A STRUCTURED APPROACH TO MODELLING LEAN BATCH PRODUCTION

A Thesis submitted for the degree of Doctor of Philosophy

By

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Abstract

A problem relating to the manufacture of automotive body panels concerns the appropriate choice of production size or batch quantity of a body panel production run that ensures a minimum inventory profile is maintained while not compromising production efficiency. Due to underlying variation within the body panel production process it is difficult to determine a relationship between the batch quantity and production efficiency.

This thesis determines the appropriate production batch size through the creation of an iterative modelling methodology that initially examines the nature of the variation within the panel production process. Further iterations of the methodology apply appropriate analytical modelling methods until a satisfactory solution is achieved. The modelling construction is designed so that it is potentially applicable to a wider range of manufacturing problems.

As there is variation inherent within the system, regression analysis, experimental design (traditional and Taguchi) are considered. Since an objective of creating the modelling methodology is the potential of apply the methodology to a wider variety of manufacturing problems, additional modelling methods are assessed. These include the operational research methods of mathematical programming (linear and non-linear and dynamic programming) and queuing systems. To model discrete and continuous behaviour of a manufacturing system, the application of hybrid automata is considered. Thus a suite of methodologies are assessed that assess variation, optimisation and networks of manufacturing systems. Through the iterative stages of the modelling approach, these analytical methods can be applied as appropriate to converge on to the appropriate solution for the problem under investigation.

The appropriate methods identified to quantify a relationship between the batch production quantity and production efficiency include regression modelling and traditional experimental design. The conclusion drawn from the application of both methods is that relative to the inherent variation present in the production system, lower batch quantities can be chosen for production runs without affecting the production performance. Consequently, a minimum inventory profile can be maintained satisfying the objective of a lean system.

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It is frequently stated that a good teacher is never forgotten and in my formative years I have been privileged to have two such exceptional teachers. I would like to begin by expressing my gratitude to Mr Malcolm Rees an outstanding and inspirational mathematics teacher who during my years as a school pupil in South Wales instilled in me what would prove to be a lifelong fascination of the subject. My second worthy teacher or more correctly instructor is Mr David Boyles who was my Propulsion Systems instructor at the Civilian Apprentice School RAF ST Athan where I trained as an Aircraft Maintenance Engineer. Both Malcolm and David have long since passed away I am deeply grateful for their positive influence on my life.

I have had the privilege of working as practicing aircraft mechanic and later work for three major automotive manufacturing companies. I gained positive experience in each organisation and gained many friends in the process. So I wish to thank all my former colleagues at the MOD, Rover (now BMW) and Honda of the UK Manufacturing.

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There are too many personal friends too mention, but I wish to extend my thanks to my friends at the Royal Wootton Bassett Hounds Running Club. Collectively we inspire each other to the best we can be and I remain PTBARWBH.

Author’s declaration

I declare that the work in this thesis is my own.

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Abbreviations

A	Inter-arrival time distribution.
B	Number of buffers
D	Deterministic
DOE	Design of Experiments
E_k	Erlang Distribution with parameter k
FIFO	First in First Out
G	General (any distribution, with specified mean and variance).
GSPH	Gross Shots Per Operating Hour
H_k	Hyper-exponential distribution with parameter k
IMVP	International Motor Vehicle Program
JIT	Just in Time
K	Population size
LAI	Lean Aerospace Initiative
LEI	Lean Enterprise Institute
LIFO	Last in First Out
M	Exponential
MIT	Massachusetts Institute of Technology
N	Number of servers
S	Service time distribution
SD	Service discipline
SIRO	Service In Random Order
SPOH	Shots per Operating Hour
TPS	Toyota Production System

1. Introduction

1.1. Purpose of the Thesis

This chapter documents the background to the research presented in this thesis. The objective of the research is realised in the construction of a modelling methodology that is initially developed to quantify an appropriate batch size for the production of automotive body panels. Within automotive body panel manufacturing there exists underlying variation within the production process with respect to set up time duration, achieved production run lengths, production rates and both machine up and down times. To ensure consistent supply of body panels to the vehicle assemblers, it is essential that that the efficiency of the production process is maximised. However, due to the variation within the production process, there is no direct relationship between batch size quantity and production efficiency.

Consequently, a modelling construct is created that initially investigates the source of variation within the production process to attempt to quantify a relationship between batch size quantity and production efficiency. The model is designed as an iterative process and begins by simplifying the problem and as system knowledge is developed, further iterations of the method are applied utilising suitable mathematical modelling methods to converge on an appropriate solution. The framework of the method is such that the approach has the potential to investigate a wider variety of manufacturing related problems.

The modelling process is applied in the context of a lean manufacturing system. Lean systems in principle attempt to replace batching processes with flow systems of production. The batch process cannot be eliminated within automotive body panel manufacturing. Through quantifying a relationship between the batch size and production efficiency, the model would effectively identify a minimum inventory profile that does not compromise production efficiency. Consequently, the development of lean systems is considered extensively within the body of the thesis. However, the thesis is understood in the context of the environment that the research is conducted. Section 1.2 therefore provides a brief description of the case study environment. The motivation for the research is described in Section 1.3, the structure of the thesis is presented in Section 1.4 and finally the research methodology is defined in Section 1.5.

1.2. The Case Study Environment

The research is conducted at an automotive body panel manufacturing facility that supplies body panels to several vehicle assembly plants in the United Kingdom. The facility manufactures a diverse range of body panels from small structural brackets to large body panels on a range of production presses. The case study environment is restricted to a single fully automated production press dedicated to the manufacture to the large body panels including roofs, floors, doors, fenders, trunk lids, tailgates and body sides.

Body panel production is complex and a full treatment of the process is provided in Omar (2011), however the basic production process comprises of two distinct operations, the blanking operation followed by the forming operation

Blanking Operation: This initial stage unwinds a coil of steel or aluminium and feeds the material into a blanking press where a flat profile of the final panel shape is produced. Figure 1.1 illustrates a blanking press configuration. A de-coiling mechanism unwinds the coil and feeds the material into the press containing the blanking tool.

The blanks are ejected into a stacking unit. Depending on the nature of the blank, the stacking unit can located at the front or at one side of the press. Some blanking arrangements allow the production of two blanks for each stroke of the press, in which case stacking units are located at one side and at the front of press. A twin stacking configuration is illustrated in Figure 1.2.

Upon a blank stack reaching a pre-determined number of blanks, modern stacking units are designed; blanks will automatically feed onto a second stack without the need to stop the blanking operation.

Forming Operation: The forming operation shapes the previously prepared flat blank into the desired three dimensional form and can comprise of several stages.

The forming operation is carried out through a series of forming dies that are held in

Figure 1-1 Blanking Press Configuration

Figure 1-2 Blanking Press with Front and Side Stacking Units

a press machine. There are two general arrangements for press machines. The first arrangement consists of a set of individual press machines arranged in a tandem line formation (Figure 1.3). The second arrangement is referred to as a ‘transfer press’, (Figure 1.4). In this arrangement, the press tools sit on a common bed and a transfer mechanism transfers the panel along the series of dies during each cycle of the press.

In each configuration, the tool change is an automated process, with tool preparation taking place on a separate tooling bed while the current production job is running. Similarly, the transfer of the partially completed body panel is transferred automatically between each pressing operation.

Consequently, modern press manufacturing operation is a realisation of the ‘Single Minute Exchange of Dies’ or SMED application. The SMED system was conceived by the Japanese engineer Shigeo Shingo (Shingo, 1988) and is a means of systematically improving the time taken to change the tooling from one job to the next. Consequently, modern automotive press tool change overs take just a few minutes compared to several hours or even days prevalent in previous configurations.

Generally, modern press tooling and press machine configurations enable the forming of a panel within the following four stages

1. **Draw Stage:** The first press draws or forms the panel into the three dimensional shape. During forming operation, the metal transforms into plastic state enabling the material to flow into the die cavity.

2. **Trim Stage:** The panel is trimmed to remove excess metal from edges and apertures

3. **Flange Stage:** The third press bends the edges of the panel to create flanges for later body assembly processes.

4. **Pierce Stage:** The fourth and final press pierces holes for the fitting of other components through the vehicle build process.

Figure 1-3 Example of a Tandem Press Line Arrangement

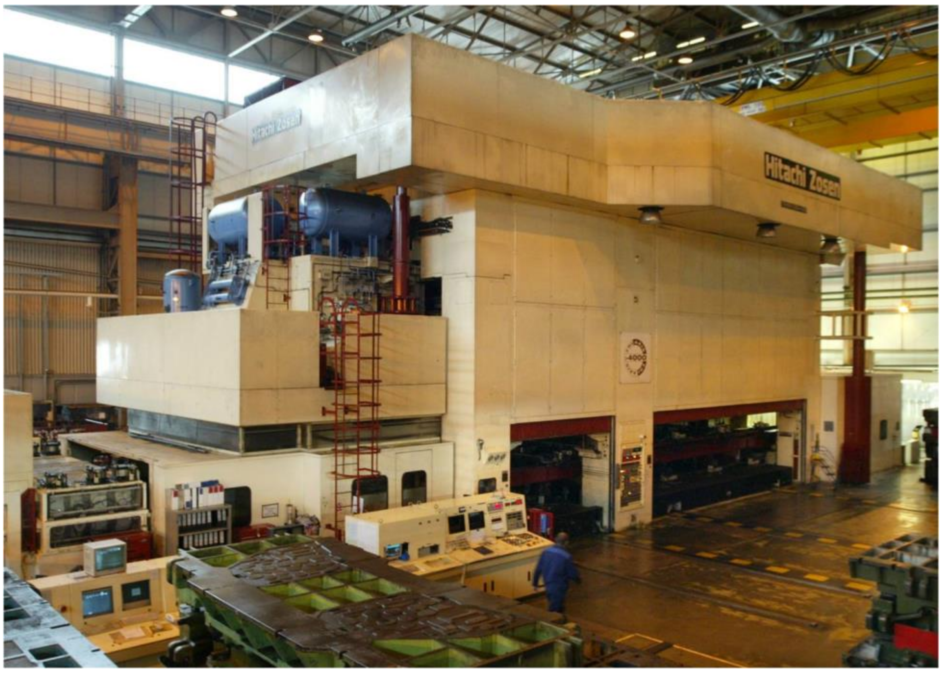


Figure 1-4 Example of Transfer Press Arrangement

Figure 1-5 Press Configuration: Tooling prepared for next production run

1.3. Motivation for the Research

The motivation for the research originated from observing the production operation of an automotive body panel manufacturer. It was clear through the both the observation of the production process and analysing performance related data that the production operation satisfied the value needs of the vehicle body assembly process through (1) the provision of dimensionally accurate body panels and (2) blemish free panel skin surfaces that satisfy the cosmetic requirements for the paint finish of the completed vehicle.

In meeting the value needs of the vehicle assembler, the body panel manufacturer reduces costs by minimising the inventory profile throughout the production operation. The inventory profile is reduced by minimising the batch size of the production runs. However, selecting too low a batch size can compromise the efficiency of the production process through increasing the frequency of tool changes. The panel production process exhibits excessive variation with respect to tool change frequency, set up times, production rates and achieved production quantities. Given the level of variation, it is too difficult to establish a quantifiable production batch size that minimises the inventory profile without compromising production efficiency.

One significant contribution of lean thinking to the manufacturing community is the wealth of improvement methods that evolved as a consequence of the growth of lean production and have been embraced by manufacturing practitioners at all levels of a production enterprise. Though the positive application of improvement methods that have resulted in tangible benefits for companies, in isolation, the methods are not effective in establishing a relationship between the production batch size and production efficiency taking into consideration the inherent variation in the production process. Thus there is scope to develop methods that aid management decision making at a holistic level taking into account the overall manufacturing process.

1.4. Thesis Structure

In addition to constructing the modelling methodology, the structure of the thesis is designed to illicit a wider understanding of the concept of manufacturing including its evolution since the beginning of the 20th century in to what is now understood to be lean production. In support of this understanding, the chapters are presented as follows:

Chapter 2: The establishes the importance of manufacturing and assesses the significant manufacturing methods that evolved during the 20th century including craft, mass production and the Toyota Production System and defines the principles that define lean thinking.

Chapter 3: Introduces the evolution of lean manufacturing examines the reasons why mass production failed and reviews the development of the Toyota Production System. The principles that define lean thinking are reviewed with specific emphasis on the principles of value and flow that is realised through Just in Time Manufacturing. Examples of the wider applications are assessed beyond the traditional general manufacturing activity.

Chapter 4: The chapter reviews a number of modelling methodologies including experimental design, Taguchi design of experiments, Operational research methods including queuing theory and mathematical programming and finally considers modelling by applying hybrid system theory. The Chapter concludes by discussing the appropriate choice of modelling method applicable to the case study environment.

Chapter 5: The specific problems associated with quantifying the batch size in the case study environment is presented that give rise to the construction of the modelling method. Subsequently, the modelling methodology is presented and applies the chosen modelling methods to quantify an appropriate batch size.

Chapter 6: The Chapter is a review the modelling methodology after application to the case study environment and considers the effectiveness of the approach and the use of the chosen mathematical methods. Both the robustness of the model and potential for extended applications are discussed.

Chapter 7: The final Chapter includes a review and discussion of the general content of the thesis. Opportunities for further work are identified. The contribution of the thesis is presented and the Chapter closes with concluding remarks.

1.5. Research Methodology

The research initially focuses on an extensive literature review to understand lean manufacturing from both an historical and contemporary context. The purpose of the review is to ultimately understand why lean principles have such wide ranging application.

Mathematical modelling methods are reviewed that have the potential for modelling manufacturing systems at a more holistic level. The modelling structure proposed within the research is applied and tested against production data collated in an automotive body panel production press shop.

2. Review of Lean Principles, TPS and Mass Production

2.1. Introduction

The primary objective of this chapter is to introduce the lean principles defined in the work, Lean Thinking (Womack and Jones, 1996). While in the chapter, the principles are introduced as a standalone construct, they are better understood in the context of their origin which is predominantly the Toyota Production System or TPS (Monden, 2012) and the mass production system that lean and more flexible systems of manufacturing would eventually replace.

Lean manufacturing has been the subject of extensive study since the early 1990’s. This is partly a reflection of manufacturers striving to increase efficiency and customer focus and consider lean methods as a means to achieve these objectives. But more significantly, the study of lean manufacturing and the adoption of the associated lean methods is also a reflection of the importance of manufacturing to sustain economic growth and innovation.

During the twentieth century, there were two major paradigmatic shifts in manufacturing (Piore and Sabel, 1986, Womack *et al*, 1990). The first shift originated in the USA during the first decade when the system of mass production would replace previously dominant craft methods of manufacturing. The second shift originated in Japan in the post war period with the development of the TPS. However it would take until the 1980's before more lean and flexible methods of manufacturing would begin to seriously permeate American and European manufacturing thinking.

Since the 1980's, mass production systems in the original Fordist sense have largely been replaced by leaner and more flexible systems. However, craft production systems as understood in the pre mass production era still exist in niche applications. Also, systems analogous to the traditional craft methods exist in specialist manufacturing applications, for example the manufacture of large scale production equipment, machine tools and aerospace. Within these applications, it is not practical to break down the division of labour to a point where each task can be carried out by unskilled workers; it requires the services of highly trained skilled mechanics and technicians. Craft methods of production, both in the traditional definition and in the modern context can aspire to lean principles.

The significance of the lean principles lie not just in their potential to deliver a more efficient customer focussed manufacturing system compared to alternative approaches. The further significance of the principles is due to the importance of manufacturing itself. Manufacturing impinges on the whole spectrum of human activity, and the efficiency in which manufacturing is delivered is key to providing employment and sustaining economies.

The opening section of this chapter introduces the nature of manufacturing and discusses the rationale why manufacturing is important. The concepts central to the understanding of this thesis are introduced, Lean Principles, the TPS, Mass and Craft Production. The concepts are not presented in what would be considered their natural chronological order but presented relative to their contribution to the understanding of the content of this thesis. The chapter concludes with a summary and comparison of each the manufacturing concepts introduced in this chapter.

2.2. The Importance of Manufacturing

Manufacturing is essential to human existence through providing the artefacts that enables human society to function. Individuals, companies and organisations of all kinds rely on a wide variety of manufactured products to conduct their daily activities. Moreover, manufacturing through delivering superior product characteristics enhances the quality of human life over and above basic human needs. In meeting the diverse needs of society, the importance of manufacturing goes beyond the basic requirement of providing products people need or desire. Due to the immense requirement for manufactured products, millions of people both directly and indirectly rely on manufacturing to provide their living. Consequently, manufacturing has the potential to sustain national economies, through the provision of employment, and generating of tax and export revenue.

The word ‘manufacture’ is derived from two Latin words, manus (hand) and fractus (make) and literally means ‘made by hand’. In this respect manufacturing has existed throughout the course of history where for the greater part of human evolution the creation of products or artefacts was achieved mainly through manual endeavours. The catalyst for the evolution of modern manufacturing where products are delivered through a combination of handwork, automated and computer controlled machinery is credited to the industrial revolution that originated in Great Britain during the 18th century (Groover 2007). The industrial revolution describes the change process from what was hitherto an agrarian economy based on handicrafts and agriculture to an economy dominated by industries serviced by machines. The industrial revolution saw the rise of the ‘factory system’ of manufacturing. The factory system is essentially a means to concentrate and organise labour and production such that output is both accelerated and increased (Mantoux, 1928). The importance of the factory system lay with the ability of the factories to house large machines where Mantoux observes:

> ‘Machinery is employed which accomplishes with infallible precision and prodigious rapidity the heaviest and most complicated tasks. Its motive power is not the limited and irregular effort of human muscles, but either natural forces such as wind and running water, or artificial forces such as steam or electricity’ (Mantoux, 1928, page 25).

While the methods of manufacturing pre and post-industrial revolution are essentially different and as the future unfolds, will continue to evolve as a result of emerging and advancing technologies, manufacturing maintains a consistent theme:

> Essentially, manufacturing is concerned with the conversion of raw materials and intermediate parts into finished products that satisfy the needs and aspirations of customers.

As a conversion process, manufacturing also has a consistent definition. For example Groover, 2007 and Rao, 2007 writing on very different aspects of manufacturing present almost identical definitions of manufacturing:

> Application of mechanical, physical and chemical processes to alter the geometry, properties and/or appearance of a given starting material to make new, intermediate or finished parts or products. This activity includes all intermediate processes and assembly operations to bring the product to its final state. (Adapted from Groover, 2007 and Rao, 2007).

While manufacturing is irrevocably linked with making or producing things, manufacturing is equally viewed as an economic activity. Manufacturing in general is conducted by commercial enterprises whose ultimate goal is to secure financial profit. If the manufacturing system is managed and organised correctly, as materials and intermediate parts move through the manufacturing process, monetary value is continually added to the product. It is the value creation potential of manufacturing that underlies its importance across a number of dimensions. Profitable manufacturing sustains the livelihoods of those people directly engaged in manufacturing and provides the basis for a manufacturing company to continue to operate. Where manufacturing companies physically exist, the local economy is in part sustained by either directly or indirectly providing services to the companies and the people who work within the company. However, it is at a national level that manufacturing is of prime importance.

There is consistent agreement amongst academics and governments that manufacturing is an essential and vital element of a nation's economy. From an academic perspective, there has been a consistent agreement over time with respect to the importance of manufacturing.

Deane (1980) contends that continuous and self-sustained economic growth (where successive generations can enjoy higher levels of production and consumption than its predecessors) is only open to those nations with an industrial base. Further, Deane states that there is a 'striking disparity' between the standards of living between the inhabitants of the so-called developed or advanced countries and the standard prevailing in today's underdeveloped countries is essentially due to the former having an industrialized base and the latter have not.

Delbridge, and Lowe (1998) assert that the manufacturing sector is 'fundamental' for the growth of mature economies. As such for the sustained growth of the United Kingdom economy an internationally competitive manufacturing sector is essential.

Nicholas Kaldor is considered a leading post war economist, (Blaug, 1989), and promoted the view that an economy will grow if that economy has a manufacturing production capability that is growing. Kaldor presents manufacturing as the 'Flywheel of Growth' underpinning economic development, international trade and improving living standards. To support his view, Kaldor presents three laws of economic growth (Thirlwall, 1983):

1: The growth of Gross Domestic Product is positively correlated to the growth of manufacturing output.

2. The growth of productivity in manufacturing industry is positively correlated to the growth of manufacturing output.

3. The Productivity in the non-manufacturing sector increases as the rate of growth of manufacturing output increases.

In a study of the decline in British Manufacturing that began in the early 1960's that continued into the 1990's, Greenhlagh and Gregory (1997) present an argument that the decline would adversely affect economic growth and future employment prospects throughout the economy. In their view, manufacturing as an economic driver is important with respect to the dimensions of *productivity*, *employment*, *technology* and *trade*:

Productivity: The growth rate in productivity is consistently higher in manufacturing than in services; manufacturing consequently makes a disproportionate contribution to economic growth.

Employment: Beyond direct employment, manufacturing generates employment through goods and service provision and generates employment in related sectors; when productive output declines, job losses are felt both directly and indirectly.

Technology: The manufacturing sector is the dominant source of innovation. During a period of manufacturing decline, the capacity to generate innovation dwindles.

Trade: In the UK, the service industry alone is insufficient to balance the demand for imported manufactured goods and a strong a manufacturing sector is necessary to maintain international trade.

More recently, Rao (2007) generalises that manufacturing as an economic activity comprises approximately some 20% to 30% of a country's goods and services and so provides the ‘backbone’ of an industrialised nation. He further contends that a country’s level of manufacturing activity is directly related to its economic health and that in general, the higher the level of manufacturing activity in a country, the higher the standard of living of its people.

Politically, within the UK during the 1980’s and 90’s a debate existed as to the strength of manufacturing’s contribution to the UK economy. In 1996, from the perspective of generating Gross Domestic Product (GDP), the UK was a service led economy where the contribution to GDP from manufacturing had reduced to 21% from 35% in 1960 (Delbridge, and Lowe,1998). However, UK political thinking since the year 2000 is to support viable manufacturing enterprises. UK government sponsored reports from 2002 outline the government’s manufacturing strategy (BERR, 2002, 2004, 2008). UK government support is based on exploiting the economic growth and employment opportunities derived from manufacturing citing that UK manufacturing accounts for a sixth of the country’s GDP, and is responsible for over half of the country’s exports contributing some £150 Billion to the UK economy (BERR, 2004, 2008). In 2004, the UK government set up the ‘Technology Strategy Board’ to drive innovation within the UK business community. The priority for manufacturing support has been directed toward ‘High Value Manufacturing’, (TSB, 2012) and is defined as:

> “… the application of leading edge technical knowledge and expertise to the creation of products, production processes, and associated services which have strong potential to bring sustainable growth and high economic value to the UK. Activities may stretch from R&D at one end to recycling at the other. Such potential is characterised by a combination of high R&D intensity and high growth”

In the USA a similar decline in manufacturing output is also observed. In particular there has been a trend to outsource manufacturing operations to countries that have much lower labour costs (Pisano and Shih, 2009, 2012). Outsourcing in their view divorces the manufacturing process from research and development and therefore suppress innovation. Moreover, the authors argue that manufacturing capabilities and partnerships within supply chains can take many years to mature and would be lost due to outsourcing and difficult to reinstate if a company decided to manufacture in-house.

In the United States, government support for manufacturing is an ongoing activity. Conscious of the decline in US manufacturing output during the 1980's, the US Defence Department sponsored a report, "Toward a New Era in U.S. Manufacturing: The Need for a National Vision" that considered how the US government should support manufacturing and how US manufacturing should be re-structured (NRC, 1986). The report recognised the 'convergence' of three trends in global manufacturing that US based manufacturers would need to respond to:

1. The rapid spread of manufacturing capabilities worldwide;

2. The emergence of advanced manufacturing technologies;

3. Growing evidence that appropriate changes in traditional management and labour practices and organizational structures are needed to improve the competitiveness of U.S. manufacturing operations.

In 2004, the U.S. government through the U.S. Department of Commerce published 'Manufacturing in America' a review of the current manufacturing landscape in the USA that set guidelines of how U.S. manufacturing should structure itself to compete globally (US1, 2004). More recently in 2007, in partnership with the National Institute of Standards and Technology, the Department of Commerce published 'Enhancing America's Competitiveness', a review of how the application of advanced manufacturing technologies supports manufacturing competitiveness (US2, 2007).

Academically, the USA is responsible for creating the lean manufacturing and agile manufacturing movements. Lean manufacturing though initially based on the manufacturing methods of Toyota , evolved through an international academic study and delivered through the management of the International Motor Vehicle Programme (IMVP) at the Massachusetts Institute of Technology (MIT), (Womack *et al* 1990). The IMVP would later influence the creation of the Lean Aerospace Initiative (LAI) also based at MIT.

Born out of a study at the Iacocca Institute at Lehigh University in Bethlehem Pennsylvania with the publication of “21st Century Manufacturing Enterprise Study”, the Agile Manufacturing movement evolved as a response to the dominance of essentially Japanese manufacturing, not just within the USA, but also globally (Gunasekaran, 2001).

From a political perspective, the importance of manufacturing is essentially stressed through manufacturing supporting economic growth and maintaining and increasing opportunities for employment. Academically, the importance of manufacturing is stressed across multiple dimensions including social, technological and economic.

Though rarely stated either within political or academic circles, historically, a strong industrial base supported by manufacturing is considered essential in respect to defending a country. Groover (2007) states in general, those countries throughout history that were ‘better at making things’ were better able to defend or conquer their enemies due the ability to make more effective weapons. In the American Civil War (1861 – 65), an advantage the North had over the South was due to its ‘industrial strength and ability to manufacture’. The historian Niall Ferguson in his assessment of military conflicts during the course of the 20th century concludes that one reason the Axis powers would lose the war is that the combined material and productive resources of the Allies and in particular the Americans were far superior. Moreover, most of the allied industrial resource was out of reach of attack from the Axis forces, located in the USA or beyond the Ural mountains in Russia (Ferguson, 2006).

Manufacturing and a strong industrial base is therefore important across multiple dimensions; it is important for individuals, communities, companies, the growth of national economies and ultimately the defence of nations. Society cannot function without manufacturing and in what is considered a seminal work on the history of the industrial revolution, Mantoux (1928) concludes:

> “*... that what nature does not provide to society, manufacturing does*”.

For manufacturing to be an enabler for employment, growth and innovation, Miltenburg (2005) argues that manufacturers must do the right things and that the right things must be ‘done well’.

Methodologies such as lean manufacturing, six sigma and total quality management within the confines of a customer focussed manufacturing strategy provide the capability for manufacturers to do the right things and to do them well.

2.3. Lean Manufacturing Principles

The term ‘Lean Manufacturing’ has been part of the manufacturing vocabulary since the late 1980’s and first used to describe the production methods of Toyota by John Krafick (an IMPV researcher) who observed that in comparison with the then traditional mass manufacturers, Toyota would use half the resources to deliver a wider variety of products to customers, Krafick (1988).

In identifying the difference between the working practises of lean Japanese automotive producers and traditional Western mass manufacturers, the IMPV researchers isolated a set of principles that a non-lean manufacturer would need to embrace to become lean.

The principles are presented in a major work by James Womack and Daniel Jones, ‘Lean Thinking’ (Womack and Jones, 1996). In the work the authors present a set of 5 interlinked principles that together work to eliminate waste within an organisation. The principles form ‘a system of thinking’ that an organisation has to embrace such that not only waste is eliminated but the totalities of the organisations activities are focussed on delivering value to their customers.

Womack and Jones present the principles in the following order:

1. Specify Value
2. Identify the Value Stream
3. Flow
4. Pull
5. Perfection

Within the lean literature, the principles are often introduced as independent constructs avoiding presenting the rationale behind the authors reasoning for the existence of the principles. Typical of such introductions include for example Murman *et al*, (2002), Chalice, (2005) and Rich *et al*, (2006). Other examples of the lean literature do not implicitly replicate the definitions of the lean principles but focus on the practical aspects of lean transformation through waste elimination, continuous improvement and the implementation of flow manufacturing (Field, 2000 and Henderson and Larco, 2003). Depending on the context under which the lean principles are introduced, their existence as an independent construct is not necessarily an issue. The presentation of the lean principles in this section is supplemented with a précis of the reasoning Womack and Jones applied to establish the principles.

Principle 1: Specifying Value

Manufacturing does not act in isolation and is supported by a complex infrastructure that includes the enabling technology to deliver the process, domestic and global supply chain management, complex information and financial systems, product design and engineering, marketing and distribution systems and not least the human resource required to coordinate the activities of the whole to bring the desired products to the customer. Though manufacturing is at the kernel of all of these activities, all activities need to work in harmony to enable product to be delivered to the customer. However it is the value created within the manufacturing operation that pays for this infrastructure. The key principle within a lean system is to deliver customer perceived value and the purpose of a lean system is therefore to manage the complex infrastructure that supports manufacturing to maximise customer value.

For Womack and Jones, the concept of value is purely defined in terms of the desires and requirements of the ‘ultimate’ customer. Since a commercial organisation can only exist if they have a customer base from which they are able to derive profit through the supply of their products and services, it is sensible that the main focus of the organisation is in the creation customer perceived value. Specifically, this means the delivery of their products and services to meet a customer’s needs at a specific price and specific time (Womack and Jones, 2003 page 16).

The need for the value principle was a consequence of the authors' observations of the general behaviour toward creating 'value' across what are considered as the three most important global industrial systems, America, Germany and Japan.

In the USA the authors observe a culture of cost cutting supported by job elimination and the diversion of revenues from downstream customers while simultaneously extracting profits from their upstream suppliers. There is an expectation that targeted customers 'will' pay a specific price for a product and or service to maintain the company in business. However, there is an applied focus on ensuring that performance and delivered quality is improved while costs are steadily reduced.

In Germany, the authors observe that a manufacturer's definition of value is based on product features that are a result of a superior application of processing methods and associated technologies. An assumption prevailed that customers desire complex product designs that could only be delivered through complex machinery. The authors assert that the assumption is not backed by any credible evidence.

Even in Japan (from where the authors synthesised lean principles) the authors note a tendency for manufacturers to attempt to create value for global customers while maintaining a purely Japanese manufacturing base with the goal of supporting home employment and supply base. The authors propose that customers across the World prefer products to be designed to satisfy local requirements and desire immediate delivery, both of which are difficult to achieve from a purely Japanese base. Hence, the immediate need of employees and suppliers take precedence over the needs of the global customer.

Each country has a different perception of what constitutes customer value:

- USA: Customer value is perceived as those attributes that maximise revenue from their customers while minimising the profit potential of the supply base.

- Germany: The perception of customer value is based on the capability of superior technologies to deliver advanced product designs regardless of whether such product attributes are actually required by the customer base.

- Japan: Value is defined in terms of what can be produced from their home manufacturing base with a view to sustain long term employment and maintain stable supplier relations.

Though these approaches are different, there is a common thread in that within each nationality, the primary focus of companies does not directly satisfy the needs, desires and aspirations of the customer. Ultimately, the lack of customer focus will not sustain the long term growth and profit potential of such companies resulting in a decline within their national economies.

The authors contend that long term sustainability, growth and maximisation of profit for a company can only begin by defining value in terms of the requirements of the ultimate customer such that specific products and services meet the needs of the customer at a specific price at a specific time.

Principle 2: Identifying the Value Stream

The value stream is simply the set of all processing steps or specific actions that are required to deliver a product or service to the customer with the dual aim of satisfying the customer value requirements and eliminating any potential waste that can be generated during the delivery.

Womack and Jones identify that value streams are applicable to three critical management tasks common to any business activity that combine to bring a product or service from concept to delivery:

1. Problem Solving Task: relevant to product concept, design, engineering and launch.

2. Information Management Task: relevant to logistic activity, order taking, scheduling and delivery.

3. Physical Transformation Task: relevant to transforming raw materials and intermediate parts into the final product.

The creation of the value stream is therefore a holistic overview of the way that value is created for a customer through the organisation. The concept of ‘stream’ is of particular importance. A process in isolation may be deemed efficient within itself, but does not necessarily contribute to the efficiency of other activities along the whole of the stream. Creation of the value stream avoids isolated ‘islands of success’ and transcends individual processes and the confines of not only departmental functional boundaries but also the organisation to embrace the whole set of activities across the supply chain.

Principle 3: Flow

Given that the identified value stream transcends departmental and company boundaries it is reasonable to conclude that the transformation of raw materials and intermediate products into the final desired product should flow seamlessly through the value stream. The applied thinking for the principle of flow is similar to that for the value stream in that there is a move away from purely departmental or functional thinking to a system of thinking that maximises the efficiency of the total process. Departmental thinking concentrates on the efficiency of the department possibly at the expense of the efficiency of the overall process. Consequently, batches of product move from department to department choking the production system with excess inventory waiting to be processed. Flow defines the continuous movement of material through the production system to which value is continually added at each processing step until the final product is created.

Principle 4: Pull Production

Within a ‘Pull Production’ system product is only manufactured on receipt of a customer order. The order triggers the flow of manufacturing activity through the value stream. Along the value stream the work carried out at a given production workstation is dictated to by the requirements of the follow on customer workstation(s); thus the product build is pulled through the value stream and synchronised to the requirements of the final customer. If an upstream workstation has no current order to produce, the downstream workstations will also not produce.

The Pull method of production avoids the build-up of unnecessary inventory since any given workstation will only produce what is required by the follow on customer workstations. This is in contrast to a Push method of production controlled by a centralised planning function. Each workstation pushes out product regardless of the requirements of any follow on workstations (Slack *et al* 2004). Consequently, the Push method of production is characterised by excess idle time, the build-up of unnecessary inventory resulting in queues of intermediate product waiting further processing at downstream workstations.

The principles of Flow and Pull Production are strongly linked. Together, compared to a batch and queue operation,

- Double labour productivity
- Reduce throughput time by 90%
- Reduce inventory by 90%
- Reduce errors by 50%
- Cut injuries

Principle 5: Perfection (Continuous Improvement)

The authors propose that due to the interaction of the preceding four principles, a lean system will by definition seek to continually improve the delivery of customer perceived value. In attempting to improve on customer value and increase the rate of flow, weaknesses are exposed in the value chain that can be removed through process improvement. Lean systems therefore become transparent in respect to revealing impediments to deficiencies in the value stream that compromise flow. In essence, everyone involved in some aspect of the value stream, from designers, through to suppliers and production staff can see everything making it easier to expose deficiencies.

2.4. The Toyota Production System

Significant emphasis in the lean literature is given to the Toyota Production System or TPS created and implemented by Taiichi Ohno. Ohno, originally a machine shop manager within Toyota and later an executive vice president, was instrumental in basing Toyota’s production method of Just in Time (JIT) delivery of parts to the production system and the ‘Pull’ method of manufacturing. For many academics and practitioners, the TPS is considered as the first truly lean system of manufacturing. From the company's humble beginnings after World War II as a serious manufacturer of automobiles, Toyota have grown to be the dominant leader in global automotive manufacturing. The foundation of Toyota's successful growth is attributed to the application and the continuing evolution of the Toyota Production System (Liker, 2004, Goldratt, 2009). Though the work and operating practices of Toyota significantly influenced the findings of the IMPV, the authors of 'The Machine that Changed the World' and 'Lean Thinking' do not advocate that manufacturers blindly copy the TPS. Rather, the authors recommend that over time manufacturers align their production and enterprise wide operations to the set of lean principles defined within their work.

In pre-war Japan, Ohno recognised that the production differential between a Japanese and an American worker was some 9-1 in favour of the Americans (Ohno, 1988). Ohno thought it inconceivable that a Japanese worker on average applied up to ten times more effort to complete comparable tasks than a typical American worker and concluded that the differential was due to inherent waste within the then Japanese working practices. Ohno understood that the identification and elimination of such waste would result in a potential ten-fold increase in Japanese productivity.

In the aftermath of World War II, Kiichiro Toyoda the founder of Toyota Motor Company with the aid of Taiichi Ohno, Shigeo Shingo and his cousin Eiji Toyoda strove to regenerate the company. They studied American manufacturing methods and were heavily influenced by the methods of Henry Ford (Levinson, 2002, Liker 2004) and the work of W Edwards Deming (Liker, 2004). However upon visiting the USA and witnessing first-hand the manufacturing methods employed by Ford and other manufacturers, it was evident to the founders of Toyota (and in particular, Ohno and Eiji Toyoda) that the fragile Japanese economy devastated by the ravages of the war could not sustain the USA style mass production. Nevertheless, Ohno and Toyoda adopted the core elements of the Ford mass production system and strove to 'engineer' out what they considered were wasteful and impractical activities. Ohno was impressed by the management of American supermarket systems and in particular the method of restocking the self-serving shelves from which the customers chose the products they wished to buy. Ohno adapted the supermarket shelf replenishment policy to develop Just in Time replenishment of raw materials and parts for manufacture and assembly. Shingo was instrumental in devising and implementing machine set up reduction methods and developed the concept of SMED (Single Minute Exchange of Dies).

The essential features of the system are designed to eliminate or at least minimise the impact of the defined seven wastes on the underlying cost base (Toyota, 1996).

The TPS is a method of production devised by the Toyota Motor Corporation to eliminate through improvement activities all forms of waste within a company (Monden, 2012). The ultimate purpose of the TPS is to secure profit through cost reduction or improvements in productivity. In the TPS costs include not only those of the manufacturing system but across the whole of the extended enterprise, for example, administration costs, sales costs and capital costs.

Central to the delivery of the TPS, is the elimination of waste. Within the TPS, seven generic forms of waste are identified:

1. **Overproduction:** Essentially this means to manufacture products before they are required. Overproduction prohibits the smooth flow of materials and degrades both quality and productivity.

2. **Waiting:** The waste of waiting occurs when products are not moving or being processed and is a typical feature of batch and queue manufacturing methods. Much of a product’s lead time will be consumed is tied up in waiting for subsequent operations as a result of poor material flow, long production runs, and excessive distances between work centres.

3. **Transporting**. Though an essential activity, transporting product between processes does not actually add value to a product; excessive transportation, movement and handling provide opportunities for damage and deterioration of quality resulting in additional costs.

4. **Inappropriate processing:** This can occur when manufacturers use expensive and perhaps high tech precision equipment where simpler facilities would be more effective. Expensive equipment encourages high utilisation to recover costs leading to overproduction. Inappropriate equipment combined with poor plant layout

resulting in preceding and subsequent operations located too far apart. This in turn contributes to excessive waiting and transportation.

5. Unnecessary inventory: Inventory in the form of Work in Progress (WIP) is a direct result of overproduction and waiting. Excessive inventory consumes space, increases storage and transportation costs, and inhibits problem identification and solving.

6. Unnecessary or excess motion: This example of waste is applied to the ergonomic issues of physically carrying out a task where health and safety issues play a dominant role. For example, excessive or unnecessary motion relating to bending, lifting, stretching or reaching.

7. Defects: Quality defects result in re-work or scrap and incur additional and unnecessary cost penalties for a company. Managing the rectification of defects results in the duplication of scheduling, inspection, handling, storage and transportation and results in a loss of capacity utilisation.

Womack and Jones (1996) introduce an additional eighth waste, that of the 'Underutilisation of Employees', recognising that many employees are able to contribute over and above their main responsibilities through their creativity and resourcefulness.

Though continuously evolving, The TPS was essentially developed over the period 1945 – 1975 mainly through trial and error methods led by Taiichi Ohno. The essential features of the system are designed to eliminate or at least minimise the impact of the defined seven wastes on the underlying cost base (Toyota, 1996).

The Elements of the Toyota Production System are:

1. Just in Time Production (JIT) and Autonomation

Simply, JIT means to produce the necessary units in the necessary quantity at the required time. JIT is the mechanism that allows inventory to flow through the production system synchronised to the demand for the completed product. Autonomation is an extension to an automated system where if a machine malfunction occurs, the malfunction is automatically detected and the machine stops.

Effectively, the machine stops autonomously without human intervention - hence the term autonomation. Autonomation supports JIT by never allowing defects from a preceding operation to flow into and disrupt a subsequent operation. Ohno (1988) considers that JIT production implemented with autonomation provide the two supporting pillars of the TPS.

2. Levelled Production (Heijunka)

Levelled production ensures that the output of the whole manufacturing system is balanced to the customer demand imposed on it. Along a typical Toyota production line it is usual to see a variety of car body types moving along the line at the same time. Each of the body types has a different build cycle time and the production of each body type is staggered over the day making efficient use of people and equipment. From the customer demand profile, a build sequence is created that distributes different specifications of vehicles evenly over the day.

3. Pull System

The key feature of the JIT process is the application of what is called the ‘Kanban’ system of manufacturing. In its simplest form a kanban is a card that is sent from a worker of one process to a worker of a preceding process requesting the release of the required quantity of product to continue production. The whole of the manufacturing system is connected by a system of kanban ensuring that only product that is required is manufactured.

This system induces a ‘Pull’ system of manufacture. Effectively, all that is required is to know the customer demand for the final product and through the kanban system, product is pulled through the production system at a rate matched to the final customer demand. In principle this reduces the need for excessive inventory as product is continuously being consumed at the subsequent production process.

4. Continuous Flow Processing

This feature of the TPS implies that work is arranged to flow smoothly to one operation to the next without any detours into storage. In the TPS this feature applies to the extended enterprise from suppliers of raw materials and components through subsequent assembly and manufacturing processes through to distributors, dealers and customers. Supporting this concept is the design of logistical systems and shop-floor layout to encourage at best single piece flow or where this is not possible, the processing of small batch quantities.

5. Match Production Rate to Market Demand

The TPS links production activity to actual customer demand. The metric to create this link is the concept of ‘Takt Time’. In the TPS, takt is the ‘pace of sales in the marketplace’. In the production system, the Takt Time is simply the quotient of daily working hours divided by the number of vehicle orders that are required for the day. Takt times will vary for each vehicle and to maintain levelled production, extra resources are applied to vehicles with short takt times at the expense of vehicles with a longer takt time.

6. Multi Skilled Operators

The TPS requires a degree of operator flexibility with regard to production tasks. Vehicles with a short takt time will be assigned more operators working on a limited number of tasks. Vehicles that have a longer takt time will absorb fewer operators who will have an extended range of activities to carry out. This flexibility is necessary and is possible because in the TPS people master a broad range of skills and processes.

7. Build Quality into Processes.

In the TPS, equipment is designed to detect abnormalities and to stop automatically whenever they occur. Moreover, operators are encouraged to stop production flow whenever they observe a problem that will affect production or quality. This concept of either mechanical or human intervention of defects propagating into subsequent stages of production is called ‘Jidoka’. The Jidoka process enables immediate illumination of a problem by stopping the machine as a problem occurs trough a communication medium – for example warning lamp or other kind of indicator.

8. Standardised work.

Standardised work is a tool for maintaining productivity, quality and safety and provides a consistent framework for performing work at the designated takt time and making improvements in work procedures. A working sequence is designed by team leaders who understand the most efficient way to carry out a task and calculate a minimum quantity of on hand stock to ensure smooth work flow relative to the takt time of the process. This is captured with in a documented procedure or guidelines and is a feature of every production task within the TPS.

9. Kaizen (Continuous Improvement)

The Standardised work approach sets a basis of operation from which team leaders and members can introduce on a continued basis, process improvements. The culture of continued process improvement is embraced within the concept of ‘Kaizen’. Kaizen embraces the idea of empowering a dynamic culture though human motivation by encouraging individuals in designing and managing their own work and so encourages improvements in standardised work.

Embraced within this system, Monden (2012) states is the cultivation of ‘Respect for Humanity’ as the system utilises human resources to attain its cost objectives. The respect is enhanced through:

- Ensuring workers perceive their job as important and significant so securing high morale.

- Creating a relationship of trust and credibility throughout the organisation through open communication.

- Empowerment through the creation of small self-contained teams that embrace a continuous improvement ethic.

- Improvement of worker conditions.

The dimensions that make up the Toyota Production System are combined and summarised within a pictorial representation, ‘The House of Toyota’, (Figure 2.1) demonstrates how each dimension is linked to support the aim of the TPS to create the highest quality products at the lowest cost in the shortest times.

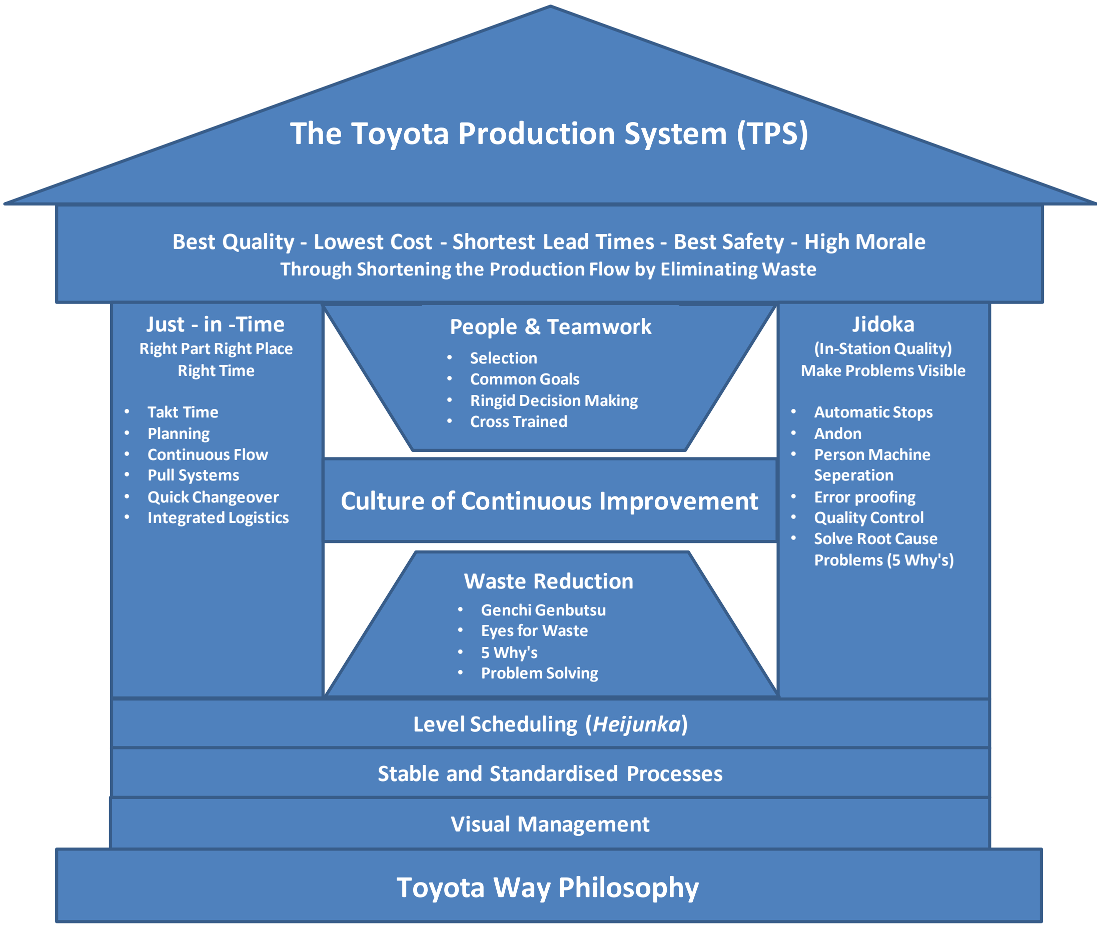


Figure 2-1 The House of Toyota (Adapted from Liker, 2004)

2.5. Mass Production

Succinctly, Mass Production is a method of organised production that focuses on attaining high rates of output such that as the quantity of output increases, the unit cost of product decreases. Mass production relies on three basic principles:

1. The division and specialisation of human labour;
2. The production of standard interchangeable parts;
3. The moving assembly line.

Historically, the concept of the division of labour has been well understood as a means of increasing productive output by reducing a work task to a series of simple tasks that can be carried by essentially unskilled workers. The division of labour is a central theme in the influential work by the 18th century political economist and philosopher, Adam Smith. In his, *'An Inquiry to the Nature and Causes of the*

Wealth of Nations ', (Smith, 1776), The advantages of the division of labour are described in an example of breaking down the production steps necessary to manufacture a pin. In 1832, the mathematician Charles Babbage published '*On the Economy of Machinery and Manufacturers*, (Babbage, 1832). Within this work, Babbage describes the benefits that are obtained from effective production planning and the division of labour. Babbage had observed that most work tasks were assigned to highly paid skilled men. By breaking down the work tasks into a series of simpler tasks, Babbage contended that the simpler tasks could be assigned to less well paid lower skilled workers and would also free the skilled workers to apply their abilities to essential work tasks. This approach to the division of labour is frequently referred to as "The Babbage Principle".

With respect to the origins of mass production, historians frequently refer to the production methods employed for the construction of ships in Venice, Italy, during the 17th century. The production methods employed at the 'Venice Arsenal' were analogous to the mass production methods adopted during the turn of the 20th century utilising "....assembly line efficiency, complex worker organisation, sub division of labour, the provision of materials and the analysis and scheduling of planned outcome", King (2003). However, mass production as a modern discipline emerged as an accumulation of activities dating from the mid-19th century Mayer (2006), and brought together by the principal architect - the American automobile manufacturer, Henry Ford.

On January 1st 1910, Henry Ford opened a new assembly plant in Highland Park, in the city of Detroit in the State of Michigan USA. The new assembly plant provided Ford with the means to expand production of the Model T motor car. The Model T was originally built at the Piquette assembly plant also in Detroit from 1908, and was Henry Ford's response to his desire to provide a car for the '*great multitude*'. Prior to 1910, the build volumes of the Model T were some 14161 units. At Highland Park, the annual production volumes of the Model T rose steadily with the improvement of production methods from some 20,000 units in 1910 to just under 95,000 units in 1912. However, it was due to the introduction at the Highland Park assembly plant of the automated moving assembly line by two of Ford's senior executives, Charles Sorenson and Peter E Martin that in 1913 production more than doubled to just fewer than 250,000 units (Batchelor, 1994). The moving assembly line had previously been utilised in the meat packing plants of Chicago in the 1870's but it was due to Ford that the assembly line became the foundation for the dominant means of mass manufacturing (Heizer, 1998).

Henry Ford pioneered the art of the 'mass production' of motor cars at Highland Park, basing the methodology on principles that evolved during the greater part of the 19th century primarily in the USA through the 'American System of Manufacturing', (Hounshell, 1984). The American System of Manufacturing describes the transition from purely artisan or craft based methods of manufacturing to a system that employed machine tools, templates, jigs and gauging systems to make standardised interchangeable parts (due to Eli Whitney). Interchangeable parts would permit a division of labour such that the subsequent assembly of parts could be carried by semi-skilled or unskilled labour. Influenced by the scientific management methods developed by Frederick Winslow Taylor, Henry Ford would ruthlessly implement the division of labour, breaking down assembly tasks to their individual component tasks, (Hooker, 1997). Previously the use of interchangeable parts was adopted by Isaac Singer with the development of the sewing machine and Samuel Colt with the development of the revolver and within the car assembly industry by Henry Leland at the Cadillac Motor Company (Grint, 2000). By the time of the outbreak of World War 1, Ford had fused his innovations in production, product design and labour management into a coherent competitive system that implied almost universal application (Talliday and Zeitlin, 1992).

Henry Ford's contemporaries included William Durant who founded General Motors (GM) in 1908, his successor Alfred Sloan and Walter Chrysler, who after a successful career at Buick (a subsidiary of GM) founded the Chrysler Corporation in 1925, would also embrace the essential elements of mass production (Weiss, 2003). A succession of European automotive manufacturers would visit the USA to understand the mass production methods applied to automotive manufacturing. Louis Renault would visit the USA in 1911 and the following year in 1912, Andre Citroen visited Ford. Marius Berliet, a French truck manufacturer, and Robert Peugeot would both send engineers to visit Ford's factories. William Morris, the first successful British mass producer of cars, visited the USA twice in 1914 to study

American manufacturing methods (Batchelor, 1994). The manufacturing methods developed by Ford and GM would also have an early influence on the development of what would become the Japanese car manufacturer Toyota in the early 1930's (Liker 2004). Sakichi Toyoda initially manufactured power looms for weaving cloth, and created the Toyota Motor Corporation in 1930. Heavily influenced by Henry Ford's book, *Today and Tomorrow* (Ford and Crowther, 1926), Toyota management would visit the USA in the understanding that they would need to adapt the mass production for the Japanese market.

2.5.1. The Ford Mass Production Model

In delivering his dream of providing a car for the ordinary American earning a moderate wage, Henry Ford set out to create an efficient production system capable of delivering to a mass market. While mass production is concerned with the manufacturing of high volume quantities of products, Ford was more concerned with the underlying methods that would deliver quantity production rather than the quantity production itself (Ford and Crowther, 1926). Ford visualised mass production as:

> "... focussing upon a manufacturing project of the principles of power, accuracy, economy, system, continuity and speed"

Principally, Ford considered the delivery of these principles as a prime management task to '*.... deliver in quantities a useful commodity of standard material, workmanship and design at a minimum cost'*.

Ford based his production methods on three distinct interrelated principles:

1. The planned orderly progression of the product through the production system;

2. Delivery of the product to the worker through the assembly line;

3. The analysis of the manufacturing operations into their constituent parts.

Ford argues that any one of the three principles implies the other two. The orderly progression through the production system requires a build plan that defines which products are made. At each assembly stage it is known what parts are required to be delivered to each work station and the required number of assemblers. That knowledge is facilitated by analysing the total manufacturing operation that defines where in the assembly process parts are fitted to the assembly.

Over and above previous methods of manufacturing management, Ford visualised that mass production would bring added benefits in addition to perceived production efficiencies:

- In contrast to previous methods of manufacturing control based primarily on financial consideration, mass production would devolve control to the shop floor where manufacturing managers are able to further refine standardisation and engender a readiness to advance and improve production methods.

- Mass production would afford the highest product quality, as maintaining mass output demands robust parts that would immediately fit to the assembly with no additional fitting or rework.

- The continuing introduction of single purpose machines would improve productive output by grouping similar operations together and would reproduce hand skills.

- Ford considered manual work a wasteful activity. Mass production transfers the physical load of work from the workers to machines, allowing workers to become the masters of their environment.

- Mass production necessitates responsible management. Financial control based on reducing wages is replaced by scientific management methods that through increasing output enable commensurate increases in both employment and wages.

- Mass production positively contributes to society through meeting the needs of consumers, so increasing the general standard of living enabling people to enhance their quality of life.

While mass production would replace the craftsman as the means to manufacture and assemble products, Ford contends that the need for skilled craftsman who would 'apply creative genius' is greater under mass production. Though not directly involved in production, the craftsmen are employed building and maintaining the machinery and tooling that facilitates mass production.

2.6. Craft Production

The procurement of artefacts through craft methods of manufacturing is unique as there is an almost total reliance on highly skilled craftsman to produce the artefacts. Within both lean and mass systems, the responsibility of manufacturing the product is shared amongst a range of distinct agents, including management and supervisory functions, industrial engineers, the suppliers of the dedicated production equipment and of course the production workers who manufacture and assemble the product. Only a limited proportion of these distinct agents would physically touch the product and is generally limited to the unskilled assembly worker. At the individual level, each assembly worker 'touches' just a small element of the complete product as it moves through the complete assembly process. Before the introduction of mass production, the craftsman would in general build significant elements of a product or indeed the complete product. Craftsmen by definition are highly skilled practitioners in a range of 'trades' such as fitting, machining, and metalworking having undergone several years of training, usually as an apprentice. Additionally, craftsmen would have extensive knowledge of the materials they work with to enable them to form, cut, machine and heat treat the materials. Traditionally noted for their handwork skills, craftsmen would frequently use hand tools that they would have made themselves as apprentices. In mass production, and in high volume lean systems, dedicated machines control the work and ultimately the worker. In contrast, in a craft system, in the use of machine tools such as lathes or milling machines, the craftsman controls the machine.

In the ‘Machine that Changed the World', (Womack *et al*, 1990), the method of craft production is presented through an example of a customer procuring an automobile at the turn of the twentieth century. As the authors describe, an automobile industry in any discernible form did not exist toward the end of the 19th century. The procurement of a car was specifically an individual activity where the potential car owner would deal directly with a manufacturer. The manufacturer would take the customer’s specification and over a period of some months would design, manufacture and assemble a unique vehicle to satisfy the customer’s requirements. The significance of the author’s example of building a car by this method emphasised the use of highly skilled artisans or 'craftsmen' across each stage of the build process. Each craftsman would work in their individual and unique way such that no two craftsmen would produce identical and interchangeable products.

To illustrate craft methods of production, Dennis (2007) also employs the example of the production of the early automobile to introduce the characteristics of the craft system. Womack and Dennis both agree on the significant features of craft production as:

- A workforce comprising quasi-independent tradesmen skilled at design, machining and fitting.
- Decentralised organisation. Small machine shops provided most parts. The owner/entrepreneur coordinated the process in direct contact with contractors, workers and customers.
- Low production volumes with high prices.

Though it is feasible for craftsmen to build dimensionally similar and 'within tolerance' components, through hand work and fitting it can be difficult to meet demanding tolerances. Womack *et al* (1990, p22) discuss the phenomena of dimensional creep, where successive parts are fitted to an assembly each deviating slightly from their nominal dimensions. Any two completed assemblies would dimensionally deviate significantly from one another, though were built from the same drawings and within same tolerances. This inherent difficulty within craft systems to build standard products coupled with the last feature listed above inhibits craft methods of production satisfying the needs of mass markets with respect to meeting volume requirements and acceptable cost to the consumer. Craft methods of production are still practised in niche applications where discerning customers are prepared to pay for the prestige of a premium brand or product attributes that are not available from volume producers. As technology has advanced and accordingly the available product attributes have over the time increased, niche craft manufacturers are not necessarily capable of replicating advanced technologies. Similar to their 'mass' supply counterparts, niche manufacturers have to outsource (generally to the same supplier base) components that they cannot replicate.

Though, in terms of manufacturing consumer based products, craft methods of manufacturing belong to niche manufacturers, mass production systems and eventually lean systems of production would rely on the craft based skills to supply and maintain the complex machinery and tooling required to support production. As time has progressed, the pure craft skills have evolved to include greater technical knowledge. A class of product exist such that the division of labour of the build process cannot be broken down to a series of finite tasks that can be achieved by unskilled labour. Applications such as aerospace, ship building and the construction industry, require trained engineers, technicians and craftsman to meet their build needs. The division of labour is supplanted by a division of 'trade' knowledge, recognising that is impractical for any one person to be skilled across a range of engineering and craft disciplines.

2.7. Concluding Remarks

Manufacturing is introduced as an enabler for economic growth and prosperity and a driver for innovation. The significance of lean manufacturing and the associated principles is in the provision of capabilities to facilitate manufacturing efficiency and customer focus and so sustain growth and innovation.

This chapter introduced the key manufacturing elements that provide the foundation to this thesis, namely the lean principles, the TSP, mass production and craft manufacturing. Through evolution, there is a relationship between each of the elements; to engender understanding, they are presented as standalone constructs.

A lean system is characterised by five interrelated principles that serve to focus the activities of a company to create value for the ultimate customer. Value stream creation ensures that only those activities that contribute to delivering value are employed. The dual principles of flow and pull production ensure that only what is required by a customer is manufactured and flows through the value stream minimising both inventory and waste. The final principle of perfection alerts the organisation to continually monitor their activities to expose weaknesses and identify opportunities to deliver even greater customer value.

The Toyota Production System is the origin of lean manufacturing. The lean principles were formulated primarily from studying Toyota's production methods. The focus of the company is to deliver customer value while simultaneously eliminating waste. Production is primarily demand led and the concepts of the kanban and JIT deliveries of supplied parts contribute to a flow system of manufacturing. The ingrained culture of the company is one of continuous improvement ensuring that value streams are maintained and improved upon. The TPS clearly aspires to the lean principles and, as such, provides the benchmark against which many manufacturing companies and service organisations model their lean roadmap.

Through Henry Ford, mass production is the convergence of technologies, manufacturing methods and management thinking that evolved during the nineteenth century as a means to lower the unit cost of standardised products that could be supplied to a mass market. Within this chapter, mass production is presented as the construct that Henry Ford envisaged, as an efficient method of manufacturing to empower managers and workers to build standard products that would appeal to a mass consumer market.

Conversely, traditional craft methods of manufacturing are characterised by highly skilled artisans generally supplying unique products to individual customers. Due to the hand crafted nature of the product build process, no real standardisation is possible within a craft system. Craft products take time to build incurring substantial cost so precluding supply to mass markets. Though craft skills are still practised within niche applications, craft skills have been absorbed within building and maintaining the equipment necessary to support mass systems of manufacture and within the provision of some classes of technically complex products.

Society is totally reliant on manufacturing to provide the artefacts and products necessary for existence and to provide a quality to life over and above the basic need to survive. Consequently, manufacturing as an entity has a guaranteed market. However, society does not require that a specific manufacturer remains in business, or indeed requires every product manufacturing is capable of providing. Indeed, given the globalisation of manufacturing and the relative speed in which products can be supplied to markets, from a customer perspective it is not essential that goods are produced locally. The observation applies equally to both purely functional products and products that also aspire to enhance the quality of life.

The onus is on manufacturers with the appropriate government support to do ‘the right things and do the right things well’ and create an infrastructure that delivers value and meets the needs of consumers and society.

3. Literature Review: The Anatomy of a Lean System

3.1. Introduction

The publication of the ‘Machine that Changed the World’, (Womack *et al,* 1990) introduced the neologism ‘Lean Manufacturing’ into the mainstream manufacturing vocabulary. The adjective ‘lean’ served to differentiate the manufacturing methods practised in Japan with the then mass production approach to manufacturing that dominated European and American thinking. It would have been significant in itself had the concept of lean manufacturing remained exclusive to the discipline of manufacturing. However, in the years since the publication of the ‘Machine that Changed the World’, not only have lean practices matured and continue to evolve within manufacturing, lean principles have found application in a diverse variety of industrial, commercial, healthcare and administrative sectors.

Though the influences of the lean principles, (Womack and Jones, 1996) are extensive, it is not necessarily the case that there is a shared understanding of what is meant by a lean system, (Stone, 2012). Lean implementations can fail as the focus of the implementation is based on misguided applications of techniques without considering the underlying philosophy, (Seddon and Caulkin, 2007).

The purpose of the literature review is to consider the diffusion of lean principles across the wider manufacturing, industrial and commercial landscapes to (1) determine if a consistent definition of what constitutes a lean system exists and (2) if the underlying principles do indeed have universal appeal.

As the origins of lean manufacturing are embedded in the development of the Toyota Production System (TPS) which itself in part evolved as a response to perceived deficiencies of the mass production model, the review begins by considering the ascendency and subsequent decline of mass production. The failure of mass production is a lesson in history of complacency and lost opportunity. Complacency, because mass production practitioners concentrated almost exclusively on output and economies of scale and lost opportunity because the complacency prevented the mass production system evolving into a system of manufacturing that focussed on the ever changing requirements of the global customer.

Lean manufacturing is a synthesis of the operating practices of the Toyota Production System (TPS). Due to the success of the Toyota Motor Company, the TPS has been studied by a variety of manufacturers, service and public companies as an example of best practice. Though it is the present day ‘mature’ TPS that is considered, from the origins of the TPS emerged principles that have proved relevant throughout the post war development of Toyota.

The evolution of lean manufacturing is presented as a response to the decline of mass production and as a means of applying the methods of the TPS to manufacturing in general. At the operational level, Just in Time (JIT) manufacturing is reviewed as it is at the kernel of daily activity that ensures the lean principles of flow and pull production is applied. The relevance of lean principles is considered across a variety of diverse applications. Since the publication of the ‘Machine that Changed the World’, the manufacturing landscape has evolved presenting alternative approaches to manufacturing. Concepts such as mass customisation, agile manufacturing and six sigma have emerged that influence the way practitioners think about and deploy manufacturing activity. These approaches are not necessarily competing with lean and could be viewed as complimentary methodologies and are reviewed as concepts in their own right and to provide a more holistic understanding of a lean system.

3.2. The Decline of Mass Production

The early literature assessing the effectiveness of lean manufacturing emphasised the advantages of the lean approach to manufacturing over the mass production model particularly within the automotive industry (McDuffie, 1995). Moreover, conclusions drawn from studies during the 1980’s of Japanese and Western Manufacturing practices asserted the superiority of Japanese manufacturing (Hayes and Wheelwright, 1984, Schonberger, 1982a, 1982b, 1986, 1987). A succinct conclusion drawn from these works is that mass production was a rigid inflexible system of manufacturing fraught with waste and failing to meet the needs of an increasingly demanding customer base. Nonetheless, as the last decade of the 20th century unfolded, Western manufacturing practices were still predominantly based on mass production. Moreover, the practices had largely remained unchanged since the inception of the method by Henry Ford and Alfred Sloan.

Conversely, mass production was originally initiated as a means to deliver products cost effectively to a mass market that would satisfy the functional and quality needs of consumers. In 1915, some seven years after Henry Ford built his first Model T Car, the manufacturing methods practised by Ford were endorsed in a series of articles in the ‘Engineering Magazine’ that were later consolidated into a book, (Arnold and Faurote, 1915). The preface to the book is written by Charles Buxton Going, an industrial engineer and university lecturer who promotes what he considers to be the genius of Henry Ford through providing:

> ‘....the requirements of true efficiency, which are: constant increase of quality, great increase of pay to workers, repeated reductions in cost to the consumer. And with these appears as at once cause and effect, an absolutely incredible enlargement of output reaching something like one hundred fold in less than 10 years, and an enormous profit to the manufacturer ’.

The manufacturing model created by Ford evolved from what is defined as the ‘American System of Manufacturing’ that focussed on manufacturing interchangeable parts machined to close tolerances through utilisation of specialist machine tools (Hounshell, 1984). Parts could be assembled sequentially by essentially unskilled workers. Consequently, in addition to already established skilled artisans, who could build, set up, maintain and improve the machines a second type of worker would emerge from the American system: the unskilled worker who would through a division of labour carry out a small but nevertheless essential assembly tasks, (Doll and Vonderembse, 1990).

The enabling technology that facilitated Ford to achieve cost effective high volume manufacturing was the introduction of the powered moving assembly line. The moving assembly line brought the work to the worker and enabled complex assembly tasks to be sub divided into a series of simple tasks each requiring the services of an unskilled worker who required the minimum of training.

The production system Ford created met the needs of a mass market through supplying a product at a price that the mass market could sustain. And it would be

Ford's understanding of the price a mass market is capable of paying for a product that would result in the creation of mass production (Levitt, 1960). However, Ford initially limited production at each of his factories to a single product and attempted to manage centrally the complete operation from production and engineering through to marketing and essentially devolving all decision making to himself.

Conversely, Alfred Sloan at General Motors would decentralise operational control and create individual business units each responsible for a specific market segment of automobile that ran incrementally from inexpensive to expensive. The strategy had a dual effect; at any one time, products had potential appeal to a wider range of income groups and as people grew older and possibly wealthier they could aspire to owning the more expensive brands. In addition to production and engineering professionals, Sloan would complete his operational structure by including financial and marketing experts. It is this *complete* system in the opinion of Womack *et al* (1990) that the term mass production applied to throughout the twentieth century.

By the 1920's mass production would be firmly at the root of American economic prosperity for the greater part of the twentieth century. Furthermore, until the beginning of the ascendency of Japanese manufacturing practices in Western culture during the 1970's, mass production would be the dominant means of global manufacturing (Tsutsui, 1998).

The diffusion of mass production throughout the USA and globally would be in part due to Ford's willingness to share the operating practices he had developed. Following the opening of the Highland Park complex in 1910, Ford would welcome visitors from Great Britain, mainland Europe and the Far East keen to learn and adapt the mass production techniques he pioneered (Womack *et al*, 1990, Shiomo 1995). Additionally during the 1920's Ford wrote two books , 'My Life and Work', (Ford, 1922) and 'Today and Tomorrow', (Ford and Crowther, 1926) that described his manufacturing methods and philosophy and would later influence Eiji Toyoda and Taiichi Ohno in the development of the Toyota Production System (Liker, 2004). It is not necessarily the case that Ford's methods would be adopted verbatim. Adoption of Ford's methods in Great Britain was slow. Herbert Austin (founder of the Austin Motor Company) and William Morris (founder of the Morris Motor Company) both visited the Ford Highland Park complex in 1914. However, it would not be until 1928 that Austin would introduce a powered assembly line and some 6 years later Morris would introduce a powered assembly line at his Cowley Plant, (Dintenfass, 1992). Even under the amalgamation of both companies in 1952 to form the British Motor Corporation (BMC), the totality of Ford's manufacturing methods was not adopted with respect to the implementation of automation and labour relations (Womack *et al* 1990, Dintenfass, 1992).

Mass production gained popular support as the American economy grew during the first decades of the 20th century. During this period, the eminent Harvard economist Joseph Schumpeter, an advocate of 'creative destruction', (McCraw, 2007) celebrated the innovation that arose on the back of mass production due in part to what Schumpeter considered the entrepreneurship of the likes of Ford and Sloan. Schumpeter would refer to Ford as the 'great innovator' and the Model T as 'this great new thing' as it was built for the mass consumer rather than the elite rich (McCraw, 2006).

Supporters of mass production were not necessarily supporters of Henry Ford himself. In 1928 Waldemar Kaempffert the then editor of Science and Engineering at the New York Times wrote a scathing account of Ford's autocratic and centric style of management, though he is nevertheless highly supportive of the contribution of Ford to the prosperity of the USA through the creation of mass production (Kaempffert, 1928). Edward A. Filene, a significant Boston business leader who had built up one of the most successful department stores in the USA and a founder of credit unions, wrote extensively supporting the virtues of mass production. Philosophically, Filene disagreed with the political and intellectual views of Henry Ford, though supported Ford's vision of the principles of mass production, distribution and customer service (Hounshell, 1984, p 316). Filene promoted the complete 'Fordizing' of American business and industry as the means of achieving economic prosperity in the face of European competition and trade barriers (Filene, 1925).

Feline visualised that mass production would *'come to all productive enterprises everywhere'*, and will be at the centre of global trade laying the course for the *'future industrial development of the world'*, (Feline, 1929). Feline concluded that a nation engaged in mass production would have the potential to produce surpluses that could not be consumed within their home market and would need to look to export the surplus. The true essence of mass production in Feline's view was the prosperity Mass Production could potentially bring to the ordinary person. In his work, "*Successful Living in This Machine Age*", (Filene, 1932), Filene wrote:

> Mass Production is not simply large-scale production. It is large-scale production based upon a clear understanding that increased production demands increased buying, and that the greatest total profits can be obtained only if the masses can and do enjoy a higher and ever higher standard of living.

Filene associates mass production with the general deployment of everyday living within the USA, including family life, education, politics, health, housing and social planning. Essentially, 1930's America, in Feline's view is intrinsically linked to mass production.

Until Japanese manufacturing methods would begin to influence western manufacturing thinking towards the end of the 1970's there no alternative significant manufacturing paradigm against which mass production could be compared and assessed. Mass production was considered to be at its zenith during the 1950's (Womack *et al*, 1990, Sako, 2004). However, significant management thinkers of the time were beginning to scrutinise the capability of the mass production approach to satisfying the needs of consumers, where product choice and variety was becoming desirable.

Mass production was beginning to be viewed as too rigid a system of manufacturing where economies of scale dictate that product variety is suppressed in favour of production efficiency. Such thinkers would include the economist Theodore Levitt, the academic and management consultant Peter Drucker and Wickham Skinner of Harvard University who was an early promoter of the importance of developing a manufacturing strategy. During the 1950's, Drucker considered mass production as the *prevailing* system of manufacturing. However, he questioned the effectiveness of the system of mass production introduced by Ford, considering the system inflexible and focussing on the manufacture of uniform products. Drucker believed that such uniformity would impede the ability to supply diverse and varied products to an ever demanding consumer base. Drucker proposed an alternative 'New' mass production, where the focus would be applied to the mass manufacture of similar components allowing the subsequent assembly of a variety of similar products (Drucker, 1954).

Drucker's proposed system of mass production did not necessarily take root within the USA. Some 10 years later in the mid 1960's Wickham Skinner echoed Drucker's opinion of the rigidity of Mass Production. Skinner proposed what he considered were the limitations of Mass Production and recommended a more flexible manufacturing model and a change in management thinking that would align a manufacturer to its potential markets (Skinner, 1966). In particular, Skinner proposed the then challenge for manufacturing is to:

> Make an increasing variety of products, on shorter lead times with smaller runs, but with flawless quality. Improve our return on investment by automating and introducing new technology in processes and materials so that we can cut prices to meet local and foreign competition. Mechanize – but keep your schedules flexible, your inventories low, your capital costs minimal, and your work force contented.

Further work by Skinner sought to align the manufacturing function within an organisation to the needs of the markets the organisation serves to effectively promote manufacturing as the 'hidden' competitive weapon (Skinner, 1969, 1985).

Levitt (1960) proposes that the relationship between mass producers and their potential customer is disconnected. Mass producers he suggests are propelled to produce all they can to take advantage of decreasing unit costs. Essentially, products are pushed into the market where the focus of the push is the needs of the seller and not the customer. Levitt contends that manufacturers should transfer their focus from selling potentially unwanted products to one of marketing their products to satisfy the needs of their customers. The essence of Levitt's argument is that manufacturers (and service providers) should remain innovative and concentrate on the current and future needs of their customers and illustrates the point by stating:

> "…. There is no guarantee against product obsolescence. If a company's own research does not make it obsolete another's will".

The continuing existence of mass production requires a comparable level of mass consumption. Piore and Sable (1984), contend that a combination of rising food prices (due to a poor Russian wheat harvest during the 1970's) rising oil prices (due to oil shortages in 1973 and 1979), allied with industrial unrest and the existence of rigid wage and economic regulations launched an inflationary spiral. The inflationary spiral would lead to slow economic growth, low productivity gains and rising unemployment. Inflationary control through monetary and fiscal policies would fuel global recessions (in 1973, 1980 and 1982-3) resulting in 'growing confusion' as to the level of demand within specific markets coupled with the price and availability of manufacturing resources. The confusion, Piore and Sable contend led to the breakup of mass markets for standard products. Manufacturers uncertain about the future and unable to predict demand were unwilling to continue to invest in the fixed cost special purpose machinery dedicated to the manufacture of a single product type.

Domestic markets in the advanced industrialised nations by the end of the 1970's would become saturated with consumer durables. In the USA, in 1979, every second resident had a car (compared to 1 in 4 in the early 1950's). In 1953 some 47% of USA households owned a television set compared to almost 100% in 1970. Similarly, by the end of the 1970's, over 90% of American residents would own a wide range of household goods including refrigerators, washing machines, radios and vacuum cleaners, (Piore and Sable, 1984 page 184). Domestic saturation would make it more difficult to *'increase economies of mass production'* through the expansion of domestic markets. Consequently, manufacturers, sought to export, resulting in the advanced industrial nations competing for each other's markets and those of developing economies. The global competition would in the view of Piore and Sable expose the weaknesses of existing economic regulatory systems. Such systems were designed to work within the confines of discrete nations. On a global scale, mechanisms did not exist that would ensure world economies would grow at a rate conducive to investing in increased production capacity. Eventually, under such conditions, demand would reduce, resulting in competition for a larger share of limited markets. Mass production, not solely from an ability to meet consumer needs, was under pressure to sustain itself and ultimately the manufacturing companies and economies. Combined with the emerging threat of Japanese manufacturing excellence, the exposed weaknesses of mass production to continue to serve both domestic and global markets would lead Western manufacturers to search for *'alternative technological capabilities and organisational structures'*, (Pietrykowski, 1999).

Additionally, mass production had become synonymous with poor quality, outdated management practices and worker alienation. Dennis (2007) synthesises the growing dysfunctionality of mass systems:

- **Quality:** Within mass production, maintaining the flow of production was the main concern; quality issues were of secondary importance. Assembly workers were regulated to carrying their specific assembly task and had no influence of the management of their job. Dennis contends that preventing the assembly worker contributing to the management of tasks restricts a source of continuous improvement. Quality control is limited to off line inspectors and any rectification is directed to a team of repair workers. Moreover, the emphasis on large batch production runs coupled with remote inspection could mean that a defect is replicated throughout the complete batch before it is found.
- **Management Practices:** The traditional mass production management model had not seriously changed since the inception of the management and marketing innovations introduced by Alfred Slone and General Motors. Sloan's management model devolved management at a functional level reporting back to a centralised corporate headquarters that had overall control. Sloan effectively managed by numbers (Womack *et al*, 1990 page 40). Providing the accountants could show a profit at the functional level, there was no concern. While Sloan made a significant contribution to the development of management science, Dennis presents two significant problems with this overall approach.
    1. The gap between the shop floor and the management became wider.
    2. Accounting practices encouraged wasteful management practices such as building to inventory rather than to customer demand.

- **Worker Alienation:** The Taylorist division of labour dictates that a task is broken down to its constituent components. This provides for most workers a mind numbing and repetitive working environment. Essentially, workers did not want to work, with Unions continually fighting for improved working conditions and reduced working hours.
- **Machinery:** In pursuit of the scale of economies, machinery would become larger and larger. To justify their expense, accounting principles dictated efficiency at the machine level rather than at the system level. This encouraged batch production and the build-up of work in progress and finished inventory. The inventory would appear as an asset on the company balance sheet even though they absorbed cost. Machines were kept running at any cost. Machine stoppages to rectify quality problems were avoided further encouraging the need to employ end of line re-workers.
- **Engineering:** Similar to the division of labour within the assembly tasks, the engineering function was also subdivided into a myriad of specialities as products became more and more complex. A consequence to this sub-division is that engineers did not communicate effectively with other engineers outside of their specific discipline. The poor communication would lead to design problems and increasing the time taken to release a design to production.

The state of what 'Classic Mass Production' became is illustrated by the operation in 1986 of the General Motors' Framingham, Massachusetts, assembly plant by the IMVP team (Womack *et al*, 1990, page 77 -78). Here the research team discovered a management team in denial and reluctant to change. The assembly line was awash with inventory at each work station. Teams of indirect workers were relieving fellow workers, or trouble shooting, running inventory or carrying out housekeeping tasks, consequently not adding any direct value to the assembly operation. Large stocks of completed car body shells were ahead of the paint shop and equally a large number of painted body shells were waiting delivery to the final assembly lines. On the assembly line itself, some workers struggled to keep up with their tasks while others were idle for a period of time. Some struggled to attach poorly fitting parts to the cars they were assembling. At the end of the line, a vast work area existed full of defective cars that required some element of rectification before they could be delivered to a customer.

The reasons for the decline of mass production are complex. It is possibly unbelievable that what became the foundation of the world's most powerful economy (the USA), mass production would be equally be a source of economic decline and disconnection with the customers it strove to serve.

Succinctly, mass production declined because it was failing to meet the changing needs of consumers; its rigidity in operation could not react to an unfolding economic decline and the requirements of an uncertain future. Mass manufacturers could not compete at a global level partly because their standard operational procedures could not be adapted to suit the conditions of the individual markets they wished to compete in. At an operational level, the management task was directed at the wrong dimensions, effectively, those attributes that would keep production moving without regard to overall system efficiency.

Lean systems are by definition managed differently to mass production systems. However, they function in global markets not dissimilar to those of the mass manufacturers of the 1970's and 80's. Indeed in some respects, the environment is harsher and more competitive. Consumers are more demanding, requiring greater customisation and functionality of their products and at a cost they are prepared to pay. Moreover, manufacturers now have to comply with global environmental standards that affect both operational and product attributes that originally would not have been considered pre 1990.

Henry Ford and Alfred Sloan had an immense influence on the industrial landscape of the 20th century and are both considered as pioneers of management practices (Wren and Hay, 1977, Heames and Breland, 2010). While the companies that they created were bastions of what is considered traditional mass production, both the Ford Motor Company and General Motors have evolved into primary exponents of lean practices and the companies continue to remain dominant global automotive manufacturers, (Cable, 2009).

Some twenty years after the publication of the 'Machine that Changed the World', mass production in the original Fordist and Sloan sense no longer exists. Most manufacturing companies are on a lean road map and are more flexible and agile. However, the transition to adopting lean practices can prove difficult as companies strive to adapt to a new culture geared toward providing customer value (Howleg and Pil, 2004).

In 1990, to strengthen the virtues of lean manufacturing, it was necessary to amplify the differences between a lean system and a mass production system and so promote the adoption of lean practices. As the twenty first century unfolds, the importance is that effective manufacturing paradigms that deliver customer value and allow a manufacturer not only to compete but to evolve remain effective. The lessons learned from the decline of mass production contribute to maintaining effective manufacturing systems for the future.

3.3. The Evolution of Lean Systems

3.3.1. The Origin of Lean Manufacturing: The Toyota Production System

The lean model of manufacturing as presented by Womack *et al* (1990) in the 'Machine that Changed the World' is predominantly a synthesis of the operations of the Toyota Production System (TPS), (Hines *et al*, 2004, Howleg, 2007). Chapter 3 of the work describes 'The Rise of Lean Production' and in particular describes the origins of the TPS during the re-establishment of the Toyota Motor Company in the immediate years after the end of World War II. The development and operation of the Toyota Production System (TPS) is widely documented within the Operations Management literature and extensive studies of the system are provided by Ohno (1988), Shingo (1988), Fujimoto (1999), Liker (2004), and Monden (2012).

Taiichi Ohno (1912 – 1990) is considered the principal architect of the TPS. His motivation in creating the system was the belief that the production process could be managed more efficiently. In 1935, while still working in the loom industry, Ohno had discovered that production output in Germany was some three times that of Japan while in America, production output exceeded Japanese output by a factor of nine, (Ohno, 1988, Shimokawa and Fujimoto, 2009). Ohno thought it inconceivable that an American worker could exert almost ten times more effort than a Japanese worker. He concluded that the production differential was not solely down to the capabilities of the American worker or to the availability of superior equipment but one of managing the production process.

Ohno concluded that to create an improved system of managing the production process, there were two fundamental requirements. The first requirement was to create a production process capable of producing small quantities of a variety of products. The second requirement, was effectively an enabler to achieving the first requirement, was to remove all forms of waste that was inherent throughout the complete production process.

While the main features of the American system of mass production would form the kernel of the production process, the system could not be totally copied. In post war America, there was sufficient demand for products to enable producers to manufacture vast quantities of standard products. Japan, conversely was recovering from the devastation of the World War II. Acute problems existed with both the Japanese domestic and industrial infrastructure and the Japanese market for cars was too small and fragmented to support the high volume of production witnessed in the USA (Liker, 2004).

Within the Toyota Truck Division, between the years 1946 – 1950, Ohno’s approach to improving efficiency resulted in an increase in productivity by a factor of six resulting in an output of some 1000 trucks per month (Shimokawa and Fujimoto, 2009). Unfortunately, Toyota did not have sufficient customers for their trucks and the unsold stock would contribute to a restructuring at Toyota that would lead to industrial unrest, unavoidable job losses and the subsequent resignation of Kiichiro Toyoda. Ohno had realised that while raising productivity and reducing costs was essential, production output had to be limited to the quantities of products that could be sold:

> The lesson we learned from the post-war crisis was that simply raising productivity is no cure-all. We discovered the importance of raising productivity and reducing costs while limiting production to the kinds of products sold, in the amounts they are sold, and at the time they are sold. In other words, we learned that imitating American-style mass production would be fatal in Japan, (Ohno, 1988).

Throughout this evolution, the concepts of JIT and Autonomation continue to be the main stays of the system and is visualised in a time line devised by Ohno in the preface of his book describing the TPS (Ohno, 1988), the main features of which are replicated in Table 3.1.

Year	**Milestone**
1948	• Introduced Pull System of Manufacturing in the Engine Machine Shop. • Increased productivity through workers operating several machines. • Workers authorised to conduct their own inspections reducing the need for post-production inspection staff.
1950	• Pull concept introduced to marketing function - enabling Toyota to build to exclusively to build to order. • Synchronised engine and transmission build to final assembly. • Indicator lights added to engine line to alert supervisors of problems.
1953	• Introduced Kanban method into Engine Machine Shop. • Instituted a standardisation programme for car and truck components to simplify procurement and manufacturing.
1955	• Synchronised body assembly to final assembly. • Introduced controls on parts deliveries to reduce inventory levels. • Small lot production of components introduced that increases utilisation of machine tools. • Mixed model production on final assembly lines further reduces inventories. • Line stop buttons introduced on assembly lines. Production workers given authorisation to stop production line if problems occurred.
1957	• Indicator lights installed on all production lines to alert supervisors of problems.
1959	• Improved movement of inventory reduces in process inventory and waiting times.
1961	• Begin to introduce Kanban to supplier base.
1962	• Extend Kanban throughout Production system - placing total company on a small-lot pull system. • Fool proof devices added to machine tools prevent defects and over production.
1963	• Labour productivity increased through workers operating up to 5 machines each.
1965	• Kanban introduced to all external parts deliveries - reducing inventories further.
1971	• Change over times reduced to 3 minutes in body panel press shops.
1973	• Toyota allows suppliers to deliver direct to production lines.

Table 3-1 Toyota Production System: Significant Milestones.
(Adapted from Ohno (1988) and Cusumano (1988))

The birth of the TPS is an amalgamation of foresight, learning from experience and learning from others. Foresight in the sense that Ohno visualised what he needed to do to improve the production process. Learning from experience in respect to the company did not ignore the lesson from the inability to sell all of the trucks and ensured all future production is matched to what could be sold. Ohno would base the TPS on what he defines as the two ‘Pillars’ of

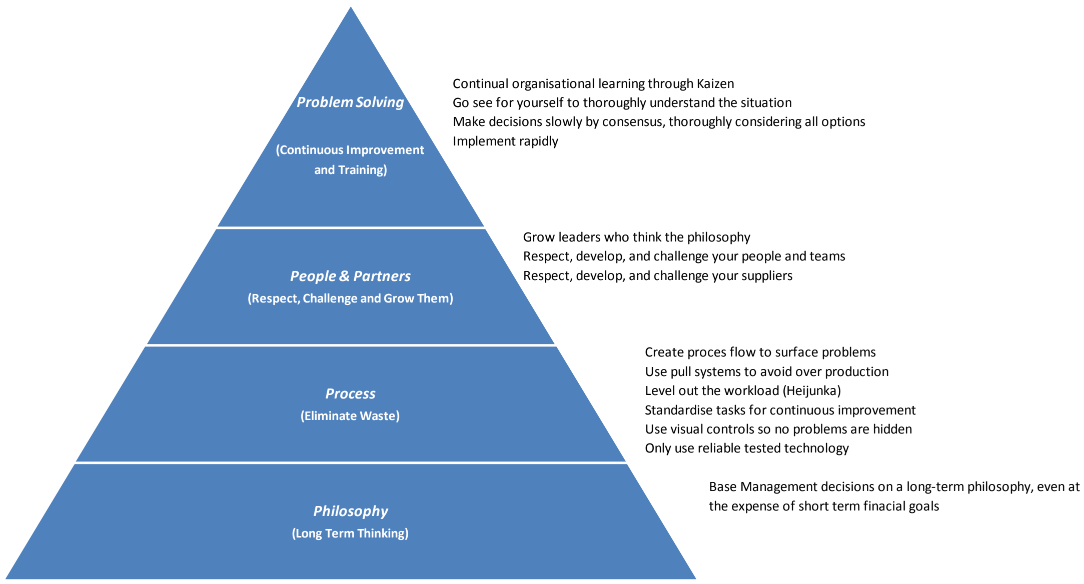
1. Just-in-time manufacturing
2. Autonomation

Within these two ‘Pillars’ is the source of the learning element of the TPS. Though Ohno is considered a pioneer of Just in Time Manufacturing, (Liker, 2004) he acknowledges that many of his ideas were inspired by the work of Henry Ford and the influence of Ford’s and Samuel Crowther’s 1926 book, ‘Today and Tomorrow’. The concept of Autonomation, Ohno would inherit from Sackichi Toyoda who had invented an automated method to enable a powered weaving loom to stop if a problem occurred.

The TPS is considered an evolutionary system that has developed through a process of trial and error as much as it has been result of planning. The current state of the TPS is that of a matured though continually evolving system. Liker, (2004) synthesises the ‘Mature’ TPS as a set of 14 Management principles (Appendix 1) that are divided into four categories consisting of Philosophy, Process, People & Partners and Problem Solving. To illustrate the principles as a coherent whole, Liker presents his 4P Model (Figure 3.1) listing the 14 principles against each category. The motivation behind the creation of Liker’s 4 P Model is based on observations during visits to USA based manufacturers where frequently he would witness the application of lean methods in a sporadic way that were not necessarily aligned to an holistic companywide objective.

Liker does not advocate pure imitation of the TPS to enable a company to improve or to adopt lean practices. Rather, companies on a lean trajectory should develop principles that are right for them that will sustain growth and achieve competitive advantage. Rather, the purpose for a company to study the TPS is as starting point for improvement.

The essence of each of the categories is as follows:



Continual organisational learning through Kaizen
Go see for yourself to thoroughly understand the situation
Make decisions slowly by consensus, thoroughly considering all options
Implement rapidly

Grow leaders who think the philosophy
Respect, develop, and challenge your people and teams
Respect, develop, and challenge your suppliers

Create proces flow to surface problems
Use pull systems to avoid over production
Level out the workload (Heijunka)
Standardise tasks for continuous improvement
Use visual controls so no problems are hidden
Only use reliable tested technology

Base Management decisions on a long-term philosophy, even at the expense of short term finacial goals

Figure 3-1 The 4 P Model of the Toyota Way (Liker, 2004)

Philosophy: Within the context of manufacturing, the concept of ‘philosophy’ is the ‘belief’ system a company embraces in terms of conducting their manufacturing and commercial activities. The belief system applies with respect to the environment where the company conducts business and satisfying the needs of their customers. The philosophy manifests as a system of ethics (the values and principles the company aspires to) and epistemological (how knowledge is acquired). The belief system should in the view of Liker, embrace a sense of purpose that delivers value to the customer, society and the economy while ensuring company growth.

Process: Companies deliver their products and services to internal stakeholders and their ultimate customer through process execution. To deliver value, Liker advocates that processes should be designed to flow and reveal any problems that could impede flow. A culture of continuous improvement supports problem resolution and a set of operating practices that prevents overburden of resources and people through an even production plan based on level scheduling. Overproduction is avoided through a ‘pull’ production system aligned to customer orders.

People and Partners: Long term growth and achieving the vision of the company’s philosophy necessities investment in the development and empowerment of people. Liker recommends internal development by growing leaders from within who can live the ‘philosophy’. The culture is one of mutual support, respect and challenging and applies both internally and externally with the supplier base.

Problem Solving: The habit or ability to continually solve problems is, in Liker's opinion, the driver for creating a 'Learning Organisation'. The learning organisation cultivates a culture of continuous improvement through the consensus of stake holders. Best practice is standardised and ensures counter measures are such that mistakes are avoided.

Though the 4 P model is presented as a hierarchy, it represents the behaviour of a system that has evolved and matured over time. A learning organisation grows over time as a consequence of solving problems that arise from creating and improving processes. The interaction between internal and external stakeholders in doing so creates the culture of respect and growth.

Dahlgaard-Park and Dahlgaard (2007) regard Toyota 'as the most excellent company within the car industry today and maybe the best managed company in the world', and conclude that it is logical to recognise the Toyota "4P" model as an example of today's excellence models.

3.3.2. The Emergence of Lean Manufacturing

Toyota's approach to continuous improvement to refine production processes would contribute to increasing production and global expansion. By 1960 production output was still less than 150,000 vehicles per annum and would steadily increase over the following years to reach over 10 million vehicles by 2012 (Figure 3.2).

Though Toyota are famous for sharing their production philosophy and values with the wider world, the methodology of the TPS remained 'within house' until the mid 1970's, (Ohno, 1988).

Other than Nissan who had adopted Just in Time methods, it was not until the oil crises of 1973, through which Toyota remained profitable that Japanese manufacturers in general began to take significant notice of Toyota's manufacturing methods and begin to introduce JIT methods of production, (Cusumano, 1988, Ohno, 1988, Hallihan *et al,* 1997). The adoption JIT manufacturing amongst western manufacturers did not become prevalent until the 1980's, (Figure 3-3).

Western manufacturing had been steadily declining since the end of World War II

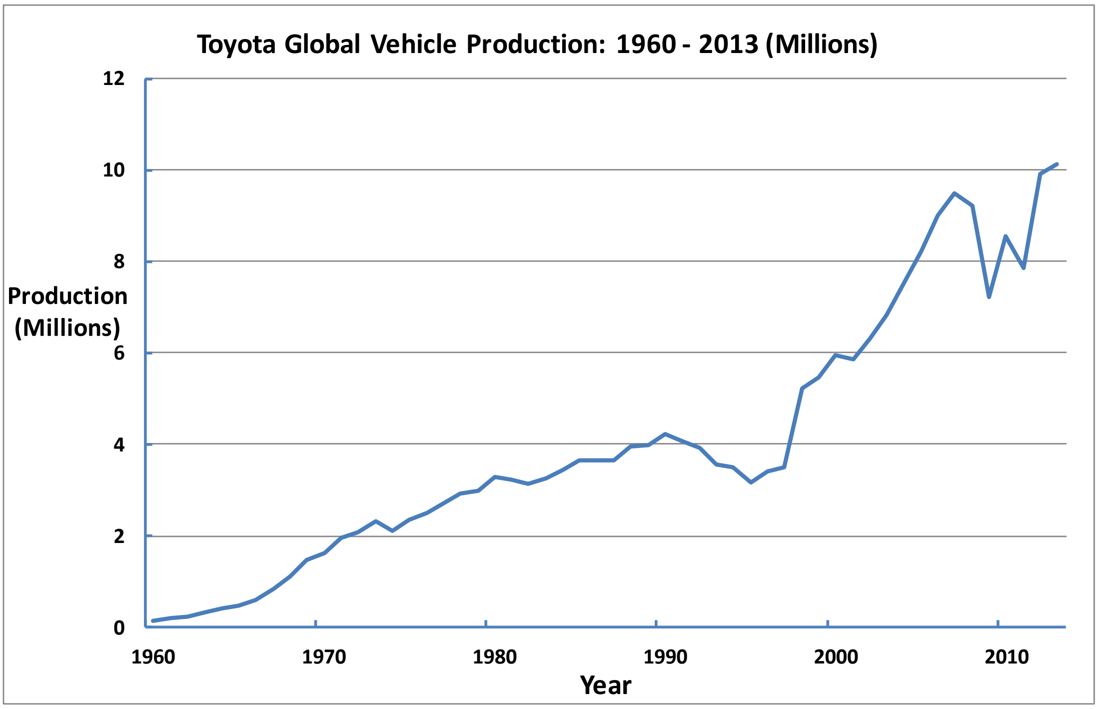


Figure 3-2 Toyota Global Vehicle Production: 1960 - 2013 (Millions) (Source: Toyota, 2013)

with the decline continuing beyond the oil crises into the 1980's. This was in contrast to Japan, where in the 1980's, manufacturing was in the ascendency, and would force Western manufactures to re-examine their methods of production and look to the emerging Japanese model for inspiration.

During the 1980's, that re-examination, led predominantly by academics, would converge onto a set of Japanese working practices, principally synthesised from observations of the working practices of the Toyota Production System (TPS), that would be christened as *'lean manufacturing'*.

The major academic study into Japanese working practices of the 1980's was conducted by The International Motor Vehicle Program (IMPV). The IMPV was founded in 1979 at the Massachusetts Institute of Technology (MIT) and is an international research consortium whose principal interests are aimed at understanding the challenges facing the global automotive industry. In 1984, the IMPV published '*The Future of the Automobile'*, (Altshuler et al, 1984), a work that considered the current and future state of the global automotive industry at that time.

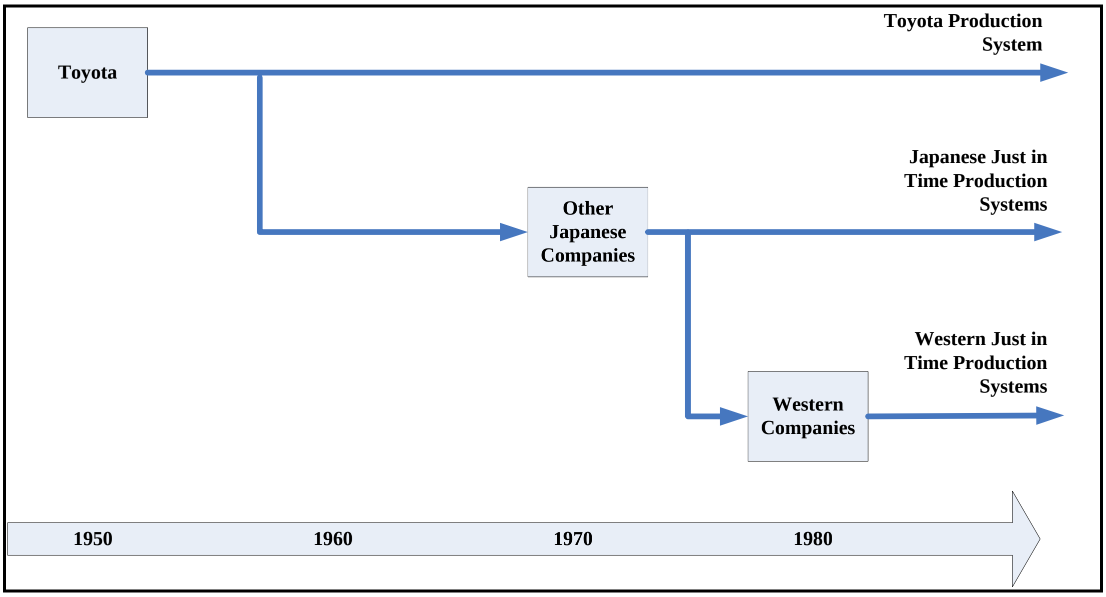


Figure 3-3 Adoption of JIT Method of Manufacturing (Hallihan et al, 1991)

The authors argued that compared to American and European automotive producers, Japanese manufacturing methods were far superior and concluded that:

> The emergence of Japanese innovations within manufacturing, supply chain and financial systems challenge the dominant Western manufacturing methodologies based on systems developed by Ford and Sloan. American and European manufactures will need to respond to this challenge through introducing organisational change forcing a reduction in labour and cost.

Along with the overall content of the '*The Future of the Automobile'*, this observation provided the motivation for further research by the IMPV into the fundamental differences between the manufacturing methods of Japanese and Western automotive manufactures that existed in the mid 1980's. That research embraced a five year investigation of the global automotive industry and for the wider manufacturing community, the output of the research was condensed in to what is regarded as a seminal work in the manufacturing literature, '*The Machine That Changed the World*', (Womack et al, 1990).

Within this work, lean manufacturing is presented as the accumulation of an evolutionary process that began with the re-establishment of the Toyota Motor Company in the immediate aftermath of World War II. That evolutionary process would by the end of the 1980's result in a 2 to 1 differential in favour of Japanese lean manufacturers over their European and American counterparts, (Womack et al, 1990, page 13). Succinctly, in each measurable product and manufacturing attribute, a Japanese lean manufacturer would consume half of the resource required by a Western non-lean manufacturer. Such resource included, people, production space, inventory, tooling investment and product development time. The authors boldly assert that lean manufacturing would '*inevitably*' spread beyond the automotive industry to '*change nearly*' every industry, providing extra consumer choice, the nature of work, success for companies and national economic prosperity (Womack et al, 1990, page 12).

That lean manufacturing would be copied and adopted throughout Western manufacturing is significant in itself. The significance of lean manufacturing is not solely because it is perceived to be a more efficient means of production than methods based on mass production. By 1990, it would have been reasonable to conclude that the Toyota Production System had matured. Though the TPS had evolved to a mature level, the system has continued to evolve through the 1990's and into the 21st century. Similar to the TPS from which lean manufacturing evolved, the real significance for lean manufacturing is that it is a continuously evolving system.

Conversely, mass production did reach a mature state and ceased to evolve. Though noteworthy management thinkers such as Alfred Sloan would modify Henry Ford's ruthless product standardisation and introduce a diverse automobile product range, and later, Peter Drucker and Wickham Skinner would advocate the adoption of more flexible methods of production, mass production would continue to prevail largely in its original Fordist and highly Taylorised approach.

Craft systems of manufacturing had reached a self-sustaining level of maturity, though this is more a reflection of the development of the individual craftsman. While a craftsman over the years would continue to hone his skills to produce a more refined and indeed complex artefact, the output of a craftsman is limited when compared to volume methods of manufacturing. And while it can be stated that all craftsmen are skilled, there are some who are more skilled than others leading to an inconsistency of output within the craft system.

That lean manufacturing is a continually evolving medium imposes continuing challenges on practitioners in maintaining an infrastructure and culture that strives to provide ever increasing levels of customer value while simultaneously reducing waste and cost.

The prophecy of the 'inevitable' spread of lean manufacturing, some twenty years post publication of '*The Machine That Changed the World*' has born fruition. Unlike mass and craft methods of manufacturing which are essentially insular activities, the underlying principles that govern lean manufacturing have found diverse application beyond traditional manufacturing. Lean principles are applied across a range of industrial sectors including construction (Hook and Stehn, 2008), aerospace (Murman et al, 2002) and ship building (Liker and Lamb, 2001). Beyond manufacturing and industry, lean principles are applied across commercial and service industries, administration (AME, 2007), government (Erridge and Murray, 1998, Radnor et al, 2006) and healthcare. Such universal application implies there is a common link across these varied disciplines centred on delivering value and efficiency while eliminating waste.

The origins of lean manufacturing as a result of the recreation of the Toyota Motor Company after World War II and its trajectory into Western manufacturing in the latter decades of the twentieth century is documented across a diverse range of literary sources. In Chapter 3 of *'The Machine That Changed the World'*, Womack et al (1990) introduce the 'Rise of Lean Production'. Within this chapter, the authors document the birth of the lean concept as a result of the managers of Toyota recognising that the Western mass production approach could not work within the fragile Japanese economy ravaged by the war. The principal architect of the TPS, Taiichi Ohno, would document the 'mechanics' and subsequent development of the TPS, (Ohno, 1988). Other senior people within Toyota would also document the characteristics of the TPS, including Shingo (1988) and Monden (2012). Holweg, (2007) writes a comprehensive review of the trajectory of lean production from the origins of the TPS through the IMVP programme at MIT and the dissemination of lean production post publication of *'The Machine That Changed the World*' in 1990. Numerous academic papers that discuss some aspect of lean production or an application of lean principles will frequently pay homage to the origins of lean and provide a provide a brief history of its evolution. Typical of such papers include Hines et al (2004), Herron and Hicks (2008) and Abdulmaleka and Rajgopalb (2007).

3.4. Lean Thinking

In the introduction to the book ‘Lean Thinking’, Womack and Jones, (1996) present the lean principles interacting in a ‘virtuous circle’ implying that by continuing to focus on providing customer value, improvements will follow in the value stream, eliminating waste, and enhancing production flow so enabling a greater response to customer demand (pull). This visualisation of the ‘virtuous circle’ is embedded in the lean culture.

The visualisation of this ‘virtuous circle’ is the embodiment of the application of lean thinking and reflects how a matured lean system operates by continually increasing customer value through continuous improvement.

Succinctly, lean thinking embodies the systematic application of the five principles to align the activities of a business to generate true value with respect to products and services for the customer and in return sustain profit and growth for the value provider (Rich et al, 2006). The application of the principles as a practical construct embraces an extensive body of knowledge. To concisely describe the body of knowledge, frequently within the lean literature, the body of knowledge is visualised as ‘The House of Lean’, though the visualisation is not necessarily consistent throughout the literature but the visualisations share common themes. Two such ‘Houses’ are illustrated in Figures 3.4 and 3.5 due to Rich et al (2006) and Wilson (2010) respectively.

Neither of the house examples is specific to a functional department. Rather the focus is on creating an understanding of what is required to eliminate waste and create value throughout a company. The elimination of waste and the creation of value are consistent and are central themes in the dissemination of the understanding of lean thinking.

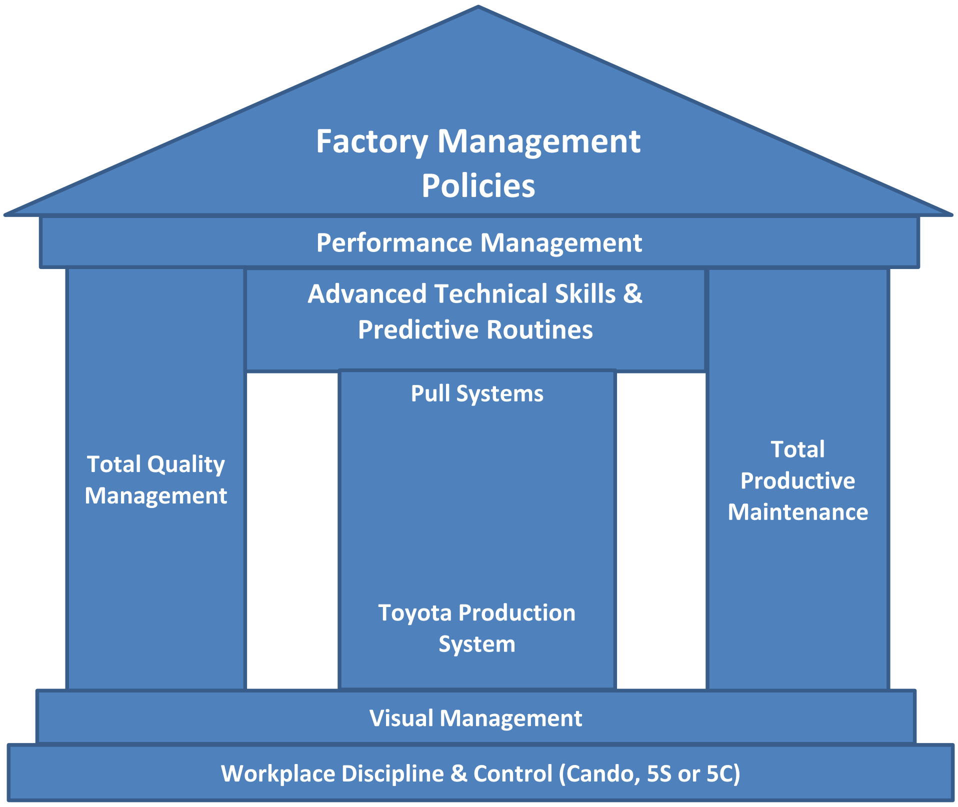


Figure 3-4 House of Lean Example 1 (Rich et al, 2006)

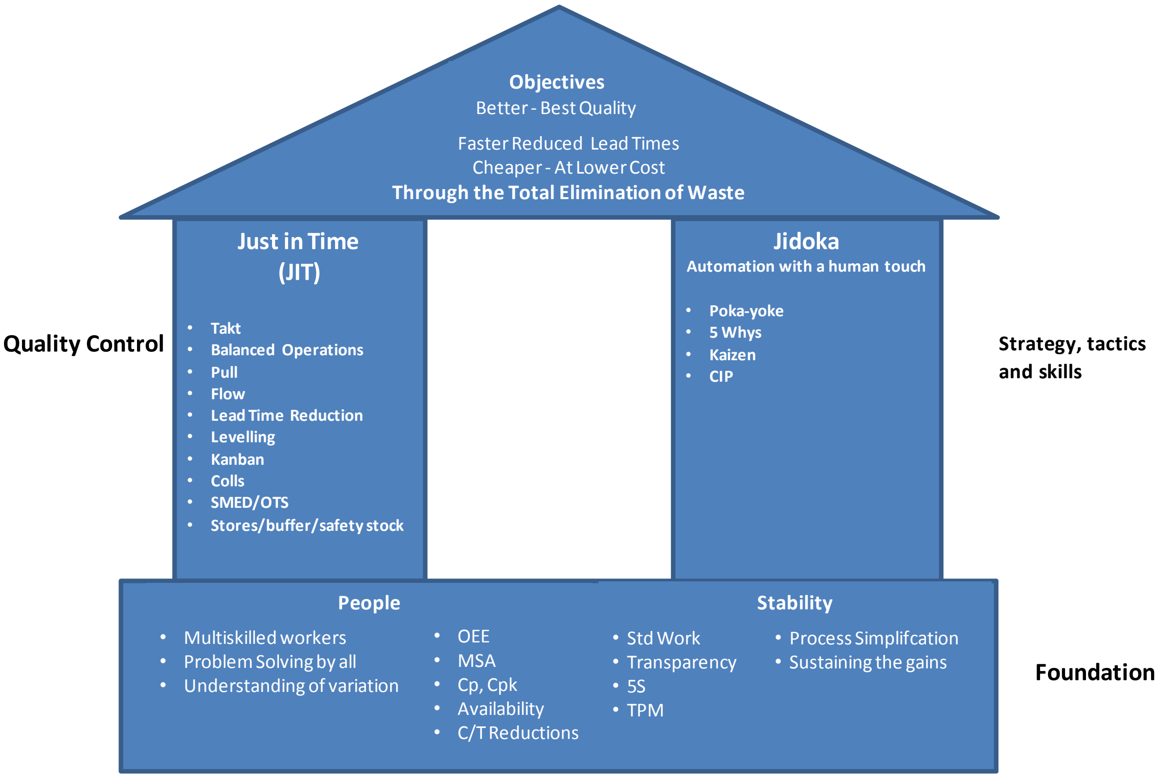


Figure 3-5 House of Lean Example 2 (Wilson, 2010)

The Lean Enterprise Institute (LEI), a USA based lean educational foundation founded in 1997, emphasise the importance of a company truly understanding customer value and waste.

The ultimate goal of a company in the view of the LEI is to '*provide perfect value to the customer through a perfect value creation process that has zero waste*' and contend that lean thinking accomplishes the goal through changing:

> '….. the focus of management from optimizing separate technologies, assets, and vertical departments to optimizing the flow of products and services through entire value streams that flow horizontally across technologies, assets, and departments to customers'. (LEI, 2014)

The themes of customer value and waste are at the core of the definition of lean thinking provided by the Lean Aerospace Initiative (LAI):

> Lean thinking is the dynamic, knowledge driven, and customer focused process through which all people in a defined enterprise continuously eliminate waste with the goal of creating value. (Murman et al, 2002).

The elimination of waste is a consistent theme within the lean literature. The LAI definition of lean thinking adds specifically targeted dimensions of 'customer focused', 'knowledge driven' and 'dynamic', where the LAI apply the following meanings to the dimensions:

> **Customer focussed:** The customer provides what the LAI define as the 'orientation' for the enterprise. The needs of the customer provide the pull necessary throughout the enterprise from product design through manufacturing to sales and after-market support.
>
> **Knowledge driven:** The LAI argues an enterprise attains customer focus through the knowledge of the people within the entire enterprise rather than from a small group of experts. The dimension of 'knowledge driven' is recognition of the critical role of *people* and the knowledge and insight they possess in creating value and eliminating waste.

Dynamic: The LAI consider that lean is an evolutionary process and through the principle of perfection will continue to evolve. In this respect, the LAI present lean as a dynamic system where the dynamism is maintained through people engaged in continuous improvement.

The dimensions of ‘knowledge driven’ and ‘dynamic’ are related through people who maintain the dynamism of lean thinking due to their knowledge. The relationship puts people and their knowledge at the core of lean thinking and emphasises the need for companies to ensure that their people receive the necessary training and development.

Though there are differing presentations of lean thinking form both academics and practitioners, there exists a common theme that converges on inspiring a mindset within enterprises and people geared toward providing customer value and the elimination of waste.

3.4.1. Lean principles revisited

The lean principles presented in Chapter 2 are described in similar manner to the presentation in the general lean literature for example by authors such as Murman et al, (2002) and Rich et al (2006). Since the consensus within the lean literature implies that the principles are applicable to areas outside automotive and general manufacturing, the principles are re-examined. In particular, the lean principle of value is considered in detail partly because the achieving the principle is the key task for any customer focussed company or organisation, partly because it is a difficult construct to define and finally because within the lean literature itself, the principle itself is inadequately defined.

3.4.1.1. Value

In their work on Lean Thinking, Womack and Jones (1996, page 16) propose that value should be defined in terms of the ultimate customer receiving a level of service and product capability that satisfies the customer’s needs at a specific price and specific time. The wider lean literature tends to reiterate the definition, and includes Bicheno (2000), Murman et al (2002), Rich et al (2006), and Hines et al (2011).

The customer centred definition of value is purely an ‘external view’; the value generation with respect to the producer, the service provider and other stakeholders is not considered. Neither is the value requirements considered for the producer with respect to their own supplier network and within their internal production systems.

The definition is also a restricted view of value that focuses exclusively on the ultimate customer and so the following considerations are overlooked:

1. How to align a company’s products and services to the needs of their customer base;

2. How to capture the specific product and service needs of customers.

Why Womack and Jones focus on value as defined by the ultimate customer is their belief that otherwise a producer would consider the provision of value in terms of their own capabilities or a localised view of customer value rather than a more global vision. Focussing on the value defined by the ultimate customer avoids a misalignment between the needs of the customer and the capabilities of the producer or service provider.

Value generation for the producer and other stakeholders is related to the profit created through delivering the customer perceived value. Dennis (2007) suggests that customers in competitive markets will only pay what they consider a reasonable price for products and services. This constrains any financial profit for the provider to be the difference between the cost of provision and the price the market is prepared to pay. Since the price is largely fixed by market conditions, profit is maximised by reducing the cost of provision. Further sustained cost reduction should in principle allow the reduction of the selling price while maintaining the profit margin (Figure 3.6). Cost reduction is maximised through increasing the efficiency of the production system, which in turn is the purpose of the lean principle of ‘Value Stream Identification’. The lean literature on value stream identification inevitably converges on classifying those activities that add value to the product in terms of the ultimate customer. Value for the provider is realised through the combined dimensions of delivering ‘customer value’ and cost reduction through identifying appropriate value added activities.

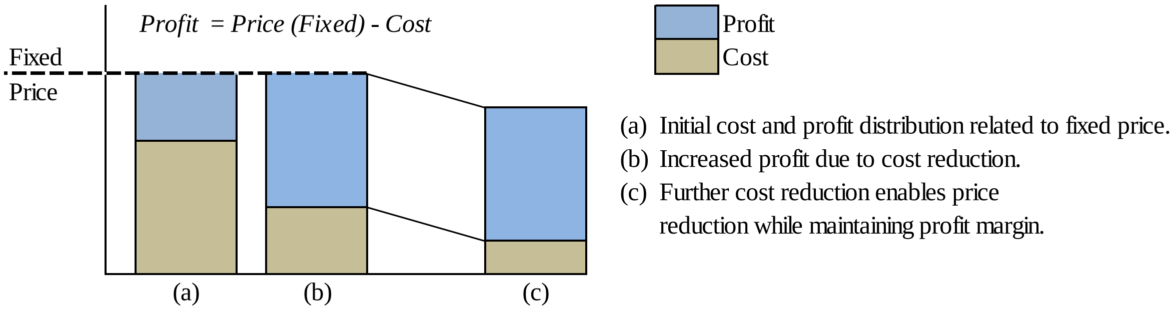


Figure 3-6 Cost Reduction as an Enabler to Increase Profit

The provision of value between a supplier and the product provider is generally well defined and formal agreements will exist with respect to the quality, function, cost and delivery attributes. Formality aside, a company will usually have a partnership or strategic alliance with their supply base so they can work together in harmony to co-create value. A strategic alliance is such that a group of partners agree to invest resources, share knowledge, co-develop products, technologies and services and build on their capabilities to provide value internally for the partnership and externally for the ultimate customer, (Gulati, 1998, p. 293, Argwal et al, 2010).

Succinctly, providing value is understood from the perspective of the ultimate customer, through the creation of the appropriate value streams, supplier partnerships and strategic alliances, internal value generation is potentially assured.

The key challenge for prospective lean providers is in understanding those features and attributes of both products and services customers will value. Subsequently, that understanding can be translated through the provision stream to achieve both customer value and the internal value necessary for providers to maintain operations and evolve.

Capturing Customer Value

The attribute of value manifests itself in terms of product and service characteristics and the challenge for any company is to align their products and services to the markets they wish to serve and anticipate the needs of that market. Companies may well have successfully met the needs of a market based on a set of assumptions that have driven policy creation and operational practices. But at some future state, without companies being aware, the assumptions that served so well for so long do not mirror the reality of the market place. Peter Drucker, the academic and business consultant defined the assumptions a company makes with respect to market alignment as ‘The Theory of Business’, (Drucker, 1994). Drucker’s hypothesis is fundamentally straightforward, a company’s ‘Theory of Business’ if not aligned to the needs of a chosen market must change so that it is.

Drucker provides examples of two companies, IBM and General Motors (GM) where their ‘Theory of Business’ either sustained or compromised their capability to responded to a changing reality. In the 1950’s IBM were convinced the future of computing was in powerful single use systems. Upon a competitor, Univac developing a prototype multipurpose machine, IBM became aware that single use machines would be obsolete. IBM changed their strategy and developed multipurpose computers to eventually become a market leader. Later, toward the end of the 1970’s Drucker argues that IBM made the wrong assumptions when responding to the threat of the emergence of the personal computer from Apple and Macintosh. IBM assumed that mainframes and PCs could coexist together and consequently developed their own range of successful PCs to become the PC industry’s largest manufacturer (Daly and Walsh, 2010). In the view of Drucker, IBM created a paradoxical situation for themselves. While the PC division became the fastest growing part of IBM, the mainframe division remained the largest source of revenue. Consequently, IBM could not ‘subordinate’ the mainframe business to the growing PC business preventing the optimisation of the PC business as the divisions were effectively competing against each other.

GM had for many years assumed that the domestic USA car market was homogeneous and need only segment their product range based on the earning potential of their customers. Against this assumption, GM continued to organise their production on mass production principles producing long runs of similar vehicles. GM had either failed to notice or ignored the changing buying trends of the US domestic market where consumers were beginning to look for greater choice and product price was now only one dimension in the consumer’s buying criteria. Moreover, GM also chose to ignore the emergence of Japanese automotive competition offering greater product variety through relatively short productions runs based on lean manufacturing.

IBM was quick to realise the potential of multipurpose computing machines but misread the market response to the consumers buying both PC and mainframe based products. GM's 'Theory of Business' had served the company well but was ill equipped to cater for changes in consumer consumption habits and the threat of an alternative competition.

To remain market focussed, Drucker identifies three sets of assumptions to his 'Theory of Business':

1. The environment of the organisation: Refers to the assumptions made about the structure of society, markets, customers and technology.
2. The mission of the organisation: The assumptions define the purpose of the organisation and how 'it envisions itself' to make a difference in the economy and society at large.
3. Core competences: Define the competences that the organisation must excel in order to maintain leadership.

For the 'Theory of Business' to be valid, the three sets of assumption must fit reality and complement each other. Also the assumptions must be entrenched in the core culture of the organisation and are so known and understood throughout the organisation. Further, assumption sets must be agile in the sense that they adapt to changes in the market and consumer taste so effectively that the organisation can change itself.

Drucker further presents the following set of indicatores to to validity of their theory:

1. On meeting objectives: The organisation will need to assess if new thinking is required to satisfy the next set of objectives to maintin focus.
2. On experiencing rapid growth: The assumptions that held pre growth may no longer apply as the organisation become less personal as it expands.
3. Unexpected success or failure: If the business theory is correct success should be fortold and prevent failure.
4. Unexpected success or failure of a competitor: Implies that the organisation's theory has missed an oppourtunity for success or is unaware of potential failure.

To maintain a valid ‘Theory of the Business’, Drucker advocates what he defines as a care system that consists of two activities. Firstly, on a regular basis, the organisation should challenge what it does in terms of product and service provision and policies and procedures to ensure that the organisation is doing the ‘right things’ and if not change. Secondly, while maintaining a focus on their core customers, the organisation should try to understand what their ‘non-customers’ are doing. Signs of change in consumer habits may manifest itself externally to the organisation rather than internally.

Ultimately, if an organisation has a valid ‘Theory of Business’ it will be realised through the ‘value’ provided to their customers. In the glossary of the work *Lean Thinking*, Womack and Jones (1996) define value as

> ‘… a capability provided to a customer at the right time at an appropriate price, as defined in each case by the customer’.

Within the work, beyond a brief discussion of a company attempting to capture the ‘voice of the customer’ through the use of Quality Function Deployment (QFD), the authors do not specify in any detail how to capture customer value. A further work by the authors, ‘Lean Solutions’, Womack and Jones (2005) focuses on improving the consumer’s purchasing experience of both products and services but no consideration is given on how to determine the product attributes that consumers would consider as valuable.

The challenge for manufacturers and service providers is to capture the needs of customers and translate the needs into desirable product and service attributes. The modern customer takes for granted functionality, reliability and safety from a product and so it is the product’s affective and emotional properties that have emerged as important factors in the successful marketing of products (Barone et al, 2009).

Specific methods for capturing the needs and requirements of consumers have been devised. Also professionals engaged in aspects of Quality Control and Assurance are also interested in quality aspects of a product or service that delight consumers beyond the functional ‘fit for purpose’ attributes that consumers take for granted. Two methods of capturing customer needs are briefly discussed namely Quality Function Deployment (QFD), and the Kano Model (Kano, 1984, Shariif Ullah and

Tamaki, 2011). This is followed by a review of the contribution of the 'Quality' movement to understanding customer perceived value.

Quality Function Deployment (QFD)

The purpose of QFD is to capture in a systematic way the 'Voice of the Customer' to influence the process of designing and developing a product or service (Summers, 2003, page 514). The method is a way to evaluate how well the product or service design meets or exceeds the expectations of the customer (Hill, 2005).

The QFD process is decomposed into four stages:

1. Strategy and concept definition
2. Product design
3. Process design
4. Manufacturing operations.

Within each stage, the customer requirements act as an input to establish the engineering characteristics of the design and are mapped into a matrix relationship illustrated in Figure 3.7 and is referred to as the 'House of Quality', (Cohen, 1995, Chan and Wu, 2005, Barone et al, 2009).

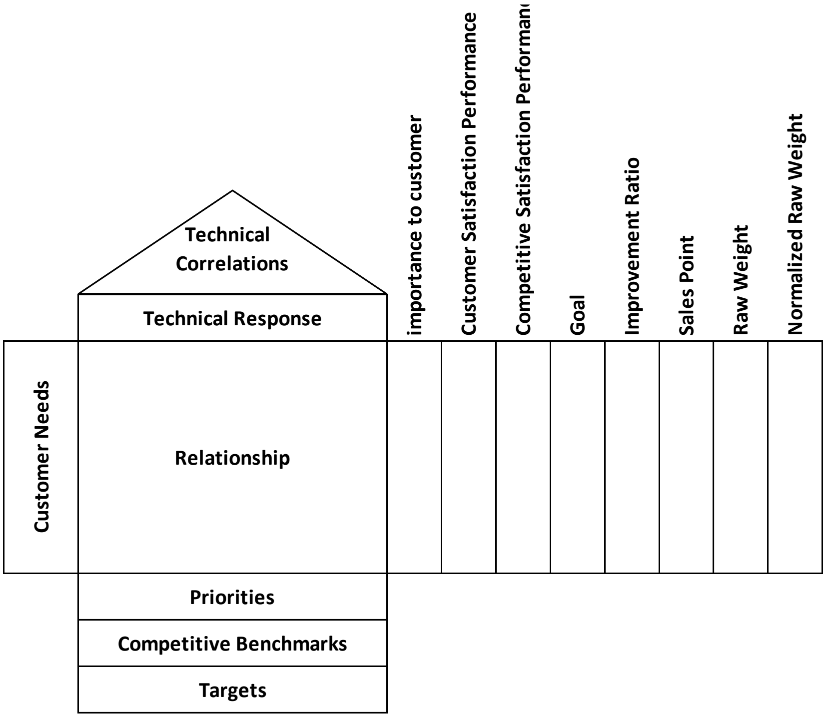


Figure 3-7 QFD House of Quality (Cohen, 1995)

The Kano Model

The Kano Model of customer satisfaction qualitatively defines the relationship between product attribute and customer satisfaction. The method applies a measure to five product attributes:

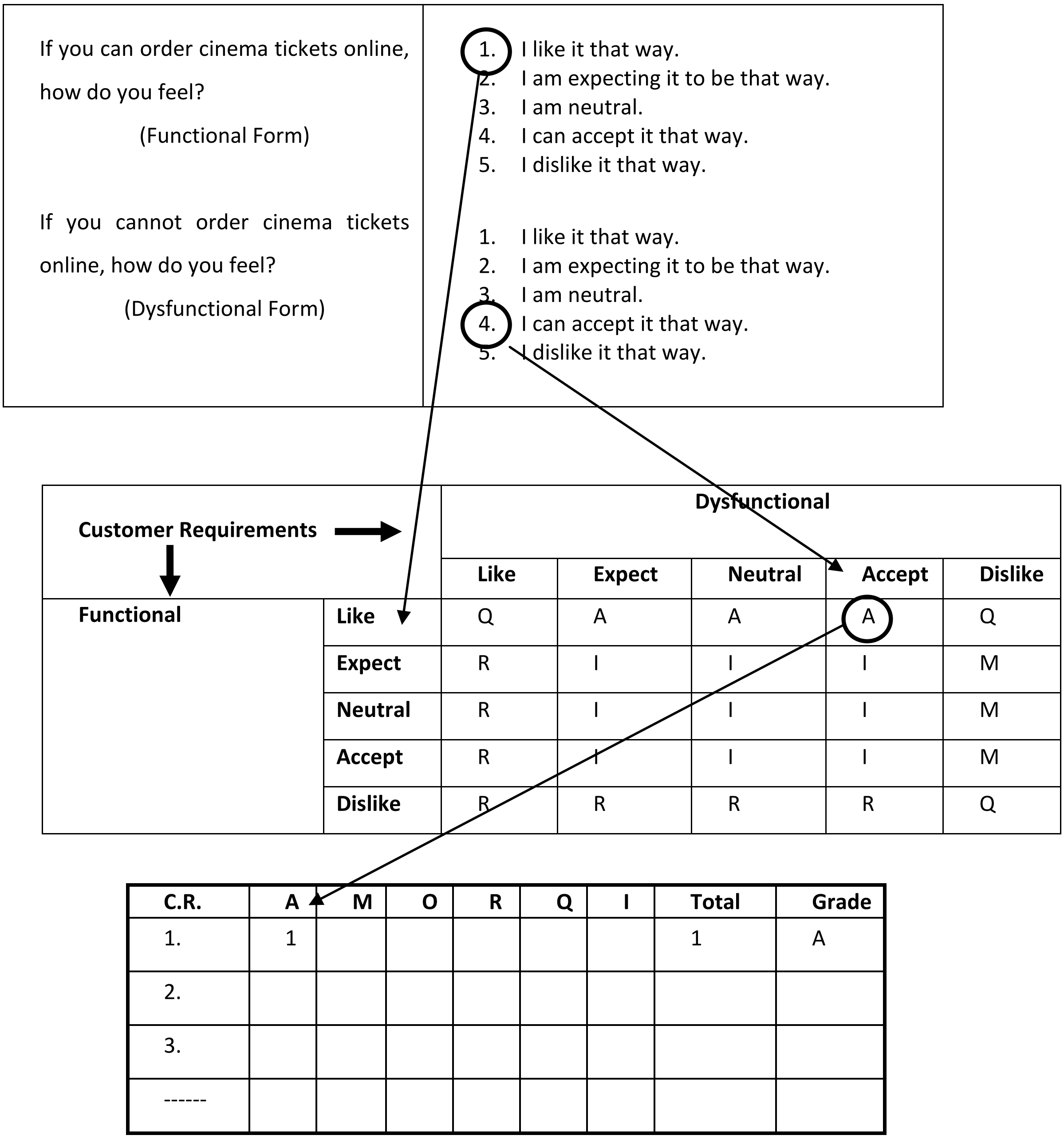
1. **Must-be (M)**: The absence of a *Must-be* attribute will cause total dissatisfaction with the product. The presence of the attribute though does not necessarily increase satisfaction.
2. **One-dimensional (O)**: The inclusion of *One-dimensional* attributes can enhance the satisfaction of the product or vice versa.
3. **Attractive (A):** An *Attractive* attribute leads to greater satisfaction, though the customer does not expect it to be there. The absence of an Attractive attribute would not cause dissatisfaction.
4. **Indifferent (I).** The presence or absence of an *Indifferent* attribute does not contribute to either customer satisfaction or dissatisfaction.
5. **Reverse (R):** The inclusion of a *Reverse* attribute will cause dissatisfaction or vice versa.

The attributes are captured via ‘Requirements Questionnaires’ for each product or service characteristic a provider is considering or evaluating to supply. Each question consequently has two parts:

1. Functional: How do you feel if the characteristic is featured in the product?
2. Dysfunctional: How do you feel if the characteristic is not featured in the product?

The responses are captured in a ‘Response Matrix’ for each characteristic. Figure 3.8 illustrates an example of a questionnaire format and response matrix (Witell and Lofgren, 2007).

The five product attributes are represented graphically by mapping user satisfaction responses against performance characteristics is illustrated in Figure 3.9.



If you can order cinema tickets online, how do you feel? (Functional Form)	[✓ 1.] I like it that way. 2. I am expecting it to be that way. 3. I am neutral. 4. I can accept it that way. 5. I dislike it that way.
If you cannot order cinema tickets online, how do you feel? (Dysfunctional Form)	1. I like it that way. 2. I am expecting it to be that way. 3. I am neutral. [✓ 4.] I can accept it that way. 5. I dislike it that way.

Customer Requirements → ↓		Dysfunctional				
		Like	Expect	Neutral	Accept	Dislike
Functional	Like	Q	A	A	[✓ A]	Q
	Expect	R	I	I	I	M
	Neutral	R	I	I	I	M
	Accept	R	I	I	I	M
	Dislike	R	R	R	R	Q

C.R.	A	M	O	R	Q	I	Total	Grade
1.	1						1	A
2.								
3.								

Figure 3-8 Kano Questionnaires and Response Matrix (Witell and Lofgren, 2007).

Contribution of Quality Thinking to Value

The ultimate goal of a lean system is to provide customer perceived value with respect to the products and services the system is designed to deliver. The 'Quality' of the product or service contributes towards the end user's perception of value and is a decisive factor in influencing potential customer's choice of provider in the selection of products and services, (Hill, 2005).

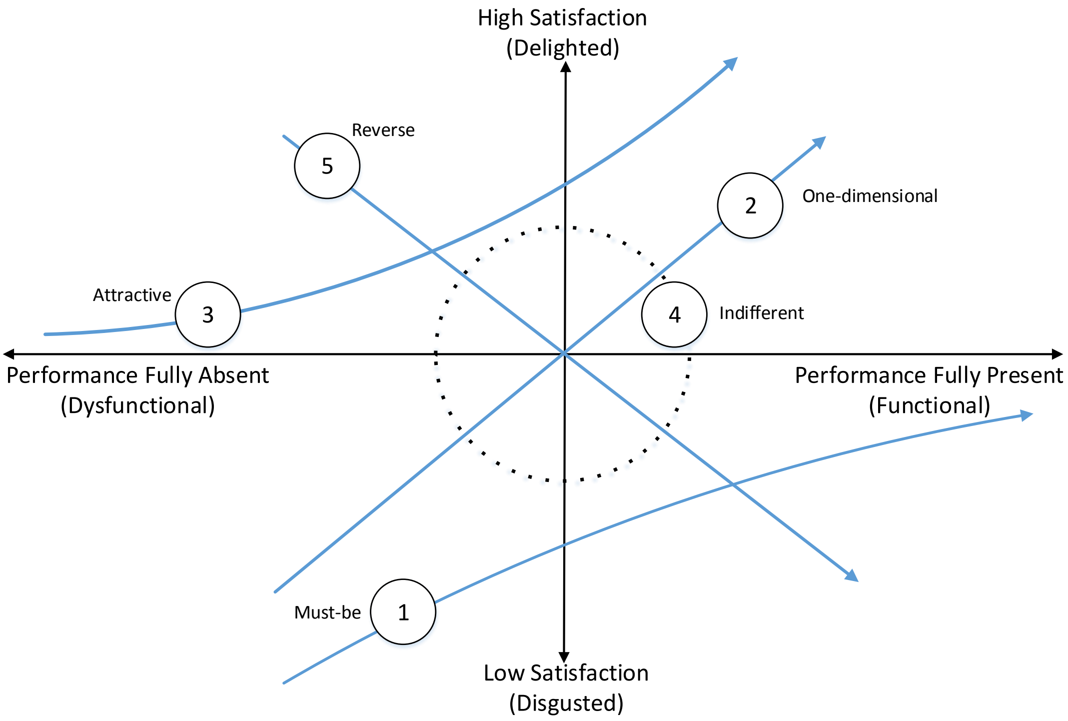


Figure 3-9 Visual Representation of the Kano Model (Kano, 1984)

There is no succinct universal single definition of quality and definitions of quality can have a different meaning depending on the context that quality is evaluated and can include 'value for money', 'fitness for use', 'consistency', 'excellence' and 'product integrity', (Kelemen, 2003). The absence of a universal definition of quality is recognised by professional bodies including. The American Society for Quality Control, define quality as (Summers, 2003):

1. A subjective term for which each person has his or her own definition;
2. In technical usage:
    a. The characteristics of a product or service that bear on its ability to satisfy stated or implied needs;
    b. A product or service free of deficiencies.

Nevertheless, individual authors have applied definitions of quality within the context of their work, amongst these include:

- "Quality is fitness for use", Juran (1974);
- "Quality is conformance to requirements or specifications", Crosby (1979);
- "Quality is inversely proportional to variability", Montgomery (2012).

A customer focussed view of quality is provided by Feigenbaum (1983) who defines quality as follows:

> “Quality is a customer determination which is based on the customer’s actual experience with the product or service, measured against his or her requirements – stated or unstated, conscious or merely sensed, technically operational or entirely subjective – and always representing a moving target in a competitive market”

Summers (2003), highlights some key points of Feigenbaum’s defintion that support the lean principle of customer perceived value:

- **Customer determination**: Only customers can determine if a product or service satisfies their requirements.
- **Actual experience**: The quality of the product or service is constantly assessed over the lifetime of the usage of the product or service.
- **Requirements**: The necessary attributes of a product or service called for by the customer may be stated or unstated, conscious or merely sensed.
- **Technically Operational**: Some required attributes of a product or a service may be clearly identified by a customer.
- **Entirely Subjective**: Some required attributes of a product or a service may be only be conjured in a customer’s personal feelings.
- **Moving Target**: Costumer needs, requirements, and expectations will change over time and are likely to increase creating more demand on the product and service provider.

Each of the aforementioned definitions of quality is within the context that they are applied correct. Equally, none of the definitions captures the full notion of what constitutes quality. But rather than attempt to elicit an all-embracing definition of quality, it would be appropriate to consider quality as a composite body of knowledge. Though not implicitly attempting to construct a ‘Body of Knowledge’, Garvin (1984, a) presents a set of five approaches that combine to provide a composite definition of quality. The approaches, Transcendental, Product Based, Manufacturing Based, Value based, and User Based are presented in Table 3.2.

In a second work, Garvin (1984, b) supplements his classification of approaches to quality by defining a set of eight quality dimensions that directly contribute to the concept of quality experienced by a consumer is presented in Table 3.3.

Approach	Description
Product Based	Product quality is differentiated by identifiable measurable product attributes. The approach invites a vertical or hierarchical dimension to quality where products can be ranked according to the level of the desired attribute.
Manufacturing Based	Quality is defined as 'the degree to which a product conforms to a design and specification' and recognises the consumers' desire for reliability. A product that deviates from design specifications is likely to be poorly made and unreliable providing less satisfaction than a made well product.
Value Based	The quality of a product or service is commensurate with the price a customer is prepared to pay or at a production cost acceptable to the manufacturer. The approach though is subjective and not clear cut. Manufacturers and service providers attempt to reduce costs through process improvement to enable enhanced quality attributes to customers at lower prices.
User Based	This approach is a subjective and is based on the attributes a consumer perceives as providing a quality product or service. The approach provides a challenge to marketing professionals who need to identify the needs of consumers and so exceed their expectations.

Table 3-2 Approaches to Quality (Based on Garvin, 1984, a)

Dimension		Description
1	**Performance**	Relates to the ability of a product to carry out its intended function.
2	**Reliability**	Implies the product is dependable and reflects the absence of failure.
3	**Durability**	The measure of the effective service life of the product. A user's perception of product quality is how long the product will last.
4	**Serviceability**	Relates to the ease in which a product can be serviced and repaired. With respect to a service function, relates to the ease in which a failure in service can be restored.
5	**Aesthetics**	Refers to the visual appearance of a product with respect to style, colour, and shape, tactile and sensory characteristics.
6	**Features**	Relates to what the product is capable of doing. Higher quality is frequently associated with products that have additional features beyond the basic requirements of the product.
7	**Perceived Quality**	Customers' perception of product and service quality can be highly influenced by the reputation of the company providing the product or service.
8	**Conformance to Standards**	Refers to the product meeting the design specification – effectively a product that conforms to standard is manufactured exactly as the designer intended.

Table 3-3 Product and Service Quality Dimensions (Based on Garvin 1984, b)

Value as an attribute experienced by a consumer is highly subjective. Consumers will experience different emotions from the same product or service. The challenge for providers is to ensure that they can appeal to these differences in emotion within the market segments they wish to compete. This requires the relevant and valid focus of the organisation to capture the needs of their potential consumers and deliver products and service that satisfy both functional and emotive requirements.

3.4.1.2. Value Stream Identification

The identification of the activities that contribute to creating customer perceived value is essentially an internal activity, (Rich et al, 2006), though companies frequently employ external companies to assist and train employees in methodologies to identify activities that generate waste and those that add value.

Rother and Shook (1999) define a value stream as:

> '... all the actions (both value added and non-value added) currently required to bring a product through the main flows essential to every product:

1. The production flows from raw material into the arms of the customer.
2. The design flow from concept to launch'.

However, their work concentrates on the production dimension of value stream identification. Their approach applies a set of pre-defined symbols applicable to various production and inventory control activities against which wasteful activities and improvements can be identified.

An alternative approach to defining value streams is promoted by Hines et al (1997) and defines seven tools appropriate to identifying value streams:

1. Process Activity Mapping: Industrial Engineering approach – studies and improves the flow of the process.
2. Supply Chain Responsiveness Matrix: A method to reduce inventory lead times
3. Product Variety Funnel: A method to ensure that derivative sensitive or customised products can be based on standard base products.
4. Quality Filter Mapping: Identifies potential quality issues within the supply chain.
5. Forrester Effect Mapping: Suppresses demand amplification.

6. Decision Point Analysis: Defines the point in time where customer pull demand is replaced by forecasting.
7. Overall Structure Maps: Provides a holistic schematic view of the total supply chain.

The separate tools are mapped to the seven wastes identified in the Toyota Production System, where the individual tools are correlated to a specific waste as either high medium or low effectiveness (Table 3.4).

	Mapping Tool						
Waste	1 Process Activity Mapping	2 Supply Chain Response Matrix	3 Production Variety Tunnel	4 Quality Filter Mapping	5 Demand Amplification Mapping	6 Decision Point Analysis	7 Physical Structure: a) Volume b) Value
1: Overproduction.	L	M		L	M	M	
2: Waiting.	H						L
3: Transportation.	H		M	L			L
4: Inappropriate Processing	H		M		H	M	L
5: Unnecessary Inventory.	M	H	M		H	M	L
6: Unnecessary motions.	H	L					
7: Defects	L			H			
H = High correlation & usefulness. M = Medium correlation and usefulness. L = Low correlation and Usefulness							

Table 3-4 Correlation of Mapping Tools to TPS Wastes (Hines et al, 1997)

3.4.1.3. Flow

At the operational level flow is the realisation of a lean system in operation. Pure process flow embodies the full spectrum of lean activities and is a consequence of establishing effective value streams, a culture of continuous improvement and reacting to customer pull. Operationally flow is achieved through a system of Just in Time (JIT) manufacturing and is considered in greater detail in Section 3.5

3.4.1.4. Pull

Though the idea of producing only what the customer requires appears as the natural and sensible way to manufacture product, pull production requires discipline and coordination. Push systems of manufacturing are not concerned with the coordination of the total manufacturing system. Consequently, while individual machines are producing product irrespective of the requirements of both upstream and downstream processes, problems emerge with respect to excess inventory consuming space, packaging and inevitably quality problems. Taiichi Ohno initially spent some five years establishing a pull system of manufacturing at Toyota and continued to refine the system over the evolution of the TPS (Ohno, 1988). Similar to flow, the ability to create a Pull system of production is a realisation of continued improvements (possibly over many years) resulting in for example set up time reduction. The need to produce to customer pull has resulted in changing the layout of manufacturing systems through the development of cellular manufacturing and strategic work stations where multi-purpose machines have given way to a dedicated facility that can produce a family of products at a rate that can be synchronised to customer demand, (Cheng and Podolsky, 1993).

3.4.1.5. Perfection

The idea of perfection from the perspective of Womack and Jones (1996) is that upon creating a lean system the act of creating further customer value is continued as is the enhancement of the remaining principles. Effectively, it is a case of do it all again. In reality the application of perfection is both continuous and applied simultaneously across each of the principles. Perfection in the sense of lean systems is a journey rather than a destination. The dissemination of perfection as a practical construct is achieved through the following:

1. Senior management support promoting an improvement culture
2. Knowledge of methodologies to implement improvement activities.

As with any company initiative, senior management support is essential to create a culture of continuous improvement and empower people to actively partake in improvement activities. The second construct is more of a practical nature and ensures people have the necessary skills, knowledge and capabilities to implement improvement activities.

The knowledge available to improvement practitioners is the result of an evolving history of process improvement. In the 20th century, the first ideas relating to improvement may be attributed to the work of Frederick Taylor through the development of scientific management (Taylor, 1911). Taylor contended that there was a best method to do any job of work. The identification of 'the best' method was established by 'educated' experts with no input from the actual workers. The application of statistical methods to monitor process variation in manufacturing were first introduced by Walter A. Shewhart at Bell Laboratories during the 1920's through the development of the control chart (Duncan, 1986).

During World War II, the USA Government introduced an industry wide training programme (Training within Industry or TWI) to provide skills to people who had to replace expert workers who had enlisted in war time military service. The TWI programme was taken up by a number of countries after the war including Japan. The TWI programme would subsequently influence the development of improvement programmes at Toyota, while simultaneously the programme is dropped in the USA, (Dinero, 2005).

During the 1950's the work of W Edwards Deming would influence the development of Japanese manufacturing through his 'System of Profound Knowledge', (Deming, 2001). Moreover, the influence of Deming's thinking has permeated through Western culture influenced by the success of Japanese manufacturing and the promotion of lean principles.

During the mid-1980's through the work of the Motorola Company a structured improvement method was developed that had at its core the application of traditional statistical methods to model system behaviour and was consequently christened as the 'Six Sigma' method, (Harry and Schroeder, 2005). The method has the goal of achieving 3.4 defects per million opportunities equating to a score of six sigma on the normal distribution scale discounted by 1.5 standard deviations to account for process shift.

The six sigma process is often compared to the Deming Cycle (Plan, Do, Check, Act (PDCA)). Though each approach has a different structure, there is synergy to the methods in that they assess a current status, model or analyse the appropriate system attribute and recommend where appropriate a solution method. Dahlgaard and Dahlgaard-Park, (2007) conducted an extensive study of Six Sigma, TQM and Lean Manufacturing and concluded:

> '…the lean production philosophy and the six sigma steps are essentially the same, and both have developed from the same root – the Japanese TQM practices (company wide quality control)'.

Companies that have succeeded in creating a lean system or are engaging on a lean transformation should equally view the principle of perfection as a strategic enabler to focus the dissemination of the other principles to ultimately eradicate waste from the system, (Murman et al, 2002).

3.5. Just in Time Manufacturing

Prior to the emergence of the lean construct, the focus of the research into Japanese manufacturing methods was in understanding the principle of Just in Time manufacturing, commonly referred to as JIT. The essence of JIT is captured within its name. Succinctly, JIT manufacturing implies only the necessary products are manufactured as they are required, and in the quantity required. A by-product to the JIT approach is that work-in-progress inventory (WIP) is minimised or indeed eliminated. The significance of JIT in manufacturing though is not limited to the timely production of product but in the creation of the 'infrastructure' that is necessary to support and deliver JIT manufacturing. That infrastructure delivers the elimination of waste, superior product quality, effective maintenance systems, shop floor organisation and, perhaps most importantly, people engaged in manufacturing and support activities at all levels that are empowered to think and actively participate in the continuing improvement of the production system. The main thrust of the research into JIT manufacturing, particularly during the 1980's, was to attempt to understand the JIT infrastructure and how JIT methods could be adopted by Western manufacturers.

JIT manufacturing at the operational level is synonymous with lean manufacturing providing a comprehensive approach to continuous improvement through the elimination of waste within manufacturing processes, (Sakakibara et al, 1993). It is the relationship between JIT and the concepts of waste elimination and continuous improvement that differentiates JIT from systems of inventory control that exist to purely maintain what is considered an appropriate level of inventory in terms of received inventory (from suppliers), work in progress (WIP) and finished inventory waiting dispatch to customers. Although elements of JIT were previously practised and indeed pioneered by Henry Ford, (Levinson, 2002, Wilson, 1995), it was through the development of the JIT methodology as an integral part of the evolution of the TPS that emphasises JIT as more than just a means of controlling inventory. A fully functional JIT system implies pure manufacturing flow relative to customer demand free of waste and supported by effective quality and maintenance systems and a culture of continuous improvement. The significance of JIT is not restricted to its functional dimension of 'inventory control' but as an integral element of a manufacturing system geared toward ensuring flow.

A common desire amongst manufacturing practitioners at all levels of an enterprise is to improve their methods of working thus enabling greater operational efficiency and so reducing cost and waste. Increasing operational efficiency should simultaneously result in improved levels of customer satisfaction in terms of both product and service attributes. Enterprises strive to provide superior levels of customer service as ultimately this engenders long term customer loyalty that sustains profitability and growth. On its own, the desire to improve is not sufficient. The desire to improve must be complemented by an infrastructure that can deliver improvement and a culture ingrained within the entire work force that continuously strives to improve.

The Just in Time method of manufacturing strives to provide both the infrastructure and culture that supports continuous improvement. At the operational level, JIT is focussed on ensuring that only those raw materials and components that are necessary for immediate consumption are available at the point of production. That focus is the very catalyst for the existence of both the infrastructure and culture. The infrastructure applies to such attributes as the layout of production facilities, operations management, and management of the supply chain, product quality and maintenance programmes. The JIT culture is more about the attitude of the enterprise and the people within the enterprise with respect to how they approach their work. The approach to working within a JIT environment is in contrast to the approach to work within a Taylorist system.

The traditional Taylorist approach to manufacturing while advocating the division of labour also introduces a 'division of responsibility'. Managers take responsibility for the thinking of how work will be carried out. Managers aided by technical specialists aim to determine 'the one best way' a task can be deployed. The responsibility for carrying out the task is assigned to a worker. Because the managers and technical specialists have determined the best way to carry out the task, the worker does not have to think beyond the mechanics of completing the prescribed task. The worker does not think about improving the task and, moreover, there is no management encouragement for the worker to do so. Similarly, Taylorist managers have no need to consider further improvements as they have hitherto established the 'one best way' to carry out the job task. The division of responsibility is well defined within a Taylorist system. Managers think and workers do; workers do not think and mangers do not do.

Within a JIT environment, managers still manage, and workers still do. However, the division of responsibility is more loosely defined. While their prime responsibility is task orientated, workers are encouraged and empowered to strive for improvements not just with respect to their immediate tasks but also within the wider enterprise environment. Managers, however, are not negating their responsibilities in devolving more of the task management to the worker. Rather managers create the environment that enables worker empowerment and provide support, guidance and training to the worker.

3.5.1. JIT Infrastructure and Culture

The origins of the JIT method of manufacturing are widely documented. Indeed, the principal architects of the TPS, Taiichi Ohno, (Ohno, 1988) and Shigeo Shingo (Shingo, 1988) both describe the rationale for the need to develop JIT systems rather than just mimic what hitherto were the accepted practices embraced within mass production. Though JIT evolved over time due in part to trial and error methods, the method would progress toward a structured system that would play a central role in the development of the TPS. Though both Ohno and Shigeo would both publish their work toward the end of the 1980's, it was a decade earlier that Western manufacturing would first become exposed to the JIT methodology primarily through a paper published by a team of Toyota engineers (Sugimori et al, 1977). The paper, titled *'Toyota Production System and Kanban System: Materialization of Just-in-Time and Respect-for-Human System'* begins by describing the conditions within Japan that required the need to develop an alternative method of manufacturing. Succinctly, despite the devastation of the Japanese economy and manufacturing base at the end of World War II, Japan is never the less geographically a small country and dependent heavily on imports for both food and raw materials for manufacturing. Future prosperity for Japan (and not just Toyota) would depend on economically producing value added superior quality products when compared to international competitors and at a lower cost.

Though the Toyota engineers recognised the disadvantages that Japan faced when compared to Europe and the USA, they also recognised the advantages Japan possessed when compared to their Western counterparts. Primarily, the advantage laid within the attitude and demeanour of the Japanese worker. The authors contend that such inherent characteristics of the Japanese worker would become apparent in the following three attributes:

> 1. Group consciousness: sense of equality, desire to improve, and diligence born from a long history of a homogeneous race;
>
> 2. High degree of ability resulting from higher education brought by desire to improve;
>
> 3. People centring their daily living around work.

The Toyota authors contend that amongst Japanese workers there exists an inherent positive attitude to the world of work. That attitude is reflected in a natural team ethic, a sense of equality, the desire to improve.

Enlightened Japanese employers, in promoting unity with a supportive workforce, would in return provide for their employees:

1. Lifetime employment system;
2. Labour unions by companies;
3. Little discrimination between shop workers and white-collar staff;
4. Chances available to workers for promotion to managerial positions.

The relationship between companies and the workers, (from the workers willingness, and the companies support), would provide the foundation for the workers to apply to their work the full potential of their capabilities.

The recognition of Toyota to perceive potential advantage over their international competitors through their workforce while seeking to overcome the advantages of such competitors through the provision of superior quality products would provide the foundation for the creation of the TPS and in particular the development of JIT manufacturing.

The paper describes the now familiar constructs of the TPS. At the core of the TPS is the necessity to eliminate waste through effectively producing at each stage of the production process only what is needed for the following process so giving rise to the concept of JIT. Beyond the deployment of operational practices to deliver a JIT system, is the promotion of the belief in the respect for the 'Human System'. The emphasis on respect implies that the efficiency of the production system is only assured if the people engaged within the system are trusted and empowered not just to function within the system but to actively strive to continuously improve the system. The freedom to engage with work related improvements is the catalyst for workers to apply their full potential to their work in what would otherwise be an arduous and monotonous environment (New, 2007).

General Japanese management principles were apparent to Western industry and commerce from at least the late 1950's. The Editorial of the August 2007 edition of the *International Journal of Production Research* (New, 2007) quotes studies by Abegglen (1958), Yoshino (1968), Cole (1971), Evans (1971), Dore (1973), Marsh and Mannari (1976). The Editorial emphasised attributes within these works that are shared within the TPS, including participation and corporate paternalism leading to lifelong employment. Significantly, these works also focussed on the socio-economic and cultural aspects of the Japanese presenting perhaps a stereotypical generalised view '*....of a workforce endowed with an unnatural enthusiasm for work and a willingness for individuality to be subsumed within collective effort*.

These generalised views were also shared by the influential American management academic Peter Drucker who had extensively studied Japanese management practices (Drucker, 1971). The significance of the Sugimori paper, while also emphasising the unique traits of the Japanese, when compared to the aforementioned body of work, is that the paper would also focus on practical methods that would enhance manufacturing efficiency. Consequently, the paper would prove to have a significant influence on the dissemination of JIT practices across Western manufacturing over the following decades. Other Japanese manufacturing professionals and academics would continue the work of Sugimori and his co-authors in disseminating and explaining Japanese working practices to the international community (including Monden (2012), Taiichi Ohno and Shigeo Shingo (both 1988) and later Cheng and Podolsky, 1993). During the 1980's, American academics would begin to study, in detail, Japanese manufacturing practices in part to attempt to understand and halt the decline in American and in general manufacturing.

Amongst the earliest of the American academics to have a profound influence on the adoption of JIT practices with the USA was Richard J Schonberger.

Schonberger understood that within Japan, the trajectory toward the development of a JIT system of manufacturing is a natural response to the awareness that Japan is a relatively small country devoid of many natural resources where space costs are at a premium (Schonberger, 1982, a). Consequently, Japan is required to import many basic commodities (including food) and is at a cost disadvantage for raw materials when compared to Europe and the USA. It is therefore natural for the Japanese to conduct their manufacturing activities with a view to eliminating all forms of waste. During the 1980’s, Schonberger was amongst the earliest American academics who would extensively study Japanese manufacturing techniques with a view to their adoption by Western manufacturers. His investigations into Japanese manufacturing methods resulted in his first work making the argument that the foundation of Japanese success is based on the concepts of Just in Time Production and Total Quality Control (Schonberger, 1982, b). This work led to Schonberger classifying what he considered are the necessary attributes required to achieve World Class manufacturing status, (Schonberger, 1986) and to the 'World Class Manufacturing Casebook', (Schonberger, 1987) where the case studies of the implementation of Just in Time and Total Quality Control methods devised in Japan are described. Schonberger identifies continuous flow production as a goal toward achieving World Class Manufacturing (WCM) status. Schonberger recognises that pure continuous flow is not achievable due to the 'Stop and Go' nature of manufacturing. The need to change over from one product type to another and the movement of in process inventory through the production route impede flow. The impediment of flow, if left unmanaged, leads to an excessive build-up of raw and semi-processed materials along with finished goods well ahead of customer requirements. Schonberger prescribes three World Class Manufacturing precepts to counteract the build-up of inventory due to flow impediment:

1. Small Lot Sizes
2. Right First Time
3. Total Preventative Maintenance

The significance of Schonberger's work is not solely because the work was amongst the earliest to disseminate Japanese manufacturing methods within Europe and the USA and through the dissemination identified the practices western manufacturers would need to adopt to compete at a World class level. Rather the greater significance of his work lies in that his core observations on how a manufacturing system should be run are universally true and are proved to be timeless. Of equal significance, Schonberger's approach is that people who work within manufacturing both directly and indirectly seek through their activities to add value to the creation of the product. Work is therefore always value adding rather than managing inefficient processes. Schonberger recognises that to move from a state of managing inefficiency to a state of continually creating value requires a transformation process. Though Schonberger does not advocate a specific transformation process method, he does advocate the adoption of specific methodologies (for example JIT, SPC, TPM). But more importantly, Schonberger contends that to create a state where adding value is inherent within the operating culture, people need to radically change the way they think with respect to how they carry out their activities. Further, Schonberger contends that the 'change of thinking' applies to people across the entire enterprise and not just those people who work directly within the manufacturing process. Those people who work within functions that support manufacturing directly engage with the production process to add value to the creation of the product. Schonberger recognises that individuals have core responsibilities within the overall manufacturing and support processes. If people did not carry out their core responsibilities consistently over time, eventually the manufacturing function would cease to operate. However, beyond their core responsibilities, people should foster a more rounded holistic and broader view of the overall manufacturing activity, and where appropriate, readily make contributions beyond the confines of their core responsibilities.

Within a lean or JIT system the concept of the division of labour still exists where tasks are broken down to their constituent elements. Any one operator or assembler will carry out perhaps just one or possibly a subset of the totality of the job elements. The lean division of labour, though, does not mimic the Taylorist approach. In the Taylorist approach, on one side of the production fence exist the direct workers who will just carry out the task, while on the other side of the production fence, are the management thinkers who define how the job tasks are carried out and are the sole arbiters for process improvement. In the lean or JIT environment in addition to carrying out their direct labour task, a variety of indirect tasks will be carried out by a worker, including preventative maintenance tasks, data recording and analysis, and problem solving. Moreover, within the lean environment, an operator will be encouraged to be more versatile and trained to perform a wider variety of direct tasks. Indeed, manufacturers who adopt the lean/JIT philosophy share the management task across a versatile, adaptable and flexible workforce (Schonberger, 1986, p 192).

What gels together the operational practices and philosophy that combines to form a JIT system as defined by Schonberger is a supporting infrastructure. Within the operations management literature there is no agreed specific definition (de-facto or otherwise) of what constitutes a JIT infrastructure. There is agreement on the pre-requisite operational practices a manufacturer must employ to achieve JIT status. Primarily, these are the practices identified by Schonberger and enshrined within the Toyota Production System. The concept of a JIT infrastructure is fundamentally about how a manufacturer organises itself to be able to build product just in time and ultimately deliver product to the customer just in time while simultaneously eliminating the source of any wasteful practices.

Since the mid 1980's an extensive literature has evolved that has studied and disseminated JIT operational practices and procedures, the application of JIT, the relationship of JIT with Total Quality Management (TQM), the contrast of JIT to Material Requirements Planning (MRP) and Optimised Production Technology , the effectiveness and advantages of JIT as well as the perceived disadvantages of JIT.

With respect to infrastructure, research has focussed on practices that are considered effective in creating an environment where JIT can evolve (Ahmed et al, 2003). Cheng and Podolosky (1993), though not necessarily the first authors to disseminate as a coherent whole what constitutes JIT manufacturing, provide a benchmark against which a JIT infrastructure can be assessed. Later authors, including Hill (2005) and Dennis (2007) though not implicitly building on the work of Cheng and Podolosky define a JIT system within similar terms.

At the root of the Cheng and Podolsky definition of JIT is the idea of manufacturing organisation. Though the authors do not implicitly reference the 5S methodology of workplace organisation, in synthesising their work on JIT, it is clear that 5S practices provide the base foundation for dissemination of JIT.

The work of Cheng and Podolsky fundamentally defines the organisation and structure of a JIT system of manufacturing. Other works that describe in detail JIT manufacturing replicate the themes covered by Cheng and Podolsky. Such works include Hutchins (1999) and Dennis (2007). The themes are also common within the general Operations Management literature that include chapters on JIT manufacturing and typical of these works are Hill (2005), Vollman et al (2005) and Heizer and Render (2008).

Predominantly focussing on the work of Cheng and Podolsky, the infrastructure to support a JIT system of manufacturing is illustrated in Figure 3.10. From the Cheng and Podolsky model, JIT is fundamentally presented as a holistic enterprise wide system. It is the complete system that delivers JIT and not just sub sets or single elements within the system.

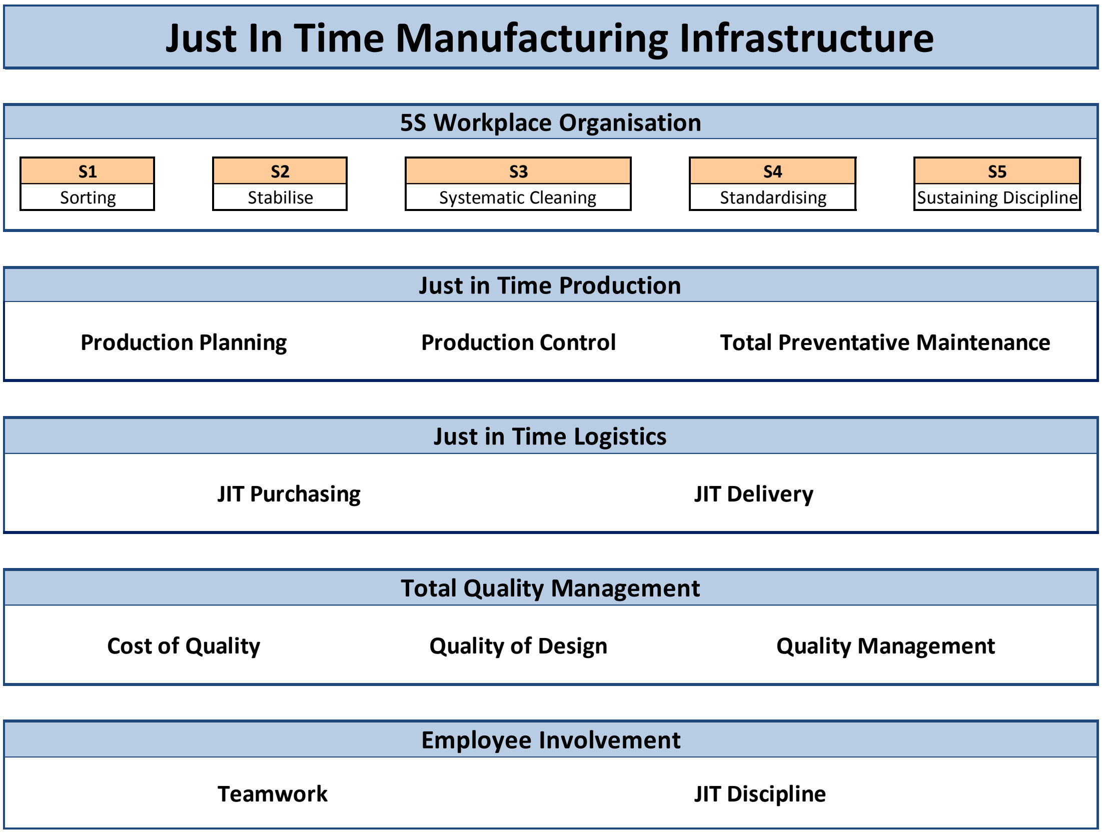


Figure 3-10 JIT Manufacturing Infrastructure
(Derived from Cheng & Podolsky, 1993)

Through a literature review supplemented by a series of visits to twelve manufacturing plants and survey responses from a further 50 manufacturers who had implemented a JIT programme, Sakakibara et al (1997) investigate the relationship between JIT and its supporting infrastructure on manufacturing performance. The authors identified a set of JIT practices complemented by a mutually supporting set of infrastructure practices that combine to increase the effectiveness of key manufacturing performance indicators that results in an increase of competitive advantage across a defined set of business activities. Figure 3.11 illustrates the linkage between the Infrastructure and JIT Practices to the increase in manufacturing performance and competitive advantage.

Within their work, the authors conclude that competitive advantage is gained through increasing manufacturing performance. They further concluded that, on their own, JIT practices had minimal effect on increasing manufacturing performance. It was through the support of a complementary infrastructure that manufacturing performance is such that a manufacturer can deliver competitive advantage. The conclusions of Sakakibara and his co-authors fundamentally agree with those of Cheng and Podolsky in that the infrastructure supporting defined operational JIT practices delivers JIT. This is a common theme throughout the JIT and Operations Management literature.

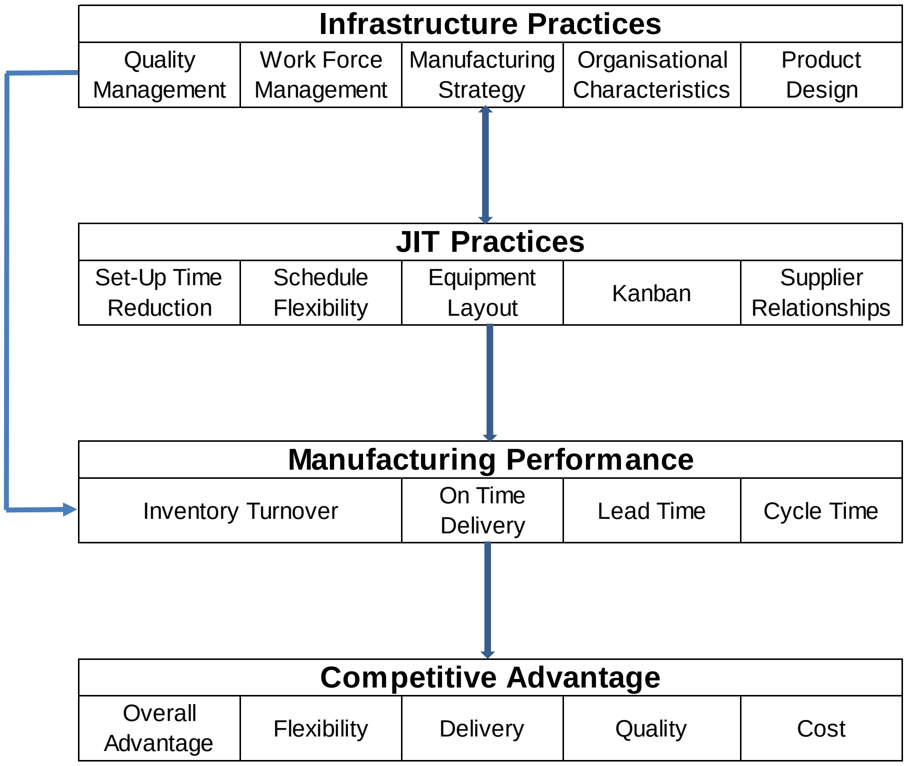


Figure 3-11 JIT Infrastructure and Practice Linkage Sakakibara et al (1997)

3.5.2. JIT Manufacturing as a Catalyst for Continuous Improvement

Continuous improvement is the process of making incremental improvements, regardless how small that eliminate waste (and therefore reduce cost) to create value added processes (Liker, 2004). The incremental steps are applied through gradual constant effort. Though each incremental improvement step is not necessarily dramatic, over time the accumulation of improvement steps can have a radical affect on operational performance.

The implementation of JIT manufacturing is predominantly a transformation process from a manufacturing system holding excessive inventory to a system where an acceptable minimum inventory level is held. While the transformation process involves the creation of the supporting infrastructure, at the operational level, JIT is concerned with the improvement of processes that enable the holding of minimum stock holdings while allowing for the timed delivery of parts and material for immediate manufacturing requirements. Consequently JIT is synonymous with the concept of improvement. Continuity derives from a universal agreement amongst quality practitioners that a true state of perfection does not exist and as such improvements need to be continuously applied. The continuous improvement theme is not confined to the philosophy of JIT but is also a central component of Total Quality Management (TQM) where the theme is presented as a 'never ending journey', (Hoffman and Mehra, 1999). The hypothesis advocates that, regardless of how efficient a system or product becomes, there is always scope for improvement.

JIT as a catalyst to continuous improvement stems from a belief that in general within manufacturing systems, the use of inventory buffers can hide problems, thus creating waste. Implementing a JIT manufacturing system will expose such problems so enabling their elimination and driving the continuous improvement of the production system, (Näslund, 2008).

The analogy often alluded to within the operations management literature is of inventory flow represented by the flow of a river, (Vollman et al, 2005, Heizer and Render, 2008, Hill, 2005). High river levels hide the rocks on the river bed that act as a metaphor for problems inherent within the manufacturing system. Such problems may be manifold and can include machine breakdowns, excess process variation, excess scrap, poor delivery performance and product quality. Many of these problems will be apparent prior to the implementation of any inventory reduction programme. Such visible problems would need to be addressed prior to any meaningful reduction in inventory. In terms of improvement the power of JIT lies in exposing hidden problems as inventory reductions are systematically introduced.

The reasons for holding excessive inventory can be many and varied. The primary purpose is to act as an insurance buffer against irregularities of supply between manufacturing processes. Effectively, the inventory buffers decouple processes from each other. Processes function autonomously and the excess inventory is in effect an impediment to flow. Other reasons for holding inventory include:

- Poor Operating Practices;
- Facility Layout;
- Accounting Practices;
- Misunderstanding of the role of Inventory.

There are reasons why inventory is maintained at a given level; succinctly inventory enables the manufacturing system to function. Reducing inventory without addressing the reasons for maintaining high stock levels would be counterproductive as the system would eventually stall and come to a halt. The implementation of a JIT programme addresses the reasons to maintain higher than necessary stock levels and systematically reduces over time inventory levels. During the transition, inventory is removed in a controlled way thereby maintaining manufacturing output but simultaneously increasing manufacturing performance.

The effectiveness of JIT therefore becomes apparent at the operational level as inventory is removed from the manufacturing system. As such, it is tempting for manufacturers to assume JIT is just a series or set of process improvement initiatives that can be cherry picked to suit a particular set of circumstances. During the 1980’s and 90’s several academic studies into the implementation of JIT by Western manufactures noted that many firms were utilising elements of JIT that were easy to implement and provided quick tangible benefits, rather than adopt an overall philosophy or system, (McLachlin, 1997). As such, JIT including infrastructure elements and respect for the worker are conveniently ignored. Consequently, the manufacturers did not derive the full benefits of a JIT implementation.

The effectiveness of JIT as a vehicle for continuous improvement is derived from the supporting infrastructure and culture that promotes continuous improvement.

Improvement opportunities, particularly those identified from the bottom up by front line workers bear fruit through a supporting culture and team work.

3.5.3. JIT Manufacturing: Case Studies

Manufacturing is a diverse activity. At one end of the manufacturing spectrum, highly customised bespoke products are designed for a limited customer base. At the opposite end of the spectrum continuous assembly lines produce high volumes of similar standardised or mass customised products for a regional or even global customer base. For a given market segment a manufacturer is attempting to appeal to, there exists specific process choices that fits the product to the particular market segment.

Hayes and Wheelwright (1979) visualised the fit of the Product-Process matrix as a means for guiding a company to match process choice with product type. The idea is that a product line can be characterised as occupying a particular region on the diagonal of the matrix that connects the dominant process choice to the volume demand of the product.

Hill (1995) contends that the process choice relative to the product type is crucial to winning orders in specific markets. Products are required to be made to meet a variety of specifications, technical, functional, safety and environmental. Products do, however, have to be supplied in a way that wins orders in the market place and, according to Hill, the appropriate manufacturing process choice is a key factor to winning orders. Hill presents an analogy to the Hayes/Wheelwright Product Process Matrix that fits manufacturing process choice to product type based on the volume demand of the product (Figure 3.12).

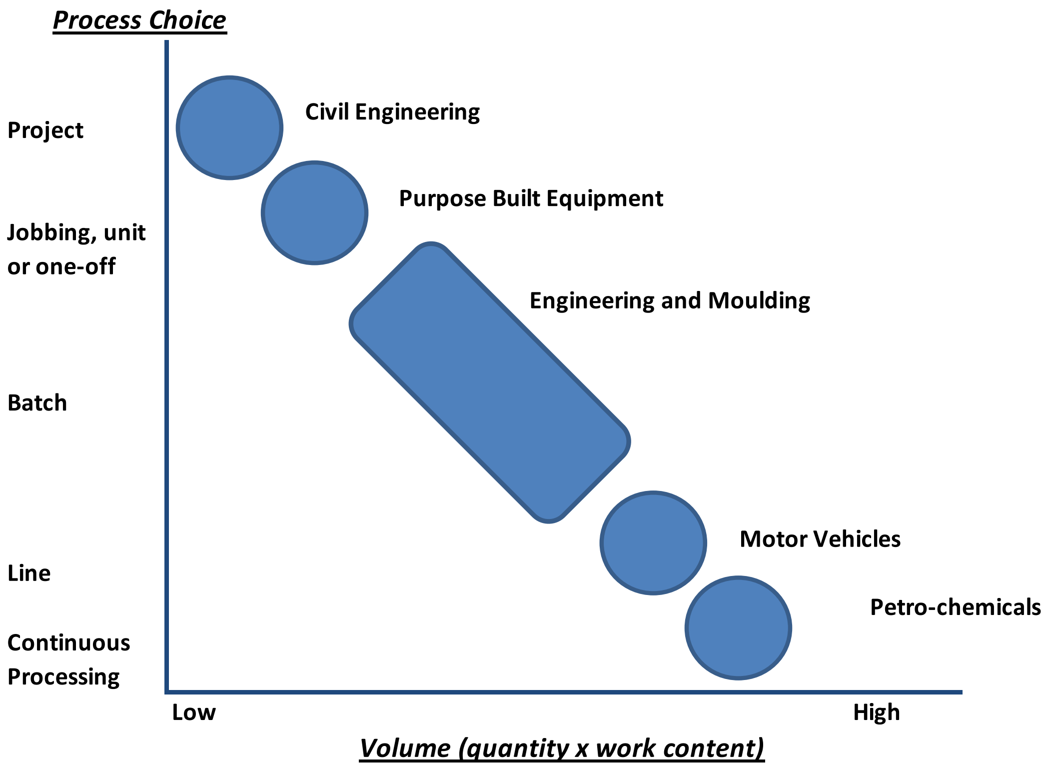


Figure 3-12 Process Choice & Product Volume Matrix (Hill, 2005)

The Toyota Production System from which JIT manufacturing evolved is primarily concerned (from a Toyota perspective at least) with the production of motor vehicles. JIT manufacturing clearly applies to motor vehicle manufacturing where there is significant volume demand and the dominant process choice is the continuously moving assembly line.

However, given the diversity of scale of manufacturing, it is reasonable to conceive that JIT has universal application across the whole spectrum of manufacturing activity?

Clearly, JIT as a total package as applied in systems that replicate the TPS, is not universally applicable. However within JIT there are attributes that will be universally applicable regardless of process choice, and in particular dimensions such as culture, infrastructure and respect for people should be universally accepted across all business activities. Harrison (1992) in a similar vein to both Hill and Hayes and Wheelwright presents a matrix that maps JIT elements to Process Choice (Figure 3.13). Specifically from this matrix it is seen that where product variety is low and volume demand is high then JIT manufacturing as defined by Cheng and Podolosky (1993) is applicable.

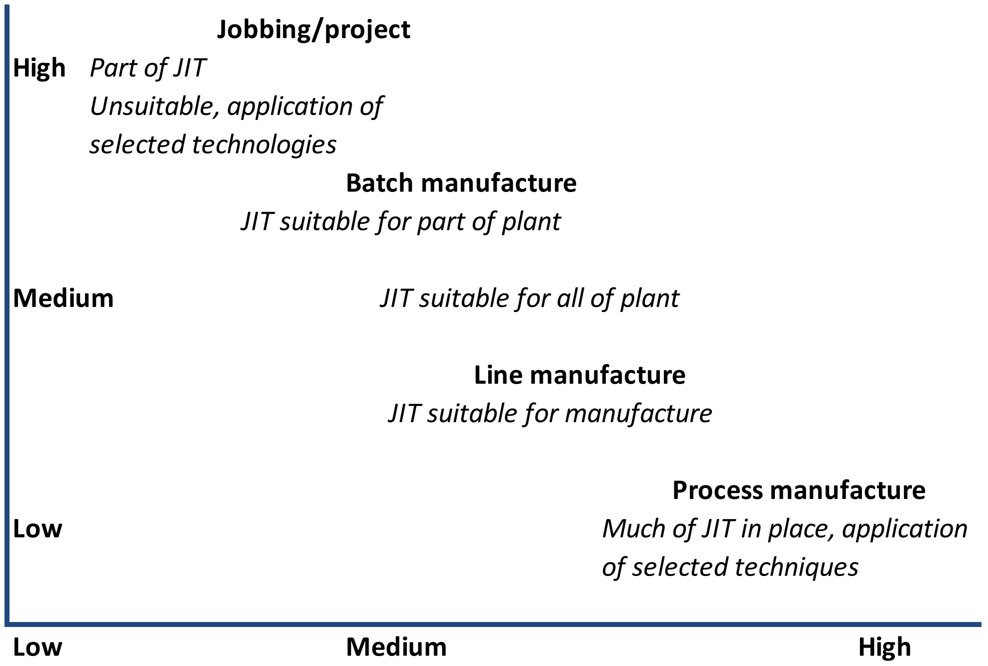


Figure 3-13 JIT and Choice of Process Matrix Harrison (1992)

Conversely, where product variety is high and volume requirements are low, fewer attributes of the JIT model are applicable. Through two case studies, the application of JIT is examined across both flow and batch manufacturing.

Case Study 1: Flow Manufacturing.

A product assembly line has a defined number of assembly work stations each carrying out specific assembly tasks. There are in total n workstations each defined by an ‘Assembly Address’, say $A_{j,}$ where $j = 1, 2, ..., n$. Each assembly station is a consistent distance from its pre and follow on workstations. Components and materials destined to be assembled to the product at assembly work station A_k will be assigned the assembly address A_k as part of its component structure within the product Bill of Material.

The takt time of the production line is determined by the Production Planning team and is balanced against the demand for the product and the rate at which the product can be built comfortably by the assemblers.

The Production Planning team determine the time in the production calendar when a specific product unit will complete assembly – the point where the product leaves the final Assembly Address An. Relative to the planned completion time or 'Assembly Off' time, given that each assembly work station is a consistent distance from each other, the assembly takt time determines the time when assembly components and materials are required at specific workstations as defined within the product Bill of Material.

Certain material handling or logistic process times are known. For example, the time to move components from a warehouse through various picking and routing processes will have been calculated. Therefore a specific time components are required to be delivered to a warehouse are known. A supplier knowing the time it takes to deliver their products to a customer knows when it is necessary to dispatch their order requirements.

This description is a simplified view of the material flow process to satisfy product build requirement, but it captures the essence that material flow is based on three interlinked factors. Firstly, the time the product is due its final assembly operation (this acts as a datum for the whole delivery process). Secondly, the assembly takt time, as relative to the planned completion time, the takt time determines when the product passes through each assembly work station. Finally, the product Bill of Material specifies the address of the Assembly Workstation where each component will be fitted.

However, in reality, most components are delivered to the assembly work stations in batches defined by how many components will fit into a container. The number of containers delivered to a workstation may only contain components that will satisfy a few hours production. Certain key components may be delivered one at a time directly from the supplier to a workstation synchronised to fit to a specific product. Suppliers may deliver once a day or several times a day or even weekly into their customer's warehouse. The frequency of supplier delivery into a customer warehouse will be dependent on factors such as demand, the container quantity and size of component.

That said, within this process the flow of inventory into the assembly lines is balanced toward the build requirements of the assembled product. Essentially, there is a one to one correspondence between the build plan and the flow of material into the assembly system. There is no safety stock in the system. The reason there may be several hours worth of inventory at a given workstation is because it is impractical to deliver smaller and more frequent deliveries. That several hours of inventory is not for protection against possible rejects or failure to supply – the inventory is assigned to a build requirement. Any rejects will have to be replaced by the supplier immediately.

This system of delivery, though in essence is a Just in Time system, it is better thought of as ‘Timed Delivery System’. Components and materials arrive at their designated assembly stations timed to the requirements of the assembly plan.

Case Study 2: Batch Manufacturing.

Lean manufacturing attempts to instil flow manufacturing based on the pull of customer demand. The goal is to implement stockless production that enables batch sizes of one. The achievement of this goal is potentially attainable in flow systems as characterised in Case Study 1.

However, some classes of manufacturing processes require that the production resource (usually a machine or series of machines) is dedicated to making a range of (usually similar) products. Under such conditions it is necessary to make a batch of one product before changing over the machine to make another product. For machines where the natural production rate is far in excess of the demand of the final product, it is impractical to dedicate the machine to the production of a single component, hence a range of components are made in pre-determined batch sizes.

The batching process requires some thinking. Too large a batch consumes excess machine time, storage space and containers and it is more difficult to maintain the product quality of large batch production. Too small a batch increases the frequency of machine change overs and compromises production efficiency. The batch size quantity for a specific component is dependent on multiple factors including demand for the part, required number of containers, storage space, the production rate of the machine and change over times. To illustrate the type of thinking required to identify a suitable batch, the application of automobile body panel manufacturing is considered.

Automobile body panels are generally manufactured on large presses in which are fitted press tools (referred to as ‘dies’) that through the press stamp out the required shape of the panel. Due to the complexity of a panel’s shape, the forming of the panel may need several pressing operations to achieve the final shape.

The Press Shop under review was built in the 1950’s was and originally characterised by a series of press lines dedicated to the manufacture of complete sets of body panels to cater for the build requirements of a variety of vehicles. Operation of the press lines was purely manual with tool change over times ranging from several hours to two to three days. By the end of the millennium, the lines had been converted to automatic operation with tool change over time reduced to between 15 and 30 minutes.

Additionally new pressing technology had been introduced in the 1990’s to include state of the art transfer presses. These large presses afforded complete automation coupled with tool change times of less than five minutes. Previous methods of batch size calculation based on economic lot sizing did not necessarily apply to such machines. Change over times, for example were so fast that their cost could not be quantified as an input to a lot sizing model. An alternate approach was to base the batch size on maintaining an efficient operation of the machine. Achieving the required machine efficiency determined the batch size. The bench mark to determine efficiency was taken from the ‘Harbour Report’ an annual publication published in North America that assesses automotive manufacturing efficiency (Harbour Associates). In the early 1990’s the Harbour Report benchmarked World Class transfer press manufacturing capability post set up time as 15 production strokes per minute at 70% efficiency giving a net rate of 10.5 production strokes per minute. Given a die change time of 5 minutes, the following graph in Figure 3.14 is obtained that illustrates the efficiency obtained for a given run length.

Beyond a run length of 1500 panels there is a limited efficiency gain on choosing a greater run length. Initially run length batch sizes were set at 2200 panels as this covered 2.5 days of customer demand. The 2.5 day run length allowed sufficient time for the tool engineers to carry out between run tooling maintenance and for the tool change team to carry out automation maintenance dedicated to the specific panel.

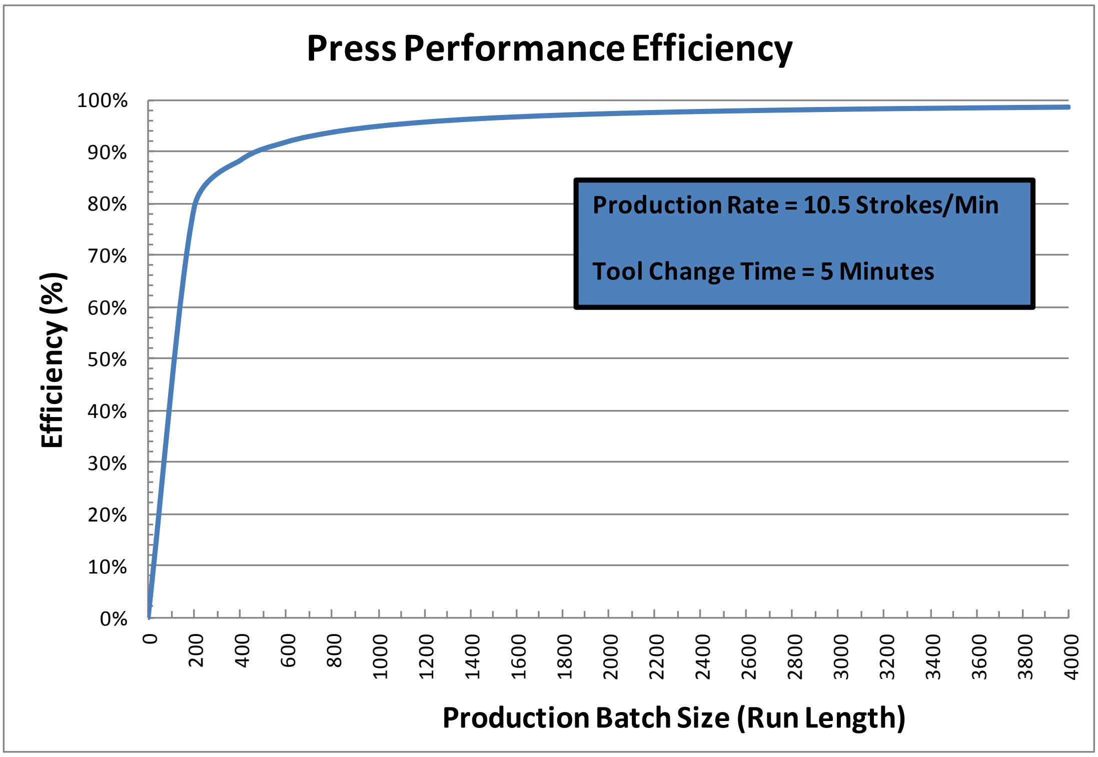


Figure 3-14 Press Performance Efficiency Related to Batch Size

Though the production planning was managed through an MRP system, the speed of production meant that the MRP system lagged behind the actual state of production. Consequently, the planning was spread sheet based, with the MRP system used to provide production run numbers, identify medium term capacity requirements and calculate the order requirements for the steel to make the body panels. The steel delivery schedule into the pressing facility was calculated by the production planner based on the press production plan. Steel was called in daily and at most one day ahead of the blanking plan. Essentially, press runs were scheduled to occur when there was less than half a day’s finished panel stock in the store providing there was a requirement for the panel. The blanking plan (the operation to make the basic flat shape of the panel form a steel coil) worked off the press plan to ensure that blanks were available at least one production shift ahead of the press requirement. The steel call off schedule was based on the blanking plan and ensured that steel arrived in the coil store at most one day ahead of requirement and frequently within one shift of the part undergoing the blanking operation.

The rationale behind the batching process was to ensure minimum levels of inventory across the three discrete stages of inventory holding, finished panels, available blanks to feed the press lines and available coils to feed the blanking press. The trigger for production is through reaching a minimum level of safety stock for a panel (providing there is a requirement for the panel); consequently inventory is pulled through the system to meet demand. Though overall production management is controlled through a MRP system, the MRP configuration is never allowed to push unnecessary inventory into the manufacturing system.

The two case studies illustrate contrasting manufacturing configurations, namely flow and batch manufacturing. Within the flow system, through creating a datum point that defines when a product assembly build is completed and combined with the assembly takt time and product bill of material, the delivery timings of assembly components and materials is known at each assembly location. Consequently the delivery of inventory into production is timed to the assembly plan. Other than inventory held at an assembly station, due to the practicalities of delivering components and container requirements, there is no safety stock within the supply chain. This places a significant responsibility on suppliers to deliver quality fit for purpose products on time in the quantities required and on the assembler to ensure that their logistic management systems manage the internal flow of inventory. Though a matter of semantics, this method of inventory management is more accurately described as a timed delivery system that supports manufacturing flow rather than a JIT system.

The JIT concept of manufacturing more accurately describes batching method of manufacturing. Within the case study panels are manufactured Just in Time relative to reaching a minimum inventory figure. That trigger pulls the requirement for blanks ready for the panel pressing operation. The blanking requirement pulls the delivery of steel in time for the blanking operation.

3.6. The Application of Lean Principles to Non-Manufacturing Applications

Since the formulation of lean principles by Womack and Jones (1996), the dissemination of the principles has found diverse application beyond the confines of traditional manufacturing. The adoptions of the lean principles are not ad-hoc implementations or just bland copies of the TPS to purely cut costs but as a structured and strategic implementation to ensure a competitive and cost effective delivery of customer value. Lean initiatives in a number of sectors have been so extensive that sector wide bodies have evolved to conduct research and support the education and training of people within their respective sectors and to disseminate and share best practice. Significant sectors include:

3.6.1. Aircraft Construction

Lean Aerospace Initiative (LAI): formed in the USA in 1993 to investigate the potential of deploying TPS best practice beyond automotive manufacturing into the aircraft construction industry. The LAI is a consortium of industrial, government, labour unions and academic representatives.

The motivation for the creation of the LAI was threefold (Murman et al, 2002):

1. Consolidation of industries due to the end of the cold war.
2. Declining defence budget (military sector).
3. Global competition (commercial sector).

UK Lean Aerospace Initiative (UKLAI) is primarily a research based consortium of UK academic institutions headquartered at Bath University and supported by the Society of British Aerospace Companies (SBAC). The UKLAI collaborates with the USA Lean Aerospace Initiative.

The implementation of lean principles has become a core strategy of global aircraft manufactures including Boeing in the USA (Leitner, 2014). In Europe, Airbus Industries consider lean manufacturing as a ‘Proven Concept in Manufacturing’ and have developed the Airbus Lean Production System (ALPS) to help their goal in securing global leadership of the aircraft construction industry (Airbus, 2014).

3.6.2. Shipbuilding

Lean Shipbuilding Initiative (LSI): A division of the National Shipbuilding Research programme, a collaboration of Shipyards in the USA with a goal of reducing costs and applying best manufacturing practice for ship construction.

The original motivation of adopting lean practices was to mitigate declining sales and become more competitive with Korean constructors (Lang et al, 2001). Lean principles continue to be applied and developed within the management of USA ship yards to increase productivity, (Kolic et al , 2012).

3.6.3. Building Construction

Lean Construction Institute (LCI): Founded in 1997 in the USA to apply lean techniques in construction primarily to ensure projects were completed on time and within budget. The focus of the LCI is the improvement of project management, moving from a centralised scheduled push management to localised flow based on pull generated by achieving project milestones.

The adoption of lean principles within the construction industry is seen as a response to counter a recognised decline in the global construction industry. Koskela (1997) identified problems endemic within the European construction industry including low productivity, poor safety records, inferior working conditions and insufficient quality and proposed the adoption of lean principles as a means to reverse the decline.

Consistent with the aims of the LCI, Aziz and Hafez (2013) contend that lean construction is achieved through project control, concurrent design and improving performance at the project delivery level.

In the United Kingdom, the influence of lean principles in the construction industry began with a British Government sponsored report (Egan, 1998) which recommended the adoption of lean principles in the construction industry to improve efficiency. A second report (Egan 2002) reflected on the success of the initiative reporting improvements along 12 key performance indicators including an increase of some 23% in service satisfaction and 16% in product satisfaction.

3.6.4. Healthcare

National Health Service (NHS) Institute for Innovation and Improvement: Set up in 2005 to transform the NHS through innovation, improvement and adoption of best practice. The institute adopted a range of traditional industry wide applied change management techniques and promoted the application of lean principles to improve the service of healthcare to patients. The institute closed in 2013, transferring the responsibility for on-going improvement to the NHS commission (NHS, 2014). Complimentary lean education programmes are also provided by the Lean Health Academy a consortium of a number of NHS Trusts that promotes the application of lean principles in healthcare.

Primarily lean in healthcare is about the provision of enhanced patient care through maximising patient flow through the hospital system by eliminating waiting time between medical procedures. Healthcare professionals recognise that lean in healthcare is at an early stage but has the potential to eliminate wasteful practices (de Souza, 2009).

Each of the above sectors is radically different with respect to their activities. Why then are lean principles relevant to such diversity of application? The lean principles are not about the manufacturing process or the service delivery process. The principles are about identifying the impediments to producing the product or delivering the service and subsequently removing them.

3.7. Alternative Approaches to Manufacturing Management

Parallel to the emergence of lean manufacturing within western manufacturing, alternative approaches to creating competitive manufacturing structures have been promoted to enhance competitiveness and customer focus. Two such approaches are Holonic and Agile manufacturing. Holonic systems strive to create an autonomous but highly cooperative structure while agile systems focus on the ability to respond to the changing needs of consumers.

3.7.1. Holonic Manufacturing Systems

Holonic manufacturing systems emerged as an approach for designing and operating autonomous, flexible and interchangeable manufacturing modules referred to as holons (Botti and Boggino, 2008). The focus of the approach is to create a manufacturing infrastructure to support low volume high variety products, combined with an agility that enables a rapid response to change in market requirements. A holon is defined as an autonomous unit that simultaneously and seamlessly interacts and communicates with a wider environment. The concept of a holon is attributed to Arthur Koestler, a philosopher who recognised that many natural and man-made systems exist autonomously and independent while simultaneously being part of a larger organisation. Koestler derived the term holon from the Greek word ‘holos’ meaning ‘whole’ combined with the ending ‘on’ taken from the proton to imply that the entity is a particle.

Within a manufacturing environment, holons are agents that carry out specific tasks. Examples include planning holon, delivery holon, and production holon and so on. The holons are the control technology of the system and behave as autonomous and cooperative agents, providing flexibility, adaptability, agility, and dynamic reconfigurability.

The origins of the holonic approach are due to the ‘Intelligent Manufacturing Systems (IMS)’ collaboration programme for research and development on new manufacturing paradigms in the early 1990’s. The IMS project was initiated in Japan by Professor Hiroyuki Yoshikawa and involves international collaboration between the USA, Canada, the EU, Australia and Switzerland (Kusuda, 1998).

McFarlane and Bussmann (2003) define the following key attributes of a holonic system as:

- **Autonomy**: the capability of a manufacturing unit to create and control the execution of its own plans and/or strategies (and to maintain its own functions).

- **Cooperation**: the process whereby a set of manufacturing units develop mutually acceptable plans and execute them.

• **Self organisation**: the ability of manufacturing units to collect and arrange themselves in order to achieve a production goal.

• **Reconfigurability:** the ability of a function of a manufacturing unit to be simply altered in a timely and cost effective manner.

The ethos of the holonic approach is to replace rigid, static and hierarchical manufacturing systems by systems that are more adaptable to rapid change, allowing manufacturers to respond to specified customer demands with small production lot sizes and a low costs base. The holonic architecture comprises autonomous ‘agents’, or holons, that have inherent intelligence. The inherent intelligence implies the holon has the necessary resource and expertise to govern itself while cooperating and communicating freely with other holons.

Holonic systems are concerned with the structure of the manufacturing system while maintaining customer focus through the ability to rapidly meet the ever changing needs of the customer. In essence holonic manufacturing is a ‘pull system’ based on small lot sizes triggered by customer demand, while maintaining a low cost base. The original rationale of the holonic approach still remains the consistent theme as illustrated by (Christensen, 1994) to a move from hierarchical systems of management to one of mutual co-operation (Figure 3-15) .

3.7.2. Agile Manufacturing

The Agile Manufacturing model emerged from work conducted at the Iacocca Institute at Lehigh University in Pennsylvania, USA in 1991, with publication of a report ‘21st Century Manufacturing Enterprise Strategy’, (Kidd, 1994). From the Iacocca report, Kidd states that three main points are made that form the basis of an understanding of what constitutes Agile Manufacturing:

1. A new competitive environment is emerging, which is acting as a driving force for change in manufacturing.

2. Competitive advantage will accrue to those enterprises that develop the capability to rapidly respond to the demand for high quality, highly customised products.

3. To achieve the agility that is required to respond to these driving forces and to develop the required capability, it is necessary to integrate flexible technologies with a highly skilled, knowledgeable, motivated and empowered workforce. This must be done within organisational and management structures that stimulate cooperation both within and between firms.

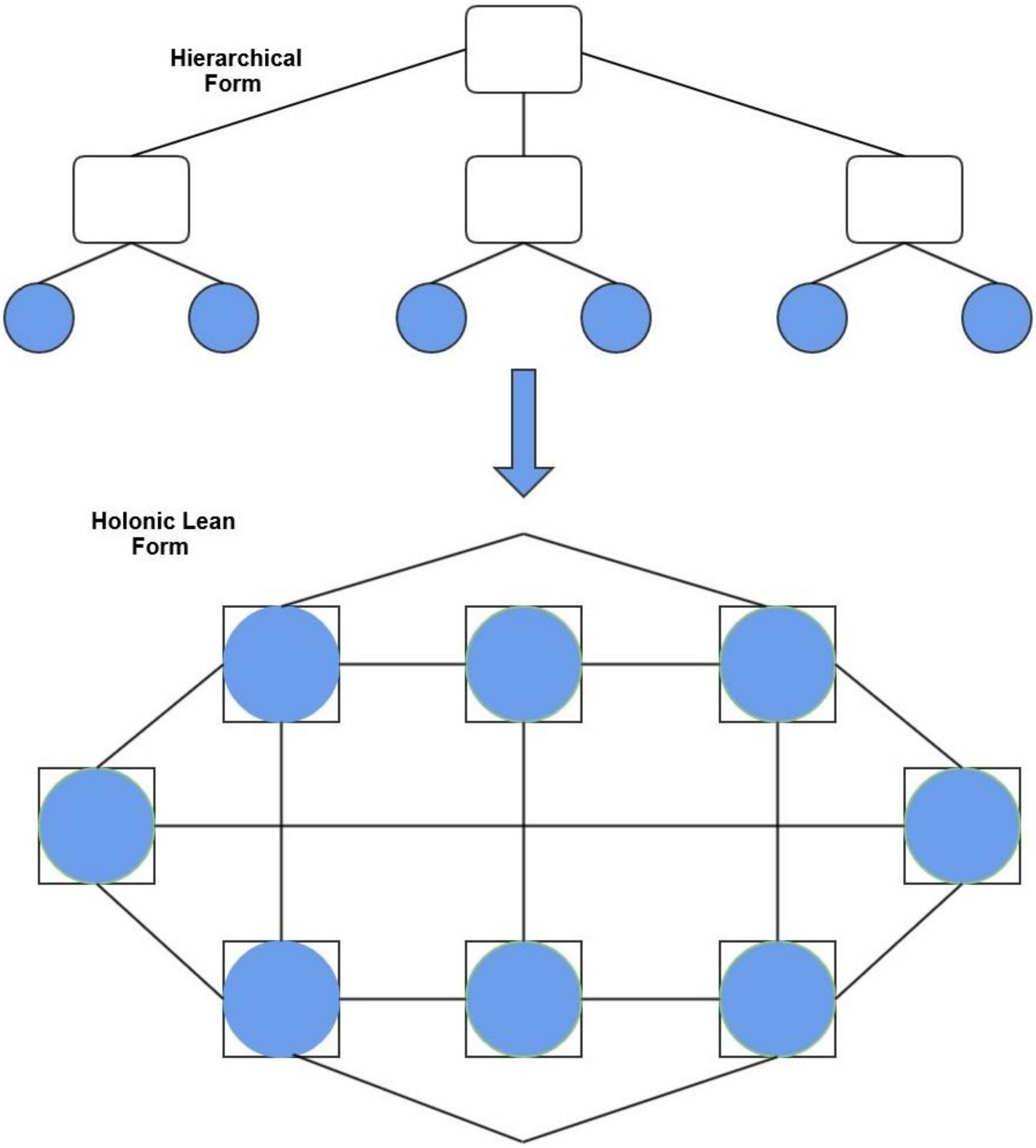


Figure 3-15 Hierarchical and Holonic Architectures (Christensen, 1994)

With regard to these points Agile Manufacturing can be considered in terms of a structure that:

- Within which, a company can develop business strategies and products;
- Is supported by the integration of three primary resources:

1. Innovative management structures and organisation;
2. A skill base of knowledgeable, motivated and empowered workforce;
3. Flexible and intelligent technologies.

Within this construct, agility is the ability to respond rapidly to changing market conditions through continuous change, quality improvement and social responsibility to both the environment and employees.

Kidd contends that the lean model is a necessary condition for an agile company, though the converse does not necessarily apply. Agile companies are capable of entering niche markets rapidly and are able to cater for the specific needs of ever more demanding customers on an individual basis (Robertson and Jones, 1999). A purely lean company is not necessarily capable of replicating this ability.

Christopher and Towill (2001) comment that lean manufacturers do not necessarily possess agile supply chains. They comment on the ability of car manufacturers to efficiently produce a car in less than 12 hours through final assembly, having some two months of finished stock with customers still having to wait weeks or even months to collect the car of their choice. Naylor *et al* (1999) suggest that the lean and agile models should be viewed as complementary systems and state that it is the nature of the supply chain will determine which model will dominate.

3.8. Concluding Remarks

The lesson from the decline of mass production indicates an essential human activity can, if not, managed correctly have devastating consequences. Manufacturing is an essential activity from an economical perspective and for sustaining people's needs. But manufacturing has to be ‘done well’. The objective of a lean production system is to ensure that manufacturing is ‘done well’ and is also aligned to the value needs of the customer. It is the ability to maintain the lean system while still providing value to the customer that is the basis for long term survival.

Of the lean principles, the principle of customer perceived value is the most subjective. Beyond the necessity of a product or service meeting basic functional requirements, what constitutes value can differ widely across the customer base. Through advances in technology, manufacturers are able to offer customers a wider variety of product attribute. As a consequence, customers are increasingly becoming more demanding and expecting greater value for money. The challenge for manufacturers and service providers is to maintain an alignment to the evolving needs of their current and potential future customers and so deliver both customer and internal value.

Lean principles bring to manufacturing, industry in general, commerce, healthcare, and construction, a system of thinking that focuses a mind set to solve problems, break down barriers through the application of tools and methods that have proved effective in improving process flow. Lean thinking involves creating the organisational structure to eliminate waste and exceed customer expectations.

The essence of why the lean principles apply to these diverse applications across industry, commerce and healthcare is that the fundamental problems the applications are experiencing are no different to the problems faced by the post war Toyota Company or experienced by Western manufacturers - essentially all industries, commercial, and service or administration experience impediments to conducting their activities.

4. Manufacturing System Analysis

4.1. Introduction

At the operational level lean manufacturing systems are in principle designed to flow. The ability for a lean system to flow is as much due to the efforts of shop floor practitioners establishing best practice and implementing improvement programs as it is to senior managers and executives creating a lean culture as a central theme within their overall corporate and manufacturing strategies. It is not a requirement that a lean system flows as fast as possible. Rather, flow is either synchronised to the rate of demand or maintained at an optimum level where demand is greater than the available rate of supply. Additionally, where demand outstrips the ability to supply, consideration can be given to providing further capacity. The nature of the additional capacity is dependent on the demand profile of the product and can range from adding overtime, increasing the number of shifts worked, upgrading production facilities, to the addition of new production lines or even new factories.

Though the effectiveness of a lean system can be assessed through how well the system flows, lean systems are also characterised by the amount of resource used to maintain flow. Since lean systems seek to minimise the consumption of resources, a complete analysis of a lean system should include an assessment of the lower bound of resource consumption required to maintain flow.

Since the introduction of Scientific Management at the turn of the 20th century when Frederick Winslow Taylor would develop time and motion studies to understand the best way to carry out work tasks, a wealth of analytical methods have evolved to study manufacturing systems. Succinctly, the array of methodologies shares a common theme: to provide manufacturing stakeholders with knowledge and understanding of the underlying behaviour of manufacturing systems. The purpose of developing system knowledge and understanding is to provide a foundation for system improvements and enhancements and reconfiguration of systems to satisfy emerging market trends (Gershwin 1993).

Within this chapter the prevalent analytical methods applied to model and assess manufacturing systems are evaluated with specific reference to modelling lean manufacturing systems.

The methodologies assessed are:

Regression Analysis

Regression analysis is a widely applied statistical method and is the study of the variation of a dependent variable subject to the influence of one or more explanatory or predictor variables. The study of regression emerged from the early studies of Sir Francis Galton while investigating the relationship between the offspring seed weights of sweet peas with the parent seed. Galton would later apply the methods to the study the heredity relationship between the heights of fathers and sons utilising the method of least squares (Daly et al, 1995).

Care must be taken in using regression analysis as to the choice of variables as it is possible to create relationships between variables that have no real physical relationship. Montgomery and Runger, (2007) contends that the only way to determine cause and effect relationships is through designed experiments. Care should also be taken in extrapolating results as frequently the results are only applicable over the range of the explanatory variables. As model extrapolates beyond the range of the predictor variables, the predicted results are less certain.

Design of Experiments

Statistical methods have been utilised to understand variation in manufacturing processes since the 1920’s with the development of statistical control charts by Dr W. A. Shewhart. Manufacturing systems by nature have inherent variability. The Shewhart control chart are used to monitor processes and will indicate if a process is moving out of a state of statistical control. Design of Experiments (DOE) methods applies a broader range of statistical methods to investigate the effect of the underlying system variation on measurable system outputs. The advantage of the DOE approach is that knowledge of system behaviour due to variation can be gained even though the system is functioning within designed parameters and is within statistical control. Further multiple inputs and their interactions into a process can be simultaneously assessed as to their effect on the system outputs.

A designed experiment is one where the investigator controls the levels of the inputs of interest into a process and determines how the measured output response accordingly varies, (Antony, 2003).

The potential of applying DOE methods to the analysis of lean manufacturing systems lies in the measuring the effect on the system of varying measurable inputs of the resources consumed by the system (facilities, manpower, hours worked) and factors such as set up times, frequency of tool changes, and production run lengths.

Taguchi Design of Experiments

During the 1950’s, Genichi Taguchi, a Japanese engineer and statistician developed statistical methodologies to improve the quality of manufactured products. The emphasis of Taguchi’s methodology is based on understanding the ‘functional variation’ as applied to metrics relating to product performance such as strength, pressure, response time and mean time between failures, (Peace 1993). The purpose of the Taguchi methodology is not dissimilar to the classic Design of Experiments in that the key factors that have the greatest contribution to variation are identified and the conditions that ascertain the least variation are derived.

The Taguchi method is product centred in that the method seeks to ensure that products perform consistently within their design parameters with minimal effect from uncontrollable operating conditions. Equally, the method is also process centred ensuring that manufacturing processes produce consistently good products that are unaffected by uncontrollable manufacturing influences. A key measure in the Taguchi approach is the concept of the ‘Loss Function’ which applies a measure as to the cost of deviations from quality targets. The Taguchi approach is holistic in the sense that the both the quality of the product and the method of production is assessed with the addition that the cost of deviation from target is understood.

The potential of the Taguchi methods to assessing lean systems is directly applicable to deriving customer perceived value and in terms of minimising resources. Minimising resources beyond a given threshold could affect the robustness of the manufacturing process that results in reduced product quality that should manifest itself through the Loss Function.

Operational Research Methods

There is no apparent agreement of what constitutes a succinct definition for Operational Research (OR) within the subject literature. Such lack of definition according to Saaty (2004) produces both bad and good effects. Bad in that an aura of mystery has grown up around the name and good in that the discipline is not confined to a specific domain meaning that contributions to OR have come from a wide variety of sources.

OR though does involve the application of applying advanced analytical methods to aid managers make better decisions. Two key methodologies within OR are Queuing Theory and Mathematical Programming (optimisation).

Queuing theory is applied to the design of manufacturing facilities with respect to understanding the rate at which work arrives and leaves at a given work station. Applied to a network of work stations, queuing theory can aid determining the layout of the network and the required number of work stations and inventory buffers that are necessary to ensure steady state flow through the system.

Mathematical programming methods seek to maximise or minimise some objective subject to a set of constraints. Typically, throughput, production efficiency and profit are objectives that are maximised while cost and scrap are examples of objectives that are minimised. Examples of constraints may be the number of people, available space and budgets.

Both of these methods have potential contributions to the analysis of lean systems from the perspective of flow and optimising resource allocation.

Hybrid Systems

Hybrid systems model dynamic systems that exhibit both continuous and discrete states. Continuous assembly production lines flow but at defined points in the production line, the flow can stop for a short period to allow for the assembly operation to take place. At assembly stages where the line does not stop, parts arrive at discrete intervals. Assembly lines are therefore an interaction of continuous and discrete elements.

The potential of hybrid system modelling to lean system analysis lies in the contribution the technique can make to understanding system flow. The approach is possibly more significant where there is a high degree of automation. The interaction between the continuous and discrete elements of the system cannot be compensated for by the manual intervention of people.

4.2. Regression Analysis

The most basic case of linear regression models the relationship with a single predictor variable x called the regressor variable and a dependent or response variable Y. The model is often referred to as Simple Linear Regression. The properties of the simple regression model are easily understood and serve to explain many properties of the multi-dimensional counterpart.

The relationship is assumed to follow a linear relationship where:

$$Y = \beta_0 + \beta_1 x + \varepsilon \tag{4.1}$$

The intercept of the relationship is defined by β_0 and the gradient by β_1. The term ε is a random error term that is assumed to have a mean of zero and constant but unknown variance σ^2. Due to this assumption, the expected value and variance of Y for a fixed value of x is respectively given by:

$$E(Y \mid x) = E(\beta_0 + \beta_1 x + \varepsilon) = \beta_0 + \beta_1 x + E(\varepsilon) = \beta_0 + \beta_1 x$$

$$V(Y \mid x) = V(\beta_0 + \beta_1 x + \varepsilon) = V(\beta_0 + \beta_1 x) + V(\varepsilon) = 0 + \sigma^2 = \sigma^2$$

The regression model is a line of mean values where such that:

$$\mu_{Y|x} = \beta_0 + \beta_1 x$$

Thus the height of the regression line at any value of x is the expected value of Y at that x. The gradient β_1 is interpreted as the change in the mean of Y for a unit change in x. Moreover, the variance of Y at a given value of x is determined by the error variance σ^2. Consequently, there is a distribution of *Y*-values at each *x* such that the variance of the distribution is the same at each *x*. The regression coefficients are calculated through the method of least squares (Montgomery and Runger, 2007) where the regression coefficient estimates $\hat{\beta}_0$ and $\hat{\beta}_1$ are given in Table 4.1.

$$\hat{\beta}_0 = \bar{y} - \hat{\beta}_0 \bar{x}\,, \quad \hat{\beta}_1 = \frac{\sum_{i=1}^{n} y_i x_i - \frac{(\sum_{i=1}^{n} y_i)(\sum_{i=1}^{n} x_i)}{n}}{\sum_{i=1}^{n} x_i^2 - \frac{(\sum_{i=1}^{n} x_i)^2}{n}}\,,$$

$$\text{Where} \quad \bar{y} = (1/n)\sum_{i=1}^{n} y_i \text{ and } \bar{x} = (1/n)\sum_{i=1}^{n} x_i\,.$$

Table 4-1 Least Squares Coefficients

A simple regression model is visualised through a scatter plot with a fitted line of best fit. One such model is illustrated in Figure 4.1 where a scatter plot is constructed for illustrates a scatter plot for randomly generated data (Using the Micro Soft Excel Rand function).

X	Y
4.69	11.67
9.38	15.86
9.41	14.89
4.78	9.81
6.38	9.39
5.68	8.11
1.01	3.84
8.71	19.76
4.69	14.30
1.21	4.51
1.17	1.87
1.69	6.11
0.87	3.95
0.83	6.29
2.72	8.25
9.62	20.91
0.22	0.56
9.85	18.69
2.08	0.55
1.91	7.19

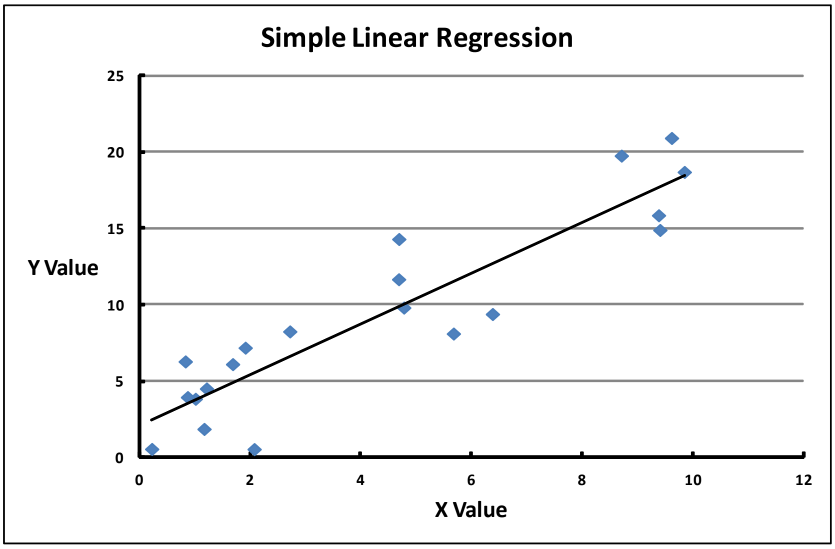


Figure 4-1 Scatter Diagram with Line of Best Fit

The calculation of the regression coefficients are generally carried using a computer statistical software package. Table 4.2 returns the Minitab analysis for the data in Figure 4.1.

```
Regression Analysis: Y versus X

The regression equation is
Y = 2.10 + 1.66 X


Predictor    Coef  SE Coef     T      P
Constant   2.1036   0.9584  2.19  0.042
X          1.6617   0.1742  9.54  0.000


S = 2.62872   R-Sq = 83.5%   R-Sq(adj) = 82.6%


Analysis of Variance

Source          DF      SS      MS      F      P
Regression       1  628.83  628.83  91.00  0.000
Residual Error  18  124.38    6.91
Total           19  753.21
```

Table 4-2 Regression Analysis Output

The analysis presented in Table 4.2 is a test of the Null Hypothesis that the regression coefficients of the fitted model have no effect on the response variable. This is verified in a number of ways:

P value: The P value is the smallest level of significance that would lead to the rejection of the null hypothesis with the given data.

T distribution value: Are low for non-significant values, high for significant values.

F value: In the Analysis of Variance Table - low for non-significant values, high for significant values. Some statistical packages return the F Test critical value.

The Analysis of Variance Table indicates through the F and P values if the model has a regressive effect on the response variable, while the Table of coefficients determines which coefficients are significant.

The R-sq value returns the value of the square of the correlation coefficient between the response and predictor variables. The R-Sq(adj) or adjusted value is a modification of the R-sq. value that adjusts for the number of explanatory terms in a model. The R-Sq(adj) increases only if the new term improves the model more than would be expected by chance. The R-Sq(adj) can be negative, and will always be less than or equal to R-Sq.

With respect to the output in Table 4.2, the model was run at the 0.005 significance level. Therefore, a regressor is significant if $P < 0.005$. The regressor *x* is significant as $P = 0$ to three decimal places. The intercept is not significant and has no effect on the value of the response variable.

Further integrity of the model is determined by studying the distribution of the residual values which for a valid model will be normally distributed. This is generally determined by inspecting plots of the residual values. The residual value plots for the fitted model are provided by the Minitab software and shown in Figure 4.2. The Normal Probability Plot should show no curvature of the plotted point – minor deviations from the line are acceptable.

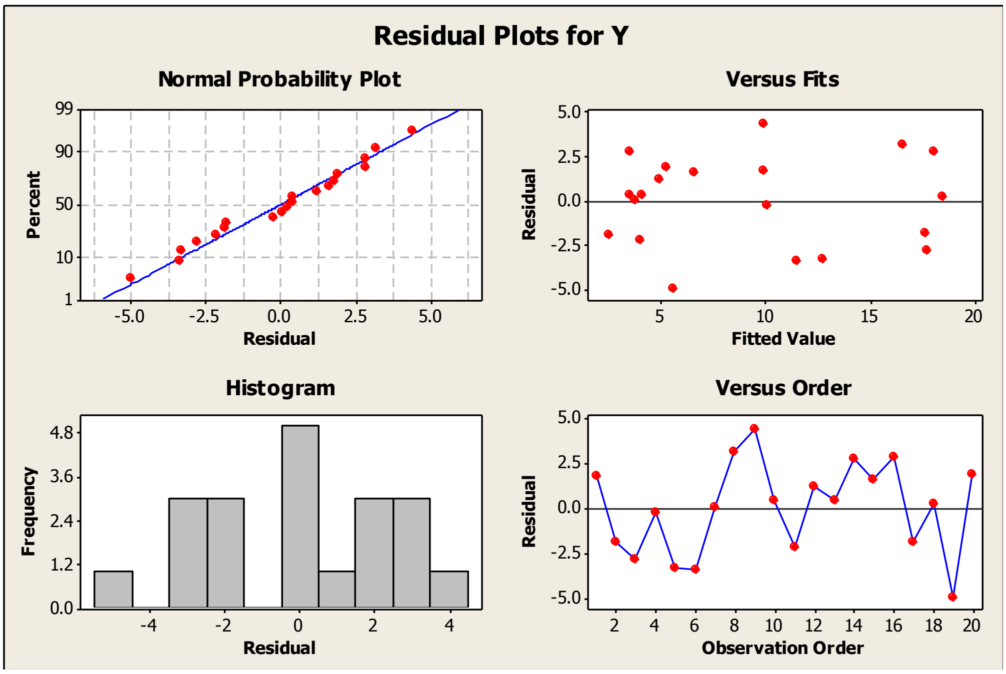


Figure 4-2 Residual Value Plot for Regression Output

If the variance of the residual distribution is not constant, the Versus Fits plot would show a pattern. Moreover the Histogram would show some skew, the Versus Order plot would also show some pattern effect. The distribution of residual values in Figure 4.2 does not show any serious departure from normality – indicating the model is robust. Individual data points that do significantly deviate from normality will be listed as ‘unusual observation’ in the regression output analysis.

The multidimensional counterpart is referred to as Multiple Linear Regression, and is defined by:

$$Y = \beta_0 + \beta_1 x_{1i} + \beta_2 x_{2i} + \cdots + \beta_k x_{ki} + \varepsilon \qquad (4.2)$$

The model defined in Equation 4.2 is analysed in exactly the same way as for Equation 4.1. The line of best fit in the two dimensional case gives way to a (*n*-1) hyperplane of best fit in *n*-dimensional space.

4.3. Design of Experiments

Variation is an inherent feature of both manufactured products and the manufacturing systems that produce the products. Design of Experiments (DOE) or Experimental Design is an approach to understanding system variation and provides a robust approach to both product and process improvement (Montgomery, 2009). Furthermore, DOE provides powerful capabilities for exploring new processes and gaining new knowledge about existing processes. Within process improvement, DOE provides additional statistical functionality that complements traditional Statistical Process Control methods based on ‘Control Charts’. When a process is discovered to be out of control, DOE methods can be used to identify the influential process variables and so aid bringing the process back into control.

Montgomery (2012) defines Statistical Process Control (SPC) as a passive statistical method. Under SPC a process is monitored until some change is observed that will lead to some investigation of the process. If, however there is no change and the process remains within statistical control, the continued observations do not yield any further information as to the inherent variability of the process. Experimental Design, alternatively, is an active statistical method. Controlled tests are carried out on a process where changes are made to the process inputs while observing the corresponding changes to the process outputs. An understanding of the inherent variability of a process emerges, even for processes that are functioning correctly within specified parameters. The ability of the DOE method to ‘visualise’ process variability provides the foundation of the method to enhance knowledge of the behaviour of manufacturing systems and system behaviour in general.

DOE methods emerged from the work in the 1920's of the English statistician Ronald Aylmer Fisher who conducted research into crop yields at the Rothamsted Agricultural Experimental Station. In his studies in attempting to understand the underlying causes for crop yield variation, Fisher began the development of a collection of statistical techniques that he would publish over the coming years including in 1935 his work, 'The design of experiments', (Fisher, 1935). Consequently the analytical and statistical methods that have emerged through the influence of Fisher's work are captured within the discipline of 'Design of Experiments'.

Within DOE a process is considered as a transformation mechanism that takes one or more measurable and qualitative inputs to produce one or more measurable outputs (response variables). A process model is visualised in Figure 4.3 (Montgomery, 2009).

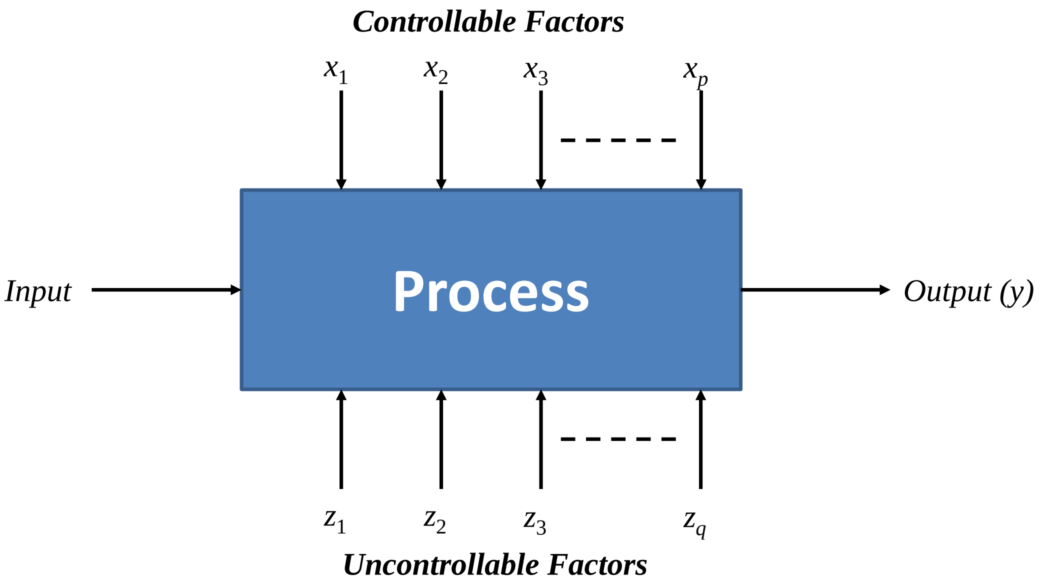


Figure 4-3 Basic Model Process (Montgomery, 2009)

Acting on the process is a series of both controllable and uncontrollable factors that influence the value of the response variables. For a given experiment only one response variable is considered. In a manufacturing process, the response variable of interest may be the production rate per unit time. So experiments are conducted that consider how the inputs and factors affect the production rate. A further set of experiments may consider how the same set of inputs and factors affect other measurable outputs and could include a product dimension, the rate of scrap, or energy consumption.

4.3.1. The Analysis of Variance (ANOVA)

To understand how the variation within a process affects the response variable, Fisher developed the statistical method of ‘The Analysis of Variance’ (ANOVA) that decomposes the overall variation within a process to its source components. The most basic application of this method is the One-Way ANOVA which considers the effect of a single factor or treatment applied at several levels to a process. The underlying theory of the One-Way ANOVA process extends to more complex processes where the variation is subject to multiple factors (Factorial Designs) or observations that need to be partitioned into groups that have similar characteristics (Block Designs).

4.3.1.1. Single Factor One-Way ANOVA

Table 4.3 illustrates the general case of recording *n* observations of a process consisting of *a* treatment levels providing $N = na$ observations.

Treatment Level	Observations						Totals	Averages
1	y_{11}	y_{12}	…..	y_{1j}	…..	y_{1n}	$y_{1\bullet}$	$\bar{y}_{1\bullet}$
2	y_{21}	y_{22}	…..	y_{2j}	…..	y_{2n}	$y_{2\bullet}$	$\bar{y}_{2\bullet}$
•	•	•	…..	•	…..	•	•	•
•	•	•	…..	•	…..	•	•	•
i	y_{i1}	y_{i2}	…..	y_{ij}	…..	y_{in}	$y_{i\bullet}$	$\bar{y}_{i\bullet}$
•	•	•	…..	•	…..	•	•	•
•	•	•	…..	•	…..	•	•	•
a	y_{a1}	y_{a2}	…..	y_{aj}	…..	y_{an}	$y_{a\bullet}$	$\bar{y}_{a\bullet}$
							$y_{\bullet\bullet}$	$\bar{y}_{\bullet\bullet}$

Table 4-3 General Observation Structure: One Way ANOVA

Each observation y_{ij} can be expressed as a deviation from an overall process mean μ due to a combination of a treatment effect τ_i, and random error, ε_{ij} such that:

$$y_{ij} = \mu + \tau_i + \varepsilon_{ij} \qquad \begin{array}{l} i = 1, 2, \ldots.., a \\ j = 1, 2, \ldots., n \end{array} \tag{4.3}$$

where it is assumed that $y_{ij} \sim N(\mu + \tau_i, \sigma^2)$ and $\varepsilon_{ij} \sim N(0, \sigma^2)$.

The total variability of the system is given by the totalling the squared deviation of each observation y_{ij} from the overall or grand mean of the output defined by $\bar{y}_{..}$. The variability is defined as the 'total sum of squares' or SS_T:

$$SS_T = \sum_{i=1}^{a}\sum_{j=1}^{n}(y_{ij} - \bar{y}_{..})^2 = n\sum_{i=1}^{a}(\bar{y}_i - \bar{y}_{..})^2 + \sum_{i=1}^{a}\sum_{j=1}^{n}(y_{ij} - \bar{y}_{i.})^2 \tag{4.4}$$

The Right Hand Side of Equation 4.4 is referred to as the fundamental ANOVA identity and partitions the variation of the observations as defined in Table 4.3 and is symbolically expressed as

$$SS_T = SS_{\text{Treatments}} + SS_E \, .$$

The variation effect due to each component is summarised in Table 4.4:

	Component	**Variation Effect**
1	Treatment $n\sum_{i=1}^{a}(\bar{y}_i - \bar{y}_{..})^2$	Variation due to the effect of the treatments quantifying the difference between the treatment means and the grand mean.
2	Error $\sum_{i=1}^{a}\sum_{j=1}^{n}(y_{ij} - \bar{y}_{i.})^2$	Variation within a treatment quantifying the difference between the treatment observations and the treatment mean.

Table 4-4 Variance Decomposition of the One Way ANOVA Model

With reference to Table 4.3 and Equation 4.3, the purpose of the analysis model is to test if the *a* treatment means are equal. The hypothesis under consideration is:

$$\begin{array}{l} H_0 : \mu_1 = \mu_2 = \cdots = \mu_a \\ H_1 : \mu_i \neq \mu_j \text{ for at least one pair } (i, j) \end{array} \tag{4.5}$$

where μ_i is the mean of the *i*th treatment and since the treatment mean deviates from the overall mean by the *i*th factor effect, then

$$\mu_i = \mu + \tau_i \, . \tag{4.6}$$

Succinctly, for the null hypothesis in Equation 4.5 to hold, it follows that in Equation 4.6 each $\tau_i = 0$, and leads to the equivalent hypothesis for the treatment effect:

$$\begin{aligned} &H_0 : \tau_1 = \tau_2 = \cdots = \tau_a = 0 \\ &H_1 : \tau_i \neq 0 \text{ for at least one } i \end{aligned} \tag{4.7}$$

If the null hypothesis holds, the treatment component of Equation 4.4 (Component 1 of Table 4.5) will sum to zero and have no effect on the overall process variation and process variation will be exclusively due to the natural error. To determine if the null hypothesis holds (either Equation 4.5 or 4.7) it is only necessary to evaluate if the variances of the components of Equation 4.4 are equal. Due to the assumptions of normality of Equation 4.3, it can be shown that each of the components of Equation 4.4 when divided by the process variance σ^2 follows a Chi Square distribution (Montgomery, 2009), where:

$$\frac{SS_T}{\sigma^2} \sim \chi^2_{N-1} \qquad (N - 1 \text{ degrees of freedom}) \tag{4.8}$$

$$\frac{SS_{\text{Treatment}}}{\sigma^2} \sim \chi^2_{a-1} \qquad (a - 1 \text{ degrees of freedom}) \tag{4.9}$$

$$\frac{SS_E}{\sigma^2} \sim \chi^2_{N-a} \qquad (N - a \text{ degrees of freedom}) \tag{4.10}$$

The statistical *F* test (Ross, 2009) is applied to determine the equality of variances from two independent populations. As the variance is assumed constant for each distribution, the test statistic is given by:

$$F_0 = \frac{SS_{\text{Treatments}} \big/ (a-1)}{SS_E \big/ (N-a)} = \frac{MS_{\text{Treatments}}}{MS_E} \, , \tag{4.11}$$

where *MS* stands for ‘Mean Square’.

It can be shown that under the null hypothesis, the expectations of each of the mean squares equate to the overall process variance σ^2. Under the alternative hypothesis, the expected value of the numerator in Equation 4.11 will exceed the expected value of the denominator due to the influence of the treatment effect. Formally, at the desired significance level α, the null hypothesis H_0 should be rejected if:

$$F_0 > F_{\alpha,a-1,N-a}$$

As it is the variance of the partitioned components of Equation 4.4 that are analysed to determine the equality of the treatment means, the process is referred as the Analysis of Variance or ANOVA. Statistical software packages contain routines for automating the ANOVA calculations. Generally, the ANOVA results are displayed in a Table format, a typical format is illustrated in Table 4.5, though the actual layout is dependent on the specific software package.

Source of Variation	**Sum of Squares**	**Degrees of Freedom**	**Mean Square**	F_0
Between Treatments	$SS_{\text{Treatments}} = n\sum_{i=1}^{a}(\bar{y}_{i} - \bar{y}_{..})^2$	a - 1	$MS_{\text{Treatments}}$	$F_0 = \frac{MS_{\text{Treatments}}}{MS_E}$
Error (Within treatments)	$SS_E = SS_T - SS_{\text{Treatments}}$	N - a	MS_E	
Total	$SS_T = \sum_{i=1}^{a}\sum_{j=1}^{n}(y_{ij} - \bar{y}_{..})^2$	N - 1		

Table 4-5 Single Factor Fixed Effects One Way ANOVA Table

4.3.2. The Randomised Complete Block Design

For some processes it may be convenient to isolate the data into homogeneous ‘blocks’ to determine if the block has an effect on the outcome of the process response variable under consideration. The term block originates from Fishers early work in crop yield analysis. Fisher would partition sections of a field into ‘blocks’ for the cultivation of specific crops. Crops were applied to a block at random and the statistical procedure Fisher developed to model the crop yield is the Randomised Complete Block Design (RCBD).

The observation structure of the RCBD is a modification of Table 4.3, where the columns provide the block structure and is illustrated in Table 4.6.

	Observations			
Treatment Level	**Block 1**	**Block 2**		**Block b**
1	y_{11}	y_{12}	.....	y_{1b}
2	y_{21}	y_{22}	.....	y_{2b}
⋮	⋮	•	.....	•
		•	.....	•
i	y_{i1}	y_{i2}	.....	y_{ib}
⋮	⋮	•	.....	•
		•	.....	•
a	y_{ai}	y_{a2}	.....	y_{ab}

Table 4-6 General Observation Structure: RCBD

Within the RCBD, an observation y_{ij} is characterised by a treatment effect τ_i, a blocking effect β_j and the effect of random error ε_{ij} to yield the following effects model:

$$y_{ij} = \mu + \tau_i + \beta_j + \varepsilon_{ij} \tag{4.12}$$

As with the One-ANOVA, the hypothesis under test in terms of the treatment means is

$$\begin{aligned} &H_0 : \mu_1 = \mu_2 = \cdots = \mu_a \\ &H_1 : \mu_i \neq \mu_j \text{ for at least one pair } (i, j) \end{aligned} \tag{4.13}$$

And in terms of the treatment effect, the hypothesis is:

$$\begin{aligned} &H_0 : \tau_1 = \tau_2 = \cdots = \tau_a = 0 \\ &H_1 : \tau_i \neq 0 \text{ for at least one } i \end{aligned} \tag{4.14}$$

The ANOVA equation for the RCBD model is given by

$$\sum_{i=1}^{a}\sum_{j=1}^{b}(y_{ij}-\bar{y}_{..})^2 = b\sum_{i=1}^{a}(\bar{y}_{i}-\bar{y}_{..})^2 + a\sum_{j=1}^{b}(\bar{y}_{.j}-\bar{y}_{..})^2 + \sum_{i=1}^{a}\sum_{j=1}^{b}(y_{ij}-\bar{y}_{.j}-\bar{y}_{i.}+\bar{y}_{..})^2 \qquad (4.15)$$

and expressed symbolically,

$$SS_T = SS_{\text{Treatments}} + SS_{\text{Blocks}} + SS_E \qquad (4.16)$$

The corresponding ANOVA Table is presented in Table 4.7. Note, that the hypothesis $H_0 : \beta_j = 0$ is not tested. This is because randomisation is only applied at the treatment level within blocks. Effectively, the blocks present a restriction on randomisation that invalidates applying the *F* test to compare block means. The blocking effect if present reduces the contribution of the random error term. The error term gives up *b* – 1 degrees of freedom to the blocking effect resulting in an increased F_0 value for the treatment effect. The RCBD consequently improves the precision on which the treatment effect is assessed. Conversely, by not considering the blocking effect, the contribution of the error term is inflated possibly masking the contribution of the treatment effect.

Source of Variation	**Sum of Squares**	**Degrees of Freedom**	**Mean Square**	F_0
Treatments	$SS_{\text{Treatments}}$	*a* - 1	$\frac{SS_{\text{Treatments}}}{a-1}$	$\frac{MS_{\text{Treatments}}}{MS_E}$
Blocks	SS_{Blocks}	*b* - 1	$\frac{SS_{\text{Blocks}}}{b-1}$	
Error	SS_E	(*a* – 1)(*b* -1)	$MS_{AB} = \frac{SS_E}{(a-1)(b-1)}$	
Total	SS_T	*N* - 1	$\frac{SS_E}{(a-1)(b-1)}$	

Table 4-7 ANOVA Table for a Randomised Complete Block Design

4.3.3. Factorial Designs

Factorial designs consider scenarios where two or more factors act on a system simultaneously at two or more treatment levels. The ANOVA decomposition for a factorial design decomposes the variation between the factors (main effects) and the interaction between each of the factors (interaction effects). As in the case of the

One Way ANOVA and Randomised Complete Block Designs, the *F* Test is applied to determine if each of the main and interaction effects is significant.

Factorial designs are more efficient than 'One Factor at a Time' experiments. For a two factor system operating at two treatment levels, six observations are required for the 'One Factor at a Time' design, while four observations are required for a factorial design yielding a relative efficiency of 1.5 in favour of the factorial design. The relative efficiency increases in favour of the factorial design as the number of factors increase (Montgomery, 2009). The 'One Factor at a Time' design will not necessarily detect factor interaction and can therefore provide misleading information. Factorial designs can yield solutions over a range of experimental conditions by fixing a level of a chosen factor and observing the system response at varying levels of the other factors. Factorial designs are considered efficient due to the simultaneous capability of the method to quantify both the main and interaction effects on the response variable.

Factorial designs are characterised by the number of factors and treatment levels under consideration. Symbolically, factorial designs are presented in the form n^m where n defines the number of treatment levels and m the number of factors.

The two factor factorial design is defined by the following effects model:

$$y_{ijk} = \mu + \tau_i + \beta_j + \tau\beta_{ij} + \varepsilon_{ijk}$$

Hypothesis tests are conducted for each main effect τ_i and β_j and the interaction $\tau\beta_{ij}$. If there are n replicates of the experiment at each factor interaction, then the analysis is defined by the 'two factor analysis of variance' where the ANOVA Table is returned in Table 4.8.

For the main effects A and B there are a and b levels of treatment leading to (a-1) and (b-1) degree of freedom respectively. The degrees of freedom for the interaction effect are just the product of the degrees of freedom of the main effects. As there are n experimental replicates repeated ab times, there will be $ab(n - 1)$ degrees of freedom for the error. These totals to $abn - 1$ degrees of freedom.

Source of Variation	**Sum of Squares**	**Degrees of Freedom**	**Mean Square**	F_0
A treatments	SS_A	$a - 1$	$MS_A = \frac{SS_A}{a-1}$	$F_0 = \frac{MS_A}{MS_E}$
B treatments	SS_B	$b - 1$	$MS_B = \frac{SS_B}{b-1}$	$F_0 = \frac{MS_B}{MS_E}$
Interaction *AB*	SS_{AB}	$(a – 1)(b -1)$	$MS_{AB} = \frac{SS_{AB}}{(a-1)(b-1)}$	$F_0 = \frac{MS_{AB}}{MS_E}$
Error	SS_E	$ab(n – 1)$	$MS_E = \frac{SS_E}{ab(n-1)}$	
Total	SS_T	$abn - 1$		

Table 4-8 ANOVA Table for the Two Factor Factorial Design

4.3.4. The 2^k Factorial Design

An important class of factorial design consists of modelling *k* factors applied at two treatment levels is designated as the 2^k design. The design provides the smallest number of runs with which *k* factors can be studied as a complete factorial design.

The design works on an understanding that given any number of factors *A*, *B*, *C*, ..., the impact of the main effects can be assessed at the lower and upper treatment levels as can combinations of the interactions between the factors, *AB*, *AC*, *BC*, *ABC* and so on. Factorial designs are represented geometrically as a square ($k = 2$) or a cube structure ($k = 3$), and through a 'design matrix'. The 2^2 factorial design consists of two factors (say *A* and *B*) and while the design is the most basic of the 2^k series of designs, the design exhibits the attributes necessary to understand the complexities of higher order designs. The ‘Cube Plot’ representing the design is provided in Figure 4.4 and the design matrix is replicated in Table 4.9.

Figure 4.4 and Table 4.9 illustrate the alternative methods of defining the lower and upper treatment levels of a factor. Within the ‘Cube Plot’, the lower and upper treatment levels are designated by -1 and 1 respectively. Correspondingly, the upper level of the factors A and B are designated by the lower case *a* and *b* while the factor interaction is designated by *ab*. By convention, the lower levels of both treatments are designated by (1). The ‘Design Matrix’ lists all possible runs of the factors at their respective treatment levels, ‘-’ (lower) and ‘+’ (upper).

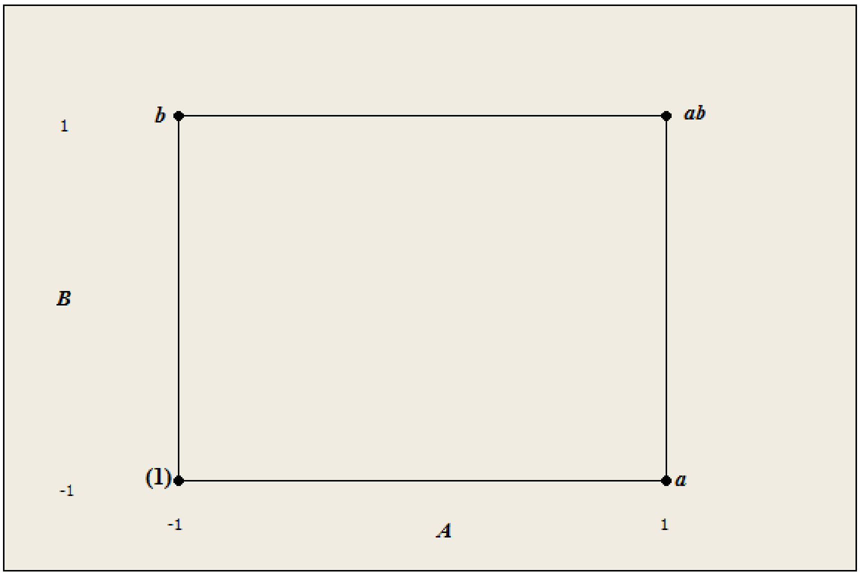


Figure 4-4 Cube Plot for the 2^2 Factorial Design

	Factor	
Run	***A***	***B***
1	-	-
2	+	-
3	-	+
4	+	+

Table 4-9 Design Matrix for the 2^2 Factorial Design

In a two level factorial design, the average effect of a factor is defined as the change in response due to the change of the treatment level of that factor over the other factor. Assuming there are *n* replicates of each treatment for both factors, by reference to the Cube Plot (Figure 4.4), the main and interaction effects are:

$$A = \frac{1}{2n}[ab + a - b - (1)] \tag{4.17}$$

$$B = \frac{1}{2n}[ab + b - a - (1)] \tag{4.18}$$

$$AB = \frac{1}{2n}[ab + (1) - a - b] \tag{4.19}$$

The term within each of the brackets is referred to as a ‘contrast’. The contrast is the total effect of the factor and is a linear combination of the parameters such that if T is the total of the treatment effects then:

$$T = \sum_{i}^{a} c_i t_i$$

Where the c_i terms are the coefficients of the parameter values t_i.

It is a necessary condition that the contrast coefficients c_i sum to zero; $\sum_{i}^{a} c_i = 0$.

Moreover, two contrasts with coefficients $\{c_i\}$ and $\{d_i\}$ are defined to be orthogonal if

$$\sum_{i}^{a} c_i d_i = 0.$$

Tests performed on orthogonal contrasts are independent and give complete subdivisions of the treatment sum of squares computed from the totals of the responses at each level of a factor (Clarke and Kempson, 1997).

By inspection of the treatments, 4.17 to 4.19, the coefficients of each of the contrast terms are either +1 or -1. For each contrast, the coefficients sum to zero. Moreover, the contrasts are orthogonal to each other.

Equation (4.20) specifies the contrast sum of squares can be evaluated for each factor that partitions the inherent variation of the system under investigation relative to each factor and factor interaction (Montgomery, 2009, Clarke and Kempson 1996):

$$SS_c = \frac{\left(\sum_{i=1}^{a} c_i t_i\right)}{\frac{1}{n}\sum_{i=1}^{a} c_i^2} \tag{4.20}$$

Applying Equation (4.20) to the 2^2 design for n replicates leads to the following sums of squares:

$$SS_A = \frac{[ab + a - b - (1)]^2}{4n} \qquad SS_B = \frac{[ab + b - a - (1)]^2}{4n} \qquad SS_{AB} = \frac{[ab + (1) - a - b]^2}{4n}$$

The sum of squares of the error term SS_E is computed by subtraction of the contrast sum of squares from total sum of squares SS_T:

$$SS_E = SS_T - SS_A - SS_B - SS_{AB} \tag{4.21}$$

The design matrix illustrated in Table 4.9 can be extended to include the factor interactions. The concept is adequately illustrated by creating a design matrix for a 2^3 design. Figure 4.5 shows the cube plot and Table 4.10 the design matrix for the 2^3 design. The matrix contains an 'Identity' column designated by *I*. The identity column recognises that any factor 'interacted on itself' will return a '+' and any factor interacted with the identity factor will return the factor as the normal arithmetic rules governing multiplication apply:

(+) × (+) = (+) (+) × (-) = (-) × (+) = (-) (-) × (-) = (-)

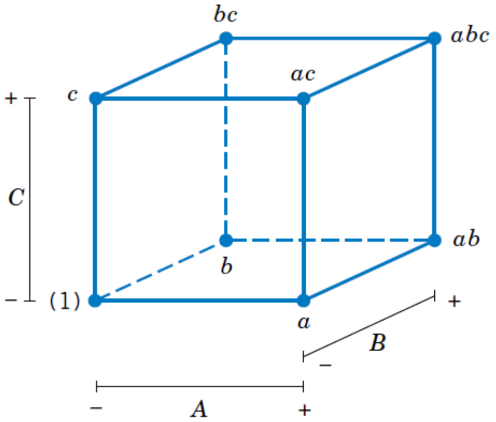


Figure 4-5 The 2^3 Factorial Design Cube Plot

Treatment Combination	Factorial Effect *I*	*A*	*B*	*AB*	*C*	*AC*	*BC*	*ABC*
(1)	+	-	-	+	-	+	+	-
a	+	+	-	-	-	-	+	+
b	+	-	+	-	-	+	-	+
ab	+	+	+	+	-	-	-	-
c	+	-	-	+	+	-	-	+
ac	+	+	-	-	+	+	-	-
bc	+	-	+	-	+	-	+	-
abc	+	+	+	+	+	+	+	+

Table 4-10 Matrix 'Effects' Design for the 2^3 Design

Estimates of the main and interaction effects are derived from inspection of the 2^3 plot. Given *n* replications of an experiment at each factor level, the average of effect *A* for example is given by:

$$A = \frac{1}{4n}[a + ab + ac + abc - (1) - b - c - bc]$$

In the 2^3 factorial design there is seven degrees of freedom associated the main and interaction effects. For *n* replications of an experiment the degrees of freedom is given by $2^3(n\text{-}1)$.

As there is a single degree of freedom associated with each effect, the sum of squares SS is:

$$SS = \frac{(\text{Contrast})^2}{8n}$$

For each factor effect the test statistic for the null hypothesis is of the form

$$F_0 = \frac{SS_{Effect}}{MS_E}$$

The properties of the 2^3 design can be generalised to the 2^k design for *n* replicates, the properties of which are summarised in Table 4.11.

4.3.5. Fractional Factorial Designs

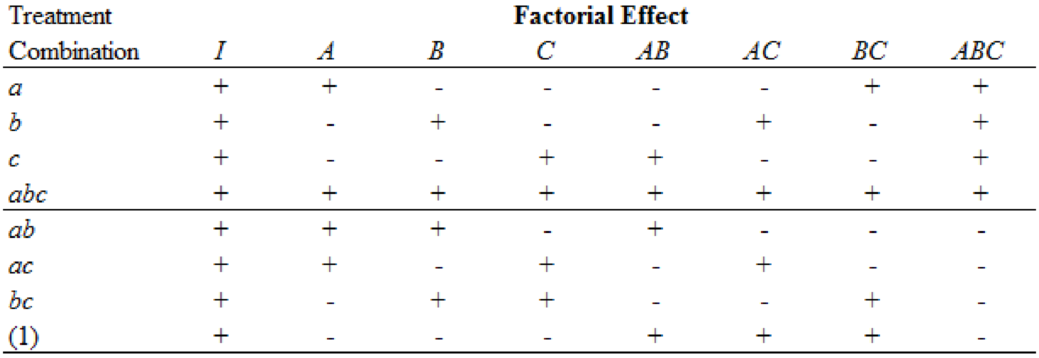
As the number of factors increase in the 2^k factorial design, the number of experiments increases exponentially by the factor *k*. Even for a moderate number of factors, the number of experiments required is significant. The 2^6 design for example requires a total of 64 experimental runs. A method for reducing the number of experimental runs is to take a ‘fraction’ of the total conditions corresponding to the complete 2^k factorial design. Specifically a 2^k factorial design containing $2^{k\text{-}p}$ runs is called a $1/2^p$ fraction or simply a $2^{k\text{-}p}$ fractional factorial design.

The principle of the fractional design is illustrated by creating a one-half fraction of the 2^3 design, and denoted as the $2^{3\text{-}1}$ design.

Source of Variation	Sum of Squares	Degrees of Freedom
k main effects		
A	SS_A	1
B	SS_B	1
$\vdots$	$\vdots$	$\vdots$
K	SS_K	1
$\binom{k}{2}$ two factor Interactions		
AB	SS_{AB}	1
AC	SS_{AC}	1
$\vdots$	$\vdots$	$\vdots$
JK	SS_{JK}	1
$\binom{k}{3}$ three factor Interactions		
ABC	SS_{ABC}	1
ABD	SS_{ABD}	1
$\vdots$	$\vdots$	$\vdots$
IJK	SS_{IJK}	1
$\binom{k}{k}$ k factor Interactions		
$ABC\cdots K$	$SS_{ABC\cdots K}$	1
Error	SS_E	$2^k(n-1)$
Total	SS_T	$n2^k-1$

Table 4-11 The General 2^k Design

With reference to Table 4.10 (the 2^3 design matrix), two sets of one-half fractions can be created from the treatment combinations *a*, *b*, *c* and *abc* and the combinations of the treatments *ab*, *ac*, *bc* and (1). The Effects Matrix for the two one-half fraction is shown in Table 4.12.



Treatment				Factorial Effect				
Combination	*I*	*A*	*B*	*C*	*AB*	*AC*	*BC*	*ABC*
a	+	+	-	-	-	-	+	+
b	+	-	+	-	-	+	-	+
c	+	-	-	+	+	-	-	+
abc	+	+	+	+	+	+	+	+
ab	+	+	+	-	+	-	-	-
ac	+	+	-	+	-	+	-	-
bc	+	-	+	+	-	-	+	-
(1)	+	-	-	-	+	+	+	-

Table 4-12 One-Half Fractional Designs of the 2^3 Design

With respect to first set of treatments, the treatments have that have a + in the *ABC* column is called the principal fraction. Consequently, *ABC* is called the generator of the one-half fraction and is often referred to as a word. From inspection of Table 4.12 it is seen that:

$I = ABC$ called the defining relation.

$A = BC, \qquad B = AC, \qquad C = AB$

Equal effects are said to be confounded or aliased to each other. So for example, factor *A* is confounded with or is an alias of the interaction *BC*. The aliases or confounding is verified directly from the defining relation. With respect to factor A, the alias or confounding is given by:

$$A \cdot I = A \cdot ABC = A^2BC = IBC = BC$$

The second one-half fraction is defined by treatments with a – in the *ABC* column and is referred to as the alternate or complimentary fraction. Here the defining relation is:

$$I = -ABC$$

The aliases for the alternate fraction are just the negative of the aliases in the principal fraction.

The degree to which the main effects of a design are aliased with the interaction effects is referred to as the design resolution. Generally, the resolution of a fractional design is one more than the smallest order interaction and is stated in roman numerals. Thus the 2^{3-1} is referred to as resolution III design. The significant levels of resolution design are:

1. **Resolution III designs:** Main effects are confounded (aliased) with two-factor interactions.
2. **Resolution IV designs:** No main effects are aliased with two-factor interactions, but two-factor interactions are aliased with each other

3. **Resolution V designs:** No main effect or two-factor interaction is aliased with any other main effect or two-factor interaction, but two-factor interactions are aliased with three-factor interactions.

Succinctly, the higher the resolution of a fractional design, the less restrictive are the assumptions that are required regarding which interactions are negligible to obtain a meaningful interpretation of the data (Montgomery, 2009). The choice of a higher resolution design will require more runs than a lower resolution design, so the economy of the design (in terms of minimising the number of runs) will be compromised.

The motivation to create a fractional factorial design is due to ‘The sparsity of effects principle’ that states that a system or process is likely to be driven primarily by some of the main effects and lower order interactions. Thus higher order interactions could be considered negligible and initial designs could be based on running a fraction of the experimental runs required for a full factorial experiment.

4.4. Taguchi Design of Experiments

Genichi Taguchi (1924, 2012) was a Japanese engineer and statistician who pioneered methods of quality control that bear his name. The key to understanding the methods Taguchi developed is based on his definition of quality:

“Quality is the loss a product causes to society after being shipped, other than any losses caused by its intrinsic functions” (Taguchi, 1986).

Taguchi restricts the meaning of loss to two categories:

1. Loss caused by variability of function
2. Loss caused by harmful side effects

The restriction in the opinion of Taguchi maintains the meaning of loss within the scope or domain of the engineer whose task it is to minimise or eliminate such losses.

Further, Taguchi quantifies loss through a loss function:

$$L(y) = k(y - m)^2 \tag{4.22}$$

Taguchi illustrates the construction of the loss function through an example of a buyer with an exact neck size of *y* purchasing a shirt with an available neck size of *m*. Defining the loss as the difference between *y* and *m* then *L*(*y*) is expressed as:

$$L(y) = L(m + y - m)$$

Expanding *L*(*y*) as a Taylor series about *m* yields

$$L(y) = L(m) + \frac{L'(m)}{1!}(y - m) + \frac{L''(m)}{2!}(y - m)^2 + \cdots$$

Since m is the exact neck size *L*(*m*) = 0. *L*(*y*) is minimal at y = m, so *L*'(*m*) = 0. By setting $k = \frac{L''(m)}{2!}$ and ignoring terms beyond the second derivative yields the loss function in the form given by Equation 4.22. To find *k*, knowledge about the financial losses that would occur if acceptable tolerances are exceeded and is derived by dividing the loss by the square of the lower or higher tolerance values.

Losses can be minimised in two ways. The first approach is by the monitoring of the production process to ensure the product meets the desired tolerances. Taguchi defines this approach as ‘On-Line Quality Control’. The second approach is for engineers to reduce the potential variation through building in quality during the design stage. This approach Taguchi defines as ‘Off-Line Quality Control’, (Peace 1993). The approaches combine to provide a comprehensive system of quality engineering as illustrated in Figure 4.6.

The system of quality engineering advocated by Taguchi is based on three concepts (Roy, 2010):

1. Quality should be designed into a product and not inspected into it;
2. Quality is best achieved by minimising the deviation from a specified target. The product should be so designed that it is immune to uncontrollable environmental factors.
3. The cost of quality should be measured as a function of the deviation from the standard and the losses should be measured system-wide.

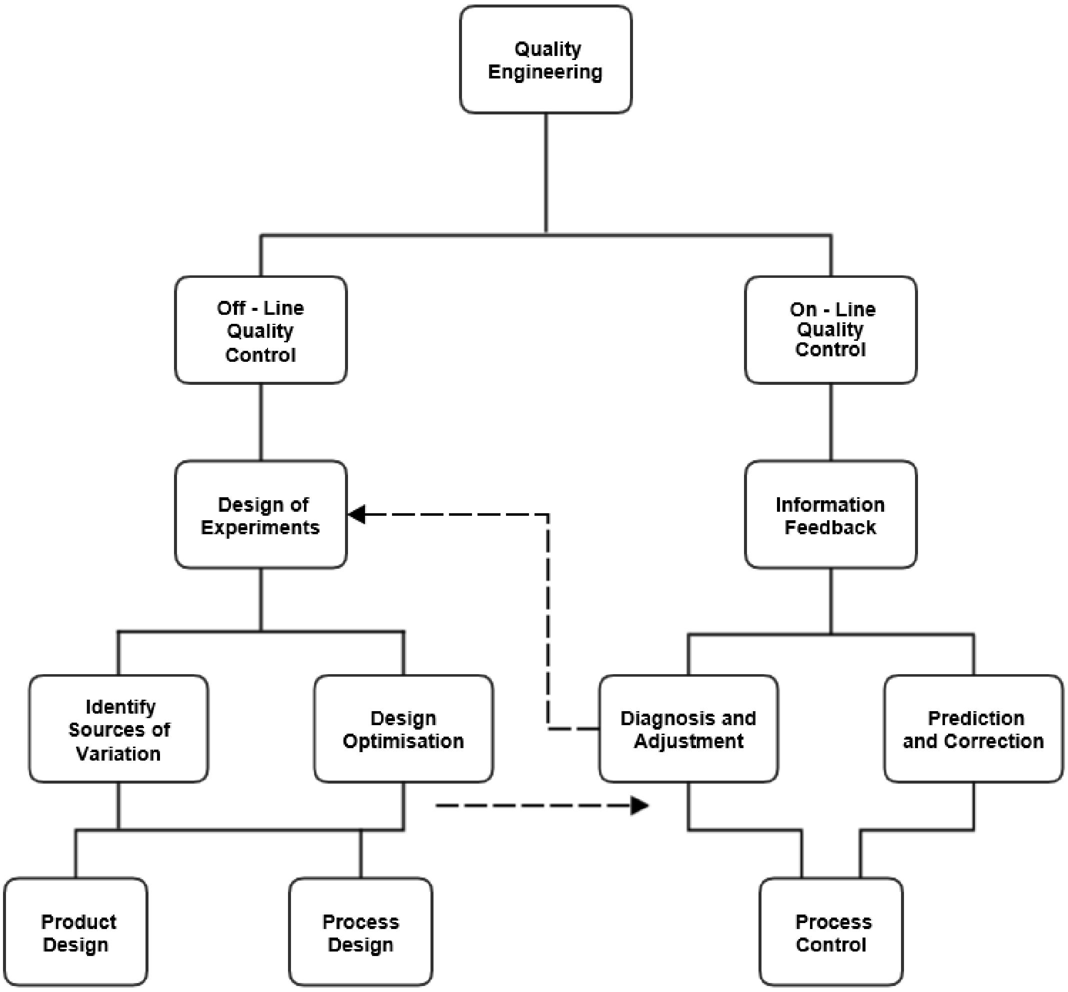


Figure 4-6 Taguchi System of Quality Engineering (Peace 1993)

In support of these concepts, the purpose of the system illustrated in Figure 4.5 is to introduce into both product design and manufacturing processes the concept of *robustness*. Robustness is defined at both the product and process level:

- **Product:** The ability of the product to perform consistently as designed with minimal effect from changes in uncontrollable operating influences or factors.
- **Process:** The ability of the process to produce consistently good products with minimal effect from changes in uncontrollable manufacturing influences or factors.

The definition of robustness in both product and process recognises the presence of influences that are uncontrollable. Rather than attempt to control what is uncontrollable, Taguchi instead attempted to find ways to shield products from uncontrollable influences. The robust design of both the product and associated manufacturing processes is about finding suitable level of factors that can be controlled that produce results most resistant to the uncontrollable influences (Roy, 2010).

Taguchi defines three sources of noise:

1. External Noise: Due to variability in environmental conditions that disturb the function of a product. Temperature, humidity, dust, and individual human differences Taguchi presents as examples of external noise.
2. Internal Noise (Deterioration): Changes that occur over time and include wear during use, deterioration due to extended storage, corrosion and colour fading.
3. Variational Noise: Differences between individual products that are manufactured to the same specifications.

The influence of noise to the product and process development is minimised through both the design Off-Line and On-Line approaches through three levels of design, System, Parameter and Tolerance (Taguchi, 1986) and are summarised in Table 4.13.

Design Level	**Off - Line QC**	**On - Line QC**
1: System (Primary)	Specifies the functional design of the product based on pertinent technology.	Applied to choose the applicable manufacturing processes selected from knowledge of the pertinent technologies.
2: Parameter (Secondary)	Method for improving quality and reducing cost and makes effective use of experimental design methods to select the appropriate factors to reduce the effects of noise	The optimum working conditions are designed for each process including the purchase of optimum parts and raw materials. So doing, the influence of harmful factors is reduced through improving process capability.
3: Tolerance (Tertiary)	Parameter design may not totally eliminate noise and tolerance design is used to limit the possibility of producing defective parts.	The tolerances of the process conditions and sources of variability are set and so suppressing the source of quality variation.

Table 4-13 Taguchi Three Stage Design Process (based on Taguchi 1986)

4.4.1. The Taguchi Experimental Design Method

The primary method Taguchi applies to minimise the effects of noise is through an experimental design method based on orthogonal arrays. An orthogonal array is a matrix of numbers where each column represents a factor which affects the outcome of the process under study, while the rows represent levels or states of the factors. Orthogonal arrays are balanced in respect to the settings of the factor levels such that every factor level occurs an equal number of times in each column regardless of the size of an array.

Orthogonal arrays are specified in the form:

$$L_a\ (b^c)$$

Where: a = Number of experimental runs;
b = Number of levels of each factor;
c = Number of columns in the array.

The 'L' notation implies the information is based on the Latin Square arrangement of factors. As an example, Table 4.14 illustrates the L_8 (2^7) orthogonal array. Within this array there are 8 experimental runs against a total of 7 factors at two levels.

The orthogonal array provides a structure that enables the calculation of signal to noise ratios (frequently abbreviated to S/N or SNR) at each factor level of the experiment. In engineering or science, the S/N ratio quantifies how much a signal is masked by noise and is defined as the ratio of signal power to the noise power corrupting the signal. A ratio higher than 1:1 indicates more signal than noise. Factor levels that maximise the S/N ratio provide supporting evidence of a significant factor effect.

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significant factor effect. Taguchi provides three standard S/N ratios each applicable to quantifying the factor effect to a desired performance response (Taguchi, 1986):

1. Smaller the better (for making the system response as small as possible)

$$\mathrm{SN_S} = -10\log\left(\frac{1}{n}\sum_{i=1}^{b} y_i^2\right)$$

2. Nominal the best (for reducing the variation around a target)

$$\mathrm{SN_T} = 10\log\left(\frac{\overline{y}^2}{S^2}\right)$$

3. Larger the better (for making the system response as large as possible)

$$\mathrm{SN_L} = -10\log\left(\frac{1}{n}\sum_{i=1}^{b} \frac{1}{y_i^2}\right)$$

$L_8(2^7)$	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	1	2	2
4	1	2	2	2	2	1	1
5	2	1	1	1	2	1	2
6	2	1	1	2	1	2	1
7	2	2	2	1	2	2	1
8	2	2	2	2	1	1	2

Table 4-14 The L_8 (2^7) Orthogonal Array

The Taguchi approach to experimental design is best described through the presentation of an example. Krishankant et al (2012) create a Taguchi experimental design to optimise the material removal rate of a turning process consisting of a single point cutting tool on a lathe. The authors identify the following factors or parameters that can affect the turning process:

a) Spindle speed: The rotational speed of the work piece held in the lathe chuck – measured in revolutions per minute (RPM)

b) Feed rate: The speed of the cutting tools lateral speed relative to the work piece measured in mm per revolution.

c) Depth of cut: The depth of the cutting tool along the radius of the work piece as it makes a cut.

The measured response variable is the Material Removal Rate (MRR) taken from the initial and final weight of the steel specimens used for the turning experiment:

MRR = (Initial weight – Final Weight)/Time Taken

The experiment consisted of 9 runs at 3 levels of the 3 parameters leading to the creation of a $L_9(3^3)$ orthogonal array (Table 4.15):

Job No	Spindle Speed (rpm)	Feed rate (mm/rev)	Depth of Cut (mm)
1	1	1	3
2	1	2	2
3	1	3	1
4	2	1	2
5	2	2	1
6	2	3	3
7	3	1	1
8	3	2	3
9	3	3	2

Table 4-15 $L_9\,(3^3)$ Orthogonal Array for the Turning Experiment

The factor levels used in the experiment are provided in Table 4.16. For clarity or with respect to manual calculation of the S/N ratios, the factor levels can be inserted into the orthogonal array overwriting the factor level numbers. The observed responses with respect to the material removal rate (MMR) are also input for each of the experimental runs.

Level	Spindle Speed (rpm)	Feed rate (mm/rev)	Depth of Cut (mm)
1	216	0.388	1.1
2	347	0.418	1.0
3	536	0.458	0.9

Table 4-16 Factor Levels for the Turning Experiment

The modified orthogonal array along with the results of the S/N calculations is provided in Table 4.17. Since the authors were interested in maximising the removal rate, the solution is provided by the 'Larger is Better' S/N calculation:

$$\mathrm{SN_L} = -10\log\left(\frac{1}{n}\sum_{i=1}^{b}\frac{1}{y_i^2}\right)$$

				Observed Data			
Run No	**Spindle Speed**	**Feed Rate**	**Depth of Cut**	**MRR 1**	**MRR 2**	**Mean**	**S/N Ratio**
1	216	0.388	0.9	1.438	1.405	1.421	3.051
2	216	0.418	1	1.267	1.298	1.282	2.158
3	216	0.458	1.1	1.525	1.537	1.531	3.701
4	347	0.388	1	2.204	2.200	2.202	6.857
5	347	0.418	1.1	2.000	2.057	2.029	6.141
6	347	0.458	0.9	2.250	2.214	2.232	6.973
7	536	0.388	1.1	0.986	0.984	0.985	-0.133
8	536	0.418	0.9	2.254	2.141	2.197	6.828
9	536	0.458	1	1.716	1.878	1.797	5.065

Response Table for S/N Ratio

Level	Spindle Speed	Feed Rate	Depth of Cut
1	2.970	3.258	**5.618**
2	**6.657**	5.042	4.693
3	3.920	**5.246**	3.236
Delta	3.687	1.988	2.381
Rank	**1**	**3**	**2**

Response Table for Mean

Level	Spindle Speed	Feed Rate	Depth of Cut
1	1.412	1.536	**1.950**
2	**2.154**	1.836	1.760
3	1.660	**1.853**	1.515
Delta	0.743	0.317	0.435
Rank	**1**	**3**	**2**

Table 4-17 Calculation of S/N Ratio for the Turning Experiment

The mean and S/N values are calculated against the responses for each factor level. The average responses are calculated for both the mean and S/N ratios at each factor level and input into their respective Response Tables. The term Delta is applied by Taguchi to define the difference between the largest and smallest average response values. The Delta values are ranked to indicate which factor has the greatest influence on the response variable. The average responses highlighted in red indicate the factor level that has the greatest influence on the response variable. Though Table 4.17 was produced on a spread sheet, statistical software packages have the capability to carry out Taguchi designs. In addition, the packages have the ability to automatically reproduce ‘Main Effects Plots’ from the Response Tables. Figure 4.7 reproduces Main Effects Plots for the mean values and Figure 4.8 reproduces the S/N responses that were created in the Minitab statistical software package.

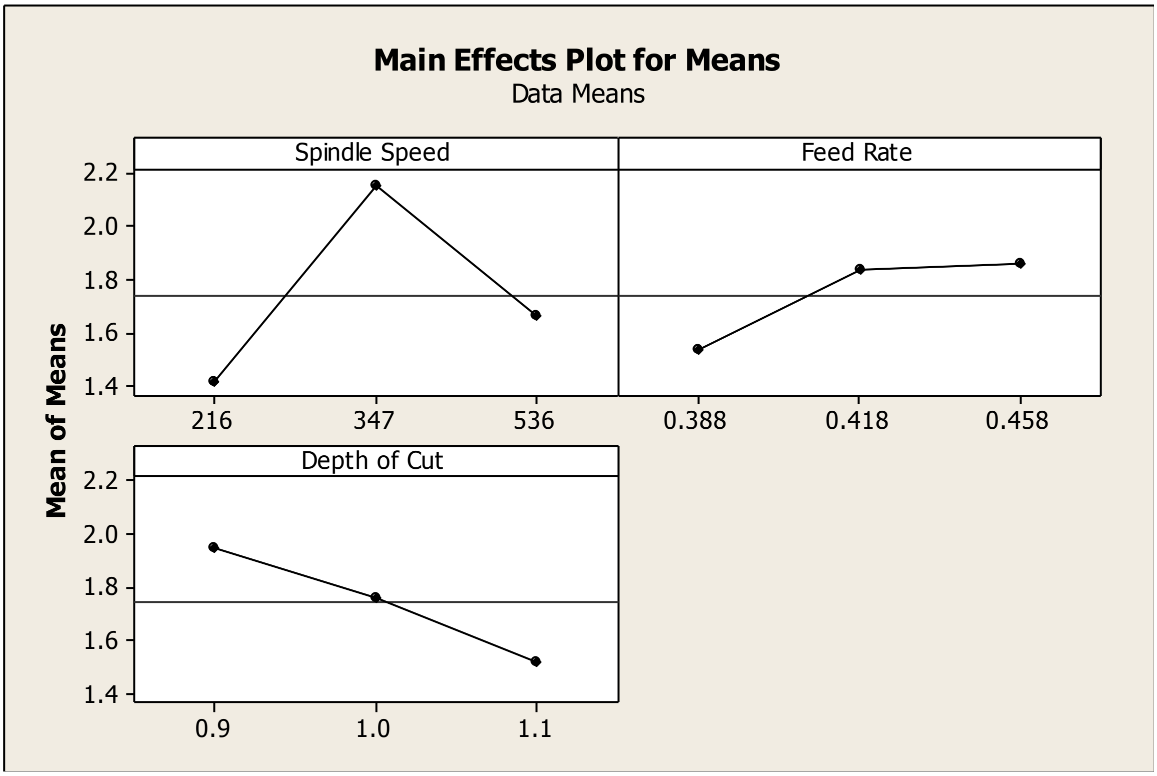


Figure 4-7 Main Effect Plots for Means

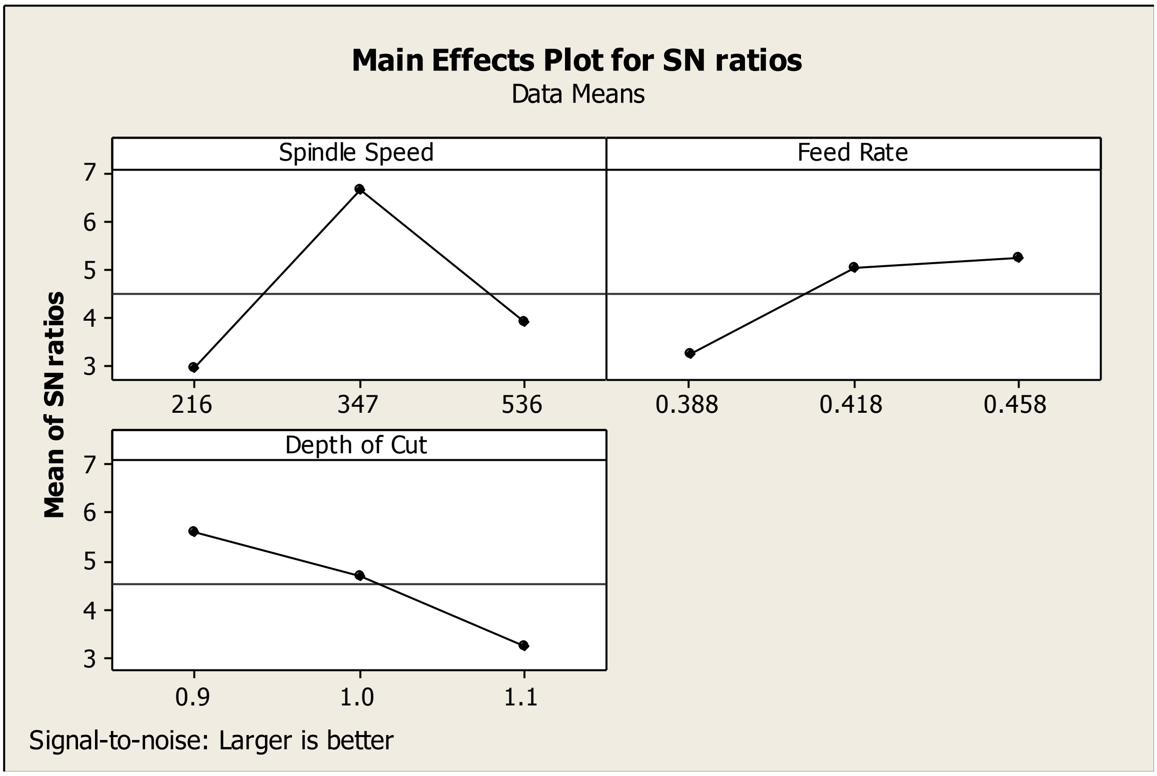


Figure 4-8 Main Effect Plots for S/N Ratios

Though in this example it is clear from the Response Tables at which factor levels the material removal rate is optimised, the use of the Main Effects plots provide a more visual guide to the behaviour of the responses.

The experiment provides evidence to support that the removal rate is optimised at the following factor levels:

Spindle Speed = 347 RPM	(Level 2)
Feed Rate = 0.458 mm/rev	(Level 3)
Depth of Cut = 1.1 mm	(Level 1)

A conventional Full Factorial design at three factor levels and three factors would require 27 runs for one observation of the response variable – this has been reduced to 9 runs applying the Taguchi method for a small loss of accuracy.

4.5. Mathematical Programming

Mathematical programming concerns the investigation of a special class of decision problems that are concerned with the efficient use of limited resources to meet desired objectives (Sinha, 2006). The first mathematical programming models concerned the modelling of systems that could be described by linear functions leading to the development of the ‘linear programme’. The adjective ‘programme’ refers to planning in the sense of ‘programming’ activities to achieve the desired result (Hillier and Lieberman, 2001, Williams, 2013). Since the emergence of linear programming in the late 1940’s, the methodology has extended to embrace the optimisation of non-linear models. Collectively, the full suite of optimisation methods is presented within the overall term of ‘Mathematical Programming’.

The science of mathematical programming evolved as a response to solving practical problems rather than from theoretical considerations. Dorfman (1984) discusses what are considered early examples of linear programmes attributed to Leonid Kantorovich (1912, 1974) and to Tjalling Koopmans (1910, 1974). Kantorovich, a Russian mathematician in 1939 devised a mathematical model to optimise the allocation of resources in the Soviet ply wood industry. During World

War II on behalf of the allied governments Koopmans, a Dutch mathematician developed a ‘transportation model’ to optimise the Atlantic shipping convoys. These developments were isolated cases of optimisation methods, and the advancement of mathematical programming methods evolved predominantly with the development of the ‘Simplex’ method to solve linear programs by George Dantzig in 1947, (Dantzig and Thapa, 1997).

4.5.1. Linear Programming

Problems that can be formulated as a linear programme (LP) model consist of a linear objective function that must be either maximised of minimised with respect to a series of constraints. Regardless of the initial formulation of a LP model it is necessary to transform the model into its canonical form (Figure 4.9) which is a necessary condition for solving the problem through the Simplex algorithm. In the canonical form notation, the objective function is maximised while the constraint equations are always expressed as equalities.

Maximise $z = \mathbf{c}^{\mathrm{T}}\mathbf{x}$

Subject to $\mathbf{Ax = b, x \geq 0, b \geq 0.}$

Equivalently:

Maximise $z = c_1x_1 + c_2x_2 + \cdots + c_nx_n$

Subject to:

$$\begin{aligned} a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n &= b_1 \\ a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n &= b_2 \\ \vdots \qquad\quad \vdots \qquad\qquad & \vdots \\ a_{m1}x_1 + a_{m2}x_2 + \cdots + a_{mn}x_n &= b_m \end{aligned}$$

$$x_1 \geq 0, \quad x_2 \geq 0, \ldots, \quad x_n \geq 0$$

Figure 4-9 Canonical Form of a Linear Programme

Through the initial constraints may include a mixture of equalities and inequalities (=, <, >, ≤, ≥) and a minimised objective function, transformation to the canonical form is achieved through the inclusion of slack and surplus variables. Any negative constraints ($b_i \leq 0$) are made positive by changing the signs of the whole constraint. Minimised objective functions are maximised by taking the negative of the objective function.

4.5.1.1. Solutions to LP Problems

Introductory test books on linear programming frequently introduce graphical methods of solving LP problems. Though solutions open to graphical methods are feasible for problems restricted to two variables, the solution process include properties that are applicable to problems in higher dimensions.

A representative example of a graphical solution to a LP problem is provided by Matousek and Gartner (2007) in describing the solution to the simple LP problem presented in Figure 4.10.

The graph is drawn for each constraint forming a convex polygon. The shaded 'bounded' region contains all the points (x_1, x_2) that are feasible solutions to the objective function. The optimised solution is found by constructing the line $z = x_1 + x_2$ and translating the line in the direction of the vector (1, 1) until it reaches the last point on the polygon which is at the vertex (3,2). The graphical method illustrates why it is necessary to transform a linear program into its canonical form. The canonical form forces the feasible region of the solutions to be bounded within a convex polygon and ensures that the optimal solution is on a vertex or one edge of the polygon.

The principles of the solution presented in the graphical method applying to two dimensions extend to higher dimensions. Formally, if the canonical form of the model has n variables, the vector $[x_1, x_2, \ldots, x_n]^T$ can be represented as a point in n dimensional space $\mathbb{R}^n$. The constraint bounds become (n - 1) - dimensional hyperplanes each dividing the whole n - space into two halves. The points satisfying the constraints will lie in one of the halves and the feasible region is the intersection of these half spaces.

Maximise $z = x_1 + x_2$

Subject to

$$\begin{aligned} &x_2 - x_1 \le 1 \\ &x_1 + 16x_2 \le 15 \\ &4x_1 + x_2 \le 10 \\ &x_1 \ge 0, \quad x_2 \ge 0 \end{aligned}$$

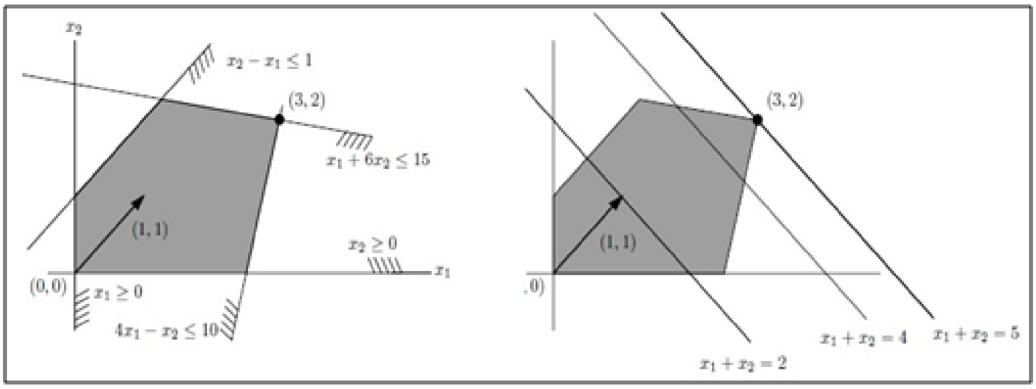


Figure 4-10 Canonical Form of a Linear Programme

Matousek and Gartner (2007)

The primary method of solving linear programs is through the Simplex method devised by George Dantzig in 1947. The algorithm has had a major impact in the field of operations research and is considered one of the most influential and significant algorithms that have been developed during the 20th century (Dongarra and Sullivan, 2000).

The simplex method is defined as a 'hill climbing method'. The basic outline of the method is as follows:

a) Find a feasible point (a point that satisfies the constraint set of the problem to be solved).
b) Is there an available neighbouring feasible point that is higher than the current feasible point? If so move to that point.
c) If all neighbouring feasible points are lower than the current feasible point, stop.

In the simplex method the analogy of height is used in determining the value of the objective function. The points around which the algorithm moves are the feasible vertices. Movement from one feasible vertex to another is only possible if the vertices are adjacent through the connection via an edge. The simplex method avoids the possibility of finding a local optimisation point. The inclusion of a local optimiser implies that part of the feasible solution region is concave. However, the canonical form of the LP problem always ensures that the feasible region is convex ensuring that if an optimised point is found, then the point must be a global optimiser.

Chong and Zac, (2013) note that the amount of time the simplex method requires to solve a linear program grows rapidly as the number of components n of the variable $x \in \mathbb{R}^n$ and in the worst case grows exponentially. The authors identify alternative methods to solving LP problems that operate in polynomial time and include:

- Ellipsoidal methods: The region of interest is enclosed in a sequence of ellipsoid whose volume steadily decreases so enclosing the optimum value within the convex region.
- Karamarker’s algorithm: The algorithm moves through the interior of the feasible region and gradually improves the approximation to the optimal solution by a fractional amount each time and so converging on to an optimal solution.

4.5.2. Non Linear Programming

Optimisation problems where the objective function and/or the constraints contain non-linear terms are not open to a linear solution and are classified as non-linear programming (NLP) problems. Figure 4.11 presents a representation the standard form of the NLP problem due to Chachuat (2007) where the objective function $f(\mathbf{x})$ is minimised, though equally the objective function could be shown as a maximum.

$$
\begin{array}{ll}
\text{Minimise} & f(\mathbf{x}) \\
\text{Subject to} & \mathbf{g(x)} \le \mathbf{0} \\
 & \mathbf{h(x)} = \mathbf{0} \\
 & \mathbf{x} \in X \\
 & X \subseteq \mathbb{R}^{n_x}, \quad \mathbf{x} \text{ is a vector of } n_x \text{ components } x_1,\dots,x_{n_x} \\
 & f : X \to \mathbb{R}, \quad g : X \to \mathbb{R}^{n_g}, \quad h : X \to \mathbb{R}^{n_h} \\
 & g_i(\mathbf{x}) \le 0, i = 1\dots, n_g \quad \text{are inequality constraints,} \\
 & h_i(\mathbf{x}) = 0, i = 1\dots, n_h \quad \text{are equality constraints.}
\end{array}
$$

Figure 4-11 Standard Form of the NLP Problem (Chachuat, 2007)

Chachuat (2007) provides the following example to illustrate the main features of a NLP problem:

$$
\begin{array}{ll}
\text{Min} & (x_1 - 3)^2 + (x_2 - 2)^2 \\
\text{s.t} & x_1^2 - x_2 - 3 \le 0 \\
 & x_2 - 1 \le 0 \\
 & -x_1 \quad \le 0
\end{array}
$$

The corresponding objective function and inequality constraints are given by:

$$
\begin{aligned}
& f(x_1, x_2) = (x_1 - 3)^2 + (x_2 - 2)^2 \\
& g_1(x_1, x_2) \le x_1^2 - x_2 - 3 \\
& g_2(x_1, x_2) \le x_2 - 1 \\
& g_3(x_1, x_2) \le -x_1
\end{aligned}
$$

Setting $f(x_1, x_2) = c$ yields a family of circles at centre (3, 2) and radius $\sqrt{c}$. The circles are defined as ‘contours’ of the objective function where the objective is to find the minimum value of *c*. This is achieved by finding the contour with the smallest radius that intersects the feasible region. For this illustrative example, the minimum value of the objective function is found graphically (Figure 4.12) and the corresponding minimum value occurs at *c* = 2 at the point (2, 1).

Unlike the linear counterpart, where the graphical method of solving the LP problem has an analogy in problems of higher dimensions and a specific algorithm (the simplex method) for finding the objective function, methods to optimise NLP problems are dependent on the nature of the NLP problem – consequently, there is no single efficient all – purpose algorithm that can be applied to all NLP problems (Hillier and Liebermann, 2001).

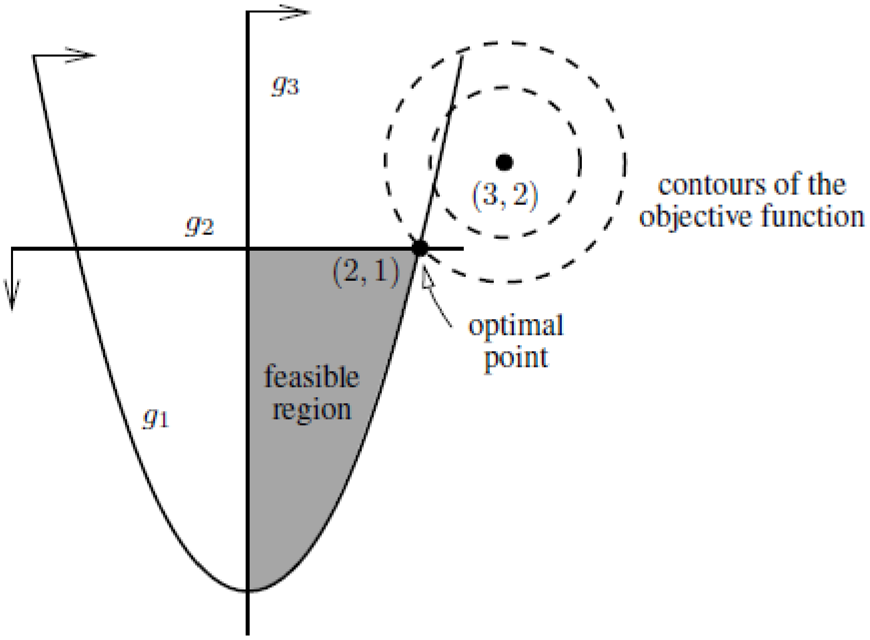


Figure 4-12 Graphical Example of a Solution to a NLP Problem (Chachuat, 2007)

Moreover, the feasible solution region may include both localised optimum solutions along with a global optimised solution and it can be difficult for the solving algorithm to determine if the solution is local or globalised. The literature is consistent on the range of methods that can be applied to solving NPL problems and includes separable programming, quadratic programming, convex and non-convex programming (Hillier and Liebermann, 2001, Sinha, 2006).

4.5.3. Integer Linear Programming

Integer linear programming (ILP) involves linear programming problems where one or more of the variables in the objective function are constrained to have integer solutions. LP problems that are constrained to include both integer and continuous variables are often referred to as Mixed Integer Linear Programs (MILP). The canonical form of the ILP and MILP problems are illustrated in Table 4.18.

(a) Integer Linear Program	(b) Mixed Integer Linear Program
Maximise $z = \mathbf{c}^T\mathbf{x}$ **Subject to** $A\mathbf{x} = \mathbf{b}$, $\mathbf{x} \geq \mathbf{0}, \mathbf{b} \geq \mathbf{0}.$ $\mathbf{x} \in \mathbb{Z}$	**Maximise** $z = \mathbf{c}^T\mathbf{x}$ **Subject to** $A\mathbf{x} = \mathbf{b}$, $\mathbf{x} \geq \mathbf{0}, \mathbf{b} \geq \mathbf{0}.$ $\mathbf{x}_i \in \mathbb{Z}, \quad i = 1,\ldots,m.$ $\mathbf{x}_j \geq \mathbf{0}, \quad j = 1,\ldots n.$

Table 4-18 Canonical Form of Integer Linear Programs

The solution methods for an ILP problem generally begin with solving the problem as a continuous linear program and applying a further procedure to isolate the integer solution. Two such approaches include the cutting plane and branch and bound methods.

4.5.4. Cutting Plane Methods

The cutting plane method begins by initially solving an integer programming problem as a linear program by dropping the integer requirement. If the resultant optimum continuous solution is also an integer, the solution is also integer optimum and the process is complete. Otherwise an additional constraint is added in the form of a cutting plane. If the optimum solution to the newly constrained problem is an integer, the process is complete. The process of introducing additional cutting planes is continued until an optimum integer solution is obtained.

4.5.5. Branch and Bound Method

The branch-and bound method takes as the starting point the initial IP (I_0) and similar to the cutting plane method solves the associated continuous linear program (C_0). Providing C_0 has a feasible solution that satisfies the integer constraints the optimum IP solution is obtained. If not two further sub problems are created – branched off from C_0 on an integer variable x_i that is not contained within the optimum solution of C_0.

If C_0 is a fractional solution, branch off from C_0 at a fractional variable x_i that should be an integer in the optimal solution. If x_i lies between the integers, L and $L+1$, then branch off at $x_i \leq L$ and $x_i \geq L+1$. The branching is illustrated in Figure 4.13. From the node C_0, the LP solutions for C_1 and C_2 are obtained. At each node, the solution corresponds to one of the following:

(i). The problem is infeasible.
(ii). The optimal value is less than the best integer value already obtained.
(iii). The solution is an integer.
(iv). The solution is fractional.

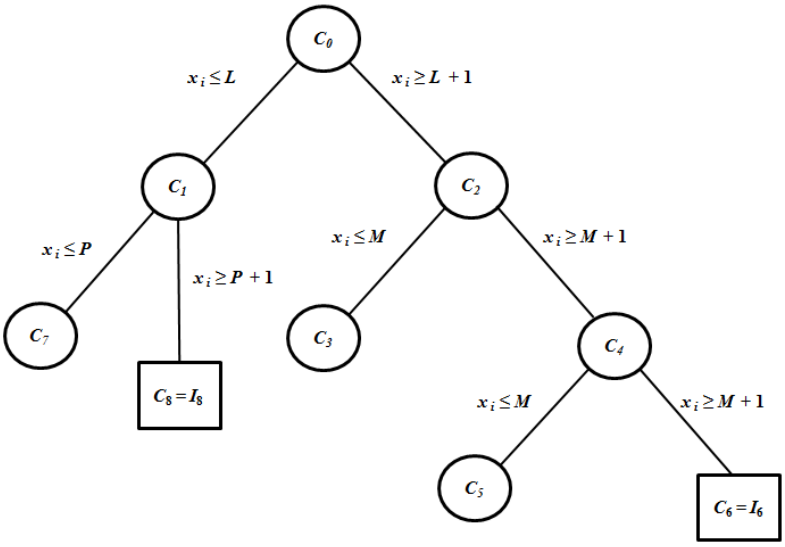


Figure 4-13 ILP Branch and Bound method

In Figure 4.13, the branching is continued at C_2. Each time a fractional solution is found at a node, the branching continues. The branching will terminate at a node if either the solution is infeasible or an integer solution is found. In Figure 4.13, an integer solution is found at C_6 (the node is represented by a box) and designated as I_6. This integer value is stored and the branching continued from another free node. The branching will only continue from a free node providing the fractional solution at the node is greater than any integer solution already found. A further integer solution is found at C_8 (= I_6). The branching completes once there are no fractional solutions greater than the best integer value already obtained. Providing the integer variables have both upper and lower bounds, there are only a finite number of branches and the search must eventually terminate (Williams, 2013).

4.5.6. Dynamic Programming

The method of dynamic programming is applied to optimisation problems that are ‘solved’ over a number of stages to arrive at an optimum solution – and hence the use of the adjective dynamic.

To explain dynamic programming, the method is sometimes explained through a ‘routing’ problem where the objective is to move from a start point to an end point in a network via a number of intermediate stages with the objective of minimising the total distance travelled. The network reproduced in Figure 4.14 is based on an example of a ‘stagecoach’ problem devised by Hillier and Lieberman (2001).

The objective is to minimise the distance travelled from *A* to *J*. From inspection of the network, the traveller must pass through three sub-destinations during the journey to *J*. The sub-destinations are grouped into stages relative to their position from *A*.

The optimisation process can begin at Stage 3. At sub destination *E*, there are two possible routes to *J*, through *H* and *I*. Through *H*, the total distance is 4 miles, while through *I*, the distance is 8 miles. Consequently any journey through sub destination *E* will ignore the route via *I* and travel to *J* via *H*. The decision process is repeated at each sub destination at each stage of the network to obtain the optimal route.

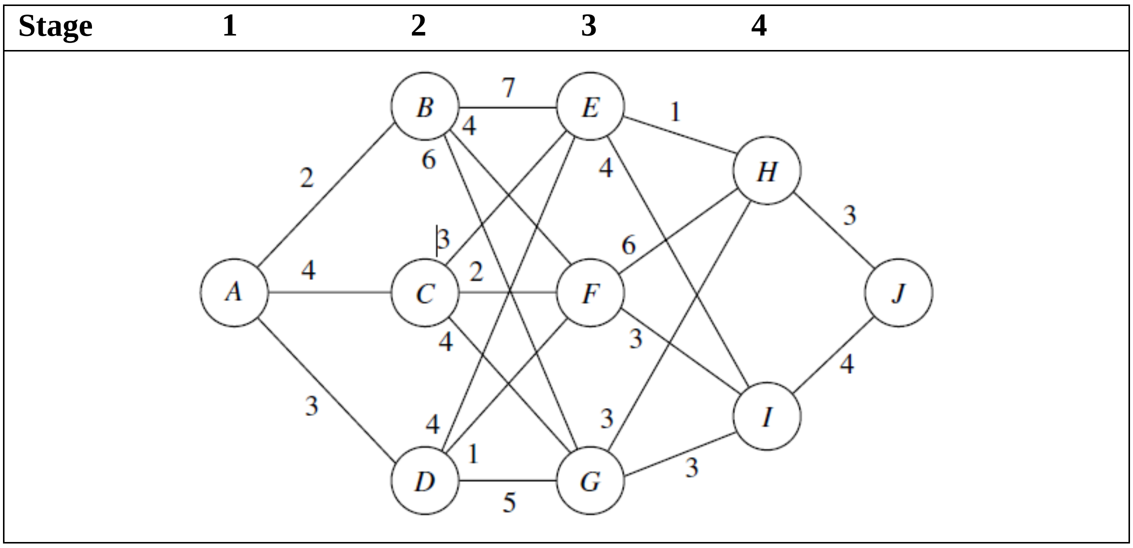


Figure 4-14 Dynamic Programme: Shortest Route Example

Hillier and Lieberman (2001)

There are three optimal routes resulting in a total distance of 11 miles and are returned in Figure 4.15 along with the modified network illustrating the solution routes in bold arrows.

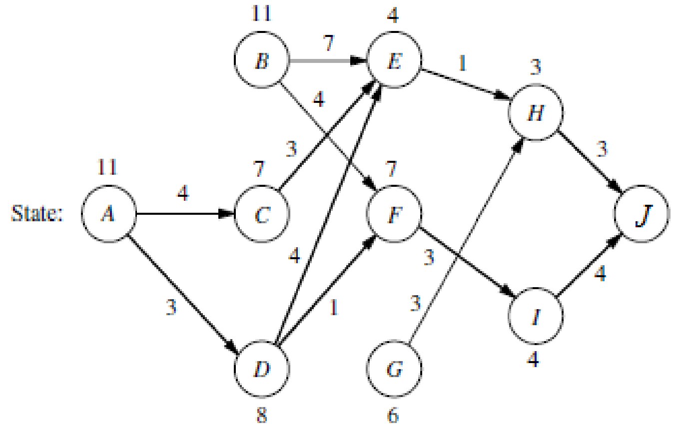
Optimal Routings	
$A \to C \to E \to H \to J$ $A \to D \to E \to H \to J$ $A \to D \to F \to I \to J$	

Figure 4-15 The Optimal Routing Solution

The process of determining the optimal journey distance between *A* and *J* capture the essential features of the dynamic programming approach to optimisation which are:

1. The problem can be divided into stages. At each stage a policy decision is required in how to proceed to the next stage. In the example, 5 stages are identified 0 to 4. The policy decision is to minimise the distance to the next stage.

2. Each stage has a number of states associated with the beginning of that stage. In the routing problem the states are the sub-destinations in each stage.

3. The effect of the policy decision at each stage is to transform the current state to a state associated with the beginning of the next stage.

4. The optimal policy at any stage is independent of the policy decisions adopted in previous stages.

In practice, the solution to a dynamic programming problem requires the creation of a recursive relation that optimises the policy decision at stage n given the optimal policy decision made at stage $n-1$. The routing problem is an example of a deterministic dynamic programme where the state at the next stage is completely determined by the state and policy decision at the current stage.

The alternative to the deterministic dynamic programme is where the state at the next stage is not completely determined by the state and policy decision at the current stage. Rather, there is a probability distribution for what the next state will be. However, the probability distribution is completely determined by the state and policy decision at the current stage. Thus a dynamic programme can be either deterministic or probabilistic (Hillier and Lieberman, 2001).

4.6. Queuing Theory

Queues are natural phenomena of daily living and people generally accept that they will need to queue for example at supermarkets, or at a taxi rank. However, delays due to excess queuing can result in a decline of service, frustration, loss of income and custom.

Within manufacturing plants, queuing is observed at machines and facilitates where work is waiting to be processed. The queue may be simple in nature where work is in a single queue waiting to be processed on a single machine. Alternatively, work may follow a complex routing through a variety of production resources with a potential for queues to form at each resource. Mismanagement of the queues either in the case of the single machine or the routing network can result in excess work in progress, delays and bottle necks in production.

To be held in a queue, means to wait. Queuing theory is the study of waiting times in its various forms through the creation of queuing models appropriate to the system under review. The models reveal how the queuing system performs and are therefore helpful in determining how to operate the system in the most effective way to strike a balance between the cost of servicing the queue and minimising waiting time, (Papadopoulos et al, 1993).

Queuing theory is consistent with other forms of mathematical modelling methods in that the theory creates an abstraction of real world phenomena. Regardless of the physical nature of the queue, the abstract approach of queuing theory considers the ‘members’ of a queue as customers and the resources applied to service the queue as servers. The abstraction provides a consistent modelling approach to understand the behaviour of a queue.

4.6.1. Queueing Terminology

The main features of queuing models created to analyse real world problems is illustrated in the general queuing literature in the form of a ‘Simple Queue’ (Figure 4.16). The queuing process is visualised as a sequence of customers who join the queue as a result of some random process from a calling population. Customers within the queue are selected for service by criteria specified in what is defined as the ‘queue discipline’. Customers are processed through a service mechanism after which they leave the queuing system.

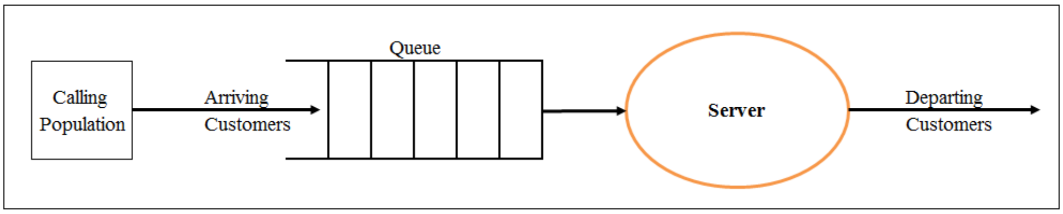


Figure 4-16 Simple Queuing System

Regardless of the complexity of a queue, all queues are specified using a shorthand notation devised by the English statistician, D.G. Kendall where the complete notation is of the form:

$A/S/N/B/K/D$

A: Inter-arrival time distribution.
S: Service time distribution.
N: Number of servers.
B: Number of buffers.
K: Population size.
SD: Service discipline.

The inter-arrival and service time distributions tend to follow one of the following probability distributions:

- M – exponential
- E_k – Erlang with parameter k
- H_k– Hyper-exponential with parameter k
- D – Deterministic
- G – General (any distribution, with specified mean and variance).

The Service discipline prioritises the way the customers leave the queue to enter the server. Some typical examples of service discipline rules include:

- FIFO: First in First Out - The customers are served in the order they arrived in the queue.
- LIFO: Last in First Out - The customers are served in the reverse order to the order they arrived in.
- SIRO: Service In Random Order - The customers are served in a random order with no regard to arrival order.
- Priority: In a priority queue, an element with high priority is served before an element with low priority. If two elements have the same priority, they are served according to their order in the queue.

The nature of the characteristics defined in Kendall's notation is listed in Table 4.19.

Queue Characteristic	**Nature of Characteristic**
Arrival Process	Customers arrive at times $t_1, t_2, \ldots, t_j$. Inter-arrival time $\tau_j = t_j - t_{j-1}$ The τ_j are independent and identically distributed (IID) random variables. The τ_j follow an arrival time distribution.
Service Time	Time spent receiving service (does not include waiting time). Service times are IID random variables and follow a service time distribution.
Number of Servers	Servers may or may not be identical Allocation of customers to servers specified in the 'Queuing Discipline'
System Capacity	Maximum number of customers in the queuing system – including those in service and can be finite or infinite.
Population Size	Total number of potential customers and can be finite or infinite.

Table 4-19 Queue Characteristics

Generally within the queuing literature it only the first three queuing attributes is specified. Two such examples are provided in Table 4.20.

The simple queue depicted in Figure 4.16 is useful for illustrating the queuing analysis process. The analysis is concerned with quantifying parameters that define the performance of a queue and include the mean number of customers in the system; the mean waiting time in the queue and the mean time the server process will be idle.

To arrive at the answers, the following assumptions are made with respect to the simple queue:

- The arrival process is modelled as a Poisson process with an arrival rate of λ and exponentially distributed inter-arrival times of $1/\lambda$.
- The departures leave the server at a rate of μ and are exponentially distributed with a mean service time of $1/\mu$.
- The arrival and departure rates are independent of each other.

***M/M*/1 Queue**	***M/D*/2 Queue**
Exponentially distributed inter-arrival times. Exponentially distributed service times. One server. Infinite number of buffers is assumed. Infinite population size is assumed. FIFO service discipline is assumed.	Exponentially distributed inter-arrival times. Deterministic server time: Takes exactly the same time to service each customer. Two servers. Infinite number of buffers is assumed. Infinite population size is assumed. FIFO service discipline is assumed.

Table 4-20 Example of Queue Specifications

With the inclusion of only one server, the scenario is modelled by the *M*/*M*/1 queue. A key measure to analysing the *M*/*M*/1 queue is the ratio of the arrival to service rate:

$$\rho = \frac{\lambda}{\mu}$$

and is known as the traffic intensity. The traffic intensity ratio determines the key performance parameters of the queue. For the *M*/*M*/1, Appendix X derives the main the main properties of the queue. Succinctly, the key parameters are derived from the traffic intensity ratio ρ, and are:

(a) Mean number N of customers in the system:

$$N = \frac{\rho}{1-\rho}$$

(b) Mean number N_q of customers waiting in the queue:

$$N_q = \frac{\rho^2}{1-\rho}$$

(c) Mean time W spent in the system (based on First Come First Served):

$$W = \frac{1}{\mu(1-\rho)}$$

(d) Mean time W_q spent waiting in the queue:

$$W_q = \frac{\rho}{\mu(1-\rho)}$$

The parameters have a finite value providing that $\rho < 1$ and imply that the server has sufficient capacity to manage the queue. As $\rho \to 1$, the number of customers in the queue and the waiting times increase. Arithmetically, for $\rho > 1$, the parameters take negative values and indicate that the server does not have the capacity to service the queue.

Simplistically, as $\rho \to 1$, the capacity of the server reduces. An objective decision can be made to increase the number of servers to cope with the intensity of the queue. There may be a simple answer to the capacity issue in just increasing the number of servers. However, depending on the level investment needed, further analysis of the *M*/*M*/*n* queue may be required to arrive at an objective decision. Conversely, as $\rho \to 0$, either the queue numbers are decreasing or the server rate is improving and an objective decision can be made to reduce the availability of the sever if the service idle time falls below an unacceptable level.

The modelling process applied to the *M*/*M*/1 queue illustrates how queuing theory elicits the main behavioural characteristics of queues that are of interest, specifically, the arrival mechanism, and queue size, waiting time, server performance and departure rates. Understanding of these parameters allows objective decisions to be made to maximise the efficiency of managing the queue relative to available $\{q_1, q_2, ...\}$ resources.

4.7. Hybrid Systems

A simplistic definition of a dynamical system is a system whose ‘state’ evolves or changes over time. The example of an interest bearing bank account adequately illustrates the meaning of state and system evolution. The state of the system is the amount of money in the account at a given point in time. The evolution of the state is governed by rules defining deposits and withdrawals to the account and the interest paid over time.

Regardless of the complexity of the dynamical system, ‘evolution’, ‘state’ and ‘time’ are the defining features of the system.

Dynamical systems are classified according to their state (Lygeros, 2004):

1. **Continuous:** The state takes continuous values in Euclidean space $\mathbb{R}^n$ ($n \geq 0$).
2. **Discrete:** The state takes a value q_i in a countable or finite set $\{q_1, q_2, ...\}$.
3. **Hybrid:** The dynamical system exhibits both continuous and discrete behaviour, so the state of the system can take values in $\mathbb{R}^n$ and in a finite set.

Systems that evolve over continues time are modelled by ordinary differential equations while evolve over discrete time are modelled by difference equations.

In a general sense, hybrid systems are a combination of real time continuous dynamics and discrete events that *interact* with each other. The dynamical system changes in response to both continuous and discrete events that are modelled by the differential or difference equations over time (Schaft and Schumacher, 2000, Lygeros, 2004).

Hybrid dynamical systems models are applied to a wide range of applications within mechanical systems, electric circuits, and chemical processing. Enabling a consistent modelling approach across such diverse applications hybrid systems are described by a formal modelling language called the Hybrid Automata. The model combines discrete control graphs (called finite state automata) with continuously evolving variables, (Raskin, 2005). Moreover, the modelling language is:

- **Descriptive:** The ability to model different types of continuous and discrete dynamics and their interactions.
- **Composable:** The capability to build larger models through the composition of simpler components.

- **Abstractable:** The capability to redefine designs with respect to both composite and individual components and study the performance of the overall system.

Within the hybrid literature the application of the hybrid automata is illustrated through examples. One such example is the temperature dynamic controlled by the operation of a heating thermostat. The dynamic is modelled as a hybrid system as the temperature continuously rises or falls within an interval controlled by the thermostat that instantaneously switches on or off when the temperature reaches either of the interval boundaries.

Consider a thermostat that turns on the heating if the temperature, *x*, drops below 70 degrees and will stop heating once 75 degrees has been reached. Without the heater, the temperature in the room falls according to

$$\dot{x} = -Kx$$

When the heater is on, the temperature rises according to

$$\dot{x} = K(h - x)$$

The control graph is shown in Figure 4.17:

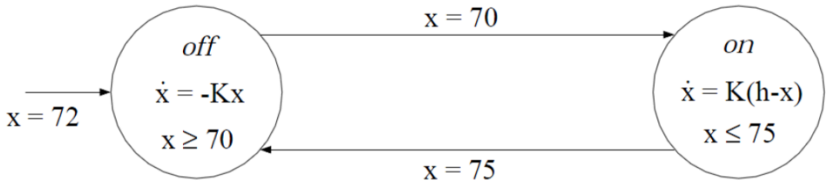


Figure 4-17 Control Graph for the Thermostat Control

Formally, a hybrid automaton is defined as a set *H* where,

$$H = (Q,\ X,\ f,\ Init, D,\ E,\ G,\ R)\text{, where}$$

- $Q = \{q1, q2, \ldots\}$ is a set of discrete states;
- $X \sim \mathbb{R}^n$ is a set of continuous states;
- $f(\bullet, \bullet) : Q \times X \rightarrow \mathbb{R}^n$ is a vector field;

- $Init \subseteq Q \times X$ is a set of initial states;
- Dom(•) : $Q \rightarrow P(X)$ is a domain;
- $E \subseteq Q \times Q$ is a set of edges;
- $G(\bullet) : E \rightarrow P(\mathrm{X})$ is a guard condition;
- R(•, •) : $E \times X \rightarrow P(X)$ is a reset map.

Through the combination of the automata and the control graph the full trajectory of the dynamical system can be described. Upon recognising that a system can be modelled as a hybrid dynamic, the ability to model the system is through the application of the hybrid automata.

4.8. Selection of Modelling Methodologies to Investigate Case Study Environment

Within the case study environment amongst the objectives to efficiently manage production performance is the combined goal of maximising the production rate of the pressing process while maintaining a low inventory profile. Maintaining a low inventory profile is a function of the batch size of the production run. The press production process is subject to variation in the both the measurable inputs and outputs to the process. Consequently, the variation inhibits making objective decisions with respect to setting an appropriate production batch size.

It is therefore appropriate to apply methods that model the effects of system variation. The purpose of which enables (1) the implementation of improvement methods to reduce variation and (2) the potential optimisation of the system through controlling input levels that influence system responses. Consequently, regression modelling and the Design of Experiments are appropriate methods to model the press production process.

Regression modelling is a proven method for quantifying the relationship between a measured response variable subject to the influence of one or more explanatory variables. As such regression modelling is an appropriate method for quantifying the nature of the variation within the panel production process. The objective of the regression model is to quantify how measurable inputs such as the production batch size, set up times, frequency of tool changes, press running speeds, machine running and downtime affect the production rate of the press.

Regression modelling though a powerful technique, the cause and effect relationship between the explanatory variables and the response variable is quantified through the application of the application of the Design of Experiments. Classical experimental design develops a statistical model that considers how a set of independent variables affect the outcome of a dependent variable to a process. The Taguchi approach focuses on product and process robustness. Succinctly, robustness implies that the process/product performance is resistant to 'noise' and is measured through the use of Signal-to-Noise Ratios, (Antony, 2003).

The classical method of design applies a range of methods to analyse variation based on the technique of the Analysis of Variance (ANOVA). With ANOVA it is possible to quantify the effect of a single factor applied at two or more treatment levels to a process trough to scenarios that quantify the effect of multiple factors applied at several treatment levels to a process.

With respect to quantifying the effect of batch size to maximising the production rate, the application of the Operational Research methods (Queuing Theory, Mathematical Programming) and Hybrid Automata are not applicable for the following reasons:

Queuing Theory: The assessment of press production efficiency is measured from the start of tool change over to the completion of the last panel off the press. Operational performance of the production press is therefore unaffected by the queue of work waiting processing. If the press is waiting for work, or if the there is too much work for the production press to manage over a given time period, the effect is measured at the facility level and not against individual production resources within the facility. Where it is necessary to understand the flow of production throughout a facility to prevent either the build-up of excessive inventory or machines unnecessarily waiting for work, the application of queuing theory is an appropriate application.

Mathematical Programming: Linear and non-linear programming will either maximise or minimise the output of an objective function subject to a set of constraints. The objective of quantifying the appropriate production batch size cannot be formulated in terms of a mathematical program. The objective function of a mathematical programme determines the levels that each attribute in the function must be set to optimise the objective. The attributes applicable to the panel production process can be planned but cannot be set. Achieved production totals, machine uptime and downtime, frequency of tool changes and set up times will vary during the execution of a production run. The attributes cannot be controlled such that the optimisation of an objective function is met. As production is demand led, the effect of constraints in the manufacturing system will also vary relative to demand. Succinctly, system constraints are managed via a planning team, through the creation of short, medium and longer term capacity statements, that identify the appropriate number of parts that can be produced over a given shift system with the necessary manpower and maintenance resource.

Dynamic programming is applied to optimising flows through complex networks. The case study environment is restricted to a single production press that is itself supplied from a single blanking facility so negating the need for a complex network model.

Hybrid Systems: The panel production process is modelled as basic input-output process, where the physical nature of the production process is not considered. Though the system is modelling a discrete number of parts over continuous time to provide a production rate, it is not necessary to distinguish between the discrete and continuous elements of the system. As such there is no benefit to considering the application of Hybrid Automata to quantifying the relationship between batch size and the optimisation of performance.

4.9. Concluding Remarks

Each of the methodologies discussed within the Chapter primarily emerged as effective responses to solve real world problems. They do however; exploit different attributes of a manufacturing system. Variation is considered an inherent feature of manufacturing systems and if not controlled can result in the deterioration of the system with respect to both operational performance and product quality attributes. Statistical process control methods are effective in controlling variation, generally they are passive methods – something has to happen before the control method is applied. Both classical and the Taguchi design of experiments are capable of determining the source of system variation and moreover quantify the contribution of the various inputs (factors) and their interactions to a system response. The capability applies even when a system is under control so enabling the maintenance of system performance.

Manufacturing systems must satisfy a variety of requirements beyond the primary purpose of providing customer value through the delivery of desirable products. Such requirements include maximising profit, minimising costs, and maximising throughput. Mathematical programming provides a suite of effective methods that aid the optimisation of system attributes enabling efficient use of resources to achieve the system objectives.

Manufacturing systems should be configured to enable the flow of product though the system. Products as they are manufactured and assembled can go through some complex manufacturing routings. There is always the possibility of inventory building up in front of a machine resource. If the machine resource cannot service the inventory at an efficient rate, islands of inventory will build up in front of a machine, and bottlenecks can result leading to a reduction is system performance. Queuing theory is a study of the waiting times of queues and has the objective of maximising the queuing efficiency relative to the ability of applying resources to manage the queue. Effective queue management should result in minimising ‘islands of inventory’ and enhancing flow through the system.

Hybrid systems recognise that manufacturing can be a combination of continuous and discrete events. Through the hybrid automata, the dynamics of the system states can be assessed. Though hybrid system modelling is an emerging methodology, the approach is finding application across a wide variety of mechanical and computing applications.

Each methodology is relevant to specific applications within the analysis of manufacturing systems and no one method is superior to another. The effectiveness of any of the methods is in the relevance of the method to the nature of requirements of the solution being sought.

The commonality of the methods lies in the understanding by manufacturing practitioners on how to apply the methods. With respect to experimental design, it is through choosing the correct factors that contribute to the system response under study. For the optimisation methods, it is understanding how to formulate the problem into the required format to run the optimisation programme. For queuing systems, it is the creation of the correct queuing discipline to model the waiting time. And finally with respect to hybrid systems it is the correct choice of automata that will dictate a meaningful representation of the dynamics of the system.

5. Analysis of a Batch Production Process

5.1. Introduction

The purpose of this Chapter is to derive a suitable model to aid the management decision process to quantify the appropriate batch size for the production of automotive body panels that maximises the production capability of the manufacturing facility while maintaining a lean inventory profile.

The model is developed against a range of production data that are collated in real time directly off the production facility through an automated data capture system.

The manufacture of automotive body panels is by necessity a batch production process. Panels are produced through a series of press tools that are fitted into a production press. The operational speed of a production press far exceeds the consumption rate of a vehicle assembler so it makes economical sense to make a range of panels through a single press line by producing the appropriate batch quantity of each panel.

Body panel manufacturing is a process that epitomises the meaning of lean production. Historically, tool changes could take days and so requiring long production runs to offset the effect of the long tool change over. Over a period of time, tool changes reduced to hours through innovative process improvements both by the panel producer and by the tooling and press manufacturer. Continuing improvements in pressing and tooling technology enable modern press lines to change over tools in a short number of minutes.

Originally, the length of a panel production run would be established through an economic lot sizing model (Elmaghraby, 1978). Such models attempted to derive an economical lot size that minimises the cost effect of holding inventory and the cost of the tool change over.

Within the case study environment, such models are no longer applicable. Tool changes take a matter of minutes (the main preparation taking place on a separate tooling bed while production is running). The production runs are relatively short supplying at most 2.5 days of vehicle build requirement. The main inventory expense is in the coil steel or aluminium used to make the panels. However the coils arrive on a timed delivery schedule at most a day before production. Moreover, the steel is paid for at the end of the calendar month following delivery. Effectively all the coils are consumed, panels manufactured and delivered to the vehicle assembler well before the coils are paid for.

There is an intuitive belief that is collectively held by both press shop managers and operational staff that production optimisation is achieved through longer run lengths. However, neither party have tangible evidence that either supports or refutes their intuition.

Section 5.1 introduces a generic modelling approach while Section 5.2 applies the approach through the application of the appropriate models. Section 5.3 provides some concluding remarks.

5.2. Modelling Approach

William Thomson (later The Lord Kelvin), the 19th century mathematical physicist and engineer with respect to the purpose of ‘measuring’ suggested that:

1. To measure is to know.
2. If you cannot measure it, you cannot improve it.

Kelvin’s quotations succinctly capture the need to measure manufacturing systems. The measurement of key attributes of the system enable managers and decision makers to understand the status of the system. Moreover, measurement is the foundation of continuous improvement regardless of the nature of the improvement method.

The definition of manufacturing as a conversion process of a collection of inputs to a collection of both desirable and undesirable outputs is visualised by Black (1976) in Figure 5.1 where he identifies a set of common measurable parameters.

With reference to Figure 5.1, the manufacturing system is affected by disturbances that will result in variation in the measured parameters. At the individual parameter level, process improvement methods attempt to reduce the effect of disturbances through variation reduction with the aim of improving the parameter effect.

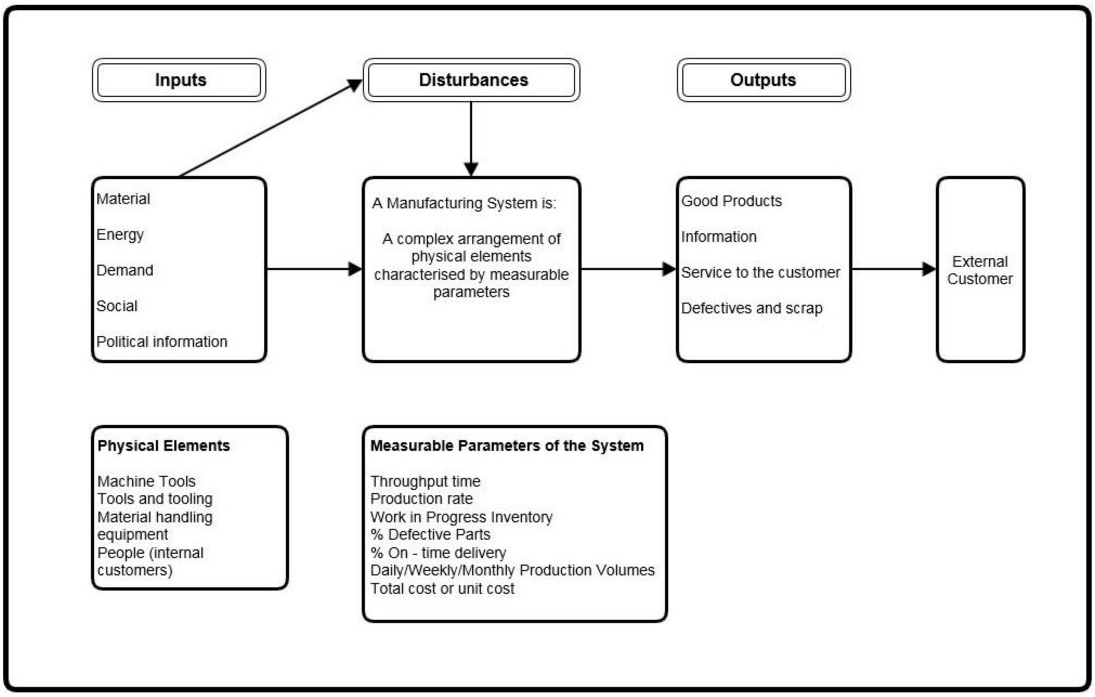


Figure 5-1 Definition of a Manufacturing System (Black, 1996)

With respect to improving the overall manufacturing system performance it is necessary to understand how each of the system parameters interact with each other. According to Black's definition, manufacturing systems are 'complex entities'. Depending on the nature of a specific manufacturing system, attempting to quantify potential parameter interaction may be infeasible. A sensible approach could begin with modelling the parameter interaction for a manageable sub-system and iteratively enhancing the model as system knowledge increases. Such a modelling methodology is visualised in Figure 5.2.

5.3. Model Development

The key performance measure within the case study environment to determine system efficiency is the productive output of the production press. This metric is defined as the Gross Shots per Operating Hour (GSPH) and is simply the quotient of the number of panels produced divided by the total machine time consumed for the production run.

The GSPH metric is of critical importance to the management of the pressing operation. The metric provides the basis for decision making with regard to the capacity loading of press lines, manpower and shift working requirements and the necessary resource and facilities for the provision of maintenance of the press tooling and press machines.

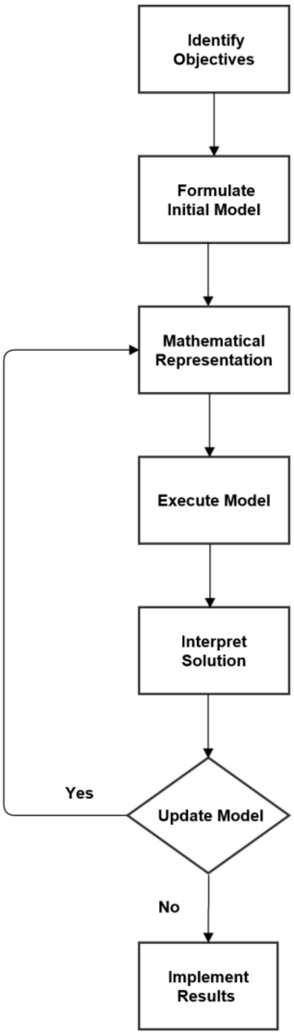


Figure 5-2 Modelling Methodology

A second metric measured simultaneously to the GSPH, is defined as the Shots per Operating Hour (SPOH). The SPOH metric ignores any set up time and down time incurred during the pressing operation and is therefore a measure of the productivity of the operation under continuous running conditions. The GSPH and SPOH metrics are visualised in Figure 5.3, where the total time for a production run is partitioned into the following distinct times:

1. Set Up Time: The time to change from the completion of a production run to the start of the next production run;
2. Run Time: The time the press machine is actually producing parts;
3. Down Time: The time the time the machine has stopped during the production run either through breakdowns or to make adjustments.
4. Machine Time: The total time to complete the production run, where:

   Machine Time = Set Up Time + Run Time + Down Time;

5. Net Machine Time: The Machine Time less Set Up Time:

   Net Machine Time = Machine Time – Set Up Time.

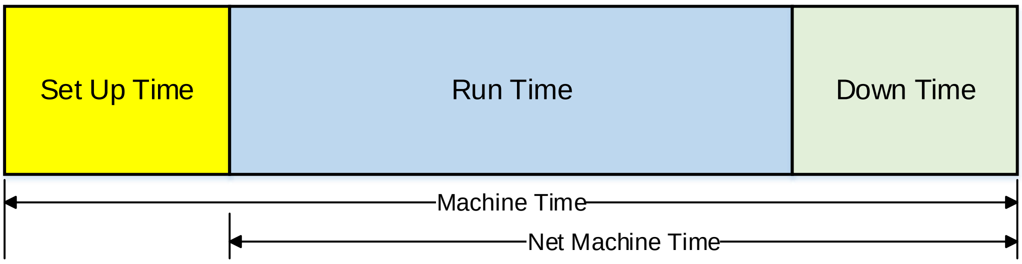


Figure 5-3 Production Time Decomposition

With reference to Figure 5.3, the calculations for the GSOH and SPOH rates are respectively:

GSPH = Run Length/Machine Time

SPOH = Run Length/ Run Time

Maximising the GSPH metric is the strategic goal of the pressing operation as this is the measure which defines productive output. However there are additional objectives the pressing department would like to achieve and include:

- Minimising production run batch quantities to minimise the WIP and finished inventory stocks without compromising production efficiency.
- Understand the impact of loading a production press with additional work to the efficiency of the pressing operation.

Over time, the measured GSPH rate is subject to considerable variation due to a combination of fluctuations in tool change over time, frequency of tool change over's and periods of machine down time during a press run. The variation of the GSPH is illustrated in Figure 5.4 (GSPH recorded for an individual part) and Figure 5.5 (GSPH calculated for each observed production week).

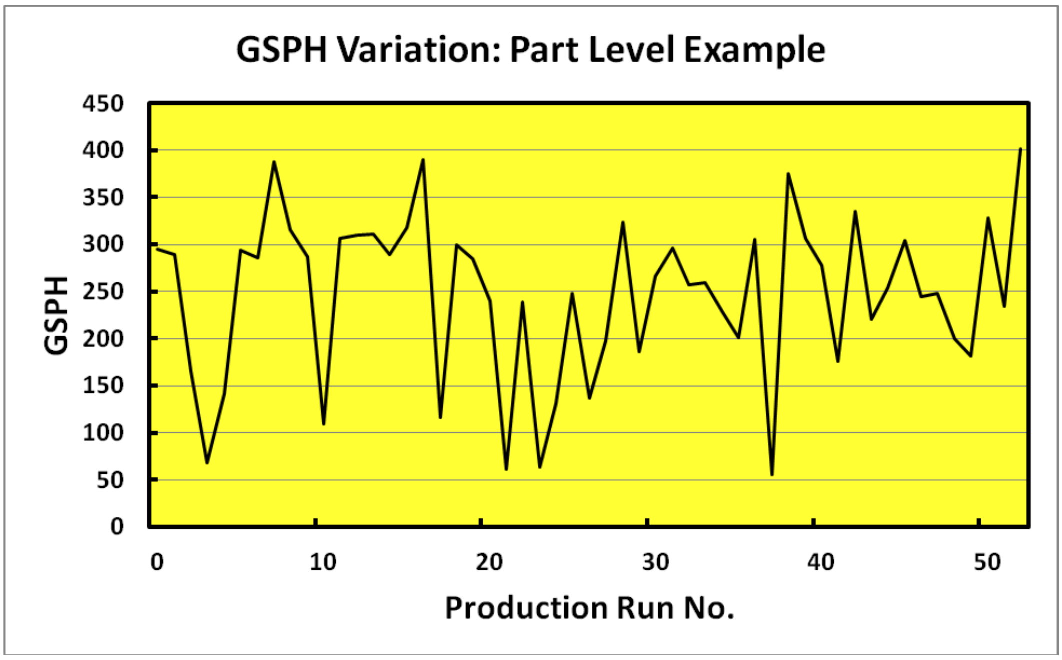


Figure 5-4 **GSPH Rate Variation: Part Level**

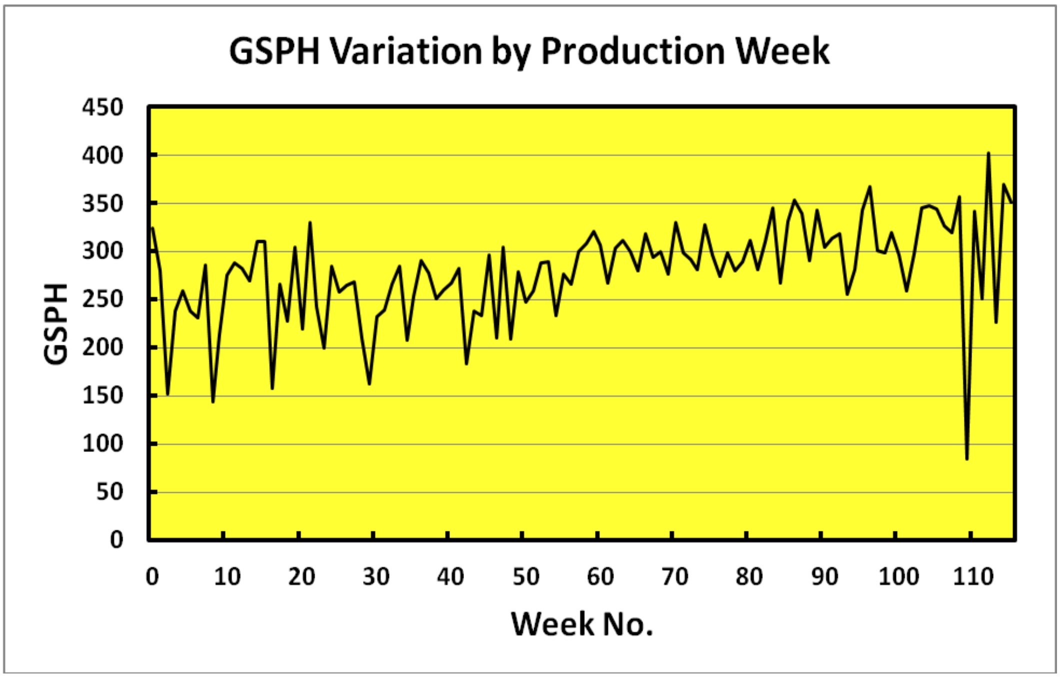


Figure 5-5 **GSPH Rate Variation: By Production Week**

The variation impedes the operations management ability to make objective decisions with respect to maximising productive output while meeting the additional objectives of inventory reduction and loading optimisation. To achieve these objectives, it is therefore necessary to investigate the causal factors of the variation of the GSPH metric.

5.4. Initial Analysis of GSPH Metric

Production related data is captured by the automated data monitoring system is stored on a series of tables held in a data warehouse. Operational characteristics such as the tool change or set up time duration, the total time of the production run, the achieved production quantity and down time measures are available for analysis. Within the data warehouse at the time of the time the investigative work, the data available spanned 116 production weeks comprising of 2365 recorded production runs.

From the recorded production data available in the data warehouse it is necessary to isolate the data attributes applicable to quantifying the GSPH rate. Figure 5.6 visualises the Panel Production Process where a number of measurable inputs to the process result in some measurable outputs. The only controllable input is the speed of the press. The speed of the press is communicated as the number of operational press strokes or cycles per minute, that result in completed body panels. However, during the production run, the speed of the press can be changed to suit the operational conditions of the run. The net production rate or SPOH is effectively the average speed of the press over an operating hour of continuous running through controlling the press speed. The achieved run length will deviate from the planned production run length (number of panels required), due to factors such as the number of panels rejected during the run or the initial availability of the raw material.

The variation in the GSPH rate is influenced by the variation in the input attributes identified in Figure 5.6. A preliminary approach to quantifying the influence of measured input (explanatory) variables to a measured output (response) variable is to construct a regression model.

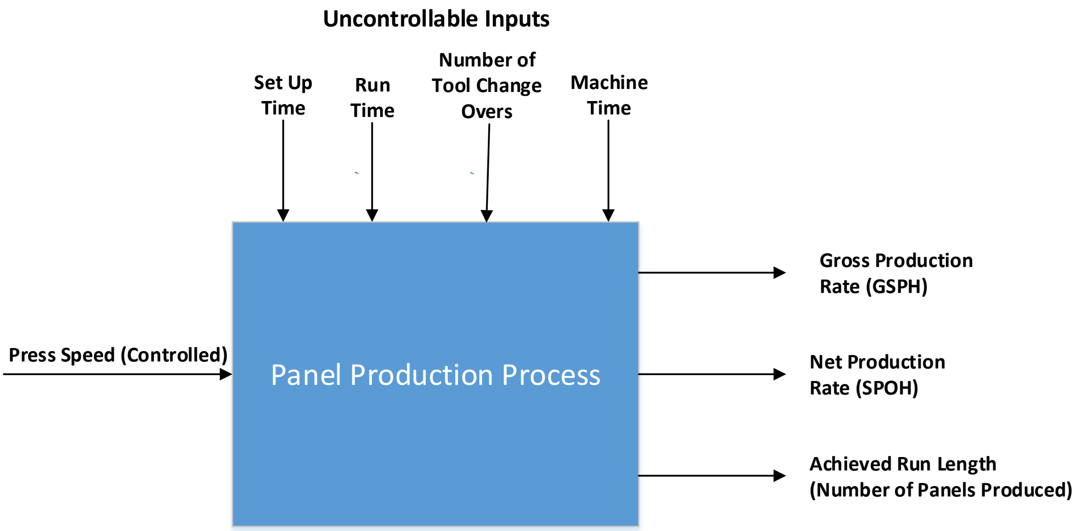


Figure 5-6 Data Inputs and Outputs to the Panel Production process

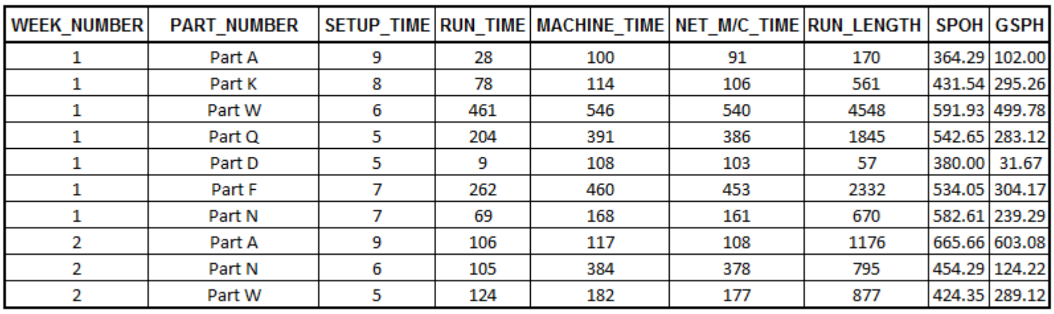
The data variables recorded during production at the part number level is shown in Table 5.1.

Variable	Type	Unit of Measure	Explanation
SETUP_TIME	Explanatory	Minutes	Measured from the completion of previous production run to start of new production run.
RUN_TIME	Explanatory	Minutes	The total time the press machine is producing parts - excludes the set up and sown time.
MACHINE_TIME	Explanatory	Minutes	The total time to complete the production run: Includes SETUP_TIME
NET_MC_TIME	Explanatory	Minutes	The total time to complete the production run: Excludes SETUP_TIME
RUN_LENGTH	Explanatory	Count	Quantity of panels produced during the production run.
SPOH	Explanatory	Shots per Operating Hour	Calculation: Shots per hour achieved during RUN_TIME (Net Production Rate)
GSPH	Response	Gross Shots per Operating Hour	Calculation: Shots per hour achieved during MACHINE_TIME (Gross Production Rate)

Table 5-1 Data Recorded During a Production Run

5.4.1. Preparation of Regression Model

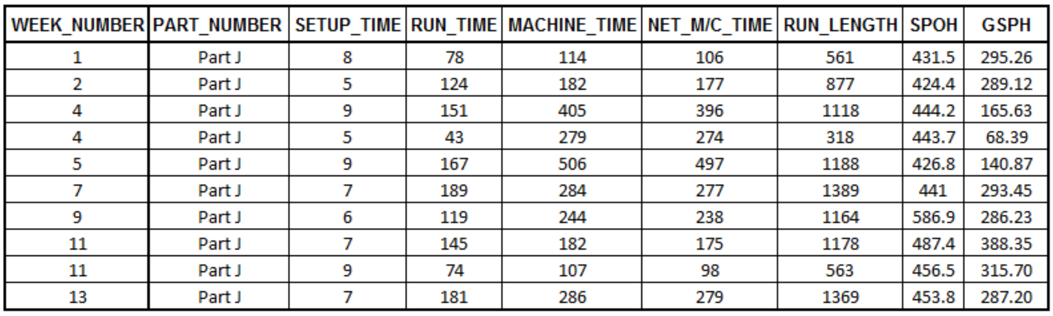
To carry out a regression model, it is necessary to obtain the observational data against each of the explanatory variables and the response variable. Production run data contained within the data warehouse is recorded at the Part Number level of the panel. The data is recorded in the production run sequence, and will include, the start and completion dates and times, the production week number and calendar year. The necessary data is exported from the data warehouse into Microsoft Excel where the SPOH and GSPH rates are calculated. Table 5.2 returns a sample of data obtained recorded against production week numbers 1 and 2.



WEEK_NUMBER	PART_NUMBER	SETUP_TIME	RUN_TIME	MACHINE_TIME	NET_M/C_TIME	RUN_LENGTH	SPOH	GSPH
1	Part A	9	28	100	91	170	364.29	102.00
1	Part K	8	78	114	106	561	431.54	295.26
1	Part W	6	461	546	540	4548	591.93	499.78
1	Part Q	5	204	391	386	1845	542.65	283.12
1	Part D	5	9	108	103	57	380.00	31.67
1	Part F	7	262	460	453	2332	534.05	304.17
1	Part N	7	69	168	161	670	582.61	239.29
2	Part A	9	106	117	108	1176	665.66	603.08
2	Part N	6	105	384	378	795	454.29	124.22
2	Part W	5	124	182	177	877	424.35	289.12

Table 5-2 Recorded Data for Production Weeks No 1 & 2

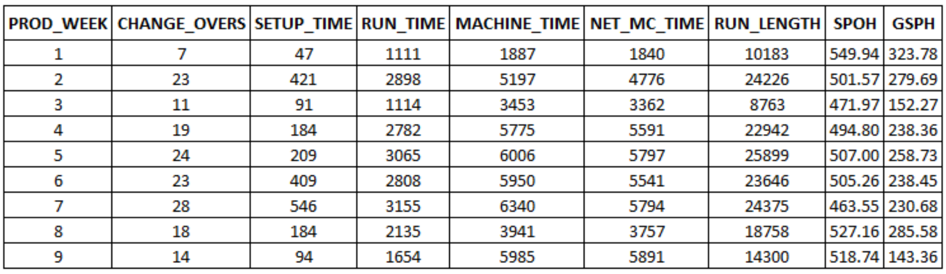
Table 5.3 returns production data collated against an individual part number over a succession of production weeks (actual Part Numbers removed).



WEEK_NUMBER	PART_NUMBER	SETUP_TIME	RUN_TIME	MACHINE_TIME	NET_M/C_TIME	RUN_LENGTH	SPOH	GSPH
1	Part J	8	78	114	106	561	431.5	295.26
2	Part J	5	124	182	177	877	424.4	289.12
4	Part J	9	151	405	396	1118	444.2	165.63
4	Part J	5	43	279	274	318	443.7	68.39
5	Part J	9	167	506	497	1188	426.8	140.87
7	Part J	7	189	284	277	1389	441	293.45
9	Part J	6	119	244	238	1164	586.9	286.23
11	Part J	7	145	182	175	1178	487.4	388.35
11	Part J	9	74	107	98	563	456.5	315.70
13	Part J	7	181	286	279	1369	453.8	287.20

Table 5-3 Recorded Production Data: Part Number Example

The data represented in Table 5.2 is summed over the total of production runs over the production week to calculate a weekly SPOH and GSPH measure. The summation over successive production weeks leads to the creation of Table 5.4 to provide the weekly SPOH and GSPH rates and provides the data for the creation of a regression model. As the number of tool changes per week has the potential to influence the GSPH rate, for inclusion in the regression model, Table 5.4 includes the number of tool changes per week (CHANGE_OVERS) for the regression model.



PROD_WEEK	CHANGE_OVERS	SETUP_TIME	RUN_TIME	MACHINE_TIME	NET_MC_TIME	RUN_LENGTH	SPOH	GSPH
1	7	47	1111	1887	1840	10183	549.94	323.78
2	23	421	2898	5197	4776	24226	501.57	279.69
3	11	91	1114	3453	3362	8763	471.97	152.27
4	19	184	2782	5775	5591	22942	494.80	238.36
5	24	209	3065	6006	5797	25899	507.00	258.73
6	23	409	2808	5950	5541	23646	505.26	238.45
7	28	546	3155	6340	5794	24375	463.55	230.68
8	18	184	2135	3941	3757	18758	527.16	285.58
9	14	94	1654	5985	5891	14300	518.74	143.36

Table 5-4 SPOH and GSPH Calculation for Total Weekly Production

5.4.2. Sampling Methodology for Individual Production Runs

It is not practical to analyse the totality of the 2365 individual production runs. Generally for a suitable regression model, at least 30 samples of data are required to generate meaningful analysis (Harrell, 2006). To obtain an objective analysis of the relationship between the explanatory variables and the predictor variable, random samples are taken of individual production runs from the total of the 2365 runs.

The total of the 2365 production run are exported into Microsoft Excel. A random number is applied to each production run record using the Excel random number function (RAND). The RAND function assigns a random number between 0 and 1. The spread sheet sort function is applied to the complete data set to sort the data in random number order (from low to high).

For analysis at the Part Number level, samples of 60 production run records are taken to run regression models in the statistical package Minitab. Regression runs frequently identify observations that can have undue influence to the output (either outliers, identified by high residual values, or points of high leverage). Choosing a sample size of 60 allows for the removal of extreme data values while leaving enough values for subsequent regression runs.

5.4.3. Regression Analysis of Weekly

To quantify if the number of tool changeovers per week affect the GSPH rate, it is necessary to run a regression model against the weekly data as represented in Table 5.4. An initial regression run is carried out in Minitab against the total of the 116 production weeks where the output of the run is presented in Table 5.5.

Regression Analysis: GSPH versus CHANGE_OVERS, SETUP_TIME, ...

```
The regression equation is
GSPH = - 346 - 0.178 CHANGE_OVERS - 0.0603 SETUP_TIME + 0.223 RUN_TIME
       - 0.0590 NET_MC_TIME - 0.0144 RUN_LENGTH + 1.28 SPOH


Predictor          Coif   SE Coif       T      P
Constant         -345.61     37.51   -9.21  0.000
CHANGE_OVERS     -0.1776    0.4455   -0.40  0.691
SETUP_TIME      -0.06031   0.01086   -5.55  0.000
RUN_TIME         0.22275   0.02312    9.64  0.000
NET_MC_TIME    -0.059047  0.002399  -24.61  0.000
RUN_LENGTH     -0.014387  0.002649   -5.43  0.000
SPOH             1.27674   0.07601   16.80  0.000


S = 14.3689   R-Sq = 91.9%   R-Sq(ad) = 91.4%


Analysis of Variance

Source           DF      SS     MS       F      P
Regression        6  254197  42366  205.20  0.000
Residual Error  109   22505    206
Total           115  276702


Source        DF  Esq. SS
CHANGE_OVERS   1    1037
SETUP_TIME     1    1074
RUN_TIME       1    9545
NET_MC_TIME    1  164446
RUN_LENGTH     1   19839
SPOH           1   58257
```

Table 5-5 Initial Regression Run for the Analysis of the GSPH

As a first model, regression model provides an adequate model of the relationship between the GSPH rate and the input variables. This is substantiated by the high R-Sq and R-Sq(ad) values indicating that the input variables account for over 90% of the GSPH variation. Moreover, the residual analysis of the data (illustrated in Figure 5.47 does not show any significant pattern in the residual plots. The high standardised residual and leverage values are reflected in the curvature in the normal probability plot, but given the volume of data input into the regression model, these can be ignored for the purpose of analysing the first model.

After each initial run, the observations identified as having high residual value or leverage were removed and the regression run again.

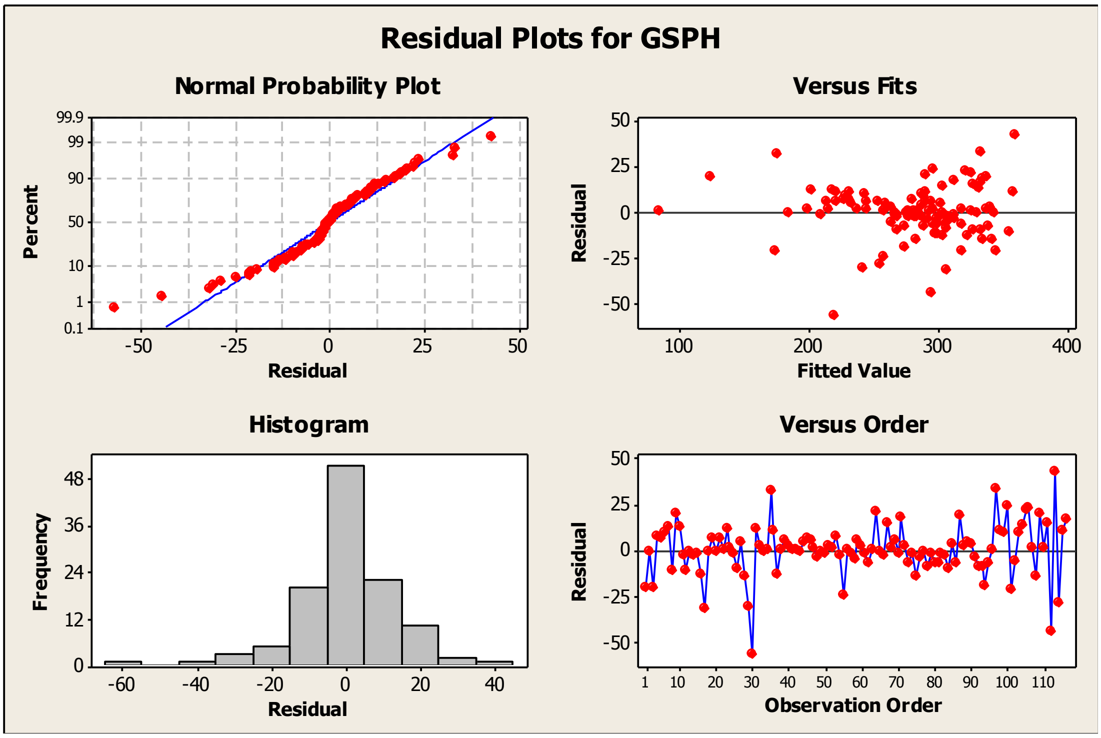


Figure 5-7 Residual Plots for First Regression Model

Table 5.6 returns the coefficients of each of the subsequent regression runs with their respective R-Sq and R-Sq(adj) values.

	Sample 1 (N = 28)			Sample 2 (N = 27)			Sample 2 (N = 25)		
Predictor	**Coef**	**T**	**P**	**Coef**	**T**	**P**	**Coef**	**T**	**P**
Constant	-482.02	-5.33	0.000	-183.3	-0.55	0.590	-328.77	-3.64	0.002
CHANGE_OVERS	-0.909	-2.03	0.055	0.046	0.04	0.965	0.454	0.93	0.364
SETUP_TIME	-0.057	-5.53	0.000	-0.064	-3.46	0.002	-0.052	-4.17	0.001
RUN_TIME	0.337	7.02	0.000	0.15	1.43	0.168	0.191	6.09	0.000
NET_MC_TIME	-0.61	-27.59	0.000	-0.064	-11.56	0.000	-0.051	-12.73	0.000
RUN_LENGTH	-0.028	-5.05	0.000	-0.004	-0.33	0.743	-0.013	-3.17	0.005
SPOH	1.59	8.81	0.000	-0.929	1.37	0.186	1.237	7.04	0.000
R-Sq	98.50%			91.60%			97.30%		
R-Sq(adj)	98.10%			89.10%			96.40%		

Table 5-6 Output of Random Sample Regression Runs

The regression models were run at the 5% significant level and consequently regression coefficients with $P < 0.05$ are considered to influence the GSPH response variable.

5.4.4. Interpretation of Regression Analysis Output.

From the initial regression run, evidence is provided that the GSPH rate is positively influenced by the RUN_TIME and the SPOH and negatively impacted by the SETUP_TIME,NET_MC_TIME and RUN_LENGTH, indicated by the low P value, (P = 0). Conversely, CHANGE_OVERS does not have a significant effect on the GSPH response variable indicated by the high P value (P =0.691).The regression outputs from the random samples substantiates the conclusion with respect to the insignificance of CHANGE_OVERS. However the regression output for Sample 2 additionally indicates that RUN_TIME, RUN_LENGHT and SPOH do not significantly affect the GSPH value (P > 0.05).

A Stepwise Regression analysis reinforces the evidence presented in the initial regression analysis that the number of change overs per week does not impact on the GSPH rate and eliminates the CHANGE_OVERS variable from the regression equation. The values of the remaining coefficients are not significantly different from the original regression equation and are compared in Table 5.7. Similarly, Stepwise Regression Analysis carried on each of the random samples also eliminates the CHANGE_OVERS variable from the regression equation.

The significance of the evidence of no effect to the GSPH rate is that further analysis can focus on random samples from the population of individual production runs rather than the concentrating on the summation of the measures successive production weeks

	CHANGE_OVERS	
Predictor	**Included**	**Removed**
Constant	-345.61	-345.52
SETUP_TIME	-0.06031	-0.06106
RUN_TIME	0.22275	0.22066
NET_MC_TIME	-0.059047	-0.05913
RUN_LENGTH	-0.014387	-0.01427
SPOH	1.27674	1.27562
R-Sq	91.9%	91.9%
R-Sq(adj)	91.4%	91.5%

Table 5-7 Regression Coefficients Comparison for CHANGE_OVERS

The initial regression model and the random sample provide the basis for further investigation based on the following observations:

Change Overs: The number of job change overs per week does is not correlated with the GSPH rate. This can be interpreted as the observed variation in frequency of change over's has no impact on the GSPH rate. It is not necessarily an indicator that increasing the number of change over's per production week will not impact on the GSPH rate.

Set Up Time: The set up time reduces the GSPH rate. Set up time cannot be avoided, but it is possible that the set up times that are excessive have a greater influence over the GSPH rate when compared to the larger proportion of set up times considered within acceptable limits.

Run Time: An increase in run time yields a positive contribution to the GSPH rate. Run Time measures continuous production. Potentially the greater the proportion of the overall machine time given over to continuous running enables the process to run faster. However, the regression output from Sample 2 suggests that the Run Time is not significant in contrast to the other regression outputs indicating that further examination of the influence of this predictor variable is required.

Net M/C Time: The net machine time is the measure the total production time post set up time. The measure has a negative impact on the GSPH rate. Potentially this is due to a greater proportion of the net machine time for longer production runs are given over to downtime.

Run Length: Increasing the run length indicates that the GSPH will reduce. But it is possible, that the greater the run length will increase the proportion of machine time given over to down time. It is necessary that the greater proportion of machine time is consumed by run time. However, it would be useful to understand at what proportion of machine converted to run time yields a positive contribution to GSPH from increasing the run length. In Sample 2, the run length is shown to have no significant influence on the GSPH which is the converse to the other regression output.

SPOH: The SPOH rate is a measure of output during continuous run time. The regression analysis implies that the SPOH rate has the significant impact on increasing the GSPH rate. Intuitively this makes sense as the ability to run the production process faster during continuous run time. Sample 2 indicates that the SPOH rate has no significant influence on the GSPH rate. The conclusion is counter intuitive as the faster or slower the pressing process performs during continuous run time should impact on the GSPH rate.

5.4.5. Analysis of Randomly Selected Production Run Data

The regression analysis is consistent in showing that the number of tool change overs per week does not significantly influence the GSPH rate. Therefore all further analysis is conducted against random samples drawn from the available population of observed production run data. Against each of the predictor variables, there is considerable variation. For two of the predictors SETUP_TIME and RUN_LENGTH, the variation is illustrated in a set of four histograms (Figures 5.5 and 5.6 respectively) constructed from drawing random samples (N = 60) from the available population.

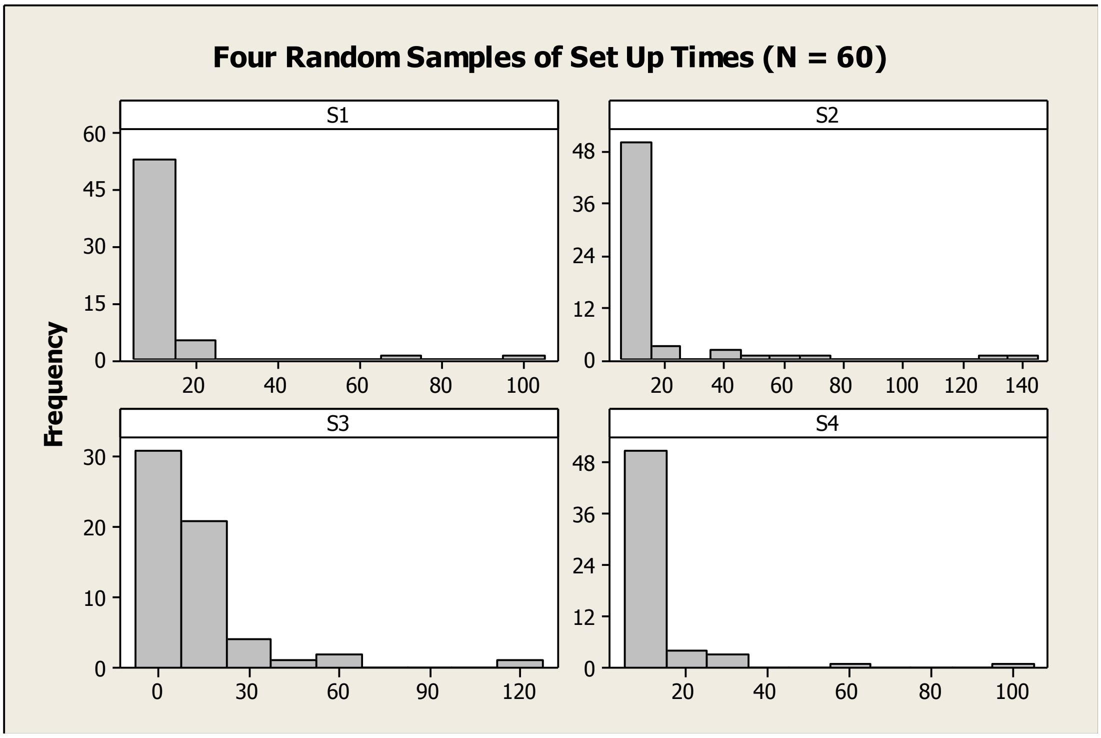


Figure 5-8 Histograms of Random Samples of Set Up Times

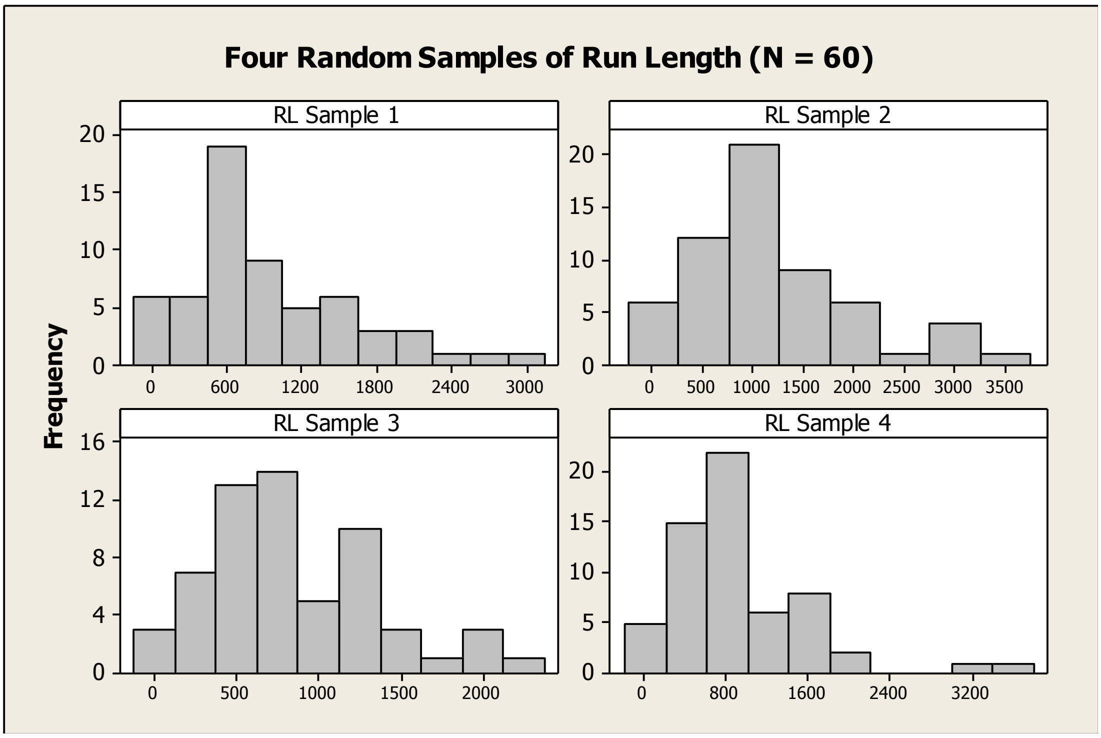


Figure 5-9 Histograms of Random Samples of Run Lengths

In each of the histograms, the random samples include a reduced number of extreme values that have the potential in a regression model to contribute to the inclusion of high residual data values and points of high leverage. Taking initial random samples of 60 observations will enable the removal of identified extreme values from the sample while leaving a sufficient number of random observations to provide an adequate regression analysis.

5.4.6. Analysis of Random Samples from Individual Production Runs

Two random samples of 60 observations each were taken from the available population of observed production runs. Each selection required three regressions runs before the removal of the high residual and leverage points yielded a reasonable regression model. The final models are presented in Tables 5.10 and 5.11 respectively.

Results for: Sample No 1 – Third Regression Run: N = 47

Regression Analysis: GSPH versus SETUP_TIME, RUN_MINS, ...

```
The regression equation is
GSPH = - 157 - 0.975 SETUP_TIME + 2.54 RUN_MINS - 1.31 NET_M/C_TIME
       - 0.0590 RUN_LENGTH + 0.962 SPOH

Predictor          Coef  SE Coef       T      P          95% CI
Constant        -156.57    54.50   -2.87  0.006 (-266.628, -46.5116)
SETUP_TIME      -0.9750   0.3354   -2.91  0.006 (  -1.652,  -0.2976)
RUN_MINS         2.5391   0.4378    5.80  0.000 (   1.655,   3.4232)
NET_M/C_TIME   -1.31147  0.06056  -21.65  0.000 (  -1.434,  -1.1892)
RUN_LENGTH     -0.05903  0.05530   -1.07  0.292 (  -0.171,   0.0526)
SPOH             0.9625   0.1175    8.19  0.000 (   0.725,   1.1999)

S = 17.0483   R-Sq = 96.9%   R-Sq(adj) = 96.5%
```

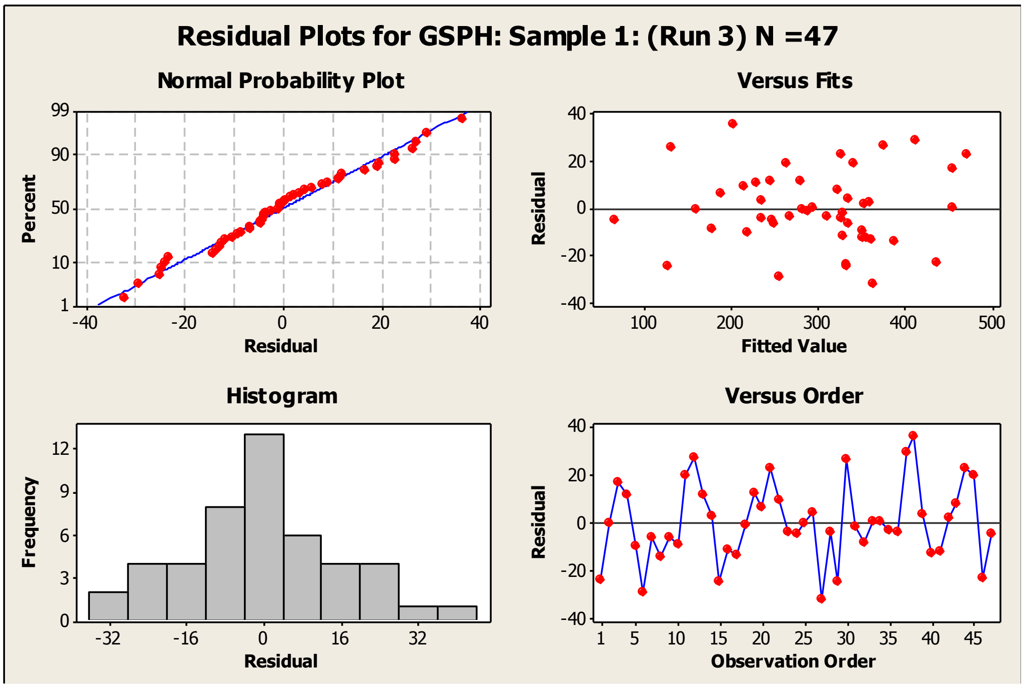


Figure 5-10 Sample No 1: Regression Model (Fragment)

Each regression model is robust accounting for 97% and 94% of the variation in Samples 1 and 2 respectively. Moreover the residual value plots in each sample indicate the residual values follow a normal distribution. Table 5.8 presents a comparison of the coefficients for the two samples. The coefficient effect is consistent across the two samples in respect to the influence to the response variable is positive or negative. With respect to the significance of the coefficient effect, other than for SETUP_TIME, the significance is consistent.

Results for: Sample No 2 – Third Regression Run: N = 45

Regression Analysis: GSPH versus SETUP_TIME, RUN_MINS, ...

```
The regression equation is
GSPH = - 57.2 - 0.405 SETUP_TIME + 2.18 RUN_MINS - 1.16 NET_M/C_TIME
       - 0.0396 RUN_LENGTH + 0.743 SPOH

Predictor          Coef  SE Coef       T      P         95% CI
Constant         -57.15    65.82   -0.87  0.391 (-190.289, 75.9861)
SETUP_TIME      -0.4053   0.5705   -0.71  0.482 (  -1.559,  0.7487)
RUN_MINS         2.1771   0.4203    5.18  0.000 (   1.327,  3.0273)
NET_M/C_TIME   -1.16363  0.06686  -17.40  0.000 (  -1.299, -1.0284)
RUN_LENGTH     -0.03958  0.04660   -0.85  0.401 (  -0.134,  0.0547)
SPOH             0.7425   0.1371    5.41  0.000 (   0.465,  1.0199)


S = 19.6674   R-Sq = 94.2%   R-Sq(adj) = 93.4%
```

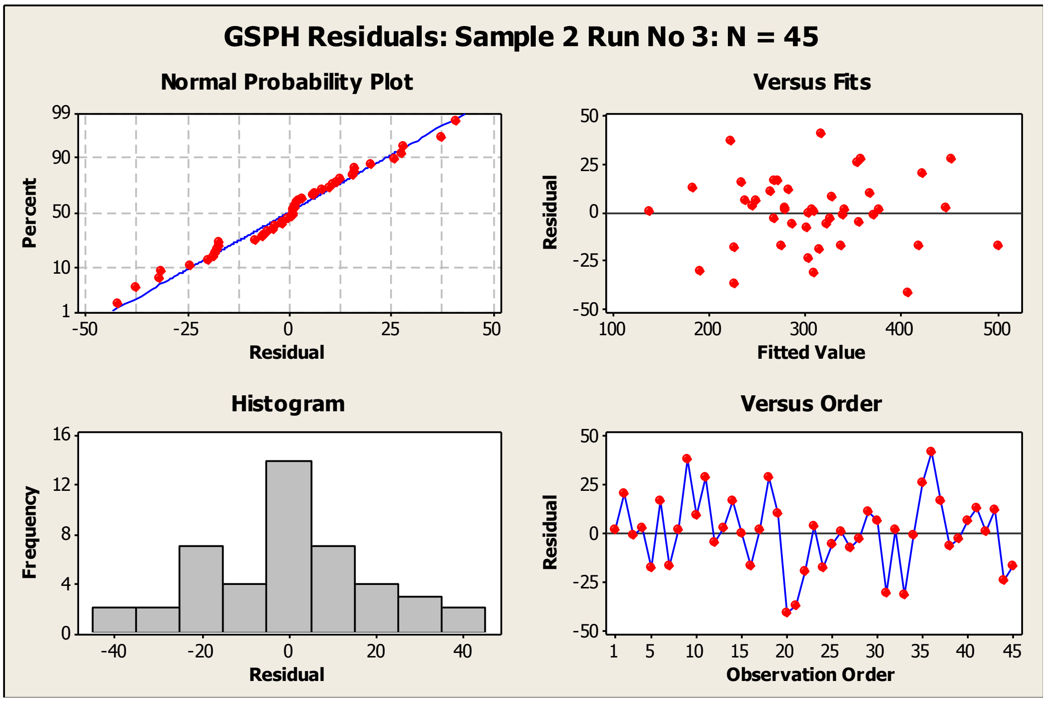


Figure 5-11 Sample No 2: Regression Model (Fragment)

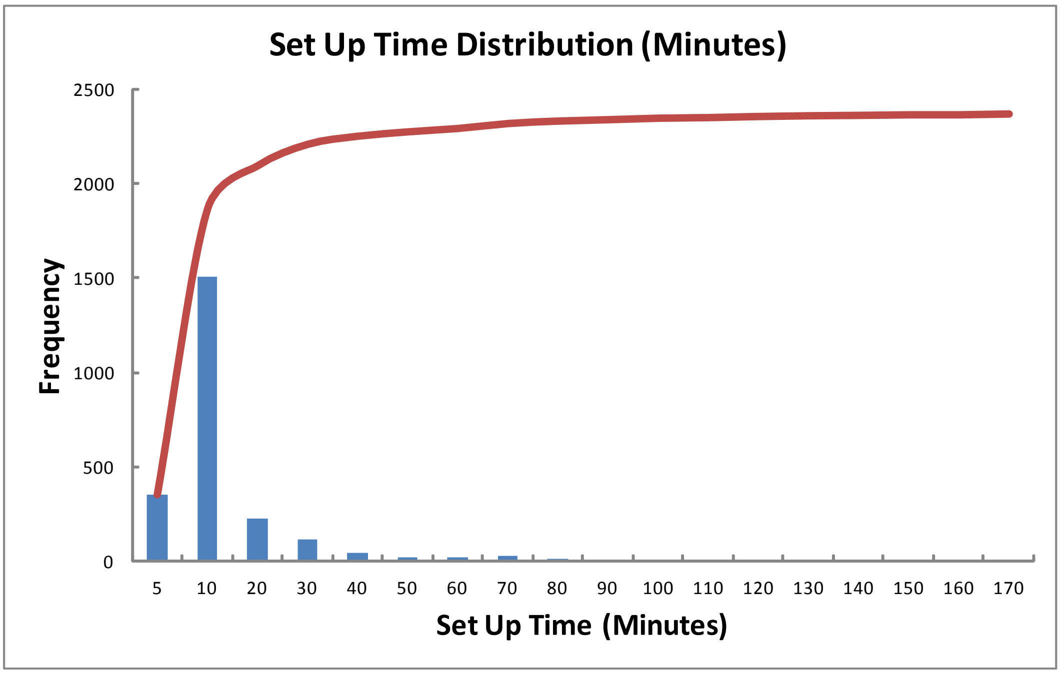
	Coefficient Effect		Significant	
Predictor	**1**	**2**	**1**	**2**
SETUP_TIME	N	N	Yes	No
RUN_MINS	P	P	Yes	Yes
NET_M/C_TIME	N	N	Yes	Yes
RUN_LENGTH	N	N	No	No
SPOH	P	P	Yes	Yes

P = Positive N = Negative

Table 5-8 Comparison of Sample Coefficients

Set Up Time

The distribution graph of the SETUP_TIME variable for all 2365 observed production run observations is returned in Figure 5.12.



Interval (Mins)	5	6 - 10	11 - 20	21 - 30	31 - 40	41 - 50	51 - 60	61 - 70	71 - 80	81 - 90	> 100
Frequency	354	1508	229	114	43	23	18	26	13	7	30
% Frequency	15%	64%	10%	5%	2%	1%	1%	1%	1%	0%	1%
% Cumlative	15%	79%	88%	93%	95%	96%	97%	98%	98%	99%	100%

Figure 5-12 Distribution of Set Up Times

The spread of the observed data provides the basis for understanding why the influence of SETUP_TIME is significant in Sample 1 and not significant in Sample 2. Almost 90% of the observed set up times takes less than 20 minutes and almost 65% of the set up time occur in the [6 – 10] minute interval. A uniform random sample of the set up times will be dominated by values in these intervals. If a random sample does not contain sufficient observations from the intervals that contain the relatively few excessive set up times, the SETUP_TIME variable will not have a significant effect.

Figure 5.13 returns the histograms of the SETUP_TIME data from the final regression runs. Sample 1 has a wider spread of data than Sample 2 reflected in the larger standard deviation. A box plot of the SETUP_TIME distributions is provided in Figure 5.14 providing further visual evidence of the difference of the spread of the data between the samples.

Further evidence to whether a regression coefficient has a significant influence on the response variable is to inspect the confidence interval for the coefficient. If the confidence interval contains zero, then the coefficient is not significant. The confidence interval for Sample 2 (-1.559, 0.7487) contains zero while for Sample 1 the interval (-1.652, -0.2976) does not contain zero but the upper bound of the interval is close to zero.

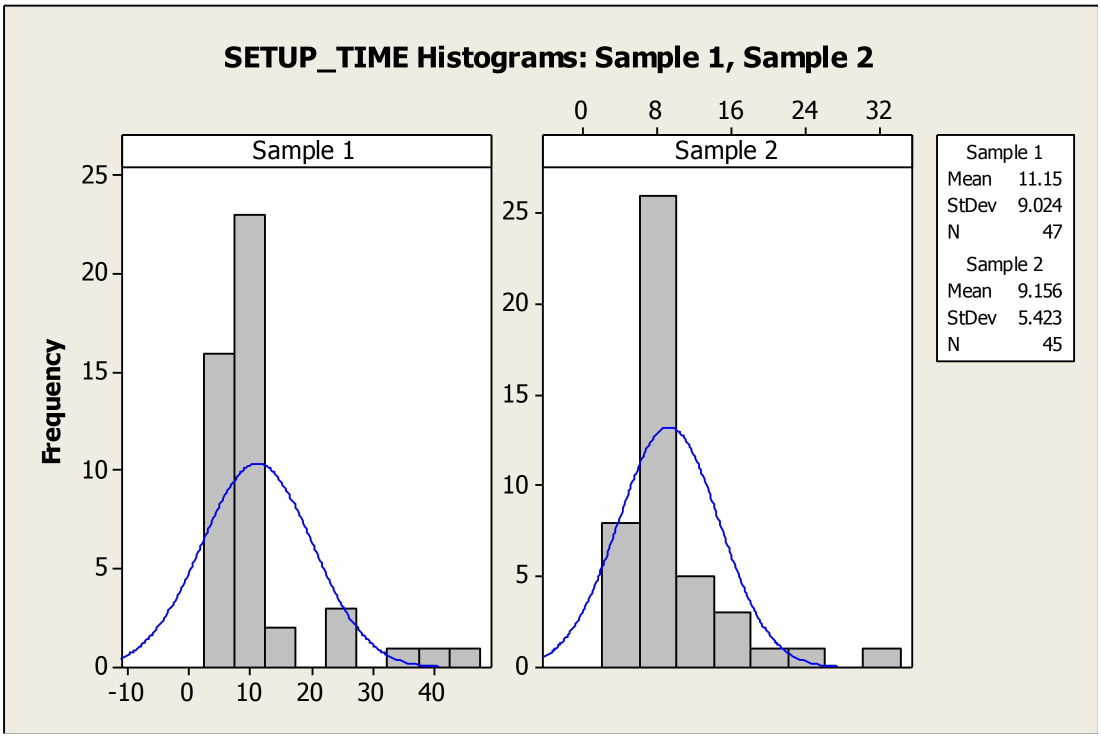


Figure 5-13 Histograms of Sample Set Up Times.

The regression models provide eveidence that the SETUP_TIME predictor variable does not significantly influence the GSPH rate.

5.4.7. Analysis of Post Set Up Production Performance

Intuitively, increasing the GSPH rate is accomplished by ensuring that the RUN_TIME proportion of the MACHINE_TIME is maximised and during continuous running the production press is run at an optimum speed so increasing the infuence of the SPOH variable.

To test this ituitive conjecture, a variable is introduced taking the ratio of RUN_TIME to MACHINE_TIME(RT/MT Ratio). A regression model is run to assess the effect of the RT/MT Ratio on GSPH on a random sample of 60 observations. The regression analysis is presented in Figure 5.15 and indicates that the ratio has a strong influence on the GSPH value as the RUN_TIME dominates the greater proportion of the MACHINE_TIME. The previous regression analysis outputs are consistent with respect to an increase in NET_MC_TIME (the total run time measured after completion of the set up process)

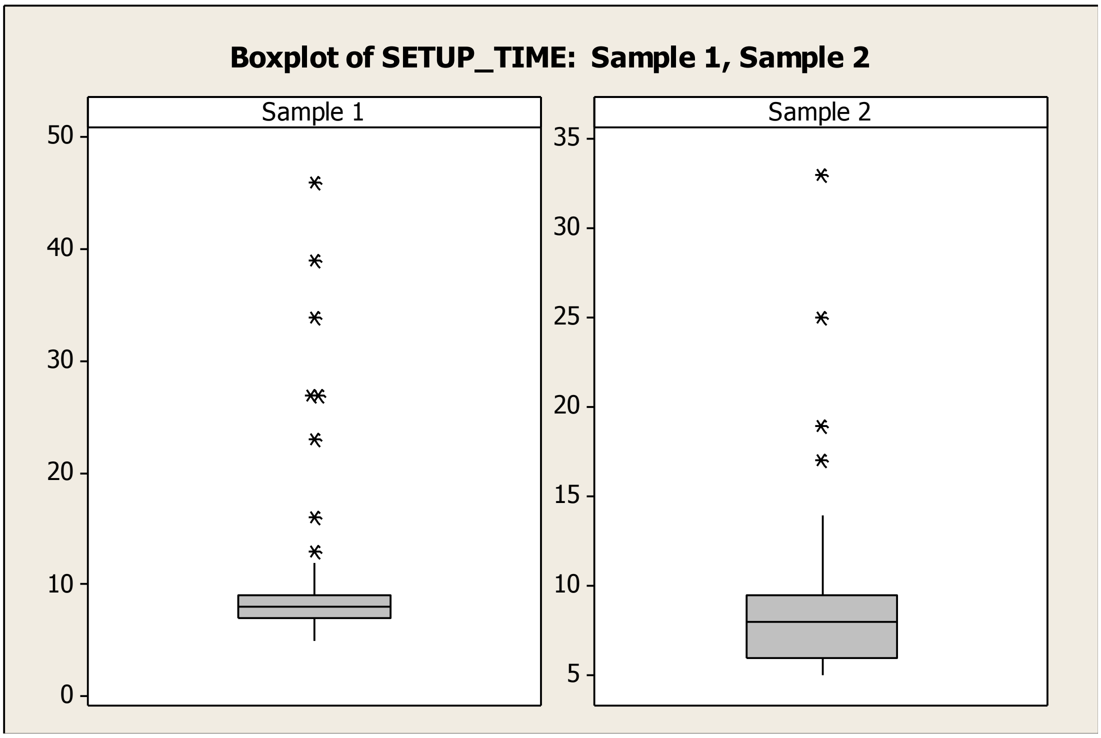


Figure 5-14 Box plots of Sample SETUP_TIME

The regression models provide eveidence that the SETUP_TIME predictor variable does not significantly influence the GSPH rate.

Potentially this implies that there exists an interaction btweeen RUN_TIME amd SPOH that contributes positively to the GSPH rate that can be investiagted through an experinetal design.

Regression Analysis: GSPH versus RT/MT Ratio

```
Regression Equation


GSPH  =  -36.8679 + 531.614 RT/MT Ratio


Coefficients

Term            Coef  SE Coef        T      P        95% CI
Constant     -36.868  17.0135  -2.1670  0.035  (-71.008,  -2.728)
RT/MT Ratio  531.614  28.4907  18.6592  0.000  (474.443, 588.784)


Summary of Model

S = 34.0475      R-Sq = 87.01%        R-Sq(adj) = 86.76%
```

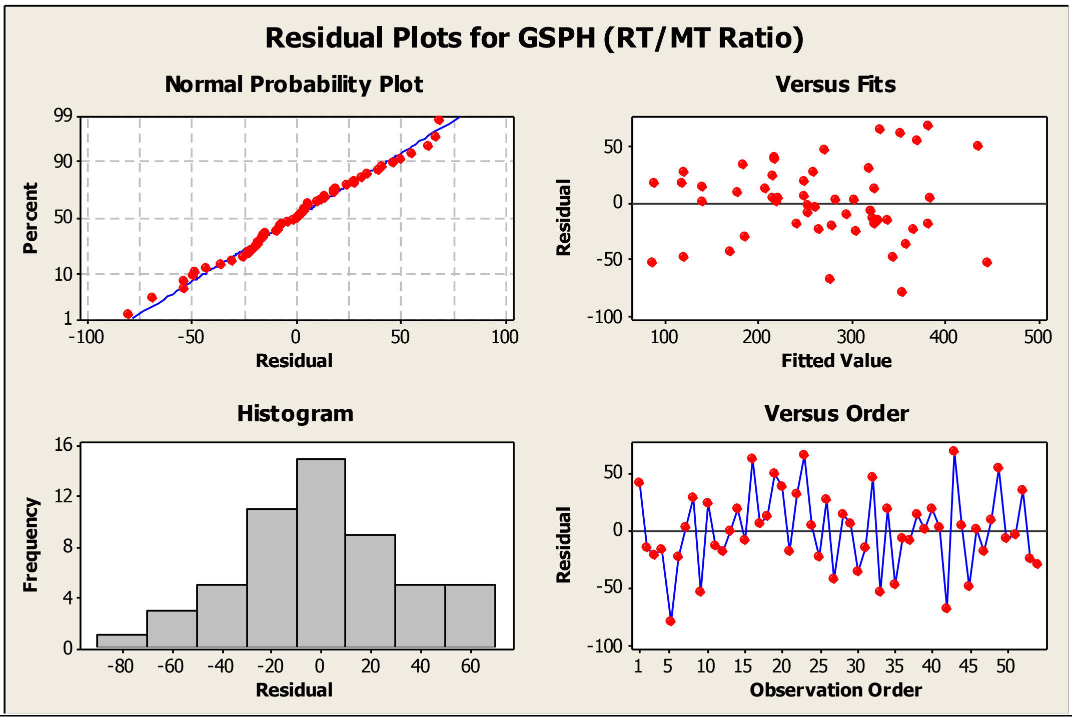


Figure 5-15 RT/MT Ratio Regression Model

5.5. Application of Experimental Design to Establish Predictor Effects

The regression analysis conducted in Section 5.4 is consistent in establishing the significance of the predictor variables influence on the response variable and if the influence is either positive or negative. Additionaly, Experimental Design is also useful for quantifying predictor effects and identifying any potential interaction between the predictor variables.

Factorial Design methods rely on the ability to fix a set of factors at an approriate number of levels to conduct the experiments. Within the press production facility the factors are the predictor variables, none of which can be fixed and become a real entity at the end of a production run. However, from the recorded production data it is possible to average the predictors over some small interval to establish a fixed factor level.

Two sets of design are constructed to test the factor and factor inteaction effect of the following predictor variables:

Design 1: RUN_TIME and SPOH. To test if an interaction exists that would imply the longer the production press is producing parts, a greater SPOH is acheived. The experiment is accomplished through a 2^2 Factorial Design.

Design 2: SETUP_TIME, SPOH and RUN_LENGTH: The experiment is carried out to verify the conclusion drawn from the regression analysis that the SETUP_TIME and RUN_LENGTH do not significantly influence the GSPH. The experiment is accomplished through a 2^3 Factorial Design.

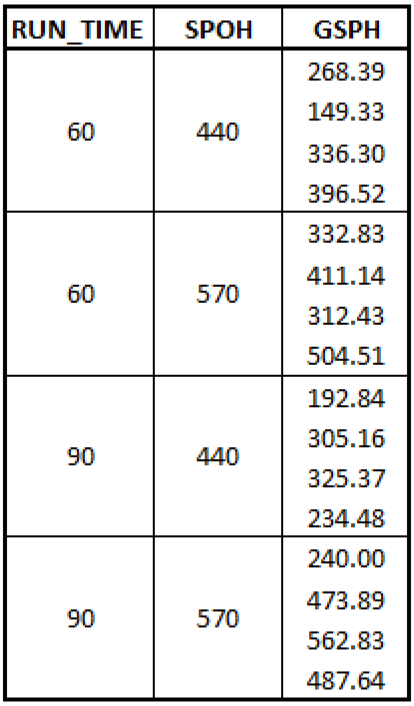
5.5.1. Design Execution

Design 1: RUN_TIME and SPOH.

Two experimental designs are constructed to assess potential interaction between the RUN_TIME and the SPOH rate. The first design is contructed against two relatively low production run times 60 minutes amd 90 minutes at a SPOH rate of 440 and 570. The second experiment is conducted against relatively longer runs at 240 and 415 minutes ata SPOH rate of 450 and 570. The data for the two experiments is presented in Table 5.10.

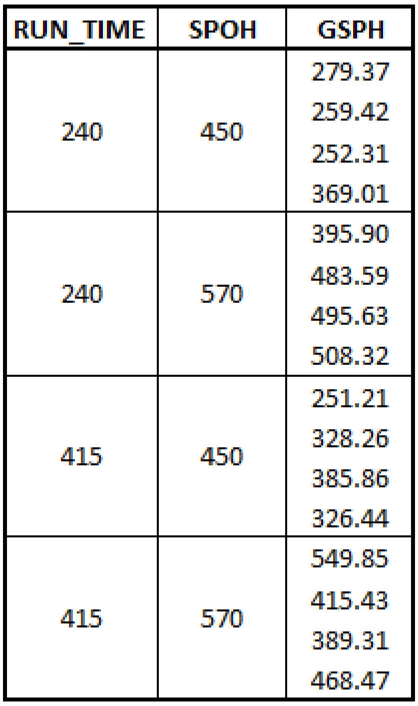
The essential output from the experemental runs carried on Minitab are presented in Tables 5.11 (Experiment 1) and Table 5.12 (Experiment 2) with the full output available in Appendix 2 and 3.

The results are consistent in that the only significant predictor varaible influencing the GSPH rate is the SPOH rate.



RUN_TIME	SPOH	GSPH
60	440	268.39
		149.33
		336.30
		396.52
60	570	332.83
		411.14
		312.43
		504.51
90	440	192.84
		305.16
		325.37
		234.48
90	570	240.00
		473.89
		562.83
		487.64

Experiment 1



RUN_TIME	SPOH	GSPH
240	450	279.37
		259.42
		252.31
		369.01
240	570	395.90
		483.59
		495.63
		508.32
415	450	251.21
		328.26
		385.86
		326.44
415	570	549.85
		415.43
		389.31
		468.47

Experiment 2

Table 5-9 Experimental Design Tables (Experiments 1 & 2)

The RUN_TIME variable and the interaction between the RUN_TIME and SPOH have no influence on the GSPH rate.

It is feasible that the absence of an interaction effect between the RUN_TIME and SPOH variables is due to the chosen running times. In Experiment 1, in particular, there is only a 30 minute difference. In that time difference it is possible nothing significant may change with respect to production performance. In Experiment 2, the lower bound on the RUN_TIME is 240 minutes (4 hours) and it is likely that the production run would have achived a consistent running rate and consequenlty there is no added gain from a performance perspective from longer production runs.

Factorial Fit: GSPH versus RUN_TIME, SPOH (Experiment 1)

```
Estimated Effects and Coefficients for GSPH (coded units)

Term               Effect      Coef  SE Coef      T      P
Constant                    345.852    25.66  13.48  0.000
RUN_TIME           13.844     6.922    25.66   0.27  0.792
SPOH              139.611    69.805    25.66   2.72  0.019
RUN_TIME*SPOH      37.017    18.508    25.66   0.72  0.485


S = 102.657      PRESS = 224820
R-Sq = 39.97%    R-Sq(pred) = 0.00%    R-Sq(adj) = 24.97%


Analysis of Variance for GSPH (coded units)

Source               DF  Seq SS  Adj SS   Adj MS     F      P
Main Effects          2   78731   78731  39365.6  3.74  0.055
  RUN_TIME            1     767     767    766.7  0.07  0.792
SPOH                 1   77965   77965  77964.6  7.40  0.019
2-Way Interactions    1    5481    5481   5481.0  0.52  0.485
  RUN_TIME*SPOH       1    5481    5481   5481.0  0.52  0.485
Residual Error       12  126461  126461  10538.4
  Pure Error         12  126461  126461  10538.4
Total                15  210674
```

Table 5-10 2^2 Factorial Design: Output of Experiment 1

Factorial Fit: GSPH versus RUN_TIME, SPOH (Experiment 2)

```
Estimated Effects and Coefficients for GSPH (coded units)

Term             Effect     Coef  SE Coef      T      P
Constant                  384.90    14.56  26.43  0.000
RUN_TIME           8.91     4.46    14.56   0.31  0.765
SPOH             156.83    78.41    14.56   5.39  0.000
RUN_TIME*SPOH    -24.00   -12.00    14.56  -0.82  0.426


S = 58.2455      PRESS = 72374.1
R-Sq = 71.27%    R-Sq(pred) = 48.93%    R-Sq(adj) = 64.09%


Analysis of Variance for GSPH (coded units)

Source               DF  Seq SS   Adj SS   Adj MS      F      P
Main Effects          2   98697  98697.5  49348.7  14.55  0.001
  RUN_TIME            1     318    317.8    317.8   0.09  0.765
  SPOH                1   98380  98379.7  98379.7  29.00  0.000
2-Way Interactions    1    2305   2304.6   2304.6   0.68  0.426
  RUN_TIME*SPOH       1    2305   2304.6   2304.6   0.68  0.426
Residual Error       12   40710  40710.4   3392.5
  Pure Error         12   40710  40710.4   3392.5
Total                15  141713
```

Table 5-11 2^2 Factorial Design: Output of Experiment 2

These two obseravtions can be substantiated or refuted by running a third model that combines the lower bound times from Experiment 1 with the upper bound times from Experiment 2. A third factorial design is created (Experiment 3) and is presented in Table 5.13.

RUN_TIME	SPOH	GSPH	RUN_TIME	SPOH	GSPH
60	450	309.77	415	450	251.21
		396.52			328.26
		292.98			385.86
		272.83			326.44
60	570	395.90	415	570	549.85
		483.59			415.43
		495.63			389.31
		508.32			468.47

Experiment 3

Table 5-12 Experimental Design Table (Experiment 3)

The output of Experiment 3 is provided in Table 5.14:

Factorial Fit: GSPH versus RUN_TIME, SPOH (Experiment 3)

```
Estimated Effects and Coefficients for GSPH (coded units)

Term               Effect     Coef  SE Coef      T      P
Constant                   391.899    14.60  26.85  0.000
RUN_TIME           -5.085   -2.543    14.60  -0.17  0.865
SPOH              142.829   71.415    14.60   4.89  0.000
RUN_TIME*SPOH     -10.005   -5.002    14.60  -0.34  0.738


S = 58.3804      PRESS = 72709.7
R-Sq = 66.75%    R-Sq(pred) = 40.89%    R-Sq(adj) = 58.44%


Analysis of Variance for GSPH (coded units)

Source              DF  Seq SS   Adj SS   Adj MS      F      P
Main Effects         2   81704  81704.3  40852.2  11.99  0.001
  RUN_TIME           1     103    103.4    103.4   0.03  0.865
  SPOH               1   81601  81600.9  81600.9  23.94  0.000
2-Way Interactions   1     400    400.4    400.4   0.12  0.738
  RUN_TIME*SPOH      1     400    400.4    400.4   0.12  0.738
Residual Error      12   40899  40899.2   3408.3
  Pure Error        12   40899  40899.2   3408.3
Total               15  123004
```

Table 5-13 2^2 Factorial Design: Output of Experiment 3

The output of Experiment 3 is consistent with the output of Experiments 1 & 2 in that the SPOH rate is significant and there is no interaction effect between RUN_TIME and SPOH. The full model is available in Appendix 4.

Design 2: SETUP_TIME, SPOH and RUN_LENGTH:

The data collected for the factorial design is presented in Table 5.15

SETUP_TIME	SPOH	RUN_LENGTH	GSPH	SETUP_TIME	SPOH	RUN_LENGTH	GSPH
10	475	2000	340.1	20	475	2000	329.7
			345.3				301.7
			276.6				352.1
			318.8				428.5
		3000	287.8			3000	408.5
			320.2				332.2
			323.9				282.7
			380.1				386.5
	575	2000	507.6		575	2000	400.7
			490.1				450.8
			398.6				452.8
			393.4				369.9
		3000	342.0			3000	287.0
			336.8				381.3
			449.4				472.8
			489.1				479.7

Table 5-14 2^3 Factorial Design Table

The output of the factorial analysis is presented in Table 5.16 and supports the eveidence presented in the regression analysis that the SETUP_TIME and RUN_LENGTH do not significantly influence the GSPH rate. The full model is aavailable in Appendix 5.

5.6. Concluding Remarks

The press production process is subject to considerable variation that makes it difficult for the managers to quantify the appropriate batch size that would contribute to optimising production performance. However the analysis has established that the RUN_LENGTH does not significantly affect the GSPH rate allowing managers to choose lower production run lengths without compromising performance.

With respect to process improvement, investigations should be applied to the causal factors of downtime as eliminating downtime contributes to increasing the GSPH rate. While the SETUP_TIME is shown not to have a significant effect on the GSPH rate, it does mitigate the need to improve the tool change over time. Change over time reduction through continuous imptovement would be welcone - but it is unlikely to realise a significant increase in GSPH.

Factorial Fit: GSPH versus SETUP_TIME, SPOH, RUN_LENGTH

```
Estimated Effects and Coefficients for GSPH (coded units)

Term                        Effect    Coef  SE Coef      T      P
Constant                            378.65    10.44  36.26  0.000
SETUP_TIME                    7.32    3.66    10.44   0.35  0.729
SPOH                         80.46   40.23    10.44   3.85  0.001
RUN_LENGTH                  -12.29   -6.15    10.44  -0.59  0.562
SETUP_TIME*SPOH             -21.32  -10.66    10.44  -1.02  0.318
SETUP_TIME*RUN_LENGTH         5.36    2.68    10.44   0.26  0.800
SPOH*RUN_LENGTH             -15.93   -7.97    10.44  -0.76  0.453
SETUP_TIME*SPOH*RUN_LENGTH    9.52    4.76    10.44   0.46  0.653


S = 59.0752     PRESS = 148902
R-Sq = 41.75%   R-Sq(pred) = 0.00%   R-Sq(adj) = 24.77%


Analysis of Variance for GSPH (coded units)

Source                        DF  Seq SS   Adj SS   Adj MS      F      P
Main Effects                   3   53423  53423.3  17807.8   5.10  0.007
  SETUP_TIME                   1     429    428.5    428.5   0.12  0.729
SPOH                           1   51786  51785.7  51785.7  14.84  0.001
  RUN_LENGTH                   1    1209   1209.1   1209.1   0.35  0.562
2-Way Interactions             3    5896   5895.9   1965.3   0.56  0.645
  SETUP_TIME*SPOH              1    3636   3635.9   3635.9   1.04  0.318
  SETUP_TIME*RUN_LENGTH        1     230    229.5    229.5   0.07  0.800
  SPOH*RUN_LENGTH              1    2030   2030.4   2030.4   0.58  0.453
3-Way Interactions             1     725    724.9    724.9   0.21  0.653
  SETUP_TIME*SPOH*RUN_LENGTH   1     725    724.9    724.9   0.21  0.653
Residual Error                24   83757  83757.2   3489.9
  Pure Error                  24   83757  83757.2   3489.9
Total                         31  143801
```

Table 5-15 2^3 Factorial Model Output of Design 2

The dominant contribution to the GSPH rate is through the SPOH rate. SPOH is just the speed the press operates during continuous running. The SPOH rate is not affected by any predictor variable. Improvements to SPOH will only come from the ability of the press to run faster.

Through the analysis providing evidence that the RUN_LENGTH does not affect performace, managers are free to choose production run lengths as they feel appropriate. Though lean thinking would suggest a lower run length, managers may want a longer run length to enable the press tools to stay in maintenance for longer between runs or free up time to the tool change time to carry out Total Preventative Maintenance activities.

The regression modelling is an appropriate modelling method to analyse variable data. Experimental design is a proven technigue but can be difficult to apply in scenarios where there is little or no controllable factors. The technique could be applied in the case study environment as there was sufficient data availble to fix some avarage factor rates.

6. Review of Modelling Methodology

6.1. Introduction

Within this Chapter the modelling approach to the case study environment is reviewed to establish if:

1. The approach is effective in respect to achieving the goal of determining a minimum production run batch size that allows optimisation of the production press.
2. The modelling approach is valid beyond the confines of the case study environment.

Capital investment in production press technology is such that to generate revenue it is critical that machine performance is optimised. The case study environment experiences variation in production output with respect to a number of measured metrics including set up time, production run lengths, down time and production rates. Consequently it is difficult for managers to rationalise the production performance such that objective decisions can be made.

While there exists uncertainty with production performance the facility is run as a lean enterprise in the true sense. In particular, there is a strong culture with respect to process improvement which is evident from the graph in Figure 5.3 showing a steady increase in GSPH rate over the observable period of just over two years production.

The difficulty for the facility managers is attempting to establish an appropriate run length or batch size that does not compromise the production efficiency of the pressing facility.

6.2. Initial Approach

The modelling methodology defined in Chapter 5 (Figure 5.2) begins by setting the objective of the investigation as the objectives define the initial model development. The facility records in real time all aspects of running performance and is archived in a data warehouse. The volume of available data enabled the application of regression modelling feasible to make sense of any potential relationship between the key performance metric, the GSPH, and other measured attributes.

With the available data, it is feasible to model the relationships at a weekly level, randomly selecting a sample of production runs or analysing the performance of an individual part number.

The first approach was to consider the performance at the weekly total level. This required the summation of the data against all production runs during the week to calculate a weekly GSPH rate.

Two sets of regression models are run. The first is a single run against all weekly totals over the observed period and the second a set of three regression runs against 30 random weekly samples. The consistent result from each of the runs was that the number of tool changeovers per week did not significantly influence the GSPH rate. The conclusion drawn from this observation is that subsequent modelling can be carried out by taking random samples from the observed data.

The subsequent regression runs from random samples were consistent in providing evidence of the following:

1. The SETUP_TIME is not significant.
2. RUN_TIME is significant.
3. NET_M/C_TIME is significant.
4. RUN_LENGTH is not significant.
5. SPOH is significant.

The evidence suggesting that the SETUP_TIME and RUN_LENGTH are not significant is counter intuitive. However, the proportion of downtime given over to setting the press tools is small relative to the overall machine downtime. This does not negate the need to improve the tooling set up times, but the improvements will not make a big impact on the GSPH rate.

6.3. Application of Design of Experiments

The conclusions drawn from the regression analysis led to a possibility of the SPOH rate and RUN_TIME interacting to jointly increase the GSPH rate. Following the advice of Montgomery (2007), that interactions can only be confirmed through an experimental design, a design was constructed to test the relationship of SPOH and the RUN_TIME on the GSPH rate. The conclusion drawn from the experimental runs, is that the SPOH rate is the only significant predictor variable. The time the press spends continuously running does not imply the tooling will run faster because the press is running longer. However, significant improvements in GSPH are achieved if the ratio of RUN_TIME to MACHINE_TIME (RT/MT) is improved in favour of the RUN_TIME.

Both the regression analysis and the DOE output is consistent with respect to the dominance of the SPOH rate and that the RUN_LENGTH is not significant. The belief that the RUN_LENGTH is an indicator of efficiency is the legacy thinking from the past when the tooling set up took several hours or even days.

6.4. Robustness of Model

The modelling approach is robust given that the two methods were consistent in output. However, the model is unable to quantify an exact batch size to run. The model does provide sufficient evidence to support the running of shorter batch runs without affecting the production rate. At least managers can make informed decisions with respect to the choice of batch and look toward a lower batch size to maintain a lower inventory profile.

The wider application of the modelling approach needs to be tested in other manufacturing scenarios before a conclusion can be drawn to the effectiveness of the modelling approach.

The approach is not about applying a specific set of mathematical methods Rather the approach promotes an understanding of the objective the potential model will need to satisfy, assessing the available data structure, applying the appropriate modelling techniques and refining the model.

The modelling approach is primarily designed to aid management decision making and should be complimentary to the vast range of proven process improvement methods.

6.5. Model Extension

The model focussed on the analysis of one single production press. The production press is one entity in a much larger manufacturing network. As the domain of the manufacturing environment is extended to include either more production presses, blanking presses, coil receipt, panel delivery, then the range of mathematical modelling methods needs to be more extensive. Chapter 4 identified a number of methods applied in manufacturing. In particular queuing theory is applicable to modelling of presses or blanking presses that feed to more than one customer.

7. Discussion, Conclusions and Further Work

7.1. Introduction

The thesis had a specific objective to formulate a modelling methodology to quantify the production batch size for an automotive panel production process that (1) minimised the inventory profile through the production process and (2) on minimising the inventory profile, the production efficiency of the production facility was not compromised. The modelling methodology was considered within the context of a lean system. To fully understand the meaning of what is considered a lean system, the evolution of lean manufacturing was considered as a process that emerged primarily from the production system developed by Toyota in the aftermath of World War II as a response to the inadequacy of Western mass production methods. Within this Chapter, the main themes of the thesis are reviewed. Section 7.2 identifies the lessons learned from the decline of mass production and the significance of the Toyota Production System. Section 7.3 emphasises the need to continue the application of lean thinking to aid manufacturers and service providers to maintain focus and alignment to the changing needs of their customers. Section 7.4 reviews the significance of the modelling approach. Further work that can continue from the work conducted within the thesis is identified in Section 7.5. The contribution to knowledge from the thesis is summarised in Section 7.5. The Chapter closes with concluding remarks in Section 7.7.

7.2. The Decline of Mass Production: The Lessons Learned

Manufacturing in common with other endeavours of human activity is an evolutionary process. The evolutionary process can fail if a system does not adapt to the unfolding changes over time that can occur within its environment. The mass production model of manufacturing developed by Henry Ford and Alfred Sloan is one such system that had failed to evolve and subsequently declined. Though the reasons for the decline of mass production are complex, two significant causal factors of decline can be identified as (1), the misalignment of the production process with the ever changing needs of an increasingly demanding customer base and (2) the complacency of manufacturing providers to recognise the need to change.

Mass production based predominately on achieving economies of scale promoted the use of large scale machinery dedicated to the manufacture of a limited product range. Manufacturers having enjoyed many years of profitable production were able to sell whatever they produced did not see the need to change or indeed recognise that customer attitudes were gradually changing. Performance measurement was related to unit output rather the efficiency of the complete manufacturing system. Consequently, product quality suffered further alienating the customer base.

In its formative years in the USA mass production was highly successful in bringing affordable products to the mass market. Consequently, the production methods of Ford in particular were copied widely by European manufactures. Similarly, Toyota engineers would also study the Ford manufacturing model. In contrast to the European manufactures that would just copy the Ford model, Toyota through Taiichi Ohno, recognised that the Ford mass production system was not a suitable application for the fragmented post World War II Japanese economy. Rather, Ohno would adapt mass production to serve the needs of the Japanese customer. Generally ignored by Western manufacturers, Toyota sought to identify and eliminate waste and improve production efficiency.

Incrementally over time, Toyota would strive to meet the objectives of waste elimination and increasing efficiency as much through trial and error as trough planning. The Toyota approach to developing their production system emphasises the significant difference between what is now recognised as lean production and mass production. Lean production through waste elimination focuses on improving the overall efficiency of the manufacturing system. Mass production predominantly focuses purely on unit output as a measure of performance. The wider operations management literature would illustrate the differences between the methods by emphasising the difference between for example push and pull production or batch production and JIT manufacturing. These are however operational differences and are symptoms due to the differences in each approach.

Taiichi Ohno, the ‘Principle Architect’ of the Toyota Production System, characterised the purpose of the system as follows:

> ‘All we are doing is looking at the time line, from the moment the customer gives us an order to the point when we collect the cash. And we are reducing the time line by reducing the non-value adding wastes’, (Ohno, 1988).

The quotation is widely replicated both in the lean academic and general training literature. Though Ohno does not reference the needs of the customer, at the operational level, the quotation succinctly defines the purpose of waste elimination. There is no equivalent statement of purpose within the mass production model.

7.3. The Need for Continuing Lean Thinking

The lesson learned from the decline of mass production is that manufacturing systems need to continually evolve to ensure alignment to the needs of customers. Due to advances in manufacturing technology, product design, the availability of new materials and information system including the internet, manufacturing has the potential to offer a wider variety of products to customers. Customers are in turn demanding more from providers with respect to the provision of desirable as well as functional product and service attributes.

Meeting these requirements manufacturers need both discipline and focus. Discipline implying that the structures are in place that ensures that focus is maintained to meeting customer needs. The underlying principles of lean production provide the catalyst for creating the manufacturing infrastructure and the focus.

Focus within lean thinking is realised through the delivery of value. Though in general, the lean literature considers the concept of value in terms of the ultimate customer. In reality, lean thinking provides two types of value. Firstly, as advocated within the lean literature, value as perceived by the customer that is realised by the provision of the product and service attributes the customer desires. The second form of value is that obtained by the provider through the revenue obtained through supplying the product and service.

Value stream identification is the lean principle that captures value for both customer and provider. For the customer, value is obtained by identifying the processes that add value to the product and for the provider trough the reduction of non-value added processes. Accepting that customers will only pay what they consider a fair price for a product or service, the elimination of non-value added processes maximises the revenue obtained for the provider.

The initial application of lean thinking is predominantly about the transition of a non-lean system to a lean system. Mature lean systems are likely to regress if the focus and discipline is not maintained. Consequently, for both emerging and mature lean systems, the continued application of the lean principles can ensure that the manufacturing system while continuously evolving is aligned to the value needs of customer.

7.4. Significance of the Modelling Approach

Specifically within the case study environment, the motivation to developing the methodology was two-fold. Firstly, the recognition that traditional economic batch quantity models were not applicable within that environment. Secondly, the recognition that manufacturing systems are complex entities and that the complexity can be mitigated by analysing manageable sub-systems and iteratively enhancing the model. It is the iterative nature of the modelling process that is the significant factor of the approach. The iteration controls the breakdown of a complex system to a series of sub-systems that are conducive to modelling by appropriate analytical methods.

7.5. Further Work Directions

Based on the work carried out within the thesis, a number of opportunities have emerged that form the basis for further investigation and work. The opportunities include:

1. **Customer Value:** Of the five lean principles, the principle of customer value is subjective. Moreover, the lean literature is weak with respect to identifying how to capture what is of value to a customer. Within a lean context there is scope to create a body of knowledge to create a consistent understanding of customer perceived value and how to identify that value. Given the increasing competitiveness within manufacturing, it is important that manufacturers have a strong grasp of what their current and potential

customers' value. Manufacturers can be successful in every operational dimension but can fail if they do not correctly anticipate their customer value needs.

2. **Additional Analysis Methods**: The analysis methods identified in Chapter 4 include the more common methods applicable to the analysis of manufacturing systems. The methods are not exclusive and given the potential complexity of manufacturing systems, additional modelling methods may be required to adequately analyse the system. It is relevant therefore to research a wider portfolio of analytical and simulation methods that can be applied in the modelling loop. Simulation methods are appropriate where the complexity of the system precludes the use of a direct analytical method.

3. **Inclusion of Process Improvement Methods to the Model:** During iterative stages of the modelling process, the model may identify some attribute or attributes of the manufacturing system where improvements are necessary to optimise the system. Potentially the modelling process can be enhanced through understanding how to include improvement methods into the modelling process.

4. **Modelling of Inventory Profiles:** Not all inventory profiles fit a JIT or MRP method of control. These can include inventory profiles that follow stochastic or weak demand or alternatively profiles resulting from manufacturing processes that cannot be finitely controlled. Though such inventory profiles are rare, if not managed effectively, significant disruption can occur to the production system As an example, during the study for this thesis a unique stochastic inventory demand profile was identified for the procurement of crank shaft shells for petrol engine construction (Davies, *et al* 2014).

7.6. Contribution of the Thesis

The objective of this thesis emerged from a desire to understand how to determine an appropriate batch size for an automotive body panel production process that ensured that production efficiency was not compromised. Economic batch sizing models were deemed inappropriate due to the quick changeover times of the production process and the rapid turnover of inventory. Moreover, the inherent variation of the panel production process across a number of measurable input parameters and the variation of the production rate precluded a holistic view of the process using standard improvement methods such as Six Sigma. In creating the modelling method to satisfy the objective, the thesis contributes the following:

1. The model provides a holistic and structured approach to analysing a manufacturing system through identifying and subsequently analysing the key inputs that influence the system objective under review.

2. The subsequent analysis provides managers with a quantifiable understanding of system behaviour against which decisions can be made that support system optimisation.

3. Operationally, multiple stakeholders to the manufacturing system can have confidence in supporting strategic decisions based on the objective analysis of the method.

4. The modelling approach provides a base against which the effectiveness of process improvement can be quantified.

5. Provides a base against which future scenario planning can be applied to the introduction of new models or products.

6. The literature review provides the foundation for a concise understanding of lean production within the evolution of manufacturing and why the lean principles are applicable across the wider industrial and commercial landscapes.

7.7. Concluding Remarks

Manufacturing is an essential human activity through providing the products necessary for people to conduct every aspect of their lives. Products satisfy both the basic needs of people and the means to enhance the quality of life. Additionally, globally manufacturing is the means of employment for millions of people and is the foundation for economic prosperity.

Manufacturing though has to be done well to meet the needs of customers and so provide the basis for sustaining employment and economic prosperity.

Mass production as developed by Ford and Sloan was successful in providing products for mass consumers with moderate means. However, as the future unfolded, due to complacency, mass producers failed to serve the changing needs of their customer base. Additionally, manufacturers could be considered arrogant as they chose not to listen to voices of warning from those who were well informed including the economist Theodore Levitt, and management thinkers such as Peter Drucker and W. Edwards Deming.

The evolution of firstly the Toyota Production System and subsequently lean manufacturing shifted the emphasis of manufacturing away from what was best for the manufacturer to what was best for the consumer. Significantly, the continued attack on waste within lean systems ensured that what was best for the customer was also best for the provider through maximising revenue.

The decline of mass production could be could be considered as a lost opportunity for Western manufacturers. If the complacency and arrogance not been prevalent, it is possible that Western manufacturers would have taken a lean trajectory or at least a trajectory toward a more customer focussed and efficient state that would have prevented the inevitable decline. That lost opportunity was generations ago but it is a lesson for the future.

The purpose of considering the mass production methods developed by Henry Ford was to understand where lean manufacturing came from and to understand why mass production failed and sense if the same fate could befall lean manufacturing. It is highly unlikely that the lean manufacturing will fail more likely the method will gradually evolve over time.

There are good reasons to believe that lean production will not fail in the future. Companies, both product and service are more customer aware, and more aware of competitive threat. The lean ethic hammers home the need to focus on value and continue to strive for perfection.

Lean manufacturing and more specifically the principles that deliver lean systems are a source of opportunity. At the company level, the opportunity to provide superior value to the customer trough both service and product attributes enabling the company to grow and prosper. At the personal level the opportunity is derived from contributing to the success of the organisation and the ability to personally develop.

It is clear in my opinion that the dissemination of lean principles across a diversity of applications is because the principles act on the impediments and barriers to the flow of the process and are therefore independent to the physical nature of the process.

The tools and problem solving methodologies that have been developed in parallel to the evolution of lean manufacturing have provided the foundation for engaged people to improve the systems they work in.

However, manufacturing systems are complex entities and problems can occur that defy solutions by conventional means and a more unorthodox approach is necessary to either solve the problem or at best manage the problem in a more structured way.

The contribution of the thesis is to develop a structured approach to either solving difficult problems within production environments or at least provide quantifiable information enabling managers to make informed decisions.

8. List of Publications Submitted During the Research

2014: The Application of Time Series Modelling and Monte Carlo Simulation: Forecasting Volatile Inventory Requirements. Applied Mathematics. Vol. 5 No 8. pp 1152-1168

2010: Applying ‘Exponential Growth Models’ to Determine OEM Warehouse Capacity Requirements: Proceedings of the 20th International Conference on Flexible Automation and Intelligent Manufacturing. California State University East Bay.

2009: Application of the Design of Experiments to Evaluate Production Efficiency in Lean Systems: Proceedings of the 19th International Conference on Flexible Automation and Intelligent Manufacturing, Teesside University, UK

2007: Optimisation of Manufacturing Output in Lean Enterprises: Proceedings of the 17th International Conference on Flexible Automation and Intelligent Manufacturing, Penn State Great Valley. Pennsylvania, USA.

2006: The Relevance of Lean Manufacturing Principles in Diverse Applications and Digital Enterprises: in Digital Enterprise Technology Perspective and Future Challenges. Cunha P.F. and Maropoulos P.G (Eds) Springer

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Appendix 1 TPS Management Principles

Section 1: Long Term Philosophy

1. Base your management decisions on a long-term philosophy, even at the expense of short-term financial goals.

Section 2: The Right Process will Produce the Right Results

2. Create a continuous process flow to bring problems to the surface:

3. Use “pull” systems to avoid overproduction: Only deliver material and produce products when they are needed.

4. Level out the workload (heijunka): Create a balanced use of labour and machines.

5. Build a culture of stopping to fix problems, to get quality right the first time (Jidoka).

6. Work with Standards: Standardised tasks and processes are the foundation for continuous improvement and employee empowerment.

7. Use visual control so no problems are hidden.

8. Use only reliable, thoroughly tested technology: Ensure there is a fit between technology, processes and people.

Section 3: Add Value to the organisation by Developing your People and Partners

9. Grow leaders internally who thoroughly understand the work, live the philosophy, and teach it to others.

10. Develop exceptional people and teams who follow your company’s philosophy.

11. Respect your extended network of partners and suppliers by challenging them and helping them improve.

Section 4: Continuously Solving Root Problems Drives Organisational Learning.

12. Go and see for yourself to thoroughly understand the situation (genchi genbutsu).

13. Make decisions slowly by consensus, thoroughly considering all options; implement decisions rapidly (nemawashi).

14. Become a learning organization through relentless reflection (hansei) and continuous improvement (kaizen).

Appendix 2 Design 1- Factorial Design: Experiment 1

Factorial Design for Experiment 1

RUN_TIME = [60, 90]
SPOH = [440, 570]

Full Factorial Design

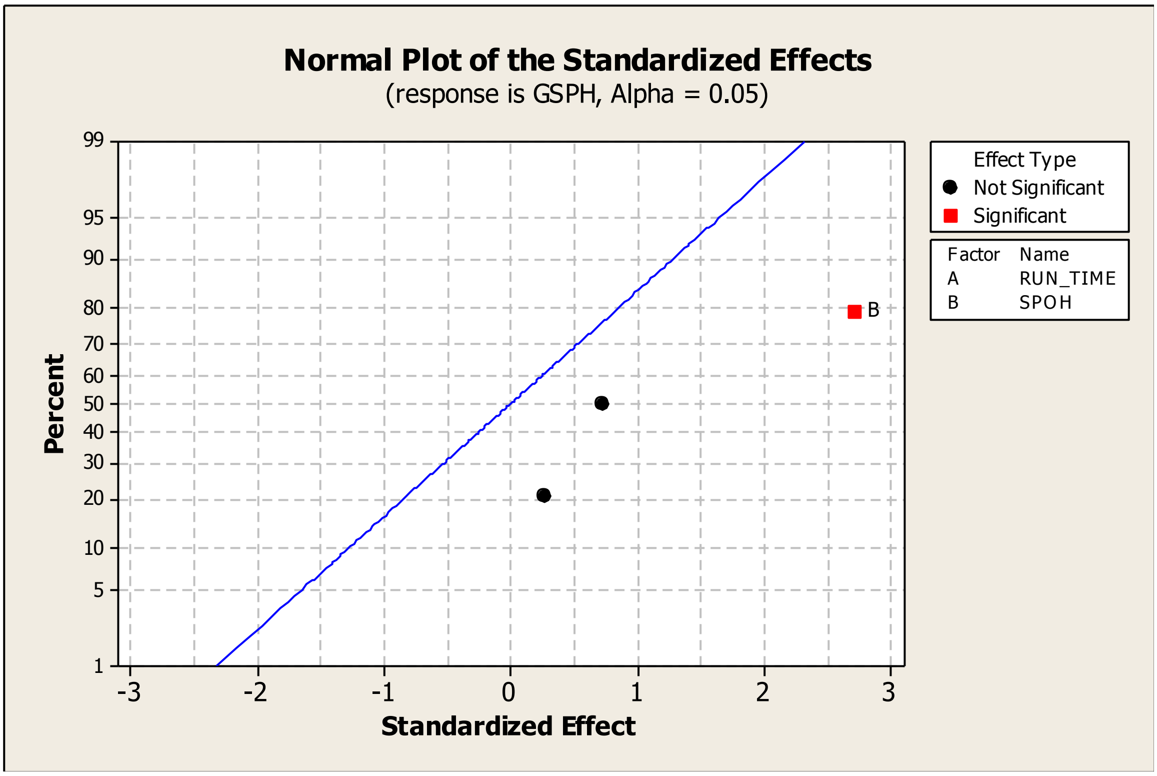
```
Factors:   2   Base Design:         2, 4
Runs:     16   Replicates:             4
Blocks:    1   Center pts (total):     0


All terms are free from aliasing.
```

Results for: 60_90Min.MTW

Factorial Fit: GSPH versus RUN_TIME, SPOH

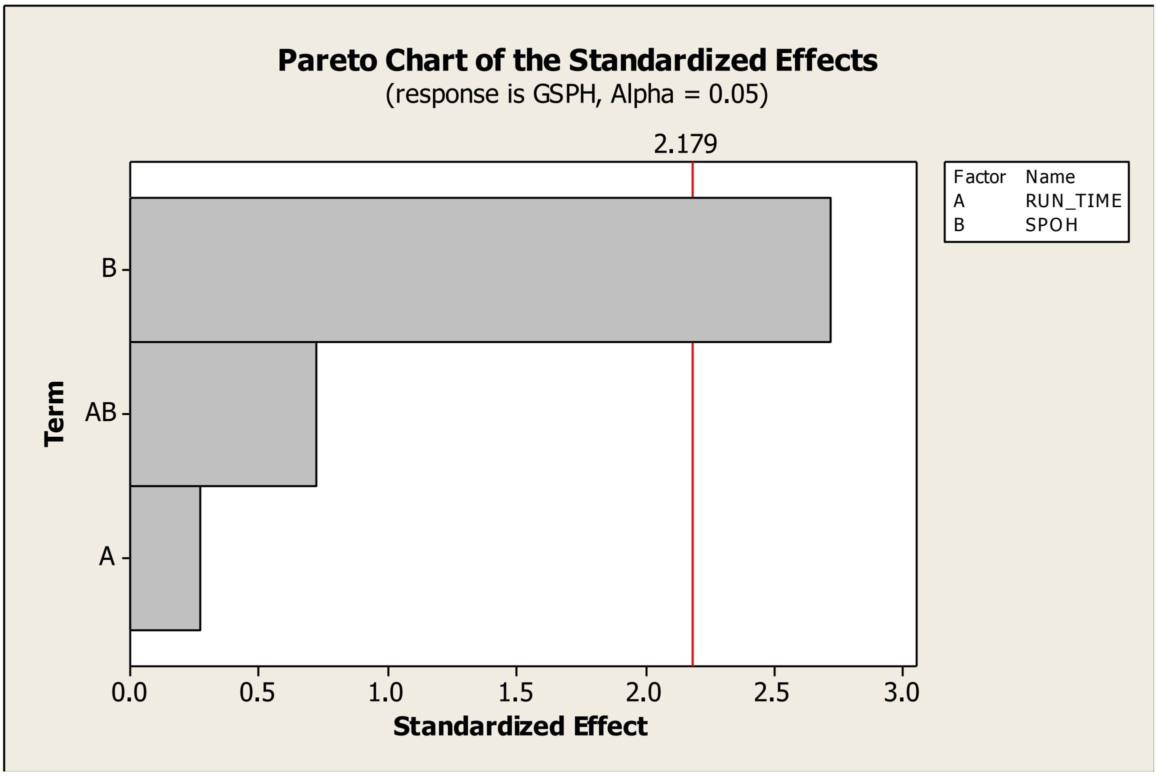
```
Estimated Effects and Coefficients for GSPH (coded units)

Term             Effect     Coef  SE Coef      T      P
Constant                 345.852    25.66  13.48  0.000
RUN_TIME         13.844    6.922    25.66   0.27  0.792
SPOH            139.611   69.805    25.66   2.72  0.019
RUN_TIME*SPOH    37.017   18.508    25.66   0.72  0.485


S = 102.657     PRESS = 224820
R-Sq = 39.97%   R-Sq(pred) = 0.00%   R-Sq(adj) = 24.97%


Analysis of Variance for GSPH (coded units)

Source              DF  Seq SS  Adj SS   Adj MS     F      P
Main Effects         2   78731   78731  39365.6  3.74  0.055
  RUN_TIME           1     767     767    766.7  0.07  0.792
  SPOH               1   77965   77965  77964.6  7.40  0.019
2-Way Interactions   1    5481    5481   5481.0  0.52  0.485
  RUN_TIME*SPOH      1    5481    5481   5481.0  0.52  0.485
Residual Error      12  126461  126461  10538.4
  Pure Error        12  126461  126461  10538.4
Total               15  210674


Unusual Observations for GSPH

Obs  StdOrder     GSPH      Fit  SE Fit  Residual  St Resid
  5         8  240.000  441.088  51.328  -201.088     -2.26R

R denotes an observation with a large standardized residual.


Estimated Coefficients for GSPH using data in uncoded units

Term              Coef
Constant        487.89
RUN_TIME       -9.1250
```

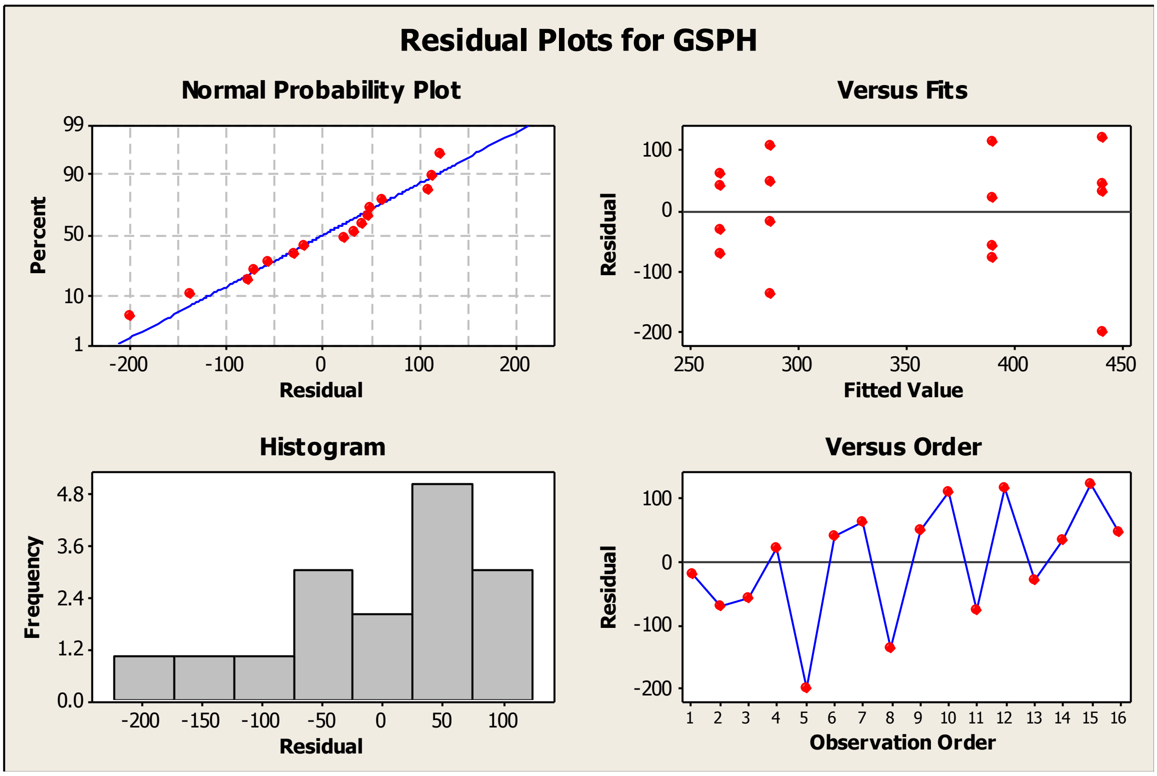
```
SPOH            -0.34980
RUN_TIME*SPOH  0.0189831


Least Squares Means for GSPH

                Mean   SE Mean
RUN_TIME
 60            338.9    36.29
 90            352.8    36.29
SPOH
 440           276.0    36.29
 570           415.7    36.29
RUN_TIME*SPOH
 60 440        287.6    51.33
 90 440        264.5    51.33
 60 570        390.2    51.33
 90 570        441.1    51.33
```

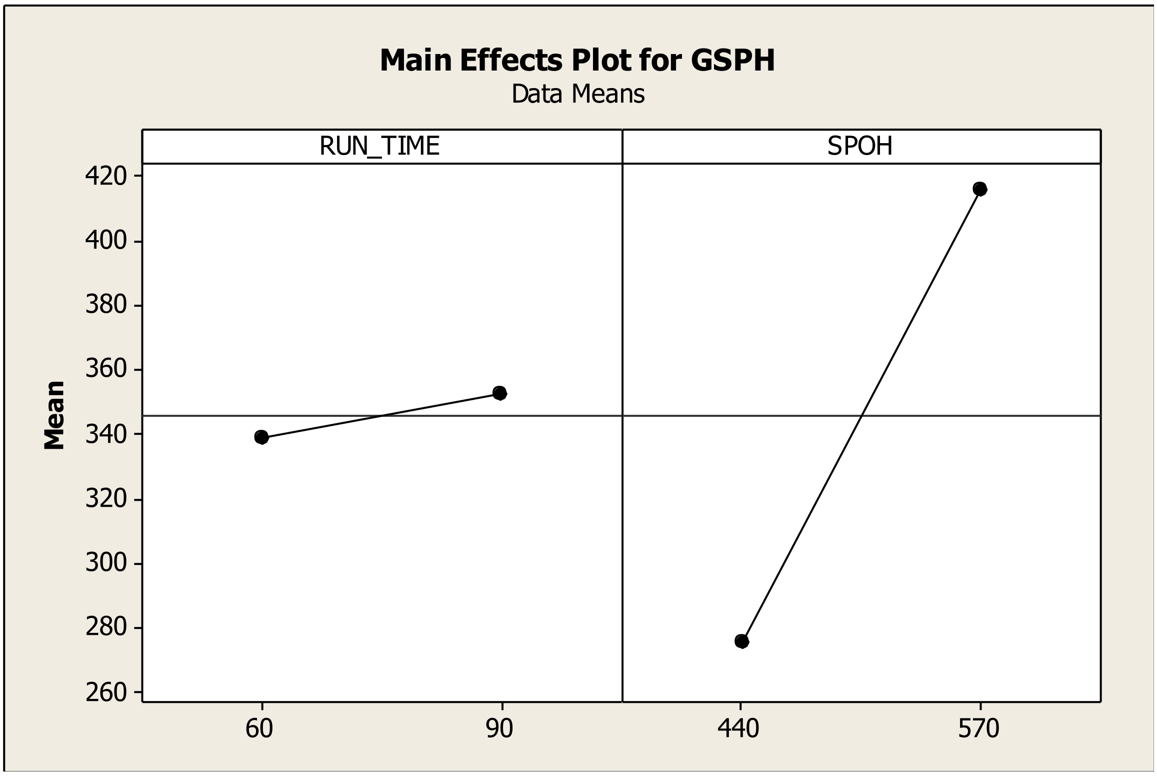


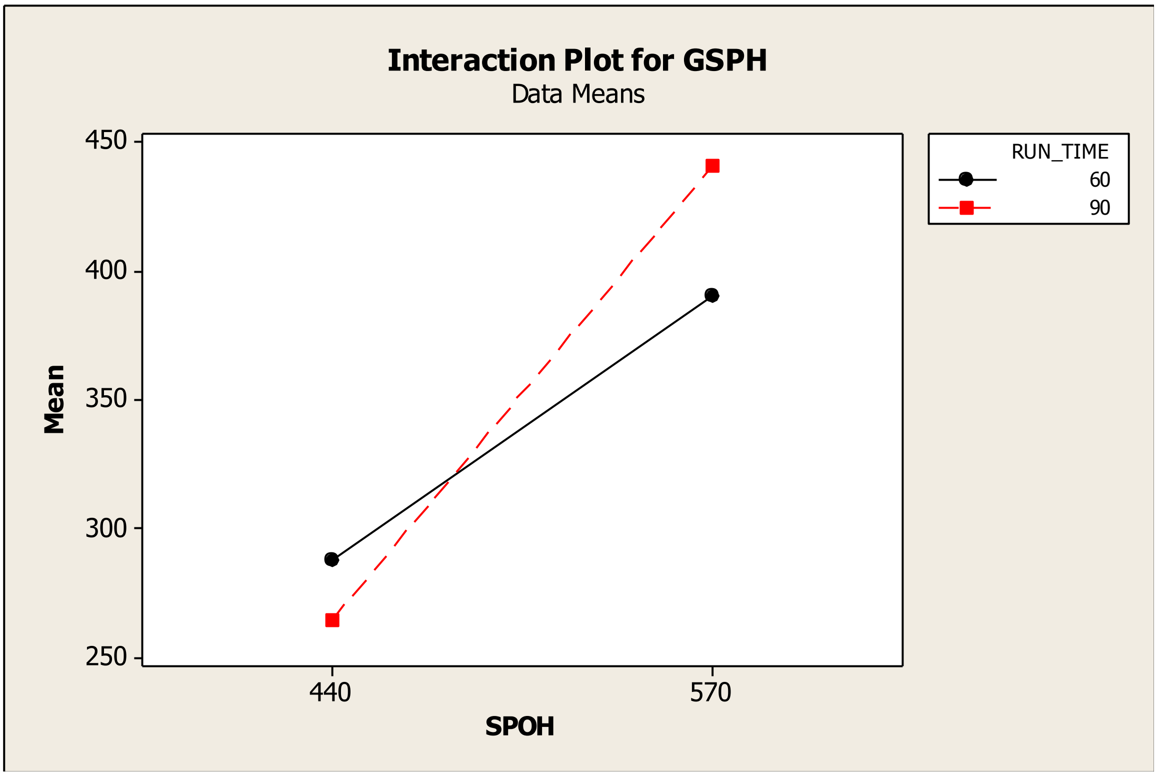
Effects Pareto for GSPH

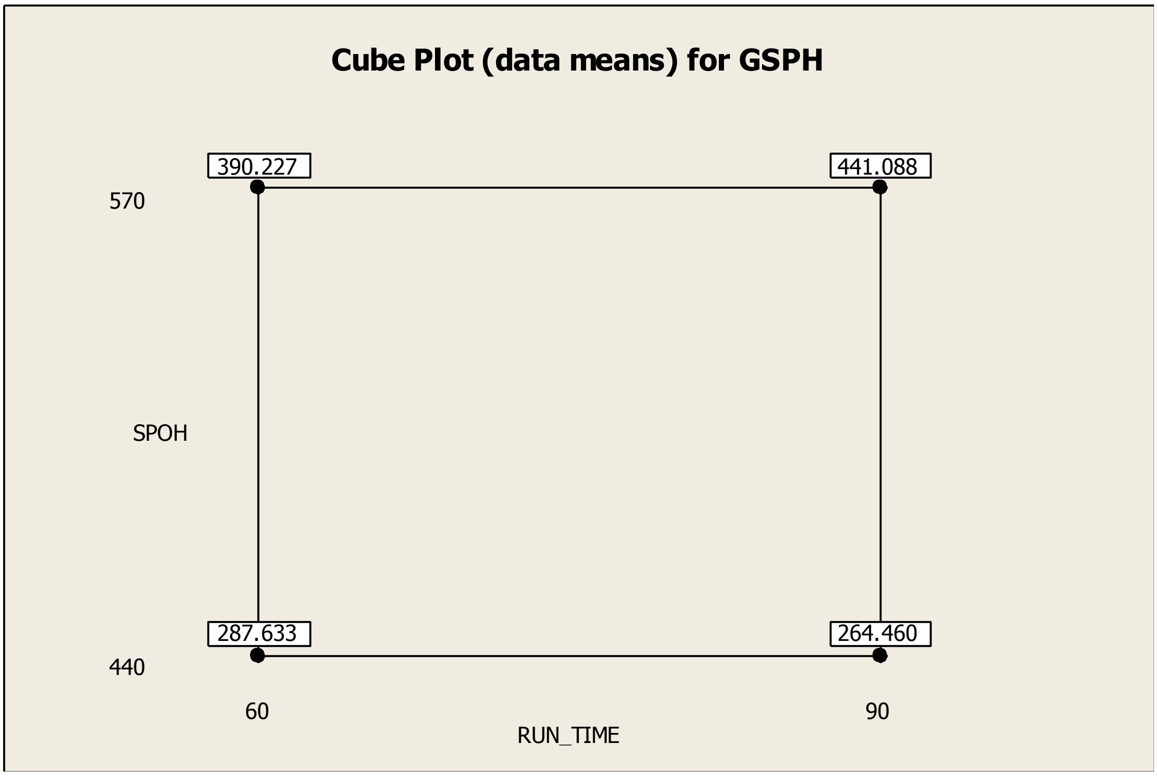
```
Alias Structure
I
RUN_TIME
SPOH
RUN_TIME*SPOH
```


Pareto Chart of the Standardized Effects
(response is GSPH, Alpha = 0.05)
2.179
Term
B
AB
A
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Standardized Effect
Factor Name
A RUN_TIME
B SPOH


Residual Plots for GSPH
Normal Probability Plot
Percent
99
90
50
10
1
-200
-100
0
100
200
Residual
Versus Fits
Residual
100
0
-100
-200
250
300
350
400
450
Fitted Value
Histogram
Frequency
4.8
3.6
2.4
1.2
0.0
-200
-150
-100
-50
0
50
100
Residual
Versus Order
Residual
100
0
-100
-200
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Observation Order


Main Effects Plot for GSPH
Data Means
RUN_TIME
SPOH
Mean
420
400
380
360
340
320
300
280
260
60
90
440
570


Interaction Plot for GSPH
Data Means
Mean
450
400
350
300
250
440
570
SPOH
RUN_TIME
60
90


Cube Plot (data means) for GSPH
390.227
441.088
570
SPOH
287.633
264.460
440
60
90
RUN_TIME

Appendix 3 Design 1- Factorial Design: Experiment 2

Factorial Design for Experiment 2

RUN_TIME = [240, 415]
SPOH = [450, 570]

Full Factorial Design

```
Factors:   2   Base Design:         2, 4
Runs:     16   Replicates:             4
Blocks:    1   Center pts (total):     0


All terms are free from aliasing.
```

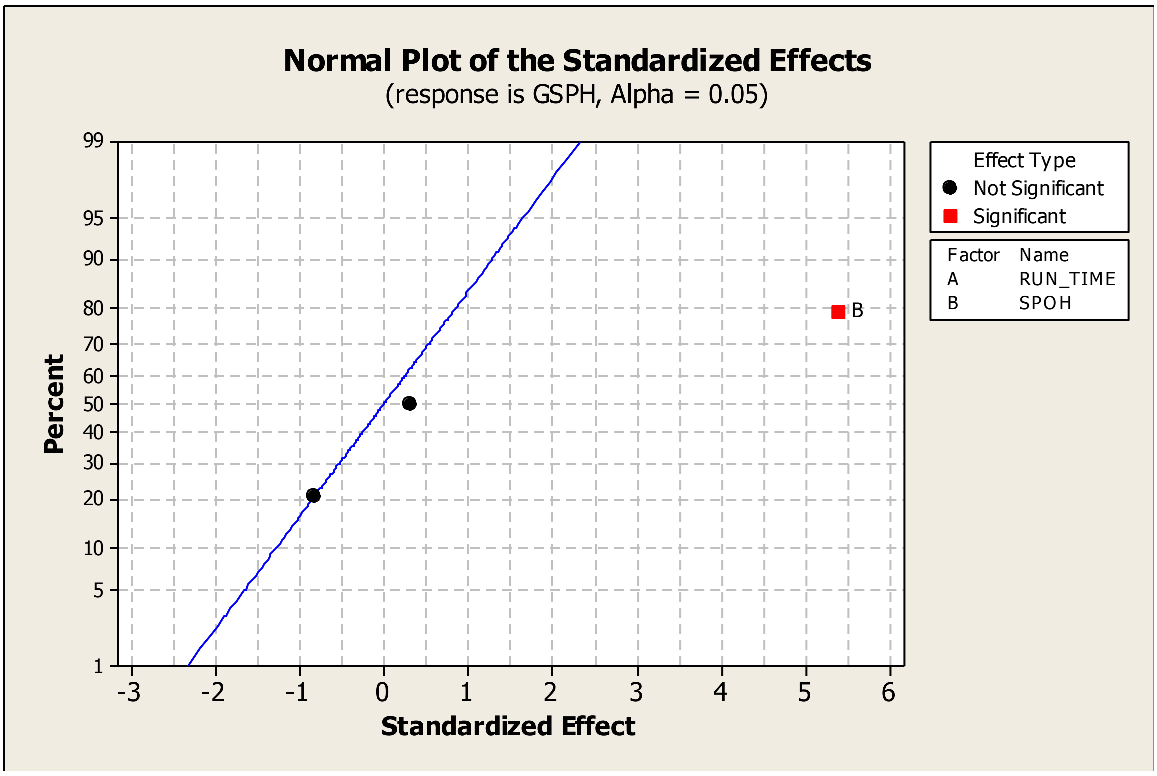
Full Factorial Design

```
Factors:   2   Base Design:         2, 4
Runs:     16   Replicates:             4
Blocks:    1   Center pts (total):     0


All terms are free from aliasing.
```

Factorial Fit: GSPH versus RUN_TIME, SPOH

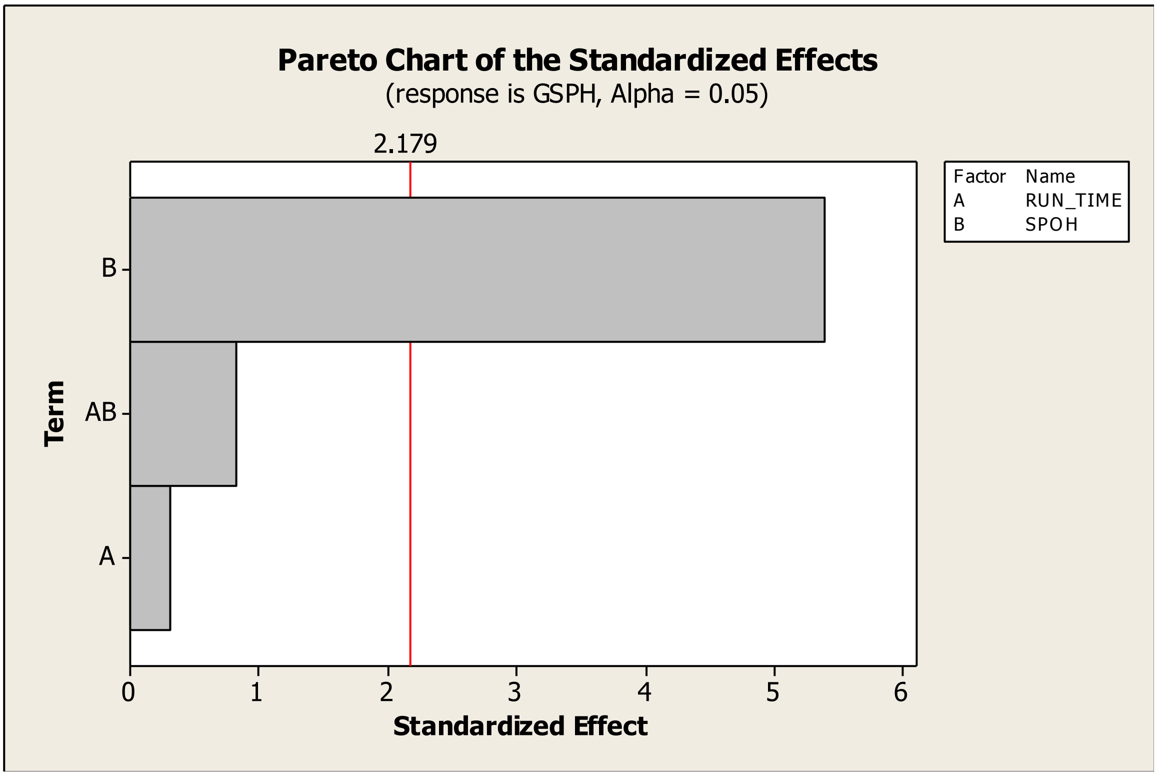
```
Estimated Effects and Coefficients for GSPH (coded units)

Term           Effect    Coef  SE Coef      T      P
Constant               384.90    14.56  26.43  0.000
RUN_TIME         8.91    4.46    14.56   0.31  0.765
SPOH           156.83   78.41    14.56   5.39  0.000
RUN_TIME*SPOH  -24.00  -12.00    14.56  -0.82  0.426


S = 58.2455     PRESS = 72374.1
R-Sq = 71.27%   R-Sq(pred) = 48.93%   R-Sq(adj) = 64.09%


Analysis of Variance for GSPH (coded units)

Source              DF  Seq SS   Adj SS   Adj MS      F      P
Main Effects         2   98697  98697.5  49348.7  14.55  0.001
  RUN_TIME           1     318    317.8    317.8   0.09  0.765
  SPOH               1   98380  98379.7  98379.7  29.00  0.000
2-Way Interactions   1    2305   2304.6   2304.6   0.68  0.426
  RUN_TIME*SPOH      1    2305   2304.6   2304.6   0.68  0.426
Residual Error      12   40710  40710.4   3392.5
  Pure Error        12   40710  40710.4   3392.5
Total               15  141713


Estimated Coefficients for GSPH using data in uncoded units

Term                 Coef
Constant         -680.119
RUN_TIME          1.21680
```

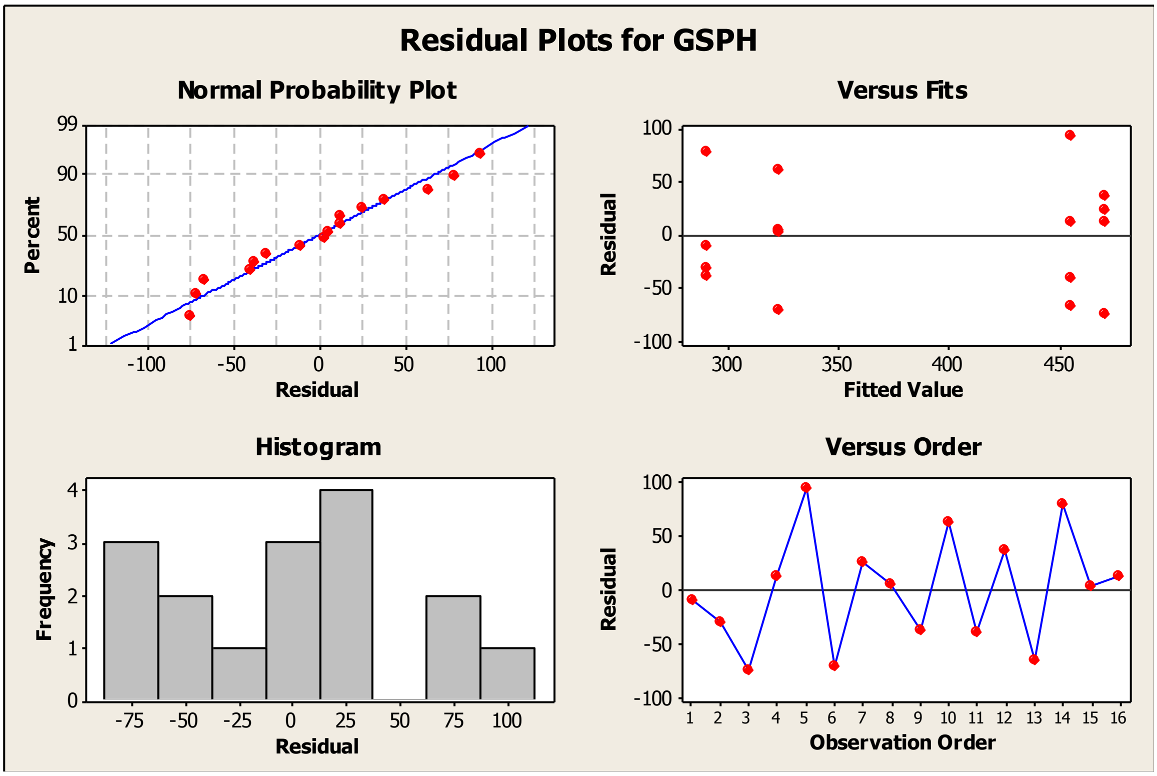
```
SPOH                 2.05556
RUN_TIME*SPOH   -0.00228601
```

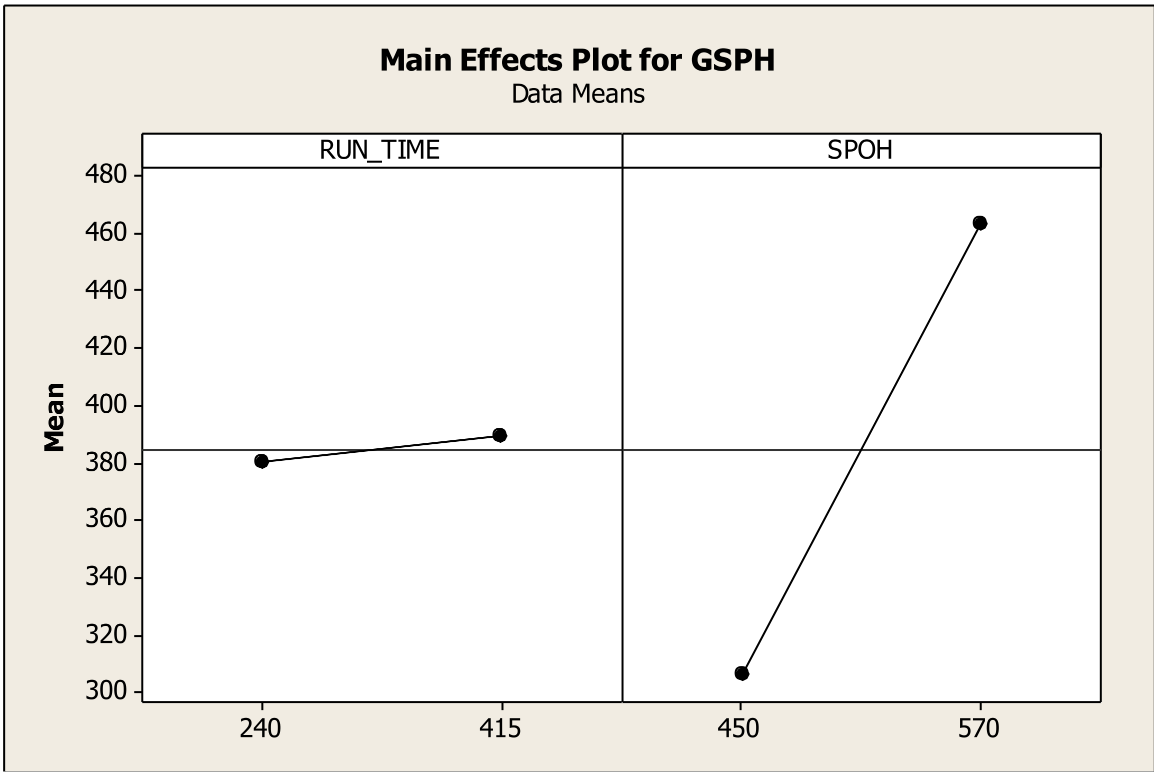


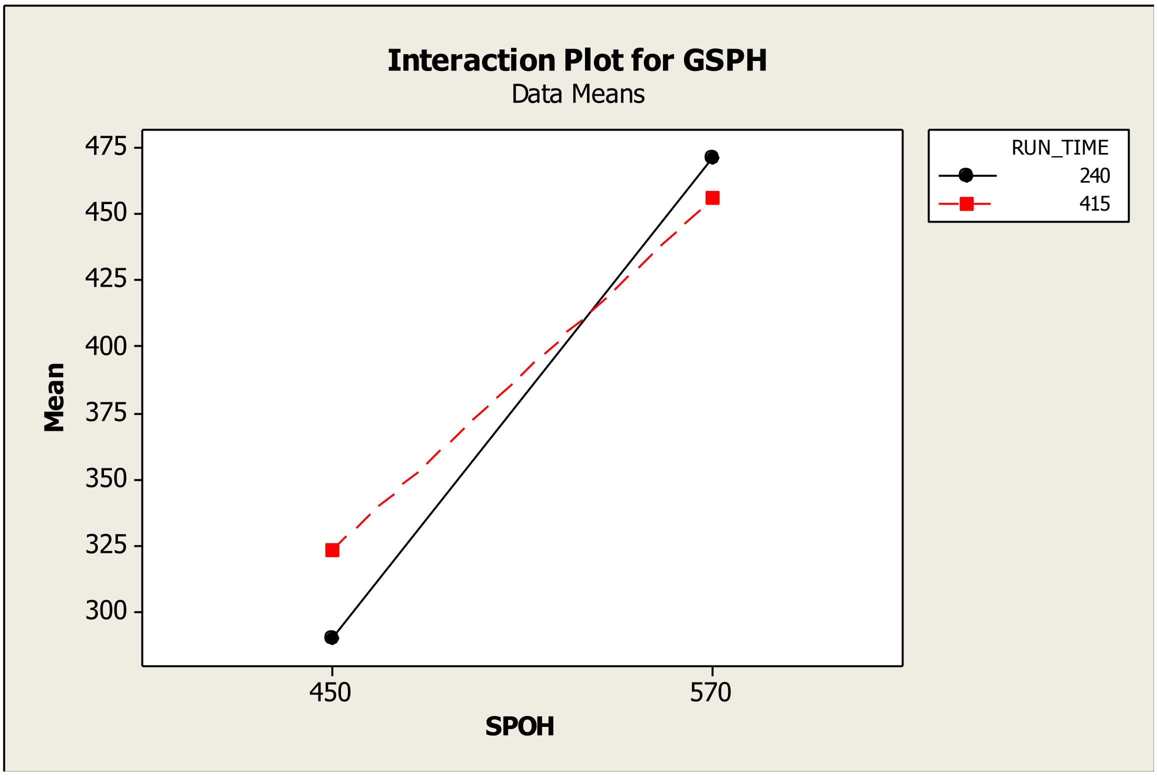
Effects Pareto for GSPH

```
Alias Structure
I
RUN_TIME
SPOH
RUN_TIME*SPOH
```


Pareto Chart of the Standardized Effects
(response is GSPH, Alpha = 0.05)
2.179
Term
B
AB
A
0
1
2
3
4
5
6
Standardized Effect
Factor Name
A RUN_TIME
B SPOH


Residual Plots for GSPH
Normal Probability Plot
Percent
99
90
50
10
1
-100
-50
0
50
100
Residual
Versus Fits
Residual
100
50
0
-50
-100
300
350
400
450
Fitted Value
Histogram
Frequency
4
3
2
1
0
-75
-50
-25
0
25
50
75
100
Residual
Versus Order
Residual
100
50
0
-50
-100
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Observation Order


Main Effects Plot for GSPH
Data Means
RUN_TIME
SPOH
Mean
480
460
440
420
400
380
360
340
320
300
240
415
450
570


Interaction Plot for GSPH
Data Means
Mean
475
450
425
400
375
350
325
300
450
570
SPOH
RUN_TIME
240
415

Appendix 4 Design 1- Factorial Design: Experiment 3

Factorial Design for Experiment 3

RUN_TIME = [60, 415]
SPOH = [450, 570]

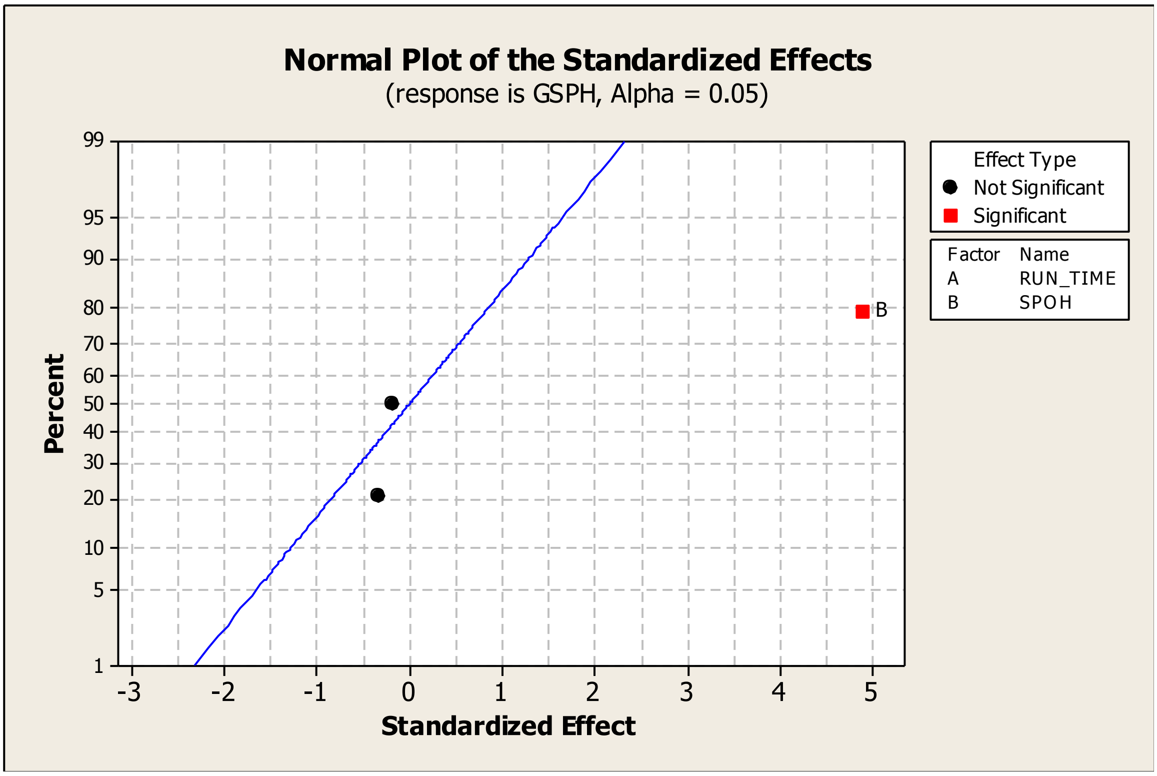
Full Factorial Design

```
Factors:   2   Base Design:         2, 4
Runs:     16   Replicates:             4
Blocks:    1   Center pts (total):     0


All terms are free from aliasing.
```

Factorial Fit: GSPH versus RUN_TIME, SPOH

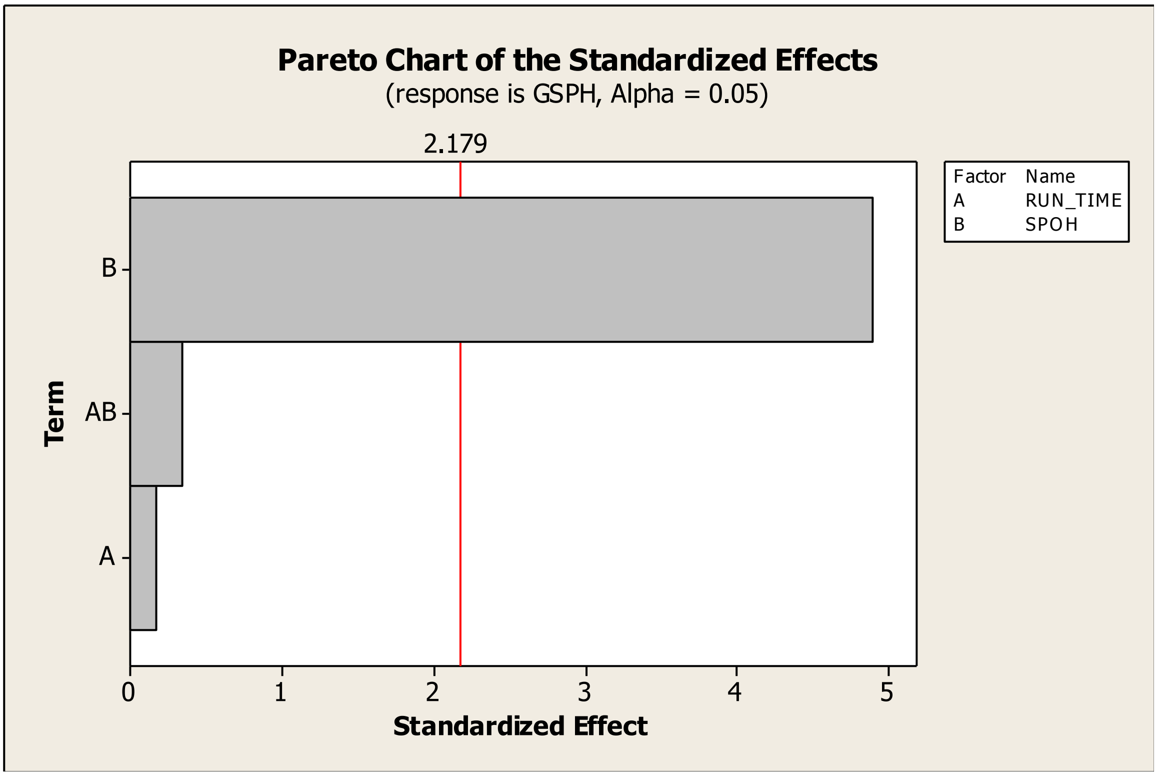
```
Estimated Effects and Coefficients for GSPH (coded units)

Term             Effect     Coef  SE Coef      T      P
Constant                 391.899    14.60  26.85  0.000
RUN_TIME         -5.085   -2.543    14.60  -0.17  0.865
SPOH            142.829   71.415    14.60   4.89  0.000
RUN_TIME*SPOH   -10.005   -5.002    14.60  -0.34  0.738


S = 58.3804      PRESS = 72709.7
R-Sq = 66.75%    R-Sq(pred) = 40.89%   R-Sq(adj) = 58.44%


Analysis of Variance for GSPH (coded units)

Source              DF  Seq SS   Adj SS   Adj MS      F      P
Main Effects         2   81704  81704.3  40852.2  11.99  0.001
  RUN_TIME           1     103    103.4    103.4   0.03  0.865
  SPOH               1   81601  81600.9  81600.9  23.94  0.000
2-Way Interactions   1     400    400.4    400.4   0.12  0.738
  RUN_TIME*SPOH      1     400    400.4    400.4   0.12  0.738
Residual Error      12   40899  40899.2   3408.3
  Pure Error        12   40899  40899.2   3408.3
Total               15  123004


Estimated Coefficients for GSPH using data in uncoded units

Term                  Coef
Constant          -268.617
RUN_TIME          0.225225
SPOH               1.30180
RUN_TIME*SPOH  -0.00046970


Least Squares Means for GSPH

                Mean  SE Mean
RUN_TIME
  60           394.4    20.64
 415           389.4    20.64
SPOH
```

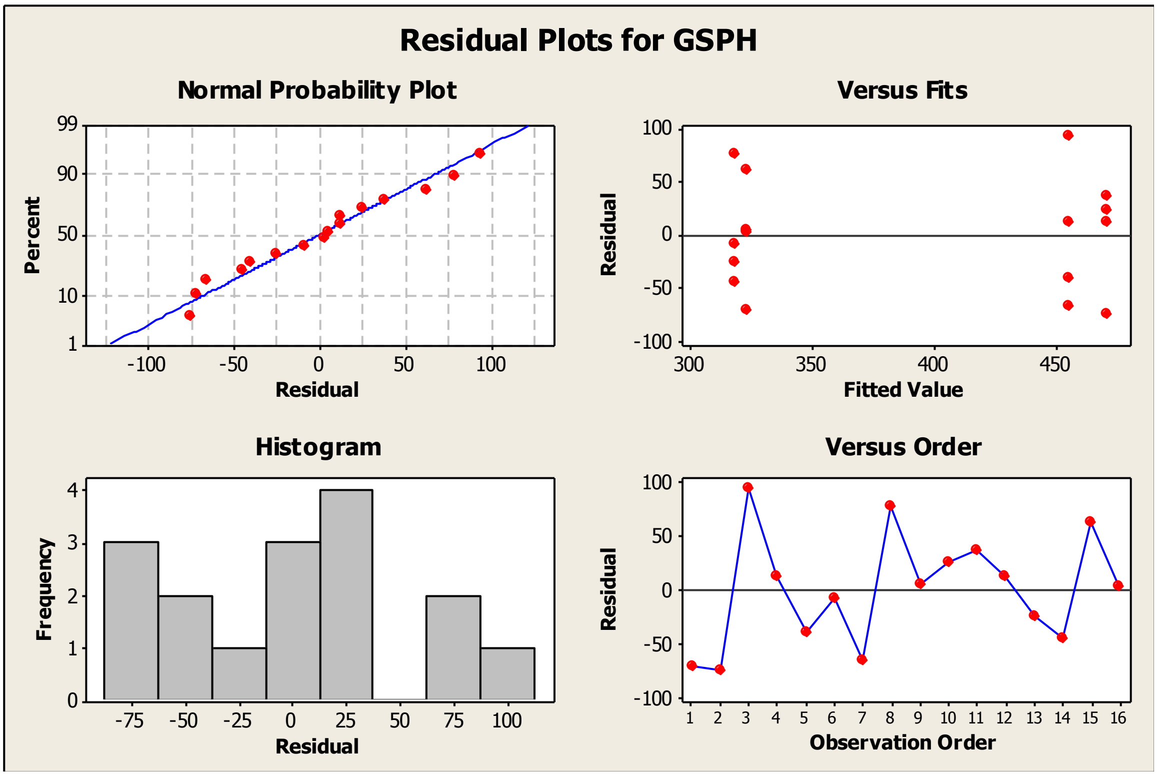
```
 450           320.5    20.64
 570           463.3    20.64
RUN_TIME*SPOH
  60  450      318.0    29.19
 415  450      322.9    29.19
  60  570      470.9    29.19
 415  570      455.8    29.19
```

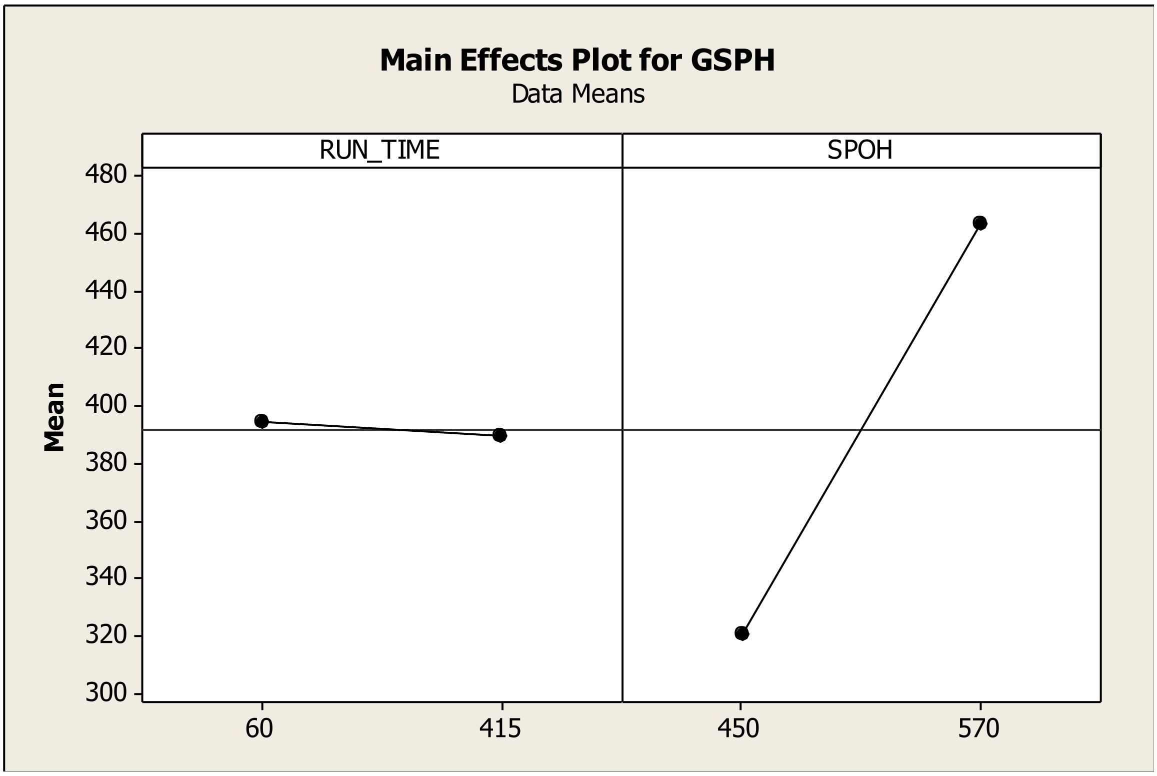


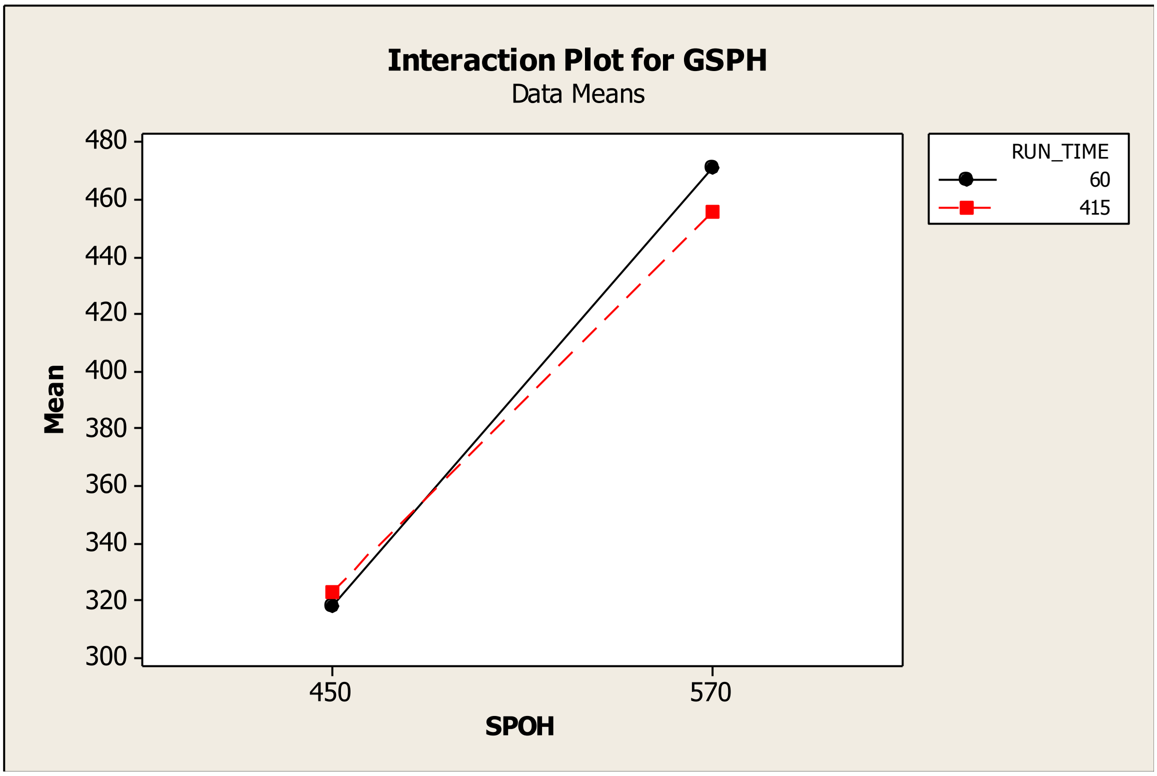
Effects Pareto for GSPH

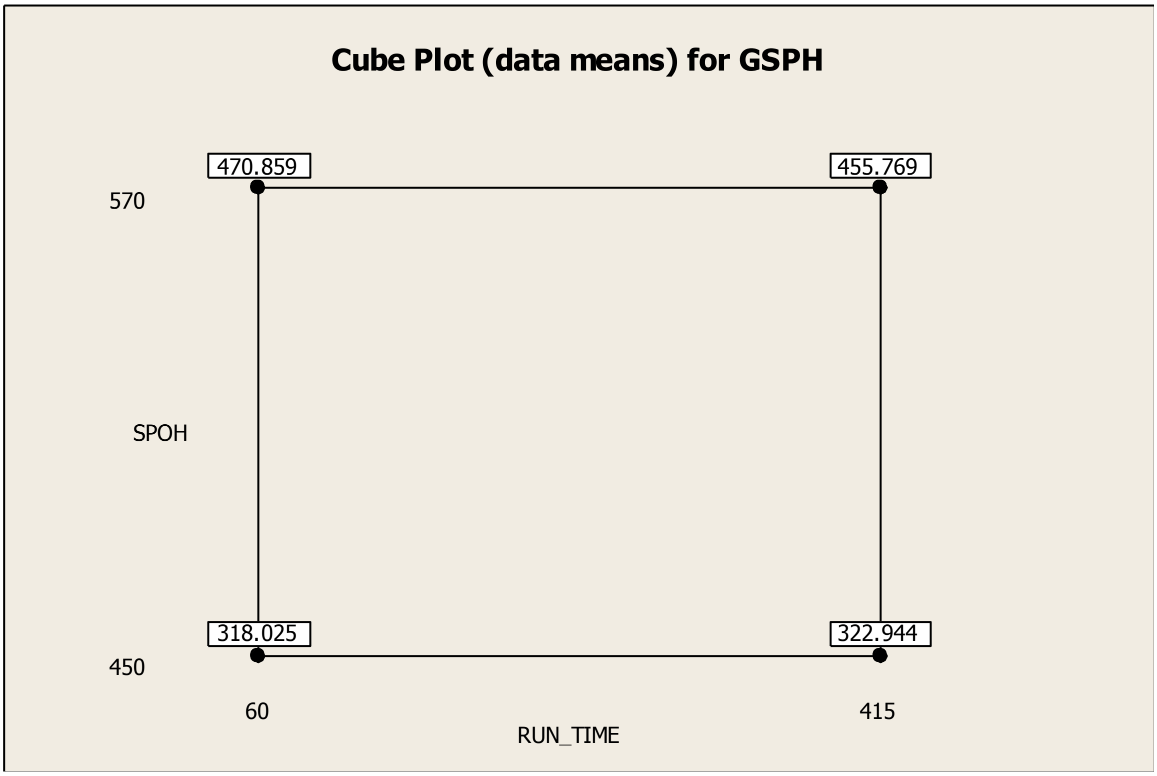
```
Alias Structure
I
RUN_TIME
SPOH
RUN_TIME*SPOH
```


Pareto Chart of the Standardized Effects
(response is GSPH, Alpha = 0.05)
2.179
Term
B
AB
A
0
1
2
3
4
5
Standardized Effect
Factor Name
A RUN_TIME
B SPOH


Residual Plots for GSPH
Normal Probability Plot
Percent
99
90
50
10
1
-100
-50
0
50
100
Residual
Versus Fits
Residual
100
50
0
-50
-100
300
350
400
450
Fitted Value
Histogram
Frequency
4
3
2
1
0
-75
-50
-25
0
25
50
75
100
Residual
Versus Order
Residual
100
50
0
-50
-100
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Observation Order


Main Effects Plot for GSPH
Data Means
RUN_TIME
SPOH
Mean
480
460
440
420
400
380
360
340
320
300
60
415
450
570


Interaction Plot for GSPH
Data Means
RUN_TIME
60
415
Mean
480
460
440
420
400
380
360
340
320
300
450
570
SPOH


Cube Plot (data means) for GSPH
470.859
455.769
570
SPOH
318.025
322.944
450
60
415
RUN_TIME

Appendix 5 Design 2- Factorial Design: Experiment 4

Factorial Design for Design 2 (2^3 Factorial Design) Experiment 4

SETUP_TIME = [10, 20]
SPOH = [475, 575]
RUN_LENGTH = [2000, 3000]

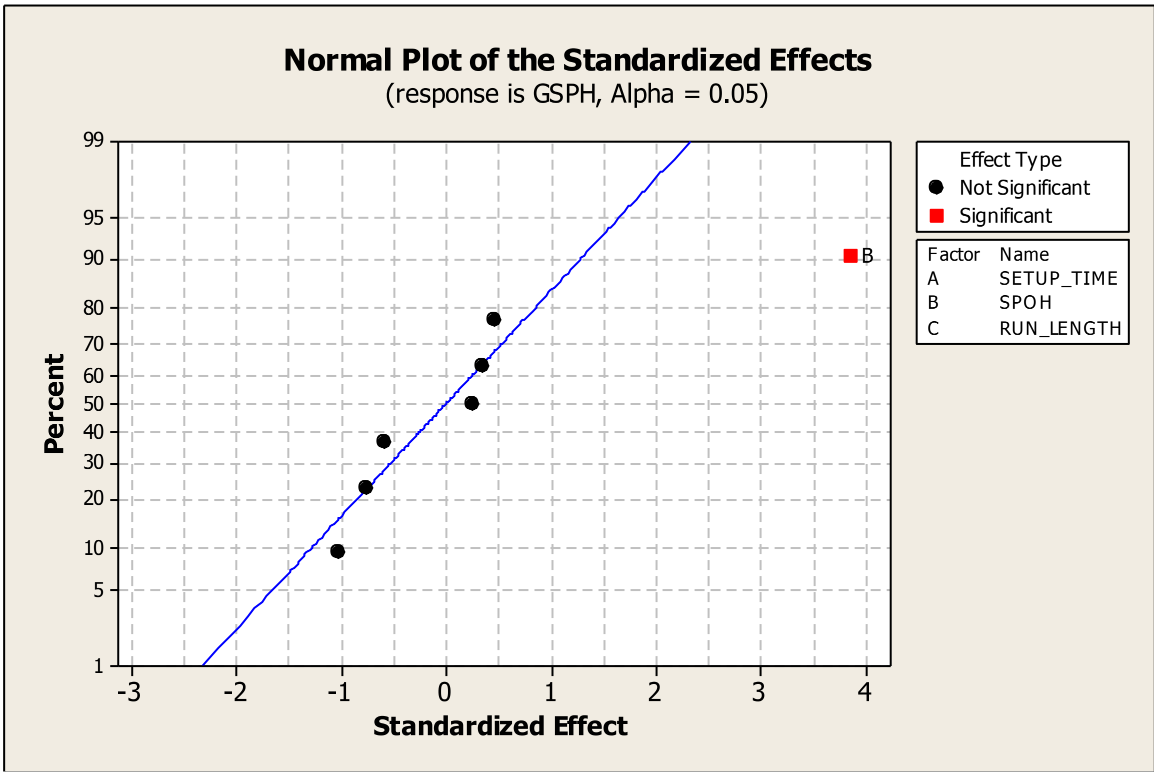
Full Factorial Design

```
Factors:   3   Base Design:         3, 8
Runs:     32   Replicates:             4
Blocks:    1   Center pts (total):     0


All terms are free from aliasing.
```

Factorial Fit: GSPH versus SETUP_TIME, SPOH, RUN_LENGTH

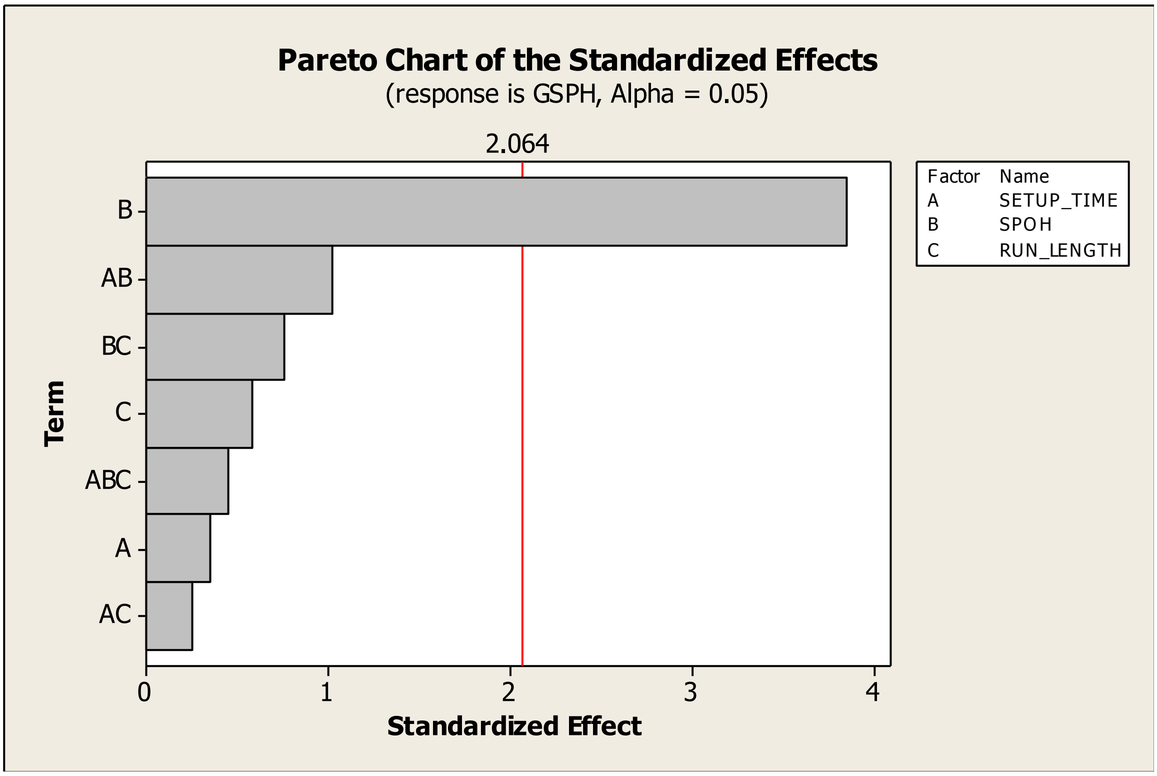
```
Estimated Effects and Coefficients for GSPH (coded units)

Term                        Effect    Coef  SE Coef      T      P
Constant                            378.65    10.44  36.26  0.000
SETUP_TIME                    7.32    3.66    10.44   0.35  0.729
SPOH                         80.46   40.23    10.44   3.85  0.001
RUN_LENGTH                  -12.29   -6.15    10.44  -0.59  0.562
SETUP_TIME*SPOH             -21.32  -10.66    10.44  -1.02  0.318
SETUP_TIME*RUN_LENGTH         5.36    2.68    10.44   0.26  0.800
SPOH*RUN_LENGTH             -15.93   -7.97    10.44  -0.76  0.453
SETUP_TIME*SPOH*RUN_LENGTH    9.52    4.76    10.44   0.46  0.653


S = 59.0752     PRESS = 148902
R-Sq = 41.75%   R-Sq(pred) = 0.00%   R-Sq(adj) = 24.77%


Analysis of Variance for GSPH (coded units)

Source                      DF  Seq SS   Adj SS   Adj MS      F      P
Main Effects                 3   53423  53423.3  17807.8   5.10  0.007
  SETUP_TIME                 1     429    428.5    428.5   0.12  0.729
  SPOH                       1   51786  51785.7  51785.7  14.84  0.001
  RUN_LENGTH                 1    1209   1209.1   1209.1   0.35  0.562
2-Way Interactions           3    5896   5895.9   1965.3   0.56  0.645
  SETUP_TIME*SPOH            1    3636   3635.9   3635.9   1.04  0.318
  SETUP_TIME*RUN_LENGTH      1     230    229.5    229.5   0.07  0.800
  SPOH*RUN_LENGTH            1    2030   2030.4   2030.4   0.58  0.453
3-Way Interactions           1     725    724.9    724.9   0.21  0.653
  SETUP_TIME*SPOH*RUN_LENGTH 1     725    724.9    724.9   0.21  0.653
Residual Error              24   83757  83757.2   3489.9
  Pure Error                24   83757  83757.2   3489.9
Total                       31  143801


Unusual Observations for GSPH

Obs  StdOrder     GSPH      Fit  SE Fit  Residual  St Resid
  7        16  287.000  405.200  29.538  -118.200     -2.31R
```

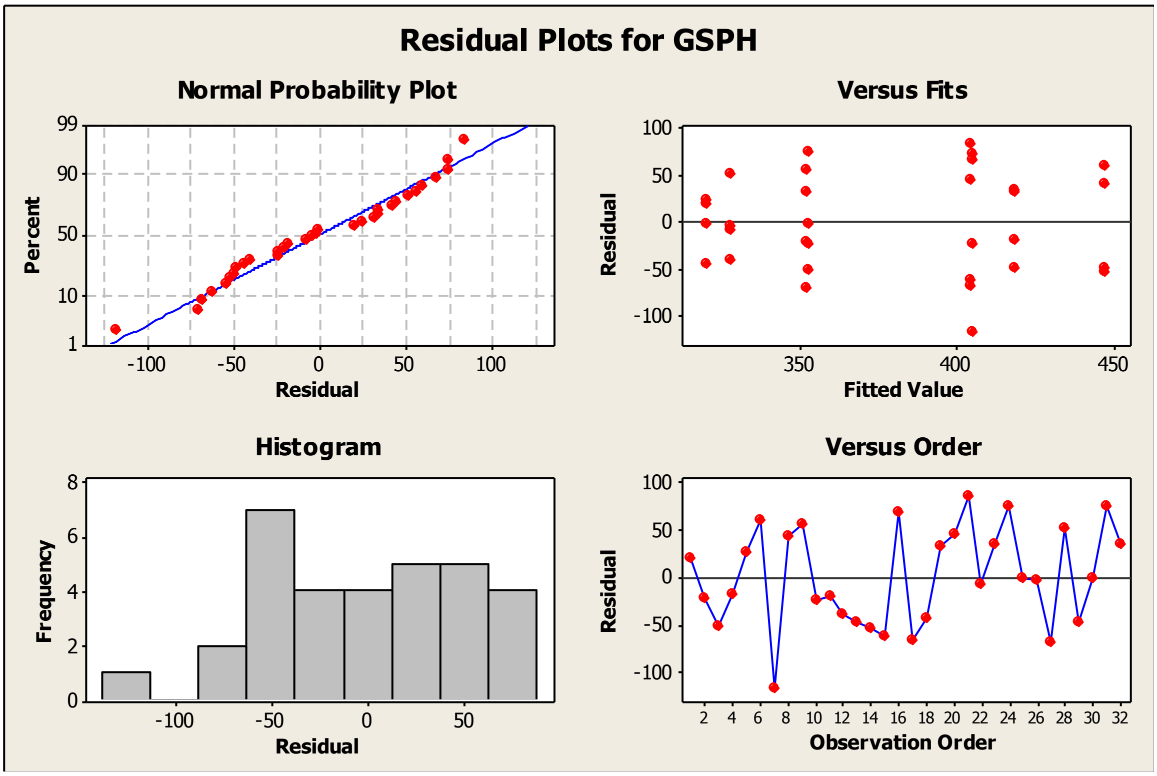
```
R denotes an observation with a large standardized residual.


Estimated Coefficients for GSPH using data in uncoded units

Term                                Coef
Constant                        -1487.39
SETUP_TIME                        70.412
SPOH                             3.66850
RUN_LENGTH                      0.438756
SETUP_TIME*SPOH                -0.137825
SETUP_TIME*RUN_LENGTH         -0.0189181
SPOH*RUN_LENGTH              -0.00088975
SETUP_TIME*SPOH*RUN_LENGTH  3.80750E-05


Least Squares Means for GSPH

                             Mean  SE Mean
SETUP_TIME
 10                         375.0    14.77
 20                         382.3    14.77
SPOH
 475                        338.4    14.77
 575                        418.9    14.77
RUN_LENGTH
 2000                       384.8    14.77
 3000                       372.5    14.77
SETUP_TIME*SPOH
 10 475                     324.1    20.89
 20 475                     352.7    20.89
 10 575                     425.9    20.89
 20 575                     411.9    20.89
SETUP_TIME*RUN_LENGTH
 10 2000                    383.8    20.89
 20 2000                    385.8    20.89
 10 3000                    366.2    20.89
 20 3000                    378.8    20.89
SPOH*RUN_LENGTH
 475 2000                   336.6    20.89
 575 2000                   433.0    20.89
 475 3000                   340.2    20.89
 575 3000                   404.8    20.89
SETUP_TIME*SPOH*RUN_LENGTH
 10 475 2000                320.2    29.54
 20 475 2000                353.0    29.54
 10 575 2000                447.4    29.54
 20 575 2000                418.6    29.54
 10 475 3000                328.0    29.54
 20 475 3000                352.5    29.54
 10 575 3000                404.3    29.54
 20 575 3000                405.2    29.54
```

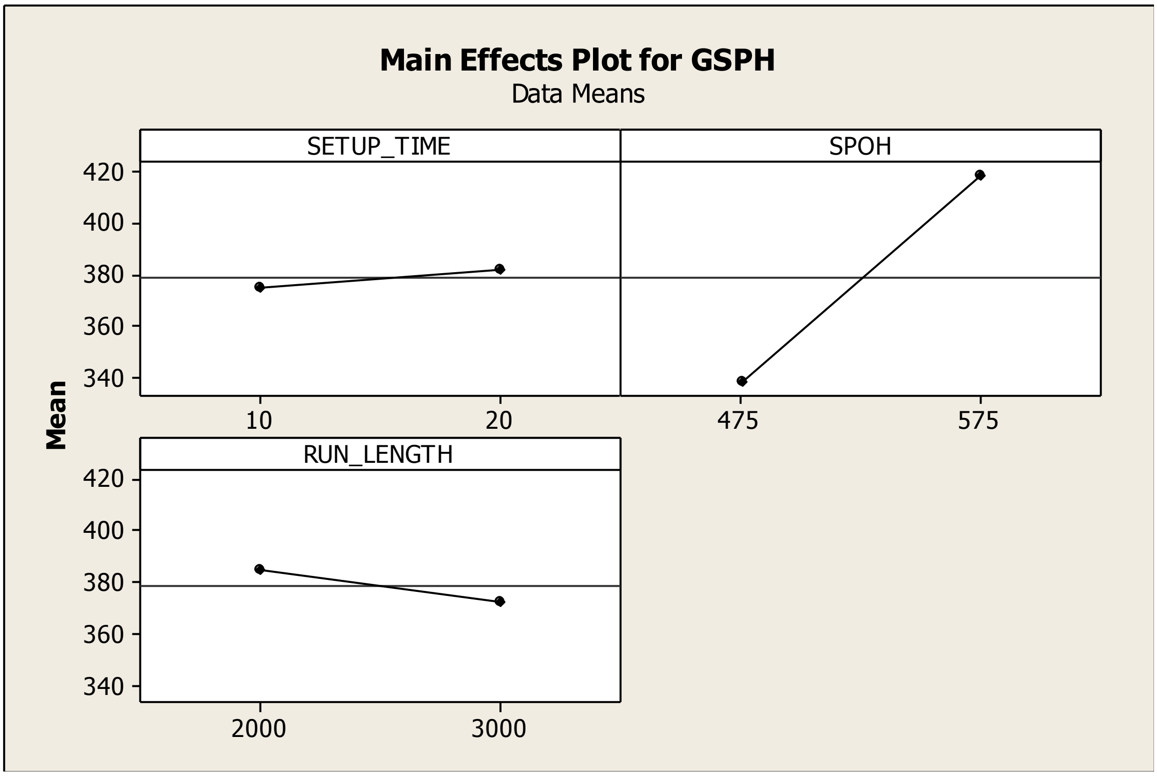


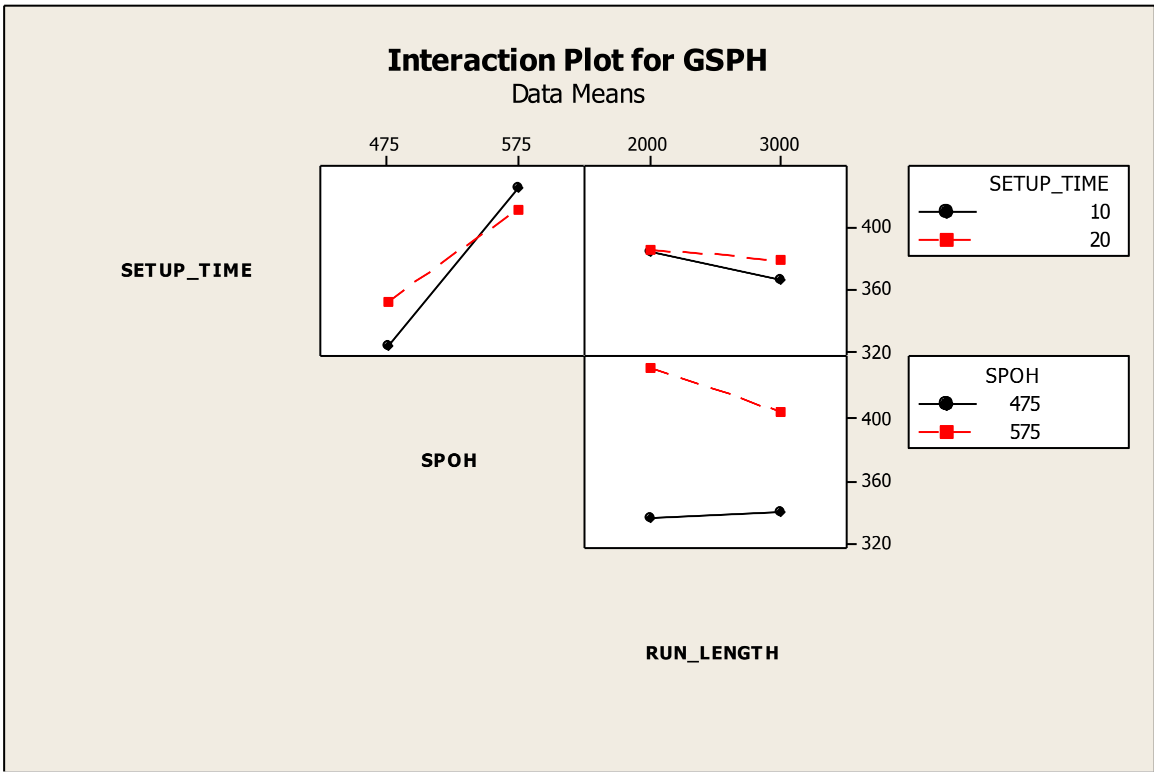
Effects Pareto for GSPH

```
Alias Structure
I
SETUP_TIME
SPOH
RUN_LENGTH
SETUP_TIME*SPOH
SETUP_TIME*RUN_LENGTH
SPOH*RUN_LENGTH
SETUP_TIME*SPOH*RUN_LENGTH
```


Pareto Chart of the Standardized Effects
(response is GSPH, Alpha = 0.05)
2.064
Term
B
AB
BC
C
ABC
A
AC
0
1
2
3
4
Standardized Effect
Factor Name
A SETUP_TIME
B SPOH
C RUN_LENGTH


Residual Plots for GSPH
Normal Probability Plot
Percent
99
90
50
10
1
-100
-50
0
50
100
Residual
Versus Fits
Residual
100
50
0
-50
-100
350
400
450
Fitted Value
Histogram
Frequency
8
6
4
2
0
-100
-50
0
50
Residual
Versus Order
Residual
100
50
0
-50
-100
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32
Observation Order


Main Effects Plot for GSPH
Data Means
SETUP_TIME
SPOH
RUN_LENGTH
Mean
420
400
380
360
340
10
20
475
575
2000
3000


Interaction Plot for GSPH
Data Means
475
575
2000
3000
SETUP_TIME
SPOH
RUN_LENGTH
400
360
320
SETUP_TIME
10
20
SPOH
475
575

Cube Plot