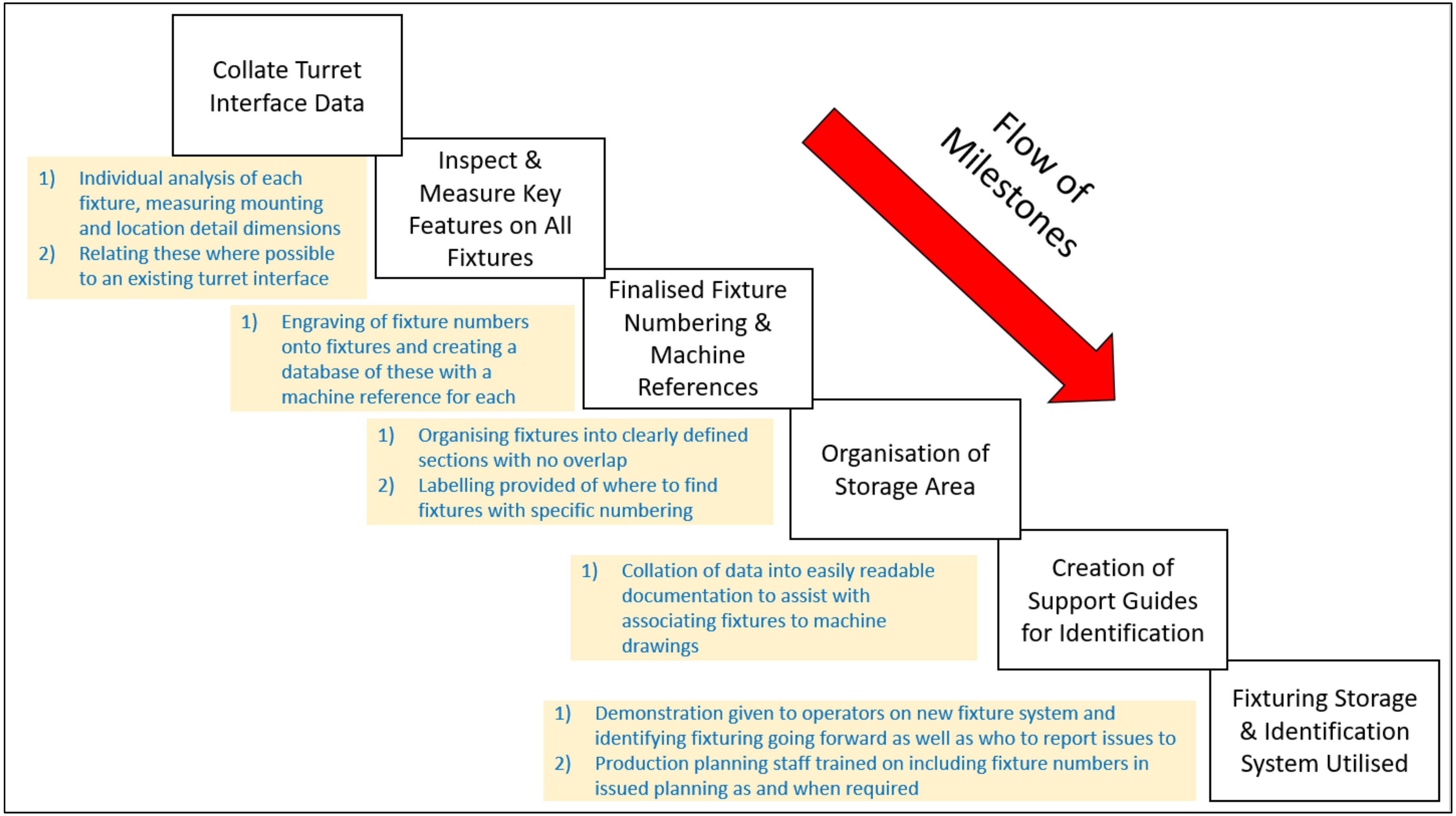
Flowchart for Bottleneck 3 Machine Monitoring Software Solution Implementation



Flowchart for Bottleneck 4 CAM Software Solution Implementation



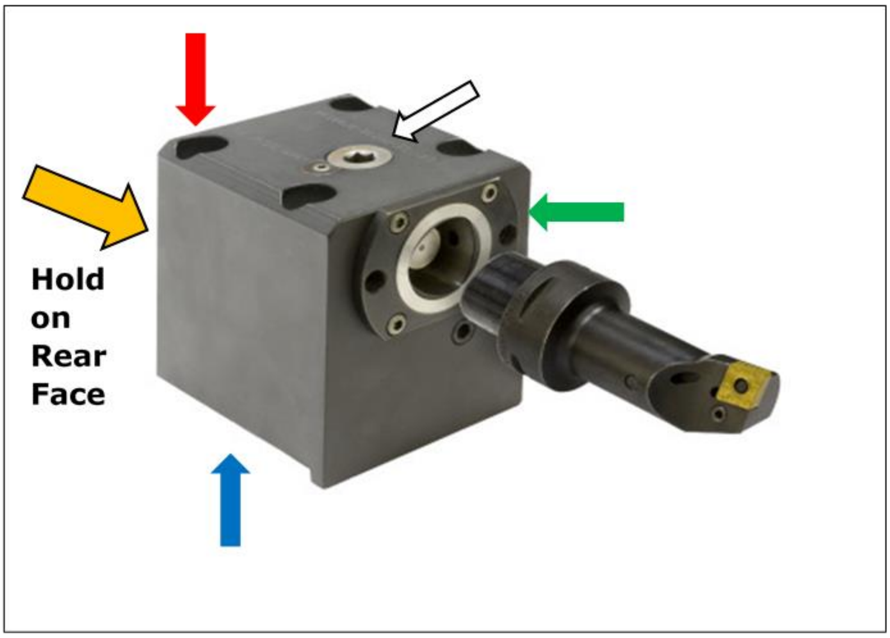
Flowchart for Bottleneck 5 CMM Inspection Solution Implementation



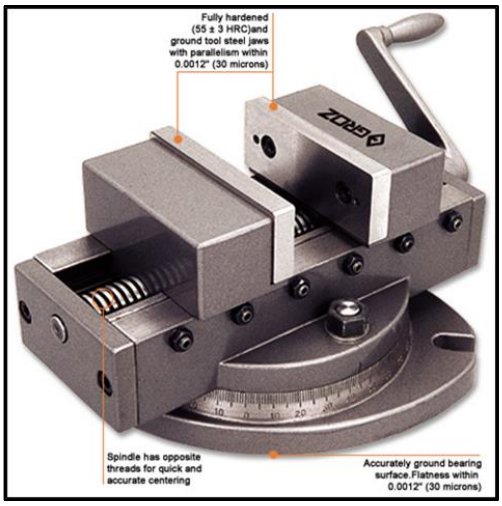
Flowchart for Bottleneck 6 Fixturing System Improvement Solution Implementation

Appendix 10 – Further Reading on Solutions Implementation

Work-Holding Approach & Machining Strategy Definition



The image above indicates that by holding on the rear face (orange arrow): 1) the base detail (blue arrow), 2) the clamping unit bore (green arrow) and 3) clamping mechanism top face hole detail (white arrow) and 4) counterbores (red arrow) can all be machined in a single setup. Typically, the rear face of tool-holders is a flat surface with minimal features to machine, in most cases drilling and tapping hole detail to allow for through-coolant capability to the front bore. For some tool-holders, the two side faces contain angled profiles, typically to provide clearance to neighbouring turret stations. For examples where this is the case it is therefore not sensible to hold on these faces for setup 1, as it adds to the machining complexity for setup 2. These examples further support the case for selecting the rear face for holding on for setup 1.



Self-centring vice discussed in chapter 5.2.2

During work-holding equipment selection it was deemed that self-centring vices were the least suitable for use due to their required height in the pallet. With taller work-holding equipment this limited the length of billets which could be machined on the 5-axis machine in comparison to the alternative solutions.

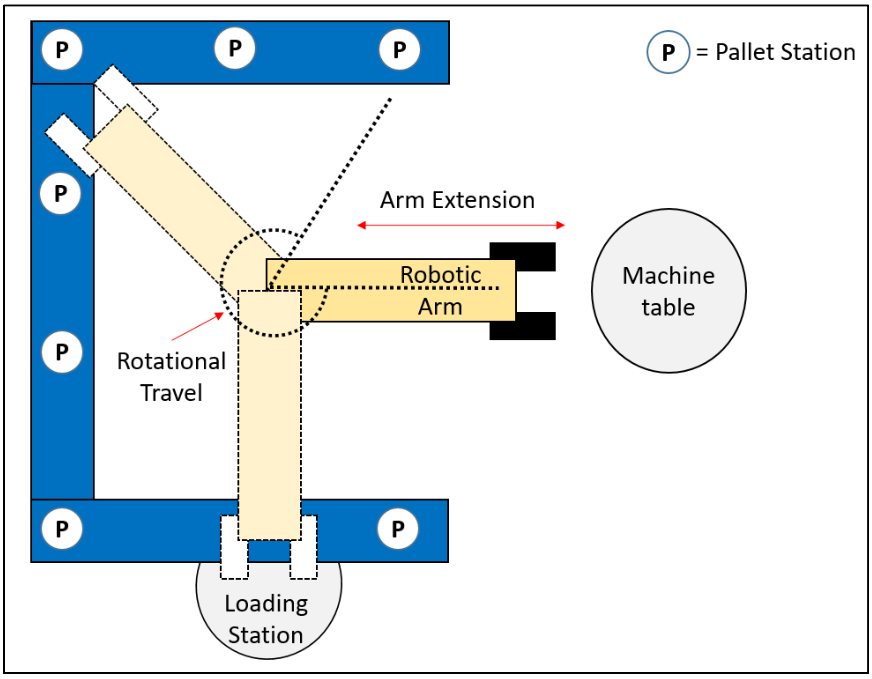
Although the dovetail vice (see above) and zero-point fixture plate (see figure 6.2-4) solutions both required billets to be pre-machined prior to their use, the dovetail vice appeared to require a more complex and precise pre-machining cycle. For the dovetail equipment, billets required two flat bands to be machined into the faces to be clamped which were parallel to each other. The zero-point plate pre-machining cycle however only required four location holes and one face machining into the billet for use with the 5-axis process.

Both equipment approaches were compared to each other with the zero-point plate selected as discussed in chapter 6.2.1 for multiple reasons including:

1) More setup and machining time required to mill the bands for the dovetail clamping as opposed to the zero-point plate requirements
2) The zero-point plate having a 27mm thickness as discussed in chapter 6.2.1
3) The zero-point plate being modular as discussed in chapter 6.2.1
4) The dovetail method being deemed unsuitable for large billets due to the small clamping surface
5) Different billets using the dovetail approach would require different size bands machining into them, introducing process variety
6) The zero-point plate has standardised preparation features to machine in relation to point 5), 4 holes of the same size on the same diameter regardless of billet size

5-Axis Machine Selection

View inside implemented machine of the rotary table and trunnion during installation



Schematic of the pallet loading system from a birds-eye view

The zero-point plates are bolted to each pallet, allowing for a modular tool-holder work-holding solution. The combination of pallet loading with robotics provides the repeatability and quick-loading required to optimise the benefits of modular fixturing. When pallets are not in the loading station or on the machine table, they are stored within multiple dedicated slots as illustrated by the birds-eye schematic above.

CAM Software Selection

The tool-holder manufacturing process utilised by the new machine was defined as a 3+2 axis process and not a full 5-axis machining process. This was because both the rotary table and trunnion rotary axes do not rotate during cutting cycles, only indexing between cutting cycles. Simultaneous 5-axis machining requires rotary axis movement during cutting cycles and is typically utilised in complex geometrical shape machining, for example in turbine blade manufacture.

	Software A	Software B	Software C
What fundamental features does the software package provide?	• 3-D milling up to 3+2 • Turning & Mill-Turning • CAD & file compatibility with existing CAD software • Post-processor for 5-axis machine tool • 3-D probing & inspection • 3 people – mill training & turn training • Post-processors for full machine list	• 3-D milling up to 3+2 • Turning & Mill-Turning • CAD & file compatibility with existing CAD software • Post-processor for 5-axis machine tool • 3-D probing & inspection • 3 people – mill training, turn training • Post-processors for full machine list	• 3-D milling up to 3+2 • Turning & Mill-Turning • CAD & file compatibility with existing CAD software • Post-processor for 5-axis machine tool • 3-D probing & inspection • 3 people – mill training, turn training • Post-processors for full machine list
Add-ons	• Some 5-axis simultaneous cycles • Network licence to share Turn/Mill-Turn & 5-axis cycles between seats • 12 months support free	• Inspection training • Inspection package additional features – probe calibration, measurement reporting	• 12 months support free • All post processors except for 5-axis machine included in support contract

Comparison table of software packages A to C considered for CAM implementation

As discussed in chapter 6.2.3 minimal difference was experienced between the three CAM packages considered as the above table indicates.

For management of machine programs on the network created through CAM, a new program naming convention methodology was used. On the existing VM machines program files were saved by drawing number, with this approach for the new 5-axis process deemed unsuitable as the drawing number does not provide specific detail about the tool-holder being machined. The full product code gives clarity on the bore size, the holder type (internal or external) and allows for easy identification in conjunction with the provided drawing.

Program Prove-Out

Key		
	(orange)	Orders - Prove Out
	(green)	Stock / Repeat Orders - Already Programmed

					MONDAY			TUESDAY		
		Qty	Product Code	Material	AM	PM	N	AM	PM	N
		5-off	Program A - Setup 1	[redacted]	P			P		
		5-off	Program A - Setup 2							
		3-off	Program B - Setup 1			3 (3)				
		3-off	Program B - Setup 2						3 (3)	
		4-off	Program C - Setup 1							
		4-off	Program C - Setup 2							

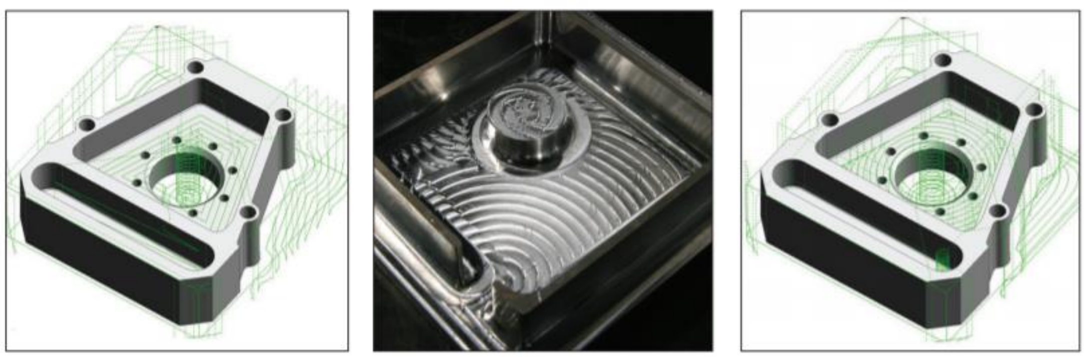
Diagram of the weekly schedule used for 5-axis machine management

In terms of the ‘prove-out’ process, the image above highlights a new scheduling approach introduced for the machine following implementation. Daily review meetings between management and senior production staff were implemented to prepare for future large workloads. As seen the day is split into an AM, PM and N shift, with N being the ‘lights-out’ period between PM and AM shifts. The prove-out process defined would ensure a program ran correctly without issue on the programming shift (AM in the example, represented by a P), prior to allowing this program to be run on the loading shift (PM in the example, with a target of 3 parts to run on each shift). The prove-out of the 1st part would see tools watched through individually, with the second part run through as a complete cycle to ensure correct machining.

The introduced schedule process above allowed quick reviews and monitoring of progress utilising the machine monitoring software. As indicated by the colour coding system under the product code heading, the status of whether a program was to be proven-out or already programmed was captured. Additionally, the cells under each shift allowed targets to be set for each shift for the cycles to run or time to be spent on proving out. The number not in brackets represents the target, with the number representing actual cycles run contained within the brackets. As with the programming status colour coding, this allowed for quick review of progress and to address where issues occurred, particularly once running on the N shift was introduced.

CAM Optimisation Tools

In the images below, some of the optimisation tools of CAM are illustrated such as waveform milling and increased depths of cut. These tools were new additions to the manufacturing process as a part of introducing CAM, with the strategies assisting in reducing machining time of tool-holders as discussed in chapter 7.1. For further reading on these optimisation tools, please refer to the Edgecam reading material contained within the reference list from which both of the below images were taken.



Traditional Toolpath Waveform Toolpath

Diagram comparing toolpath strategy from traditional programming and waveform toolpath achievable through CAM software (Edgecam, 2018)

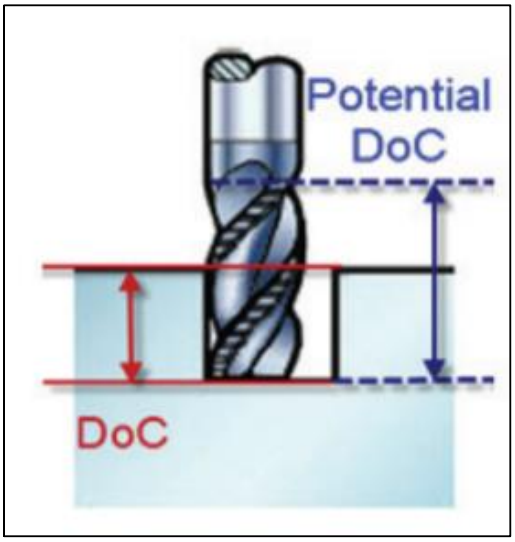


Diagram illustrating the increased depths of cut achievable through CAM use for optimisation of machining (Edgecam, 2018)