Framework development for Identifying and Implementing Lean Principles and Tools within High Mix Low Volume Environments

University of Wales Trinity Saint David – Swansea

B.Eng. Manufacturing Systems Engineering (Hons)

Dissertation

Paul Thomas May 2020

Declaration of Authenticity

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: P.Thomas Date: 20/05/2020

Acknowledgements

I would primarily like to thank my project mentor Andrew Thorne for their continual support and guidance throughout this rewarding process. His extensive subject knowledge and unwavering assistance have been an invaluable resource to guide my major project.

An additional thank you must go to my friends and colleagues at Ford Bridgend Plant. Their financial, resource and most importantly personal support has been fundamental to the success of my project. A noteworthy thanks must go the Gareth Haney (Dept Foreman) and Mark Thomas (Plant Engineering Manager) for the initial opportunity and their continued support.

Finally, the biggest thank you must go to my immediate and extended family. Their unrelenting support and encouragement have been the driving force behind my accomplishments. Notably my wife Jessica, my children Ada and Blake for their understanding and inspiration.

Abstract

Although Ford were one of the pioneers of the lean mass manufacturing revolution, Internal support departments within Bridgend engine plant have been typically excluded from this invaluable methodology. There is a common perception that the adoption of lean methodology can provide plentiful opportunities for improvement in every aspect of the business. This report aims to research and identify appropriate lean tools for successful implementation within BEP toolroom. At present the author believes his employer to be representative of so many other large firms that have only partially adopted the lean principles. Typically, High Mix Low Volume manufacturing such as in BEP toolroom have been slow in their adoption of Lean or any of its variants. HMLV manufactures are less likely to begin productivity improvement initiatives due to lack of knowledge, time commitment issues, fear of change, and lack of resources. Lean manufacturing is typically considered as a universal tool for all manufacturing environments. But the complex nature of manufacturing flow within the toolroom and other HMLV environments requires additional thought.

This report compiles an extensive review of current lean methodology literature, subsequently identifying appropriate tools for implementation within this specific manufacturing environment. It employs tools such as SIPOC, process mapping and cause and effect diagrams to establish the current process state. This process is essential for creating an associated business case for lean initiate implementation.

A data collection strategy is identified and implemented to quantify the anticipated nonvalue adding waste within the current manufacturing process. Subsequently this essential data collection is scrutinised and complied into detailed graphical illustrations. The results of this analysis process are combined with the invaluable knowledge acquired through in-depth research to select the most appropriate lean tools.

The report develops a detailed action plan of proposed process improvements and quantifies their success through comparison of current and future value stream maps. The optimised process produces a 22% reduction in component lead time and subsequent £263004 per annum cost efficiency.

Contents

Declaration of Authenticity 1
Acknowledgements 2
Abstract 3
List of Figures 7
List of Tables 9
Acronyms and Abbreviations 10
Introduction 12
Ford Motor Company 12
Bridgend Engine Plant (BEP) 12
The Toolroom 13
CNC Machining Centres 18
Reason for Interest in the Study 19
Aims and Objectives of the Project 21
Literature Review 23
Lean Manufacturing 24
Value 26
Flow 28
Value Stream Mapping 30
Examples of the Current State and Future State VSM 32
Contact diagram 33
Single Minute Exchange of Die (SMED) 34
5S 36
Change Management Models 38
Kotter's 8 Step Model for Change 38
Kurt Lewin's 3 Step Change 39
Problem definition 41
Business Case 42
High Level Process Map (SIPOC) 43
Process Map 45
Cause and Effect 46
Toolroom Added Value? 47

Waste Identification 47
Overproduction 47
Inventory 48
Scrap and Defects 50
Waiting 50
Motion 51
Transportation/ Conveyance 52
Over processing 53
Knowledge, skills and creativity 53
Data Collection Strategy 54
Data Collection 54
Archived Toolroom Data Collection 55
Waste Identification Data Collection 57
Product Family 64
Cycle time (C/T) and Changeover (C/O) Data 65
Contact Diagram 67
Analysis 68
Archived Toolroom Data 68
Current State - Value Stream Map (VSM) 68
Over-processing 72
Motion 73
Setup 75
Waste Identification Data 76
Current Contact Diagram 79
Process Improvement Tools 81
Information flow 81
5s 81
SMED 87
Future State - Value Stream Map (VSM) 95
Contact Diagram – Proposed 100

Management of Change 102
Covid-19 Impact Statement 103
Conclusion 103
References 106

List of Figures

Figure 1-– Ford insignia from 1903 to present-day (Ford Motor Company, 2018) 12
Figure 2 – Ford Bridgend Engine Facility (Ford Motor Company, 2018) 13
Figure 3 – The toolroom BEP 14
Figure 4 –Material stores BEP toolroom 16
Figure 5 – BEP toolroom layout 17
Figure 6 –CNC Machining Centre (Devlieg V4) 18
Figure 7 –CNC Machining Centre (Devlieg V5) 18
Figure 8 –Lean manufacturing eight wastes (Lean Enterprise Institute, 2018) 24
Figure 9 - Lean manufacturing five step procedure (Lean Enterprise Institute, 2018) 29
Figure 10 – Visual state map material flow signs (Thomas, 2018) 30
Figure 11 – Visual state map signs (Thomas, 2018) 31
Figure 12 – Visual state map - Current state sample (Chen, et al., 2010) 32
Figure 13 – Visual state map - Future state sample (Chen, et al., 2010) 32
Figure 14 - Example of Spaghetti diagram 33
Figure 15 - The 5S steps (Lean Enterprise Institute, 2018) 36
Figure 16- Batch productions decreasing impact on setup time within CNC manufacturing. 41
Figure 17 – CNC milling operation process map 45
Figure 18 – Cause and effect diagram 46
Figure 19 - Stored inventory of finished parts 48
Figure 20 – WIP of reworked parts. 49
Figure 21 - Toolroom Steel Store 49
Figure 22 - Examples of motion waste within the toolroom. 51
Figure 23 - Toolroom shop floor layout 52
Figure 24 - Archived CNC work 55
Figure 25 - CNC product family 64
Figure 26 - Sigma LH location jaw 65
Figure 27 – Components location and application 65
Figure 28 – Tool room layout diagram for contact analysis 67
Figure 29 - Pareto chart of process steps 69
Figure 30 - VSM Toolroom Current State 71
Figure 31 - % of components hardened 72
Figure 32 - Total heat treatment time for identified components 73
Figure 33 - Retained material example 74
Figure 34 - % of raw material removed in manufacturing process 74
Figure 35 - % of repeat work 75
Figure 36 - pareto chart of toolroom batch quantities 76

Figure 37 – Waste identification data chart results (Motion, Waiting, Defects, Over processing) 77
Figure 38 - Waste identification data chart results (Transportation, Overproduction, Inventory) 78
Figure 39 – Contact diagram for typical basic CNC manufactured component 79
Figure 40 - Sort technique diagram 82
Figure 41 - Red Tag and Red Tag isolation area (Pasale & Bagi, 2013) 82
Figure 42 – Set in Order example solutions (theleanwarehouse, 2020) 83
Figure 43 - Further Set in Order examples (theleanwarehouse, 2020) 84
Figure 44 - Tool storage cart (Warfield, 2020) 91
Figure 45 - CNC tooling documentation 92
Figure 46 - Tool presetter example equipment (Warfield, 2020) 92
Figure 47 - Modular fixture tooling plate (Warfield, 2020) 93
Figure 48 – Work holding design considerations 94
Figure 49 – Toolroom VSM Future state 99

List of Tables

Table 1- Toolroom sections and machine types 14
Table 2 - Lean tools for machine shops (Fabtech, 2016) 20
Table 3 – Literature review subject matter 23
Table 4 - CTQ Customer requirements example 26
Table 5 - Kano Model 27
Table 6 -Toolroom process breakdown 28
Table 7 - SIPOC 43
Table 8 – High level process map (SIPOC) 43
Table 9 – List of cause and effect 6M's 46
Table 10 – Data collection plan 54
Table 11- Data collection of archived CNC work 56
Table 12- Waste Identification archived data 58
Table 13 - Waste identification data collection 59
Table 14 - Data collected for manufacturing process 66
Table 15 - Current VSM values 68
Table 16 – Pareto Chart results 70
Table 17 - ABC analysis 83
Table 18 – Shine – machine cleaning scheduling example 85
Table 19 – 5S auditing documentation 86
Table 20 – 'FAST' SMED and process step descriptions (Shiego, 1996) (Ulutas, 2011) (Pellegrini, et al., 2012) 87
Table 21 - SMED Feasibility assessment 88
Table 22 - Future state VSM results 98

Acronyms and Abbreviations

5S 5 elements:

Seiri (Sort), Seiton (Set in order), Seiso (Shine), Sieketsu (standardize), Shitsuke (Sustain)

BEP - Bridgend Engine Plant

CTQ - Critical to Quality

C/T - Cycle time

C/O - Changeover

DMAIC - Design, Measure, Analyse, Improve, Control

ERP - Enterprise Resource Planning

FMEA - Failure Mode and Effect Analysis

FPS - Ford Production System

HMLV – High mix low volume

JIT - Just-in-Time

LMHV - Low mix high volume

MRF - Maintenance request forms (MRF).

MRR - Material removal rate (MRR).

NVA - Nonvalue added

SAP (System Applications and Products in Data Processing)

SIPOC - Supplier-Input-Process-Output-Customer

SMED - Single Minute Exchange of Dies

SOP - Standard work procedures

SPC - Statistical Process Control

TPM - Total Productive Maintenance

TPS - Toyota Production System

TQM - Total Quality Management

VA – Value added

VSM – Value stream mapping

VOC - Voice of the Customer

WHO – World Health Organisation

WIP - Work in progress

Introduction

This thesis will take place within the toolroom of Ford Bridgend engine plant. This section will introduce Ford Motor Company, Bridgend engine plant and the function of the toolroom.

Ford Motor Company

Ford Motor Company was founded by Henry Ford in Dearborn, Michigan in 1903 (Ford Motor Company, 2018). In 2018, Ford was ranked as the third biggest manufacturer of automobiles worldwide. Its 6.0% market share closely trails Volkswagen (7.5%) and Toyota (9.5%) (statista, 2018).

Figure 1-– Ford insignia from 1903 to present-day (Ford Motor Company, 2018)

The Ford Production System (FPS) was developed and implemented by Ford in 1995. It successfully transformed Ford from a mass production into a lean production system. Continuous improvement is a fundamental constituent of process standardisation within the FPS methodology. This is undertaken through the stabilisation and normalisation of manufacturing processes (Ford Motor Company, 2018).

In 2007, Ford Motor Company launched the ‘One Ford’ programme. This was initiated as a strategy to mitigate the effects of the near collapse of world financial markets. Ford consolidated the business and sold off partner automotive brands including Aston Martin, Jaguar, Volvo and Land Rover. This enabled Ford to concentrate solely on the ‘Ford’ brand and reinforce its vehicle roster (Buss, 2012).

Bridgend Engine Plant (BEP)

In 1980, Ford Motor Company opened Bridgend engine plant (BEP). It is a vital constituent of Ford of Europe’s engine manufacturing capacity (Ford Motor Company, 2019). BEP

currently produces the 1.6 L I4 EcoBoost Sigma Engine and 1.5 L I3 Dragon Engine for Ford With addition volume of 5.0 L V8 AJ133 Petrol Engine and 3.0 L V6 AJ126 Petrol Engine for Jaguar/Land Rover.

Figure 2 shows an aerial display of the BEP plant, the facility encompasses an area of 140,501 m^2 (Ford Motor Company, 2018). BEP plant volume peaked in 2015, where it reached 760000 units per/annum. However, the recent plant closure announcement for Sept 2020 means this figure is expected to decrease to 125,000 as the Jaguar/Land Rover AJJ133 and the Sigma engine is phased out before the closure.

Figure 2 – Ford Bridgend Engine Facility (Ford Motor Company, 2018)

The Toolroom

The Toolroom is part of BEP's estates maintenance facility (Figure 3). This consists of complementary departments which provide a comprehensive maintenance service to the plant. It includes the precision grinding, welder/tinsmith electronics, central (electrical/mechanical) and Condition Based Monitoring maintenance. The toolroom is responsible for making precision components from raw materials. These components are typically used to supplement maintenance activities and replenish stores items. The department currently employees 12 toolmakers on a four shift 156-hour shift pattern.

Figure 3 – The toolroom BEP

Table 1 comprises a list of the toolroom machining sections and the different machine types within each section. A variety of combination of machine type are typically used for the manufacturing process components within BEP toolroom.:

Table 1- Toolroom sections and machine types

Toolroom Section	Machine Type
Turning	Manual lathe CNC lathe
Milling	Manual milling machine CNC milling machine
Grinding	Cylindrical grinder Surface grinder
Drilling/Boring	Jig boring machine Manual drill Radial drill
Gear cutting	Gear hobbing machine
Supplementary	Slotting machine Bandsaw Heat treatment furnaces Overhead gantry cranes

ERP (Enterprise Resource Planning) and SAP (System Applications and Products in Data Processing) type software are critical for effective resource management in large scale manufacturing processes (Helo & Addo-Tenkorang, 2011). BEP utilises an integrated manufacturing resource system called Maximo. The Maximo software is utilised to generate maintenance request forms (MRF). This MRF contains vital information critical to the scheduling process for incoming work to the toolroom. They should contain an attached engineering drawing, description of task, customer department/foremen information and a priority value. Upon receipt of an MRF, the department work schedule must be generated to prioritise work based on the availability of machines, material, production and customer department demand. The priority value is broken down into three categories:

1. Highest – , Replacement/repaired part required - Production on stop due to breakdown.
2. Medium - Replacement/repaired part required – Production currently unaffected.
3. Lowest - Replacement/repaired part required – Spare part for stores or routine maintenance.

Once the dept schedule has been decided, each toolmaker will evaluate their job and decide a suitable manufacturing process. Typically, this requires the acquirement of a material suitable to manufacture the required component. Conventional materials used within the manufacturing process comprise of mild/tool steel, aluminium, nylon (various types), brass, copper and phosphor bronze. An inventory of standard sizes for each material are retained on site in the toolroom material stores (Figure 4). However, a wide variety of materials and sizes are required for the unpredictable work that is required of the toolroom. This often

requires specific materials to be ordered from an external supplier for manufacturing uncommon components.

Figure 4 –Material stores BEP toolroom

Figure 5 is a diagram representative of the toolroom layout. The aisles are shown in yellow; these are suitable for forklift/vehicle entry which is often required for large and heavy materials. All machines and areas are suitably labelled, the overhead crane gantries are identified by the dotted red lines.

Figure 5 – BEP toolroom layout

= Overhead gantry crane areas

CNC Machining Centres

There are two CNC machining centres also known as CNC mills utilised within the toolroom. These are the DeVlieg V4 (Figure 6) and DeVlieg V5 (Figure 7). The V4 is the smaller of the two, it has a 500x400mm (X,Y) travel machine bed whereas the V5 has 1000x500mm (X,Y) travel machine bed. In addition, the V5 can utilise a 4th/5th axes attachment, this is of particular use for increased flexibility requited for manufacturing complex components.

Figure 6 –CNC Machining Centre (Devlieg V4)

Figure 7 –CNC Machining Centre (Devlieg V5)

Reason for Interest in the Study

It must be believed that essentially all companies can benefit from the correct introduction of Lean as an organisational tool for productivity improvement (Jeffrey K. Liker, David Meier, 2005). The author has spent most of his career working in toolroom / machine shop environments with several different companies. These companies could be considered leaders in the adoption of lean methodologies into their manufacturing processes. Ford Motor Company have taken the fundamentals of TPS founded by Toyota and adapted it to create the FPS system. Whilst these lean Methods have been adopted throughout high-volume areas, the smaller support departments have been ignored. As the author is an employee of a large manufacturer and student studying lean methodologies. They could not understand why these principles are not adopted plant wide. According to (Thorn, 2018), the adoption of lean methodology can provide plentiful opportunities for improvement in every aspect of the business. At present the author believes his employer to be representative of so many other large firms that have only partially adopted the lean principles.

Typically, HMLV have been slow in their adoption of Lean or any of its variants. Unfortunately, these industries are less likely to begin productivity improvement initiatives due to lack of knowledge, time commitment issues, fear of change, and lack of resources. Although the uptake of these methodologies would evidently beneficial, according to (Womack, et al., 1991) Lean organizations produce less waste (in its many forms), have improved product quality with shorter lead times, and have employees who are more engaged. .

Lean manufacturing is typically considered as a universal tool for all manufacturing environments. But the complex nature of manufacturing flow within the toolroom and other HMLV environments requires additional thought. Therefore, only suitable Lean processes/tools must be correctly selected and implemented. (Austin, 2013) describes how lean strategies are often publicised as the “best”, “newest” or “most profitable”, with many businesses selecting tools not suitable for their requirements. Whereas (Wilson, 2015), states that the productivity efficiencies produced by lean practises typically differentiate the industry leaders.

Whilst the toolroom is unlike the mass production environment, it must also eliminate all unnecessary waste. The TPS system is tuned for low mix high volume (LMHV) and not the high mix low volume (HMLV) of toolroom work. As a result, special thought is required when trying to implement lean methodologies. According to (Fabtech, 2016), there are many special characteristics which separate the toolroom from high volume production. They need careful consideration, these include: -

- A diverse mix of products and batch sizes.
- The manufacturing process can differ widely for each type of product.
- The facility layout is based around machine type, where each product can pass through several areas of the facility, possibly several times.
- Product demand fluctuates extensively.
- Production bottlenecks vary for each product.
- Production scheduling and control is complex and varies daily
- When applying lean tools within the toolroom, adding value must be of the upmost importance.

According to (Fabtech, 2016) the HMLV requirements of the toolroom necessitate the need for a different strategy to the LMHV. Table 4 below identifies lean tools which are potentially most appropriate for implementation within a machine shop.

Tools that *will* Work in Most Jobshops	**Tools that *will not* Work in Most Jobshops**
Strategic Planning (aka Hoshin Kanri)	**Value Stream Mapping**
Top-Down Leadership	Assembly Line Balancing
Employee Involvement	One-Piece Flow Cells
5S	Product-specific Kanbans
TPM (Total Productive Maintenance)	FIFO Sequencing at Workcenters
Setup Reduction (SMED)	Pacemaker Scheduling
Error-Proofing (Poka-Yoke)	Inventory Supermarkets
Quality At Source	Work Order Release based on Pitch
Visual Controls & Visual Management	Production based on Level Loading (Heijunka)
Product and Process Standardardization	Mixed Model Production with Takt Time
Right-sized Machines	
Jidoka	
Standard Work	

Table 2 - Lean tools for machine shops (Fabtech, 2016)

Aims and Objectives of the Project

The aim of this project is to produce a report researching the implementation of lean methodology with the toolroom in BEP. Additionally, this research would provide a framework which can be implemented in other HMLV environments. Lean methodology principles have long been implemented in in Low Mix High Volume (LMHV) environments, whereas the uptake in HMLV environments has been considerably slower. Current research literature does not provide a suitable framework for implementing Lean in these smaller HMLV industry sectors.

To accomplish this aim of applying Lean principles within HMLV sectors. A thorough investigation of the current manufacturing process within the toolroom of BEP is of paramount importance. For this report the author will focus on the CNC milling section within the toolroom, this is due to the high volume of components manufactured on these machines and the level of complexity produced that is impossible via manual machines. This analyse will provide a suitable benchmark for the research, identification and implementation of applicable lean tools to improve its performance.

To achieve this aim, the current methods used within the CNC process will be analysed so that improvements can be made using lean principles. This will involve identifying the process flow through the toolroom, value-stream mapping (VSM) the current process, identify the value-added activities whilst also identifying the necessary and unnecessary non-value-added activities and finally identifying improvements and producing a VSM of the future state. For the analysis of the CNC process, data will be collected from a selection of components produced on the CNC milling machines. The author proposes to utilise this data to identify waste within the process and assist the implementation of suitable lean tools.

To satisfy the key principles of any lean methodology. (Lean Enterprise Institute, 2018) describes “gathering he low hanging fruit” or targeting areas of most benefit to produce the greatest result with smallest effort.

The aim of this case study is to provide a theoretical framework and an in-depth example of how a small toolroom can efficiently implement a suitable lean methodology, and ultimately producing a tailored action plan for implementing Lean Manufacturing Principles.

Aims	Objectives
To identify and introduce lean tools which can be suitably utilised in the toolroom of Ford Bridgend Engine Plant	• Collect suitable data of component manufacturing from toolroom archives • Analyse data to determine any potential sources of waste • Produce High level process map • Identify toolroom process map • Produce a current/future state VSM • Determine the value-added and non-value-added activities • Research change management models (Lewin's and Kotter's models) • Discuss and suggest a plan for change according to the selected change model.

Literature Review

The information gathered for this thesis must be of suitable merit and therefore requires careful consideration to maximise its value. All literature must target pre-identified areas of interest relevant to the thesis topic. The Literature review enables the author to establish a comprehensive understanding of a subject matter by studying previous works by distinguished authors. According to (Arshed & Danson, 2015) "In academic circles this is referred to as reviewing literature and allows you to understand the current state in a subject area, to relate this to the ongoing research and to identify gaps in this knowledge". This can be corroborated by (Oliver, 2012) who states "A literature review is a discussion on published information about a subject and can be considered as the foundation upon which a successful project is constructed".

As result of preliminary research, the author has identified the topics listed in of interest which they consider both relevant and beneficial to the success of this report.

Topic	Thesis Significance
Lean manufacturing Principles	Lean manufacturing principles
Value	(Wilson, 2015) states the importance of identifying value in lean manufacturing. Value can be defined by activities the customer is willing to pay for
Process mapping and Flow	(Wilson, 2015) defines the importance of establishing product flow and pull from the downstream activities. Additionally, explaining how the manufacturing process can be made leaner as result.
Value Stream Mapping (VSM)	Value stream mapping (VSM) is utilised to map the current state and assist creation of a leaner future state of operation.
Waste identification and elimination : 8 Wastes	Waste identification and elimination of NVA activities are significant to the value of product or service being provided (Balaji, et al., 2016).
Set up reduction	Setup reduction and Single minute exchange of dies (SMED) are crucial to reducing waste within the changeover over process (Moubray, 1991)
Change management	(Kotter, 2012) describes how change management is an essential technique required for smooth transitioning and reducing employee resistance, when replacing out date work practices.
5s	It was devised to standardise the workplace, streamline the working practices, decrease or eliminate unnecessary activities, and finally improve quality and safety (Dana, 2015).

Table 3 – Literature review subject matter

Lean Manufacturing

Lean manufacturing can be defined as a complete management philosophy. It was developed by Taiichi Ohno as an executive at Toyota Motor Company, he was responsible for pioneering the identification of the seven wastes within the Ford Model T assembly process (Chahal & Narwal, 2017). This revolutionary insight was fundamental to the development of the Toyota Production System (TPS) (Herron & Hicks, 2008). The system was designed to identify and eradicate inherent waste within the manufacturing process. Womack and Jones (2003), describe lean production as "doing less, with less human effort, less equipment, less time and less space while coming closer and closer to providing customers with what they wanted". Whilst (Chahal & Narwal, 2017), (Pieńkowski, 2014) state, TPS involved empowering the workforce to drive lean practices, resulting in increased quality, efficiency and reduced costs. TPS recognises three basic forms of waste, Mura-unevenness, Muri-overburden, and Muda-wastefulness. According to (Chahal & Narwal, 2017) these wastes are in-stringently interlinked and their classification was vital to the success of the TPS system.

Figure 8 –Lean manufacturing eight wastes (Lean Enterprise Institute, 2018)

According to (Lean Enterprise Institute, 2018), organisations will accomplish an measurable reduction in waste, with a marked increase in its value to its customers as the result of implementing lean manufacturing techniques. Creating supplementary increases in company profitability and therefore supporting a company's competitiveness. The modern

interpretation now identifies eight categories of waste (Figure 8): talent, inventory, motion, waiting, transportation, defects, overproduction and over-processing (Pieńkowski, 2014).

The TPS philosophy has been embraced by Ford Motor Company, where they have employed the fundamental ideologies and developed the FPS (Ford Production System). The tools within the six-sigma philosophy are critical to a lean production system. (Chandran & Nair, 2018) describe that the aim is to eliminate variation, six sigma in its basic form is the struggle for minimal variation, it is a clear illustration of how well a process performs. The manufacturing system must also generate value from the customer perspective and fundamentally create flow from the customer. This effective pull of the manufacturing process must drive production demand.

This report aims to identify the different types of waste that occur within the toolroom at Bridgend Engine Plant (BEP). These types of waste can be identified and eliminated through use of Six Sigma techniques, highlighting the possible problems, costs and solutions of these wastes. Lean manufacturing identifies waste as any activity within a process, that does not add value to the finished product (Wilson, 2009). Further to this (Pieńkowski, 2014) describes the considerable waste within manufacturing, highlighting the small proportion of time which can be considered value-added.

There are plenteous resources validating the successful implementation of lean methodology within high volume manufacturing processes. (Wilson, 2015) establishes global instances where lean tools have been successfully implemented, therefore producing dramatic reductions in waste and inventory, with further benefits to process quality control. (Davim, 2018) reinforces this, evidencing recent case studies of lean manufacturing implementation within different industry sectors. Both texts clearly reference the TPS, highlighting the benefits of its techniques such as Just in Time (JIT), Kaizen activities and Critical measurables to maximise company performance.

Value

In lean manufacturing, value is measured from the customers perspective. (Wilson, 2015) states that when a customer does not see value in a product, then they will be reluctant to pay for it. A fundamental component of the six-sigma methodology is appropriately understanding a customer's needs. This is defined as the Voice of the Customer (VoC) (Griffith & Hauser, 1991). Identifying the VoC is essential to gaining the necessary information needed to provide a satisfactory product or service to the customer (Martin, 2008). This information is regularly referred to as Critical to Quality (CTQ), CTQ's define the customer critical requirements for a product or service. Table 4 is an example of typical CTQ requirements.

Table 4 - CTQ Customer requirements example

Product Quality	Service Quality	Cost
Performance	Competence	Total Costs
Features	Reliability	Terms and warranties
Timeliness	Timeliness	
Conformance	Accuracy	
Serviceability	Responsiveness	
Reliability	Access	
Aesthetics	Communication	
Durability	Courtesy	
Reputation	Credibility	
Completeness	Security	

Lean methodology applies countless tools to analyse and understand a customer's requirements. The Kano model is one such tool for understanding the VoC. According to (Wang & Ji, 2010), the Kano model is vital for measuring customer satisfaction. There are 5 basic classifications within the Kano model. These 5 categories highlight different areas of customer satisfaction, these are: - basic, primary, excitement, indifferent and reverse. Table 5 below explains the different categories and their basic requirements .

Table 5 - Kano Model

Classification	Contents
Basic Attributes (Must Be)	These needs are expected by the customer. If they are unfulfilled, the customer will be dissatisfied, but even if they are completely fulfilled, the customer would not be particularly satisfied.
Primary Satisfier (More is Better)	These needs have a linear effect on customer satisfaction. The more these needs are met, the more satisfied the customer will be.
Excitement Attributes (Delighters)	These needs do not cause dissatisfaction when not present but satisfy the customer when they are present.
Indifferent Attributes	These are attributes to which the customer pays no attention. If they are present, it is nice. If they are not present it does not matter.
Reverse Attributes	If needs are fulfilled, the customer will be dissatisfied. If they are unfulfilled the customer will be satisfied.

Value stream mapping is a lean methodology tool used to define a process into separate activities, these activities are then categorised into value or non-value added (Onofrejova & Janekova, 2015). Value added (VA) or Nonvalue added (NVA) are activities that either did or did not add value to a product or service. (Crawford, 2016) states that correctly understanding customer requirements is critical to correctly determining if activities are VA or NVA. Furthermore, nonvalue added NVA's can be divided into necessary or unnecessary NVA's. When considering the fundamentals of lean manufacturing, eliminating waste is the definitive requirement. Therefore, reducing unnecessary NVA's from a process is vital as the customer is unwilling to pay for such NVA's.

Table 6 demonstrates the different toolroom processes and how they can be broken down into VA and NVA's. VA's are the elements of the process which are considered essential to satisfy the customer requirements. According to (Thorn, 2018) VA activities can be defined as those which alter fit, form or function. The elements of the process which are essential to customer requirements, are the elements which remove material as they alter fit, form and function of a part machined within the toolroom. Therefore, in the toolroom machining ordinarily indicates VA (value added) and non-machining indicates NVA (non-value added). Table 6 also identifies NVA 's within the process, many of the NVA's can be considered necessary as a part cannot be produced without them. The NVA's can be identified from the eight basic wastes of lean methodology, including over-processing, defects, reworks, inventory, waiting-time, handling, and motion (Rawabdeh, 2005). Examples of the

unnecessary NVA's are, the Idle time between machine cycle times, excessive transport time between processes or excessive time selecting or locating material or tools.

Ultimately, the customer will not be prepared to pay for any elements of waste or NVA within a process. According to (Davis & Davis, 2011) NVA's do not contribute to value, they merely deplete resources. Whilst (Fernández-Solís & Rybkowski, 2012) maintain that to achieve value, the provider must fulfil customer requirements.

Table 6 -Toolroom process breakdown

Bandsaw	Turning	Milling	Grinding	Heat-treatment
Select material (NVA)	Set up Machine (NVA)	Set up Machine (NVA)	Set up Machine (NVA)	Set up Machine (NVA)
Load into saw (NVA)	Select tools (NVA)	Select tools (NVA)	Select tools (NVA)	Insert box in furnace (NVA)
Measure (NVA)	Set up tools (NVA)	Set up tools (NVA)	Set up tools (NVA)	Temperature control (VA)
Machine Setup (not cutting) (NVA)	Load material (NVA)	Load material (NVA)	Load material (NVA)	Remove box from furnace (NVA)
Machine Cut material (**VA**)	Machine movement (not machining (NVA))	Select speeds and feeds (NVA)	Machine movement (not machining (NVA))	Cooling period (NVA)
Inspect (NVA)	Machine workpiece (**VA**)	Machine movement (not machining (NVA))	Machine workpiece (VA)	Reheating (**VA**) (0:30)
Return material to racks (NVA)	Measure (NVA)	Measure (NVA)	Measure (NVA)	Quench workpiece (VA)
Clean machine (NVA)	Adjustment of tools (NVA)	Adjustment of tools (NVA)	Adjustment of tools (NVA)	Temper workpiece (VA)
Transport workpiece to process (NVA)	Remove workpiece (NVA)	Remove workpiece (NVA)	Remove workpiece (NVA)	Shot-blast workpiece (NVA)
	Clean machine (NVA)	Clean machine (NVA)	Clean machine (NVA)	Clean area (NVA)
	Transport workpiece to next process (NVA)	Transport workpiece to next process (NVA)	Transport workpiece to next process (NVA)	Inspect hardness (NVA)
				Transport workpiece to next process (NVA)

Flow

Figure 9 represents how the continuous improvement cycle aims to achieve an optimum state with no inherent waste (Lean Enterprise Institute, 2018). (Fernández-Solís & Rybkowski, 2012) state the importance of eliminating non-value adding (NVA) activities and therefore creating a more balanced process flow. This results in value-adding (VA) activities becoming more closely concentrated. Similarly, (Wilson, 2015) defines the importance of establishing pull from downstream activities and generating product flow. "Establishing pull" is described by (Wilson, 2015) as the ability to control flow though customer demand. i.e. "pulling" product through a production process rather than pushing unnecessary product unwanted by the customer.

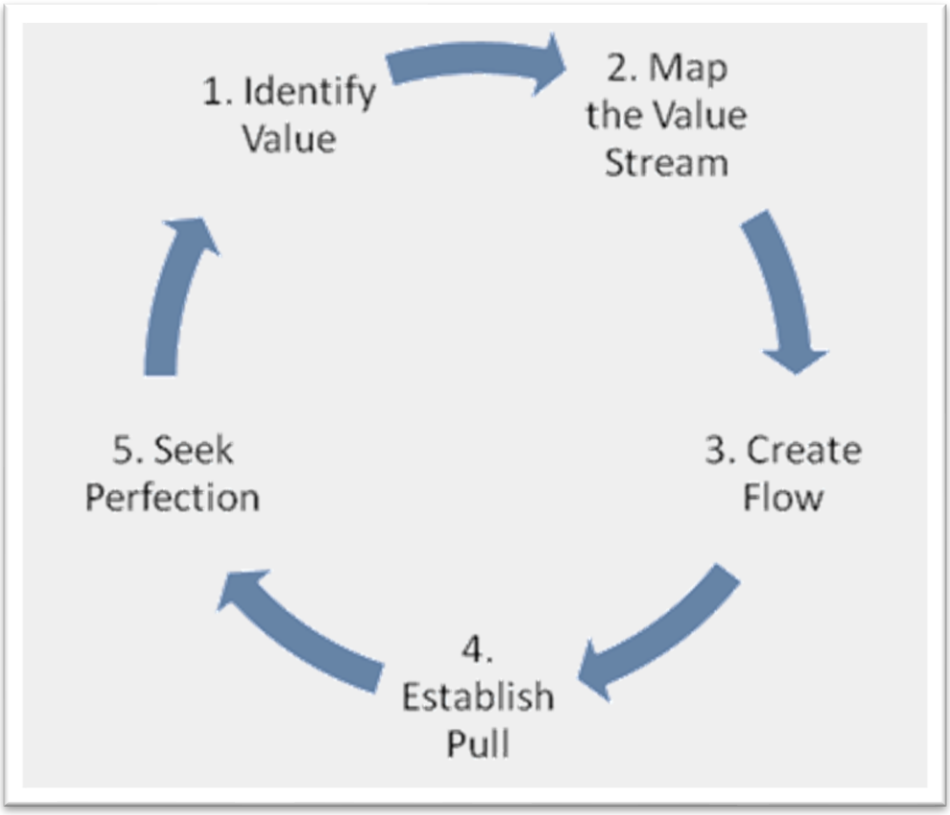


Figure 9 - Lean manufacturing five step procedure (Lean Enterprise Institute, 2018)

Value Stream Mapping

Value stream mapping (VSM) is an essential lean manufacturing technique for identifying inherent waste within a process (Onofrejova & Janekova, 2015; Chen, et al., 2010). (Stadnicka & Litwin, 2019) describe how the technique can be utilised to restructure a process and make it leaner. VSM identifies materials and process illustrating the flow through a manufacturing system. The VSM technique fundamentally enables the creation of a map identifying the product value stream. Typically, VSM creates three distinct maps: Current, future and ideal state (Austin, 2013).

The expression 'value stream' was developed by (Womack, et al., 1991) in his renowned work titled 'The Machine that changed the World'. (Martin & Osterling, 2014) refer to Value Stream Mapping's ability to lessen waste, transform management rational, identify strategy/priority and finally ensure customer satisfaction.

There is conflicting reasoning for the implementation of VSM within toolroom environments. (Murugesan, et al., 2016) states the importance of creating a VSM of current and future state for a machine shop. This is reinforced by (Alves, et al., 2005; Austin, 2013) who emphasise the benefits of executing a VSM to eliminate waste and establish flow. Whilst (Fabtech, 2016), explain that the fundamental basis of a machine shop manufacturing does not enable a VSM to be created at a high level. Although, defines opportunities do arise to apply VSM to focused areas of the process. This is collaborated by (Rother, 2009), who explains the need to focus on one distinct product category.

The graphical symbols used within the VSM process can be seen in Figure 10 and Figure 11. (Thomas, 2018) describes the function of each feature as follows.

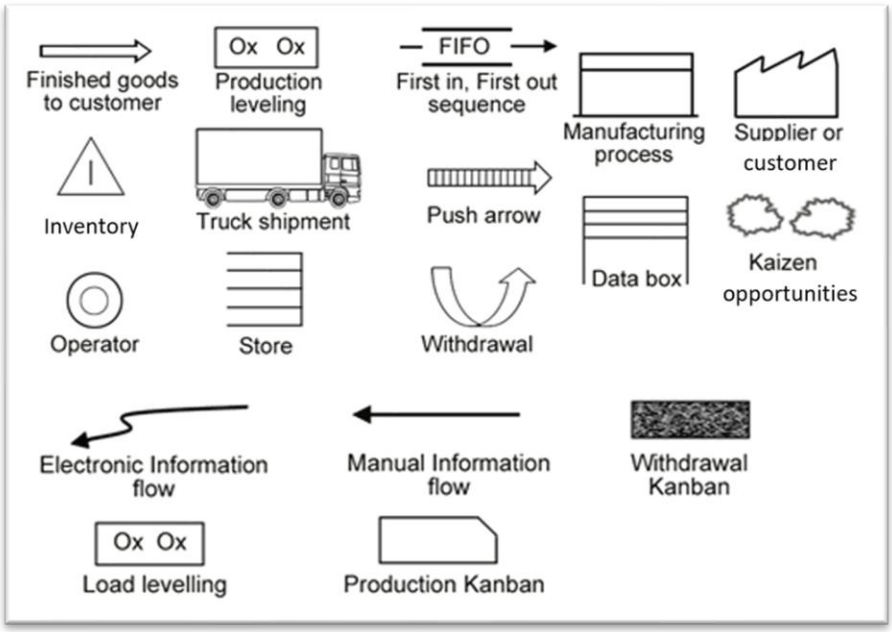


Figure 10 – Visual state map material flow signs (Thomas, 2018)

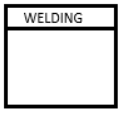
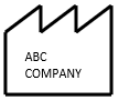
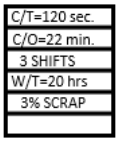
Icon	Represents	Notes
	Manufacturing Procedure	Identifies a single section of uninterrupted flow. I.e. differing departments.
	External Resources	Indicates clients, suppliers and external manufacturing procedures.
	Activity Information Box	Records data concerning a department or manufacturing process etc.
	Inventory	Tally and duration are recorded.
	Delivery Consignment	Frequency of deliveries is recorded.

Figure 11 – Visual state map signs (Thomas, 2018)

Examples of the Current State and Future State VSM

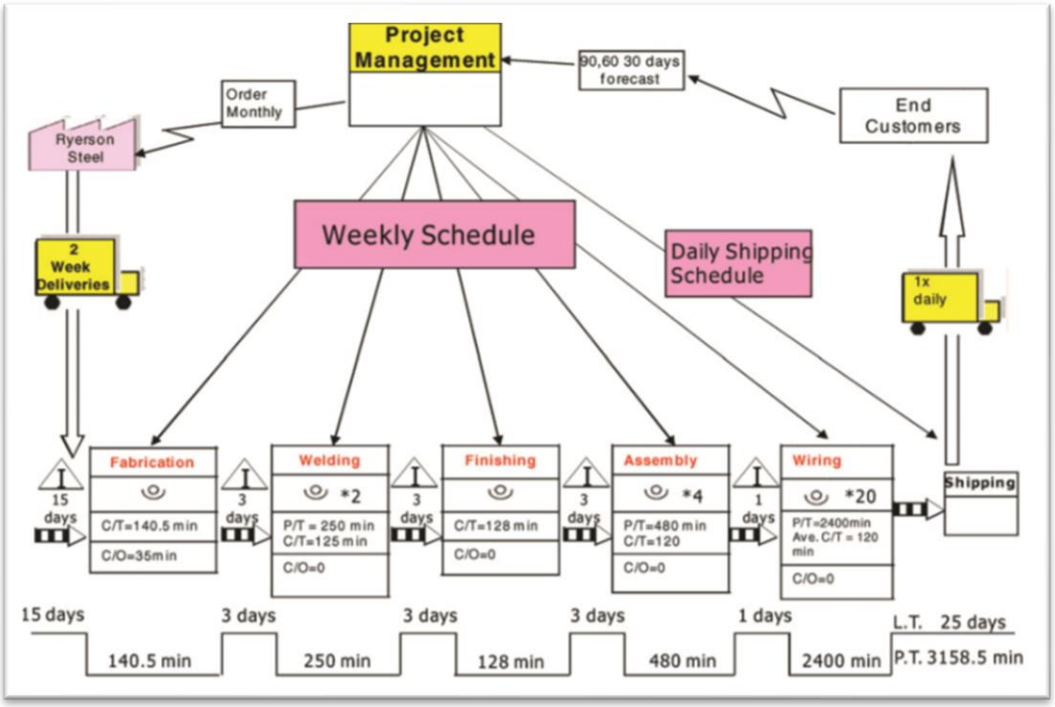


Figure 12 – Visual state map - Current state sample (Chen, et al., 2010)

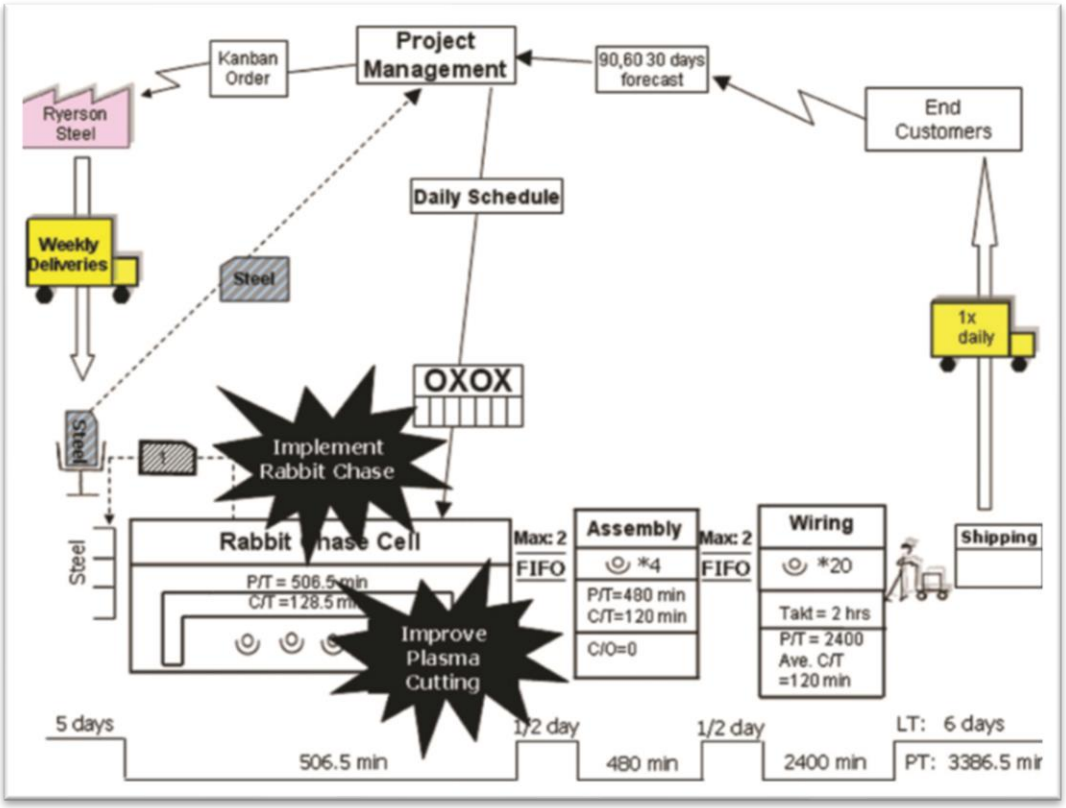


Figure 13 – Visual state map - Future state sample (Chen, et al., 2010)

Contact diagram

Contact or Spaghetti diagrams are an essential tool to track and illustrate the movement of man, component and/or material through a manufacturing process see Figure 14. They have taken their name from the resemblance of the diagram to strands of spaghetti (Senderska, et al., 2017).

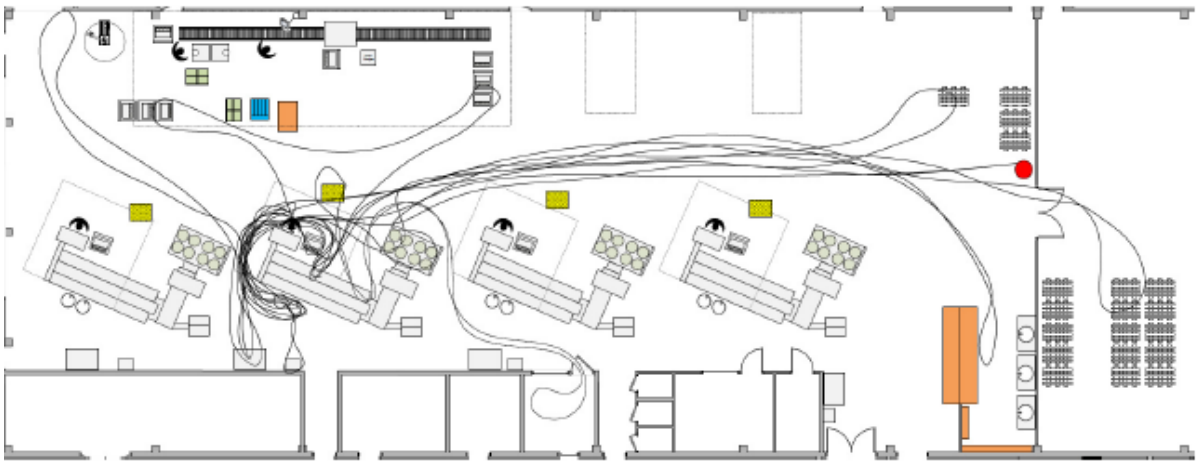


Figure 14 - Example of Spaghetti diagram

Contact diagrams are an invaluable technique to trace a complete manufacturing process. The technique allows for further identification of refined sections by implementing different colours for separate analysis. The resultant diagram supports the analysis of any movement within the manufacturing process, for example the quantity, distance and time of such movements. Therefore, efficiencies can be made through improvements to layout, manpower and processes.

Single Minute Exchange of Die (SMED)

Setup time can be defined as, “the time taken from the completion of the last good part of the original setup, to the first good part from any new setup” (Albert, 2004). Within lean methodology, this is commonly referred to as single-minute exchange of die (SMED) and was developed by Shigeo Shingo of the Toyota motor company in 1969. Whilst the term refers to “exchange of dies”, it has been adopted as a description of setup and preparation reduction in the changeover for a machine/process (Yash & Nagendra, 2012). According to (Austin, 2013) “Customers do not value setup; they value output”. Whilst setup is essential for a machine/process to complete a VA activity. It does not directly influence the manufacturing of a component and therefore must be considered NVA. This is reinforced by (Womack & Jones, 2003), who state “To be considered value-added, an activity must transform the raw material in a way that contributes to the end value as defined by the customer”. Modern manufacturing constraints, such as shorter life cycles, reduced inventories and the increased demand for flexibility within manufacturing processes drive the demand of SMED improvements (Yash & Nagendra, 2012). As a result, setup time reduction is an essential prerequisite within manufacturing processes to reduce or eliminate NVA time. (Albert, 2004) describes how reduced setup\times increase process flow and generate less work in progress (WIP). Where traditionally companies have looked to technology to provide savings in process efficiencies, SMED has been proven to eliminate NVA activities and increase capacity.

SMED methodology consists of adequately identifying all essential operations, tools and materials needed to changeover a machine or process from one product to another. The description of SMED does vary between sources but the process can be described in the following steps.

1. Classify internal and external setup operations.

External operations can be determined as those that can be completed while a process is running. For example, preparing a die press used for the next production run or preparing paper stock for the following print batch (Rubrich & Watson, 2004)

Internal operations can be determined as those that must be executed when a process/machine is stopped. For example, the mechanical press process must be stopped during die press changeover (Rubrich & Watson, 2004).

2. Converting setup operations from internal to external

An efficient setup conversion requires a process to be evaluated objectively, questioning the status quo and determining opportunities of improvement. Every opportunity must be taken

to remove unnecessary activities and reduce internal operations. This is reinforced by (Meng & Chen, 2010), (Balaji, et al., 2016) who state that to successfully reduce setup\times, internal operations must be transformed to external operations.

3.Process standardisation

(Albert, 2004) explains the advantages of embracing employee ownership and implementing lean tools such as 5s and visual factory. Additionally, (Austin, 2013) debates the implementation of standardised fixturing, fasteners and all necessary supplementary tooling to substantially speed up changeovers. When a thorough evaluation of the process has been undertaken, standard procedures should be documented for consistency during changeovers.

4. Continuous improvement

The process must be continually evaluated, driving further improvements. Process performance should be accurately measured and documented to clearly demonstrate prior efficiencies. Employees should be empowered by their progress and be encouraged to make additional improvements. This continuous improvement process cycle is a hallmark of Lean methodology. Any measurable reduction in respect to component lead time, and the associated costs are fundamental to improving operating performance and flexibility (Yash & Nagendra, 2012).

5S

The 5S system originated from the foundations of lean methodology, its development was directly compliant with techniques such as Total Productive Maintenance (TPM) and the Toyota Production System (TPS) (Kazmierski, 2016). According to (Imp, 2011), the implementation of 5S empowers the standardisation and simplification of the workplace. Furthermore, creating opportunity to improve process quality, safety and reducing unnecessary activities. (Imp, 2011) describes how 5S can establish a lean manufacturing environment, supporting continuous process flow and driving further lean improvements.

Figure 15 - The 5S steps (Lean Enterprise Institute, 2018)

(Kazmierski, 2016) describes that 5S originated from an acronym for the Japanese words SEIRI, SEITON, SEISO, SEIKETSU, and SHITHSUKE. When translated into English, these are SORT, SET IN ORDER, SHINE, STANDARDISE and SUSTAIN see Figure 15.

Each of the 5 steps must be implemented to eliminate waste and improve product flow:

1. Sort. Identify all tooling and work holding, determining what is significant to the process and remove used items. This is reiterated by (Kazmierski, 2016) who confirms the merits of removing all unnecessary items from the workplace.
2. Set in order. This success of this step is encapsulated by the term ‘there is a place for everything and everything in its place’. This step enables newly sorted items to be allocated a location which systematically benefits the process. By example, (Imp, 2011) justifies the use of shadow boards to ensure tools are returned to their correct location.
3. Shine. The shine step ensures areas are kept clean and orderly, with tools and materials stored appropriately. Primarily this process is responsible for ensuring items are returned correctly but additionally results in checks to their condition (Imp, 2011; Dana, 2015).

4. Standardise. Involves identifying 5S routines by standardising and scheduling tasks for employees to follow. Implement visual tools such as colour coding, equipment markings, work procedures and progress charts. This is corroborated by (Kazmierski, 2016; Imp, 2011), who explains the benefits of visual tools such as standardised operating procedures (SOP) and communication boards.
5. Sustain. The success of 5S is determined by the ability to sustain the gains made through implementation of the preceding steps. Employee engagement and confidence will further drive the program, addition benefits are realised as others are encouraged to make positive contributions. (Imp, 2011) argues the importance of leadership participation to drive the 5S program, this reinforces gains within the workplace culture (Imp, 2011).

Change Management Models

(Burnes, 2014) describes the availability of change management techniques to an organisation's management, these can be implemented to overcome an employee disagreement or dissension that may be faced. (Mullins, 2016) debates that change can occur naturally through the replacement of outdated procedures within the workplace. By contrast, planned change typically comprises of management led improvements to operations or procedures deemed essential to stay ahead of competitors. Two change management methodologies will be considered for this project:

1. Kotter's 8 step change model
2. Kurt Lewin's 3 step model and.

Kotter's 8 Step Model for Change

Pollack & Pollack (2015) describe that Kotter's model is widely considered as a benchmark procedure for managing change. (Kotter, 2012) developed an 8-step model in his book 'leading change', this renowned literature introduced a systematic 8 step approach .

<u>Step 1: Establishing a sense of urgency</u>

To initiate change, it is critical to create a sense of urgency. This urgency is driven by a series of leadership led actions which involve critical participants. It is important that employees understand that the status quo is unacceptable why change is no longer optional.

<u>Step 2: Creating a guiding coalition</u>

The formation of a group who can effectively lead the change is vital to its success. Leaders must identify capable and influential figures; these can include internal employees or external change agents. The successful outcome of the program is highly dependent on both their leadership skills and their belief and commitment to the change.

<u>Step 3: Developing a vision and strategy</u>

The third step requires the leadership coalition to formulate and develop the driving vision and strategy. The vision must be fully understood and embraced by everyone involved in the change. This can involve the conception of a distinct mission statement.

<u>Step 4: Communicating the change vision</u>

It is essential that the vision for change is fully understood for a successful completion. Communication is critical for the reinforcement of the message throughout the workforce.

Pollack & Pollack (2015) dictates, leadership typically misjudge the extent of communication required to safeguard the understanding of the change vision.

Step 5: Empowering broad-based action

The fifth step primarily involves the elimination of obstacles which could potentially inhibit change. Additionally, it is vitally important to encourage bold thinking by the workforce, whilst removing the obstacles to change . Employee contribution should be encouraged and rewarded and therefore further empowering the workforce.

Step 6: Generating short-term wins

This step requires actions aimed at generating optimistic attitudes to the change. Short term wins boost the confidence within a workforce. This increased optimism demonstrates the viability and reasoning for change. According to (Kotter, 2012), short-term wins must be considered and relatable to the workforce, therefore reiterating the objective of the change.

Step 7: Establishing gains and creating further change

Any improvements made, must be consolidated, it is critical to avoid complacency. Therefore, leadership must celebrate areas of success and identify further areas for improvement. Constant scrutiny is vital to the protracted success of the change and secure its establishment within the workforce.

Step 8: Anchoring change in the culture

The eighth and final step is to reinforce the change, it must develop into a fundamental element of the company ethos. The success of the change should be fully embraced and conveyed to all departments within the organisation. It is imperative that leaders continue to drive the change so that improvements are develop into a lasting culture within the organisation.

Kurt Lewin's 3 Step Change

(Burnes, 2014) describes that the three-step model for change was conceived by Kurt Lewin in 1947. It followed in the success of his renowned 'Force Field Analysis' developed in 1946 (Cummings, et al., 2016). Kurt Lewin's theory implements three simple steps to achieve a successful change.

Step 1: Unfreeze the existing state

According to (Cummings, et al., 2016) this stage ensures employees are fully engaged and equipped to commence the change. Employee motivation and engagement require a significant managerial influence for a successful change event. (Iowa State University,

2017) describe the importance of Lewin's Force Field Analysis to relinquish the status quo and subsequently drive change by eliminating opposition to the change.

Step 2: Commencing change

(Burnes, 2014) (Cummings, et al., 2016) dictate the success of change is subject to employee engagement and empowerment. This requires employees and management to come together to cascade new work practices and ensure adequate training.

Step 3: Refreezing change

The newfound status quo requires management engagement to drive new work practices ensuring that standards do not revert back. This is reinforced by (Cummings, et al., 2016), who state it is the responsibility of leadership to encourage and further implement new work practices. Once the change becomes stable then it becomes the new normal working practise. It is the responsibility of management to ensure the working practises do not revert to the old ways (Cummings, et al., 2016).

Problem definition

According to (Conner, 2001), CNC machining centres provide an essential service within a machine shop environment. Their ability to produce large batch numbers of identical components can provide measurable improvements to cost effectiveness. Whilst this is true, the CNC process is less efficient for smaller batch numbers. This is predominantly due to an extended lead time as a result of several primary influences. These are non-value adding activities, which are characteristically considered as 'waste' within the process. Some of these activities include machine setup, CNC programming, component fixturing and material procurement.

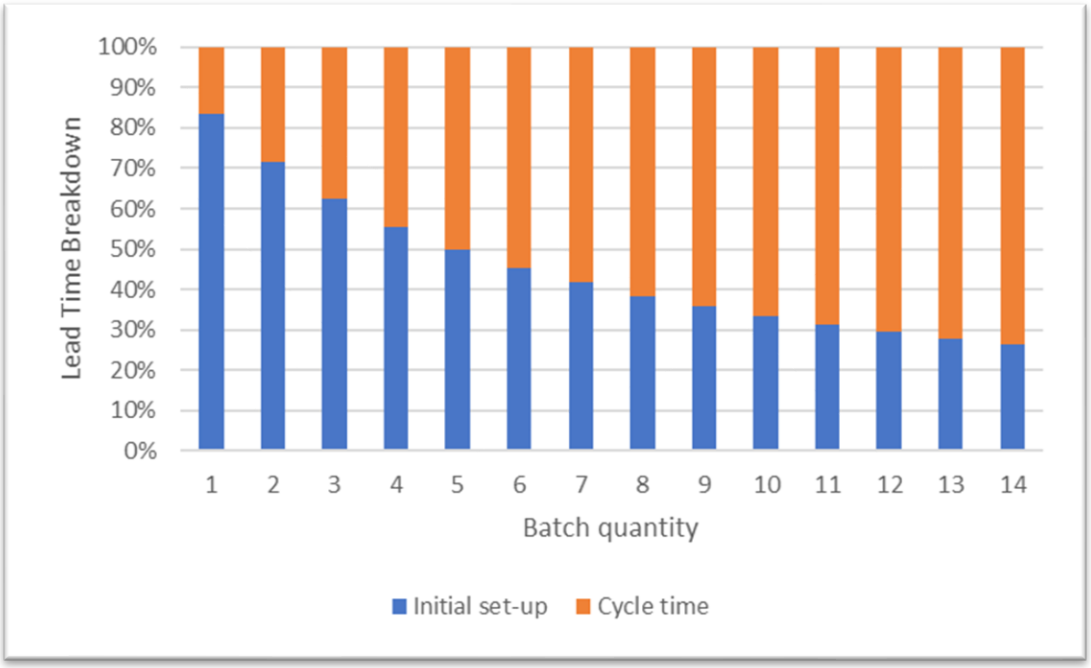


Figure 16- Batch productions decreasing impact on setup time within CNC manufacturing

CNC machining centre manufacturing's cost effectiveness or economy of scale is directly proportional to component batch numbers. The author has generated a simple graph to illustrate the effect of setup and cycle time within CNC manufacturing. Figure 16 depicts the percentage of component lead time attributed to both the setup and the total cycle time for the entire batch. It clearly demonstrates the positive effect of increased batch size in the cost effectiveness of CNC machining. The evidently detrimental effect of machine setup diminishes as the batch number increases. When high priority breakdown components require machining on a CNC mill, the setup time is typically a large proportion of the components lead time. This setup procedure typically increases with a component's complexity.

In addition, raw material storage and retrieval is a critical element of component lead time within the manufacturing process in BEP. The ineffective and substandard material selection

available and the associated storage is a waste of both company capital and limited floor space. Material storage and retrieval is currently responsible for excessive waste within the CNC process at BEP. Where Just in Time (JIT) material procurement would be superlative, the dynamic workload scheduling within the toolroom currently operates by storing a selection of material on site for breakdown situations. The reduced lead times resultant of any waste reduction would enable the toolroom to increase internal customer satisfaction within BEP.

Business Case

The toolroom is often required to repair or replace a high priority component for a breakdown within an internal customer department within the BEP. The costs associated with any breakdown incident can be significant. When a high priority component enters the toolroom system, time becomes a critical measurable of its success. The speed at which a quality component can be provided for production to continue is vital. To fully understand the cost implications the author has included a typical breakdown of costs which could be the result of a production breakdown period. The data is split into the labour rate, lost sales, material/processing adjustment and an overall total cost.

Labour Rate Sigma Assembly = 165 idle employees Labour rate = £56.20	*£53.20 x 165 staff =* ***£9273 per hour.***
Lost Sales Engine Cost= $(1250) Or £935.65 Cycle Time = 27 secs	*£936.65 x 133 engines =* ***£128,487 per hour.***
Material/Processing Costs Adjustment Assumption - 30% of material/production costs due to ceased production	*£128487 x 30% =* ***£38,546 per hour***
Total Cost – P/Hr of Lost Production	*£9273 + £38546 =* ***£47,819 per hour.***

The material/processing cost adjustment has been included to factor in the value of the in-process stock (WIP) and the reduction in material and processing costs resulting from a cease in production. A conservative assumption of 30% of any lost engine sales has been estimated for this data.

The author conservatively estimates that more than 25hrs could be squandered p/annum through existing practices within BEP toolroom. The current manufacturing process of breakdown components which can direct link to engine production is deemed inefficient. This

could hypothetically equate to loses of £1195475 in lost sales and labour costs. Therefore, any measurable reduction to component lead time could lead to significant annual savings:

- *10% = £119,547*
- *20% = £239,095*
- *30% = £358641*

High Level Process Map (SIPOC)

High level process mapping is encapsulated by the acronym SIPOC (Suppliers, Inputs, Processes, Outputs and Customers). The SIPOC model is an essential tool for the recognition of all process inputs, intermediate steps and outputs within a manufacturing process. According to (Cooper, 2013), the SIPOC process proves to be a vital component for minimising waste within an efficient process

A SIPOC process map is generated by considering the following questions listed in

Table 7.

Suppliers	Who provides process inputs?
Inputs	What inputs i.e. materials, data of other resources are required?
Processes	Defined series of steps applied to transform inputs into outputs?
Outputs	What are the resultant products or services from the process?
Customers	Who are the recipients of outputs?

Table 7 - SIPOC

Table 8 – High level process map (SIPOC)

Suppliers	Inputs	Processes	Outputs	Customers
-Facility internal maintenance staff -Material providers -Tooling providers	-Work order placed by customer departments via Maximo system	-Raw material is processed -Work holding selected and set up -Tooling selected and set up -Component machining cycle -Component deburring - Ancillary processes are completed if required -Component final inspection	-Completed components stored for collection by customer departments	-Facility internal maintenance staff

The process map or SIPOC for the toolroom typically comprises of the following steps seen in Table 8. The primary variation typically occurs within the processes step of the process map. This is due to the wide variety of machining processes required for different activities within the department.

Process Map

(Cooper, 2013) defines process mapping as an essential tool to enable the visualisation of a manufacturing process. The illustrative process can facilitate a comprehensive understanding of the process, this is specifically significant for the identification of rework loops and hidden factory. The importance of which is reinforced by (Wilson, 2015) who rationalises that unnecessary manpower, time, floor space otherwise referred to as 'hidden factory' is responsible for driving waste within the process . Figure 17 is the current process map illustration for the CNC machining section. It includes a rework loop or 'hidden factory' which is responsible for identifying and reworking components which do not meet the customers' requirements.

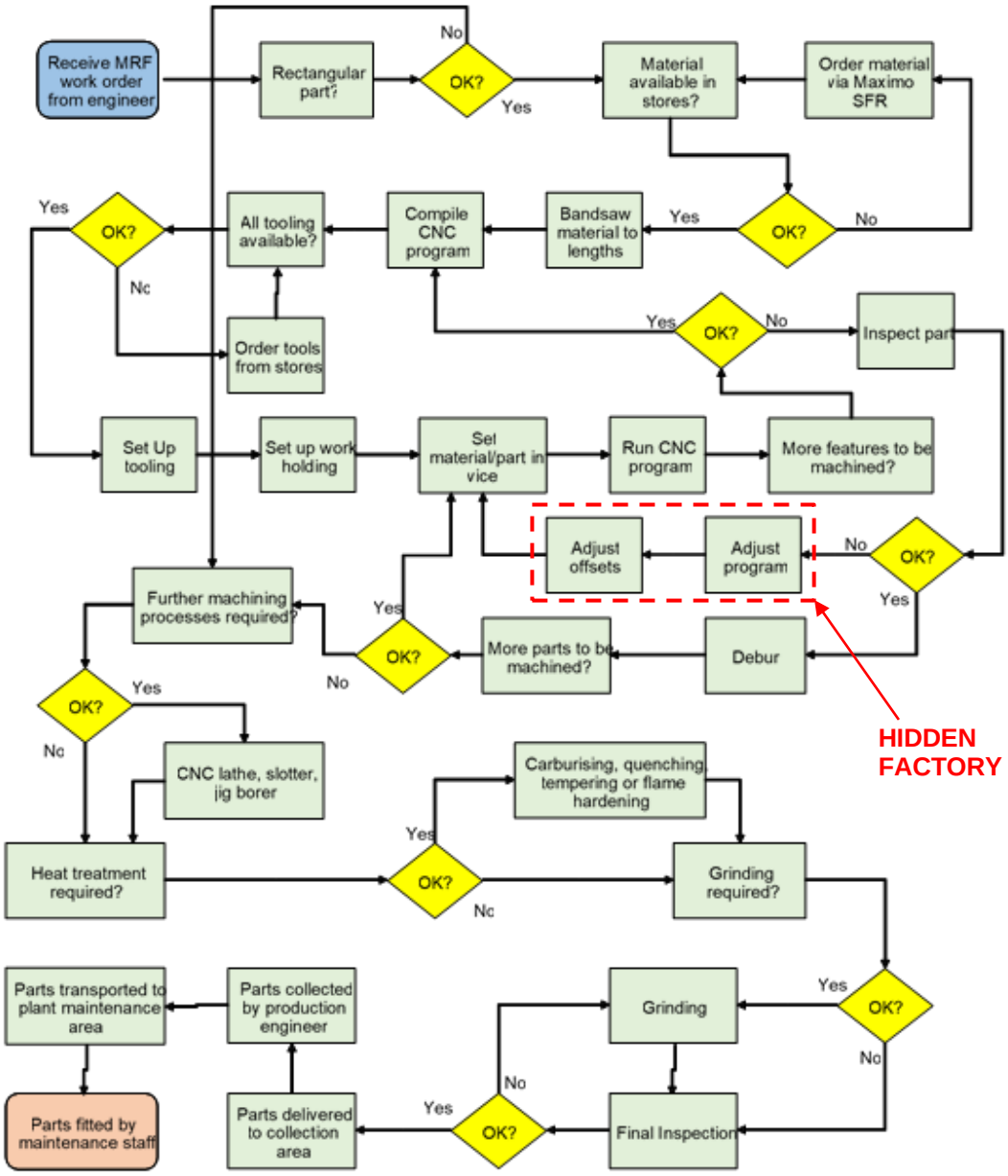


Figure 17 – CNC milling operation process map

Cause and Effect

(Chahal & Narwal, 2017) describe the benefits of employing lean methodology to identify the underlying issues that can potentially impact to a process. One such tool is cause and effect or Ishikawa diagrams. The diagrams vary but are typically referred to as the 6M's: Method, Machine, Material, Measurement, Man and Management. These are possible causes that contribute towards the unwanted effect (George, et al., 2005). Figure 18 shows a cause and effect diagram identifying the 6M's for the CNC milling process within BEP.

Table 9 – List of cause and effect 6M's

Method	Are methods well established and/or reliable?
Machine	Are there prospective maintenance concerns?
Materials	Are there prospective supply chain or raw material concerns?
Measurement	Are there prospective measurement system errors or inconsistencies?
Man(People)	Are there potential workforce concerns? i.e. Training or manpower
Management	Are there adequate management resources? i.e. Experience or process

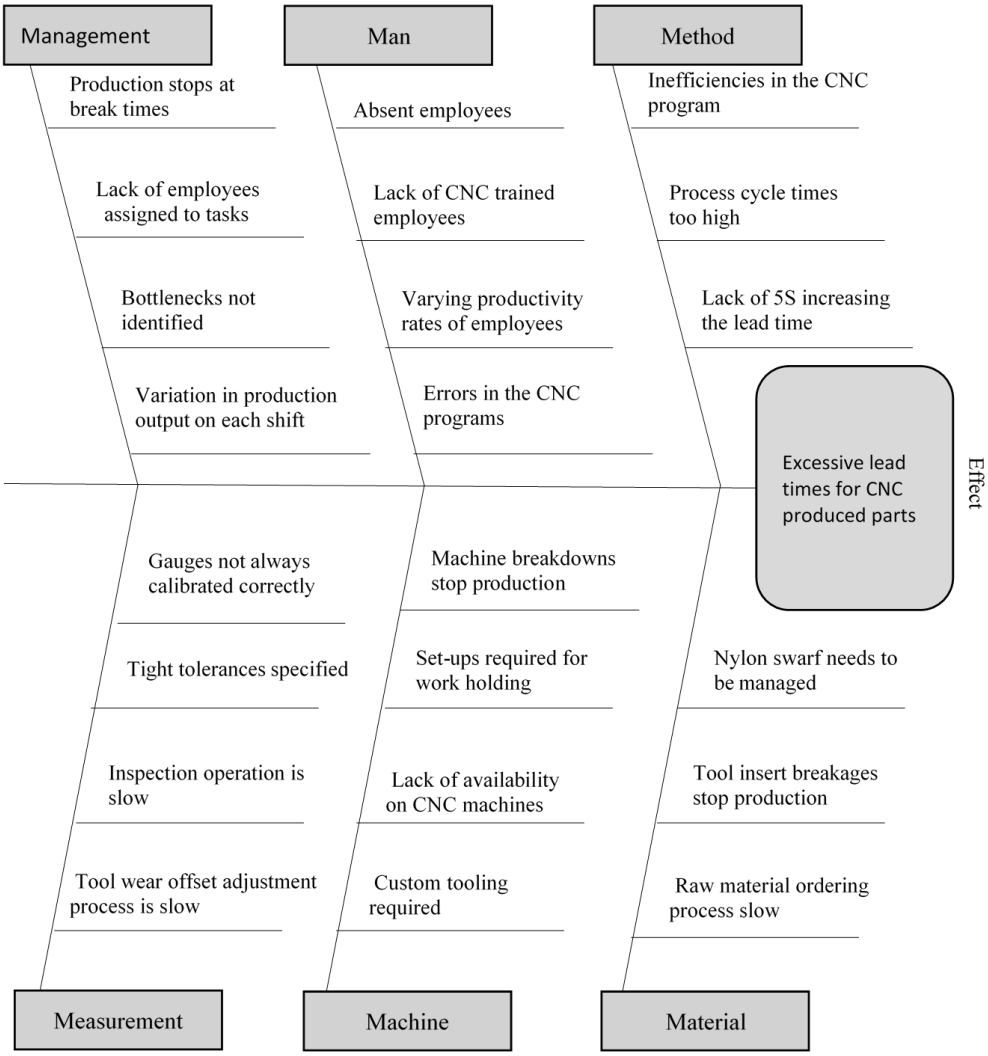


Figure 18 – Cause and effect diagram

Toolroom Added Value?

Indirect or supplementary support departments provide little or no direct value to manufacturing process. Therefore, its contribution to the manufacturing process requires an in-depth consideration. The toolroom has the primary function of maintenance support to its internal customers within BEP. Whilst the department can run at low capacity or be ineffectual when internal customers have limited use for its function. Its ability to design, repair and manufacture components in minimum lead time to internal customers can redress its ability to add value. Therefore, these irreplaceable services must render the toolroom of enough importance to regard its service invaluable to modern high-volume manufacturing facilities. Although to do this effectively, the toolroom must be able to produce a service equal or superior to an external provider. This requires a service which can turn around parts quicker, cheaper and of equal or greater quality. When the volume of mass-producing parts is considered, time is of the upmost importance. The time and therefore cost saving provided by internal support facility like the toolroom clearly demonstrates the potential for added value. But only the functions which add value are of advantage to the company. The burden of overheads such as wages, materials and energy bills do not add value. As a result, a toolroom must apply lean practices to ensure it value to the company.

Waste Identification

Overproduction

Overproduction is repeatedly identified as a fundamental element of the eight wastes. (Kobayashi, 1995) describes it as the primary driver for waste and excess work in progress (WIP) and finished goods. (Fernández-Solís & Rybkowski, 2012) describe it in its most basic form, ‘production out stripping demand’.

However, it may be claimed that overproduction at the toolroom in BEP, is not typically recognised as a waste. The customer or receiving production areas in BEP, will often request unnecessary spares. This is to ensure that there are buffer stocks, these are often held back by different shifts ready to be utilised in machining and assembly maintenance issues, see Figure 19. This strategy of trying to protect BEP in the event of major equipment failure and lost production, is short sighted. Whilst the potential of stopping customer plants and the associated fines is considerable. Ordering and making parts purely for speculative maintenance issues, will result in overproduction of parts which are often out of date to current specifications. Whilst this seems a sensible solution, it can lead to considerable levels of redundant inventory (Thomas, 2019).

Though overproduction is often driven by the customer, this is not always the case. The complex machining of small batches is unlike the mass production environment. The

toolroom environment is truly prohibitive to just in time (JIT) manufacturing. There are numerous limiting factors which do not allow for the JIT methodology to be effectively implemented. The balance of selecting the right batch size and not overproducing is vital to the implementation of lean methodology within a toolroom. The toolroom has a varied mix of volume and batch sizes to consider at any one time. Simple parts can be completed in minutes, whilst complex high-volume items can take several weeks or months. The complexity of machine setups can add considerable time to any job, so it needs careful consideration when deciding batch sizes (Thomas, 2019).

Figure 19 - Stored inventory of finished parts

Inventory

The TPS methodology identifies excess inventory as one of the primary wastes. (Jeffrey K. Liker, David Meier, 2005) describe this waste as the excess of raw materials, work in progress (WIP) and finished goods. This wasted inventory, is clearly evident within the toolroom. Increased inventory is incompatible with lean manufacturing methodology. One area where this is apparent is within the steels store. The toolroom holds a wide variety of stock, different types of materials, sizes and shapes, see Figure 21.

The balance between having available material for a quick turnaround and carrying excess inventory is a difficult one. According to (Tatikonda & Tatikonda, 1991) this form of inventory will incur additional costs to the company as result of increased carrying, storage, handling, time, and increased opportunities for damage. A solution to this would be to use the services of a local steel supplier. The intangible increased cost of material would be offset by the ability to order the exact amount of material required. This would address the need

for material to be carried, stored, handled and reduce opportunity for damage. This would be of particular use when using more expensive materials.

WIP can also be identified as inventory, this is evident within the toolroom. The reworking of out of tolerance parts, results in various parts of WIP being held. These parts are either being processed or waiting to be processed. This is an opportunity for WIP inventory to be easily unaccounted for, this results in reduced quality control and stock control (Thomas, 2019).

Figure 21 - Toolroom Steel Store

Figure 20 – WIP of reworked parts.

Scrap and Defects

Defects are a form of waste that comprise of parts that are scrapped or require rework. This form of waste is an expense in relation to both labour and raw material cost. The type of work undertaken in the toolroom is predominately the manual use of machines to produce various parts. This increases the possibility of defective parts, as human error is a mitigating factor in machine shop defects. Whilst the production of defective parts is infrequent, the result of an unidentified defect can be significant. A defect should be easily identified, at each phase of a correctly controlled production process. But due to the batch production nature of a toolroom manufacturing, when a defect is found, then the whole batch may be defective. In the toolroom environment, defects contribute significantly to increased lead time and to lost production. The scrapping or reworking of parts increases the amount of material required, amount of allocated machine time and tooling wear. This considerably increase costs which must be absorbed by the machine shop as they cannot be passed on to the customer.

Generally, when a defect is identified in the batch manufacturing of parts it can create both idle man and machine time. The manufacturing process can often involve many different machines and operations. A single defect could affect the flow through this process (Thomas, 2019).

Waiting

Waiting can be simply defined as idle time within a process, an idle toolmaker can be the result of many influencing factors. The waste of waiting is also referred to as queuing, (Sternberg, et al., 2013) defines the process as one step waiting for another. The toolroom invokes a different way of thinking in relation to idle time. The batch nature of manufacture within a machine shop, denotes that idle time can either be attributed to the part waiting or the toolmaker waiting. The manufacturing flow can frequently result in a part waiting for the toolmaker to complete a part so that he can complete the next, on large batches this can be considerable. The opposite of this would be the toolmaker waiting for material stock to be sourced and cut, heat treatment to complete or simply a cnc operation to complete. The cumulation of this idle time adds considerably to part completion time, WIP and inventory of finished parts waiting to be despatched within the toolroom (Thomas, 2019).

Motion

In lean manufacturing, unnecessary motion refers to employee movement which does not add value to a process or product. The waste of motion can take many forms, such as searching for parts, drawings or equipment. According to (Rawabdeh, 2005), poor ergonomics initiate waste once employees excessively bend, stretch or walk. More specifically any excess movement between machines and associated tools or controls. To improve an inefficient process, such actions must be avoided (Haider, et al., 2015).

Figure 22 - Examples of motion waste within the toolroom.

Figure 22 above clearly illustrates how a poorly organised toolroom can affect waste in terms of motion. The lathe and tool cupboard are both very unorganised, tools and chucks are left in disarray. There is no standard to be maintained by employees, the result is the machinist's searching for the correct tools and machine accessories. The toolroom environment results in machinists being exposed to excessive wasted motion due to the hugely varying flow of production. The type of part being produced can be as simple as using one machine to be completed or multiple machines and processes, both require completely differing levels of motion. To keep any waste to minimum, toolmakers must strive to be as efficient as possible. When starting a job, a clear strategy of the process and equipment would be hugely beneficial. Utilising CNC cycle or heat treatment times to set up or plan other jobs, or simply deburring parts between cycle times to maximise efficiency. Ultimately wasted motion must be limited by applying lean methodology such as work balancing, visual factory and standardised work practices.

Further to considering the waste within motion, the cascading effect must also be considered. Any wasted motion will potentially produce other waste, for example waiting. This is due to the wasted motion slowing done a process and making another process wait, resulting in work imbalance (Thomas, 2019).

Transportation/ Conveyance

Any unnecessary transportation or conveyance within any process is considered waste. This form of waste considers the movement of material or goods. (Chahal & Narwal, 2017) discuss double handling and excessive handling of material, with the increased risk of damage and decline. Further to this (Rawabdeh, 2005), consider the distance between processes and the proportional relationship to waste. They demonstrate clear evidence of the relationship in identifying quality issues, reporting time and corrective measures. The overall value of a product is directly affected by unnecessary transportation, resulting in increases in time and expense. Transportation must be kept to a minimum within the JIT manufacturing methodology. (Kootanaee, et al., 2013) states that for a JIT system to work effectively, waste must be reduced in all areas.

The manufacturing process within a toolroom starts with raw material, this is transported to the toolroom from the steel stores or an outside supplier. Then parts are transported from process to process as each feature is processed in sequence. Finished parts are then picked up by the relevant department. The flow of a workpiece through the toolroom, results in parts being potentially handled multiple times; the consequence is habitually excessive levels of waste. Figure 23 above shows the vast area of the toolroom. The toolmaker benches are located at the bottom left of the picture and the steel stores is out of picture at the far end. Parts flow through the department requiring toolmakers and the parts to potentially cover large distances between processes (Thomas, 2019).

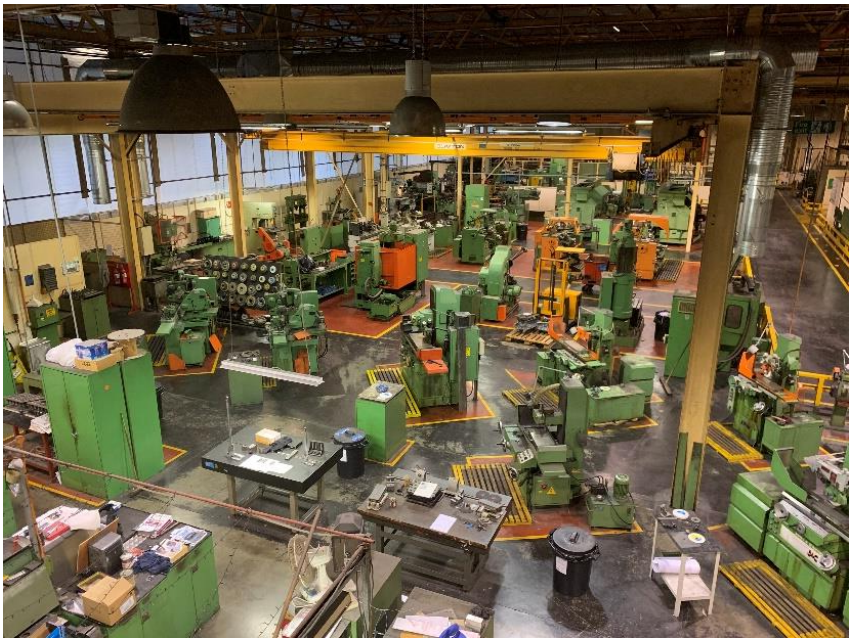


Figure 23 - Toolroom shop floor layout

Over processing

The waste of Over processing can be defined as manufacturing products to a higher standard than required. The addition of futile processes or features generates unnecessary work. These processes or features require time and resources but don't create added value. (Rampersad,K. El-Homsi, A., 2007) define added value, as something a customer is willing to pay for. An example of this would be specifying a ground finish where a standard machined finish would be acceptable.

When considering over processing specifically within a toolroom, numerous issues can be identified. Parts are often created from part drawings; these include tolerances of part dimensions. Machinists time can often be spent trying to create parts of mean size or the perfect part. Making full use of any tolerances is perfectly acceptable, making perfect parts is potentially creating waste.

This type of waste may be incorporated in the hidden factory and may not be clear until detailed process verification has been carried out (Thomas, 2019).

Knowledge, skills and creativity

The 8th waste considers the untapped human potential. (Liker, 2004) discusses the waste of an employee's knowledge and natural creativity. (SKhmot, 2017) investigates lean methodologies need to specify standard operating procedures, and how this can be counterproductive if an employee input is stifled.

This type of waste can be identified in the toolroom as toolmakers complete their work at a level that does not exceed their training level. It could be beneficial for the company to encourage employees to suggest new ideas to improve their working methods or provide additional training.

These 8 categories of waste have one significant characteristic in common. They add cost to the manufacturing process and reduce the overall profitability of the company as a whole (Thomas, 2019).

Data Collection Strategy

This section will identify and collate suitable data to enable a complete evaluation of the current process and any potential waste within it. In addition, this data will be used to determine a benchmark for the departments process performance. The identification of a suitable benchmark is vital to ascertain the effect for any improvements made to the process (SKhmot, 2017).

Data Collection

It is essential to develop a data collection plan capable of collating both variable and attribute data. (Ford 6-Sigma, 2006) states the importance of recording both the existence of a process or event in addition to the related measurable data. Table 10 lists the different sources of data also further explaining the reasoning for each source. For the construction of a current state VSM the following data has been obtained (Table 10).

Table 10 – Data collection plan

Type of data Variable V Attribute A (and/or)	Reason	Provider	Method	Source	Location
Archived CNC component data (V and A)	Baseline assessment	Machinist	Data collection form	CNC archived of work	Toolroom
Archived CNC component data (V and A)	Waste Identification	Machinist	Data collection form	CNC archived of work	Toolroom
CNC cycle times (V)	Create existing state VSM	Machinist	Data collection form	CNC machining cycles	CNC mill section
CNC changeover times (V)	Create existing state VSM	Machinist	Data collection form	CNC production cycle	CNC mill section

Archived Toolroom Data Collection

The author has decided to collate data from components manufactured in the CNC section within the toolroom see Figure 24. This involved analysing archived work over a 12-month time period to eliminate any seasonal trends because of shutdown maintenance periods.

Table 11 displays the data collected from the archived CNC manufacturing drawings. It collates both attribute and variable data to fully evaluate the manufacturing process. Attribute data includes material selection and any requirement of a secondary heat treatment process. The variable data includes part quantity, complexity value, material removal and priority. Data has been utilised to calculate the volume of material that must be removed from the raw stock size. When combined with generic feed and speeds used it can calculate a material removal rate (MRR). The combination of MRR and material volume will generate an approx. cycle time for material removal (Harveyperformance, 2018). This data is essential for the estimation of manufacturing cycle times, therefore removing the requirement to physically time the machining process. This also allows to estimate the cycle time of any historical work undertaken in the toolroom.

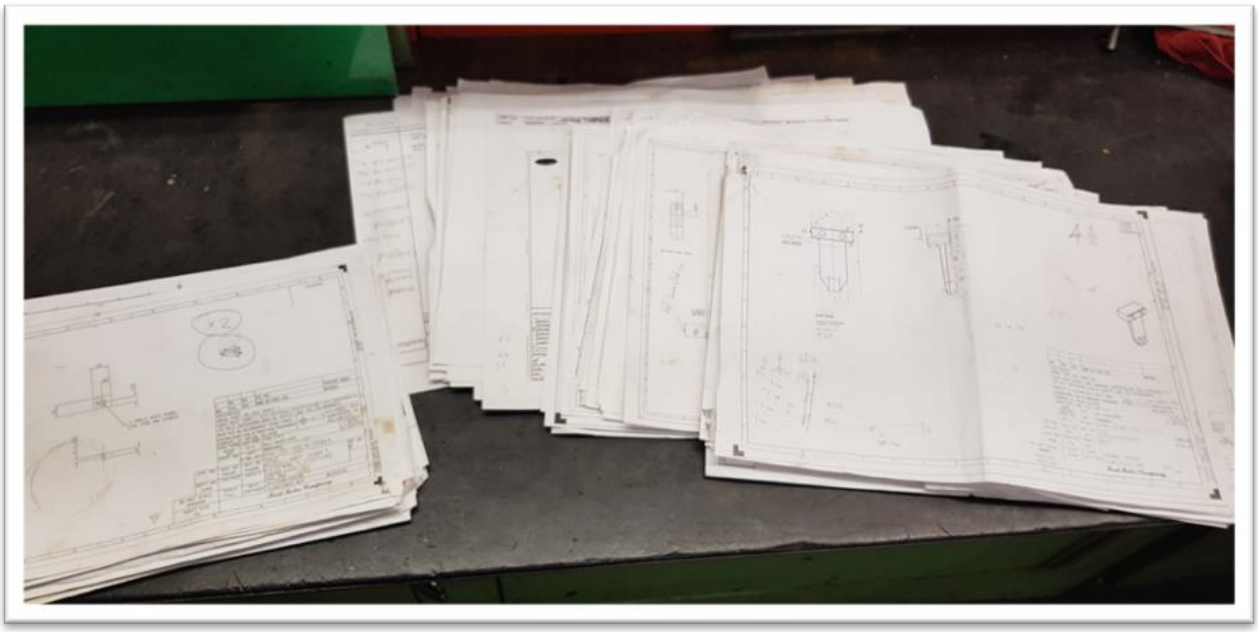


Figure 24 - Archived CNC work

Table 11- Data collection of archived CNC work

Job	Component Description	Quantity	Repeat Order Y=1/N=2	Material	Rough stock size req. (mm)			Vol. Rough stock (mm^3)	Finished part outside Dim. (mm)			Vol. part (mm^3)	Volume % of Rough Stock	Volume of Material removed	Priority	Complexity (1-3) 1 Lowest	Cut Material	Mill - total	Mill - Cycle Time	Mill - Programmed setup	Hardness - Rockwell	Hardening - Cycle time	Total
					L	W	H		L	W	H												
1	AJ126 Finished Crank to Platten Wear Pad 1	3	1	Nylon	135	95	4	51300	127	89	4	45212	88.13	6088.00	1	2	19	54.37	25.37	29	N/A	0	73.37
2	AJ126 Finished Crank to Platten Wear Pad 2	3	1	Nylon	90	70	4	25200	86	64	4	22016	87.37	3184.00	1	2	19	42.27	13.27	29	N/A	0	61.27
3	AJ126 Finished Crank to Platten Wear Pad 3	3	1	Nylon	25	25	30	18750	20	20	26	10400	55.47	8350.00	1	2	19	63.79	34.79	29	N/A	0	82.79
4	AJ126 Finished Crank to Platten Wear Pad 4	3	1	Nylon	40	40	30	48000	39	30	25	29250	60.94	18750.00	1	2	19	107.13	78.13	29	N/A	0	126.13
5	AJ126 Finished Crank to Platten Wear Pad 5	3	1	Nylon	25	20	4	2000	20	15.5	4	1240	62.00	760.00	1	2	19	32.17	3.17	29	N/A	0	51.17
6	AJ V6 piston: block buffer nose	1	2	Nylon	100	100	25	250000	80	80	22	140800	56.32	109200.00	2	5	13	204.67	151.67	53	N/A	0	217.67
7	Pad Clamp	1	2	Tool steel	30	30	20	18000	25	25	16	10000	55.56	8000.00	3	1	13	24.11	11.11	13	58	390	817.11
8	Zetec SE clamping fixture	1	1	Mild steel	125	80	30	300000	120	65	24	187200	62.40	112800.00	3	3	13	189.67	156.67	33	65	780	1762.67
9	Cam timing chain tensioner	2	1	Aluminium	455	80	12	436800	450	64	8	230400	52.75	206400.00	1	4	16	619.33	573.33	46	N/A	0	635.33
10	AJ piston carrier lockplate	20	1	Mild steel	100	80	4	32000	98	64	3	18816	58.80	13184.00	1	2	70	446.22	366.22	80	65	780	2076.22
11	AJ piston carrier dual lockplate	20	1	Mild steel	130	100	4	52000	124	98	3	36456	70.11	15544.00	1	2	70	511.78	431.78	80	65	780	2141.78
12	Zetec SE spindle drive sensor	1	2	Mild steel	100	100	40	400000	82	82	37	248788	62.20	151212.00	2	4	13	253.02	210.02	43	65	780	1826.02
13	AJ fuel rail injector service tool	12	1	Tool steel	60	20	10	12000	53	15	9	7155	59.63	4845.00	1	5	46	166.75	80.75	86	58	390	992.75
14	Bearing mount plate	4	2	Mild steel	100	100	50	500000	84	82	44	303072	60.61	196928.00	1	1	22	1116.04	1094.04	22	N/A	0	1138.04
15	AJ damper mounting block	4	2	Nylon	60	60	40	144000	50	50	40	100000	69.44	44000.00	1	1	22	266.44	244.44	22	N/A	0	288.44
16	Water pump lube base	1	2	Nylon	265	205	40	2173000	260	200	30	1560000	71.79	613000.00	2	3	13	884.39	851.39	33	N/A	0	897.39
17	Knock sensor harness connector check handle	1	1	Aluminium	155	60	60	558000	150	55	45	371250	66.53	186750.00	3	2	13	282.38	259.38	23	N/A	0	295.38
18	Locator	1	2	Mild steel	80	60	30	144000	60	54	24	77760	54.00	66240.00	3	1	13	105.00	92.00	13	65	780	1678.00
19	Transfer fixture clamp shoe	1	1	Tool steel	40	40	20	32000	36	22	18	14256	44.55	17744.00	3	4	13	67.64	24.64	43	N/A	0	80.64
20	Transfer fixture clamp shoe	4	1	Tool steel	40	40	20	32000	36	22	18	14256	44.55	17744.00	1	4	22	150.58	98.58	52	N/A	0	172.58
21	Camshaft gauge reference V	24	2	Bronze	60	60	20	72000	56	45	15	37800	52.50	34200.00	1	2	82	1232.00	1140.00	92	N/A	0	1314.00
22	Rotary actuator camshaft claw	2	1	Tool steel	125	40	20	100000	120	35	19	79800	79.80	20200.00	3	5	16	112.11	56.11	56	N/A	0	128.11
23	Spindle support fixture	1	1	Nylon	125	100	16	200000	122	93.5	13.5	153994.5	77.00	46005.50	3	2	13	86.90	63.90	23	N/A	0	99.90
24	Supercharger end effecter RH clamp jaw	1	1	Nylon	125	80	80	800000	121	77	65.5	610263.5	76.28	189736.50	3	4	13	306.52	263.52	43	N/A	0	319.52
25	Zetec SE gripper assembly clamping jaw	2	1	Brass	80	60	25	120000	60	52	20	62400	52.00	57600.00	5	4	16	206.00	160.00	46	N/A	0	222.00
26	AJ crank OP160 plate	2	2	Mild steel	350	60	20	420000	340	57	16	310080	73.83	109920.00	1	3	16	341.33	305.33	36	N/A	0	357.33
27	Untightening unit grip lever	4	2	Tool steel	80	40	25	80000	66	40	20	52800	66.00	27200.00	2	2	22	183.11	151.11	32	58	390	985.11
28	Dragon crank palm locking tool	1	2	Aluminium	340	205	16	1115200	335	200	15	1005000	90.12	110200.00	1	4	13	196.06	153.06	43	N/A	0	209.06
29	Flange prism block	1	2	Nylon	130	100	100	1300000	127	85	82	885190	68.09	414810.00	3	3	13	609.13	576.13	33	N/A	0	622.13
30	SC End effector LH clamp jaw	1	1	Nylon	100	80	40	320000	81	70	33	187110	58.47	132890.00	3	2	13	207.57	184.57	23	N/A	0	220.57
31	Zetec SE crank fixture	1	1	Mild steel	145	100	60	870000	140	90	56	705600	81.10	164400.00	2	2	13	251.33	228.33	23	N/A	0	264.33
32	OP70 Clamp finger	2	1	Mild steel	80	40	40	128000	65	30	24	46800	36.56	81200.00	3	3	16	261.56	225.56	36	65	780	1837.56
33	Press in unit stop plate	1	2	Mild steel	75	40	5	15000	70	34	4	9520	63.47	5480.00	3	1	13	20.61	7.61	13	N/A	0	33.61
34	Pump bolt lube tray	2	2	Aluminium	145	40	10	58000	140	40	7	39200	67.59	18800.00	1	2	16	78.22	52.22	26	N/A	0	94.22
35	Camshaft gauge reference V	20	1	Bronze	60	50	16	48000	56	45	15	37800	78.75	10200.00	1	2	70	363.33	283.33	80	N/A	0	433.33
36	AJ auto grease bracket	2	2	Nylon	120	100	30	360000	115	82	25	235750	65.49	124250.00	1	3	16	381.14	345.14	36	N/A	0	397.14
37	Sigma head fixture	1	2	Mild steel	80	60	50	240000	65	58	50	188500	78.54	51500.00	1	4	13	114.53	71.53	43	65	780	1687.53
38	Sigma crank op5 flange end support bracket	1	1	Mild steel	115	80	80	736000	110	50	50	275000	37.36	461000.00	3	2	13	663.28	640.28	23	N/A	0	676.28
39	V6 piston block buffer nose	1	1	Nylon	100	100	25	250000	80	80	22	140800	56.32	109200.00	2	2	13	174.67	151.67	23	N/A	0	187.67
40	Sigma GTDI Op160.1 transfer support block	2	1	Mild steel	200	60	60	720000	198	50	40	396000	55.00	324000.00	1	2	16	926.00	900.00	26	N/A	0	942.00
41	Zetec SE locator block	1	1	Tool steel	100	30	40	120000	97	24	35	81480	67.90	38520.00	3	1	13	66.50	53.50	13	N/A	0	79.50
42	Advance roller plate	1	2	Aluminium	405	255	40	4131000	400	250	30	3000000	72.62	1131000.00	1	4	13	1613.83	1570.83	43	N/A	0	1626.83
43	AJ head assembly valve compressor block	1	2	Mild steel	250	80	80	1600000	245	70	61	1046150	65.38	553850.00	3	4	13	812.24	769.24	43	N/A	0	825.24
44	AJ conrod piston parking fixture	4	1	Nylon	450	100	30	1350000	445	80	25	890000	65.93	460000.00	1	5	22	2617.56	2555.56	62	N/A	0	2639.56
45	Transfer fixture clamp shoe	4	1	Tool steel	40	40	20	32000	36	22	18	14256	44.55	17744.00	3	2	22	130.58	98.58	32	58	390	932.58
46	Transfer fixture clamp shoe	11	1	Tool steel	40	40	20	32000	36	22	18	14256	44.55	17744.00	1	2	43	324.09	271.09	53	58	390	1147.09
47	Famatec sump manipulator lower jaw	1	1	Nylon	105	30	40	126000	100	25	32	80000	63.49	46000.00	3	1	13	76.89	63.89	13	N/A	0	89.89
48	Platen engaging rail	1	1	Mild steel	525	100	10	525000	520	95	9.5	469300	89.39	55700.00	3	2	13	100.36	77.36	23	N/A	0	113.36
49	Rotary actuator camshaft claw	2	1	Tool steel	125	40	20	100000	120	35	19	79800	79.80	20200.00	2	4	16	102.11	56.11	46	N/A	0	118.11
50	Rear step block A Bank	9	2	Nylon	100	60	50	300000	94	55	45	232650	77.55	67350.00	2	2	37	888.88	841.88	47	N/A	0	925.88
51	AJ Dataman bracket	2	2	Nylon	100	80	100	800000	80	79	93	587760	73.47	212240.00	2	2	16	615.56	589.56	26	N/A	0	631.56
52	Op70 bracket	1	2	Mild steel	100	100	12	120000	97	80	10	77600	64.67	42400.00	1	2	13	81.89	58.89	23	N/A	0	94.89
53	Adjusting block	1	2	Mild steel	265	100	30	795000	260	100	25	650000	81.76	145000.00	1	3	13	234.39	201.39	33	65	780	1807.39
54	Part location pin post	4	1	Tool steel	60	40	20	48000	52	32	13	21632	45.07	26368.00	2	2	22	178.49	146.49	32	N/A	0	200.49
55	Sensor swipe plate	2	2	Nylon	155	155	30	720750	150	150	20	450000	62.43	270750.00	2	3	16	788.08	752.08	36	N/A	0	804.08
56	Op110 head drive key	6	1	Mild steel	60	20	30	36000	50.5	18	25	22725	63.13	13275.00	3	3	28	158.63	110.63	48	N/A	0	186.63
57	AJ Force gauge adapter	1	2	Aluminium	85	50	30	127500	80	40	20	64000	50.20	63500.00	1	2	13	111.19	88.19	23	N/A	0	124.19
58	Force gauge push pin	1	2	Mild steel	20	20	40	16000	16	16	30	7680	48.00	8320.00	1	1	13	24.56	11.56	13	65	780	1597.56
59	V6 piston block buffer nose	1	1	Nylon	100	100	25	250000	80	80	22	140800	56.32	109200.00	2	3	13	184.67	151.67	33	N/A	0	197.67
60	Zetec SE gripper assembly vee block	8	1	Brass	68	55	12	44880	60	52	20	62400	139.04	17520.00	2	3	34	140.67	194.67	54	N/A	0	106.67
61	Transfer fixture clamp shoe	1	1	Tool steel	40	40	20	32000	36	22	18	14256	44.55	17744.00	3	2	13	47.64	24.64	23	58	390	840.64
62	Transfer fixture clamp shoe	4	1	Tool steel	40	40	20	32000	36	22	18	14256	44.55	17744.00	1	2	22	130.58	98.58	32	58	390	932.58
63	ASRS pallet bumper	4	2	Nylon	50	20	15	15000	45	16	10	7200	48.00	7800.00	2	3	22	85.33	43.33	42	N/A	0	107.33
64	Gripper stop plate	1	2	Mild steel	185	100	25	462500	180	80	20	288000	62.27	174500.00	1	1	13	255.36	242.36	13	N/A	0	268.36
65	Zetec SE gauge measuring blade	1	2	Tool steel	60	40	10	24000	56	32	6	10752	44.80	13248.00	2	4	13	61.40	18.40	43	58	390	854.40
66	Gripper base plate	1	2	Aluminium	80	80	12	76800	72	76	10	54720	71.25	22080.00	1	2	13	53.67	30.67	23	N/A	0	66.67
67	Tappet Assy machine lever	1	2	Mild steel	50	30	10	15000	46	26	6	7176	47.84	7824.00	1	1	13	23.87	10.87	13	N/A	0	36.87
68	Press in unit stop plate	4	2	Mild steel	80	40	6	19200	70	34	4	9520	49.58	9680.00	3	2	22	85.78	53.78	32	65	780	1667.78
69	Turbo trolley block	10	1	Nylon	105	80	40	336000	100	60	36	216000	64.29	120000.00	2	2	40	1716.67	1666.67	50	N/A	0	1756.67
70	Turbo trolley mount	20	1	Nylon	105	40	30	126000	100	30	28	84000	66.67	42000.00	2	3	70	1256.67	1166.67	90	N/A	0	1326.67
71	Bearing shell drill fixture	1	1	Mild steel	85	50	30	127500	80	40	20	64000	50.20	63500.00	1	4	13	131.19	88.19	43	N/A	0	144.19
72	Zetec SE lift and carry unit stop	1	2	Mild steel	70	40	30	84000	63	35	20	44100	52.50	39900.00	3	3	13	88.42	55.42	33	65	780	1661.42

Waste Identification Data Collection

This section will develop a selection of suitable criteria for identifying sources of waste within the toolroom manufacturing process. This criteria will be integrated with the archived toolroom data in Table 11 to produce quantifiable data for the potential quantity of waste within previous toolroom work. Table 12 has been formulated to identify typical wastes in 8 distinct categories related to toolroom manufacturing process.

1. Material Acquirement
2. Bandsaw Saw
3. CNC Programming
4. Setup Work holding
5. Setup Tooling
6. CNC Machining
7. Deburring
8. Component Collection

Further to this, Table 12 data collection will identify the wastes related to one or more of the seven wastes listed below:

1. Waiting / Queuing Time: (Employees idle. Inventory at stand-still)
2. Overproduction: (Producing in addition than specifically required)
3. Scrap / Defect: (Component error)
4. Motion: (Any wasted motion by man or machine)
5. Over processing: (manufacturing products to a higher standard than required)
6. Inventory: (Retaining unnecessary inventory)
7. Transport Unnecessary: (Moving material unnecessarily or long distances)(Double handling material).

The data will be collected by the machinists working within the toolroom. The author reasons that machinists are directly involved with the manufacturing process and therefore most capable to accurately evaluate the process. The chosen criteria are designed to capture waste which has been previously identified by the research from the preceding waste identification section. The author fully appreciates that the system will not capture every form or instance of waste within the process. Although the author feels that the initial chosen criteria will identify the most fundamental wastes and highlight the opportunity for their removal. The criteria would be part of a continuous improvement process, where modifying the criteria would provide further scrutiny of the waste within the process This is reinforced by (Thorn, 2018), who states the importance of identifying

the ‘low hanging fruit’ as these are typically the simplest and most inexpensive to eliminate.

Table 12- Waste Identification archived data

Job	Component Description	Quantity	Repeat Order Y/N=2	Material	Waiting Y/N (Score 1-8)		Overproduction Y/N (Score 1-8)		Defects Y/N (Score 1-8)		Motion Y/N (Score 1-8)		Inventory Y/N (Score 1-8)		Over processing Y/N (Score 1-8)		Transportation Y/N (Score 1-8)	
1	AJ126 Finished Crank to Platten Wear Pad 1	3	1	Nylon	Y		Y		Y		Y		Y		N		Y	
2	AJ126 Finished Crank to Platten Wear Pad 2	3	1	Nylon	Y		Y		Y		Y		Y		N		Y	
3	AJ126 Finished Crank to Platten Wear Pad 3	3	1	Nylon	Y		Y		Y		Y		Y		N		Y	
4	AJ126 Finished Crank to Platten Wear Pad 4	3	1	Nylon	Y		Y		Y		Y		Y		N		Y	
5	AJ126 Finished Crank to Platten Wear Pad 5	3	1	Nylon	Y		Y		Y		Y		Y		N		Y	
6	AJ V6 piston: block buffer nose	1	2	Nylon	N		N		N		Y		N		Y		N	
7	Pad Clamp	1	2	Tool steel	N		N		N		N		N		Y		N	
8	Zetec SE clamping fixture	1	1	Mild steel	N		N		Y		Y		Y		N		N	
9	Cam timing chain tensioner	2	1	Aluminium	Y		N		N		Y		Y		Y		Y	
10	AJ piston carrier lockplate	20	1	Mild steel	Y		Y		Y		Y		Y		Y		Y	
11	AJ piston carrier dual lockplate	20	1	Mild steel	Y		Y		Y		Y		Y		N		Y	
12	Zetec SE spindle drive sensor	1	2	Mild steel	Y		N		N		Y		N		N		N	
13	AJ fuel rail injector service tool	12	1	Tool steel	Y		N		Y		Y		Y		Y		Y	
14	Bearing mount plate	4	2	Mild steel	Y		N		Y		Y		N		Y		N	
15	AJ damper mounting block	4	2	Nylon	Y		Y		Y		Y		N		Y		N	
16	Water pump lube base	1	2	Nylon	Y		N		Y		Y		Y		N		Y	
17	Knock sensor harness connector check handle	1	1	Aluminium	N		N		Y		N		N		N		N	
18	Locator	1	2	Mild steel	N		N		N		Y		Y		N		N	
19	Transfer fixture clamp shoe	1	1	Tool steel	Y		N		N		Y		Y		N		Y	
20	Transfer fixture clamp shoe	4	1	Tool steel	Y		Y		Y		Y		Y		Y		Y	
21	Camshaft gauge reference V	24	2	Bronze	Y		Y		Y		Y		Y		Y		Y	
22	Rotary actuator camshaft claw	2	1	Tool steel	Y		N		Y		Y		Y		N		N	
23	Spindle support fixture	1	1	Nylon	Y		N		N		Y		N		N		N	
24	Supercharger end effecter RH clamp jaw	1	1	Nylon	Y		N		N		Y		Y		N		N	
25	Zetec SE gripper assembly clamping jaw	2	1	Brass	Y		Y		Y		Y		Y		N		Y	
26	AJ crank OP160 plate	2	2	Mild steel	Y		N		N		Y		N		N		N	
27	Untightening unit grip lever	4	2	Tool steel	Y		N		Y		Y		Y		Y		Y	
28	Dragon crank palm locking tool	1	2	Aluminium	N		N		N		Y		Y		N		Y	
29	Flange prism block	1	2	Nylon	N		N		N		Y		N		N		N	
30	SC End effector LH clamp jaw	1	1	Nylon	Y		N		Y		Y		Y		N		N	
31	Zetec SE crank fixture	1	1	Mild steel	Y		N		N		Y		Y		N		N	
32	OP70 Clamp finger	2	1	Mild steel	Y		Y		Y		Y		Y		N		N	
33	Press in unit stop plate	1	2	Mild steel	Y		N		Y		N		N		N		N	
34	Pump bolt lube tray	2	2	Aluminium	Y		N		N		Y		N		Y		Y	
35	Camshaft gauge reference V	20	1	Bronze	Y		Y		Y		Y		Y		Y		Y	
36	AJ auto grease bracket	2	2	Nylon	Y		N		Y		Y		N		N		N	
37	Sigma head fixture	1	2	Mild steel	Y		N		N		Y		Y		N		N	
38	Sigma crank op5 flange end support bracket	1	1	Mild steel	Y		N		Y		Y		Y		N		N	
39	V6 piston block buffer nose	1	1	Nylon	Y		N		N		Y		Y		N		N	
40	Sigma GTDI Op160.1 transfer support block	2	1	Mild steel	Y		N		Y		Y		N		Y		N	
41	Zetec SE locator block	1	1	Tool steel	N		N		N		Y		N		N		Y	
42	Advance roller plate	1	2	Aluminium	N		N		N		N		N		N		Y	
43	AJ head assembly valve compressor block	1	2	Mild steel	Y		N		Y		Y		Y		N		N	
44	AJ conrod piston parking fixture	4	1	Nylon	Y		Y		Y		Y		Y		Y		N	
45	Transfer fixture clamp shoe	4	1	Tool steel	Y		Y		Y		Y		Y		Y		Y	
46	Transfer fixture clamp shoe	11	1	Tool steel	Y		Y		Y		Y		N		Y		Y	
47	Fanatec sump manipulator lower jaw	1	1	Nylon	Y		N		Y		Y		N		N		N	
48	Platen engaging rail	1	1	Mild steel	Y		N		N		Y		Y		N		Y	
49	Rotary actuator camshaft claw	2	1	Tool steel	Y		N		Y		Y		Y		Y		N	
50	Rear step block A-Bank	9	2	Nylon	Y		Y		N		Y		Y		Y		N	
51	AJ Dataman bracket	2	2	Nylon	Y		N		Y		Y		Y		N		N	
52	Op70 bracket	1	2	Mild steel	Y		N		Y		Y		N		N		N	
53	Adjusting block	1	2	Mild steel	N		N		N		Y		N		N		N	
54	Part location pin post	4	1	Tool steel	Y		Y		Y		Y		Y		Y		Y	
55	Sensor swipe plate	2	2	Nylon	Y		N		N		N		Y		N		N	
56	Op110 head drive key	6	1	Mild steel	Y		Y		Y		Y		N		Y		N	
57	AJ Force gauge adapter	1	2	Aluminium	Y		N		Y		Y		Y		N		Y	
58	Force gauge push pin	1	2	Mild steel	Y		N		N		Y		Y		N		N	
59	V6 piston block buffer nose	1	1	Nylon	Y		N		N		Y		Y		N		N	
60	Zetec SE gripper assembly vee block	8	1	Brass	Y		Y		Y		Y		N		Y		Y	
61	Transfer fixture clamp shoe	1	1	Tool steel	Y		N		Y		Y		N		N		Y	
62	Transfer fixture clamp shoe	4	1	Tool steel	Y		Y		Y		Y		N		N		Y	
63	ASRS pallet bumper	4	2	Nylon	Y		Y		N		Y		Y		N		N	
64	Gripper stop plate	1	2	Mild steel	Y		N		Y		Y		Y		N		Y	
65	Zetec SE gauge measuring blade	1	2	Tool steel	Y		N		N		Y		Y		N		Y	
66	Gripper base plate	1	2	Aluminium	N		N		Y		Y		N		N		Y	
67	Tappet Assy machine lever	1	2	Mild steel	N		N		Y		Y		N		N		N	
68	Press in unit stop plate	4	2	Mild steel	Y		Y		N		N		N		Y		N	
69	Turbo trolley block	10	1	Nylon	Y		Y		Y		Y		Y		Y		Y	
70	Turbo trolley mount	20	1	Nylon	Y		Y		Y		Y		Y		Y		Y	
71	Bearing shell drill fixture	1	1	Mild steel	N		N		N		N		Y		N		N	
72	Zetec SE lift and carry unit stop	1	2	Mild steel	N		N		Y		Y		N		N		N	

Table 13 - Waste identification data collection

Waste	Material Acquirement	Bandsaw Saw	CNC Programming	Setup Work holding	Setup Tooling	CNC Machining	Deburring	Component Collection
Waiting / Queuing Time: (Employees idle. Inventory at stand-still)	Waiting for material procurement	Waiting for Forklift. Idle time cutting large batch of raw stock		Idle time waiting for fixturing to be manufactured.	Idle time waiting for tooling	Idle time between components cycle time	Queuing time between components	Waiting time from job completion to collection.
Overproduction: (Producing in addition than specifically required)		Additional stock cut and stored for future batch production			Additional tooling required as result of overproduction	Extra components manufactured to differing stages of completion	Extra components manufactured to differing stages of completion	

Scrap / Defect: (Component error)		Power Saw blades wander as they cut. Undersize material	Component geometry or process programming error. First run component check	Component work holding error.	Tooling setup or excessive wear error.	Inaccurate components	Inaccurate components	
Motion: (Any wasted motion by man or machine)	Distance to material stores. Motion locating, and moving raw material in stores	Motion required for cutting raw material in material stores	Repeated programming for repetitive components.	Repeated work holding set-up for repetitive components. Excessive movement in component work holding.	Repeated tooling set-up for repetitive components	Excessive motion in cycle time, i.e. tooling home or standoff position.		Excessive motion between machines, equipment and /or material.

Over processing (manufacturing products to a higher standard than required)			Programming complexity increased due to unnecessary component features or tolerancing	Breaking down set-ups to process rushed order	Extra and specialist tooling required due to unnecessary component features or tolerancing	Machining complexity increased due to unnecessary component features or tolerancing		
Inventory (Retaining unnecessary inventory)	Required material not available. Difficulty identifying suitable material.	Large number of spare blades held in material stores.			Additional tooling held in CNC milling section. Redundant tooling accumulated in section.	Additional WIP and finished components held in CNC section.	Additional WIP and finished components held in CNC section	Excessive reworked WIP and finished components held in CNC section for return to suitable department.

Transport Unnecessary: (Moving material unnecessarily or long distances) (Double handling material)	Material is delivered and left outside steel stores - double handling. Steel stores at perimeter of toolroom.	Excessive forklift movement needed to move some material to saws. Material often needs to be moved to access other material or to operate saw.		Fixturing and work holding is located at varying locations throughout the shop. Not allocated locations – no standardisation.	Tooling is in non-prod stores and requires ordering and collection - double handling			

Product Family

According to (Rother, 2009), a successful VSM should focus on a specific product family. Within the machine shop manufacturing environment, a wide variety of 'product families' can be categorised. Where the definition of 'product family' is defined as the distinct processes and/or equipment required for a category of component manufacture. The author has chosen to concentrate on a product family which is primarily undertaken within the CNC section see Figure 25. Parts typically manufactured on CNC machines consistently require fewer secondary operations, unlike manual machined components which can easily incorporate between two and typically a lot more additional processes.

		Process Steps and Equipment							
		Cut-off saw	CNC mill	CNC lathe	Heat treat	Cylindrical grinding	Surface grinding	Deburring	Suitable materials
Product Families	Cylindrical, Hardened, Ground	X		X	X	X		X	Mild steel, tool steel
	Cylindrical, Ground	X		X		X		X	Mild steel, tool steel
	Cylindrical	X		X				X	Mild steel, tool steel, aluminium, bronze, brass, plastic
	Angular, Hardened, Ground	X	X		X		X	X	Mild steel, tool steel
	Angular, Ground	X	X				X	X	Mild steel, tool steel
	Angular	X	X					X	Mild steel, tool steel, aluminium, bronze, brass, plastic

Figure 25 - CNC product family

Cycle time (C/T) and Changeover (C/O) Data

The author has selected the Sigma LH location jaw from Table 11 as aa appropriate component to review for the VSM for the current state for the CNC section. Figure 26 below is a picture of the finished component produced in the CNC section. Figure 27 illustrates the location and application of the component within the manufacturing process.

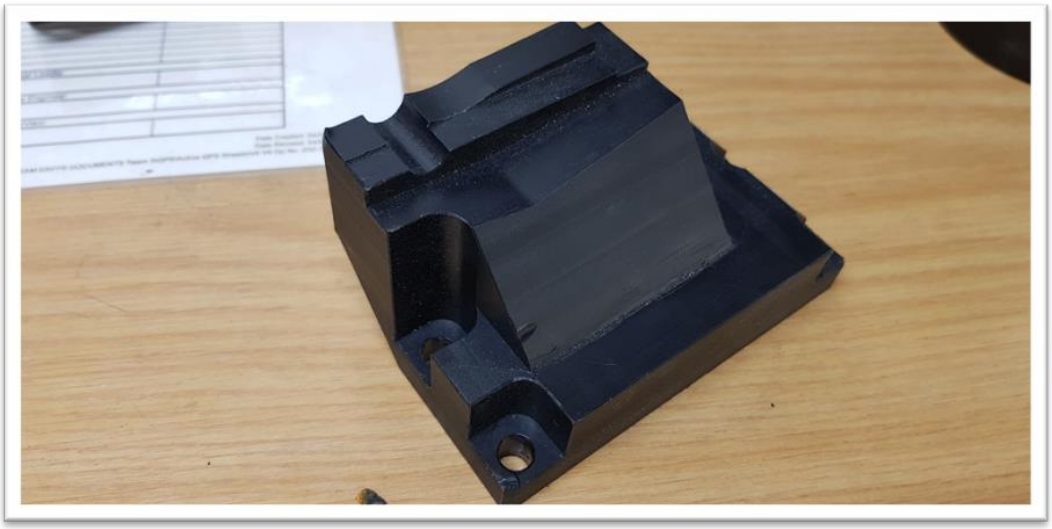


Figure 26 - Sigma LH location jaw

The Sigma LH location jaw is part of a set of three other similar components used to clamp the Sigma block during a transfer process. The complex geometry of the part is consistent with mating features on the block being clamped. This part is typically manufactured and stored as it is deemed a critical 'touching part' necessary for the assembly process.

Figure 27 – Components location and application

The author has developed a data collection form to collate data from manufacturing the Sigma LH location jaw. A stopwatch has been utilised to measure and record each step of the manufacturing process on the CNC mill. **Error! Reference source not found.** explains the type and reason for the data collected during the manufacturing process. The result of this data collection is collated in Table 14.

Table 14 - Data collected for manufacturing process.

Process Step	C/T	C/O
Material acquirement	24hrs or 1440 min	N/A
Horizontal bandsaw	18 min	15 min
CNC programming	121 min	N/A
Tooling setup	126 min	N/A
Work holding set-up	122 min	N/A
CNC machining	105 min	26 min
Deburring	27 min	N/A
Inspection	24 min	N/A
Collection	116 min	N/A

Contact Diagram

The author has produced a layout diagram of the toolroom within BEP see Figure 28. This layout will be utilised to generate a contact diagram for a typical component manufactured within the toolroom. The author has maintained a precise level of layout accuracy to allow for an accurate appreciation of the distance, direction and flow within the current process.

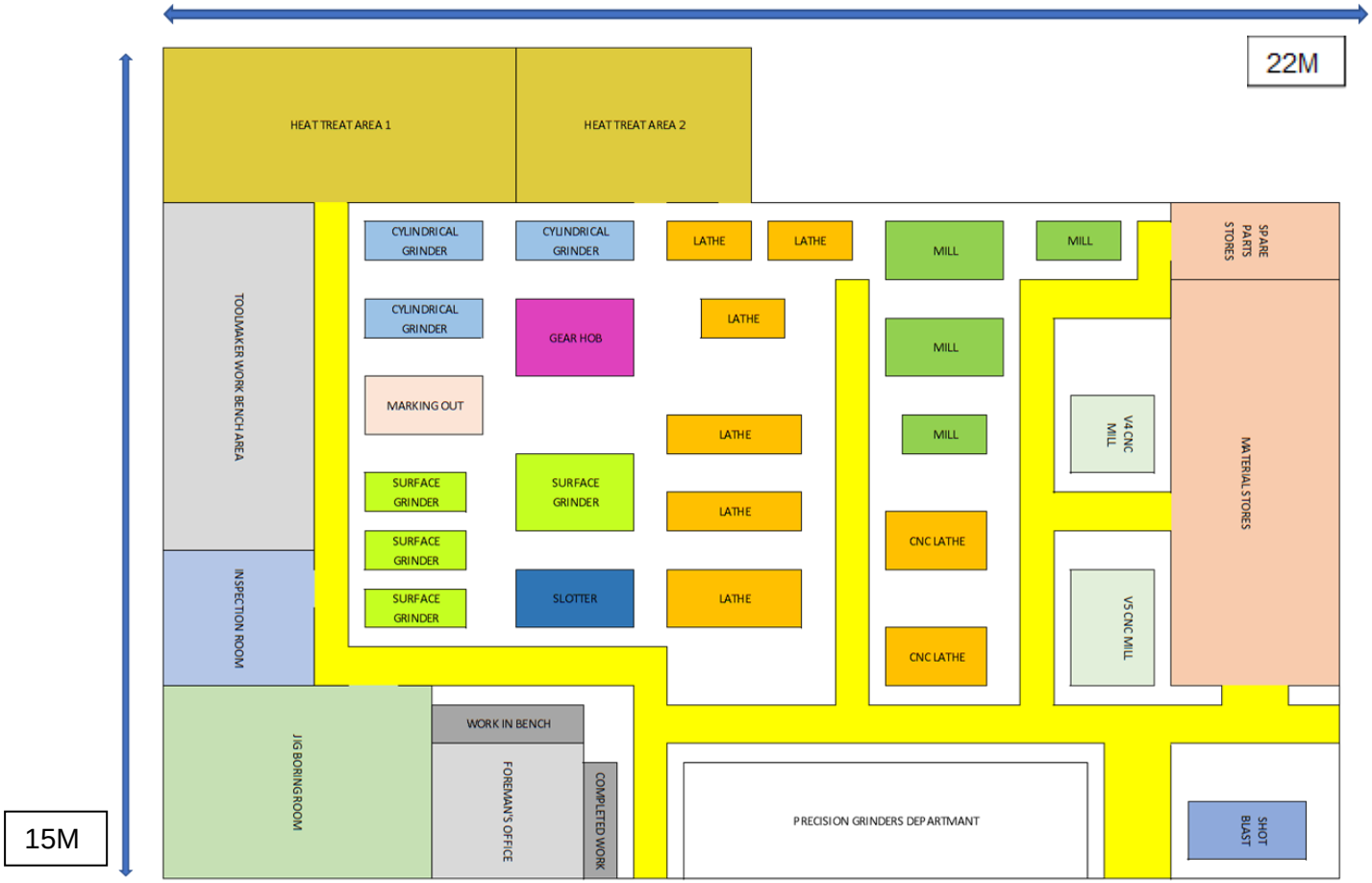


Figure 28 – Tool room layout diagram for contact analysis

Analysis

Archived Toolroom Data

The data collection can be exploited to develop a complete understanding of the manufacturing process for typical components manufactured in the toolroom. The analysis will be split into two distinct sections. The first will interpret and evaluate data collected from archived toolroom work, the second will target data collected in relation to the waste identified within the process, see Table 11 and Table 12. The analysis will incorporate the use of graphical documentation to assist the evaluation process. One such tool will be the Pareto notion, typically referred to as the 80/20 rule. According to (Pandey, et al., 2013), (Powel & Sammut-Bonnici, 2015), Pareto methodology dictates that 80% of consequences derive from 20% of causes, therefore is commonly referred to as “the law of the vital few”.

Current State - Value Stream Map (VSM)

The CNC manufacturing process has been graphically modelled using the Cycle time (C/T) and Changeover Over (C/O) Data to generate a VSM of the current process state. According to (Murugesan, et al., 2016) (Balaji, et al., 2016), the creation of the current state VSM is essential to establish and improve areas of NVA activities. This is reinforced by (Rother, 2009), who defines the ability of VSM to identify the critical value within a manufacturing process. In addition, he describes the importance of product flow through elimination of WIP/inventory.

Figure 30 is the VSM of the current CNC process. The author has selected a typical component manufactured within the section and graphically modelled the process. They have included cycle time (C/T), changeover time (C/O) and lead time (L/T). According to (Rother, 2009), (Balaji, et al., 2016) (Murugesan, et al., 2016) C/T is the amount of time taken to complete each part of the manufacturing process. C/O quantifies all changeover time required for different processes and/or components. Finally, L/T can be defined as the total time required to complete all processes required for manufacture.

Table 15 - Current VSM values

Current VSM	Total Lead Time	Value added Time
Time (hr:min)	34:51 (100%)	1:19 (3.42%)

Table 15, is a breakdown of the total lead time and value-added time quantified within the current VSM shown in Figure 30. As defined by (Davim, 2018), (Chowdhury, et al., 2016) and (Alves, et al., 2005), value is ultimately a result of any process directly altering fit, form and/or function. Therefore, only CNC programming and the bandsaw can be considered

value adding steps within the total lead time. Further consideration is required to fully understand the subsequent value of the remaining process steps. Where nonvalue adding processes require further thought to understand their worth within the total lead time.

The current state VSM utilises the cycle time information for one chosen component indicative of typical milling work, therefore providing a snapshot of the current manufacturing process.

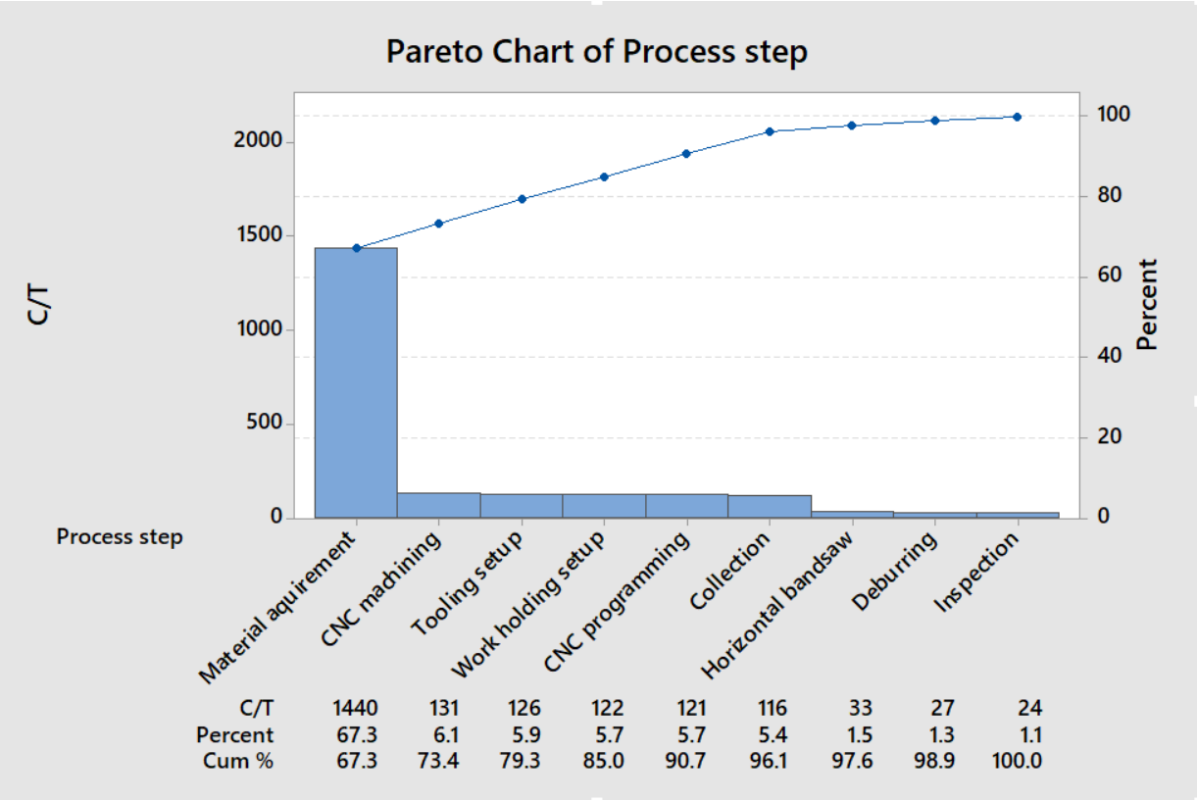


Figure 29 - Pareto chart of process steps

Further to this, the cycle time data can be plotted on a pareto chart demonstrating the total cycle time dedicated to each process step (Figure 29). This pareto analysis is a vital tool for identifying and quantifying the waste and therefore the areas that rewire the most attention. For this specific component, it is evident that material procurement has had the greatest impact on the total lead time (67%). Therefore, a considerable decrease in component lead time would result from identifying improvements to this process. The remaining processes can be split into two distinct subdivisions as shown in Table 16. The middle section identifies additional areas for improvement within the manufacturing process totalling a further 28.8% of the total lead time. In this instance they will provide a lesser gain when compared with material procurement, although the experience of the author and research undertaken by the author clearly demonstrates a wide variety in the material requirement time. Therefore, it can be assumed that the middle section could become the primary area of

improvement for a different component. The final section combines to provide a total 3.9% of the total lead time. Consequently, it indicates that any improvement would have very limited effect on reducing the components lead time.

Table 16 – Pareto Chart results

Process	Cumulative Percentage %
Material Procurement	67.3% (67.3%)
CNC Machining Tooling Setup CNC Programming Work Holding Setup Collection	6.1% 5.9% 5.7% 5.7% 5.4% (28.8)%
Bandsaw Deburring Inspection	1.5 1.3 1.1 (3.9%)

To summarise the result of utilised Cycle time (C/T) and Changeover (C/O) Data. The findings of the subsequent VSM and pareto analysis have identified critical manufacturing processes that require further in-depth reflection. These have been identified as the leading sources of waste within the process and include the following processes: Material procurement, CNC machining, tooling setup, CNC programming and work holding setup. Consequently, the archived toolroom data collected in Table 11 enables further insight into these identified areas. The author will be further utilising this data to develop an in depth understanding of waste in relation to: Material procurement, Scheduling and set-up, Over processing and motion within the above processes.

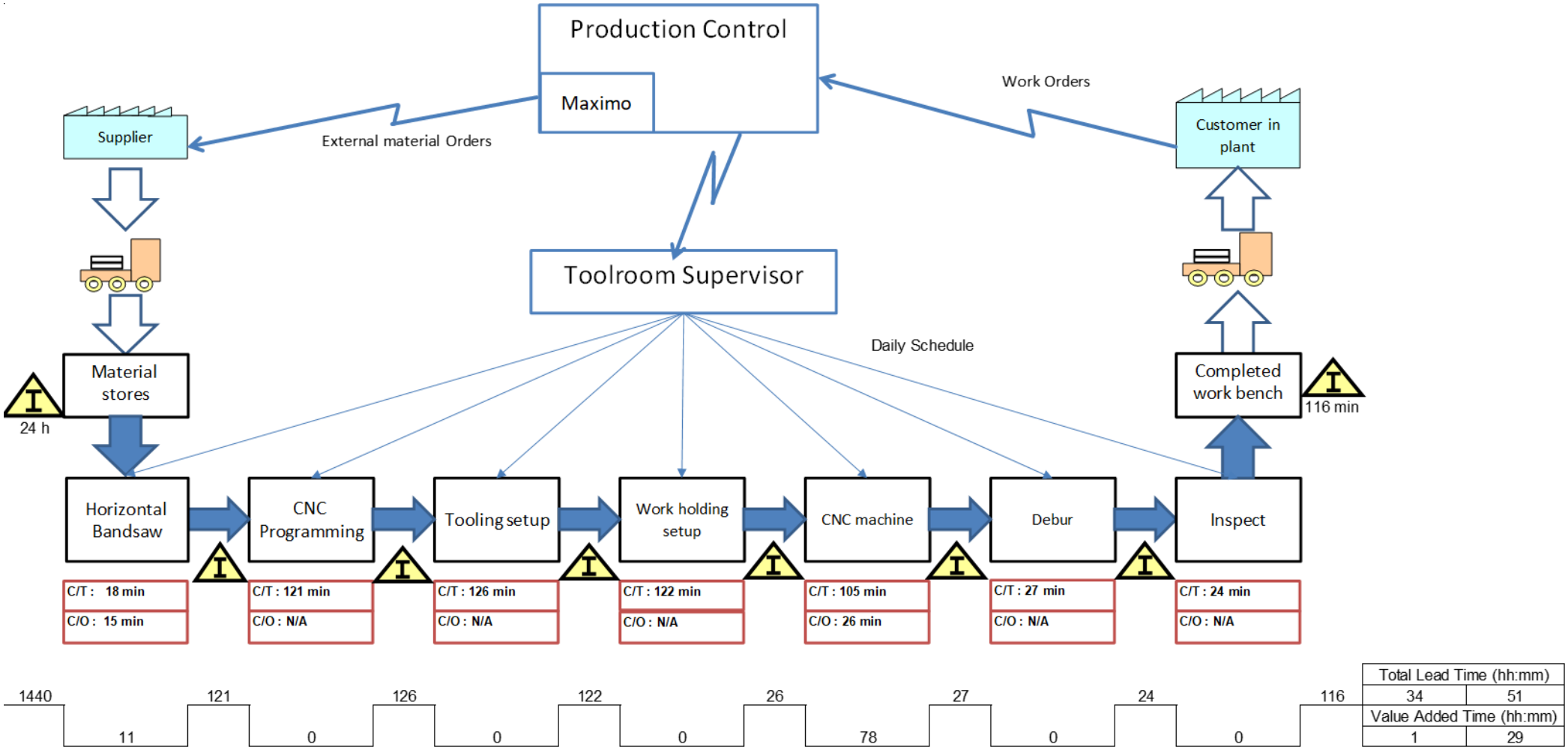


Figure 30 - VSM Toolroom Current State

Over-processing

Over processing has essentially become the prerequisite of machine shop philosophy. Historically an employee would be encouraged and often rewarded for achieving perfection. Whilst an admirable characteristic, the requirement of perfection cannot be perceived to be adding value from the customer perspective. Consequently, the balance between manufacturing excellence and unnecessary over processing must be achieved. The identification of unnecessary over processing and therefore nonvalue adding (NVA) features provides an excellent opportunity for reducing waste and/or component lead time. Examples of over processing within the component machining include, disproportionate tolerancing, material and geometric specifications.

Typically, many components manufactured within the BEP toolroom are done so using a tried and tested 'copy and paste' approach. According to (Pieńkowski, 2014), organisations must continually improve their existing manufacturing techniques. This is corroborated by (Rawabdeh, 2005) who state the need to continually review and update manufacturing practices. In addition (Dahmus & Gutowski, 2004), (Haider & Hashimi, 2014) discuss the influence of unnecessary non value adding processes on the environmental impact of manufacturing. Over processing within BEP toolroom is responsible for in additional lead time, manufacturing processes, excess material specification and subsequently is a contributory factor of machine wear and tear.

The data collection strategy has identified the heat treatment process as one potential source of over processing. The chart in Figure 31 illustrates the % of components currently subject to the potentially unnecessary additional resources attributed to the heat treatment

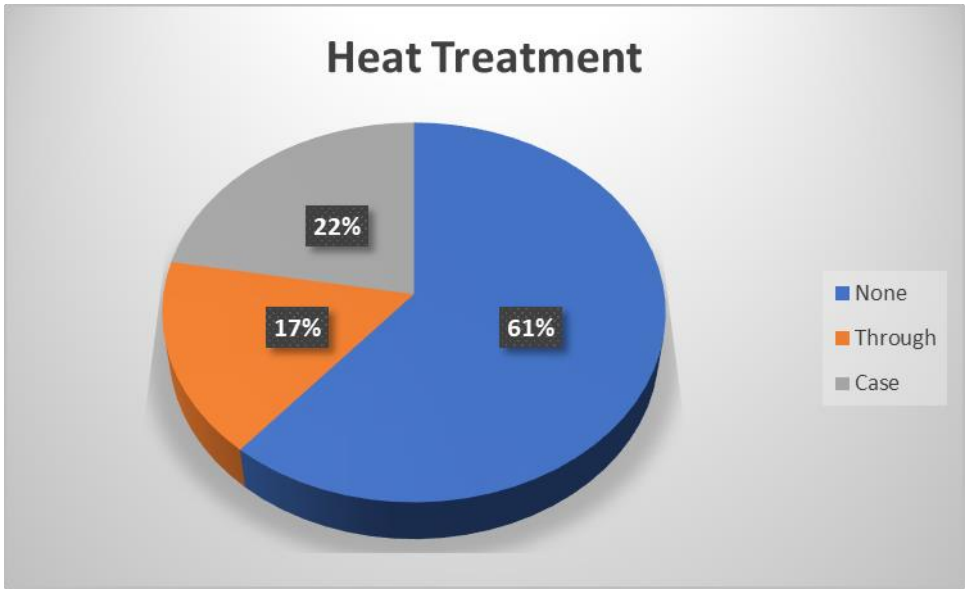


Figure 31 - % of components hardened

process. According to (ASM International, 2006), the hardness of a material is its ability to withstand wear and penetration by another material. Hardness of steel is typically controlled by means of an intensive time and energy consuming heat treatment process. Figure 32 has been generated from the data set and clearly demonstrates the excessive resource in terms of time required. The identification of any over processing in relation to heat treatment would provide substantial reductions in components lead time.

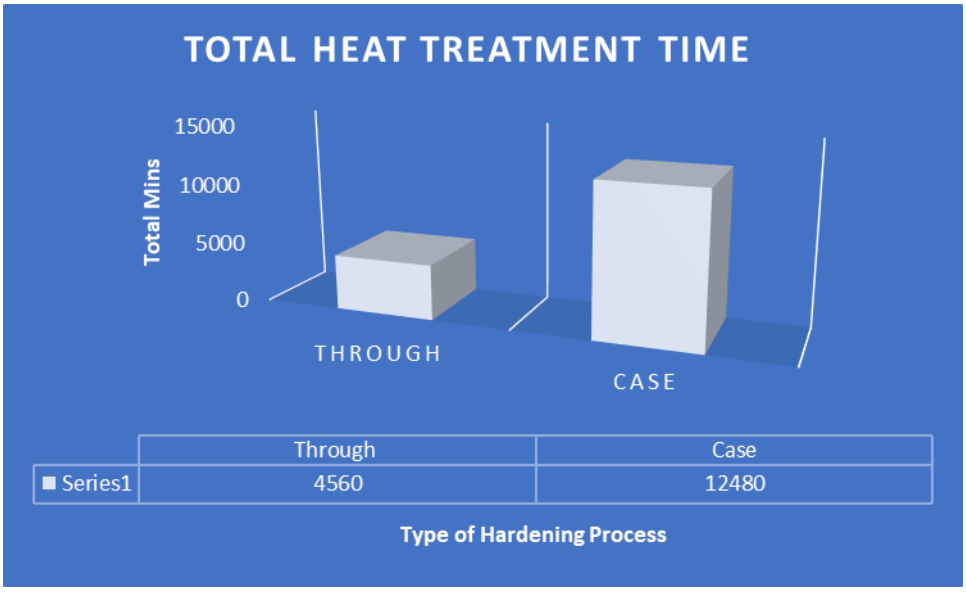


Figure 32 - Total heat treatment time for identified components

Motion

Excessive and wasteful motion can be identified as the inherent waste within machine shop manufacturing process. This is typically considered to be an employee waste but must also be a considered as a wasteful factor of the machining process. The diverse nature of HMLV manufacturing processes provide additional obstacles when striving to eliminate wasted motion from the process (Rawabdeh, 2005).

The complied data set has been designed to capture the volume of material removed through the subtractive manufacturing process. The data has complied the volume of the initial and finished material dimensions with the objective of calculating the volume of material being removed from components being manufactured. For illustration, Figure 33 displays a model of a typical type of component and the material that might be removed for the final geometry. The results of this data set can be seen in Figure 34. This chart clearly indicates that a large volume of material is removed from all items produced in the toolroom, with leading group removing between 59-70% of the raw material. The current method of material acquirement is clearly detrimental to the efficiency of the machining process. Therefore, the priority must be to target the current process of material procurement with the

aim of sourcing the correct size material. The appropriate material will provide measurable improvements to material waste/cost, CNC cycle times, CNC tooling costs and ultimately the component lead time.

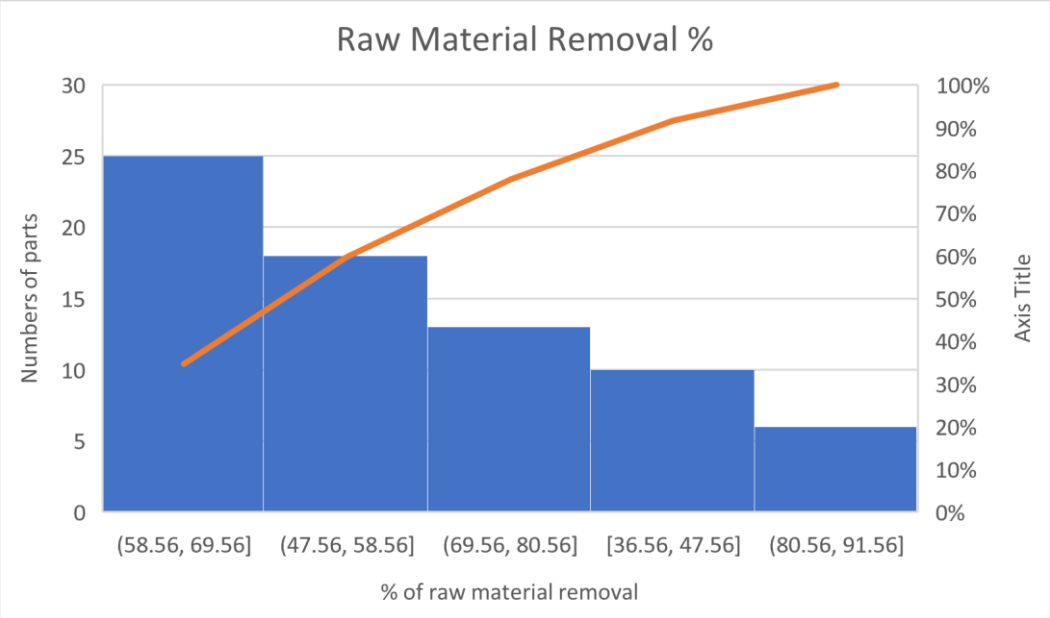


Figure 34 - % of raw material removed in manufacturing process

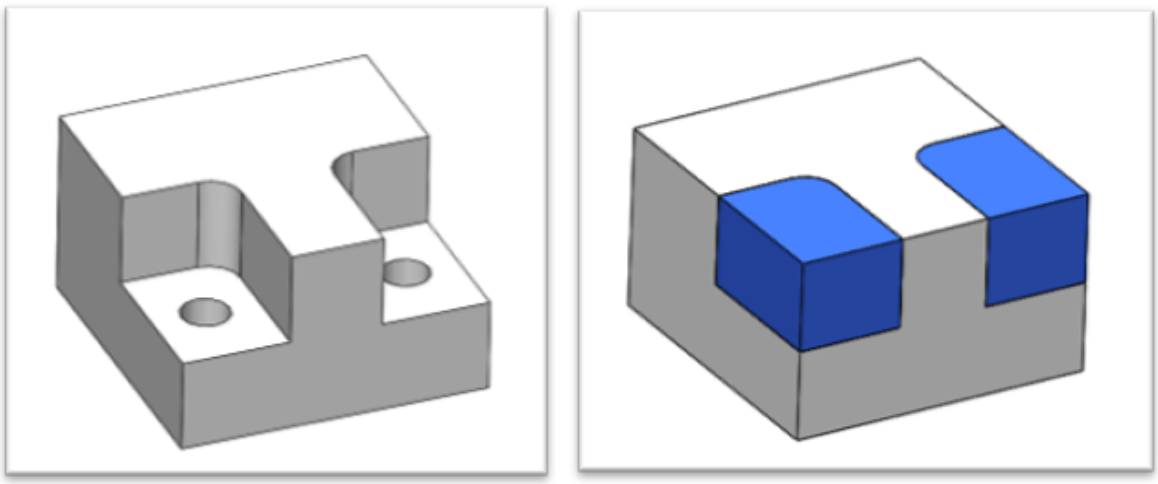


Figure 33 - Retained material example

Setup

Archived toolroom data has quantified the volume of repeat work undertaken in the toolroom within BEP. Figure 35 and Figure 36 present the % of repeat components and the recorded batch numbers required within the archived data. This is of specific interest as it will be directly linked to the potential waste involved in unnecessary repeat setups involved in machining common components. Setup can be defined as the total time taken to change from the last component from one order to the time taken to manufacture the first component of the next order (Albert, 2004).

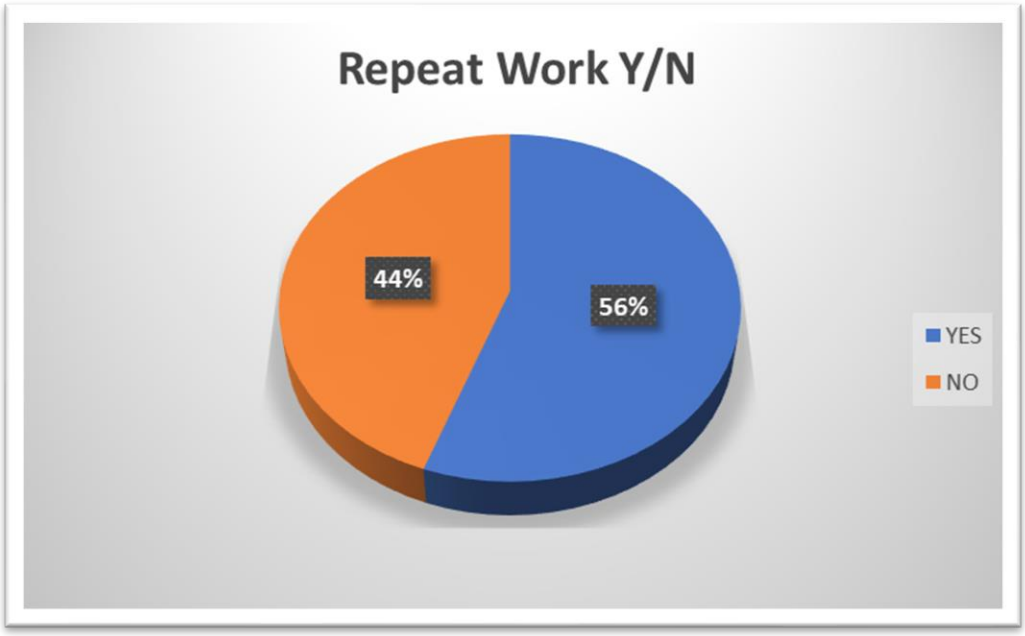


Figure 35 - % of repeat work

For example, within the toolroom manufacturing environment this can involve breakdown of previous order work holding and/or tooling. Followed by the new work holding and tooling setup with additional requirements of material procurement and CNC programming. The balance between order fulfilment and reduction of unnecessary setup is one requiring extensive experience and forward planning. To eliminate waste the penultimate aim would be to eradicate changeable setups all together but within HMLV manufacturing this continually proves to be unachievable. Therefore, the setup and changeover process must be justified and planned within the manufacturing process and reduced as much as possible. The introduction of appropriate lean tools is essential to standardise the process and minimise of setup and changeover.

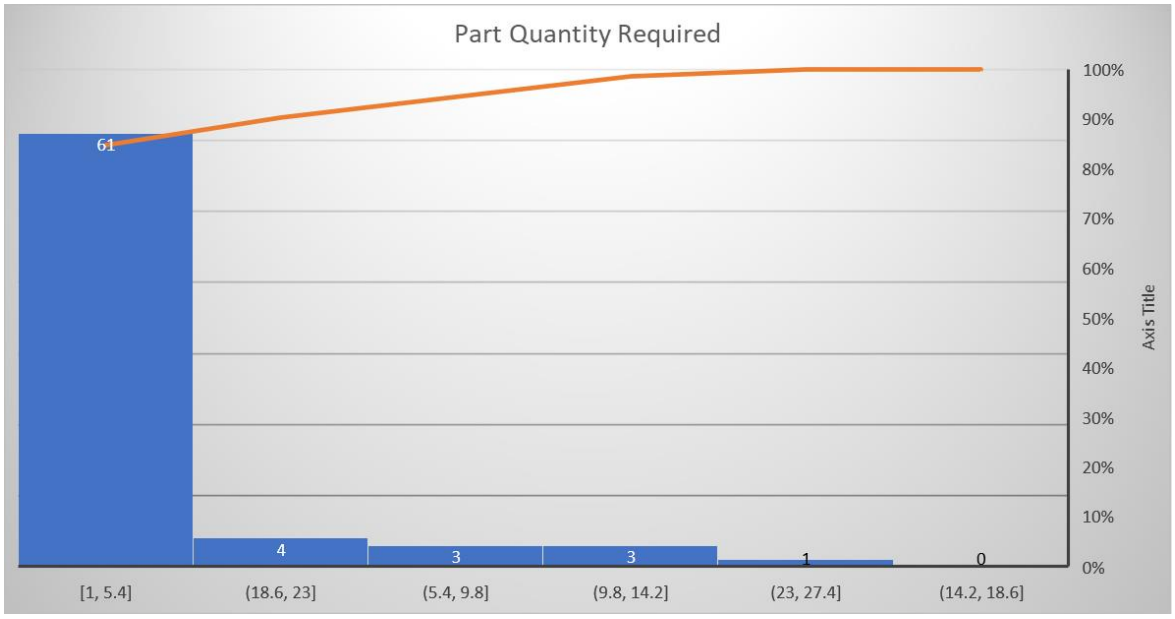


Figure 36 - pareto chart of toolroom batch quantities

Waste Identification Data

The criteria devised for quantifying the current levels of manufacturing process waste has been exploited to compile and illustrate the data analysis through a series of charts, see Figure 37 and Figure 38. The data has been developed to integrate machinist's extensive process knowledge and experience. The subsequent charts have been arranged in descending order to demonstrate the areas of utmost process waste. The wastes categorised as motion and waiting are the most frequent, recorded in excess of 80% of components manufacturing. This is followed closely by defects and over processing which were found in excess of 60% of components. The frequency decreases significantly for the three remaining categories of transportation, overproduction and inventory.

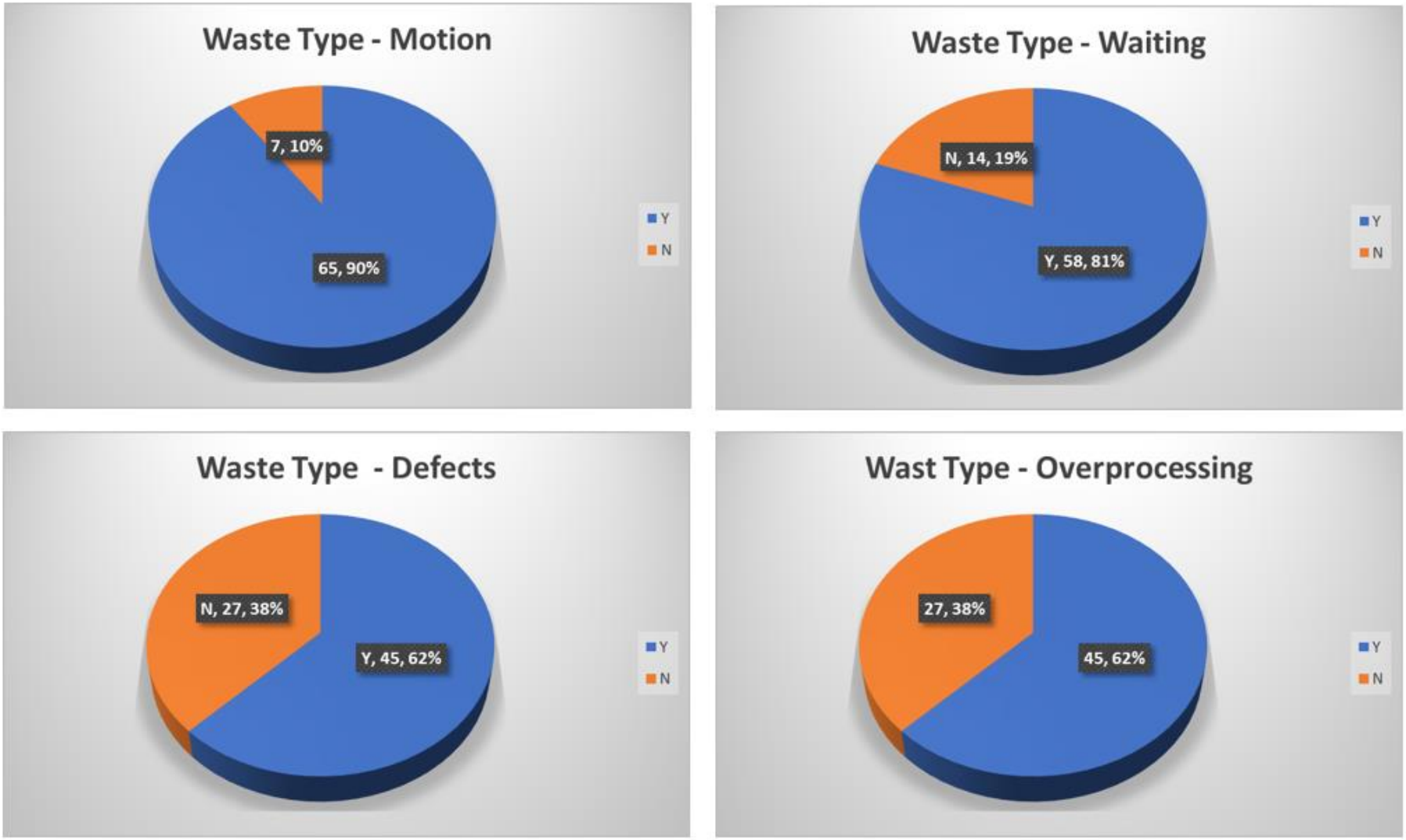
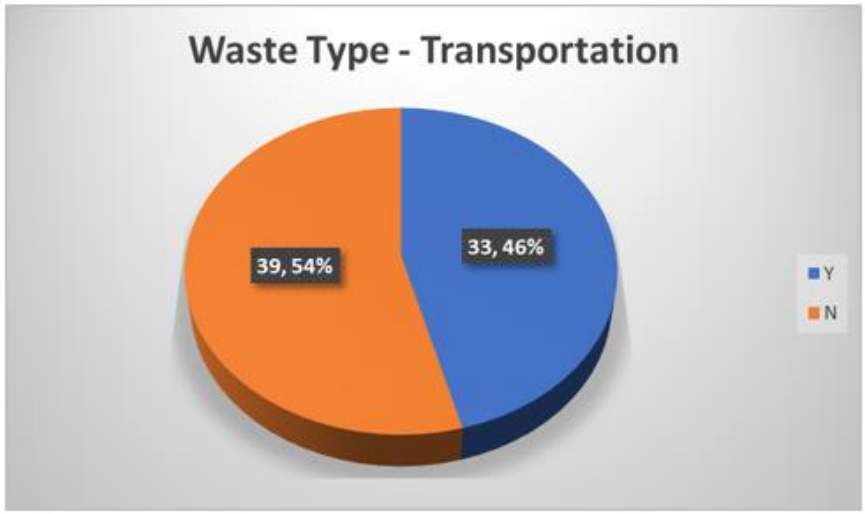
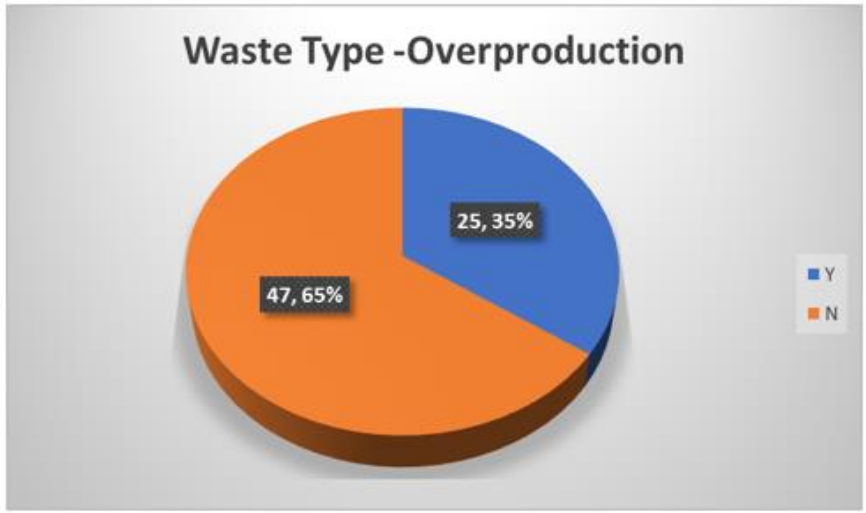


Figure 37 – Waste identification data chart results (Motion, Waiting, Defects, Over processing)





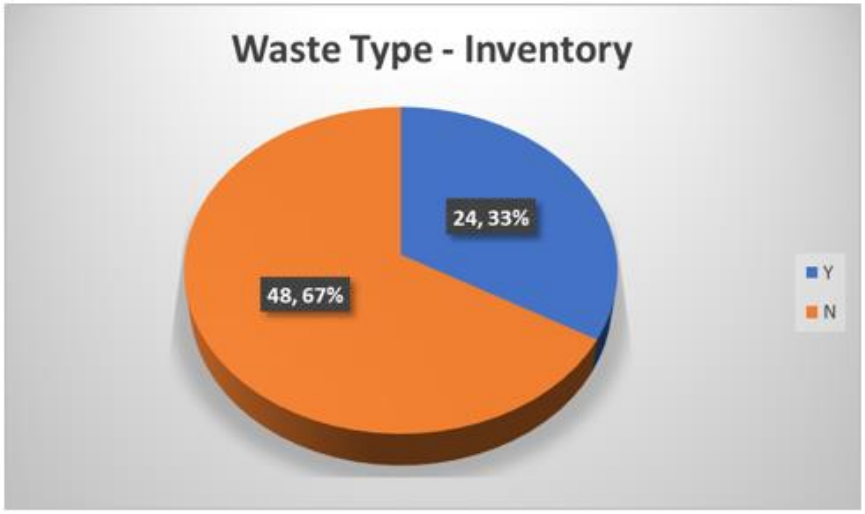


Figure 38 - Waste identification data chart results (Transportation, Overproduction, Inventory)

Current Contact Diagram

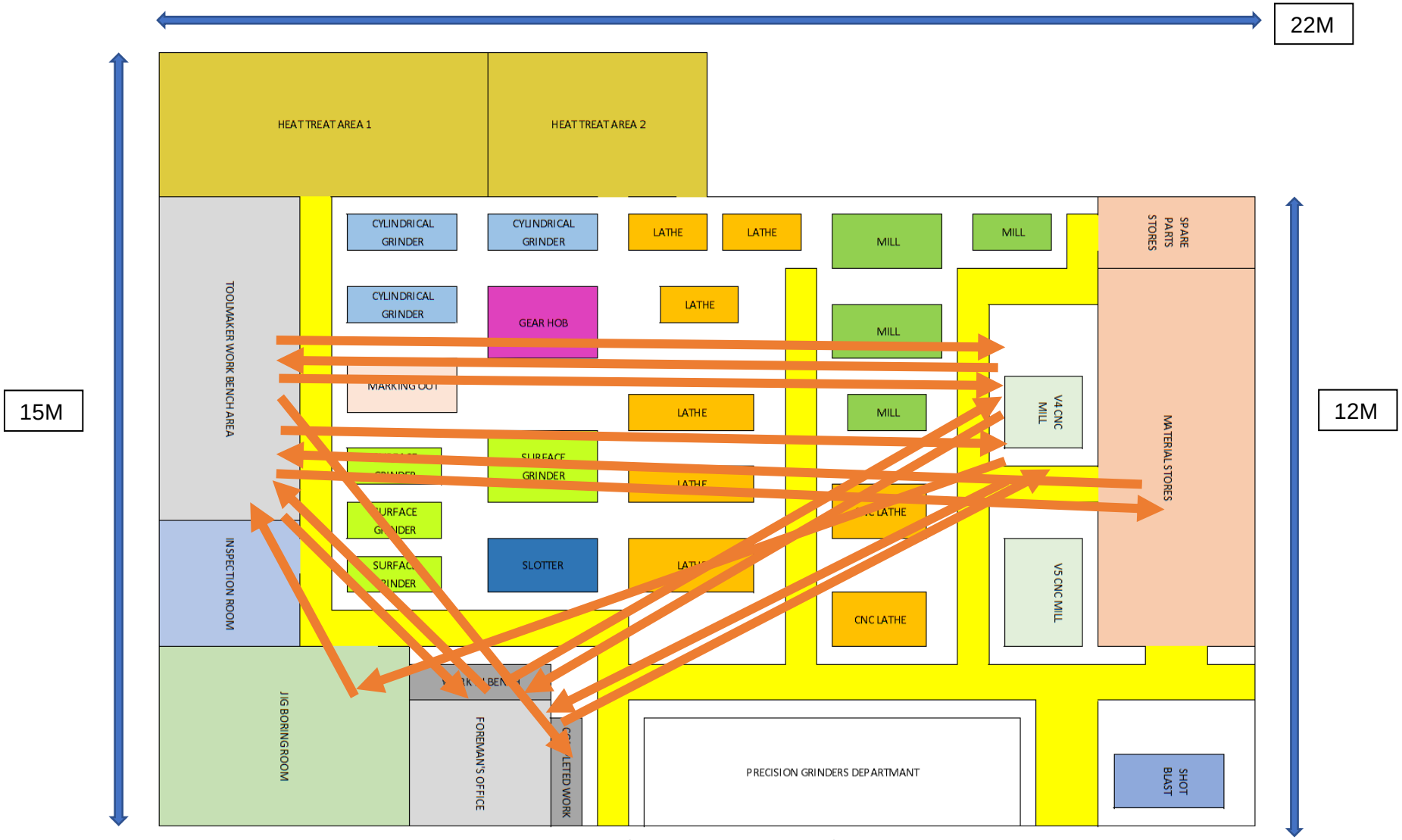


Figure 39 – Contact diagram for typical basic CNC manufactured component

Figure 39 above illustrates the typical contact points for manufacturing of a typical CNC mill component. The scale attached to the diagram gives a clear indication of the distance travelled by the component, equipment and/or operator. This example incorporates the 14 steps listed below although this could vary considerably for differing components. While this example is only relevant for one basic component, a contact diagram provides a clear demonstration of the different process steps. It tracks the product, material, machinists, and all supplementary equipment.

1) Walk to foreman's office / receiving work bench
2) Walk to toolmakers bench to study drawing and decide work plan
3) Walk to material stores to identify suitable stock
4) Walk to toolmakers bench to select appropriate tooling/equipment
5) Walk to CNC section to select available machine and evaluate appropriate working holding and job process.
6) Walk to computer outside foreman's office and order missing material/tooling or equipment
7) Walk to CNC to start programming
8) Walk to collect items delivered from stores required for work order
9) Walk back to CNC section and setup required tooling
10) Walk to toolmakers bench to collect additional tooling/equipment
11) Walk to CNC section finish setup and proceed machining
12) Walk to Jig boring section to complete manual machining tasks
13) Walk to toolmakers bench to deburr and complete quality checks
14) Walk and deliver work order to completed workbench for collection

Whilst for this example most of the manufacturing was undertaken on one machine, the movement between operations could be considered excessive. The part, raw material and all other supplementary items were moved between locations potentially over 50m apart. The level of variety and complexity involved in HMLV manufacturing can become particularly difficult to manage efficiently. Careful management of manufacturing resources are of paramount importance to manage potential obstacles which include infrequent order scheduling and multiple machining requirements which take place over extended time periods with interchanging employee availability.

Process Improvement Tools

The data analysis undertaken by the author has identified and most importantly quantified the inherent waste within the current manufacturing system implemented within BEP's toolroom. Consequently, this data analysis has successfully established plentiful opportunities for process improvement. The authors research has addressed the difficult task of identifying which lean tools are suitable for HMLV manufacturing environments. Therefore, the author will introduce the detail required for such techniques for successfully applying suitable lean tools is of fundamental importance.

Information flow

The current method for information flow through BEP toolroom is manged via the Maximo MRF internal computer system. The system is utilised plant wide and uses a generic data capture form for all BEP departments. This data is then used to generate, automate and prioritise incoming work orders to the toolroom. The results of the data analysis have identified a numerous sources of waste which could be addressed through a rethink of the MRF system. Currently, machinists manufacture comments to provided drawings or sample parts. Supplementary support information is inconsistent or non-existent. Batch volumes, critical dimensions and material details can be vague or even missing. The system would benefit from input from the toolroom dept. so that vital information was included in the work order process. Toolroom scheduling and component manufacture are often undertaken with an element of guess work through the insufficient data flow through the process. Measurable savings of process waste could be generated through the reduction of unnecessary heat treatment, machine setups and cycle times. According to (Batra, et al., 2016), efficient collection and cascading of information is critical to toolroom performance. It can streamline cycle time, changeover time, setting times and eliminate unnecessary over processing.

5s

The 5s technique has been identified as an essential tool to for reducing wasted motion and ultimately component lead time within the current system. The first stage of the technique is 'Sort'. This involves requires employee engagement to organise, prioritise and declutter and must involve all equipment within the CNC department. Figure 40 is an illustration of the structure implemented during the Sort process. All equipment and miscellaneous items must be evaluated and classified as either required, not required or possibly required. The utilisation of the 'Red tag' system as discussed by (Pasale & Bagi, 2013) would simplify and standardise the system. The 'Red Tag' system requires items to identified and tagged before being stored in suitable isolated 'Red Tag' area.

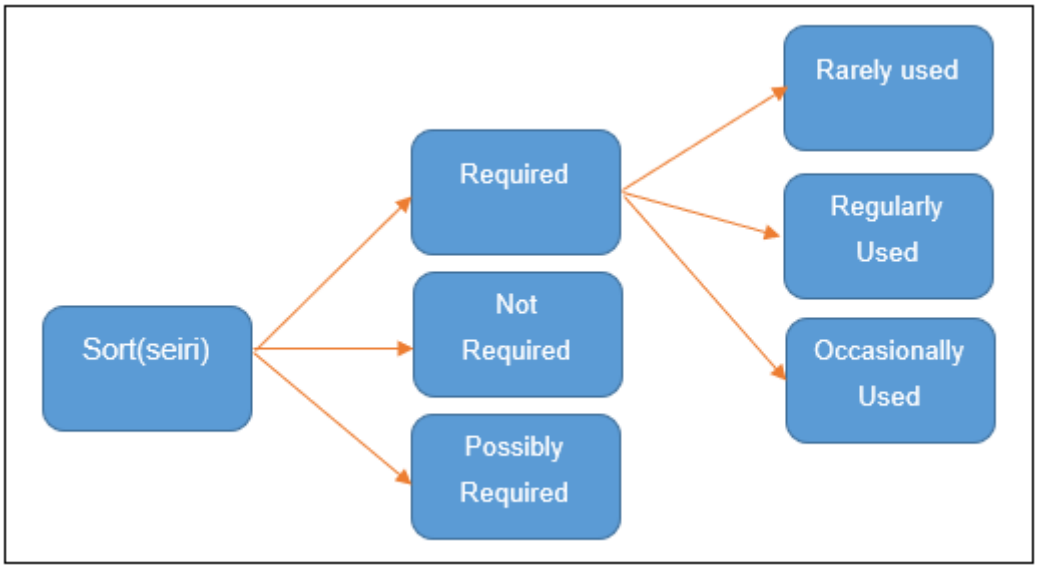


Figure 40 - Sort technique diagram

Figure 41 demonstrates an example of a 'Red Tag' and the 'Red Tag' isolation area that would be implemented. The elimination of these unrequired items will have multiple benefits to operators, leadership and visitors to the department. These provide fundamental benefits including reduced wasted motion required to find and use required equipment but also indirect and often overlooked benefits. These include improved lines of sight and decreased distraction from unnecessary items and their related storage. The Sort process must be balanced and structured with clear leadership. An uncontrolled and unstructured process can be unnecessarily severe with limited benefits. The Sort process must be considered one of continuous improvement and can be refined further in future.

Figure 41 - Red Tag and Red Tag isolation area (Pasale & Bagi, 2013)

The second stage is to "Set in Order", encapsulated by the statement "A place for everything, everything at its place" (Dana, 2015). This stage requires all equipment, material and other items to have considered and appointed locations. As acknowledged by (Pasale & Bagi, 2013), The implementation of ABC analysis will enable the author to rationally allocate and layout appropriate equipment locations see Table 17. The reduction of non-value activities i.e. searching for missing items or sorting through unnecessary items will directly reduce component lead times.

Table 17 - ABC analysis

Rate of utilisation	Class	At machine	Nearby	Stored Remotely
Daily – Weekly	A	Yes	Yes if not at machine or hand	No
Weekly - Monthly	B	If possible	Yes	No
Monthly – Annually	C	No	No	Yes

The author is aware that the process of "Set In Order" should not be limited to the primary items involved within the manufacturing process. The obvious equipment items such as tooling could be stored as illustrated in Figure 42. But the Set in Order process should

Figure 42 – Set in Order example solutions (theleanwarehouse, 2020)

extend to all work holding/fixturing, tooling and supplementary item such as cleaning items this is demonstrated in Figure 43.

Figure 43 - Further Set in Order examples (theleanwarehouse, 2020)

The solutions mentioned above would be of very little cost and could be implemented almost immediately. To broaden the scope of the "Set in Order" step would require a superior level of time and capital investment. The contact diagram has revealed the large distance covered by machinist, materials and equipment in the current process. Currently machines are organised by category and the toolmakers benches, material/equipment stores and inspection equipment are stored on the periphery. Although a huge upheaval, the layout would greatly benefit from the support items being stored centrally and therefore potential reducing the distances covered significantly. The balance between this huge reorganisation and the benefits would need greater investigation but should be considered when any new machining investment takes place.

Shine is the third step in the 5s process, this is typically referred to as cleaning, tidying and cleanliness. For the toolroom, this should include all machines, equipment, gauges and all supplementary items. The most evident benefits are the advantages to the workforce working in clean and tidy work areas. Although when undertaken correctly, the Shine process incorporates inspection and is therefore becomes a vital tool for the early identification of potential maintenance issues and/or leaks, spills of coolants. This process will enable these potential maintenance issues to be addressed early and thoroughly planned for rather than becoming breakdown procedures.

The three initial steps are the fundamental tools of improving the workplace. These typically require less determination and are often embraced by employees. The fourth step "Standardise" is a vital step to uphold new initiatives and drive the continued participation of the workforce. The new standards can quickly lessen as the workforce moves back to the previous status quo. Consequently, the implementation of documenting standard procedures is to essential to maintain the new norms. These can take many forms but typically involve the use checklists (Table 18), standard work procedures (SOP), flowchart, employee

appraisals, process reviews. The balance between generating unnecessary paperwork and process control and reinforcing the benefits because of new initiatives will require careful leadership.

Table 18 – Shine – machine cleaning scheduling example

Cleaning Schedule	M/c 1	M/c 2	M/c 3	M/c 4	M/c 5	M/c 6	M/c 7
Monday							
Tuesday							
Wednesday							
Thursday							
Friday							
Saturday							
Sunday							

Further consideration should be given to the visual impact of "Set in Order" actions, to assist standardisation all floors, walkways, storage, equipment should be colour coordinated. This would be especially useful to control instances where duplicate tooling is used in different machines/sections. In addition, the control and calibration of measurement equipment and work holding such as chucks/vice would be beneficial to the standardisation process. Traceability and the identification of suitable measuring and work holding equipment would assist the ability of chosen tools to match the tolerance requirement of different components. To provide further process control, final inspection documents would be generated. This documentation would be responsible for collating critical drawing dimensions and the machinist, machine, tooling, gauge and work holding identification utilised.

The final stage is "Sustain", typically this phase can be defined as the 'Monitor, expand and refine'. This phase is leadership led, reinforcing improvements, cascading evidence of success and finally recognising the input of employees. The 5s auditing process enables leadership to measure, reinforce and continuously improve the success to date. The 5s model would then be expanded to different machining areas harnessing the experience gained through the learning process. This is relevant to author, as this project has focused on the CNC milling section but could be rolled out to other areas within the BEP toolroom. The author has generated an auditing form in Table 19, this record would provide an invaluable document capable of monitoring, expanding and refining the 5s process.

Table 19 – 5S auditing documentation

	Question	Y/N	Comment
Sort	Is machinery and support equipment required?		
	Are tools, gauges and equipment required?		
	Are storage mediums required?		
Set in Order	Is area and all machines and equipment clearly marked, labelled and/or colour coordinated?		
	Are equipment locations clearly labelled?		
	Is all equipment in its designated location and clearly labelled?		
Shine	Is the floor and surrounding area clean (including mats and duck boards)?		
	Are all machines clean & free of waste and unnecessary items?		
	Is all support equipment clean and working correctly?		
	Are storage mediums clean and working correctly?		
Standardise	Cleaning plan/schedule is displayed and adhered to?		
	Gauge and work holding stored and calibrated correctly?		
	Evidence of 5s Continuous Improvement Activities?		
	Tooling clearly labelled and stored with appropriate min/max quantities?		
Sustain	Is relevant process control data displayed?		
	Is all data on display boards up to date?		
	Is the auditing process being undertaken appropriately?		
Total			

SMED

As commonly referred to "Setup time, or changeover time, is defined as the time from completion of the last good part of one lot to completion of the first good part in the next lot" (Albert, 2004). Although this generalisation encompasses large scale manufacturing processes, applying SMED within the CNC milling section will differ and requires an in depth understanding of HMLV manufacturing. Therefore, the author will apply the fundamental ideology behind the SMED methodology but only utilise tools relevant to the manufacturing environment. A suitably customised SMED implementation will still provide measurable benefits to the toolroom within BEP which include:

- Efficient refined changeover processes
- Increased flexibility/capability to manage variable batch size
- Ability to retool and adapt current process to meet variable customer demand.
- Standardisation of SMED changeover, providing improved quality and machine utilisation.

SMED based literature by (Pellegrini, et al., 2012), (Ulutas, 2011) describe the significance of 'FAST'. The acronym encapsulates the basic process steps prior to the implementation of SMED methodology, leading to the proportion setup time taken by the different 'FAST' setup steps Table 20.

Table 20 – 'FAST' SMED and process step descriptions (Shiego, 1996) (Ulutas, 2011) (Pellegrini, et al., 2012)

F	"Foresight or preparation step: work that is done to prepare for the new setup or changeover (i.e. finding materials, tools, gauges, etc.)"
A	"Attachment or mounting/dismounting Step: work for taking tooling off the machine and putting on the new, required tooling"
S	"Setting, centring, dimensioning: fine-tuning the tooling and equipment to run the next part"
T	"Trial runs and adjustments: setting up the tooling and equipment to run the parts according to specifications"

Step	Proportion of Setup Time
Preparation, Final process adjustments, Work holding and tooling checks	30%
Setup of tooling and work holding	5%
Measurements, Settings, and Calibrations	15%
Initial part runs and subsequent adjustments	50%

According to (Shiego, 1996), tooling and work holding setup require up to 35% of the total setup time see Table 20. The author has combined his extensive experience of this manufacturing process, pareto analysis results with newfound SMED understanding and the fundamentals of the 'FAST' acronym approach. This has resulted in identification of two distinct areas for a tailored SMED application:

- CNC tooling setup
- CNC Work holding/fixturing

These proposed improvements must be subject to the 1st, 2nd and 3rd phases of SMED implementation, ultimately aiming to simplify and standardise the changeover process. This is a continual improvement process involving the of assessment, elimination and conversion of internal/external processes. The aim being a "Standard Operating Procedure" (SOP). The criteria identified in Table 21 have been developed to provide a structured method for assessing the feasibility of proposed improvements.

Table 21 - SMED Feasibility assessment

Principle	Description
Practicality	How feasible is proposed improvement?
Effect	What is expected impact setup time proposed improvement?
Accessibility	How simple is implementation of proposed improvement?
Safety	How safe is the proposed improvement?
Cost	What are the cost implications of proposed improvement?

After further consideration of the author believes the proposed improvements meet all feasibility criteria, therefore the stated proposals need further detailed in-depth analysis. CNC tooling setup typically involves the use of an automatic tool changer which enables the storage of set tools used within the machining cycle. This tooling system is fully automated and controlled entirely through the CNC HMI or current CNC program. A correctly utilised CNC tool changer should improve efficiency through the organised, pre-set storage of all required tooling. The current setup system is protracted and is predominantly an internal operation and therefore can only be undertaken when the machine is on stop. Current limitations include the small number of available tool holders and/or slots in the toolholder. Subsequently this requires tooling to be switched over and consistently subject to protracted setup procedures. An ideal state must be to enable machinists to start the machining process with limited or no additional tooling setup.

The current process :

- Identify suitable tooling required for current component manufacture
- Ascertain tooling currently loaded in CNC machine (2 stage process)
    - Check tool detail set in CNC parameters via HMI
    - Clarify that tools set in parameters physically match tooling in autochanger.
- Order and collect from stores any tooling currently unaccounted for
- Remove unnecessary tooling from tool holders for required tool setup
- Set tool in holder, identify space in both CNC radius compensation parameter and autochanger location
- Probe tool offset utilising CNC tool setup macro
- Repeat setup for each required tool

The second SMED proposal implicates the current CNC fixturing situation. It is apparent the current CNC fixturing setup is an internal operation and a source of inherent waste within the manufacturing process. As the component being manufactured on CNC mills changes the method of fixturing typically requires substitution to suit. The current work holding equipment utilised within the toolroom manufacturing process is a miscellaneous assortment collected over time. Consequently, these miscellanies of equipment have a profound detrimental effect for manufacturing setup procedures.

The current method involves:

- Work holding/fixturing must be removed, cleaned, substituted, clamped, and realigned.
- Requiring the time and skill of experience operators.
- Miscellaneous fixturing systems including vastly differing styles/techniques.
- Each system will have differing dimensions, therefore typically resulting in uncommon clamping methods and further careful consideration of positioning on machine bed.
- Manual clamping methods, typically using mallet and chuck/vice key. As such the clamping pressure generated when using a vice 3,4 or 6 chuck, is operator influenced.
- Work holding/fixturing methods require setup, alignment and the adjustment of CNC parameters/offsets to begin component run.
- The standard of current work holding/fixturing is limited for manufacturing to the highest tolerancing requirements. This variation could affect the operator’s ability and/or lead time to achieve tolerances requirements

Proposed SMED improvements will require varying investments in regard to time and capital. Therefore, the author proposes a three term (Short, Mid and Long) phased implementation plan:

- Short Term - Low cost immediate solutions
- Mid-Term – Implementation of setup reductions requiring manufacturing or procurement of equipment and/or supplementary training
- Long Term – Implementation of escalated investment including machinery, equipment or large-scale reorganisation.

In the short term the implementation of a successful 5s approach will empower and assist SMED improvements. The common goal of removing inherent waste will result in measurable gains for each process. As discussed in the previous section the 'Sort, Set in Order, Shine and Standardise' stages of 5s are responsible for eliminating, organising, cleaning and standardising of machines and equipment. The aim is to reduce and/or eliminate any unnecessary sourcing, searching or preparing activities. The outcome should be a more organised workplace with all necessary equipment at hand and any unnecessary distractions removed. The 5s process is critical for establishing a streamlined baseline for implementation of proposed SMED improvements.

There will be preliminary benefits for the identified SMED improvements of CNC tooling setup and CNC Work holding/fixturing. The 5s process will have a dual purpose, firstly to sort, organise and store the current selection of tooling and work holding utilised within the department. Secondly, this process will facilitate the evaluation, classification and identification of items that are either of appropriate standard or will need upgrading or replacing. The creation of appropriate equipment documentation would enable further reviews to take place after the initial short-term activities had taken place. This method would expand the simple 'in or out' red tag system, where it would review and catalogue the long-term suitability of equipment until additional funds were made available.

The Midterm improvements would involve the design, procurement and installation of specialist equipment solutions. Some of these improvements would be the result of 5s methodology covered in the previous section. These include specially designed tooling and fixturing storage to assist changeover and eliminating the waste associated with 'go get' activities. These ideas can be developed further through the implementation of SMED methodology. The ability to utilise the CNC auto-changer to its full potential requires tools to set and ready to use. This can be achieved through different methods, the balance between cost and availability will drive the efficiency of the tool changers utilisation. Optimally there would be an unlimited number of tool holders and locations in the tool-changer, but this is an

unachievable goal for most manufacturers. Therefore, the goal must be to have as many tools in tool holder and in the autochanger as possible. Where this is not possible, tools and toolholder should be setup and stored as close as practicable to the associated machines. This can be achieved through the utilisation of specialist tool storage carts as in Figure 44. This type of storage method has additional benefits as it could be moved between suitable machines or transferred to a suitable location away from section if not required for an extended period.

Figure 44 - Tool storage cart (Warfield, 2020)

To refine this system further, the author proposes that CNC tool setup sheets would be generated to catalogue essential tooling data see Figure 45. This documentation would collate the essential tooling setup information, which would enable machinists to quickly identify the critical information of in-situ tooling without undertaking their own unnecessary investigations and have a noticeable effect on setup time. There is the potential to store items in the tooling cart but retain their critical information within the CNC tool offsets so that the tool changeover will measurable improved. In addition, secondary identification of setup tooling would be via a tag or label. This would allow for a rapid visual method of detection which could be checked against the setup sheet for further detail.

CNC Setup Sheet							
Part Description	Sigma baffle plate LH						
Operator	Paul Thomas						
Machine	V4 DeVlieg CNC Mill						
Machine Offset	(G55,56,57 etc)						
Tool Number	Tool Description	Holder Number	Cutter Diameter	Cutter Length	Tool Location	Tool Offset	Comments
T1							
T2							
T3							
T4							
T5							
Print Name				Sign			

Figure 45 - CNC tooling documentation

The CNC machines within the toolroom currently utilise a Renishaw probe for tool setting. This system is controlled through a CNC probing macro, whilst supremely accurate and reliable feature determines it can only be classified as an internal SMED function. Consequently, this setup procedure creates waste through idle machine time. The author proposes the introduction of an offline tool presenter such shown in Figure 46.

Figure 46 - Tool presetter example equipment (Warfield, 2020)

The process would be a simple but effective technique for converting the process from internal to external. The operator would be able to setup multiple tools while the CNC machine was running. The system would require appropriate approval by machine operators to work effectively but the positive effect on setup would be measurable.

The work holding and fixturing setup in the midterm will also benefit from a thorough upgrade process. The specification of current work holding equipment is both substandard and nonstandard. Consequently, this is detrimental to operators during machine setups procedures. The use of nonstandard work holding means that machine setups are protracted and typically require extra consideration even for frequently manufactured components. The typical setup involves fastened a vise to the machine bed using a series of T-nuts and clamps in the associated machine bed T-slots. Although a simple, flexible and inexpensive location technique the process is typically a protracted one. The nature of its design offers limited repeatability and typically requires significant cleaning operations to clear T-slots in changeover situations. Additionally, selection of suitable T-nuts, bolts and clamps for miscellaneous work holding items significantly increases changeover times. Additionally, any work holding equipment selected can be positioned anywhere on the machine bed and will need to referenced appropriately through utilisation of the CNC probing macro process. Therefore, the adoption of a standardised work holding system would dramatically reduce changeover times through conversion of internal to external SMED functions. An ideal process state would allow machinists to substitute pre-set work holding equipment minimising any changeover effect on component lead times. This requires careful consideration to correctly pinpoint and adopt a robust, accurate and standardised offline system.

Figure 47 - Modular fixture tooling plate (Warfield, 2020)

Therefore, the author proposes the procurement and installation of standardised modular work holding. The modular tooling plate in Figure 47 utilises a series of location dowels and supplementary treaded bolt holes. This creates a versatile, repeatable and most significantly an exceptionally accurate work holding system. Work holding changeovers become a significantly simplified process. The clearly labelled location positions can be pre-programmed into CNC machine G-code zero points and selected appropriately by the CNC programmer. This modular system provides further advantages as a result of the wide variety of work holding items that can be purchased eliminating the need to manufacture specialist fixturing in house. To supplement the modular tooling plates, appropriate work holding needs identification. The procurement of standardised vise/chuck selection is critical to the success of proposed improvements. These should be carefully considered to accommodate components frequently manufactured in the BEP toolroom.

Figure 48 – Work holding design considerations

The selection of work holding could be extended to include specialist items of equipment such as double jaw or dovetail vise. These low-cost work holding methods will provide measurable process waste savings through their intelligent designs. The double jaw vise enables two components to be manufactured in one process, consequently reducing machining cycle times and the component rough stock changeover times. The dove tail vise jaw enables a component to be machined from the smallest possible rough stock due to the efficient jaw design. The dovetail design draws the blank down allowing heavy machining stress unachievable with standard work holding equipment. Both designs reduce or eliminate sources of waste identified in the aforementioned data analysis.

The long term SMED proposals for improving the work holding and tool setup procedure would require a significant investment in new machines to implemented effectively. Many modern machining centres have adopted advanced automated systems where the CNC G code identifies its own work holding and tooling requirements. This information is cross referenced with a database of setup work holding and tooling stored within the department. Work holding, tooling and toolholder data are stored via a barcode identification system.

Future State - Value Stream Map (VSM)

The current state – VSM, provides a baseline evaluation of the current component lead time (Saraswat & Kumar, 2014). This evaluation can be combined with supplementary process information captured in the contact and cause-effect diagrams. This fundamental process knowledge can form the foundation for developing actionable improvement opportunities.

The future state VSM is an essential technique to generate a visual presentation of potential process improvements (Hines & Rich, 1997). The process of transitioning from current to future state VSM identifies and eliminates waste whilst reinforcing end to end process improvement. It can be further utilised as a communication tool for assisting change leaders, providing a platform for cascading crucial information to employees (Thomas, 2018). The technique effectively secedes key processes for improvement by providing a clear quantifiable targets for each target.

The future state VSM should ultimately create an improved process for manufacture. According to (Alves, et al., 2005) critical future state objectives include continuous flow, improved efficiency and reduced lead times with a reduction in unnecessary non-value adding activities.

Figure 49 is the future VSM for BEP toolroom, including five areas of improvements specific to the Sigma LH location jaw. This process is clearly beneficial for improving the manufacturing process of this specific component, although consideration must be given to the changeable flow of differing components in HMLV manufacturing as discussed by (Fabtech, 2016).

The pareto analysis in the previous section has proved to have been essential technique to quantify the effect of different processes in relation the total component lead time. This analysis enables the waste to be visualised using 'kaizen burst boxes' within the future state VSM.

<u>Speedier supplies</u> – the pareto analysis determined material procurement to be the largest contributor toward the total lead time. Therefore, according to (Thorn, 2018) the most efficient application of resource should be to target the 'low hanging fruit'.

As depicted within the current state VSM, material procurement typically takes in the region of 24hrs. This can be extended significantly for exotic and unusual material or sizes. The current procedure for requisitioning material within BEP plant is protracted and antiquated. Typically, this system can include between four and seven steps of internal and external resources for any approval. These include:

- Internal - MRF material order request
- Internal -Management clearance
- Internal - Financial control clearance
- External - Raise order with sub contracted procurement team.
- External - Order quotation from approved suppliers
- Internal – Financial approval
- Internal – Material ordered and added to BEP systems.

Therefore, procurement could be improved significantly by initiating immediate channels of coordinated procurement with approved suppliers. For instance, dependable regional sources of material such as 'Express Metals' (www.expressmetals.co.uk) can provide just in time (JIT) access to a wide variety of materials. Material requirement can be achieved within a vastly reduced procurement period. Consequently, the author will assume a conservative reduction of six hours. Therefore, generating an improved lead time of 18 hours.

CNC programming – beside material procurement, CNC programming is part of a group containing the other main contributors to the manufacturing lead time. The selection of appropriate feed, speed and standoff position are potential areas for creating a substantial volume process waste. This is of the upmost importance within large batch manufacturing, as any waste within the program will be amplified exponentially . Implementation of efficient programming techniques require employees to have suitable machining experience and a supporting skill set. This is can only be achieved through employee investment with methods such as appropriate training and management support.

The application the above measures with specific attention to the selection of appropriates machining speeds, feeds and most importantly limiting unnecessary machine movements would produce a 21min reduction. Therefore, the CNC programming would now take an estimated 100min for the future state component lead time.

5S application – other main contributors to the total lead time are component, tooling and work holding setup. All the above include the use of supplementary equipment to assist the manufacturing process. Therefore, the introduction of 5s methodology would be of substantial significance. The five-step process of sort, set in order, shine, standardise and sustain will empower employees to be fully engaged and invested in the process. The setup and machining process would benefit from all the

correct tooling, work holding and supplementary equipment being well organised and stored within an immediate proximity to any employee operating machines within the CNC section. Whilst a straightforward system, the implementation of shadow boards would be simple, inexpensive and effective visual technique for control with the process. Standard operating procedures (SOP) could be of further consideration for components which include large batch numbers or are regularly manufactured within the toolroom. These would enable an operator unfamiliar with the manufacture of a particular component to benefit from previous the experience of their colleagues. The result of introducing and applying 5s techniques would be responsible for a 16min lead time reduction. Therefore, for this example the future state tooling setup time will now be 110min. Although further implementation would also provide time savings for the work holding setup.

CNC machining improvements – Although this operation is where form, fit and function are typically transformed. CNC machining has proven to be the area containing the highest quantity NVA. Therefore, the succinct identification of what is VA and NVA both necessary and unnecessary are paramount to the success of any savings to component lead time. The cycle time (C/T) and change over (C/O) provide two areas for significant waste improvement within the machining process. Cycle time waste can be acknowledged in the form of component over processing. Typically, components manufactured within the toolroom include unnecessary tolerancing or complex geometric dimensioning which add substantial time constraints to the machining cycle time. Over processing could be substantially reduced through CNC programmer experience if he were empowered to identify and replace complex geometry with replacement features. A typical example would be the replacement of a radius with a chamfer. The setup process has addressed and identified numerous improvements to the current system. In addition, machine utilisation in the form of machine speeds, feeds and standoff position as previously mentioned would result in further time savings. The potential reduction of waste resultant of these changes could conservatively produce a 9min lead time saving.

Customer delivery improvements – any improvement of customer delivery will result in a significant reduction in the component lead time. The current state process flow from order to completion presents distinct time saving opportunities. The optimal lead time would result from first in first out manufacturing, where every order is completed in order. In HMLV manufacturing this rarely an option, therefore the management of

machine, employee and material utilisation is key. Further improvements to process flow, inventory and WIP are critical. Careful consideration of managing setup times for small batch numbers or potentially introducing increased WIP of frequently manufactured components. These issues require knowledgeable and transparent guidance from the leadership charged with component scheduling. The introduction of these recommendations would produce a 55 min component lead-time decrease.

Therefore, the future state VSM following the successful completion of all recommended proposals would improve the future component lead time by:

Table 22 - Future state VSM results

Current state lead time = Time hr:min	34:50
Future state lead time = Time hr:min	27:08
Lead time improvement	22%
Cost reduction (Supposition of 25:00hr)	25 x £47819 x 22% = £263004 per annum

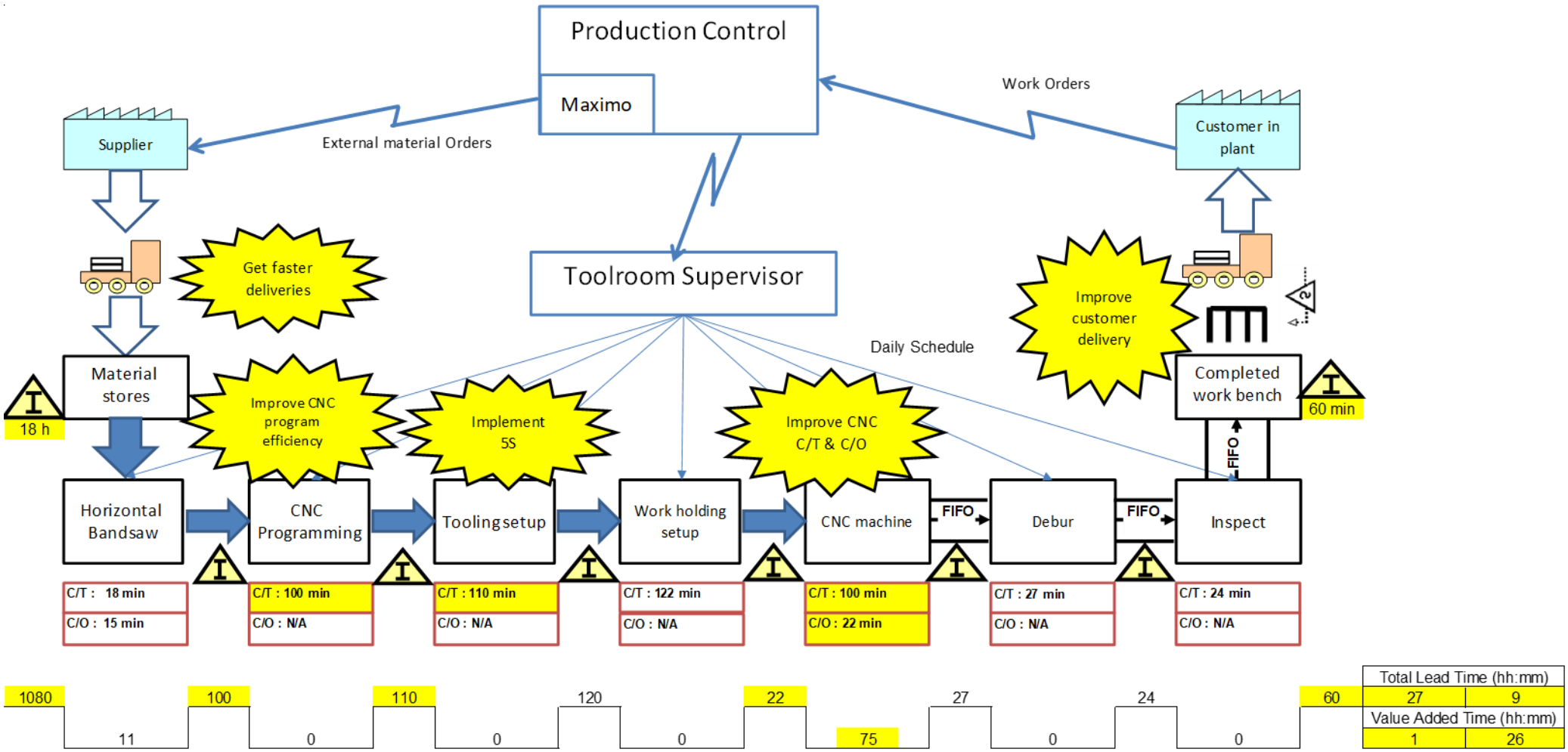


Figure 49 – Toolroom VSM Future state

Contact Diagram – Proposed

The data analysis has identified the large distances covered by machinist, equipment and components during the manufacturing process. The current contact diagram for a typical component was crucial for illustrating the inefficient toolroom layout. The some of the steps involved covering distances in excess of 50m for unnecessary 'go get' activities. The 5s and smed proposals will reduce and eliminate many of the 'go get' activities but there are still large distances to cover for necessary activities. The author has generated a revised layout which would significantly reduce the excessive distance. Although the author is aware that any layout modification would have significant financial and time implications and therefore should be carefully considered for feasibility and possibly undertaken in a period of new machine installation and investment .

Typical component process steps:

1) Walk to foreman's office / receiving work bench

2) Walk to toolmakers bench to study drawing and decide work plan

3) Walk to material stores to identify suitable stock

4) Walk to toolmakers bench to select appropriate tooling/equipment

5) Walk to CNC section to select available machine and evaluate appropriate working holding and job process.

6) Walk to computer outside foreman's office and order missing material/tooling or equipment

7) Walk to CNC to start programming

8) Walk to collect items delivered from stores required for work order

9) Walk back to CNC section and setup required tooling

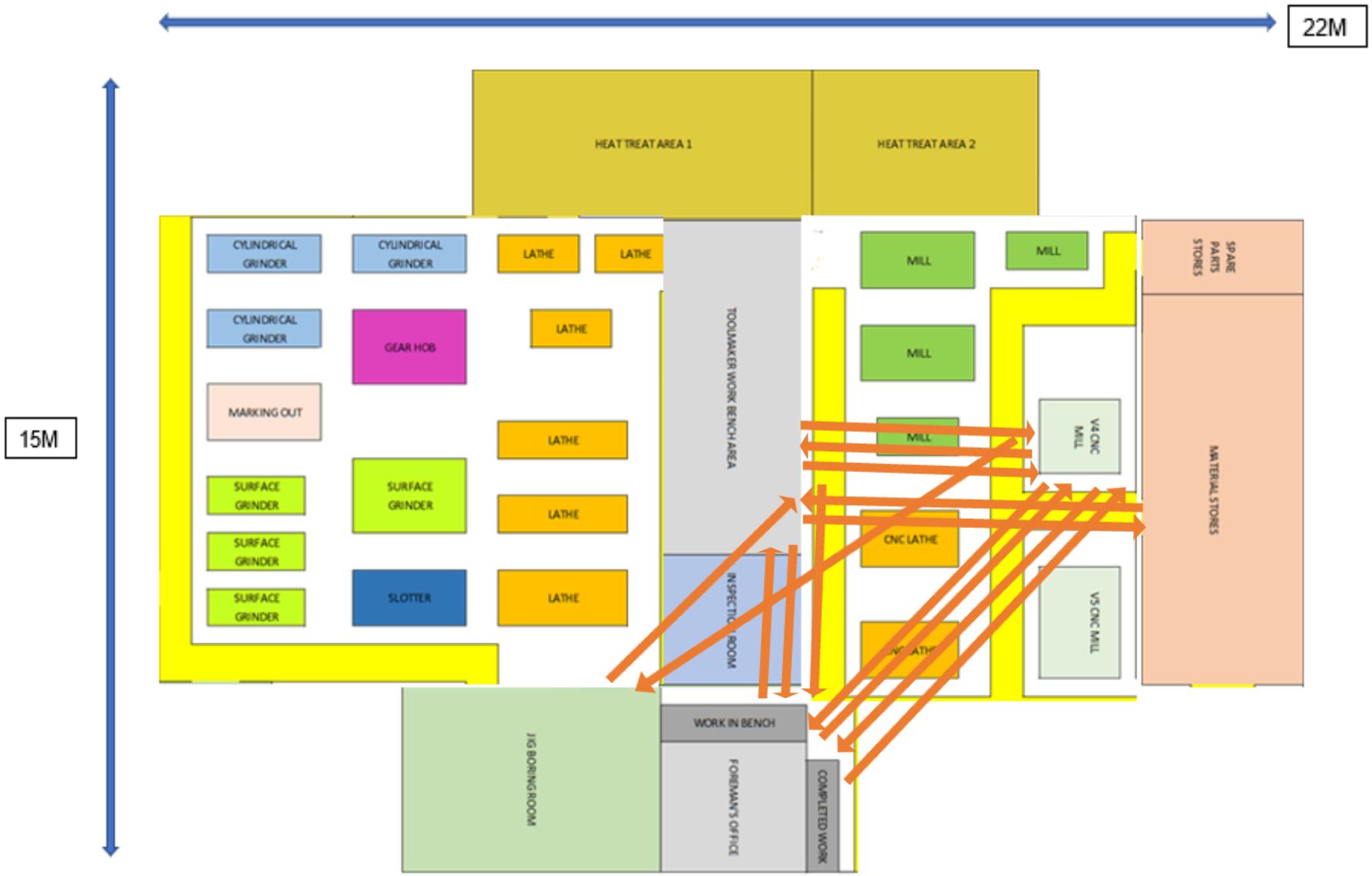
10) Walk to toolmakers bench to collect additional tooling/equipment

11) Walk to CNC section finish setup and proceed machining

12) Walk to Jig boring section to complete manual machining tasks

13) Walk to toolmakers bench to deburr and complete quality checks

14) Walk and deliver work order to completed workbench for collection


22M
15M
HEAT TREAT AREA 1
HEAT TREAT AREA 2
CYLINDRICAL GRINDER
CYLINDRICAL GRINDER
LATHE
LATHE
CYLINDRICAL GRINDER
GEAR HOB
LATHE
MARKING OUT
LATHE
SURFACE GRINDER
SURFACE GRINDER
LATHE
SURFACE GRINDER
SURFACE GRINDER
SLOTTER
LATHE
TOOLMAKER WORK BENCH AREA
INSPECTION ROOM
MILL
MILL
MILL
MILL
CNC LATHE
V4 CNC MILL
V5 CNC MILL
SPARE PARTS STORES
MATERIAL STORES
JIG BORING ROOM
WORK IN BENCH
FOREMAN'S OFFICE
COMPLETED WORK

Management of Change

The changes proposed by the author will require clear leadership to ensure a smooth transition and full employee engagement. Replacing antiquated work procedures with up to date methods will cause employee resistance and poor results if not managed successfully. The author has considered Lewin's three step model but believes that Kotter's eight step model considers additional factors and therefore provides a more comprehensive approach. (Pollack & Pollack, 2015) underline this opinion, stating Kotter's method is recognised as one of the most effective change ideologies. The author has utilised Kotter's methodology to identify the following change steps:

- Proposed improvements and subsequent implementation should be clearly communicated to all toolroom employees, clearly stating the potential financial and time saving benefits.
- The proposed changes require appropriate leadership that should incorporate employees from differing levels within the company i.e. management, engineering, foreman and toolmakers.
- The unique mindsets associated with differing age groups need careful consideration Toolroom employee demographics must drive a suitable vision and change strategy. i.e. younger employees are more receptive to new ideas, whereas older employees have vital transferable skills and experience.
- The clear communication of the proposed changes, company vision and planned strategy are essential. This should be presented through clear concise communication channels reinforcing the benefits of proposed changes.
- The strategy should include suitable training and information channels to limit any resistance to change.
- Immediate gains can be delivered by separating the entire process into short, mid and term aspirations.
- The consolidation of all delivered gains is vital to drive the continuous change process.
- Lastly, all gains need recognition, reward and reinforcement to establish change within the workplace.

The current method for implementing change within BEP is an authoritarian top down approach. There is clear need for improved workplace integration with company leaders empowering all levels of employees to be fully imbedded in the change process. The change vision and identified steps rely on strong leaders and excellent communication. This is

reinforced by (Mullins, 2016), who states the importance of communicating the change concept, identify demographic motivation factors and engaging a diverse range of employee.

Covid-19 Impact Statement

On 11th January 2020, the World Health Organisation (WHO) announced the outbreak of a novel coronavirus later confirmed as 'Covid-19' (World Health Organisation (WHO), 2020). The seriousness of this new infectious disease quickly escalated to a pandemic status and on 23rd of March the British government announced a national 'lockdown'. The 'Lockdown' enforced strict restrictions on many organisations requiring people to stay at home unless deemed a 'Key worker'. BEP furloughed its entire workforce on 20th March 2020 with no idea when it would return to normal operations (BBC, 2020).

The Covid-19 pandemic has had an inconceivable multi-faceted impact on the lives of all British citizens. Many family's lives have been changed irrevocably, through lost loved ones or the health, social or financial impacts. The negative economic impact is predicted to bigger any other in history, many business will not recover prompting large-scale job losses.

The Covid-19 pandemic has unfortunately negatively affected the scope of my major project. BEP has closed indefinitely and therefore the implementation of proposed improvements have become a theoretical process rather than a physical one as planned. Although on a personal note I feel very fortunate that mine, my extended family and friends' lives have been largely unaffected by the most serious consequences of this terrible situation.

Conclusion

To conclude, the primary purpose of the project was to research, identify and implement suitable lean tools to eliminate waste within the high mix low volume manufacturing environment of BEP toolroom. As discussed in the Covid-19 impact section the implementation stage of the project has become a theoretical rather physical one. Therefore, the author has utilised their judgement and experience to establish suitable assumptions where necessary.

The development of appropriate data collection plan enabled the generation of current manufacturing process baseline. This baseline was assessed by creating a current state value stream map (VSM). The current and future state VSM compare and quantify the optimised manufacturing process as a result of proposed improvements. This process estimated a 22% reduction to component lead time and subsequent £263004 cost reduction. Although these figures are very positive and reinforce the use of VSM as a lean tool within HMLV manufacturing. The author is mindful that the results were created through a

theoretical improvement implementation stage. The application of VSM was a challenging process to implement successfully. The characteristics of toolroom batch manufacturing conflict with the fundamentals of the VSM methodology. The required process 'pull' is difficult to establish as component routings can combine various machine, inventory and streams. Consequently, the current VSM process would be incompatible with the random and variable routings of the toolroom as a high level VSM. Therefore, the author tailored the process by selected one component and studied its unique route through the manufacturing process. This was a crucial decision to the successful application of VSM within the BEP toolroom. Therefore, the author believes that VSM method can still be beneficial to HMLV manufacturing if the limitations are understood and tailored accordingly.

The author created a data collection plan focused on collating archived toolroom work and quantifying the evidence of the eight wastes in the toolroom. This data was essential for detailing a clear understanding of the components manufactured within the toolroom. The fundamental data included batch size, repeat work, raw/finished stock size and complexity. The author was able to apply this data, quantifying the effect of material selection, removal and the subsequent effect on machining times. Furthermore, the identification of secondary processes such as heat treatment and their subsequent effect on component lead time. The author believes the data collection strategy and supporting literature review were responsible for facilitating a comprehensive analysis process. This process identified three distinct areas of waste within the archived data: Over processing, motion and set-up.

Furthermore, the waste identification data collection plan was designed to quantify the volume of the seven wastes within BEP toolroom manufacturing. The author identified a criteria of typical wastes within the current manufacturing process and complied the results of machinist observations. The author is fully aware that the criteria were clear and simplistic areas of waste, however the criteria would evolve because of a continuous improvement process. The results of the aforementioned data identified considerable waste within all seven classifications. The author complied the data through a series of charts for a clear and succinct illustration of the analysis results. Although there was waste evident in all seven categories the analysis identified motion, waiting, defect and over processing as the leading areas for improvement.

The comprehensive review of current lean methodology literature was an essential process to ascertain a broad foundation of relevant knowledge. The author has combined this newfound knowledge with the data collection and subsequent data analysis. This process has provided the author with a comprehensive basis to propose suitable improvements

opportunities. Subsequently the author proposed considering the tailored application of lean methodologies including: VSM, 5s, SMED and Change management.

5s is commonly accepted as the most widely implemented lean initiative in manufacturing. It has the obvious benefit of improving cleanliness but correspondingly sorting and standardising the workplace. The author has proposed and detailed the implementation of various initiatives. The tangible advantages of these proposals will include the following. Increased machine availability through early identification of potential machine issues which can be addressed through planned maintenance procedures. A safer workplace with considerable space saving resultant of the sort, set in order, standardise process. Improved agility, flexibility and overall departmental performance, including reduced lead times, lower defect rates, reduced overheads and more efficient changeovers as a consequence of reducing unnecessary motion or ‘go get’ activities.

SMED is a similarly extensively employed lean methodology but another which requires tailoring for HMLV manufacturing. The author has developed a series of proposals of specific importance to the issues identified through the data analysis. The proposals will deliver significant improvements to the current setup procedures including the following. Reduced setup inaccuracies and associated unnecessary test runs and defective test parts. The introduction of standardised operating procedures (SOP)’s delivering improvements in quality, setup and component lead times. Simplified and therefore minimised equipment levels with the associated gains to safety, housekeeping and expenditure. Skills and experience are shared as setup can be prepared and designed at source rather than at the machine.

The author has developed a series of proposals for short, mid and long-term implementation. Where the primary initiatives require little or no financial investment and mid and long-term proposals are still of moderately low cost.

References

Aboelmaged, M. G., 2010. Six Sigma Quality: A Structured Review and Implications for Future Research. *The International Journal of Quality & Reliability Management,* 27(3), pp. 269-318.

Albert, M., 2004. *Setup reduction: At the heart of lean manufacturing..* [Online]
Available at: https://www.mmsonline.com/articles/setup-reduction-at-the-heart-of-lean-manufacturing
[Accessed 01 03 2020].

Alves, T. d., Tommelein, I. D. & Ballard, G., 2005. *VALUE STREAM MAPPING FOR MAKE-TO-ORDER PRODUCTS IN A JOB SHOP.* San Diego, ASCE Construction Research Congress.

Arshed, N. & Danson, M., 2015. The Literature Review. In: K. O. Robert MacIntosh, ed. *Research Methods for Business and Management.* London: Goodfellow, pp. -.

ASM International, 2006. Fundamentals of the Heat Treating of Steel. In: *Practical Heat Treating.* Ohio: ASM International, pp. -.

Austin, A., 2013. *A Case study of value streams and lean implementation for a small print shop,* Rochester: Rochester Institute of Technology.

Balaji, K., Hari Prasad, V., Gopi, S. & Karthick, N., 2016. APPLICATION OF LEAN TOOLS (VSM, SMED, KAIZEN) IN MINIMIZING THE LEAD TIME IN GEAR MANUFACTURING PROCESS. *International Journal of Scientific & Engineering Research,* 7(5).

Batra, R., Nanda, S., Singhal, S. & Singari, R., 2016. *Study of Lean Production System Using Value Stream Mapping in Manufacturing Sector and Subsequent Implementation in Tool Room,* Delhi: SAE Technical Paper.

BBC, 2020. *Coronavirus: Ford shuts down UK production due to virus.* [Online]
Available at: https://www.bbc.co.uk/news/uk-wales-51976376
[Accessed 20 03 2020].

Berardinelli, C. F., 2012. *To DMAIC or Not to DMAIC?.* [Online]
Available at: http://asq.org/quality-progress/2012/11/back-to-basics/to-dmaic-or-not-to-dmaic.html
[Accessed 7 August 2018].

Bozzone, V., 2001. *Speed to market : lean manufacturing for job shops.* s.l.:AMACOM/American Management.

Burnes, B., 2014. *Managing Change.* Sixth ed. London: Pearson.

Buss, D., 2012. *Ford: Go Further.* [Online]
Available at: https://www.forbes.com/sites/dalebuss/2012/06/14/go-further-brand-message-is-aimed-at-fords-employees-too/#1ab9b691471b
[Accessed 8 June 2019].

Chahal, V. & Narwal, M. S., 2017. An empirical review of lean manufacturing and their strategies. *Management Science Letters,* 7(7), pp. 321-336.

Chen, J. C., Li, Y. & Shady, B. D., 2010. From value stream mapping toward a lean/sigma continuous improvement process: an industrial case study. *International Journal of Production Research,* 48(4), pp. 1069-1086.

Chowdhury, A. H., Shahriar, S., Hossen, T. & Mahmud, P., 2016. Reduction of Process Lead Time Using Lean Tool - Value Stream Mapping (VSM). *Applied Mechanics and Materials,* Volume 860, pp. 74-80.

Conner, G., 2001. *Lean Manufacturing for the Small Shop.* 1st ed. Dearborn: Society of Manufaturing Engineers.

Cooper, T., 2013. Use Process Mapping to Improve Quality. *Chemical Engineering Progress,* 109(8), pp. 45-52.

Crawford, M., 2016. *5 Lean Principles Every Engineer Should Know.* [Online]
Available at: www.asme.org
[Accessed 12 June 2018].

Cudney, E. A. & Agustiady, T. K., 2016. *Design for Six Sigma.* 1st ed. Boca Raton: CRC Press .

Cummings, S., Bridgman, T. & Brown, K., 2016. Unfreezing Change as Three Steps: Rethinking Kurt Lewin's Legacy for Change Management. *Human Relations,* 69(1), pp. 33-60.

Dahmus & Gutowski, T., 2004. *AN ENVIRONMENTAL ANALYSIS OF MACHINING.* Anaheim, International Mechanical Engineering Congress and RD&D Expo - IMECHE.

Dana, B. G., 2015. 5S IN QUALITY MANAGEMENT. *Annals of the University of Oradea,* 25(1), pp. 1297-1306.

Davim, J. P., 2018. *Progress in Lean Manufacturing.* New York: Springer.

Davis, C. E. & Davis, E. B., 2011. *Managerial Accounting for Strategic Decision Making, Preliminary Edition.* USA: Wiley and Sons.

De Freitas, J. G., Costa, H. G. & Ferraz, F. T., 2017. Impacts of Lean Six Sigma over Organizational Sustainability: A Survey Study. *Journal of Cleaner Production,* Volume 156, pp. 262-275.

Fabtech, 2016. *Value network mapping an alternative to value stream mapping for implementing lean in a high mix low volume hmlv fabrication facility.* [Online]
Available at: https://www.fabtechexpo.com/blog/2016/08/17/value-network-mapping-an-alternative-to-value-stream-mapping-for-implementing-lean-in-a-high-mix-low-volume-hmlv-fabrication-facility
[Accessed 10 07 2019].

Fernández-Solís, J. L. & Rybkowski, Z. K., 2012. A Theory of Waste and Value. *International Journal of Construction Project Management,* 4(2), pp. 89-105.

Ford 6-Sigma, 2006. *Green Belt Training,* Dearborn: Ford Motor Company.

Ford Motor Company, 2018. *About Ford.* [Online]
Available at: www.ford.com
[Accessed 8 February 2018].

Ford Motor Company, 2018. *Global Rapid Manufacturing Centers.* Dearborn: Ford Intranet.

Ford Motor Company, 2019. *Ford Motor Company Intranet,* Dearborne: Ford.

George, M., Rowlands, D., Maxey, J. & Price, M., 2005. *The Lean Six Sigma Pocket Toolbook.* London: McGraw-Hill.

Griffith, A. & Hauser, J., 1991. The Voice of the Customer. *Marketing Science*, 02.

Haider, A., Jahanzaib, M. & Wasim, A., 2015. Lean capacity planning for tool room: An iterative system improvement approach. *Advances in Production Engineering & Management,* Volume 10, pp. 169-184.

Haider, J. & Hashimi, M., 2014. Health and Environmental Impacts in Metal Machining Processes. *Comprehensive Materail Processing,* 8(1), pp. 7-33.

Harveyperformance, 2018. *Harveyperformance.* [Online]
Available at: https://www.harveyperformance.com/in-the-loupe/material-removal-rate-efficiency/
[Accessed 25 03 2020].

Helo, P. & Addo-Tenkorang, R., 2011. Enterprise Resource Planning (ERP): A Review Literature Report. *World Congress on Engineering and Computer Science,* 2(-), pp. -.

Herron, C. & Hicks, C., 2008. The transfer of selected lean manufacturing techniques from Japanese automotive manufacturing into general manufacturing (UK) through change agents. *Robotics and Computer-Integrated Manufacturing,* Volume 24, pp. 524-531.

Hines, P. & Rich, N., 1997. The seven value stream mapping tools. *International Journal of Operations and Production Management,* 17(1), pp. 44-46.

Imp, S., 2011. USING LEAN AND 5S TO DRIVE MANUFACTURING PROCESS IMPROVEMENTS. *Quality,* 50(9), pp. 30-33.

Iowa State University, 2017. *Force Field Analysis.* [Online]
Available at: http://www.extension.iastate.edu/communities/force-field-analysis
[Accessed 26 January 2017].

Jaroszewicz, J., 2017. *REDUCTION OF CHANGEOVER TIME IN A CNC MILLING MACHINE USING EROWA ZEROING SYSTEM BASED ON THE EXAMPLE OF SAMASZ COMPANY, BIAŁYSTOK,* Bialystok: University of Technology in Bialystok.

Jeffrey K. Liker, David Meier, 2005. *The Toyota Way Fieldbook.* New York, U.S: McGraw Hill Professional.

Kazmierski, R., 2016. Key Factors That Affect 5S Implementation in the Automotive Industry. *The Journal for Quality and Participation,* 39(2), p. 13.

Kobayashi, I., 1995. *20 keys to workplace improvement.* Portland: Productivity Press.

Kootanaee, A. J., Kootanaee, S. G., Solehboni, Z. A. & Kootanaee, J. A., 2013. Just-in-Time manufacturing system, Revolution in Management Accounting From concept to implement. *International Review of Management and Business Research,* 2(1), pp. 133-148.

Kotter, J. P., 2012. *Leading Change.* Boston: Harvard Business Review Press.

Kumar, S., Dhingra, A. & Singh, B., 2018. Process improvement through Lean-Kaizen using value stream map: a case study in India. *The International Journal of Advanced Manufacturing Technology,* 96(5), pp. 2687-2698.

Lean Enterprise Institute, 2018. *Principles of Lean.* [Online]
Available at: www.lean.org
[Accessed 5 July 2018].

Liker, J., 2004. *The Toyota Way: 14 Management Principles from the Worlds Greatest Manufacturer..* USA: CWL Publishing Enterprises.

Martin, J. W., 2008. *Lean Six Sigma for the Office.* USA: CRC Press.

Martin, K. & Osterling, M., 2014. *Value Stream Mapping: How to visualise work and align leadership for organisational transformation.* London: McGraw-Hill.

Marzagão, D. & Carvalho, L., 2016. Critical success factors for Six Sigma projects. *International Journal of Project Management,* 34(8), pp. 1505-1518.

Maylor, H., 2010. *Project management.* 4th ed. Harlow: Harlow : Financial Times Prentice Hall.

Meng, B. & Chen, L., 2010. The application of setup reduction in lean production. 6(7), pp. -.

Moubray, J., 1991. *Reliability-centred Maintenance.* 1st ed. Oxford: Butterworth-Heiniemann.

Mullins, L. J., 2016. *Management and Organisational Behaviour.* Eleventh ed. London: Pearson.

Murugesan, V., Rajenthirakumar, D. & Chandrasekar, M., 2016. Manufacturing Process Improvement using Lean Tools. *Annals of the Faculty of Engineering Hunedoara,* 14(2), pp. 151-154.

Oliver, P., 2012. *Succeeding with your literature review a handbook for students.* Berkshire, England: McGraw-Hill.

Onofrejova, D. & Janekova, J., 2015. Value Stream Mapping and its Significance in the Production Process. *Acta Logistica,* 2(3), pp. 13-16.

PAC, 2020. *5S-Handbook,* London: PAC.

Pandey, V., Bhattacharya, A. & Bhattacharya, S., 2013. Application of the Pareto Principle in Rapid Application Development Model. *International Journal of Engineering and Technology,* 5(3), pp. 2649-2654.

Pasale, R. & Bagi, J., 2013. 5S Strategy: A workplace improvement lean tool. *Journal of Engineering And Technology Research,* 1(1), pp. 100-107.

Pellegrini, S., Shetty, D. & Manzione, L., 2012. *Study and Implementation of Single Minute Exchange of Die (SMED) Methodology in a Setup Reduction Kaizen.* Istanbul, Industrial Engineering and Operations Management.

Pieńkowski, M., 2014. Waste Measurement Techniques For Lean Companies. *International Journal of Lean Thinking,* 5(1), pp. 9-24.

Pollack, J. & Pollack, R., 2015. Using Kotter's Eight Stage Process to Manage an Organisational Change Program: Presentation and Practice. *Systemic Practice and Action Research,* 28(1), pp. 51-66.

Powel, T. & Sammut-Bonnici, T., 2015. *Wiley Encyclopedia of Management - Pareto Analysis.* 12 ed. London: John Wiley & Sons.

Rampersad,K. El-Homsi, A., 2007. *TPS-Lean Six Sigma: Linking Human Capital to Lean Six Sigma : a New Blueprint for Creating High Performance Companies.* Chicago , U.S.A: Infomation Age Publishing .

Rawabdeh, I. A., 2005. A model for the assessment of waste in job shop environments. *International Journal of Operations &Production Management,* 25(7/8), pp. 800-822.

Rother, M., 2009. *Learning to see : value-stream mapping to create value and eliminate muda.* 1.4 ed. Cambridge, MA: Lean Enterprise Institute.

Rubrich , L. & Watson, M., 2004. *Implementing world class manufacturing.* 9 ed. Fort Wayne: WCM.

Saraswat, P. & Kumar, D., 2014. APPLICATION OF VALUE STREAM MAPPING TOOL TO REDUCE WASTES IN BEARING INDUSTRY. *International Journal of Recent advances in Mechanical Engineering (IJMECH),* 3(4), pp. -.

Senderska, K., Mares, A. & Vaclav, S., 2017. Spaghetti diagram application for workers' movement analysis. *U.P.B. Sci. Bull,* 79(1), pp. -.

Shiego, S., 1996. *A Revolution in Manufacturing: The SMED System.* 1st ed. London: Routledge.

SKhmot, N., 2017. *The 8 Wastes of Lean.* [Online]
Available at: https://theleanway.net/The-8-Wastes-of-Lean
[Accessed 07 01 2018].

Stadnicka, D. & Litwin, P., 2019. Value stream mapping and system dynamics integration for manufacturing line modelling and analysis. *International Journal of Production Economics,* Volume 208, pp. 400-411.

statista, 2018. *Global car market share of the world's largest automobile OEMs in 2017.* [Online]
Available at: www.statista.com/statistics/316786/global-market-share-of-the-leading-

automakers
[Accessed 8 February 2019].

Sternberg, H. et al., 2013. Applying a lean approach to identify waste in motor carrier operations. *International Journal of Productivity and Performance Management,* 62(1), pp. 47-65.

theleanwarehouse, 2020. *theleanwarehouse.* [Online]
Available at: https://www.theleanwarehouse.co.uk/
[Accessed 26 04 2020].

Thomas, J. R., 2018. *Value Stream Mapping Workshop.* Swansea: JRT Consultancy.

Thomas, P., 2019. *Problem Solving and Quality Improvement.* UWTSD: Unpublished Asignment.

Thorn, A., 2018. *Lean and Agile manufacturing Systems.* Swansea: UWTSD.

Ulutas, B., 2011. An application of SMED methodology. *World Academy of Science, Engineering and Technology International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering,* 5(7), pp. -.

UWTSD, 2020. *Coronavirus | General Information.* [Online]
Available at: https://www.uwtsd.ac.uk/coronavirus/key-information-links/
[Accessed 25 03 2020].

Wang, T. & Ji, P., 2010. Understanding customer needs through quantitative analysis of kano's model.. *The International Journal of Quality & Reliability Management,* 27(2), pp. 173-184.

Warfield, B., 2020. *Smed - Lean manufacturing setup reduction: Lean manufacturing principles part 6.* [Online]
Available at: https://www.cnccookbook.com/smed-lean-manufacturing-setup-reduction-lean-manufacturing-principles-part-6/
[Accessed 10 05 2020].

Wilson, L., 2015. *How to implement lean manufacturing.* Second ed. New York: Mcgraw-Hill Education.

Wilson, L., 2015. *How to Implement Lean Manufacturing.* Second ed. New York: Mcgraw-Hill.

Womack, J. & Jones, D., 2003. *Lean thinking: Banish waste and create wealth in your corporation..* 1 ed. New York: Free Press.

Womack, J. P. & Jones, D. T., 1996). *Lean Thinking.* New York: Simon & Schuster.

Womack, J. P., Jones, D. T. & Roos, D., 1991. *The Machine That Changed the World.* New York: HarperCollins Publishers.

World Health Organisation (WHO), 2020. *Coronavirus.* [Online]
Available at: https://www.who.int/health-topics/coronavirus#tab=tab_1
[Accessed 25 03 2020].

Yash, D. & Nagendra, S., 2012. Single Minute Exchange of Dies: Literature Review. *Lean Thinking,* 3(2), pp. -.

Yash, D. & Nagendra, S., 2012. Single Minute Exchange of Dies: Literature Review. *International Journal of Lean Thinki,* 3(2), pp. -.