Developing Integrated Performance Measurement Systems for Improving the Efficiency of Mixed Model Flow Lines

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A thesis submitted in partial fulfilment of the requirement of De Montfort
University for the Degree of Doctor of Philosophy

April 2010

Abstract

The current trend for manufacturing organisations to compete within global markets based on the provision of high levels of customisation and product choice has impacted on their ability to continue to provide high levels of delivery reliability and quality expected by customers as well as reductions in associated costs on a year-by-year basis.

In order to provide efficient manufacturing environments mixed and multi-model flow processing lines are increasingly being adopted by a wide range of industrial sectors. To demonstrate the efficiency levels expected of customers in these processing environments the adoption of lean manufacturing techniques is essential.

The effective management and control, and therefore use, of such techniques in high product variety environments requires a high level of performance measurement in order to identify and verify when, where and the level of improvements made, identifying critical processes such as bottlenecks and focussing improvement activities at such critical processes.

Current research is, therefore aimed at developing an integrated performance measurement system that is capable of detailed performance measurement of a mixed-model flow processing line. This research covers the little knowledge of the relationships used between the shop floor level and strategic level. Also it promotes and directs continuous improvement activities indicating where organizations need to make improvements. This can be achieved using the performance metrics that have been recognized from the literature review. Relationships between them have been found using correlation analysis and quantified with regression analysis. Also, relationships have been developed between performance measurements and causes of inefficiencies as well as relationships between causes of inefficiencies and lean enablers that help improving the inefficiencies of the mix flow lines.

Acknowledgements

First I would like to express a deep gratitude to my supervisor Prof. D. Stockton for his invaluable advice and guidance throughout the course of this study

Also, I would like to thanks my second supervisor Dr. Riham Khalil for her advice and support throughout the course of this study.

My special thanks go to my colleagues and friends Mr Lamprou S., Mr Gournas, Mr Pischinas A., Mr Kouros, G., and especially to Mr. Kounis L. In particular, I wish to thank my ex- supervisor Mr. Lonis Ch., for his encourage me to get this course and their valuable support during this period.

Finally, I would like to thanks my family for their support during this research. Also, I want to dedicate this project to my son.

Declaration

I declare that the work described within this thesis was originally undertaken by myself, (Dimitris Labovas) between the dates of registration for the degree of Doctor of Philosophy at De Montfort University, October 2003 to October 2009

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Abbreviations and Glossary

RPW	Ranked Positional Weight
MRPII	Material Require Planning II
APICS	Advancing Productivity Innovation and Competitive Success The Association for Operation Management
TOC	Theory Of Constrain
DBR	Drum Buffer Rope
MPS	Master Production Schedule
SMED	Single Minute Exchange Dies
5S	Sort, Set in order, Shine, Standardize, Sustain
TPM	Total Productive Maintenance
ZQC	Zero Quality Control
Cp	Capability process
TPS	Toyotas Production System
TQM	Total Quality Management
CM	Cellular Manufacturing
GT	Group Technology
WIP	Work in Progress
TPM	Total Productive Maintenance
OEE	Overall Equipment Effectiveness
SPC	Statistical Process Control
DASA	Name of German company
MIS	Management Information System
SIMUL8	Software Package
MTTR	Mean Time To Repair
DoE	Design of Experiment
WS	Workstation
Thr/put	Throughput
Proc	process
ROI	return on investment
CIM	Computer integrated manufacturing
LD	Lean Time
DES	Discrete Event Simulation

Notation

$$T_{thr} = a - b \times \Pr ocess_{time}$$

T_{thr}	Total Throughput
a=	The intercept constant
b=	Regression coefficient
$\Pr ocess_{time}$	Process Time

CHAPTER 1 Introduction

1. Introduction

Over the last decade manufacturing within the EU has witnessed fierce competition in the global market, especially from the emergence of new manufacturing organizations from China and India that have low labour costs, fewer overheads and longer working hours. (Brandes, 2008).

To offset this increased cost-based competition EU manufacturers are seeking to achieve competitive advantage by increasing the levels of customisation and product choice offered to customers. (McKellen 2002).Achieving this aim in a cost-effective manner requires the rigorous embedding of lean techniques across manufacturing. (Davies and Kochhar, 2002, Dimancescu et.al. 1997). Such lean practices have the ability to significantly increase business competitiveness through the elimination of waste labour, time and material resources while delivering quality products on time, at least cost and lead time, and with greater efficiency.(Miyake, Enkawa and Fleury,1995). The basic underlining idea of these techniques is to minimise the consumption of resources that do not add value to a product.

When we use the philosophy of lean manufacturing and its enabling tools, it is essential for organisations to monitor overall performance. This is normally achieved using a performance measurement system,(Kasul and Motwani1995) which is vital, for organisations, because it enables the short-term operations of individual manufacturing areas to be integrated into the long-term objectives of the organization.

Historically, companies began as early as the 1900's to measure and monitor their performance using primarily the financial measures such as "Return On Investment" and "Return Of Assets". However, in the early 90's, authors such as Maskell (1989), Kaplan and Norton (1992), and Cross and Lynch (1988-1989), identified that financial measures are not the only measures that can be used to indicate overall business performance.

Since this research, many new performance measurements frameworks have been created, such as the “Balanced Scorecard” (Kaplan and Norton 1992), “Smart” (Cross and Lynch1988-1989) and the “Performance Prism” (Neely et.al.2001) to cope with previous limitations. However, these performance measurement systems are not able to link the business level strategic objectives with those at shop floor level, therefore, not enabling everyone in an organization to be aligned with business targets. Ghalayini and Nobble (1996) also rightly claim that, these frameworks can not indicate where organisations may improve their efficiencies, ie a function that is essential for effective performance management.

This research will investigate the issue concerned with manufacturing systems that exhibit both high levels of process-connectedness as well as high levels of product and process variability. As an example, it can be referred the mixed-model flow processing systems that need to effectively cope with the high levels of customer choice offered, as well as quality, delivery reliability, lead-time and cost performance which customers are increasingly expecting.

In order mixed-model flow processing systems to be effective, they must take into account each individual manufacturing system’s component influence on overall system performance. Since performance measurement systems which are able to assist in this task are not available, this research is intended to fill this gap.

In addition, the performance measurement system to be developed is able to meet the requirements identified by Maskell (1990), Neely et.al. (1995), Ghalayini and Nobble (1996), and Kaplan and Norton (1992), providing performance measurement information able to promote and direct continuous improvement activities through indicating, where the organizations need to make improvements. To achieve this aim, the limitation identified by Sanchez and Perez (2001): “very little is known about the relationship between the use of production indicator and the company’s competitiveness" has been resolved, i.e. the lack of knowledge of relationships between performance indicators.

The metrics for the mixed flow lines, the relationships between them and the developed relationships between cause of inefficiencies and lean enablers, supports the aims and the objectives of this research. Specifically, the aim of this research is to develop a set of performance measures for mixed-model production systems that can improve the efficiency of line and link production performance with business levels

Moreover to identify which tool or techniques should be used, it supports the objective of this research that is to make use of performance metrics to identify lean enablers. The latter will improve the capacity and/or optimise existing capacity of mixed-model lines. As such the relationships between 'lean enablers' and individual performance metrics has established. In this respect the basic 'wastes' that lean practices attempt to minimise, have been identified.

For this research developed a table of the relationships between the existing lean enabler and the ten generic causes of inefficiencies. This could lead to choose lean enabler in order to improve each station that causes inefficiency in the line. Also, the experiments that carried out show that exist relationships between the performance metrics and the metrics that related to the tactical level are related.

Hence, this methodology can be applied either in an existing aero structural production line or to new production flow lines. Also, can be applied in where discrete manufacturing goods are produced.

Developing a performance measurement system that is able to identify the effect of individual system components in the overall performance of mixed-model flow lines is a complex process because:

i. There are a large range of individual performance metrics (PMs) that need to be included.
ii. Complex relationships often exist between performance metrics, i.e. increases in work in progress levels may have varying effects on lead times.

iii. The performance metric is one characteristic of an overall performance measurement system, hence other characteristics such as skills and training of the personnel using the PM must be taken into consideration.
iv. There needs to be at least 3 different PM system levels i.e. Strategic, Tactical and Operational, and the relationships between PMs at each level needs to be identified.

1.2 Aim and Objectives of Research

The aim of this research is to develop a set of performance metrics for mixed-model production systems that can promote synchronous flow, promote smooth material flows, assist in improving the efficiency of flow lines, link production with customer demand and link production performance with strategic business performance.

1.3 Research Methodology

The research methodology is as follows:

i. To examine the range of performance metrics in use, recognizing the necessarily elements that a performance system should include, examination of manufacturing systems design and the factors that influence it, and the tools that are used in lean manufacturing.
ii. To identify the cause and effect relationship amongst the generic performance metrics.
iii. To identify the effectiveness of using simulation modelling to identify cross-PM relationships, i.e. simulation model of actual manufacturing data from the flow processing production line within the relative Aerospace Industry.
iv. To use the results of the simulation to develop an integrated performance measurement systems for improving the efficiency of mixed model flow lines.

1.4 Chapters Overview

Chapter 1 explains how the manufacturing environment is evolving towards increasing levels of customization and product choice being used to offset cost-based competition from overseas. It also indicates the use of lean techniques for ensuring that the high variability manufacturing environments that result from this competitive position, require the rigorous and wide spread introduction of lean techniques throughout the manufacturing process. The need for an integrated performance measurement system is then explained to enable effective lean implementations to be undertaken.

Chapter 2 introduces Mixed-Multi Model Flow Lines and examines their design, planning and control. Capacity management is examined, ie the process of planning and controlling the effective capacity of an operation in order that it can respond to customer demands within a particular time period, and the metrics of use for planning and control identified. The layout of processing work stations along a flow line is examined together with work station job allocation such that effective line balancing can be achieved. The importance of sequencing jobs onto flow lines is then examined along with methods used to achieve effective sequences. Finally this chapter critically reviews the literature on performance metrics, identifies those metrics essential to the design, planning and control of mixed-model flow lines and the relationships between them.

Chapter 3 critically reviews the research literature on lean manufacturing and principles. In particular it identifies the basic causes of operational inefficiencies and the process and system based ‘lean enablers’ that are available to address them, ie the methods by which changes are physically made to reduce the impact of these inefficiencies. This chapter identifies the relationships between individual inefficiencies and the lean enablers used to resolve these inefficiencies.

Chapter 4 develops an experimental plan, using Taguchi orthogonal arrays, for identifying the relationships between pairs of metrics, using correlation analysis, and quantifying these relationships using regression analysis. A discrete event simulation model is developed for the mixed-model flow line within case study company and used to generate the experimental results. Chapter 5 reports the results of the simulation experiments, and draws attention to key relationships.

Chapter 6 draws together the key concepts of the thesis to form a proposed performance measurement system for managing and controlling mixed-model flow processing lines.

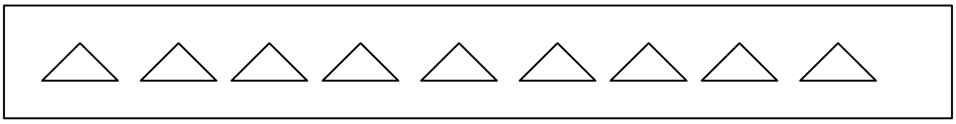
Chapter 7 draws the conclusions of the research and Chapter 8 laying the ground for further research.

CHAPTER 2 Design, Planning &Control for Mixed-Model Flow Lines

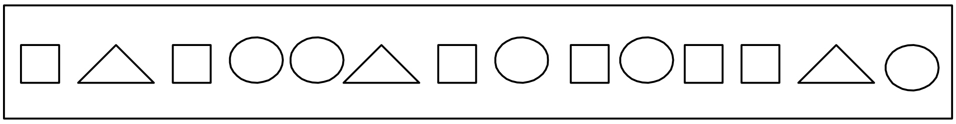
2.1 Introduction

Buxey et al. (1973) have identified three basic types of flow lines as show in figure 2.1

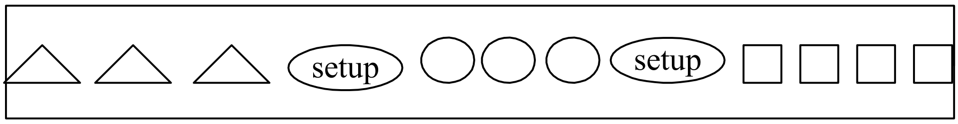
i) Single model in which only one product is produced.
ii) Mixed model in which more than one product is produced simultaneously.
iii) Multi-model involving flow production in batches of different products which are produced in the same line.



Single-model line



Mixed-model line



Multi-model line

Figure 2. 1: Flow Lines

This research is concerned with mixed-model lines in terms of frequency and length of the set-up as well as activities required to change from one model to the next in the sequence.

In addition, there must be sufficient customer demand for the product range to ensure cost effectiveness of a product based layout, ie. in this layout all the items of equipment, needed to manufacture the product range, are arranged in the sequence of the manufacturing process.

Traditional methods of layout equipment according to the needs of products being manufactured are used to design mixed–model lines with their associated ‘best practice’ of:

a) Positioning sequential items and equipment such that travel distances between them are minimized (Hirano and Black, 1988).
b) Adopting ‘U’ shaped lines such that visible communications can be provided between workstations to facilitate quick response to quality, change over and breakdown repair activities.(Sekine, 1992).
c) Operators work inside the U-line (Miltenberg, 2001).
d) One operator supervises the entrance and the exit of the line (Miltenberg, 2001).
e) Operators should be a multi skilled to operate several different machines or processes (Shingo, 1989).
f) Machine work is separated from operator-work as much as possible (Miltenberg, 2001).
g) Standard operations charts specify exactly how all work is done(Moden, 1998).
h) Product flow and hence operator movement may be clockwise or counter clockwise (Black, 2001).
i) Undertaken a ‘line balancing’ exercise to determine when tasks we carried out at which workstations along the line and the relative ‘sequential’ and ‘parallel’ relationships between this tasks. (Sparling & Miltenberg, 1998).
j) Undertaken a rebalancing periodically when production requirements change. (Hall, 1998).
k) Implementing pull production control (Spearman and Zazanis, 1988).
l) Implementing one piece flow. (Sekine, 1992).

2.2 Capacity Management for Mixed-Multi Model Flow Lines

Capacity management is the process of planning and controlling the effective capacity of an operation in order that it can respond to customer demands within a particular time period.

When designing a manufacturing system, whether batch flow or fixed layouts, it is essential that a method, for ensuring that the correct amount of process and labour capacity, is available. In this respect, both short term functional and long terms changes in customer demand must be accounted for.

The failure to provide effective capacity management can significantly affect business performance in terms of cost, revenues, working capital, quality, and delivery reliability. In terms of developing and operating mixed model flow lines three basic activities are involved in the capacity management process, i.e.:

i. Line balancing,
ii. Capacity planning
iii. Capacity control

2.2.1 Line Balancing

The allocation of tasks to work stations along a flow line is termed ‘line balancing’ since the aim is to ensure that all workstations processes equal cycle times.(Milas, 1990) This enables the work between each workstation to be ‘synchronized’ with their preceding and succeeding workstations in the line. Takt time is the heart of any lean production system and sets the pace of production to match the rate of customer demand (Jack&Collins,2005). In this way, workflow can be controlled using an appropriate Takt time based on meeting customers demand. Line balancing as been examined by:

Helgeson and Birnie (1961) introduced the rank positional weight (RPW) method for a single model line balancing and propose five steps:

1. Drawing a precedence diagram to identify all the sequential activities, and their times.
2. Knowing the demands, calculation of the cycle time and minimum number of workstations takes place.
3. Calculation of rank positional weights

4. Allocation of the work elements to work stations, and
5. Calculation of the balanced delay and balancing loss.

In terms of mixed model flow lines are difficult to achieve due to a variability of levels (Becker and Scholl 2006),

i. Individual product task times,
ii. Mix of individual product models allocated to the flow line,
iii. The individual tasks required for each model type,
iv. Different precedence relations between models,
v. Not using up the maximum time available in each station,
vi. Station times of different models have to be smoothed for each station (horizontal balancing) in order to avoid operating inefficiencies, e.g. work overload or idle time,
vii. Variations between workstation times,
viii. Cycle time restrictions for each model,
ix. Work overload minimized,
x. Minimized idle time
xi. Instability of humans with respect to work rate
xii. Position related constraints are relevant for work pieces which are heavy, large or fixed at the conveyor belt
xiii. Restriction in operator related to different skills.

Traditional line balancing techniques, such as rank position weight, assume that no variability exists in terms of the work tasks allocated to each work centre.

However, in a mixed-model production where more than one model is produced, variability in these areas may exist. Researchers have approached this problem in several ways: i.e. Helgerson and Birnie (1961) used a weighted average time rule, ie. the average amount of time required at a workstation to perform tasks where the weighted average time at each workstation could not exceed the required cycle time for all product models.

Thomopoulos (1967) used a slight modification of the single model line balancing in order to balance a mixed model lines. This were focused on assigning work to stations such that each station has the same quantity of work on a daily or shift basis rather than in divided cycle time. The research also showed that sequencing can be used to increase the efficiency on mixed model assembly lines.

Thomopoulos (1970) also, proposed a modified mixed model balancing algorithm that yielded smoother model assignments in each station in the line in continuous assembly situations. Moreover this work showed that this procedure can apply to assembly lines that operate on a batch basis.

In the 1990's many factories started to use the principle of JIT, this lead to changes in the arrangement of production lines in to U-shaped lines. Miltenburg J. and Winjngaard (1994) have introduced and defined the problem of simple line balancing in U-line. Techniques for traditional a Line Balancing problem like modified ranked positional weight method and showed that simple problems can be solved. Also, they used dynamic programming to find the optimal balance of U-lines. However, this technique cannot determine more complex balances i.e. where workstations are allocated tasks in more one flow line.

Sparling (1998) completed the previous study of Miltenburg et.al. (1994) considering more complex situations of U-line balancing. He looked at several U-lines that operate in close proximity, in order to balance two or more U-line together and reduce the total number of stations and hence the travel times. He proposed a heuristic solution algorithm for two cases: first the general case where there are no restriction on the location of U-line and then the more restricted problem in which U-line location are fixed.

Noorul Haq et al. (2006) work on mixed model assembly lines balancing, considered *n* models, using a hybrid genetic approach. In their study, they first used modified RPW for mixed model balancing and then the genetic algorithm approach. Results from each method combined to make a hybrid generic algorithm, resulting to minimize the number of workstations.

Chakravorty and Shtub (1985) dealt with the problem of line balancing and lot sizing in a multi–product environment using the concepts of echelon inventory, echelon holding cost and the consecutive ordering property which minimized the inventory and setup cost along with the station idle time cost.

Sparling and Miltenburg (1998) illustrated that there are differences between straight lines and U-line in the mixed model production. In U-lines, the tasks performed in the front part of U- line are different in size and frequency than from the end tasks of the line.

Sparling and Miltenburg (1998) first developed an algorithm to balance the mixed-model U-lines and suggested four steps. The first two steps transform the multi-model problem in an equivalent single-model problem. The third step finds the optimal balance. The fourth step adjusts the balance from the previous step to make it feasible for the original multi-model problem. In addition the dynamic balance that can be achieved, depended on the product and parallel line, this is an added workstation, when the weighted average task time is too large.

A multi model flow line is prepared for producing one model and before the second batch model starts, adjustments are made in the line. So, each line is treated as a single line-balancing item. Also, in a mixed model line the line balancing might be considered as a balancing problem of different single models. This means, that different product which are similar can be balanced and that each work element is allocated to each workstation independently, results in the balancing loss being minimized. (Wild 1995)

McMullen and Frazier (1998) have used the simulated annealing method to deal with the assembly line balancing problem for multiple objective problems such as those paralleling of workstations. They were interested in two performance objectives i.e.

‘total cost per part’ and the ‘amount of desired cycle time being achieved’. The results of the experiments showed simulated annealing gave enhanced solutions on ‘cycle time’ but no improvement in cost performance.

Another approach for designing parallel workstation mixed models line undertaken by McMullen and Tarasewich (2003), who used the ‘ant’ technique to solve the assembly line balancing problem. Balancing performance compared with other heuristic approaches, such as simulated annealing, was found to be similar.

2.2.2 Capacity Planning

Capacity is an important factor for every company because; balancing the capacity and the demands can produce profit for the organization and customer satisfaction. Reducing capacity tends to decrease the level of service and increase the capital that is tied up. On the other hand, excess capacity is associated with increases in cost. Avoiding these faults, Jonsson and Mattsson (2002) pointed out that the available capacity should match the required workload.

According to APICS (2005) capacity planning can be defined as:
“*The process of determining the amount of capacity required to produce in the future*”.

Slack et al. (1995) categorise capacity planning in three levels:

Level i. The resource requirements planning
Level ii. Rough-cut capacity planning
Level iii. Capacity requirement planning

Resource planning is concerned with aggregate or long range capacity planning of gross labour hours, floor space, and machine hours, in time horizon of months or years.

Both Hammesfahr et.al. (1993) and Jonsson and Mattsson (2002), identified that production capacity decisions for new or existing facilities have a direct impact in the firm’s competitive position, profits and return on investment. They proposed a methodology for creating a capacity plan that decreases the total costs of production and increases profitability. They identified that excess holding capacity leads to increases in overhead costs, reduced competitive advantage and decreased profit. Whilst been under capacity requested in lost of sales and shrinking of market share.

Rough-cut capacity planning, use the master production schedule to determine the requirements for the key resources such as labour and equipment.

A survey conducted by Burcher (1992) to identify factors influencing effective capacity planning in an MRPII experiment identifying that companies need to concentrate at the rough cut capacity planning stage, or planning only critical or bottleneck resources in order to avoid costs of collected evaluations detail shop floor data.

Capacity requirements planning, involved, in detail, the amount of labour and machine resources, required to accomplish needed production tasks. Other requirements included need for determining time standards, lead times, planned orders, routings, and bill of materials and the status of current orders at each work centre.

The capacity of a manufacturing system is affected by demand fluctuations, and in order to cope these Evans (1993) proposed the following methods, i.e.

i. level capacity plan i.e. maintain equal amount of each period.
ii. chase demand plan and /or monitor capacity with demand.
iii. demand management i.e. change the demand to much capacity.

Melnyk and Christensen (2000) identified that, the amount a process produces is influenced by factors, such as:

i. length of product runs
ii. Accuracy of time standards
iii. Past experience with the products i.e. learning factors

iv. Stability of priorities, i.e. when priorities frequently change capacity
v. Scheduling methods, and /or
vi. Level of workload, i.e. how much work is waiting to be processed

In addition Anderson (2001) identified that capacity and operational performance can be affected by product mix. The problem of capacity estimation of a multi product line composed of unreliable workstations has been addressed by Kader and Gharbi (2002) who showed that the capacity of manufacturing system can be affected by levels of workstation failure, repair and setup.

Flynn (1987) observed the effect of setup time on output capacity by using simulation experiments to reveal that reduction in setup times leads to greater output capacity.

At the ‘aggregate production planning level’ resources can be transferred among production lines (Techawiboonwong and Yenradee 2003). They used a spreadsheet-solver technique to produce that using optimal aggregate plans for managing the available production capacity and operators

Balachandran et.al. (1997) argued that if it is possible to augment all resources on an as needed basis, then optimal capacity planning can be undertaken for each individual resource. This study is showed that capacity planning needed to focus on identifying expected bottleneck resources, dominate product or developer resource-level capacity plans.

In production level, the resources which are not constrained can increase the capacity, especially in U shape lines; the capacity should be increased or decreased either adding or subtracting staff. The capacity of non constraints stations varied during simulation experiments conducted by Blackstone and Cox (2002). These experiments showed that line output increased as inventory at non constraints stations. This is contrary to traditional line design principle which state that output is governed by the station with the lower capacity. TOC is an overall management philosophy that recognizes constraint on any system restricts the maximum performance level that the system can obtain in relation to its goal. (Siha,1999). Therefore, theory of constraints (TOC) recognizes that balancing the capacity of resources in a plant can be inefficient, and suggests releasing work to a process according to the constraints work station capacity.

2.2.3 Capacity Control

Capacity can be measured either in terms of output, e.g. numbers of units per week or in terms of input, e.g. machine hour available.

Within manufacturing there exist three types of capacity ie.

i. Design capacity, which indicates the maximum capacity that can be achieved under ‘ideal’ conditions. However, it is difficult for the operations to remain at maximum capacity, due to factors such as breakdowns, tool changes, and planned maintenance.

ii. Effective capacity which is the remaining proportion of the design capacity, often subtracting the capacity losses arising from the factors above.

iii. Achieved capacity takes into consideration the losses of efficient capacity that arise from such cause of lack of skilled operators, use of poor quality materials, tools and/or equipment.

The following equations have been defined by (Slack 1995) for measuring these types of capacity ie.

The ratio of actual output gain to design capacity is called utilization.

$$\text{Utilization} = \frac{\text{Actual.output}}{\text{Design.capacity}} \qquad (1)$$

The ratio of actual output that is gained from the process ie. effective capacity, is called the efficiency of the plant.

$$\text{Efficiency} = \frac{\text{Actual.output}}{\text{Effective.capacity}} \qquad (2)$$

The achieved capacity is measured as:

$$\text{Achieved capacity} = \text{Design capacity} \times \text{Utilization} \times \text{Yield} \qquad (3)$$

When estimating total available system capacity the following have been found (Naylor, 1996), to affect capacity levels, ie:

- Processes in parallel, ie. Capacity is added in order to assess the whole capacity of the system.
- Processes in series, ie. Arranged in a line, the capacity is equal to the rate of the slowest process step.
- Joint processes, e.g. when two production lines produce components and feed one or more of the final assembly lines. In these conditions the production line with the lowest capacity is used to establish the total capacity of the system.

Once capacity planning has been undertaken, the next step is to ensure effective control of this capacity. APICS (2005) defines capacity control as:

> *"The process of measuring production output and comparing it with the capacity plan, determining if the variance exceeds preestablished limits, and taking corrective actions to get back on plan if the limits are exceeded".*

There are two methods of control, ie. the open and closed loop systems.
In a mixed model flow line due to wide variety of factors that affect the performance, such as setup, process time and maintenance, the most appropriate system of control is closed loop.

The basic stages as can be seen in Figure 2.2, involved in closed loop control Beer (1966) and Blackstone et.al. (1997) are:

i. Input
ii. Modified input
iii. Process
iv. Output
v. Monitoring
vi. Modified process or Input

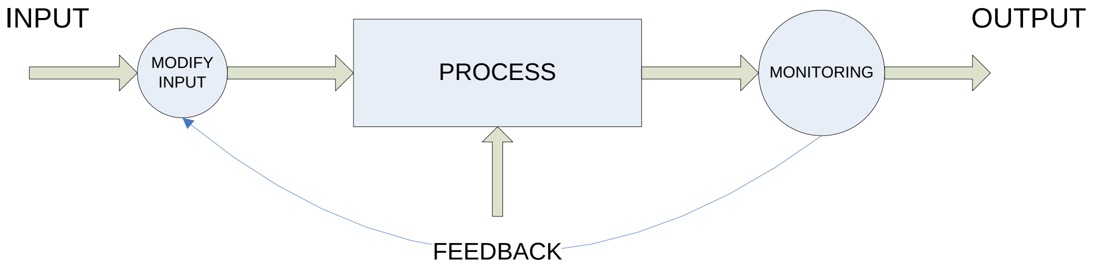


Figure 2. 2 Feedback Control Diagram

2.3 Mixed-Model Flow Lines Sequencing

The objective of sequencing is to determine the optimum order of model entry to the flow line in order to optimise the utilization of operators is possible. Thomopoulos (1967) identified that effective planning of mixed model assembly lines entails two separate but related problems i.e. line balancing and model sequencing. In addition, Miltenburg (2002) also suggests that model sequencing should not be independent of line balancing.

In multi-model lines, Schronbergers et.al. (1994), the order sequence of models is determined by minimizing the total setting-up cost over a given period of time. Setting-up cost includes the cost of tools, the machine changeovers, tools and re-setting, machine and labour idle time.

2.3.1 Bottleneck Scheduling

Bottleneck scheduling is an effective element of the Drum-Buffer- Rope (DBR) techniques defined by Goldratt and Fox (1986), which form part of the theory of constrains (Spencer and Cox, 1995). With DBR the bottleneck with a system sets the pace of production, synchronized to the needs of the bottleneck using the following principles, ie.

2.3.2 Drum

The production rate of the capacity constraint resources is typically linked to the rhythm of a drum, and it provides the pace for the rest of the system.

The drum is the detailed bottleneck schedule, and serves as the Master Production Schedule (MPS) for the entire system.

2.3.3 Buffer

Buffers in front of the bottleneck are used to protect the constrain from running out of materials to protects and hence costing available capacity

2.3.4 Rope

The rope is a communication mechanism which ensures that raw material is not introduced into the production process at a rate faster than the capacity constraint resource can accommodate i.e.it prevents unnecessary build up of work-in-progress.

Corbet and Csillag (2001) analysing seven different companies that had implemented the Drum-Buffer-Rope approach concluded that the benefits are quite uniform across all companies in that DBR lead to increases in capacity, improvement in due-date delivery performance, decreases the lead time and reduction in work in process. Moreover, there were increases in levels of revenues per employee.

Chakravorty (1996) found that the improvement of lead times and operator productivity levels resulted though implementation of Cellular Manufacturing and DBR despite declines in overall. Guide and Ghiselli (1995) proved that DBR could be successfully implemented in high complex production lines in such as those involved in remanufacture of complete engine systems.

Riezedos Korte and Land (2003), managed to further reduce lead times, from those gained from initial implementation DBR, in focusing in order acceptance and buffer management systems, using workload control principles. Demmy and Demmy. (1994) concluded that scheduling within DBR should not be limited in shop floor but can prove useful whenever "synchronized flows of work can improve productivity".

2.4 Performance Measurement

Performance management is essential to show performance against targets and to enable opportunities for improvements to be recognised.

2.4.1 Definitions

Neely et al. (2005) gave several precise definitions of performance measurement ie.

i. *Performance measurement can be defined as the process of quantifying the efficiency and effectiveness of action.*
ii. *Performance measure can be defined as a metric used to quantify the efficiency and effectiveness of action*
iii. *Performance measurement system can be defined as the set of metrics used to quantify both the efficiency and effectiveness of actions.*

In the definitions above, two fundamental dimensions of performance measures exist ie. efficiency and effectiveness.

Here effectiveness refers to the extent to which customer requirements are met, where efficiency is a measure of how economically the firm's resources are utilised when providing a given level of customer satisfaction.

2.4.2 Traditional Performance Measurement Systems

Ghalayini et al. (1996) revised the research literature relating to performance measurement identifying two main types ie. traditional performance metrics which relied on financial measures such as, a return on investment, productivity, utilization, efficiency and profit, and measures which concerned with new technologies and philosophies such as Computer Integrated Manufacturing, Just in Time and Total Quality Management. Skinner (1986) argues that companies need to focus on short lead times, customer service, flexible capacity, quality and rapid product introduction in order to be competitive.

With the increasing levels of global competition traditional financial based metrics have been found to be insufficient to measure the performance.

2.4.3 Limitations of Traditional Performance Measures

Financial performance measurement systems are limited due to their assumption that standard products are made with long production runs (ie. mass production), without changes in the characteristics and specifications of the product.(ie. customisation)

In addition financial performance measures are unable to manage and control the manufacturing skills and competencies that companies need to employ to remain competitive (Kaplan, 1992).

For these reasons, traditional performance measures are no longer adequate because of the many limitations that have been observed, which includes:

- Traditional management accounting systems emphasises costs of labour.
- Metrics make use of historical data and hence are limited in making future decisions.
- Metrics lack direct relationships with corporate strategy.

- Metrics are difficult to implement in practice due to lack of understanding in shop floor operators, collection data is expensive, conflicts exist with continuous improvement needs and inflexibility between departments.

The reduction of cost, and the limitation of profit, do not offer evidence of good operations and control and moreover do not suggest areas for improvement (Ghalayini et al. 1996)

However, in order to avoid these pitfalls, new performance frameworks of measurements and integrated performance measurements systems have been developed with emphasis on non-financial measures.
In terms of these non-financial metrics Medori and Steeple (2000) mention their advantages and disadvantages which include:

Advantages

1. Measures are more timely than financial-based metrics
2. Measures are measurable and precise
3. Measures are consistent with company goals and strategies
4. Measures are flexible and can be changed in accordance to market needs

Disadvantages

Because there are a large variety of non financial measures, it is difficult to select which individual measures a company should use.

Normally organisations would adopt combinations of the non-financial and financial measures

2.4.4 New Performance Measurement Systems

A number of ‘integrated’ performance measurements systems have been developed in order to provide a holistic picture of a company’s performance and to avoid any sub-optimisations ie.

- Balanced scorecard (Kaplan and Norton, 1997, Kaplan and Norton, 1996)
- SMART - strategic measurement analysis and reporting technique (Cross and Lynch, 1988-1989);
- Performance measurement for world class manufacturer (Maskel, 1989);
- Performance measurement questionnaire (Dixon *et.al*, 1990);
- Performance criteria system (Globerson, 1985);
- Cambridge performance measurement design process (Neely *et at*, 1995; 1996).
- Performance Prism (Neely *et at*, 2001)

Of these systems the balanced scorecard appears the most popular with many companies implementing the approach successfully; Pineno (2004) and Letza (1996), provide the benefits for implementing this type of system. However, not all attempts used the Balanced Scorecard have been successful; for example according to Schneiderman (1999) the balanced scorecard concept fails by not identifying the correct non-financial measures, using poorly defined metrics, and not providing a deployment system and quantitative relationships between non-financial and expected financial results.

The Balanced scorecard provides information only for senior managers because it designed to provide an overall view of performance, not performance at the factory floor level. Also, Fehlman (2003) claimed that balanced scorecard metrics are such a high level that it is not possible to examine current individual business practices. This view was supported by a recently survey carried out by Ittner and Larcker (2003) who showed that companies tend to fail to identify, analyse, and act on the correct non financial measures ie. cause-and-effect links between improvements in non-financial areas could not be demonstrated. Also, because of lack of linking with business, the managers, decide for the measures, some of them could choose and manipulate it for the purpose of making they look good and earning nice bonuses.

In addition, Kaplan and Norton (1992) mention that the major limitation of the balanced scorecard approaches is its lack of suitable information systems, within the companies.

General limitations with all integrated performance measurement systems are that they cannot be used to measure improvements or predict future performance. In addition they do not provide a specific tool that could be used to model, control, monitor and improve the activities at the factory shop floor, and are not mechanisms for specifying the objectives that should be achieved in a specific time horizons. (Ghalayini et.al ,1996)

2.4.5 Performance Metrics

The literature review Mejadi (2003), Tangen (2003), Ward & Haque (2001), White (1996), Dixon et.al. (1990), Dhavale (1996), Bauly (1994) Neely (2001) and Kaydos (1999) identified a large number of potential metrics, which are presented in Appendix (A).

Both Medori and Steeple (2000) and Neely et.al.(1997) have addressed the issue of how to choose appropriate metrics. In the latter work made the following recommendations for designing measures, i.e.

1. Performance measures should be derived from strategy
2. Performance measures should be simple to understand
3. Performance measures should provide timely and accurate feedback
4. Performance measures should be based on quantities that can be influenced, or controlled, by the user alone or in co-operation with others.
5. Performance measures should reflect the “business process”
6. Performance measures should relate to specific goals (targets)
7. Performance measures should be relevant

8. Performance measures should be part of a closed management loop
9. Performance measures should be clearly defined
10. Performance measures should have visual impact
11. Performance measures should be focus on improvement
12. Performance measures should be consistent (in that they maintain heir significance as time goes by)
13. Performance measures should be provide fast feedback
14. Performance measures should have an explicit purpose
15. Performance measures should be based on an explicitly defined formula and source of data
16. Performance measures should employ ratios rather than absolute numbers
17. Performance measures should use data which are automatically collected as part of process whenever possible
18. Performance measures should be reported in a simple consistent format
19. Performance measures should be based on trends rather than snapshots
20. Performance measures should provide information
21. Performance measures should be precise-be exact about what is being measured
22. Performance measures should be objectives-not based on opinion

Additional issues identified by Tangen (2005), were:

- metrics should not indirectly support negative behaviour
- metrics should not measure activities or resources over which they have no control
- metrics should not be based on misleading “weighting” of parameters within them.

In terms of the current research the above criteria for selecting and designing metrics have been reduced to the following set, i.e.

Timely, enable targets to be set, identify problem areas, represent true cause and effect relationships, visual indicators, understood by users, owned and supported by users, enable activities to be monitored.Using these criteria a list of measures have been created i.e.

- Work entry rate
- Material waiting time
- Material moving
- Material queuing time
- Floor space
- Workstation utilization
- Processing time
- Machine utilization
- Machine availability
- Quality rate
- OEE
- Throughput rate
- Unscheduled downtime
- Scrap rate
- Rework & repair rate
- Set up time
- Scrap cost
- Total cost per part

Table 2. 1 List of Generic Metrics

2.4.6 Relationship Between Performance Metrics

The literature research was examined in order to identify the relationships between the performances metrics listed in table 2.1.

Taylor (1999), Taylor (2002) compares in terms of their buffer control systems and their effects on equipment utilisation. They would found that reducing the level of WIP inventory reduces the station utilisations which in turn affects the levels of equipment wear and maintenance which in the long run reduces the total operating expenses. Moreover, to reduce the operating expenses leads in greater return on investment (ROI) and increases the cash flow, and as a result higher levels of competitive advantage in world markets. In addition, reductions in WIP make production areas less cluttered which improve quality levels and then reduce lead times which then increases competition in world markets.

Zozom et.al. (2003), addressed the problem of releasing jobs to the shop floor while meeting delivery dates and minimizing the work in process inventory. The algorithms developed proved that varying release time can be used to minimize WIP. In addition the less likely a job is to queue and therefore be delayed, the greater will be due-date performance.

When comparing functional and cellular layout with regards to the effects of setup time reduction, and lot size on flow time and throughput, Faizul et.al. (2001). found that both of types of the layouts have significant affects an throughput at lot sizes up to 55 but no significantly affects for lot sizes 60 or greater. Furthermore, he states that reducing set up time enables batch sizes to be reduced leading to less waste in the form of scrap and WIP, and faster responses to market needs.

Karmarkar (1987), points out that long lead times impose costs due to higher work-in-process and larger safety stocks, and results in a poor performance to due date. In addition, long lead times become a direct result of capacity limitations, which itself is affect by lot size. In addition, queueing delays arise as a result of variability in processing times, variability in the arrival of work at machines and the level of traffic intensity and extent of loading of the machine. Traffic intensity of the system is affected by setup time and batch size. Generally speaking, queuing behaviour affected by lot size, release times of batches to the shop, sequencing at machines, capacity at work centers, product mix and the heterogeneity of parts. Finally the cost of queues prevents the machines from being fully utilised.

Gung and Steudel (1999) have identified the following relationships between metrics, ie.

i. setup levels effect work in progress level
ii. setup costs effect batch sizes
iii. batch sizes effect work in progress levels
iv. work in progress effects lead time

The research described in section 2.4.6 and that undertaken by the following researchers have been used to identify the relationships between metrics identified in table 2.2, i.e.

Woodcock (1989),Wacker (1996), Wacker (1987), Hall (1988), Taylor (2000), Missbauer (1997), Enns (1998), Ward (2001), Betchte (1988), Andries&Gelders (1995), Kuikand Tielemans (1997), Moden (1998), Narasimham and Melnykast (1990), Ljungberg (1998), Chand and Shirvani (2000), Maskell (1991), Sarker,et.al. (1994), have found many relationships among different measures.

CAUSE	EFFECT	Work entry rate	Material waiting time	Material moving	Material queuing time	Floor space	Workstation utilization	Processing time	Machine utilization	Machine availability	Mean time btwn failures	Quality rate	OEE	Throughput rate	Unscheduled downtime	Scrap rate	Rework & repair rate	Set up time	Scrap cost	Rework& repair cost	Total cost per part	Manufacturing lead-time	Adherence to schedule	Work in progress	Distance traveled	lot size/batch size
Work entry rate		■			X																					
Material waiting time			■			x																				
Material moving				■																						
Material queuing time					■	x																X				
Floor space						■																				
Workstation utilization							■							X												
Processing time					X			■																X		
Machine utilization									■				X	X								X				
Machine availability										■			X	X												
Mean time btwn failures					X					X	■		X													
Quality rate												■	X									x				
OEE												X	■	X									X			
Throughput rate										X				■												
Unscheduled downtime										X			X	X	■											
Scrap rate																■					X					
Rework & repair rate																	■				X	X		X		
Set up time					X		X		X							X		■				X	X	X		X
Scrap cost																			■		X					
Rework& repair cost																				■	X					
Total cost per part																					■					
Manufacturing lead-time							X		X												X	■	X	X		
Adherence to schedule																							■			
Work in progress					X	X	X		X			X										X	X	■		
Distance traveled																						X	X	X	■	
Lot size/batch size		X	X		X	X	X	X	X			X				X						X	X	X		■

Table 2. 2 Cause and Effect Relationships

The following chapter looks in depth the relationships among the performance metrics that create inefficiency in the flow lines and the Lean tools and techniques that could help in reduce or eliminate these inefficiencies.

CHAPTER 3 Lean Improvement Techniques

3.1 Introduction

Manufacturing efficiency, and ultimately business competitiveness, can be achieved through 'reducing processing batch sizes' and 'increasing the range of products available to customers'. In the first case, reducing batch sizes can reduce inventory levels leading to reduced need for working capital. In addition, delivery lead times can be significantly reduced and the flexibility and responsiveness with which manufacturers can make customer-required changes increases. However, as Figure 3.1 indicates batch size reduction and product variety increases can, without implementing a lean infrastructure, lead to increased levels of operational inefficiency.

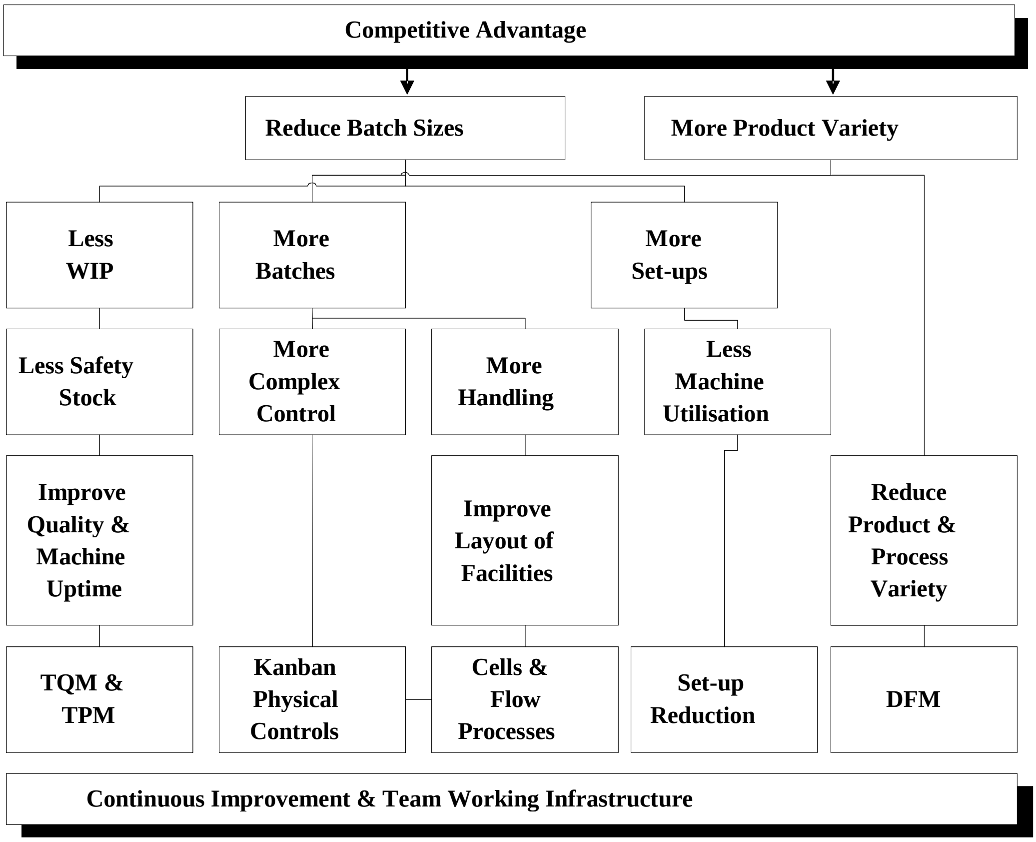


Figure 3 1 Relationships between Competitive Advantage and Lean Infrastructure (Stockton 2003 Lectures notes)

From the literature, Rawabdeh (2005), Hines and Rich (1997) Robinson et.al.(1992), Hale and Kubiak.(2007), Tersine (2004), Chand and Shirvani (2000), a comprehensive list of causes of manufacturing inefficiency has been identified, i.e. Table 3.1.

i. Transportation & Material Handling
ii. Inventory, Batch Size & Work -in-Progress
iii. Overproduction
iv. In-process Queueing Time
v. Waiting, Idling & Minor Stoppages
vi. Over-processing
vii. Non-added Value Motions
viii. Material Shortages
ix. Quality-Process & Non-Process Defects
x. Equipment Failure from Breakdowns
xi. Set-up & Adjustment
xii. Reduced Processing Speed
xiii. Lack of Flexible Labour
xiv. Poor Line Balancing
xv. Poor Job Sequencing
xvi. Variable Cycle Times
xvii. Poor Facilities Layout

Table 3.1Causes of Inefficiency

Chapter 3 examines each of the lean tools and techniques that currently exist, for addressing the ‘causes of inefficiency’ listed in Table 3.1. These can be divided into two basic categories, i.e.:

i. Problem solving tools which enable the basic problem solving steps to be undertaken, i.e. data collection, problem specification, generation of alternative solutions and identification of best solutions from amongst the alternatives. Examples of tools in this category include ‘string diagrams’ and ‘value stream mapping’ (Rother and Shook 2003).
ii. Lean enablers, which are methods by which lean solutions, can be physically implemented and sustained within the work place. Examples of tools in this

category include ‘SMED’, ‘5Ss’, ‘TPM’ and ‘Kanbans’ (Dillon and Shingo(1985), Nakajima (1988), Hirano (1996), Monden (1998)).

Problem solving tools, make use of a wide variety of performance metrics to measure the gap that exists between ‘planned’ and ‘actual’ performance states, i.e. that currently exist and will exist should specific lean enablers be implemented. Lean enablers, need to include auditing procedures, based on the use of performance metrics, to ensure that the correct level of improvements have been obtained and are being sustained.

3.2 Process Based Improvement Enablers

At assembly workstation and equipment processing levels there are essentially 3 categories of lean enablers (Bicheno 2005), i.e. those that assist with:

i. Improving shop floor operator work performance.
ii. Reducing the level of defective items produced.
iii. Improving the planning and control of shop floor areas.

Increasing operator work performance and reducing numbers of defective items can both be achieved by reducing the batch sizes, use of multiskilled operators and through the use of Standard Work practices which involve defining and using the most efficient manufacturing methods using available equipment, people, and material, i.e. Standard Work depicts the key process points, operator procedures, production sequence, safety issues, and quality checks that should be employed to ensure fastest, safest and highest quality work can be undertaken.

In Standard operation procedures each step in the process should be defined and must be performed repeatedly in the same manner. However, variations in the process will create quality problems requiring costly rework or scrap. Multi-skilled operators provided with tools such as mistake proofing and process capability, that make them able to improve the quality of the products, leading in reduction of the defects items.

The third enabler that can improve assembly workstation and equipment processing is the planning and control of the shop floor. This is normally achieved through ‘levelling’ of production by both volume and product mix, the total quantity of orders in a period are divided into equal model and mix quantities that should be made each period, i.e. normally per day.

3.2.1 Operator performance

Here the basic methods involve ‘reducing processing batch sizes’, ‘multi-skilling employees’ and ‘standardising work practices’. Reducing processing batch sizes improves the responsiveness with which changes in order priorities can be made, leading to increased levels of flexibility responding to customer demands. In addition, decreases in inventory levels can be as a result. However, this increase in flexibility arise the need to more frequently change from one product model to another and/or moving operators between tasks such as undertaking routine maintenance and statistical quality control. Standardised work is a central tool employed in the lean workplace. It enables repeatability and control of the process; insures that everyone is using best known practices for critical cost, safety, quality and efficiency operations within the overall process, whilst leaving operators with the ability to modify non-critical operations in order to increase the efficiency..

3.2.1.1 Reduce Processing Batch Size

Historically manufacturing has operated under the assumption of large batch sizes to maximise machine utilisation and minimise machine changeover times and costs. Lean methodologies work towards to adopt single piece flow and batch sizes of one. This ultimately reduces inventory carrying costs, work in progress and improves lead times and quality levels. The determination of batch sizes involves considering the complex relationships between the batch size and the wide range of factors that influence it, including manufacturing lead time, work in progress levels and finished stock levels.

Processing parts in batches is preferable to the processing of parts in lots of size one, when setup times are significant. However, by grouping part types that have similar manufacturing requirements, the frequency of setups can often be reduced. Batching is also desirable when material handling is carried out by a set of discrete transporters (e.g., automated guided vehicles, forklift trucks and tow carts). The concept has two elements 'transfer' batches and 'process' batches. A process batch is a batch of work that is processed by a person, team or system. Process batches are grouped for efficiency or other constraints, such as the size of a physical machine, or natural conditions such as hours of daylight. Every batch has a setup and a cleanup cost. Process batches tend to be optimised for efficient use of resources, communication, costs or effort expended such as efficiency of time on task and time in motion.

Transfer batches tend to be optimised for the costs incurred by the next stage in the process or value chain, i.e. according to Goldratt (1990), "often reducing batch size is all it takes to bring a system back into control".

Lot/batch sizes greater than customer order delivery sizes tend to increase inventory. Often batch production is necessary when a manufacturer is producing similar productswith variants. This means stopping between each batch, i.e. to change or clean machines, or prepare to add new dies for the next variation. The necessity of stopping between batches is called "Breakdown", which increases process queuing time, and batch production is becoming an inefficient manufacturing process. Batch size determination is also important in synchronous manufacturing to ensure that processes can start and end in synchronisation and/or inventory is always available when a process needs them. For bottleneck resources, larger batch sizes are desirable to maximise capacity and throughput, and for non-bottleneck resources, smaller process batch sizes are desirable to reduce work-in-process inventory.

Evaluating and minimising the batch size of various processes can yield substantial results. Large batch sizes lead to the potential for greater quality errors and increased lead time. Reducing batch sizes throughout the process, can provide better agility to respond to customer demand. In addition, large batch sizes can result in downstream constraints in the process. Reducing batch sizes, allows the product or service to move on to the next process in less time, ultimately being completed faster and needing less space for in-process inventory.

Excessive batch sizes can result in performance deterioration, i.e. a great part of total manufacturing lead-time is the queuing time rising from processing large batches that affects delivery lead times, May (1990), Stockton & Lindley (1998), Monden (1983), Edwards (1991), and Johnson & Stice (1993). Increasing batch sizes, increases the batch processing times at machines. Before leaving a machine, a part must wait for the entire batch to be processed, before it can be transferred to the next machine. This longer processing time can eventually erode the savings in flow time gained from the reduced frequency of setups and material transports. The deterioration in performance caused by larger process batches can be, in part, limited by allowing for smaller transfer batches between machines. However, this may not always be beneficial since the smaller transfer batches can result in increased loading of the material handling system, Askin & Iyer (1993, 1994) Russell and Fry (1997), Flynn (1987).

3.2.1.2 Multi-Skilling of Employees

Lean environments recognise as important to efficiency factors concerning employees, a) High Motivation b) Team Work and Flexibility c) Flexibility and Multi-Skilled. Arunachalam, Ichimura and Page (2007). Multi-skilling is a workforce strategy that has been shown to reduce indirect labour costs, improve productivity and reduce turnover. A multi-skilled workforce is one in which the work force possess a range of skills that allow them to participate in more than one work process. The success of multi-skilling greatly relies on the ability to assign workers to appropriate tasks and to compose crews effectively, (Gomar et.al. 2002)

Multi-skilling falls into the following categories as defined by Cordery (1995), ie. Vertical Multi-skilling and Horizontal Multi-skilling with the latter being of two types, ie. Skill broadening and Cross skilling/dual skilling. Allen et.al. (2001) have suggested the amounts of training employees should receive in such areas as total productive maintenance, change-over, mistake proofing and standardised work.

Multi-skilling program has been shown to deliver multiple benefits including reduced turnover of employees, measurable return on training investment, increased productivity and reduced waste such as work in progress, (Puttick 2008) through more skilled and engaged employees. Multi-skilling has also proved beneficial in improving quality and reducing costs and delays incurred from use of sub-contractors, (Cipriano 1996), Rosemary (2001), Rutledge (1996), Scott P. and Cockrill A. (1997), Oliver P.(2006), Dufficy M. (2001),),Cua et.al. (2001), Ahmed et.al. (2005).

3.2.1.3 Standardise Work and Operations

Standard Work (also called Standardised Work) is defined as "the most effective combination of manpower, material, and machinery". It is the foundation of daily improvement since it enables the creation of a repeatable process with defined steps, times and layout that achieves the desired result of low cost and high quality.

By documenting the current best practice, standardised work forms the baseline for kaizen or continuous improvement. As the standard work is improved, the new standard becomes the baseline for further improvements, and so on. In mixed model flow lines, multifunction worker development is important i.e. each operator must know, at minimum, how to do the jobs directly before and after his own.

Standardised work consists of three elements:

- Takt time, which is the rate at which products must be made in a process to meet customer demand.

- The precise work sequence in which operators need to perform tasks. The working sequence defines the step-by-step order in which each processing or assembly operation is to be performed.
- The standard inventory, including units in machines, required to keep the process operating smoothly. Standard in-process stock specifies the number of parts that should be in-process at any given time.

Establishing standardised work relies on collecting and recording data which is then used by engineers and supervisors to design the process and by operators to make improvements to their own jobs.

Standardised work is also a learning tool that supports audits, promotes problem solving and involves team members in developing Poka-Yokes.

The benefits of standardized work include documentation of the current process for all shifts, reductions in variability, easier training of new operators, reductions in injuries and strain, and a baseline for improvement activities. Process variations that create quality problems, involving costly rework or scrap, may be avoided through standardised work, which requires each step in a process to be precisely defined and performed uniformly every time it is repeated. Standardising reduces procurement costs, complexity and opportunity for error. Standardising equipment reduces spare parts requirements and improves maintenance know-how. Standardising processes aids in employee rotation, cross training/flexibilityand quality improvements, Allen and Robinson (2001). In addition, it helps create facilities layouts with minimum wasted space, identify minimum work in process needs Whitmore (2008), limit overproduction and prevent build-up of inventory.

3.2.1.4 Training

The term training refers to the acquisition of knowledge, skills, and competencies as a result of the teaching of vocational or practical skills and knowledge that relate to specific useful competencies. In addition to the basic training required to continue training beyond initial qualifications, to maintain, upgrade and update skills throughout working life. People within many professions and occupations may refer to this sort of training as professional development.

Some commentators use a similar term for workplace learning to improve performance: training and development. One can generally categorize such training as *on-the-job* or *off-the-job*:

- On-the-job training takes place in a normal working situation, using the actual tools, equipment, documents or materials that trainees will use when fully trained. On-the-job training has a general reputation as most effective for vocational work.
- Off-the-job training takes place away from normal work situations — implying that the employee does not count as a directly productive worker while such training takes place. Off-the-job training has the advantage that it allows people to get away from work and concentrate more thoroughly on the training itself.

Training differs from exercise in that people may experiment in exercise as an occasional activity for fun. Training has specific goals of improving one's capability, capacity, and performance.

In work place Training is a form of organisational change; allowing employees to learn and demonstrate new concepts, build skills, solve problems, become multi-skilled and develop interpersonal relationships (Rusaw, 2000).

The implementation of many tools such JIT, TQM, KAIZEN etc.are dependent upon the quality of people working within an organisation to achieve excellence (Eastgate, 2000). The benefits of education and training are broad, not only will workers achieve new skills and knowledge but also in terms of flexibility they become more flexible and responsive (Lange et al., 2000), hence improving the competitiveness of a company.
Tate points out that:
Training is an important lever to bring about change if anchored sensibly to a sound business agenda, but it is just one lever among many and a weak one if pulled on its

own. Training will only help if organisations learn to be wise in how they use individual’s capability, marrying talent with healthy cultures, systems and processes, serving well-conceived business goals (Tate, 1997).

There is much training that is wasted, simply because of the training that is provided is not used immediately in the work place, and hence any benefits, the training may have provided are lost (Idhammar, 1997). It is noted that most successful companies provide much more training than average (DTI, 1996).

Also, training and educating the workforce in soft skills it is a necessary for companies’ success. Soft skills training can be defined as incorporating problem solving, team working, communication, leadership skills, quality tools and techniques and customer service (Simon, 1999).. Culture, trust and teamwork can produce significant effects on some of the tangible effects of TQM (Lau and Idris, 2001).

The area of soft skills can be an excellent grounding for the Sociotechnical systems (STS) theory which is based on self-managed work teams. To achieve this concept of self-managed teams, companies undergo several stages of development, which can involve changes in culture, attitude, levels of training and commitment (Green, 1994). The benefits of training as recognised by Khan et.al. (2007) are team works, multifunctional people, direct feedback to shop-floor workers and CI, increased competitiveness of supply chain, increased employee involvement, better communication, multi-skilled workforce, Increased flexibility and versatility, Improved individual efficiency, Increased standardization of jobs, heightened morale, Routine scheduling is enhanced with the ability to move staff about the "Operation". Also, offers better coverage, increased flexibility and ability to cope with unexpected absences, emergencies, illness, etc. Can increase the "employability" of staff that has the opportunity to train in areas they were not originally hired for.

3.2.2 Quality management

3.2.2.1 Mistake Proofing

Poka-yoke (Shingo 1986) ie. mistake-proofing, attempts to eliminate mistakes that happen from human error or manual errors, (Snell and Atwater 1996). They are normally physical devices that are used either to prevent the special manual errors that result in defects, or to inexpensively inspect each item that is produced to determine whether it is acceptable or defective.

A Poka-yoke device is therefore any mechanism that either prevents a mistake from being made or makes the mistake obvious at a glance. The ability to find mistakes at a glance is essential because, as Shingo (1986) writes, "The causes of defects lie in worker errors, and defects are the results of neglecting those errors. It follows that mistakes will not turn into defects if worker errors are discovered and eliminated beforehand".

Each operation performs both production and quality inspection. Effective Poka-yoke devices make such an inspection system possible by reducing the time and cost of inspection to near zero (Grout 1997). Because inspections entail minimal cost, every item may be inspected. Provided that work-in-process inventories are low, quality feedback used to improve the process and it can be provided rapidly Manivannan (2007). Reducing setup error, using the correct tooling or setting machine adjustments correctly leading in less variable cycle time. Moreover, it prevents personal injury, promotes job safety, eliminates faulty products and prevents machine damage. Manivannan S. (2006). Additional reading can be found in Stewart and Melnyk (2000), Ghinato (1998)

3.2.2.2 Process Capability

Process capability means how capable one process produces output that satisfies customers' requirements ie. specification limits. When examine the natural variability, two characteristics is important, ie. where process variables lie in relation to their target values, and the process variance (Delery and Vannman 1999). The process is considered more capable when the output of the process is closer to its target value and has smaller process variance, Delery and Vannman (1999).

For measuring the process capability several indexes have developed, ie. Cp index (Juran 1974), Cpk (Kane 1986), Cpm (Siang and Taguchi 1985), and (Chan et.al1988), Cpmk (Pearn et.al.1992). These indexes differ in their method of calculation and the statistical properties used (Kurekova 2001).

3.2.3 Operations Planning

3.2.3.1 Production Schedule Levelling and sequencing

Production levelling is the balancing or levelling of production over a fixed period of time. Under the Toyota Production System (TPS) this process is referred to as heijunka. Production levelling is essential to the success of pull production, continuous flow and just-in-time manufacturing techniques.

Heijunka levels production by both volume and product mix. This system does not build products according to the actual flow of customer orders. Heijunka takes the total volume of orders in a period and levels them out so the same amount and mix are being made each day.

Production levelling is a lean manufacturing technique because its purpose is to reduce waste. The basis of Heijunka is to reduce fewer inventories, on reducing the time and cost of changeovers so that much smaller batches-ideally lots of one-could be produced without a severe cost penalty, either due to lost production time or significant quality problems, (Miltenburg and Sinnamon 1989)

In short, Heijunka allows line loads to be smoothed by mixing the order of product manufacture. This assists stability and standardisation of work. This removes the waiting time of the operators and the idle and minor stoppages from the machines.

3.2.4 Process Waste

3.2.4.1 5S

The 5S are prerequisites for any improvement program. The basic assumption states "wastes are potential gain, eliminating wastes is a gain". The 5S philosophy is a way of thinking, focusing on effective work place organization, simplified work environment, strives for waste reduction while improving quality and safety.

5S activities include, Sort, Set in order, Shine, Standardize, and Sustain, (Osada 1991). Following paragraphs define and present the benefits of implement of the 5S.
5S is defined (Hirano 1996) as:
“Seiri” = Sorting = Cleaning up: eliminating unnecessary material
“Seiton” = Storage = A place for everything and everything in its place
“Seiso” = Shining = Cleaning: eliminating dirt/oil: make like new
“Seketsu”= Standardizing: procedures and responsibilities
“Shitsuke” = Sustaining: making continued compliance automatic, a habit

The effects of continuous improvement leads to less waste, better quality and faster lead times. The 5S System (Sort, Set in Order, Shine, Standardize, and Sustain) improves workplace organization, standardization, and safety. Its benefits also show improvements in quality at the source, reduced changeover time and machine down time, cycle times, storage costs, as well as boosting employee morale and improving the work environment. A neater and clean workplace through the use of Lean methodologies, Reduces demand for space Layout, Time spent on searching is reduced, Visuals and Teams increases productivity.(Hirano 1996, Ho 1999, Krupp 2005).

3.2.4.2 The 7 Wastes

Waste is the use of resources over and above what is actually required to produce the product as defined by the customer. If the customer does not need it or will not pay for it then it is waste, this includes material, machines and labour. The 7 wastes are: Overproduction, Waiting, Transportation, Inventory, Motion,Over-processing, Defective, (Ohno 1988)

The concept of the 7 wastes is useful because it allows a company to categorise problems and then focus attention in the appropriate areas once they have been identified.

Overproduction, often caused by quality problems, (Robinson and Schroeder 1992),a company knows that it will lose a number of units along the production process so produces extra to make sure that the customer order is satisfied.

Waiting, i.e. this arises when materials wait in factories, either as finished goods or work in progress (WIP). WIP is commonly caused by producing large batch sizes.

Transportation, Factory layouts can often be the fundamental cause of excess transportation. Re-laying out of equipment within a factory, from a functional to a cellular layout, has been found to help not just reduce transportation waste but also reduce WIP and waiting (Wood 2004). Excess inventory levels can also lead to wasted handling.

Inventory, many companies order over and above what is required to fulfil the order, this may be due to quality problems along the production process or ordering and/or producing in larger quantities (Hines and Rich 1997). Excess inventory will require extra storage space, extra transportation; processing steps and unnecessary motion and add to product lead times.

Motion, Simple if operators have to walk excessively, stretch, bend, pick up, or move in order to see better this means the operator is tiring as consequence a problem in quality and productivity exists (Bicheno, 2000).

Over-processing, Rework is a typical example of over processing as discussed earlier reducing the root cause of the quality problem is solution eliminating rework (McKellen 2002).

Defective units, caused by quality related issues. Defects which lead to rework or scrap are perhaps the most obvious waste (Daniel and Cary 2002). Not only do they have a direct impact on the bottom line, but also they lead to additional waste through otherwise unnecessary processes, transportation, waiting time and motion.

More information can be found in Womack and Jones (1994), Shingo S. (1989), Robinson and Schroeder (1992)

3.3 System based improvement enablers

3.3.1 Operations Design

3.3.1.1 Implement Cellular Manufacturing

Cellular manufacturing (CM) is an application of GT where families of parts are produced in manufacturing cells where machines physically located are close together and normally process only the family of parts (Mansouri et al. 2000). Group technology is defined by Mitrofanov (1966) as “a method of manufacturing piece parts by the classification of these parts into groups and subsequently applying to each group similar technological operations”

Cellular manufacturing is an approach that helps build a variety of products with as little waste as possible. Equipment and workstations are arranged in a sequence that supports a smooth flow of materials and components through the process, with minimal transport or delay, (Irani 1999). Cellular manufacturing can help make a company more competitive by cutting out costly transport and delay, shortening the production lead time, saving factory space that can be used for other value-adding purposes, and promoting continuous improvement by forcing the company to address problems that block just-in-time (JIT) production.

Many firms utilizing cellular manufacturing have reported near immediate improvements in performance. Cited improvements which seem to have occurred fairly quickly include reductions in work-in-process, finished goods, lead time, late orders, scrap, direct labour, and workspace. As set-up times decrease through the use of identifying families of parts and using common tools, batch size can be reduced thus a lower work-in-process (WIP) created. The shorter the set-up time the smaller the batch size. Moreover a batch size of one is often feasible when set-up time is zero. Reducing the level of work in progress less space is utilized. Also, improvements in product quality occur since operators normally check quality at each step of the process. Moreover reducing work-in-process (WIP) makes identification of defects faster, hence less should be produced.

Within a cell, small batch sizes do not travel very far as machines are collocated, sothis results in reduction of material handling. Also, it eliminates motion waste and prevents unwanted WIP accumulation. Moreover, it results in shorter lead times and much less complexity in production scheduling and shop floor control. (Chan et.al. 2004), (Askin and Huang 2001)

Empirical evidence indicates reductions in throughput time, rework, scrap, labour, set-up time, and defects as a result of implementing cells (Wemmerlov and Hyer 1989). Also, in cellular manufacturing operators are normally multi-skilled in order to enable more visible working, hence rotation of jobs is necessary to retain the process knowledge gained, (Reynolds 1998). Systematic job rotation and training in multiple skills also makes possible quick, flexible work assignments that can be used to alleviate bottlenecks occurring within the cell. Since normal cell operation requires the workers to master all the skills internal to the cell, little or no additional training should be needed when workers have to be redeployed in response to volume or sales mix changes.

3.3.2 Operations Planning

3.3.2.1 Implement One-Piece Flow/Small Batch Production

Sometimes referred to as "single-piece flow" or "continuous flow," one-piece flow is a key concept within the Toyota Production System. Achieving one-piece flow helps manufacturers achieve just-in-time manufacturing where, the right parts can be made available when they are needed in the quantity they are needed. In the simplest of terms, one-piece flow means that parts are moved through operations from step to step with no work-in-process (WIP) between either one piece at a time and a small batch at a time. This system works best in combination with a cellular layout, in which all necessary equipment is located within a cell in the sequence in which it is used.

Conditions that need to exist in order to implement one-piece flow, (Sekine 1990) include processes able to consistently produce good product, process times repeatable as well. Equipment must have very high (near 100 percent) uptime, and processes must be able to be scaled to the rate of customer demand i.e. the Takt time.

One-piece flow production is the combination of a batch flow production system with principles of line flow production system. The elements included in this system in order to be applicable are Takt time, standard work, flow manufacturing in U-shape lines, pull production and Jidoka. In addition personnel should be a multi skilled, all operators are capable working at each process stage with the cell and recognize quality defects. (Meer et.al. 1992), (Miltenburg 2001) and (Sekine 1990).

There are some benefits of implementing one piece flow, include

1. Improves safety. Transition to one piece flow reduces the need to lift heavy pallets and containers of material. Also, one piece flow often reduces the number of forklifts moving about. (Miltenburg 2004)
2. *Builds in Quality*. Defects are detected almost immediately, usually at the next work station forcing immediate corrective action. (Wemmerlov and Hyer 1989).
3. *Improves Flexibility*. One piece flow production has shorted lead times than batch processing. This allows longer scheduling the order (and still delivering on time). (Renner 1998).
4. *Reduces inventory*. With one piece flow, work in process (WIP) is reduced in dramatic fashion. This frees cash due to reduce movement, storage, and manage piles of inventory. (Sekine 1990).
5. *Improves productivity*. Many of the wastes so inherent with batch and queue production eliminate motion waste, prevent unwanted WIP accumulation, transportation, and waiting are greatly reduced with one piece flow. As a result, productivity increases. (Sekine 1990).
6. *Frees up floor space*. As already discussed, one piece flow reduces the amount of WIP stored on the floor. Additionally, in order for one piece flow to function, work stations must be connected and not isolated on their own island. All this frees up valuable floor space which allows the company to grow their business. (Miltenburg 2004)
7. *Makes kaizen take root*. One piece flow is hard since the buffers and buffers of inventory are gone. Further, quality must constantly improve, machine reliability must increase, changeovers must be shortened, etc. In short, kaizen must take root. (Sekine 1990)

8. *Improves morale*. Employees want to do good work to see progress and they want be involved. Implementing one piece flow brings all these things, together. (Sekine 1990)

3.3.2.2 Balance Production Processes-Line Balancing

Line balancing can be defined (APICS 2005) as: “The balancing of the assignment of the tasks to workstations in a way that minimises the number of workstations and minimises the total amount of idle time at all stations for a set output level”.

Line Balancing has been researched by Falkenauer (2005), Chakravarty and Shtub (1985), Hoffmann (1990), Sabuncuoglu, Erel, and Tanyer (2000), Wood (2004). For decreasing production time, maximizing the output or minimizing the cost of a product, it is quite an important tool. When the product has many operations and the demand is high, the process of balancing the line becomes more and more difficult. Line balancing concerns as it is assigning tasks to workstations.

When tasks are grouped according to lean manufacturing principles, if all their times are equivalent to each other the line will be balanced perfectly and work flow will be regular. But it's an exception because tasks require widely different times in general and also precedence constraints will exist among tasks due to grouping, i.e. each task can be assigned to a station only after all its predecessors have been assigned to stations. Station idle time should be minimised. Two types of optimization problem exist when line balancing, (Ajenblit, 1998) i.e. Type I where the objective is to minimise its number of workstations and Type I problems which occurs when a new assembly line is being to developed, and Type II where the number of workstations or workers is fixed and the objective is to minimize the cycle time.

Benefits that should be gained through balancing flow line are reduced idle time, waiting time and overproduction, waste of motion, maximum usage of operators and machine capacity, and maximum usage of man power and machine capacity.

3.3.3 Operations Control

3.3.3.1 Implement Kanban Control

Kanban is a Japanese term meaning "signal". The term is widely used today, worldwide, to denote a form of replenishment signal used to transmit information generally regarding the movement or production of products. A Kanban System can signal the authorization to move material or product from the supplying location to the consuming location. They can also be used to signal the authorization to produce additional product. This signal can be cards either single or double. Berkley (1992) recognized factors such as number of kanbans numbers of part types, batch sizes, station container sequencing rules, machine reliability, worker flexibility, material –handling operation container sequencing rule; all contribute to the success of the Kanban system.

Huang and Kusiak (1996) and Akturk and Erhun (1999) have identified the interaction between these design parameters and operational issues such as lead time and delivery reliability.

Kanban systems normally operate in ‘repetitive’ environments however in more dynamic environment where the demand and processing times are variable it is less appropriate (Krajewski et.al 1987, Hall 1981) due to difficulties attaining line balancing and synchronization. To overcome these problems, Chang and Yih (1994) proposed the modified Kanban system, Gaury et.al (2000) focused on seeking a methodology of choosing a control system and Monden (1998) examine the use of Toyota production system principles.

Kanban systems physically limit an inventory build-up. Since when the Kanban is full, no additional product can be made or moved, into that location. Putting limits on inventory has some very big benefits such as; less cash is tied up and the space that used to hold the inventories reduced. In addition, all of the space freed by the implementation of a Kanban system can be used for future expansions or new opportunities.

Quality control improves since small Kanban lots again allow for early inspection and detection of errors. (Gravel and Price 1988) Also, Kanbans prevent overproduction because parts are only created at the visual Kanban signal; inventory is much less likely to be overproduced so, resulting in significant savings in the holding of stock.

The flow of Kanban (cards, bins, pallets) will stop if there is a production problem. This makes problems more visible quickly, allowing them to be corrected sooner. Kanban reduces wait times by making supplies more accessible and breaking down administrative barriers. This results in an increase in production using the same resources

3.3.3.2 Implement visual planning and control

Visual control methods aim to increase the efficiency and effectiveness of a process by making the steps in that process more visible. The theory behind visual control is that if something is clearly visible or in plain sight, it is easy to remember and keep at the forefront of the mind. Another aspect of visual control is that everyone is given the same visual cues and therefore is likely to have the same vantage point. There are many different techniques that are used to apply visual control in the workplace. Some e.g. companies use visual control as an organizational tool for equipment tooling control. A clearly labelled shadow board lets employees know exactly where each tool belongs and which tools are missing.

Visual devices are also used to identify lubrication and other preventative and predictive maintenance points, facilitating the proper handling of autonomous maintenance tasks by machine operators and equipment failure from breakdown and idling and minor stoppages. (Nikkan 1995). This serves to minimize variability, improve equipment reliability, and simplify root cause analysis when troubleshooting.

Visual management also cuts waste of correction as problems are prevented or quickly detected. It provides transparency of operational reality and clarity of deviations against detailed standards of performance, work procedures, scheduling, inventory, and scrap. Suzaki (1987).

There are two basic types of visual control implementation i.e. ‘actual’ or ‘analog’, (Greif, H. 1989), Examples of actual items that can be implemented through visual control are items that are designed to designate a location/position for each item, indicate quantity including inventory levels, distinguish items from each other and specify form. Analog items that can be implemented through visual control include use of graphs and electronic lights.

Visual information enables shop floor operator to know at a glance what to do, how to do it properly, and where to find the items needed to complete jobs. Improvements, that arise include increases in throughput, reduced materials handling, decreased floor space, decreased flow distances, reductions in rack storage, decreases in number of forklifts, decreases in engineering cycle times, decreases in annual physical inventory time and decreases in defects (Galsworth 2005). The potential impact through use of visual control on productivity, quality, on-time delivery and inventory, and equipment reliability can be significant.

3.3.4 System Based Lean

3.3.4.1 Implement Kaizen and Continuous Improvement Exercises

Kaizen was created in Japan following World War II. The word Kaizen means "continuous improvement". It comes from the Japanese words 改 ("kai") which means "change" or "to correct" and 善 ("zen") which means "good".

Kaizen is a concept, which combines a large number of applications under its umbrella. Imai (1986), who introduced the term Kaizen, defines it as “ongoing improvement involving everyone-top management, managers and workers”.

Kaizen therefore involves every employee from upper management to the cleaning crew, encourage them to generate small improvement suggestions on a continuous basis, not for example once a month or once a year. (Teian 1992). Within companies, such as Toyota and Canon, a total of 60 to 70 suggestions per employee per year are generated shared and implemented.

In most cases these are not ideas for major changes. Kaizen is based on making little changes on a regular basis, ie. Always improve productivity, safety and effectiveness while reducing waste. Suggestions are not limited to a specific area such as production or marketing. Kaizen is based on making changes anywhere that improvements can be made. Kaizen in Japan is a system of improvement that includes both home and business life and even includes social activities. It is a concept that is applied in every aspect of a person's life. (Berger 1997).

In business, Kaizen encompasses many of the improvements enables of Japanese businesses that have been seen as a part of their success, ie. Quality circles, autonomation, suggestion systems, just-in-time delivery, Kanban and 5S.

Kaizen involves setting standards and then continually improving those standards. To support the higher standards Kaizen also involves providing the training, materials and supervision that are needed for employees to achieve these higher standards and maintain their ability to meet these standards on an on-going basis. (Brunet and New 2003)

Kaizen involves every employee in making change--in most cases small, incremental changes. It focuses on identifying problems at their source, solving them at their source, and changing standards to ensure problems stay solved.

These continual small improvements normally add up to major benefits. They result in improved productivity, improved quality, better safety, faster delivery, lower costs, and greater customer satisfaction. (Ozgurler et.al. 2002),

In addition, Kaizen reduces waste in areas such as inventory, waiting times, transportation, worker motion, employee skills, over production, excess quality in processes, queuing time and removes unnecessary motions as well as improving space utilization, product quality, use of capital, communications, production capacity and employee retention. (Manos, 2007),(Jahovic et.al. 2005).

Kaizen can provide immediate results, without the need for large, capital intensive improvements. Large, capital projects and major changes will still be needed, and Kaizen will also improve the capital projects process, but the real power of Kaizen is in the on-going process of continually making small improvements that improve processes and reduce waste.

3.3.4.2 Implement Planned Maintenance and TPM

The primary objective of planned maintenance is to maintain equipment functioning in a safe and efficient manner. This allows production to meet production targets with minimum operating cost and increased profits, (Rushton 2005).

Maintenance helps operations achieve higher production by increasing "on-line time" or "up-time". Production involvement is extremely important. Without this, any maintenance program will be jeopardized. Commitment to the success of a maintenance program must extend from top production management through the front-line supervisors. Basic to the philosophy of planned maintenance is the concept that maintenance will continually attempt to increase on-line-time and decrease internal costs. The benefits of planned maintenance are listed below (Rushton 2005).

1. Provides procedures to plan, execute, monitor and control maintenance resources.
2. Reduces delays in waiting for men, material, tools after a job is in progress.
3. Provides a daily plan for front-line supervisors.
4. Allows hourly employees to be 100% work loaded.
5. Performance reporting allows upper management to judge maintenance progress.
6. Reduces maintenance costs.
7. Provides a tool for operations to assign priorities.

Total Productive Maintenance (TPM) seeks to engage all levels and functions in an organization to maximize the overall effectiveness of production equipment, (Eti et.al. 2004) Whereas maintenance departments are the traditional centre of preventive maintenance programs, TPM seeks to involve workers in all departments and levels, from the plant-floor to senior executives, to ensure effective equipment operation, (Mc Kone et.al. 2001). Often the implement of Total Productive Maintenance requires at least 2 to 3 years, (Ireland and Dale 2001, Midgley 2001)

TPM is a methodology for proactive and progressive maintenance which analyses Overall Equipment Effectiveness (OEE) (Nakajima 1988). Its goal is the total elimination of all losses, such as equipment failure from breakdowns, equipment setup and adjustment losses, exchange of die in mouldings machines and presses, and idling and minor stoppages due to abnormal operation of sensors. In order to measure losses data that needs collecting such as working hours, planned downtime, downtime losses, setup time, output, number of defects, ideal cycle time and actual cycle time. (Ljungberg 1998).

The ultimate goals of TPM are zero equipment breakdowns and zero product defects, which lead to improved utilization of production assets and plant capacity increases in OEE as equipment availability increases in performance efficiency and decreases in quality defects. Increasing equipment availability reduces buffer inventories needed to protect downstream production from breakdowns and increases effective capacity, (Katila 2000). The fast changeovers, increased capacity and reduced buffer inventories lead to decreased lead times since jobs are not waiting as long in queues. The reduced need for buffer inventory directly reduces inventory costs and increasing effective capacity allows more throughputs and lowers the cost per unit. Increases in the rate of quality products not only reduces buffer inventories and increases effective capacity, but this increase means that there is less scrap and rework, which not only reduces costs, but also yields a higher rate of quality, (Fredendall et.al. 1997).

3.3.4.3 Implement TQM and SPC

Total quality management (TQM) is a business philosophy. It describes ways to manage people and business processes to ensure complete customer satisfaction at every stage. TQM is often associated with the phrase “doing the right things right, first time”,(Sila and Ebrahimpour 2003). TQM recognises that all businesses require "processes" that enable customer requirements to be met. TQM focuses on the ways in which these processes can be managed with two key objectives, i) 100% customer satisfaction ii) Zero defects. The elements of TQM are continuous improvement, empowerment, customer satisfaction, management responsibility, benchmarking, and supplier relationship, (Collin 1994, Dean and Bowen 1994, Aderson et.al. 1994, Oakland 1997). For TQM to deliver such benefits it is necessary to provide to shop floor employees the necessary resources, a fair reward system, a fitting culture and structure and the necessary skills through training, (Jabnoun 2002)

The main principles that underlie TQM are summarised below:
Prevention, Prevention defects is better than reworking defective item. *Zero defects*, the ultimate aim is no (zero) defects, *Getting things right first time,* better not to produce at all than produce something defective, *Quality involves everyone,* Quality is not just the concern of the production or operations department it involves everyone, *Continuous improvement,* Businesses should always be looking for ways to improve processes to help quality, and *Employee involvement* those involved in production and operations have a vital role to play in spotting improvement opportunities for quality and in identifying quality problems.

TQM demands that all employees will be cross-trained, develop multi skills and are flexible. Usually the benefits of implementing TQM appear in long term although some appear within two to four month’s time, (Cheng and Podolsky 1993)

The advantages of TQM include: controlling quality, reducing waste and protecting against tool and parts damage. Implementation of total quality management also, helps in the following aspects:
1. reduction of defects because TQM promotes quality awareness and participation of all members of the organization.
2. ease of problem solving, through measurement such as SPC, failure analysis and other techniques.
3. improved efficiency of people and machines.
4. reduced defects

Statistical Process Control (SPC) is a technique used within the TQM framework for reducing variation in processes which we deal with everyday. It is a powerful technique to control, manage, analyze and improve the performance of a process by eliminating special causes of variation such as tool wear, operator error, errors in measurements, and use of improper raw material, (Mason and Antony 2000). The successful application of SPC requires a combination of skills like engineering, management, statistical, teamwork and planning skills (Antony 2000).

3.3.4.4 Implement Jidoka and Automation -Autonomation

One of the pillars of Toyota Production System (TPS) is Jidoka. Jidoka means autonomation or automation with a human touch. Originally it referred to a machine's ability to stop when an out of standard condition existed.

There are two parts to Jidoka:

1) *Separate human from machine*. Based on the belief that humans should do work only humans can do, and machines should do the work of machines, jidoka aims to make processes safe, reliable and self-running through low cost automation.

2) *Give machine the intelligence to stop when a defect is produced***.** Sensors of various types are built into machines so that the first defect is detected and the machine is stopped from producing any more. Workers are alerted and problem solving begins.

This idea of "detect errors and stop" is extended to manual operations such as assembly by empowering workers to stop the line when they detect a problem. This is one of the ways for building quality in to the process by removing the source of the defect soon after it is found and setting the new method as the standard.

3.4 Summary

From the literature review of performance metrics and cause of inefficiency table 3.2 has been produced

Table 3.2Relationships between performance metrics and the cause of inefficiency

CAUSES OF INEFFICIENCY PERFORMANCE METRIC	Transportation & Material Handling	Inventory, Batch Size & Work -in-Progress	Overproduction	In-process Queueing Time	Waiting,Idling & Minor Stoppages	Over-processing	Non-added Value Motions	Material Shortages	Quality-Process & Non-Process Defects	Equipment Failure from Breakdowns	Set-up & Adjustment	Reduced Processing Speed	Lack of Flexible Labour	Poor Line Balancing	Poor Job Sequencing	Variable Cycle Times	Poor Facilities Layout
Work entry rate								X						X		X	
Material waiting time		X												X		X	
Material moving	X																
Material queuing time		X	X	X								X		X		X	
Floor space	X	X	X														X
Workstation utilization			X				X	X					X	X	X	X	
Processing time				X		X						X				X	
Machine utilization			X		X		X	X		X			X		X	X	
Machine availability					X	X				X		X	X		X	X	
Mean time between failures									X	X							
Quality rate									X		X						X
OEE					X	X	X		X		X	X	X				
Throughput rate		X	X	X	X			X	X	X		X	X	X	X	X	
Unscheduled downtime								X		X							
Scrap rate	X								X		X						
Rework & repair rate									X		X						
Set up time											X						
Scrap cost									X		X						
Rework& repair cost									X								
Total cost per part	X	X	X			X				X			X			X	
Manufacturing lead-time		X	X	X				X				X	X	X	X		
Adherence to schedule			X					X							X		
Work in progress		X	X	X										X	X		
Distance traveled	X																X
Lot size/batch size		X															

From the literature review of lean tools and techniques Table 3.3 has been produced.

Efficiency Improvement Enablers	Causes of Inefficiency	Transportation & Material Handling	Inventory, Batch Size & Work -in- Progress	Overproduction	In-process Queueing Time	Waiting,Idling & Minor Stoppages	Over-processing	Non-added Value Motions	Material Shortages	Quality-Process & Non-Process Defects	Equipment Failure from Breakdowns	Set-up & Adjustment	Reduced Processing Speed	Lack of Flexible Labour	Poor Line Balancing	Poor Job Sequencing	Variable Cycle Times	Poor Facilities Layout
Implement multi-skilling			X			X				X	X			X				
Reduce processing batch size			X		X	X												
Standardise work and operations				X	X	X	X			X	X							
Implement “mistake proofing”										X	X						X	
Improve process capability									X	X	X		X				X	X
Production Schedule Levelling and Sequence			X			X			X			X						
Improve workplace area using 5S		X	X			X		X		X	X	X						
The 7 Wastes		X	X	X		X		X		X	X		X					X
Implement cellular manufacturing		X	X					X		X		X						X
Implement one-piece flow/small batch production		X	X	X	X	X				X	X	X						
Balance production processes-line balancing		X	X	X		X	X	X		X					X	X	X	
Implement kanban control			X			X											X	
Implement visual planning and control		X	X		X	X		X	X	X	X		X				X	X
Implement Kaizen and continuous improvement exercises		X	X	X	X		X	X		X								X
Implement planned maintenance and TPM					X	X			X	X	X	X					X	
Implement TQM and SPC		X	X					X		X								
Implement Jidoka and automation			X			X				X								

Table 3.3 Relationships between Lean Enablers and Cause of Inefficiency

CHAPTER 4 Experimental Design

4.1 Introduction

Ghalayini et al. (1996), Neely (2001), and White (1996), suggest that the performance measurement systems should enable identification of continuous improvement actions for flow production lines. This chapter presents the research methodology that can lead to such improvements of the mixed model flow lines through recognising problematic workstations and indicating courses of action that will improve such workstation.

The two main research strategies examined with respect their suitability to the current research were:

Generally, there are two main research strategies that a researcher has to perform.

- The *quantitative method* i.e. a research that focuses on the collection and analysis of numerical data and statistics as introduced/discussed by Key (1997).
- The *qualitative method* i.e. a research method that relies on interviews, observations, questionnaires, focus groups, subjective reports and/or case studies

4.1.1 Qualitative Research

There are many different techniques the main types of Qualitative Research are:

Case study: Attempts to shed light on phenomena by studying in depth a single case example of the phenomena. The case can be an individual person, an event, a group, or an institution

Grounded theory: Theory is developed inductively from a corpus of data acquired by a participant-observer

Phenomenology: Describes the structures of experience as they present themselves to consciousness, without recourse to theory, deduction, or assumptions from other disciplines

Ethnography: Focuses on the sociology of meaning through close field observation of sociocultural phenomena. Typically, the ethnographer focuses on a community

Historical: Systematic collection and objective evaluation of data related to past occurrences in order to test hypotheses concerning causes, effects, or trends of these events that may help to explain present events and anticipate future events. (Gay, 1996)

4.1.2 Quantitative Research

In analyzing the suitability of the research method the work of Katsuko (1995) has been used.

i) Experimental approach

Experimental approach is an attempt to determine how specific factors influence the result of an experiment, taking in to account all the factors that might influence these results. Quantitative methods use numbers and statistics. This was considered the most suitable approach since: data could be generated and managed by including and using simulation models of actual flow lines. (Katsuko 1995)

ii) The survey approach

The purpose of survey research is to extrapolate a sample into a population, (Ratcliff 2002). (Gill et. al. 2008) (Creswell 2009).This can be achieved by providing a quantitative or numeric description of trends and also with attitudes which can be determined by studying a sample of the population. However in order to collect data, questionnaires, or structured interviews structured record reviews and/or observations need to be undertaken. The amount of detailed information the current research would be available through use of these methods.

The work of Creswell (2009) suggested that a quantitative approach was the most suitable since it deals with a problem, based on the following concepts:

1. it enables identification of those factors that affect an outcome i.e. maximised flow line efficiency
2. it enables interventions to be identified that will help to improve outcomes
3. it enables understanding of more detailed the best predictors that affect outcomes

This research work has therefore used an experimental approach technique of quantitative method. The method used is able to locate and quantify existing relationships between different performance metrics at both operational and tactical levels. Element of qualitative research are used to collect data from the production area using an unstructured interviews.

4.2 Research Methodology

The methodology that used consists of the following steps:

Step 1 *Data Collection and Interviews.*

Literature review was carried out to identify the generic performance metrics in (Section 2.4.5) and the causes of inefficiencies with flow lines (Section 3.1).

Interviews with production staff as production controller, supervisors in the departments of sheet metal, chemical processes and painting were undertaken in order to gather data for producing the “low front panel floor” sub-assembly, i.e. the data collected included:

- sub-assembly components parts,
- quality levels required and obtained,
- process time, at each sub-assembly work area,
- setup times, at each sub-assembly work area,
- Mean Time to Repair, for each item of process equipment within work area

ie. for the Deburr workstation, Marking workstation, Primer workstation and Painting workstation.

Data collected was then used to build a discrete event simulation (DES) model.

Step 2 *Development and use of the DES Model*

This research used simulation modelling as tool to validate relationships between different performance measurements. The DES model was developed for the “low front panel floor” production process. The model includes 8 workstations. The DES model simulated for 19600min of production time each experiment. Parameters values for each variable were determined using a Taguchi orthogonal array. Taguchi’s DoE are used to minimise the number of experiments that need undertaking.

The Taguchi orthogonal arrays for each of the workstations shown in tables 4.1 to 4.4.

A/A	Input Parts	Operation Time	Setup Time	Quality	Mean Time To Repair
1	15	5	1	0	60
2	15	10	8	2.5	90
3	15	15	12	5	120
4	15	20	16	7.5	150
5	15	25	20	10	180
6	30	5	8	5	180
7	30	10	12	7.5	60
8	30	15	16	10	90
9	30	20	20	0	120
10	30	25	4	2.5	150
11	45	5	12	10	150
12	45	10	16	0	180
13	45	15	20	2.5	60
14	45	20	4	5	90
15	45	25	8	7.5	120
16	60	5	16	2.5	120
17	60	10	20	5	150
18	60	15	4	7.5	180
19	60	20	8	10	60
20	60	25	12	0	90
21	75	5	20	7.5	90
22	75	10	4	10	120
23	75	15	8	0	150
24	75	20	12	2.5	180
25	75	25	16	5	60

Table 4. 1 L25 Taguchi Orthogonal array of Deburr workstation

A/A	Input Parts	OperationTime	Setup Time	Quality	Mean Time To Repair
1	15	1	5	0	2
2	15	9	9	2,5	5
3	15	16	12	5	8
4	15	24	16	7,5	11
5	15	32	20	10	14
6	30	1	9	5	14
7	30	9	12	7,5	2
8	30	16	16	10	5
9	30	24	20	0	8
10	30	32	5	2,5	11
11	45	1	12	10	11
12	45	9	16	0	14
13	45	16	20	2,5	2
14	45	24	5	5	5
15	45	32	9	7,5	8
16	60	1	16	2,5	8
17	60	9	20	5	11
18	60	16	5	7,5	14
19	60	24	9	10	2
20	60	32	12	0	5
21	75	1	20	7,5	5
22	75	9	5	10	8
23	75	16	9	0	11
24	75	24	12	2,5	14
25	75	32	16	5	2

Table 4. 2 L25 Taguchi Orthogonal array of Marking workstation

A/A	Input Parts	OperationTime	Setup Time	Quality	Mean Time To Repair
1	15	100	6	0	5
2	15	125	12	2,5	10
3	15	150	18	5	15
4	15	175	24	7,5	20
5	15	200	30	10	25
6	30	100	12	5	25
7	30	125	18	7,5	5
8	30	150	24	10	10
9	30	175	30	0	15
10	30	200	6	2,5	20
11	45	100	18	10	20
12	45	125	24	0	25
13	45	150	30	2,5	5
14	45	175	6	5	10
15	45	200	12	7,5	15
16	60	100	24	2,5	15
17	60	125	30	5	20
18	60	150	6	7,5	25
19	60	175	12	10	5
20	60	200	18	0	10
21	75	100	30	7,5	10
22	75	125	6	10	15
23	75	150	12	0	20
24	75	175	18	2,5	25
25	75	200	24	5	5

Table 4. 3 L25 Taguchi Orthogonal array of Primer workstation

A/A	Input Parts	OperationTime	Setup Time	Quality	Mean Time To Repair
1	15	100	5	0	5
2	15	120	10	2.5	10
3	15	140	15	5	15
4	15	160	20	7.5	20
5	15	180	25	10	25
6	30	100	10	5	25
7	30	120	15	7.5	5
8	30	140	20	10	10
9	30	160	25	0	15
10	30	180	5	2.5	20
11	45	100	15	10	20
12	45	120	20	0	25
13	45	140	25	2.5	5
14	45	160	5	5	10
15	45	180	10	7.5	15
16	60	100	20	2.5	15
17	60	120	25	5	20
18	60	140	5	7.5	25
19	60	160	10	10	5
20	60	180	15	0	10
21	75	100	25	7.5	10
22	75	120	5	10	15
23	75	140	10	0	20
24	75	160	15	7.5	25
25	75	180	20	5	5

Table 4. 4 L25 Taguchi Orthogonal array of Painting workstation

Step 3 *Identification of relationships between performance metrics*

A two step process was used to identify, those parts of performance metrics that exhibited caused relationships, ie.

Step 3i *Identification of relationships through correlation analysis*

In order to identify potential relationships among performance metrics paired performance metrics statistical Correlation Coefficients were used. Those pairs with coefficients between +∏ and +1 and between -∏ and -1 where considered having sufficiently strong correlations to variant their inclusion in step 3(ii)

Step 3ii *Quantification of relationships through Regression analysis***.**

Regression analysis were used because this technique permits the quantification description of the relationship between variables using mathematical functions, estimate how the value of a dependent variable changes when changes in any one of set of independent variables is varied. The tables will filled in with R^2 that it is an indicator that ranges from 0 to 1 and which measures how closely the estimated values correspond to actual values. In addition, the values of **S** will completed, where **S** is measures in the units of the response variable and represents the standard distance data values fall from the regression line. For a given study, the better the equation predicts the response, the lower **S** is.

Step 4 *Improvements of mixed flow lines*

Since, a problematic workstation has identified through the comparison of goal target and actual target, the appropriate lean enabler is used in order to improve it. This can be achieved through use of table 3.3 in 3.4, i.e. depending in which inefficiencies are causing problems.

Step 5 *Develop a performance measurement system*

A range of performance indicators (Zozom et.al. 2003) and relationships, are presented in Appendix C. Based on company specific experiments this work will develop a performance measurement system capable of improving mixed model flow line efficiencies.

4.3 Experimental design

The experimental developments within these steps were undertaken as follow:

Identification of generic metrics relevant to mixed model flow process lines are briefly described in table 4.5 below and provided in Appendix A:

Table 4.5 Mixed-Model Flow Line Performance Metrics

1. *Work entry rate*, the rate parts enter the production process.
2. *Material waiting time*, measures the time that parts are waiting to move to the next workstation.
3. *Material moving* time, the time needed to move parts from one station to their next station.
4. *Material queuing time*, the time parts wait until a workstation becomes free to process items.
5. *Floor space*, the floor space occupied by work-in-progress.
6. *Workstation utilisation*, the percentage of time the workstation is not idle.
7. *Processing time*, the time the workstation processes components.
8. *Machine availability*, the time that a machine is available for work.
9. *Mean Time To Repair*, the time needed to repair a workstation after it has broken down.
10. *Quality rate* the percentage of non-defective parts produced.
11. *Overall Equipment Effectiveness*, a measure of a machine’s overall performance in producing parts.
12. *Throughput rate*, the rate that finished components exits the system.
13. *Unscheduled downtime*, the time the machine is not operating due to unscheduled events.
14. *Scrap rate*, the percentage of damaged or defective parts.
15. *Rework & repair rate*, the percentage of defective parts that have been reworked/repaired.
16. *Set up time*, the time the operator needs to change the machine in order to be ready to process the next product.

17. *Scrap* cost, the cost recovered through of materials within defective parts.
18. *Rework& repair cost,* the cost of reworking defective parts.
19. *Total cost per part,* the total cost of manufacturing a component.
20. *Manufacturing lead-time,* the total time required to manufacture a component.
21. *Adherence to schedule,* the different between scheduled requirements and actual parts made.
22. *Work in progress,* inventory waiting processing in the shop floor.
23. *Distance travelled,* measures the distance that part move between workstations.
24. *Lot size/batch size,* the quantity within each process batch.

The completion of this step is designed to result in the identification of metrics that are related to specific causes of inefficiencies. As presented in 3.4, relationships have been found between these inefficiency-causing metrics and Lean Enablers, which could be used by to improve or eliminate these inefficiencies.

Table 4.6 Causes and Flow Line Inefficiencies

1. Transportation & Material Handling
2. Inventory, Batch Size & Work -in-Progress
3. Overproduction
4. In-process Queuing Time
5. Waiting, Idling & Minor Stoppages
6. Over-processing
7. Non-added Value Motions
8. Material Shortages
9. Quality-Process & Non-Process Defects
10. Equipment Failure from Breakdowns
11. Set-up & Adjustment
12. Reduced Processing Speed
13. Lack of Flexible Labour
14. Poor Line Balancing
15. Poor Job Sequencing

16. Variable Cycle Times
17. Poor Facilities Layout

A common set of process parameters were identified by comparing the list of mixed model flow line performance metrics and those into lean manufacture, for including experiments with the i.e.

1. Numbers of input parts
2. Operation time
3. Setup time
4. Quality
5. Mean time to repair

These parameters were used in to describe workstation DES modelling elements and their values varied as part of the experimental design.

SIMUL8 (Hauge and Paige 2002) was chosen for developing the simulation model. The capabilities of the package are summarised below:

a. simplicity in the task and layout execution, in particular in cases of model development by using default parameters,
b. user-friendly,
c. accurate determination of a model’s efficiency and effectiveness, and
d. task-specific for developing the appropriate performance measurement mixed model.

Direct observation was used in order to familiarise oneself with the production process. The data collected includes measures pertaining to each workstation, such as setup time, operation time, transportation time and distance.

The application of the SIMUL8 software package resulted in the development of a model of the chosen flow line. The model (Figure 4.1) consists of ten workstations listed below:

1. *Work entry point*, the point where the parts enter in the simulation process.
2. *The Modic workstation*, where the aluminium profile is formed.
3. *The Deburr workstation*, where rough edges of the ‘long’ parts, created by the Modic workstation are removed.
4. *The Deburr machine*, where ‘small’ parts have their smooth edges.
5. *The marking workstation*, where part identification information e.g. part number and serial number, are printed on to parts.
6. *Quality control, where* dimensions of parts are checked against tolerances.
7. *Anodize workstation,* where part surfaces are chemically processed.
8. *Primer workstation,* where the parts are spray painted with primer.
9. *Painting workstation,* where protecting paint is applied.
10. *Work exit point,* From which parts are moved to the storage area awaiting assembling.

The model is presented in the following figure.

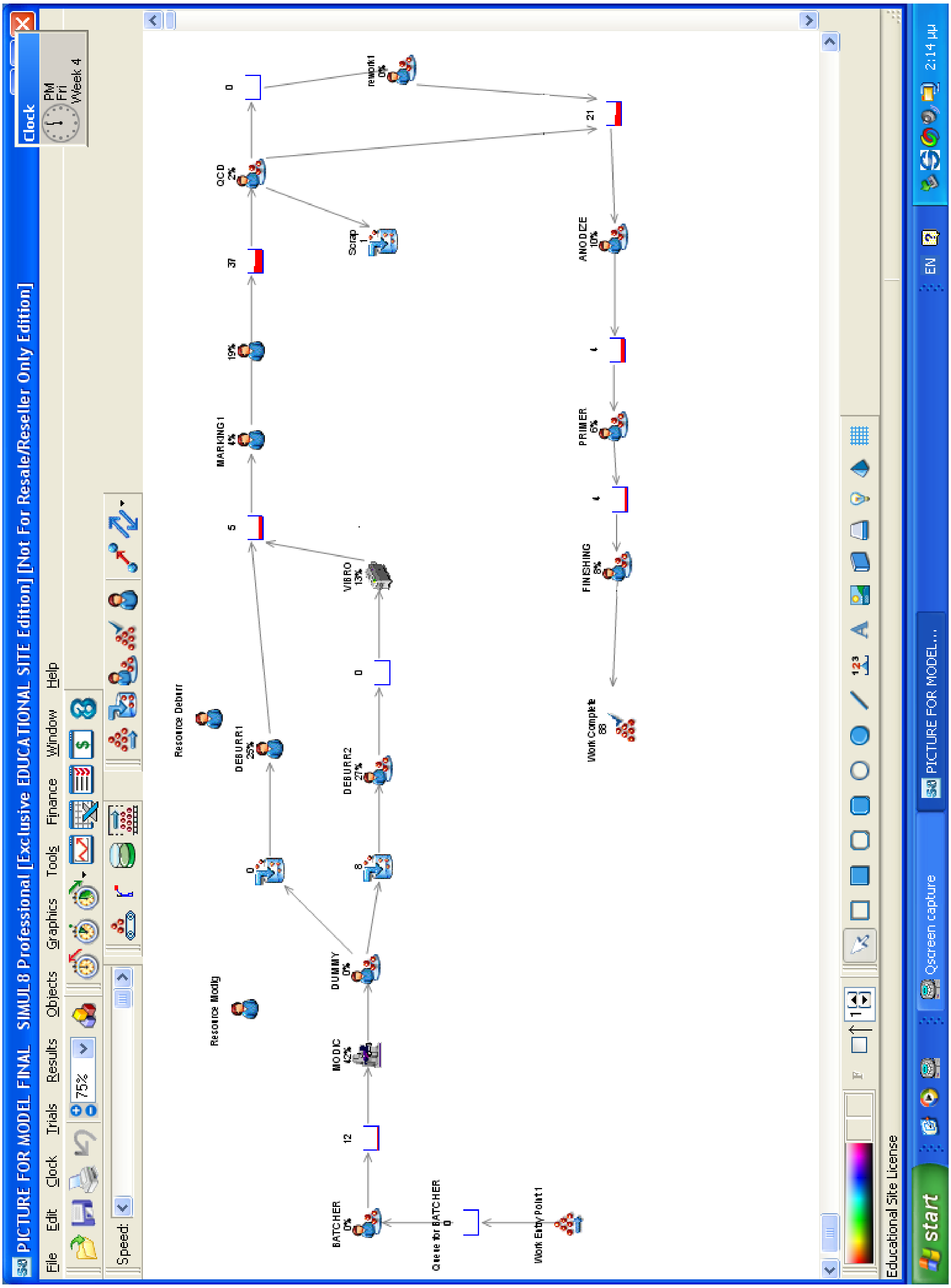


Figure 4. 1 Simulation Model

The time used for running the simulation model was 19600 minutes. This is considered as an appropriate time for experiments since it represents the manufacturing lead time offered to customers.

Triangular distributions were used to represent workstation operation times, to represent the variability in level in these lines.

Orthogonal arrays showing values of parameters used are in tables 4.7 to 4.10. Each column in the orthogonal array represents a specific factor and the values (i.e. level) for each set of experiments which for each workstation is 25 experiments.

Within these tables definitions for each factor are:

i. *Input*, represents the number of parts that enters the system.
ii. *Operation time,* the time, in minutes, that the workstation operates.
iii. *Set up time,* the time, in minutes, that the operator needs to change the machine in order to be ready to process the next product.
iv. *Quality,* represents the percentage (%) of defective parts produced at a workstation.
v. *Mean time to repair,* the average time in minutes between the occurrence of a breakdown and its resolution.

Factors	Level 1	Level 2	Level 3	Level 4	Level 5
Input Parts	15	30	45	60	75
Operation Time	5	10	15	20	25
Setup Time	1	8	12	16	20
Quality	0	2.5	5	7.5	10
Mean Time To Repair	60	90	120	150	180

Table 4. 7 Deburr workstation values

Factors	Level 1	Level 2	Level 3	Level 4	Level 5
Input Parts	15	30	45	60	75
OperationTime	1	9	16	24	32
Setup Time	5	9	12	16	20
Quality	0	2.5	5	7.5	10
Mean Time To Repair	2	5	8	11	14

Table 4.8 Marking workstation values

Factors	Level 1	Level 2	Level 3	Level 4	Level 5
Input Parts	15	30	45	60	75
OperationTime	100	125	150	175	200
Setup Time	6	12	18	24	30
Quality	0	2.5	5	7.5	10
Mean Time To Repair	5	10	15	20	25

Table 4.9 Primer workstation values

Factors	Level 1	Level 2	Level 3	Level 4	Level 5
Input Parts	15	30	45	60	75
OperationTime	100	120	140	160	180
Setup Time	5	10	15	20	25
Quality	0	2.5	5	7.5	10
Mean Time To Repair	5	10	15	20	25

Table 4. 10 Painting workstation values

Relationships identified through analysis were shown in tables 4.11 Correlation and Regression

	Input Part	Process Time	Setup Time	Quality	MTTR Time	WS Thr/put	WS %Non- Zero	WS Working	Total Thr/put	Total L T
Input Part										
Process Time										
Setup Time										
Quality %										
MTTR Time										
WS Throughput		√	√							
WS %Non- Zero	√	√	√		√	√				
WS Working		√	√		√	√	√			
Total Throughput		√	√		√	√	√	√		
Total Lead Time		√	√	√	√	√	√	√		

Table 4. 11(i) Correlation&Regression relationships for Deburr workstation

	Input Part	Process Time	Setup Time	Quality	MTTR Time	WS Thr/put	WS %Non- Zero	WS Working	Total Thr/put	Total L T
Input Part										
Process Time										
Setup Time										
Quality %										
MTTR Time										
WS Throughput		√	√							
WS %Non- Zero	√	√	√		√	√				
WS Working		√	√			√	√			
Total Throughput	√	√	√	√		√	√	√		
Total Lead Time	√	√	√	√	√	√	√	√	√	

Table 4. 11(ii) Correlation&Regression relationships developed for Marking workstation

	Input Part	Process Time	Setup Time	Quality	MTTR Time	WS Thr/put	WS %Non- Zero	WS Working	Total Thr/put	Total L T
Input Part										
Process Time										
Setup Time										
Quality %										
MTTR Time										
WS Throughput	√	√	√							
WS %Non- Zero	√	√	√	√	√	√				
WS Working	√	√	√			√	√			
Total Throughput	√	√	√	√		√	√	√		
Total Lead Time	√	√	√	√		√	√	√	√	

Table 4. 11 (iii) Correlation&Regression relationships developed for Primer workstation

	Input Part	Process Time	Setup Time	Quality	MTTR Time	WS Thr/put	WS %Non- Zero	WS Working	Total Thr/put	Total L T
Input Part										
Process Time										
Setup Time										
Quality %										
MTTR Time										
WS Throughput		√	√	√						
WS %Non- Zero		√	√	√		√				
WS Working		√	√			√	√			
Total Throughput		√	√	√		√	√	√		
Total Lead Time		√	√	√		√	√	√	√	

Table 4. 11(iv) Correlation&Regression relationships developed for Painting workstation

Once the relationships have been identified and quantified, the next step was to identify the relative effects of variables on dependent variable ie. the total lead time. At operational level it was, therefore, necessary to compare the ‘total values’ of the system with the ‘target value’ required by customers ie.

- Total Lead Time target of 14 days(7840 min),
- Total throughput target of 85 shop orders,
- Quality 2% target of defective items

Also, the following targets values for the each workstation briefly mentioned below,

- Modic workstation Lead Time target of 2.5 days
- Deburr workstation Lead Time target of 2.5 days
- Vibro Deburr Lead Time target of 2 days
- Quality workstation Lead Time target of 2,5 days
- Anodize workstation Lead Time target of 1.5 days
- Primer workstation Lead Time target of 2 days
- Painting workstation Lead Time target of 2 days

For any workstation deviating from the above predetermined target values workstations a problem in the production line needs to be identified, i.e. it is necessary to identify the factors contributing to the inefficiency of the overall workstation. This was designed to be achieved by using the relationships developed in section 3.4 to indicate the type of Lean Enabler that could be used to remove the specific cause of the inefficiency.

CHAPTER 5 Experimental Results

5.1 Introduction

In chapter 4 a methodology was developed for (i) identifying performance metrics for a mixed model flow lines (ii) the metrics related to lean manufacturing interventions and (iii) the relationships between (i) and (ii). Simulation experiments were carried out to validate these relationships.

Added simulation experiments using new models were their carried out, to validate the relationships.

This chapter presents the results from these experiments and provides a brief analysis. A more detailed analysis is provided in chapter 6.

5.2 Experimental Results

The following results were obtained from the simulation experiments.

5.2.1 Model Parameter Values

Tables 5.1 to 5.4 contain the values of the model parameters used Input Parts, Quality, Process Time, Setup Time, Mean Time to Repair, to construct the DES model.

Factors	Level 1	Level 2	Level 3	Level 4	Level 5
Input Parts	15	30	45	60	75
Operation Time	5	10	15	20	25
Setup Time	1	8	12	16	20
Quality	0	2.5	5	7.5	10
Mean Time To Repair	5	10	15	20	25

Table 5. 1 Deburr workstation Data

Factors	Level 1	Level 2	Level 3	Level 4	Level 5
Input Parts	15	30	45	60	75
Operation Time	1	9	16	24	32
Setup Time	5	9	12	16	20
Quality	0	2.5	5	7.5	10
Mean Time To Repair	2	5	8	11	14

Table 5. 2 Marking workstation Data

Factors	Level 1	Level 2	Level 3	Level 4	Level 5
Input Parts	15	30	45	60	75
Operation Time	100	125	150	175	200
Setup Time	6	12	18	24	30
Quality	0	2.5	5	7.5	10
Mean Time To Repair	5	10	15	20	25

Table 5. 3 Primer workstation Data

Factors	Level 1	Level 2	Level 3	Level 4	Level 5
Input Parts	15	30	45	60	75
Operation Time	100	120	140	160	180
Setup Time	5	10	15	20	25
Quality	0	2.5	5	7.5	10
Mean Time To Repair	5	10	15	20	25

Table 5. 4 Painting workstation Data

5.2.2 DES Model Results

A table 5.5 provides the results obtained from the models for the ‘Deburr’ workstation.

Part	Time	Time	%	Time	Throughput	%Non- Zero	Working	Throughput	Lead Time
15	5	5	0	5	208	0.39	7859	94	7837
15	18	9	2.5	10	125	8.41	17828	88	8439
15	32	13	5	15	85	13.33	18584	72	8494
15	46	17	7.5	20	56	21.9	18590	43	9997
15	60	21	10	25	35	29.32	18700	24	9087
30	5	9	5	25	208	0.63	7859	94	7697
30	18	13	7.5	5	119	16.8	17285	87	8296
30	32	17	10	10	74	24.55	18304	60	8742
30	46	21	0	15	54	37.29	18278	44	10413
30	60	5	2.5	20	37	37	19233	27	9248
45	5	13	10	20	207	0.86	7855	93	7490
45	18	17	0	25	118	21.92	16824	88	8550
45	32	21	2.5	5	75	32.66	17857	64	9499
45	46	5	5	10	59	41.12	19143	47	10396
45	60	9	7.5	15	37	37.36	19092	25	9193
60	5	17	2.5	15	205	1.21	7847	94	7825
60	18	21	5	20	118	24.34	16403	87	8465
60	32	5	7.5	25	81	34.52	18951	65	9491
60	46	9	10	5	58	41.24	18921	41	10077
60	60	13	0	10	36	36.54	18963	26	9077
75	5	21	7.5	10	204	1.61	7845	93	7685
75	18	5	10	15	124	20.94	18112	88	8104
75	32	9	0	20	80	34.82	18667	69	9684
75	46	13	2.5	25	56	40.66	18672	45	10336
75	60	17	5	5	36	36.9	18839	25	8772

Table 5.5 **Deburr workstation results**

A table 5.6 provides the results obtained from the models for the ‘Marking’ workstation.

Input	Process	Setup	Quality	MTTR	WS	WS	WS	Total	Total
Part	Time	Time	%	Time	Throughpu	%Non- Zer	Working	Throughput	Lead Time
15	1	5	0	2	183	0.17	1391	83	9190
15	9	9	2.5	5	172	4.41	11609	83	9166
15	16	12	5	8	118	9.27	14727	79	9279
15	24	16	7.5	11	88	12.85	15240	69	9647
15	32	20	10	14	70	16.01	15754	54	9711
30	1	9	5	14	183	0.23	1391	83	9093
30	9	12	7.5	2	169	6.74	11438	83	9027
30	16	16	10	5	118	16.08	14292	78	9305
30	24	20	0	8	86	21.73	14976	72	9691
30	32	5	2.5	11	72	25.34	16681	61	10313
45	1	12	10	11	183	0.27	1391	83	8894
45	9	16	0	14	164	7.45	11246	83	9234
45	16	20	2.5	2	117	19.84	13878	78	9556
45	24	5	5	5	93	26.7	16107	70	10020
45	32	9	7.5	8	67	32.71	16475	55	9932
60	1	16	2.5	8	183	0.33	1391	83	9141
60	9	20	5	11	161	8.1	11058	83	9137
60	16	5	7.5	14	119	16.38	15480	79	9326
60	24	9	10	2	88	29.63	15819	70	9988
60	32	12	0	5	67	33.5	16305	63	10316
75	1	20	7.5	5	183	0.48	1391	83	9003
75	9	5	10	8	177	6.15	11863	83	8919
75	16	9	0	11	118	17.44	15050	82	9370
75	24	12	2.5	14	87	30.09	15566	70	10134
75	32	16	5	2	67	34.07	16075	60	10543

Table 5. 6 Marking workstation results

A table 5.7 provides the results obtained from the models for the ‘Primer’ workstation.

Input Part	Process Time	Setup Time	Quality %	MTTR Time	WS Throughpu	WS %Non- Zer	WS Working	Total Throughput	Total Lead Time
15	100	6	0	5	146	6.46	14658	86	9113
15	125	12	2.5	10	114	9.14	14296	85	9067
15	150	18	5	15	94	11.03	14100	85	8986
15	175	24	7.5	20	80	12.82	14002	74	9197
15	200	30	10	25	69	14.49	13980	64	9224
30	100	12	5	25	138	11.33	13821	85	8930
30	125	18	7.5	5	109	16.62	13745	85	8902
30	150	24	10	10	91	19.61	13653	81	8911
30	175	30	0	15	78	22.12	13649	77	9256
30	200	6	2.5	20	77	22.15	15513	76	9208
45	100	18	10	20	131	13.77	13165	85	8811
45	125	24	0	25	105	21.3	13132	85	9086
45	150	30	2.5	5	88	25.64	13239	85	9110
45	175	6	5	10	87	25.63	15368	81	8997
45	200	12	7.5	15	75	27.88	15119	69	9184
60	100	24	2.5	15	125	15.37	12565	85	9054
60	125	30	5	20	101	22.71	12665	85	8973
60	150	6	7.5	25	100	22.92	15103	85	8915
60	175	12	10	5	85	27.41	14913	76	8962
60	200	18	0	10	73	28.97	14749	72	9239
75	100	30	7.5	10	120	16.93	12010	85	8889
75	125	6	10	15	119	17.2	14905	85	8824
75	150	12	0	20	97	24.15	14584	85	9099
75	175	18	2.5	25	82	27.79	14402	80	9086
75	200	24	5	5	72	29.52	14400	67	9186

Table 5. 7 Primer workstation results

A table 5.8 provides the results obtained from the models for the ‘Painting’ workstation.

Input	Process	Setup	Quality	MTTR	WS	WS	WS	Total	Total
Part	Time	Time	%	Time	Throughput	%Non- Zero	Working	Throughput	Lead Time
15	100	5	0	5	83	0	8396	83	9110
15	120	10	2.5	10	83	0	10050	82	9190
15	140	15	5	15	83	0.05	11705	79	9185
15	160	20	7.5	20	83	0.03	13361	77	9229
15	180	25	10	25	76	3,26	13749	70	9293
30	100	10	5	25	83	0	8390	79	9140
30	120	15	7.5	5	83	0	10045	77	9183
30	140	20	10	10	83	0	11701	77	9208
30	160	25	0	15	83	0.03	13355	83	9193
30	180	5	2.5	20	83	0.05	15035	82	9252
45	100	15	10	20	83	0	8384	77	9163
45	120	20	0	25	83	0	10041	83	9145
45	140	25	2.5	5	83	0	11695	82	9225
45	160	5	5	10	83	0	13375	79	9194
45	180	10	7.5	15	82	0.56	14819	76	9263
60	100	20	2.5	15	83	0.05	8380	82	9180
60	120	25	5	20	83	0	10035	79	9175
60	140	5	7.5	25	83	0	11714	77	9194
60	160	10	10	5	83	0	13371	77	9218
60	180	15	0	10	80	1.41	14484	80	9235
75	100	25	7.5	10	83	0	8375	77	9173
75	120	5	10	15	83	0.05	10056	77	9173
75	140	10	0	20	83	0	11711	83	9155
75	160	15	2.5	25	83	0.04	13365	82	9237
75	180	20	5	5	78	2.22	14168	74	9245

Table 5. 8 Painting workstation results

*5.2.*3 Workstation Performance Metrics Correlation Coefficients

Tables 5.9 to 5.12 provide the Correlation Coefficients values indicating the strength of relationships between the paired-performance metrics of the Deburr, Marking, Primer, and Painting workstations respectively.

Using correlation analysis the following results collected for each workstation

	Input Part	Process Time	Setup Time	Quality	MTTR Time	WS Thr/put	WS %Non- Zero	WS Working	Total Thr/put	Total L T
Input Part										
Process Time										
Setup Time										
Quality %										
MTTR Time										
WS Throughput		-0.94	-0.03							
WS %Non- Zero	0.29	0.85	-0.07		0.01	-0.91				
WS Working		0.87	-0.07		-0.01	-0.93	0.85			
Total Throughput		-0.99	-0.03		0.02	0.89	-0.81	-0.68		
Total Lead Time		0.73	-0.03	-0.15	0.06	-0.80	0.86	0.73	-0.7	

Table 5. 9 Deburr workstation relationships

	Input Part	Process Time	Setup Time	Quality	MTTR Time	WS Thr/put	WS %Non- Zero	WS Working	Total Thr/put	Total L T
Input Part										
Process Time										
Setup Time										
Quality %										
MTTR Time										
WS Throughput		-0.98	-0.04							
WS %Non- Zero	0.27	0.91	-0.08		-0.14	-0.92				
WS Working		0.87	-0.06			-0.84	0.81			
Total Throughput	0.06	-0.92	-0.04	-11		0.89	-0.79	-0.63		
Total Lead Time	0.14	0.89	-0.06	-20	-0.12	-0.89	0.92	0.67	-0.85	

Table 5. 10 Marking workstation relationships

	Input Part	Process Time	Setup Time	Quality	MTTR Time	WS Thr/put	WS %Non- Zero	WS Working	Total Thr/put	Total L T
Input Part										
Process Time										
Setup Time										
Quality %										
MTTR Time										
WS Throughput	-0.05	-0.95	-0.24							
WS %Non- Zero	0.64	0.63	0.06	-0.10	-0.09	-0.68				
WS Working	-0.06	0.59	-0.79			-0.36	0.28			
Total Throughput	0.07	-0.84	-0.18	-0.18		0.76	-0.4	-0.35		
Total Lead Time	-0.23	0.67	0.21	-0.55		-0.62	0.27	0.25	-0.66	

Table 5. 11 Primer workstation relationships

	Input Part	Process Time	Setup Time	Quality	MTTR Time	WS Thr/put	WS %Non- Zero	WS Working	Total Thr/put	Total L T
Input Part										
Process Time										
Setup Time										
Quality %										
MTTR Time										
WS Throughput		-0.53	-0.3	-0.15						
WS %Non- Zero		0.54	0.29	0.15		-1				
WS Working		0.99	-0.04			-0.42	0.43			
Total Throughput		-0.28	-0.16	-0.83		0.63	-0.63	-0.21		
Total Lead Time		0.85	0.21	0.27		-0.6	0.62	0.82	-0.49	

Table 5. 12 Painting workstation relationships

5.2.4 Workstation Performance Metric R^2 and S Values

Tables 5.13 to 5.16 present the results of the regression analysis using the **R^2** Coefficient and (in brackets) the **S** values i.e. the estimated error, for the Deburr, Marking, Primer, Paint workstations consecutively.

	Input Part	Process Time	Setup Time	Quality	MTTR Time	WS Thr/put	WS %Non- Zero	WS Working	Total Thr/put	Total L T
Input Part										
Process Time										
Setup Time										
Quality %										
MTTR Time										
WS Throughput		0.89(20.66)								
WS %Non- Zero	0.73(7.77)					0.83				
WS Working		0.60(2796)				0.86	0.71(2373.18)			
Total Throughput		0.97(4.5)				0.79(12.28)	0.65(15.79)	0.45(19.86)		
Total Lead Time		0.54(631.2)				0.64(555)	0.74(469.8)	0.53(629.6)	0.49(658.6)	

Table 5. 13 Deburr workstation relationships

	Input Part	Process Time	Setup Time	Quality	MTTR Time	WS Thr/put	WS %Non- Zero	WS Working	Total Thr/put	Total L T
Input Part										
Process Time										
Setup Time										
Quality %										
MTTR Time										
WS Throughput		0.96(9.31)								
WS %Non- Zero		0.82.8(4.94)				0.84(4.75)				
WS Working		0.75(28757)				0.70(3124)	0.65(3379)			
Total Throughput		0.86(3.9)				0.79(4.51)	0.62(6.07)	0.96(9.31)		
Total Lead Time		0.80(221.2)				0.80(220.8)	0.84(192.06)	0.45.2(366)	0.72(260)	

Table 5. 14 Marking workstation relationships

	Input Part	Process Time	Setup Time	Quality	MTTR Time	WS Thr/put	WS %Non- Zero	WS Working	Total Thr/put	Total L T
Input Part										
Process Time										
Setup Time										
Quality %										
MTTR Time										
WS Throughput		0.90(7.06)								
WS %Non- Zero	0.41(5.27)	0.40(5.31)				0.45(5.05)				
WS Working		0.62(574.7)								
Total Throughput		0.71(3.62)				0.58(4.36)				
Total Lead Time		0.45(101)				0.39(107.3)			0.44(102.5)	

Table 5. 15 Primer workstation relationships

	Input Part	Process Time	Setup Time	Quality	MTTR Time	WS Thr/put	WS %Non- Zero	WS Working	Total Thr/put	Total L T
Input Part										
Process Time										
Setup Time										
Quality %										
MTTR Time										
WS Throughput										
WS %Non- Zero		0.73(7.77)				0.83(6.12)				
WS Working		0.60(2796.3)								
Total Throughput				0.69(1.86)		0.79(12.28)	0.65(15.7)			
Total Lead Time		0.53(631.2)				0.64(555.4)	0.74(469.8)	0.67(24.6)		

Table 5. 16 Paint workstation relationships

5.2.5 Relationships between Workstation

Performance metric Correlation Coefficients were used to identify potential relationships between workstations, i.e.:

Table 5.17 Painting workstation and Deburr workstation

Table 5.18 Painting workstation and Marking workstation

Table 5.19 Painting workstation and Primer workstation

	TOTAL THR/PUT	TOTAL LT	WS %NON ZERO	WS WORKING
TOTAL THR/PUT	0.36	-0.94	-0.37	-0.95
TOTAL LT	-0.19	0.76	0.19	0.75
WS %NON ZERO	-0.23	0.85	0.23	0.88
WS WORKING	-0.21	0.78	0.22	0.81

Table 5. 17 Correlation Coefficients between Deburr workstation and Painting Performance metrics

	TOTAL THR/PUT	TOTAL LT	WS %NON ZERO	WS WORKING
TOTAL THR/PUT	0.36	-0.94	-0.37	-0.95
TOTAL LT	-0.19	0.76	0.19	0.75
WS %NON ZERO	-0.23	0.85	0.23	0.88
WS WORKING	-0.21	0.78	0.22	0.81

Table 5. 18 Correlation Coefficients between Marking workstation and Painting Performance metrics

	TOTAL THR/PUT	TOTAL LT	WS %NON ZERO	WS WORKING
TOTAL THR/PUT	0.44	-0.97	-0.45	-0.98
TOTAL LT	-0.26	0.86	0.26	0.86
WS %NON ZERO	-0.26	0.87	0.27	0.93
WS WORKING	-0,26	0.86	0.27	0.89

Table 5. 19 Correlation Coefficients between Primer workstation and Painting Performance metrics

5.3 Workstations Performance Metrics Scatter Diagrams

Tables 5.9 to 5.12 provide the correlation coefficient values between performance metrics for each workstation. Figures 5.1 to 5.50 provide scatter diagrams of the actual results from which the correlation coefficients were derived, ie.

5.3.1 Deburr

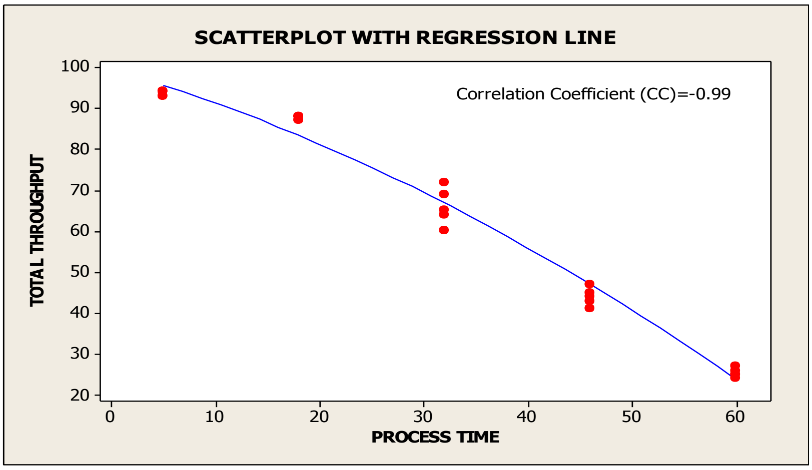


Figure 5. 1 Total throughput and Processing time

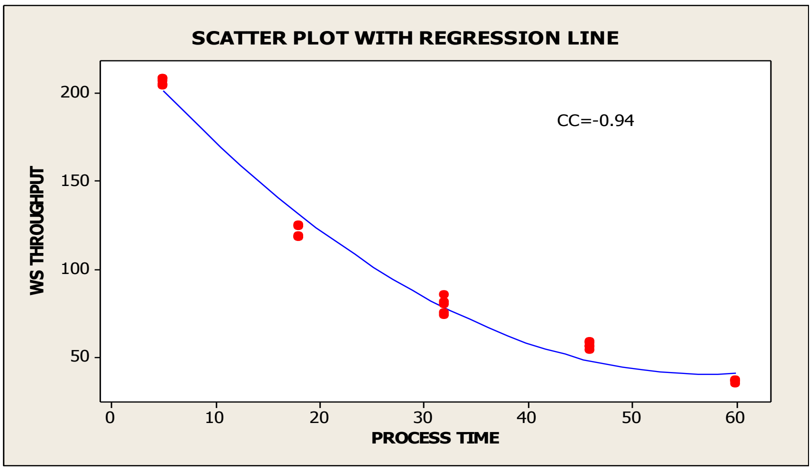


Figure 5. 2 Workstation throughput and Processing time

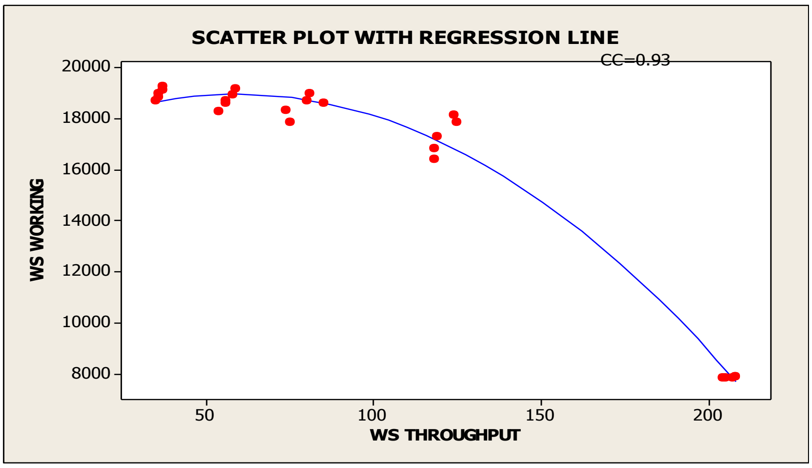


Figure 5. 3 Workstation working and Workstation throughput

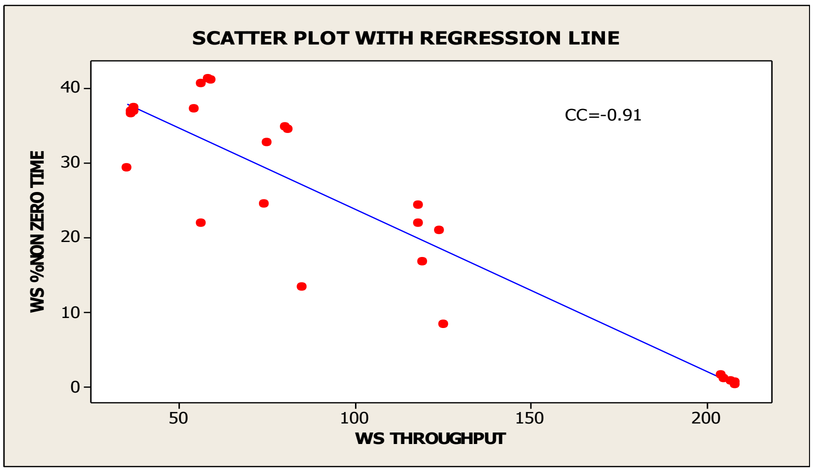


Figure 5.4 Workstation % Non-Zero time and Workstation throughput

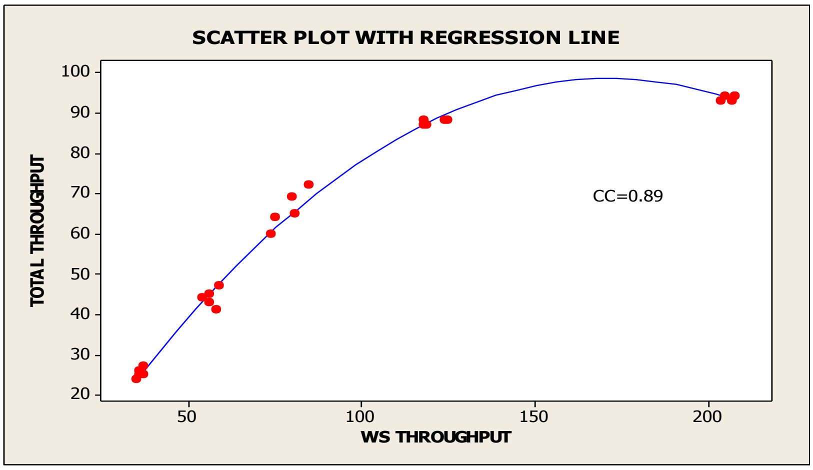


Figure 5. 5 Total throughput and Workstation throughput

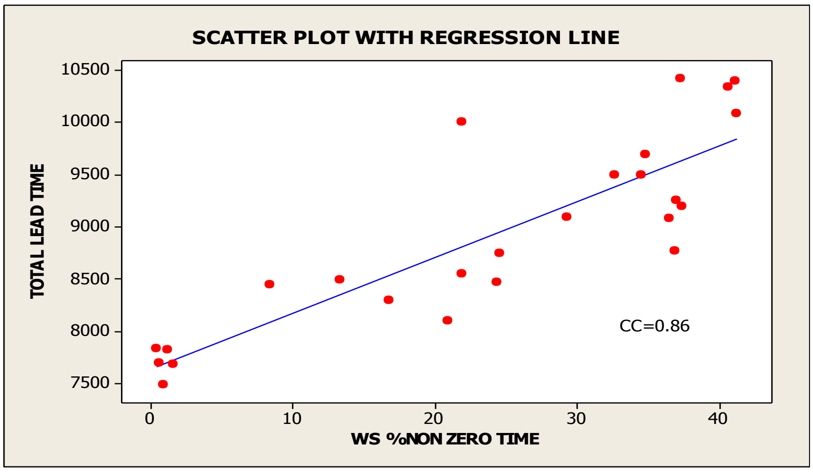


Figure 5. 6 Total Lead Time and workstation % Non-Zero time

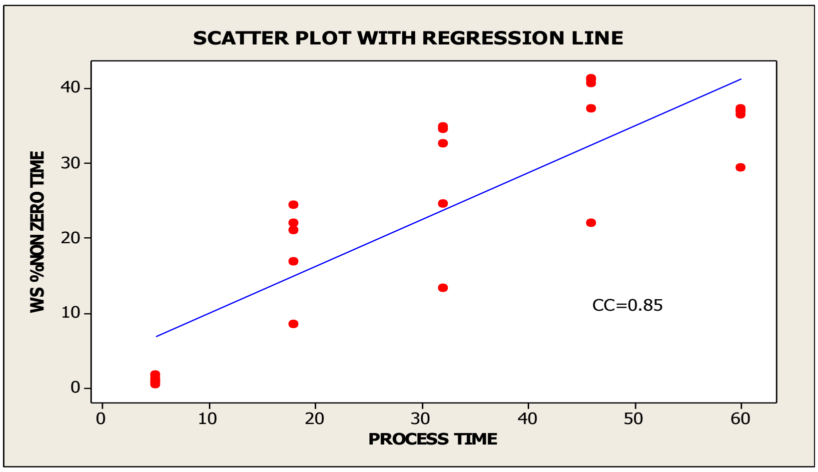


Figure 5. 7 Workstation % Non-Zero time and Processing time

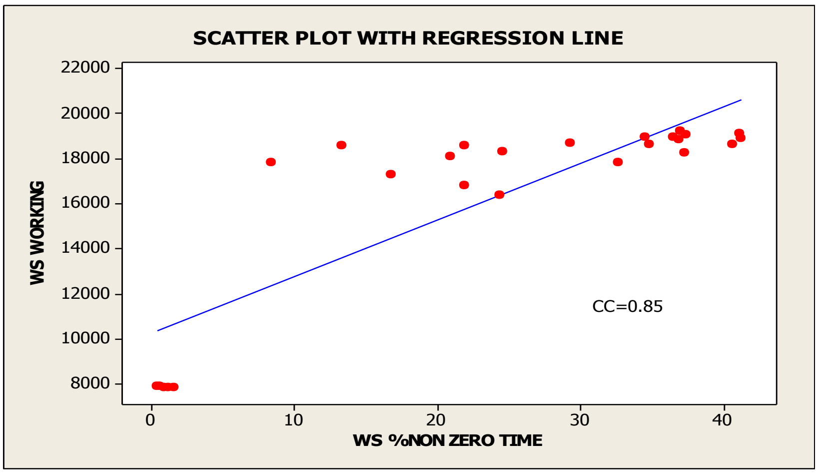


Figure 5. 8 Workstation working and workstation % Non-Zero time

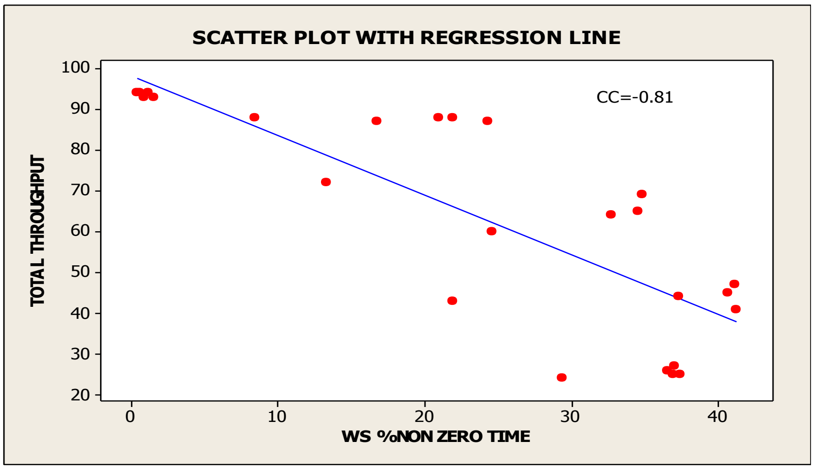


Figure 5. 9 Total throughput and workstation % Non-Zero time

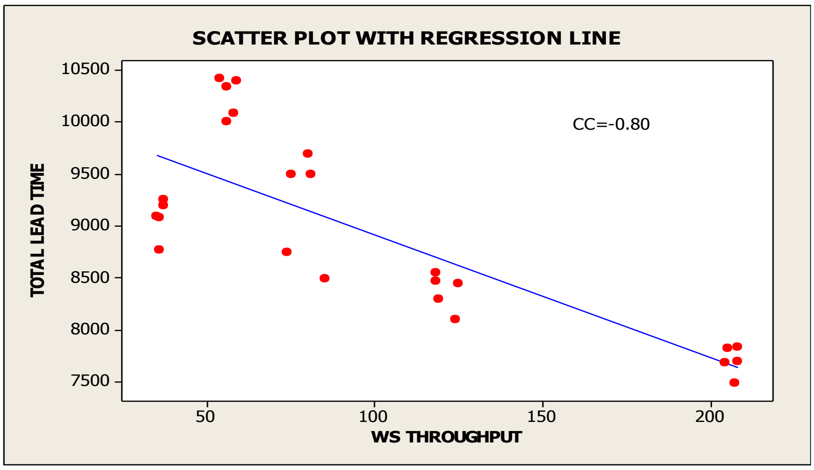


Figure 5. 10 Total Lead Time and workstation throughput

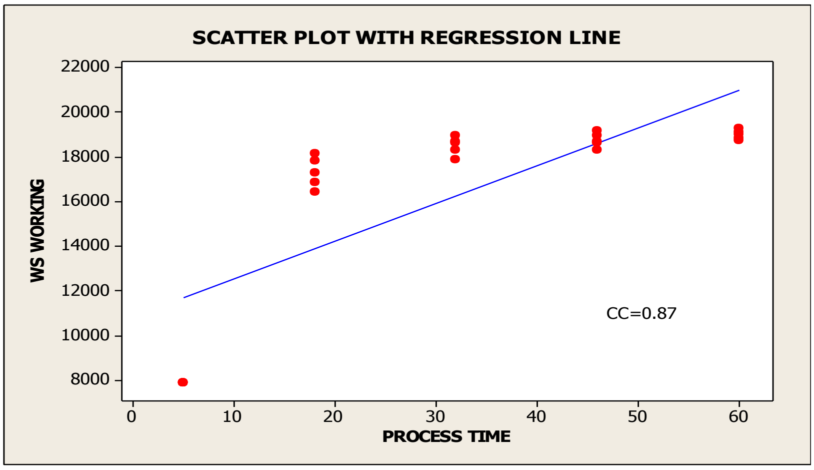


Figure 5. 11 Workstation working and Processing time

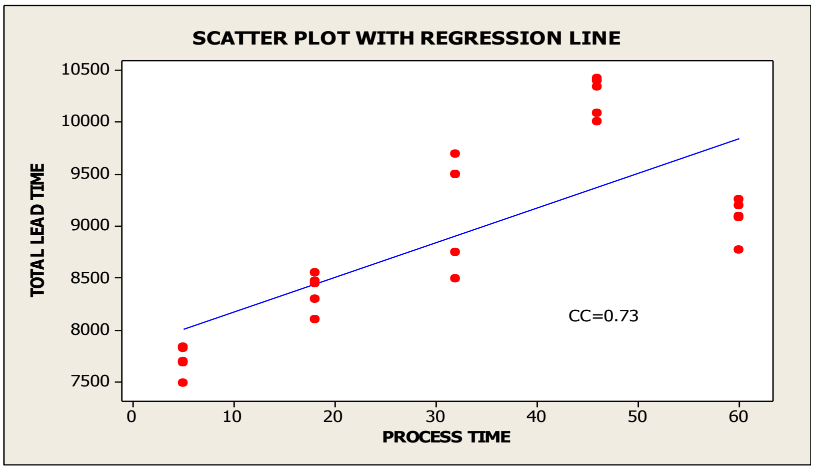


Figure 5. 12 Total Lead Time and Processing time

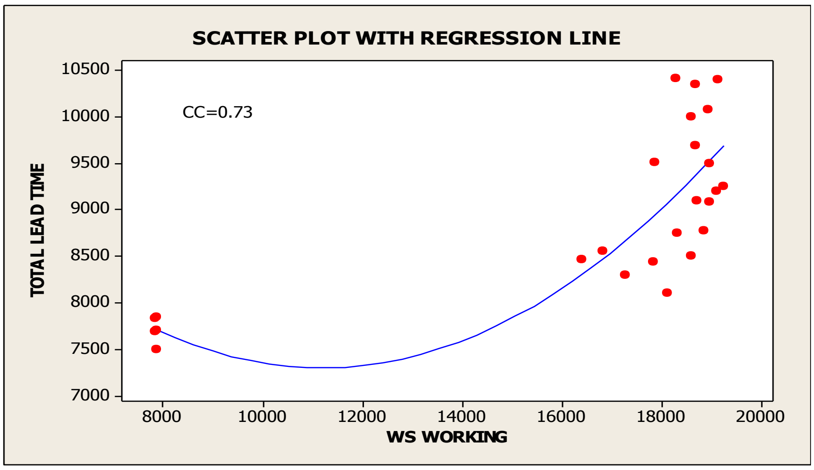


Figure 5. 13 Total Lead Time and Workstation working

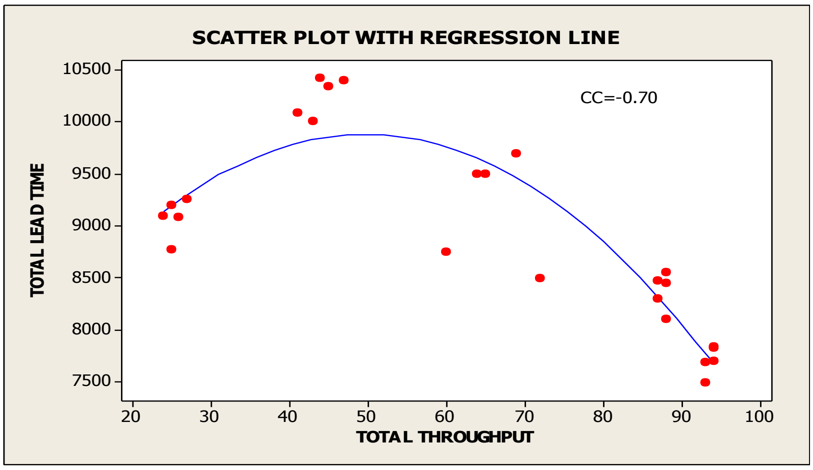


Figure 5. 14 Total Lead Time and Total throughput

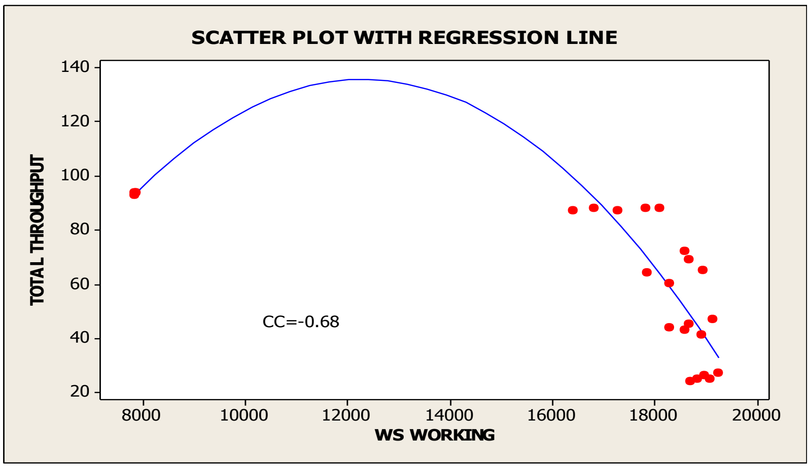


Figure 5. 15 Total throughput and Workstation working

5.3.1 Marking

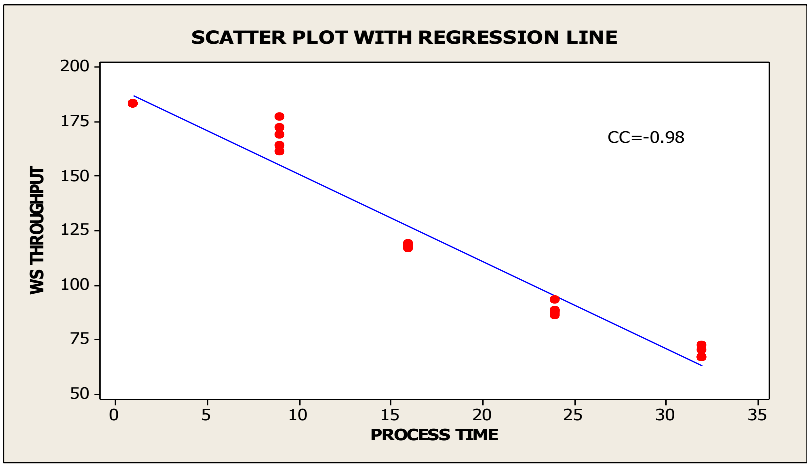


Figure 5. 16 Workstation throughput and Processing time

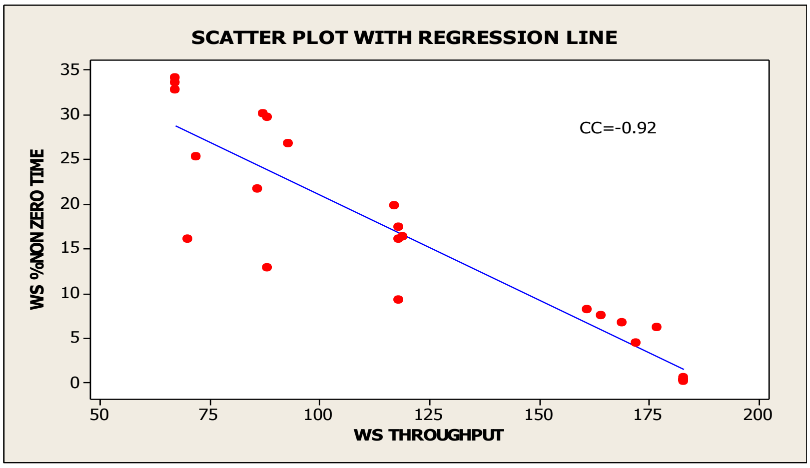


Figure 5. 17 Workstation % Non-Zero time and Workstation Thr/put

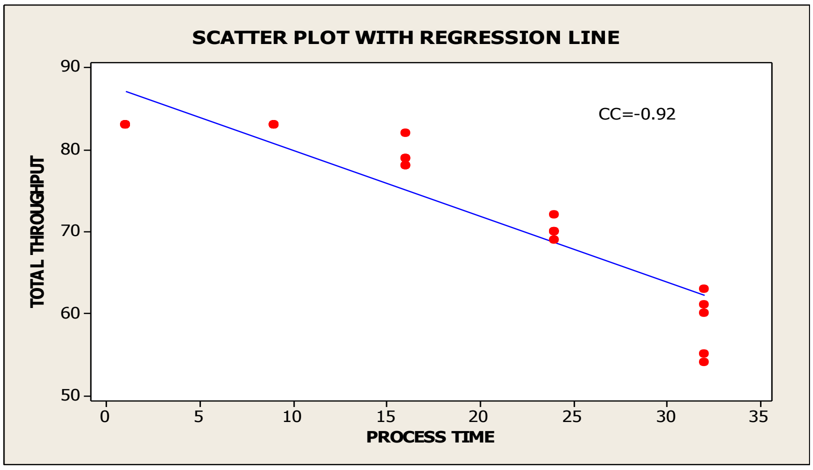


Figure 5. 18 Total throughput and Processing time

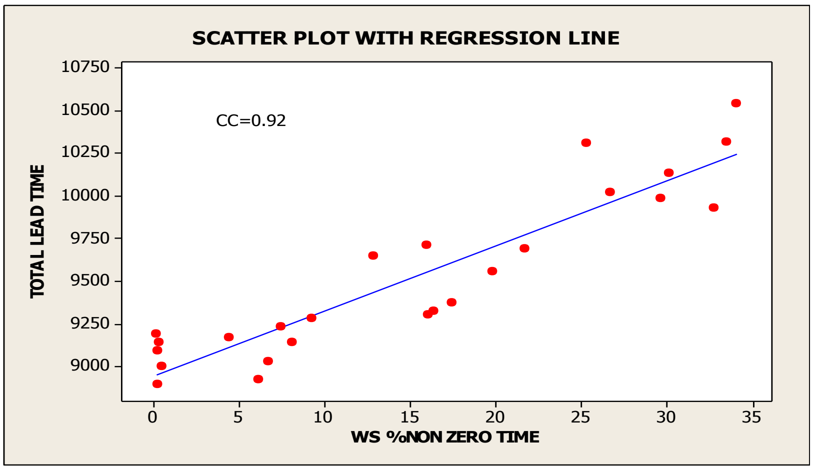


Figure 5. 19 Total Lead Time and workstation % Non-Zero time

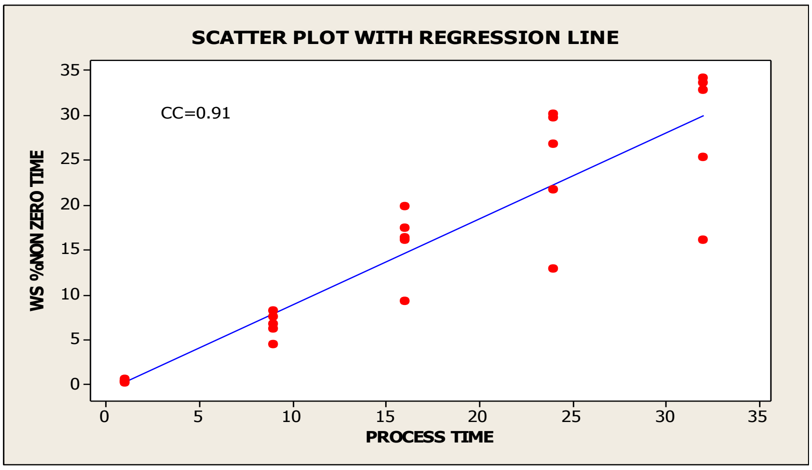


Figure 5. 20 Workstation % Non-Zero time and Process time

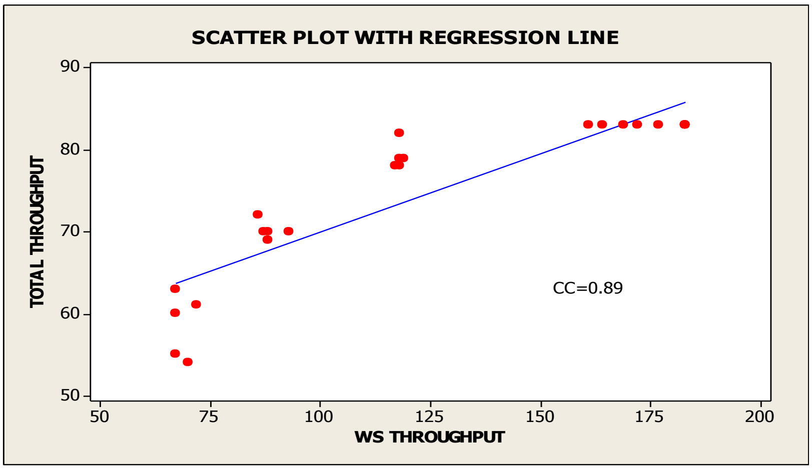


Figure 5. 21Total throughput and Workstation throughput

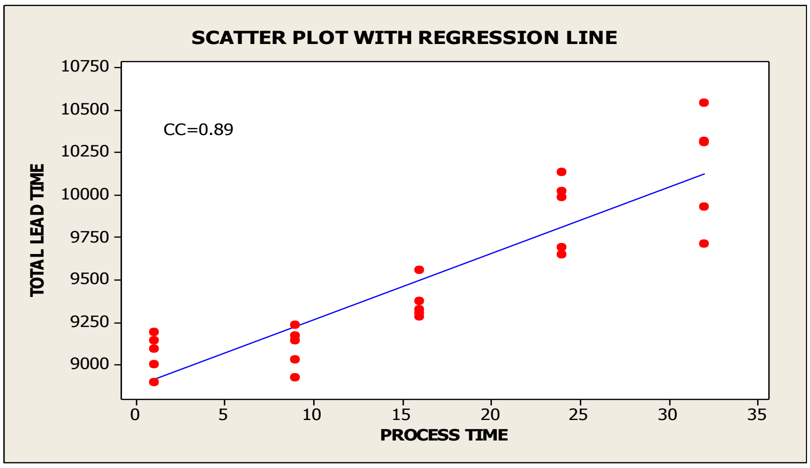


Figure 5. 22 Total Lead Time and Processing time

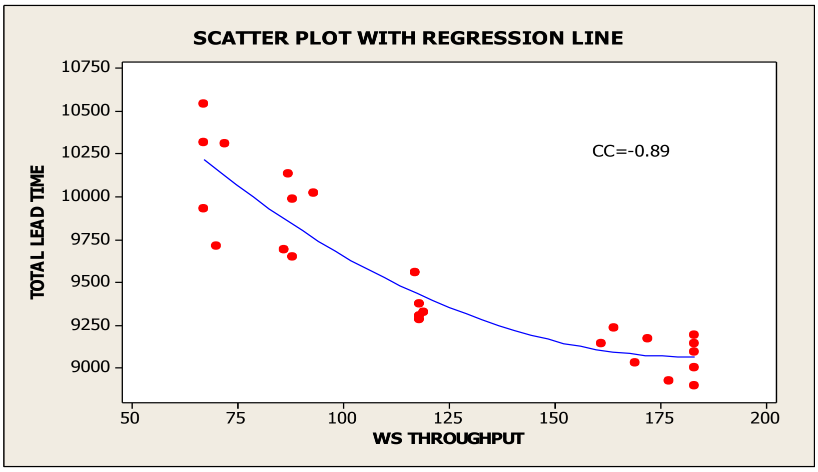


Figure 5. 23 Total Lead Time and workstation throughput

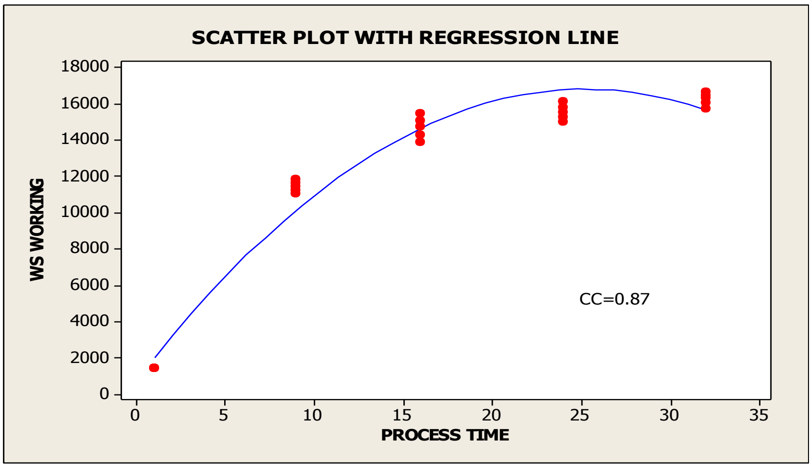


Figure 5. 24 Workstation working and Processing time

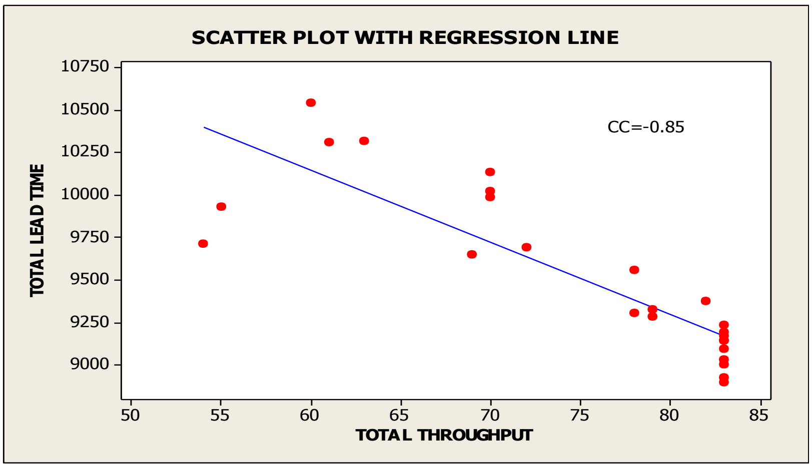


Figure 5. 25 Total Lead Time and Total throughput

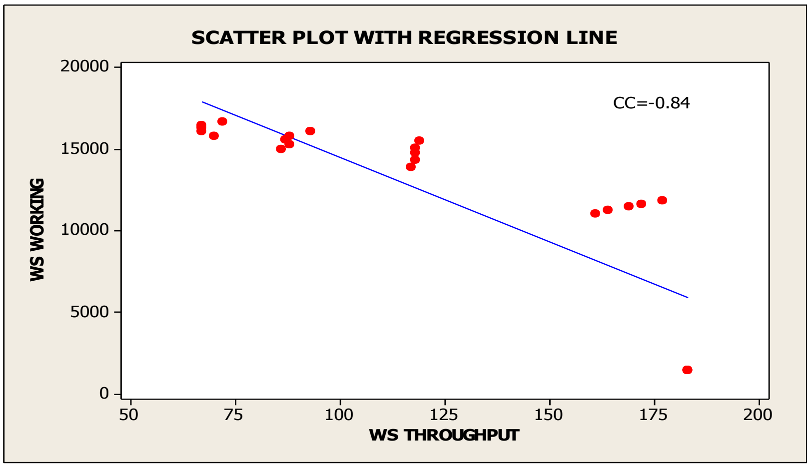


Figure 5. 26 Workstation working and Workstation throughput

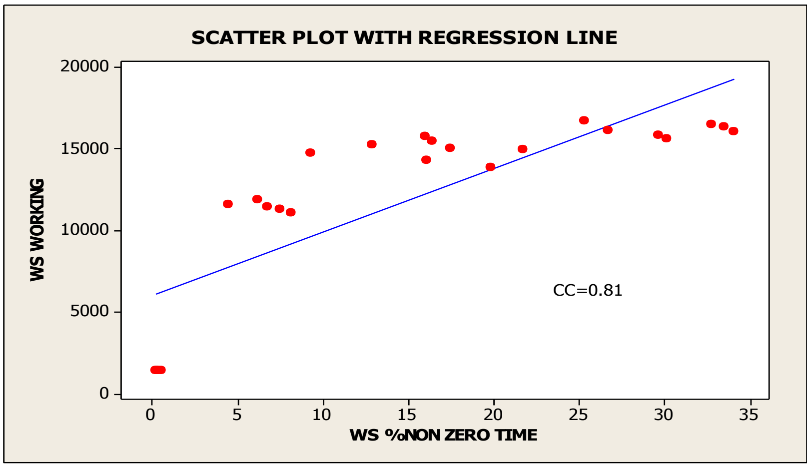


Figure 5. 27 Workstation working and workstation % Non-Zero time

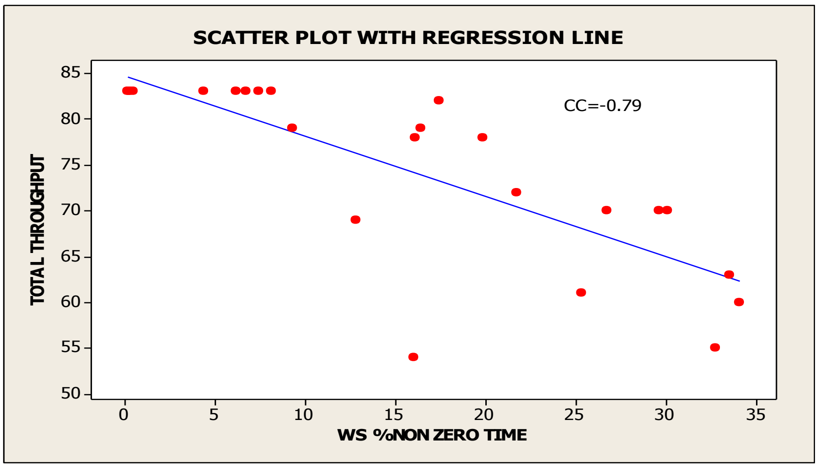


Figure 5. 28 Total throughput and workstation % Non-Zero time

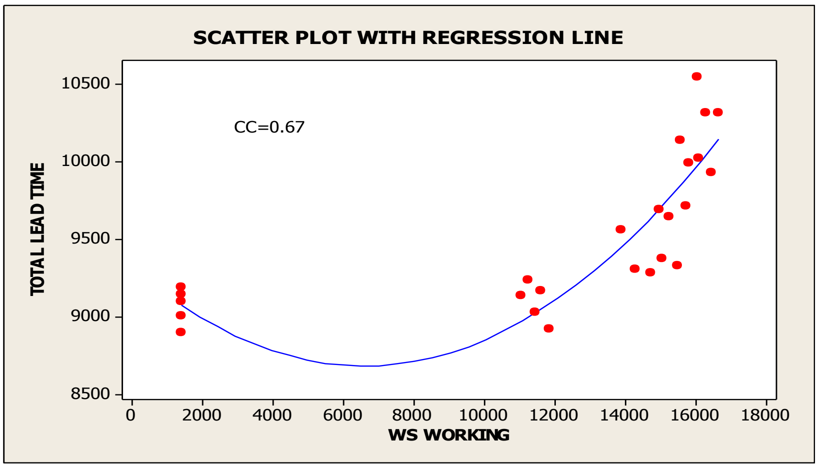


Figure 5. 29 Total Lead Time and Workstation working

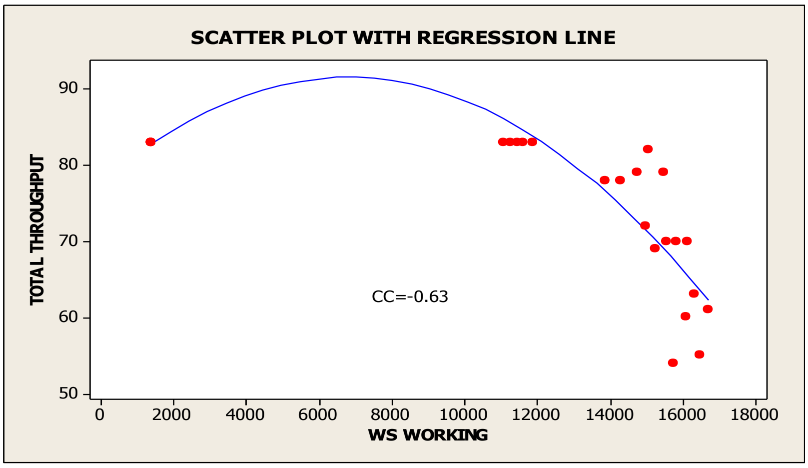


Figure 5. 30 Total throughput and Workstation working

5.3.3 Primer

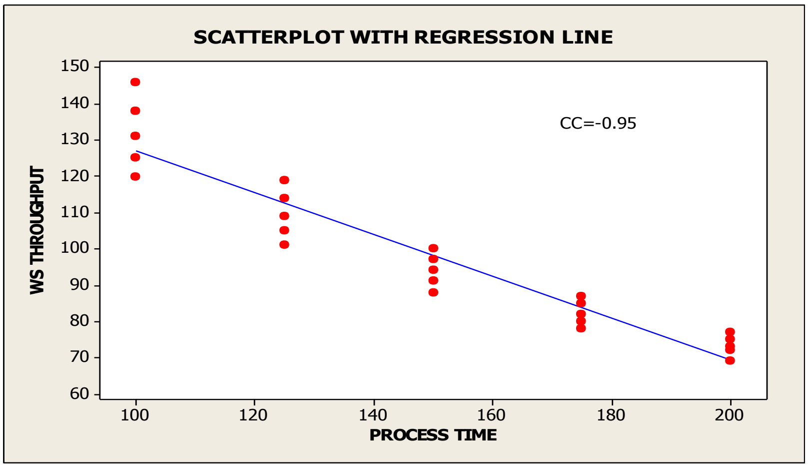


Figure 5. 31 Workstation throughput and Processing time

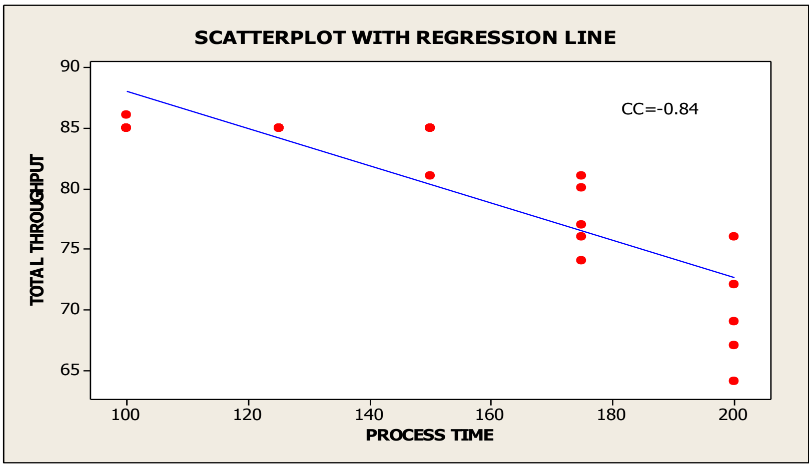


Figure 5. 32 Total throughput and Processing time

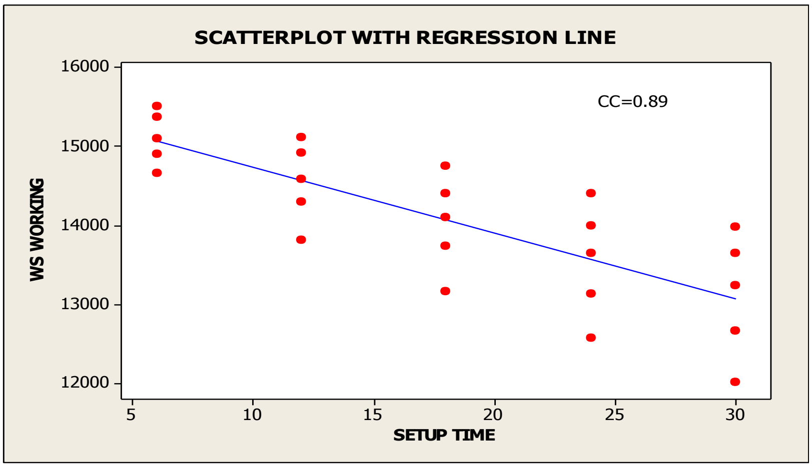


Figure 5. 33 Workstation working and setup time

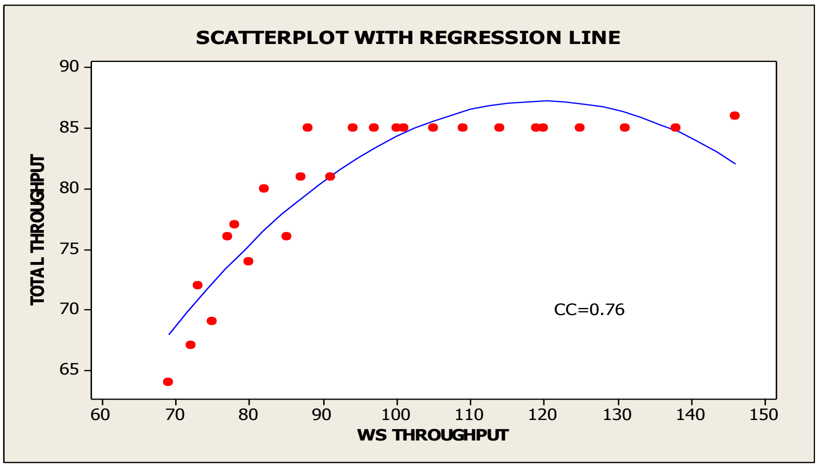


Figure 5. 34 Total throughput and Workstation throughput

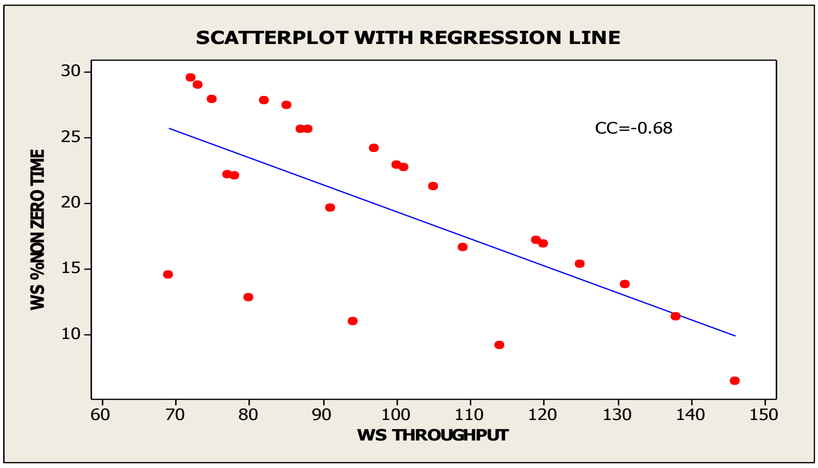


Figure 5. 35 Workstation % Non-Zero time and Workstation thr/put

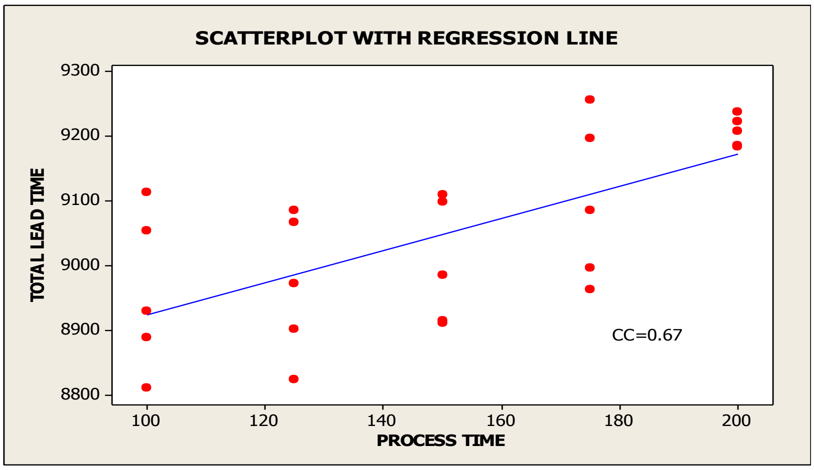


Figure 5. 36 Total Lead Time and Processing time

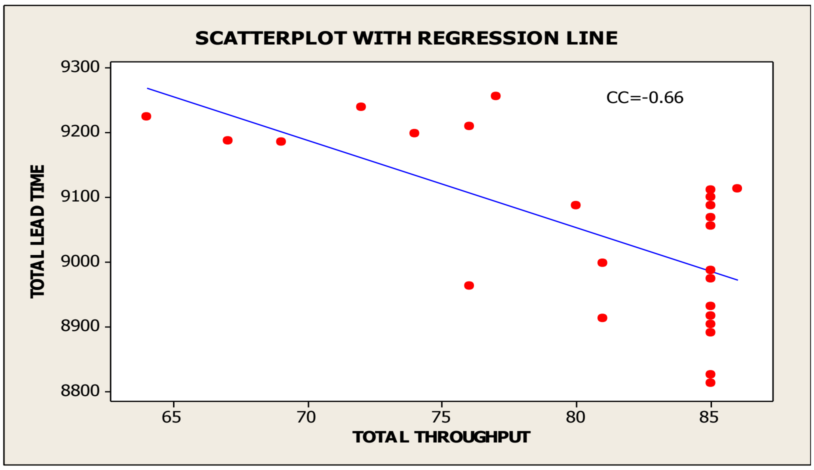


Figure 5. 37 Total Lead Time and Total Throughput

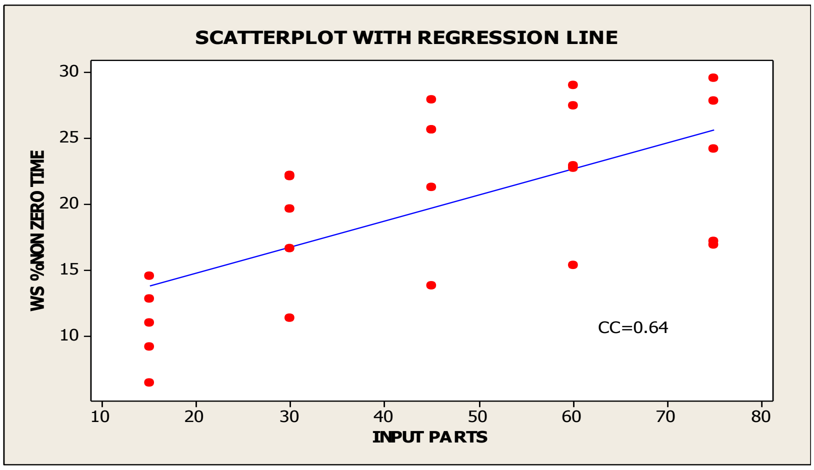


Figure 5. 38 Workstation % Non-Zero time and Input parts

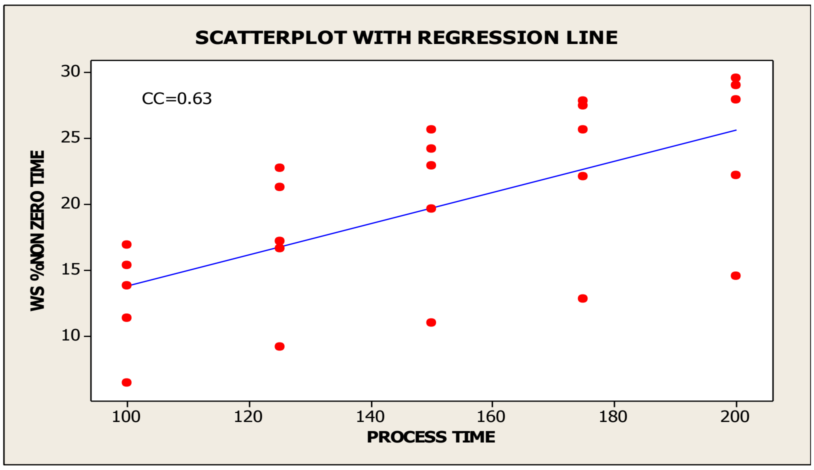


Figure 5. 39 Workstation % Non-Zero time and Processing time

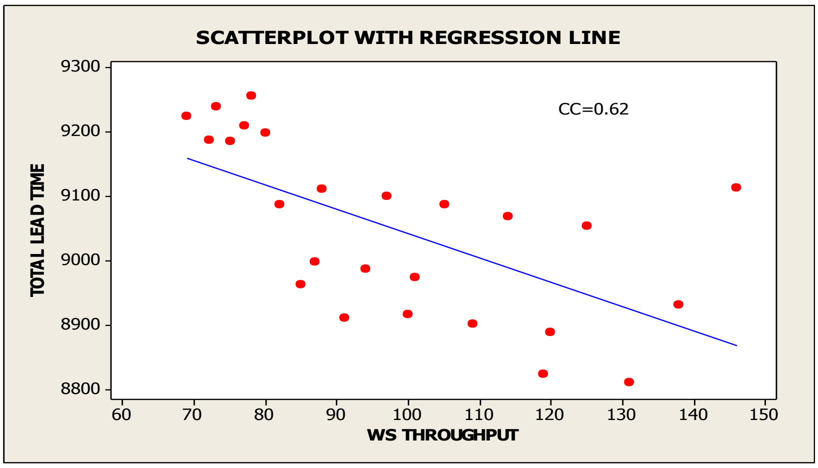


Figure 5. 40 Total Lead Time and workstation throughput

5.3.4 Paint

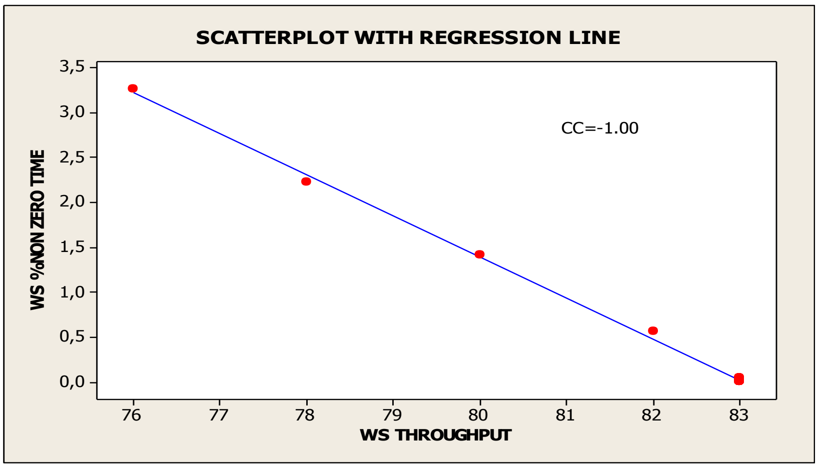


Figure 5. 41 Workstation % Non-Zero time and Workstation thr/put

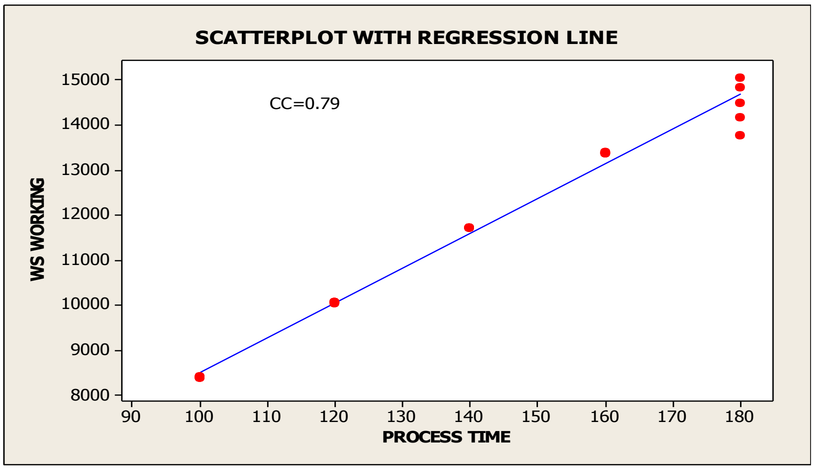


Figure 5. 42 Workstation working and Processing time

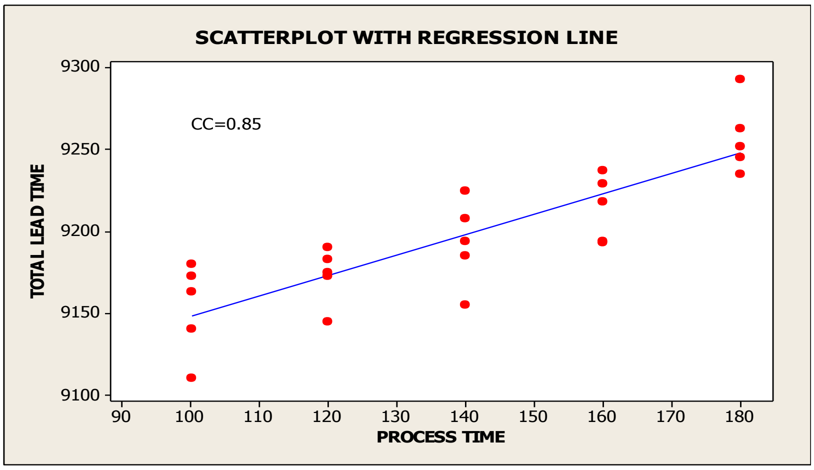


Figure 5. 43 Total Lead Time and Processing time

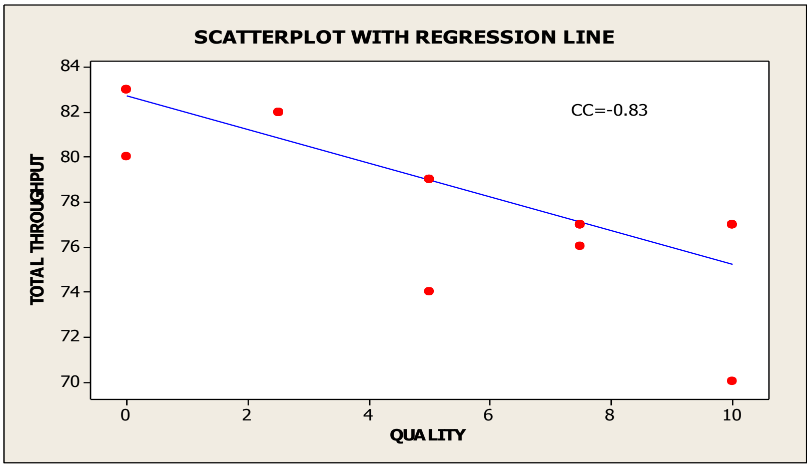


Figure 5. 44 Total throughput and quality

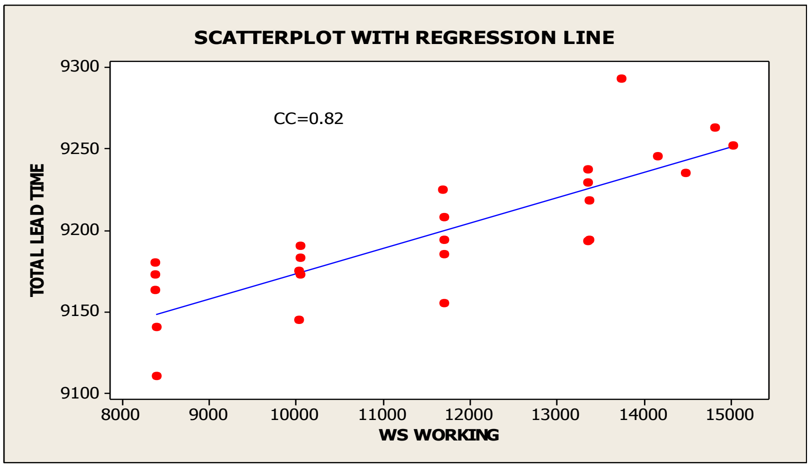


Figure 5. 45 Total Lead Time and Workstation working

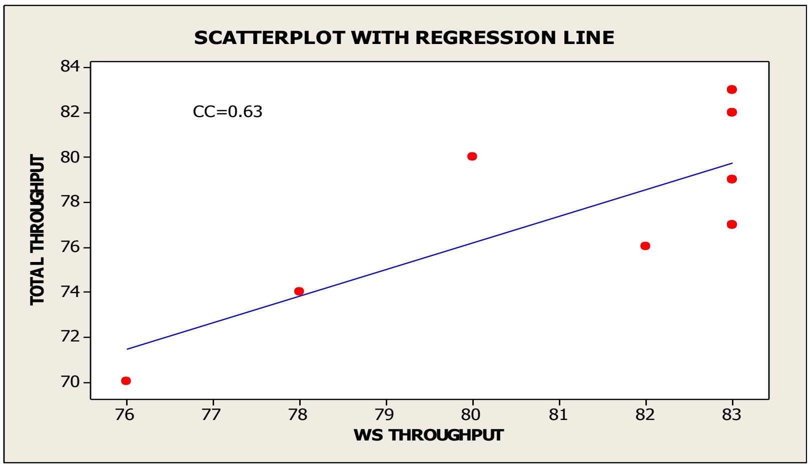


Figure 5. 46 Total throughput and Workstation throughput

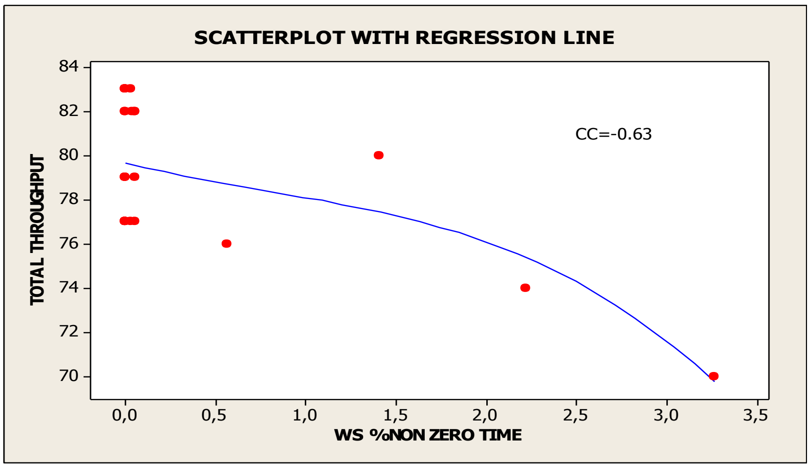


Figure 5. 47 Total throughput and Workstation % Non-Zero time

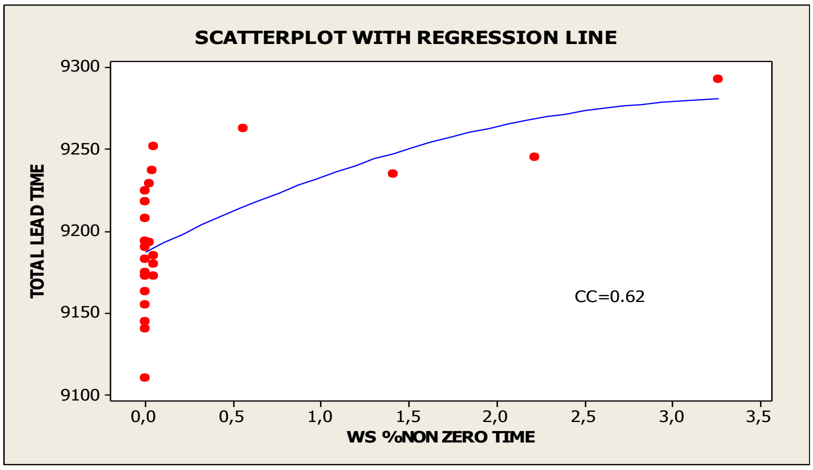


Figure 5. 48 Total Lead Time and Workstation % Non-Zero time

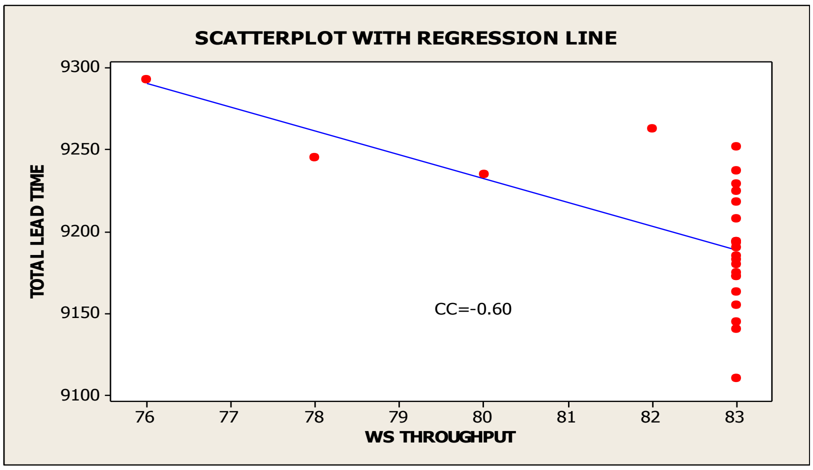


Figure 5. 49 Total Lead Time and Workstation throughput

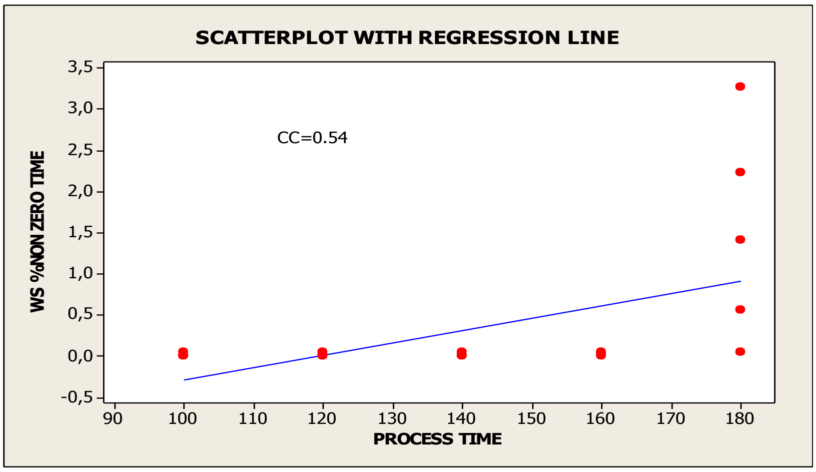


Figure 5. 50 Workstation % Non-Zero time and Processing time

The relationships established between 'efficiency improvement enablers' and 'cause of inefficiencies' is shown in table 5.20

Efficiency Improvement Enablers	**Causes of Inefficiency**	Transportation & Material Handling	Inventory, Batch Size & Work -in-Progress	Overproduction	In-process Queueing Time	Waiting,Idling & Minor Stoppages	Over-processing	Non-added Value Motions	Material Shortages	Quality-Process & Non-Process Defects	Equipment Failure from Breakdowns	Set-up & Adjustment	Reduced Processing Speed	Lack of Flexible Labour	Poor Line Balancing	Poor Job Sequencing	Variable Cycle Times	Poor Facilities Layout
Implement multi-skilling			X			X				X	X			X				
Reduce processing batch size			X		X	X												
Standardise work and operations				X	X	X	X			X	X							
Implement "mistake proofing"										X	X						X	
Improve process capability									X	X	X		X				X	X
Production Schedule Levelling and Sequence			X			X			X			X						
Improve workplace area using 5S		X	X			X		X		X	X	X						
The 7 Wastes		X	X	X		X		X		X	X		X					X
Implement cellular manufacturing		X	X					X		X		X						X
Implement one-piece flow/small batch production		X	X	X	X	X				X	X	X						
Balance production processes-line balancing		X	X	X		X	X	X		X					X	X	X	
Implement kanban control			X			X											X	
Implement visual planning and control		X	X		X	X		X	X	X	X		X				X	X
Implement Kaizen and continuous improvement exercises		X	X	X	X		X	X		X								X
Implement planned maintenance and TPM					X	X			X	X	X	X					X	
Implement TQM and SPC		X	X					X		X								
Implement Jidoka and automation			X			X				X								

Table 5.20 Relationships between Lean Enablers and Causes of Inefficiency

5.4 Validation

In order to validate the relationships, a simulation model was run. For each workstation, one equation was chosen. The equations that have taken into account were presented in the figures 5.6, 5.18, 5.31, 5.45. As shown by the results, the equations validated. An indication of the validation is presented in the following paragraphs describing the primer workstation. The model was run initially with the basic values and the following results collected:

For the system’s level are:

- Total throughput: 83 shop orders
- Total lead time: 9124 minutes

A flow line performance metrics level is:

- Completed Jobs: 84 Shop Orders

Flow line performance metrics workstation levels are:

- Working: 69.31%
- Awaiting: 18.54%
- Changeover: 12.14%
- Queue: 95 Shop Orders

After these above results the equation that created and presented in Figure 31 (Appendix B) was chosen to validate the improvement of the flow line. This equation was chosen by chance and not for a specific reason.

So, the regression equation is $T_{thr} = a - b\,\mathrm{Pr}\,ocess_{time}$ (4)

Where a= 103

b= 0,154

Substituting the values to the equation (4) takes the form

$$T_{thr} = 103 - 0.154 \times \mathrm{Pr}\,ocess_{time} \quad (5)$$

The constant has a practical interpretation only if the range of x values in the sample includes zero. Since the range of values is from 100 to 200 minutes, the y intercept has no practical interpretation.

Thus, the Throughput is:

$$T_{thr} = 0.154 \times \mathrm{Pr}\,ocess_{time} = 118 \text{ Shop orders} \quad (6)$$

After that, the model was running again with less process time showing that process time was the cause of inefficiency and targeted, and the following results collected:

For the system's level are:

- Total throughput: 118 shop orders
- Total lead time: 7844.27 minutes

Flow line performance metrics levels is

- Completed Jobs: 118 shop orders

Flow line performance metrics workstation levels are:

- Working: 62.18%
- Awaiting: 20.19%
- Changeover: 17.43%
- Queue: 58 Shop Orders

The above results validate that the process time caused inefficiency to the flow line. This inefficiency removed and as it is obvious the 'total lead time' reduced, the completed jobs increased and this justified by the equation, working less, and the queues reduced respectively. However, awaiting time and changeover have slightly increased.

5.5 Experimental results Summary

In accordance to experimental results the following observations have been done:

1. In figure 5.1 have shown that Process Time has a negative effect to the Total Throughput. This means as the process time increased then the total throughput is reduced. Also, a common result was taken from figure 5.18, 5.32, with a smaller relationship values than the figure 5.1.
2. Also, in figure 5.2, 5.16, 5.31 have found that the process time has a very strong negative effect in the workstation throughput. This means that when the process time increased then the workstation throughput is reduced.

3. In figure 5.5, 5.21, 5.34, 5.46 there are common results shown that as Total Throughput increased then the workstation throughput increased respectivelly.

4. Mapes et.al. (2000) claimed that if the more process time variability is reduced the more the throughput is produced, as it can be obvious from the three observations, there is a hierarchical relationship among those metrics. That means as the process time decreased, the workstation throughput increased, and also, the total throughput increased.

5. In figure 5.3, it has found that workstation throughput increased by reducing the workstation working. Also, this relationship appears in the figure 5.26 with less stronger relationship among the other workstations.

6. In figure 5.4, 5.17, 5.35 have indicated that workstation throughput increased by reducing the workstation % non-zero time. However a strongest relationships exists in the last workstation(Primer workstation)

7. While, in figure 5.6, 5.19, have found that Total Lead Time increased as the workstation % non-zero time increased.

8. Also, a very strong relationships exist between the process time and workstation % non-zero time as it is presented in figure 5.7, 5.20. It has concluded that as the process time increased also the workstation % non-zero time increased.

9. In figure 5.8, 5.27 show that as the workstation % non-zero time increased the workstation working increased respectively.

10. While, the figures 5.9, 5.28, 5.47 shown that as the workstation % non-zero time increased the Total Throughput increased respectively.

11. Common results derived from the figure 5.11, 5.24, 5.42.These figures shown that as the process time increased the workstation working increased respectively.

12. In figure 5.12, 5.22, 5.36, 5.43 have found that the Total Lead Time increased as the process time increased respectively.

13. Similar relationships have been found to exist between the workstation working and Total Lead Time. These presented in the figure 5.13, 5.29, 5.45, showing that when the Workstation working increases then the Total Lead Time increases respectively.

14. While the Total Lead Time and the total throughput as they presented in figure 5.14, 5.25, 5.37, have a negative relationship. This means that when the Total Lead Time increased then the Total throughput decreased respectively.

15. In figure 5.15, 5.30, 5.45 have found that a negative relationship between these two variables of workstation working and total throughput. This means as the workstation working increased then the total throughput decreased respectively.

16. Hopp et.al (1990) argued that setup time reduction decreased the flow line variance but it caused a small reduction in mean flow time. However in figure 5.33 have been found that the setup time to influence the workstation working in a negative way. This means that as the setup time decreased the workstation working time increased respectively. In addition this finding comes to confirm Gilmore&Smith (1998) that show as the setup time reduced then the machine utilization increased respectively.

17. As it can be observed in figure 5.11, 5.13, there is a hierarchical relationship among the process time working time and total lead time. That means as the process time decreased the workstation working degreased respectively and also decreased the total lead time.

18. Also, in figure 5.6, 5.7, there is a hierarchical relationship among the process time workstation % non-zero time and total lead time. This means in order to degrease the total lead time the workstation % non-zero time decreased, and the process time should be reduced respectively.

19. In figure 5.44 it has been found that a very strong relationship exists between the total throughput and the quality. Between these two variables there is a negative relationship that means when the Quality decreased then the Total throughput increased respectively

20. In last figures 5.33 and 5.44 can be noticed that two pair of relationships has appeared in the last two workstations of the flow line. From these relationships derive that two variables setup and quality has great effect in the last parts of the flow lines.
21. Comparing each station’s results against the final one, Table 5.17, Table 5.18, Table 5.19, it has been found that the first workstation appears to influence the second one and so on. The last station is affected by the station positioned before the last station.
22. In figures 5.38 it has been found that a moderate relationship exists between the workstation % non-zero time and the input parts. Between these two variables there is a negative relationship that means when the input parts increased then the workstation % non-zero time increased respectively. Also, in table 5.11 exist a lower negative relationship between the total lead time and the input parts. This Indicate that as the input parts increased the total lead time decreased respectively.

The following chapter 6 concerns the analysis of the finding results of the experiments that presented analytically in the current chapter 5.

CHAPTER 6 Discussion

6.1 Introduction

Increasing global competition is forcing organisations to adopt business strategies aimed at competing in areas such as delivery reliability, product choice, quality and cost, delivery lead time (White 1996). These objectives are indeed difficult to achieve due to pressure on organisations to reduce costs by minimizing inventory levels. In order to resolve these conflicting aims emphasis needs to be placed on enabling individual functional areas within an organisation to both identify and work towards common business goals, (Stockton 2004). In this respect, performance measurements are essential in enabling the short term operations of individual manufacturing areas to be integrated into long term objectives of an organisation. It is therefore, becoming ever more important for organisations to ensure that the performance measurements used are compatible with the environments they are controlling.

6.2 Performance management

Traditional performance measurement relied on financial measures such as, return on investment (ROI), productivity, utilisation, efficiency and profit, (Ghalayini et al. 1996). During the late 80s, the introduction of new technologies and philosophies, such as CIM (Computer Integrated Manufacturing), JIT(Just-in-Time) and TQM (Total Quality Management), performance measurement techniques initiated the use of non-financial measures, (Skinner, 1986), short lead times, customer service, flexible capacity, and quality.

As it has been stated in 2.4.3, traditional performance measures are nowadays limited in their applications because of the observed limitations in such areas as providing imperfect signals that problem exists and there is lack of relation with corporate strategy.

However, in order to avoid these pitfalls, new performance frameworks of measurement and integrated performance measurement systems have been developed, section 2.4.4 with the emphasis being placed on non-financial measures in order to gain an overall picture of the company's performance.

Past research indicated that amongst the performance measurement systems outlined above, the balanced scorecard has been widely used and provides an acceptable performance measurement system. Many companies have implemented the balanced scorecard successfully, although some others have failed due to its inability to identify the correct non-financial measures, and other factors that include lack of its inability to link with business objectives. The integrated performance measurements that currently exist have limitations such as their lack of use, as improvement tools, or to control shop floor activities.

Taking into consideration the results of the experiments it can be stated that the problems mentioned in Section 2.4.2, 2.4.3, 2.4.4, have been solved by this research as justified by the following points:

i. The performance metrics provided in Section 2.4.5 can be used as basic metrics for controlling flow lines.

ii. The relationships developed between performance measures in, Section 2.4.6, aids in linking the strategic performance measures with operational level performance metrics.

iii. Cause-and-effect links have been developed between the various Lean enablers and the causes of inefficiencies Section 3.4, to enable areas for improvement to be identified and indicate those lean enabler tools necessary to facilitate these changes to be chosen.

In general sense, this research fills a research gap, since there are no indications of continuous improvements that exist among the performance measurements as pointed out by Ghalayini and Nobble (1996).

The metrics identified are able to form a substantial element of a flow lines performance measurement system. In order to measure the performance of a flow line it was necessary to develop indicators so as to inform the system. By doing so, the management will receive a feedback and be in a position to take actions in order to accomplish the objectives as outlined on a strategic level. As such close loop system can be used that have been described in 2.2.3

A number of hierarchy levels exist between individual performance metrics which is organisation-specific. However, a minimum number of levels would have to include senior management, departmental management and individual or teams of shop floor operators.

In developing the relationship network of “cause-and-effect”, two approaches have been considered i.e.

(1) the strategic level, a top-down approach,
(2) the operational level, a down-top tactic, and then to incorporate the metrics in the corresponding integrated performance system.

This research work selected the top down approach due to the fact that the range of metrics at the strategic level is less than these at the operational level.

Apart from the relationships described in Section 2.4.6, it is necessary to develop the relationships between individual performance metrics as well as the lean enablers that address the improvements of the performance metrics. These relationships are developed and presented in Section 3.4.

Thus it can be possible to develop a performance measurement system that is capable to recognise and improve the mixed model flow lines.

The following figure presents the relationships between cause of inefficiencies and the different level of performance measurement. These are presented more obvious in Appendix C.

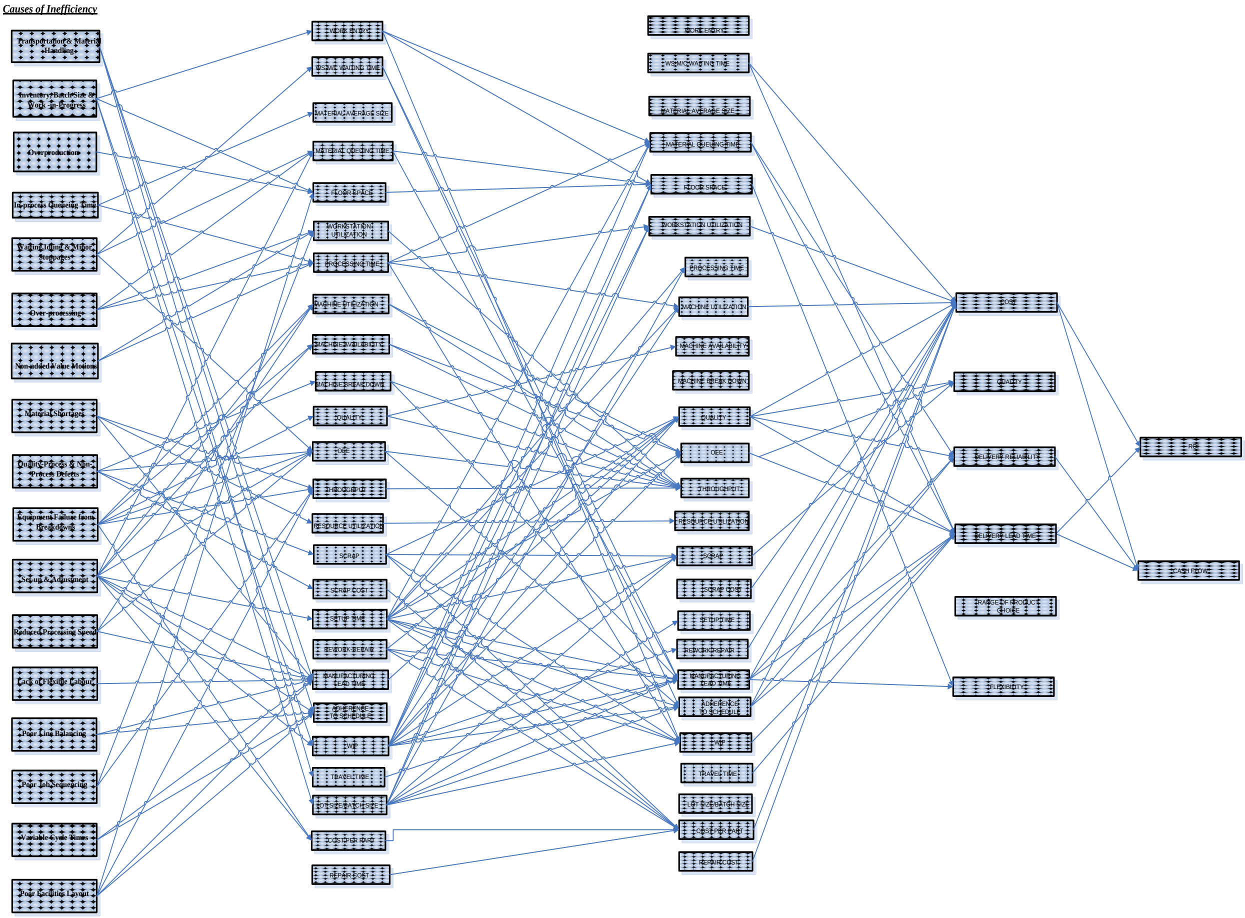


Figure 6.1 Relationships among hierarchical levels

Many relationships have found as indicated from the above results. Moreover a validation of one of the results have been done using the mathematical equation of regression analysis presented in Section 5.4

Important functions involved in the manufacturing systems design of a mixed-model flow line are capacity planning and control and facility layout i.e.

a. Facilities design, i.e. in terms of line balancing and shape of the flow line,
b. Scheduling techniques of mixed-model flow lines, and
c. The use of drum-buffer-rope methods to ensure utilisation of system bottlenecks

In order to achieve the aims of this research, during the manufacturing systems review process, particular attention was placed on identifying the individual performance metrics that are used to design, plan and control the processing capacity of mixed-model flow lines. Categorising the individual performance metrics as identified in Section 2.4.5 and the additional metrics presented in Appendix A, the following generic metrics have been established, i.e.:

a. cost
b. quality
c. delivery reliability
d. delivery lead time
e. range of product choice, and
f. flexibility.

The main characteristics of mixed model flow lines which affect the aforementioned performance metrics include:

a. inventory levels

b. defect levels
c. the ability/inability to adhere to schedules
d. the utilisation of processing equipment
e. the allocation of work to work areas, and
f. the levels of planned maintenance.

In view of the above, many of these characteristics are themselves performance metrics. In this respect performance metrics have been found to be related as follows:

i. Hierarchically, i.e. the outputs of metrics at one level may form the inputs to metrics at the next level up in the hierarchical structure.
ii. Through cause-and-effect relationships, which may exist between performance metrics, e.g. increasing ‘batch sizes’ affects both ‘lead times’ and ‘inventory levels’.
iii. Through the sequence of process activities, e.g. the metric of one process is linked to the metric of process next in the operation sequence, this can link individual metrics.
iv. The existence of planning controls and physical limitations, e.g. if the inventory is not allowed to be build-up through the use of physical constraints, the “inventory” will no longer represent a valid metric. However, the physically constraining inventory can have effects on other metrics such as ‘lead time’ and ‘adherence to schedule’.

The examined performance metrics establish the need for:

i. Adopting a systems approach, i.e. ensuring that the performance metric forms part of a valid performance management system, (Nadler 1970) which includes:

- *Function*: is to provide performance related information that can be used to enable an organisation to identify courses of action in order to achieve specific objectives
- *Inputs*: the data that needs to be collected in order to determine values for the performance measurement indicators
- *Outputs*: is the values of the performance measurement indicators and the method of presenting these values
- *Human factors/agents*: the personnel responsible for the collection of data, analysis of data and communication of performance results
- *Physical catalysts*: the methods used to change input data to output performance values.
- *Sequence*: is the individual stage involved in converting inputs to outputs.
- *Environment*: is the higher level system that the performance measurement system forms part of, i.e. this will respect the overall supply chain, including the manufacturing organisation itself and its customers and suppliers.

ii. Establishing relevant characteristics by which the validity and effectiveness of each part of a performance management system can been identified (Tangen, 2005), and may include amongst others the following characteristics:

- Relevancy
- Time-based
- Enabling of targets to be set
- Problem area(s) identification
- Representation of valid cause-and-effect relationships
- Visual indicators
- User-friendly
- Owned and supported by users
- Enabling the monitoring of activities
- Metrics should be specific, measurable and attainable
- The implied equation(s) should be easily measured and understood
- Objective criteria should be used in the formulae rather than subjective

- Ratios should be used instead of absolute numbers
- The formula should stimulate improvement and should be designed in such a manner so as to facilitate a continuous performance measurement of the people involved
- The formula should be as accurate as possible and incorporate a high precision level
- Group measures should be used rather than measures based on individual performance

iii. Suitable methods for linking operational level performance metrics with those used at strategic levels.

This method developed has satisfied all the above conditions in order to have an integrated performance measurement system that improves mixed model flow line efficiencies.

6.3 Experimental results

So far, the research work has discussed the importance of performance metrics in the design, planning and control of manufacturing systems. In particular, their significance has been documented in mixed-model flow lines, as well as in the lean enablers for improving overall operational efficiency.

The experiments presented in Section 5.1 were carried out in order to validate the relationship among metrics observed. The approach has been described in Section 4.2 and the results have been outlined in Section 5.2.

Taguchi experimentations were carried out in order to validate the relationships found.

Correlation analysis was used in order to confirm the relationships presented in Section 5.2 and also, information about regression analysis has been presented in Appendix B. In accordance to experimental results as have been presented in page 103, some more observations presented in the following paragraphs:

The evaluation of the results obtained indicates that ‘the total lead time’ is strongly affected by workstation ‘% non zero time’, at the ‘marking’ workstation, Figure 5.19. The second important relationship occurs between workstation ‘working’ and ‘set-up time’ at the ‘primer’ workstation, Figure 5.33 ie. as the set-up time is increased, the workstation working is decreased.

Four workstations were taken into consideration at different positions in the flow line with each having different influences on the production line efficiency. The first station was selected because of its high utilisation (Deburr) and is located at the beginning of the line. The second station with a lower utilisation (marking-station) is located at the middle of the line. The third station with a high level of WIP (primer-station) is positioned one place before the end. Last in the line is the ‘painting’ station.

There are three levels of metrics used within the flow line with level one being at machine level and include metrics such as, input parts, operation time, set-up time, quality and mean time to repair. The second level is associated with the metrics that measure the workstation contribution to flow line efficiency and include workstation throughput, workstation percentage of non-zero parts, and workstation working time. The third level is the system’s level, which includes total throughput and total lead time.

The results of the experiments show that the metrics ‘set-up time’, ‘input parts’, and the ‘quality of the first station’ have no effect on stations’ throughput and working time. However, ‘processing time’ does have an influence in the throughput and working time. This can be seen in the relationships presented in Section 5.2.

The second station has the same effect. However, the relationship appears to be a little lower as opposed to the first station.

Some effects start from the station just before the end, where set-up times seem to indicate a stronger relationship with the metrics at the workstation level. By observing the Figure 5.44 it can be seen that the last station has a stronger relationship in ‘quality’ and the one before the end a stronger relationship in ‘set up time’.

The relationships amongst indicators show that these seem to have a form of causation. Causation is defined as the cause-and-effect relationship. Kai Yang, Jayant Trewn (2004) claim that the existence of a cause-and-effect relationship of two variables requires the following:

1. the existence of sufficient degree of correlation between two variables
2. that one variable occurs before the other
3. that one variable is clearly the outcome of the other
4. that there are no other reasonable causes for the outcome

In view of the above, the processing time has a sufficient degree of correlation with Lead Time and it occurs after the process time. In this respect, set-up time and processing time cause changes to the Lead Time and the Throughput levels.

Comparing each station’s results against the final workstation, (Table 5.17, Table 5.18, Table 5.19) it can be seen that the stations situated at the beginning of the line does not have any effect on the last station. However, the station positioned before the last station plays a significant role. This is associated with the decision required concerning the improvement levels necessary at different workstations. Moreover, performed analysis indicates that at two adjacent stations, the first appears to influence the second one.

Taking into consideration the results of the experiments and the relationships that have been found among several metrics, a concept of controlling the efficiency and effectiveness of a mixed model flow line can thus be established.

Detecting problem-specific areas, a range of performance metrics can be used. These indicators do not convey any message until goals have been set. As Locke and Latham (2002) claim, "*goal setting and feedback have been proven to improve productivity*." Hence, a target has been set in order to compare the performance metrics with them such as Lead Time less than 8000min and throughput 85 shop orders.

At a strategic level, the company was aiming at competing on a Delivery Lead Time. This implies reducing current lead times of the flow line from 9000 minute(s) to less than 8000 minute(s), i.e. the latter of which coincides with set target values.

The targets that have been established by the production control manager, to reduce lead times, have been accomplished using the proposed methodology. This can be found in Section 5.4 where a new experiment was carried out in order to validate the relationships. The validation results have illustrated that the objective of reducing the lead time has been achieved.

The aforementioned target should be communicated to the tactical level. It shows that the lead time has a relationship with the operational level as mentioned herein. Equally, a target has been set in each workstation in order to identify stations with inefficiencies. This work has used as an example the primer station and analysed it.

Once a station appears to have a problem, e.g. long lead time, the next step is to consult the correlation analysis in Figure 5.40. This shows that lead time has a negative relationship with workstation throughput (-0.62). This in turn, means that to reduce the lead time the throughput must be increased.

A strong negative relationship also exists between Workstation throughput and processing time (-0.95) Figure 5.31. This means that workstation throughput can be increased by reducing the processing time.

Practical implications dictate the necessity of reducing the Total Lead Time by looking at a workstation’s process variability, the latter of which is the cause of inefficiency.

In view of the above, the process variability would need to be reduced. In Section 3.4 it was that development of the relationships was undertaken between lean enablers and the causes of inefficiencies. The latter exist in the mixed flow lines and is presented in Table 3.3. Lean enablers can help to reduce or to eliminate the causes of inefficiencies apparent in mixed model flow lines.

As process variability has been identified as a main cause of constraints, this need to be removed. In order to reduce process variability, Table 3.3 should be used. This table, which has been developed by lean enablers and the cause of inefficiencies depicts that the following Lean enablers can be used. These are:

- the implementation of planned maintenance TPM,
- the application of a Kanban control system, and
- the operation of a mistake proofing system.

With this method presented a link has been established between the upper and lower level of management using the metrics hierarchy developed which provides possible solutions for improving the efficiency of mixed model flow lines. Hence, this methodology can be applied either in an existing aero structural production line or to new production flow lines. Generally, because this method uses non-financial indicators, it can be applied in most production lines that make use of synchronous flow systems such Just in Time. The outputs of this research can be applied to different industrial sectors where discrete manufacturing goods are produced, i.e. automotive industry, electronics, appliances, computer parts assembly, in motorcycles and scooters, air-conditioning systems for cars and bicycle components, in building airplanes etc.

Chapter 7 Conclusion

Changes in the manufacturing environment, arising from the advent of global competition, mass customisation, and greater product choice as well as continuing importance of maintaining high levels of cost, quality and delivery performance, have placed emphasis on the use of highly efficient mixed-model flow processing lines. These demands have meant that the operational efficiency of mixed-model flow lines must be radically improved through improved design, planning and control and the rigorous use of lean practices. In this respect this research has:

1. Identified the individual performance metrics specifically applicable to designing, planning and controlling flow processing lines at an operational level as well as those performance metrics that can translate operational performance up to an organisations tactical and strategic management and control levels.
2. Developed a hierarchical model of the relationships between performance metrics at operational, tactical and strategic levels.
3. Quantified and/or confirmed the relationships within this hierarchical model.
4. Identified the relationships between the basic causes of operational inefficiencies within mixed-model flow lines and the performance metrics specifically used within such flow lines.
5. Identified the relationships between the basic causes of operational inefficiencies within mixed-model flow lines and the process and system based ‘lean enablers’ that are available to address them.
6. The tables linking (i) performance metrics with performance metrics, (ii) performance metrics and causes of inefficiencies and (iii) causes of

inefficiencies and lean enablers, and (iv) the diagram showing the hierarchical relationships between performance metrics provide tools for both integrating the operational, tactical and strategic management of a mixed-model flow line as well as tools for identifying which lean enablers should be used to improve specific inefficiencies as monitored using one or more performance metrics.

Concluding, this research achieved to connect the three level of management confirming or developing the necessary metrics’ relationships and managed to join the operational level metrics with the causes of inefficiencies in a mixed model flow lines. Moreover, this research achieved the connection between the causes of inefficiencies and the lean tools and techniques, ensuring continuous improvement of the system.

Chapter 8 Further Work

The work has highlighted several areas for further research:

1. More detailed investigations need to be undertaken with regard to the performance metrics that measure the 'agility' of a manufacturing system and how such agility affects tactical and strategic business performance. This will require developing suitable performance metrics for measuring the 'Adaptiveness' and 'Flexibility' of mixed-model flow lines and identifying their relationships with existing performance metrics that measure the responsiveness, capability and reliability of such lines.

2. Investigations need to be undertaken to identify how generic the performance metrics are to wider ranges of manufacturing system types, including non-flow processing systems and mixed-model lines with higher levels of product and process variety.

3. The application of the tools within non-manufacturing environments, where the emphasis is on transactional processing and/or provision of services could be possible. However, a more detailed gap analysis would need to be undertaken to identify how any additional performance metrics that need to be developed and linked to causes of inefficiencies and lean enablers.

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APPENDIX A PERFORMANCE METRICS

Ability to perform multiple tasks efficiently
Absenteeism
Accuracy of cost estimating
Achieve quality
Achieve statistical process control
Achieve target product factory costs
Actual v allocated process times (minutes)
Adherence to schedule
Assembly line defects per 100 units
Audit deficiencies
availability of skills and tools
Average delay
Average time between innovations
Breakeven time
Capital productivity
Cash generated increase (%)
Cell audits
Company morale and satisfaction
Compare with standard costs
Concessions (ppm)
Cost of failures (% of sales)
Cost of production per day
Cost of quality
Cost Per Unit
Cost reduction improvements (time to achieve improvements)
Cost relative to competitors
Cost savings
Cp/ CpK – component manufacture
Customer satisfaction
Cycle time (make time/total time)
Cycle times
Decision cycle time
Defect level as perceived and measured by customers
Design cost
Development adherence to schedule (average days slip)
Development time for new products
Direct labour
Direct labour as a % of sales
Direct material as a % of sales
Disruption caused by breakdowns
Distance travelled
Distribution cost

Drawings returned to planning
Due date adherence
early and sufficient project team involvement.
Economic value added
Employee awards/rewards
Enquiry and order build-ups
Expected product life
Extent to which cost is unaffected by mix/volume changes
Extent to which delivery performance is unaffected by mix/volume changes
Extent to which quality is unaffected by mix/volume changes
External failures (% of sales)
Factory loading
Factory margin increase (%)
Field failure (per cent)
Field performance, returns and complaints
Flexibility relative to competitors
floor space
Growth in market share
How quickly plant responds to product mix changes
How well plant adapts to volume changes
Increase in sales (%)
Increase in weekly capacity
Indirect labour
Inventory accuracy (%)
Inventory levels
Inventory turns
Inventory turns increase (%)
Inventory value (£)
Is there/ was there a good product plan?
Is there/was there a rugged marketing and product strategy
JIT performance
Job classification
Labour efficiency
Labour productivity
Lapse rate, renewal rate, retention rate
Lead time
Lead time improvements (%)
Lead/ throughput times (days)
Lot size
Lot sizes Production run time between set-ups
machine availability
Machine down time Number of hours machines are standing due to
Machine productivity
Machine utilization

Malfunction in relation to total machine time
Manufacturing cost
Manufacturing hours – final assembly
Manufacturing improvement team initiatives completed %
Margin improvement (Gross margin % increase per annum)
Material handling cost
Material handling time(moving)
Material queueing time
Material throughput time
Material waiting time
Mean time between failures (MTBF)
Milestone achievement (days late or early)
Milestones achieved in CI activities (e.g. number of people trained)
New product introduction versus competition
New product lead time reduction
No. of certified skills per person
No. of defects per unit
No. of problems tracked and solved by SPC
Non-conformance reports
Number of changes in projects
Number of complaints
Number of part types process simultaneously
number of parts in queue
number of suppliers
On-time delivery (0 days late, 3 days early)
Order processing time
Overall equipment effectiveness (%)
Overdues (£)
Overhead
Overtime
Paperwork throughput time
Pass rate
Perceived flexibility
Perceived relative cost performance
Perceived relative product flexibility
Perceived relative quality performance
Perceived relative reliability
Perceived relative volume flexibility
Percentage average set-up time improvement per product line
Percentage change of order without lead time change
Percentage conform to targets
Percentage decrease in number of bottleneck workcenters
Percentage defect reduction
Percentage first competitor to market

Percentage improvement in labour/desired labour
Percentage improvement in output/desired output
Percentage increase in average number of direct labour skills
Percentage increase in average number of set-ups per day
Percentage increase in multipurpose equipment
Percentage increase in portion of delivery promises met
Percentage inventory turnover increase
Percentage multipurpose equipment
Percentage of inspection operations eliminated
Percentage of orders with incorrect amount
Percentage of slack time for equipment, labour, etc.
Percentage of surveyed customers satisfied
Percentage on-time delivery
Percentage on-time for rush jobs
Percentage product returns or warranty claims reduction
Percentage products using pull system
Percentage programmable equipment
Percentage reduction in employee turnover
Percentage reduction in lead time per product line
Percentage reduction in purchasing lead time
Percentage reduction in time between defect detection and correction
Percentage reduction in total number of data transactions per product
Percentage scrap value reduction
Percentage supplier reduction
Percentage unscheduled downtime reduction
Percentage with no repair work
Percentage workforce cross-trained
Percentage workforce doing more than one job per month
pressure – overtime/night/weekend/holiday
Process flexibility relative to competitors
Processing time
Product reliability
Product reliability relative to competitors
Production capacity per month
Production/ manufacturing efficiency (actual hours v standard/planned hours)
Productivity
Productivity increase (%)
Project delivery achievement (days late or early)
Quality audits on key suppliers
Quality rate
Quality relative to competitors
Ramp up
Ratio of non-value added to value added activities
Raw material cost

Reduction in batch sizes
Reduction in consumable tooling costs
Reduction in defects
Reduction in inspection time
Reduction in inventory levels
Reduction in production project management time
Labour cost
Relative R&D expenditure
Reliability relative to competitors
Repairmen per assembly line direct labourer
Repeat concessions
Reputation
resources for critical path tasks
Response time
Return on capital employed
Returned equipment (ppm)
rework & repair rate
Rework Value of rework in relation to sales
Rework%
Repair cost
Right first time (%)
ROI, ROA, ROS (for the product)
Sales per employee
Sales turnover
Sales/ clocked hours (£/hr)
Satisfaction of the suppliers
Schedule adherence % (to customer specified target)
Schedule attainment
Scrap and rework (£/%/no. of items)
scrap cost
scrap rate
Scrap Value of scrap in relation to sales
Service call rate
Set-up time reduction
Set-up time
Set-up times Amount of time needed for die changes
Shortages
Smallest economical volume
Staff turnover
Supplier performance
Supplier quality levels
Throughput rate
Time from customer’s recognition of need to delivery
Time from idea to market

Time lag between market readiness (ordemand) and product availability
Time lost due to accidents
Time lost due to less than 100 per cent
Time lost waiting for decisions
Time to break even
Time to market
Time to replace tools, change tools, assemble or move fixtures
Time to Yield
Total cost per part
Total distance travelled
Total lead time
Total manufactruring lead-time
Total product cost as a function of lead time
Total work in progress
Trend analysis of repeat problems
Unscheduled downtime reduction %
Up-time percentage
Use of pull systems: number of kanban links to customers/ suppliers
Value added as per cent of total elapsed time
Value added time v standard time
Value of returned merchandise
value-added as % of total elapsed time
Vendor lead time
Vendor quality
Vendor rating
WIP (work on station/total)
WIP levels
work entry rate
Work in progress Value of work in progress in relation to sales
workforce cross-trained %
workstation utilization

APPENDIX B REGRESSION ANALYSIS

Deburr Workstation Results

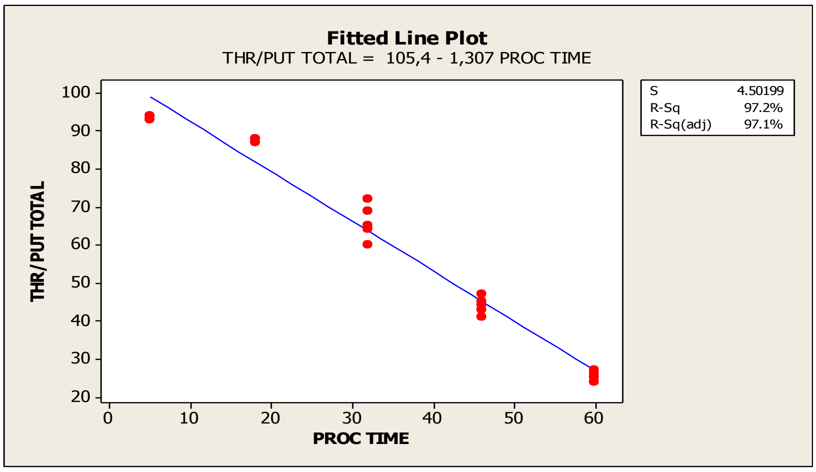
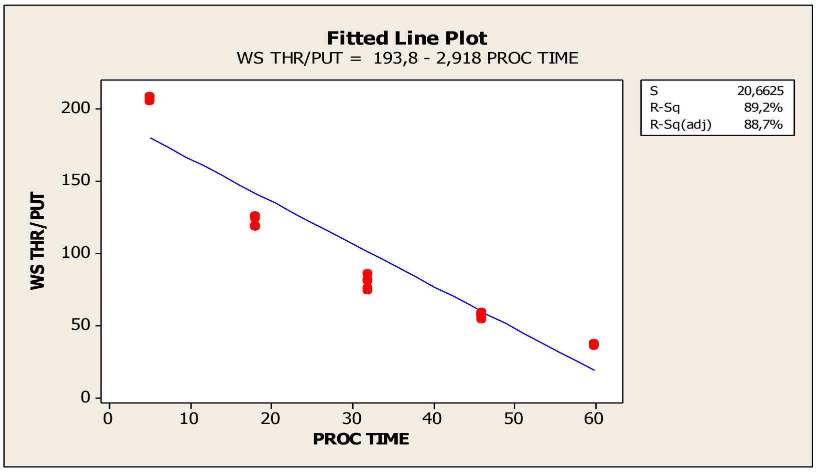


Figure 1



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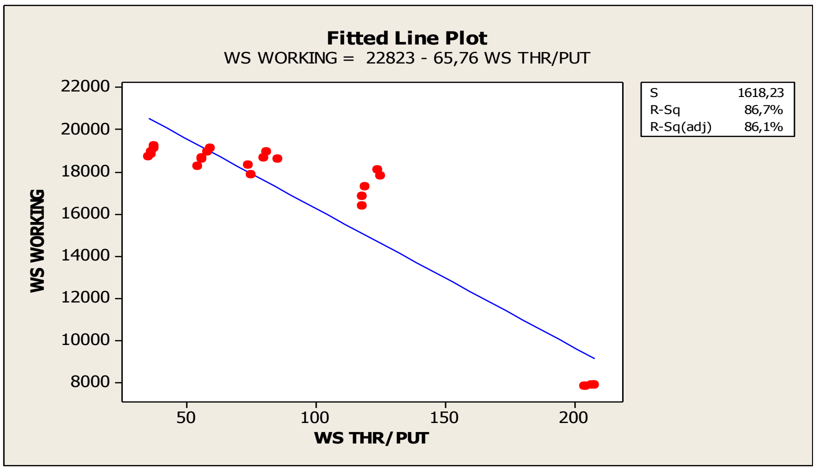

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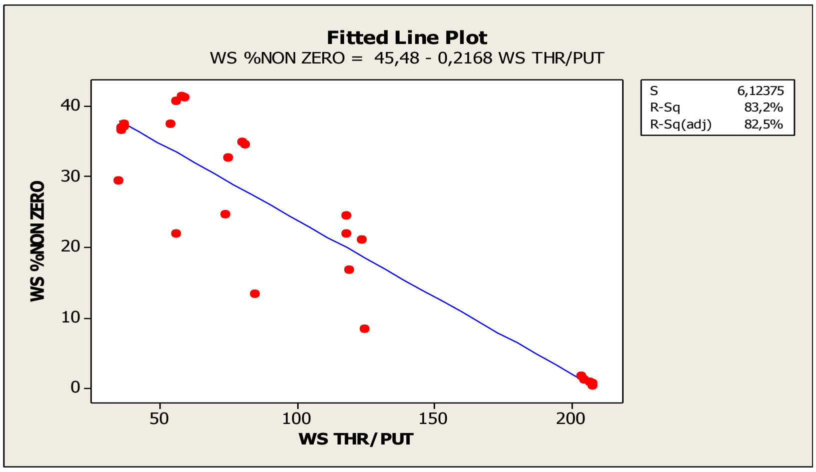


Figure 4

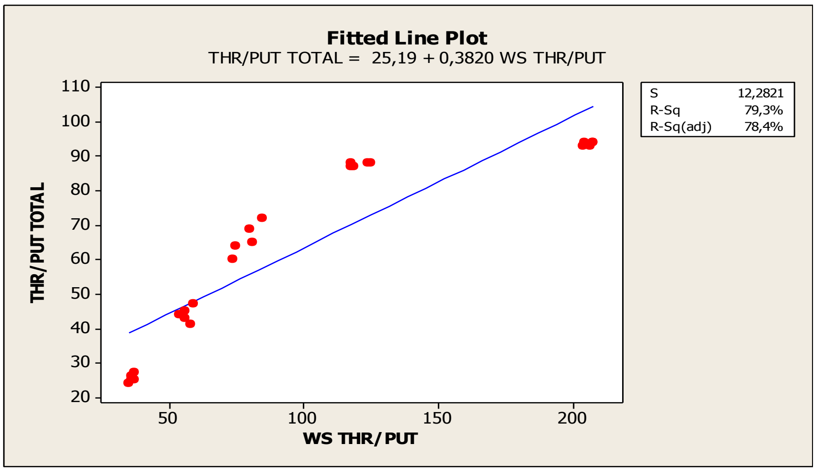


Figure 5

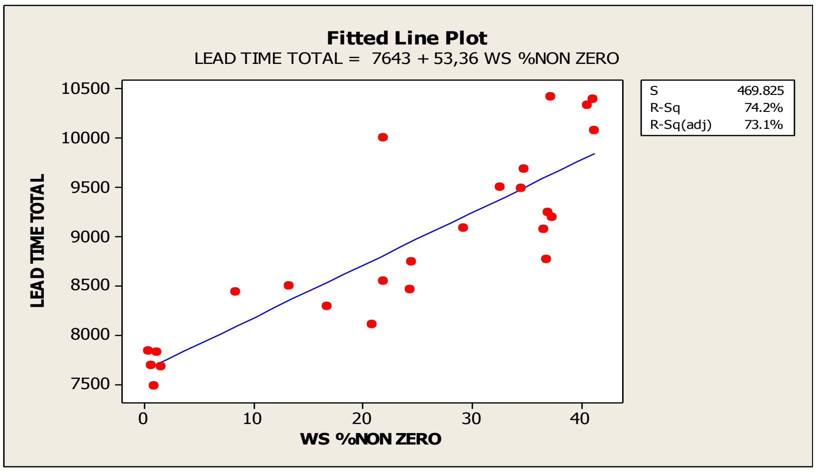


Figure 6

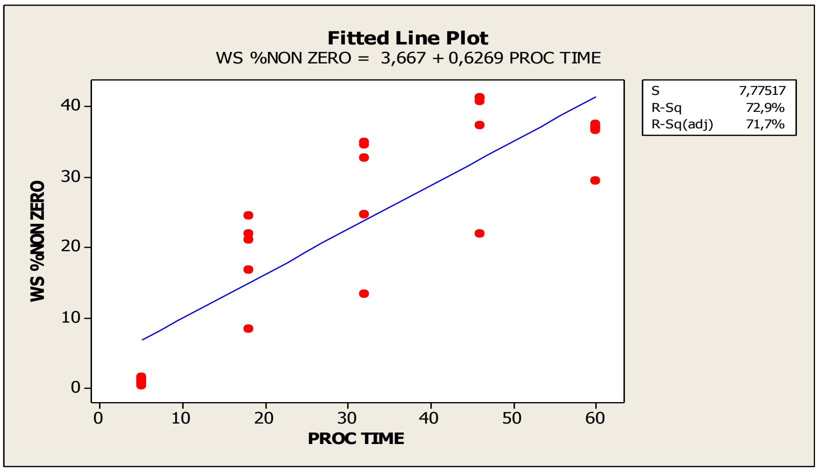


Figure 7

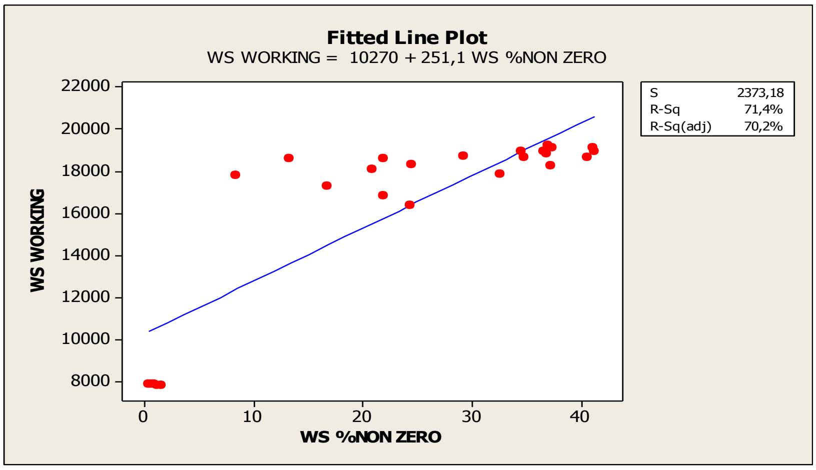


Figure 8

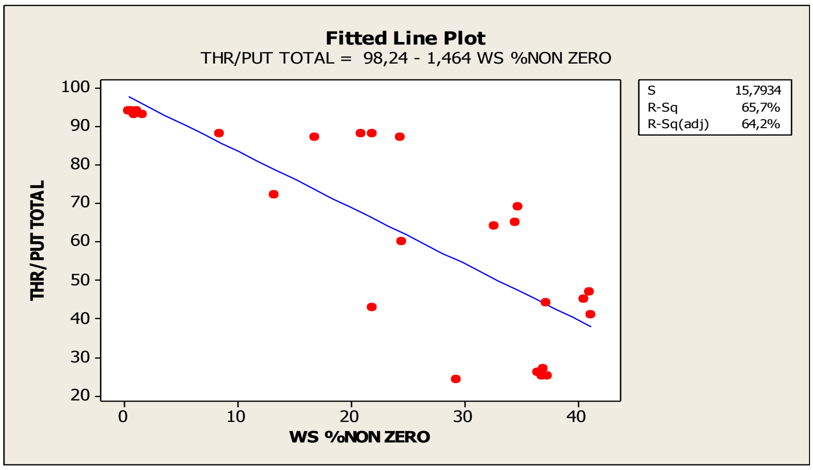


Figure 9

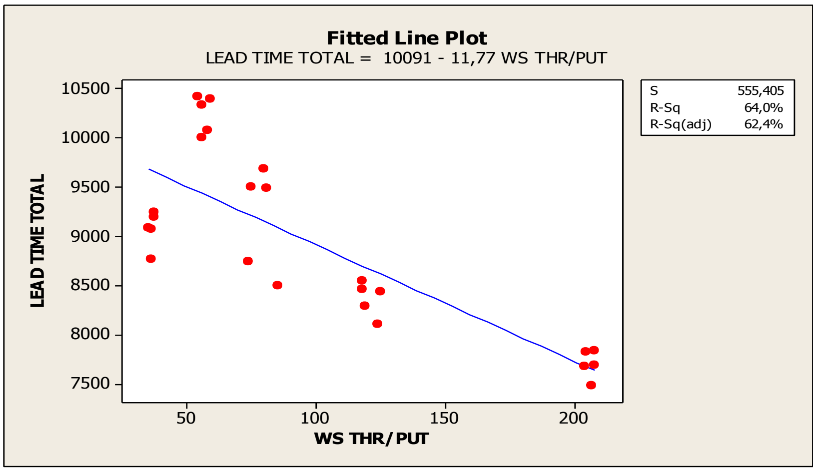
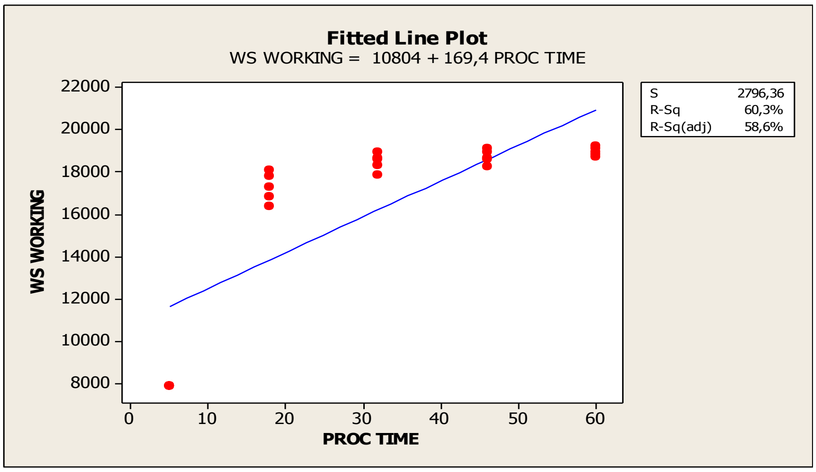


Figure 10



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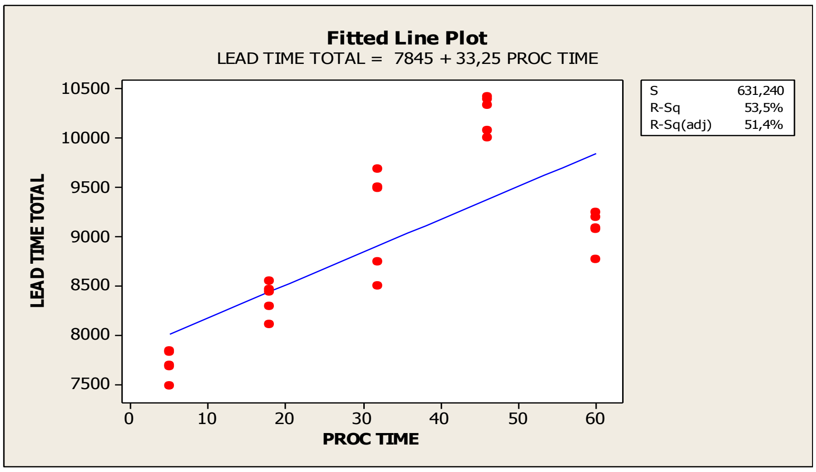
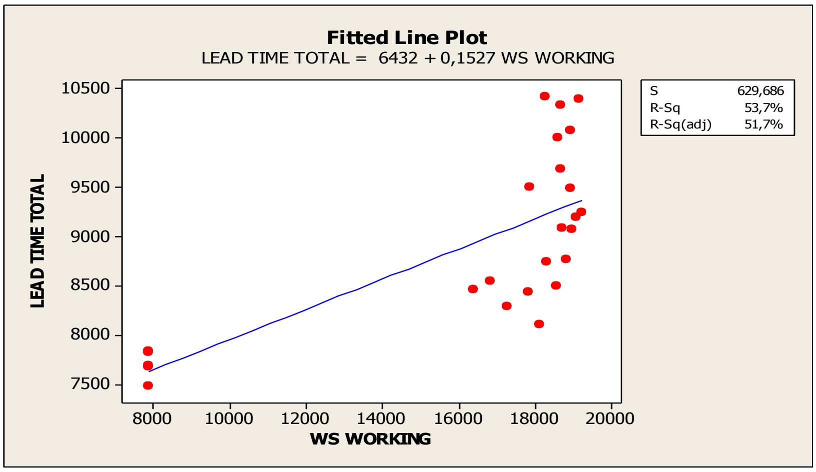


Figure 12



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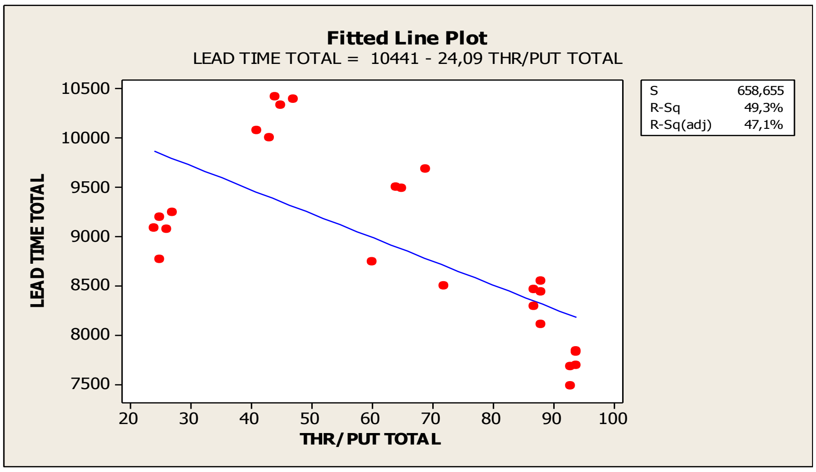

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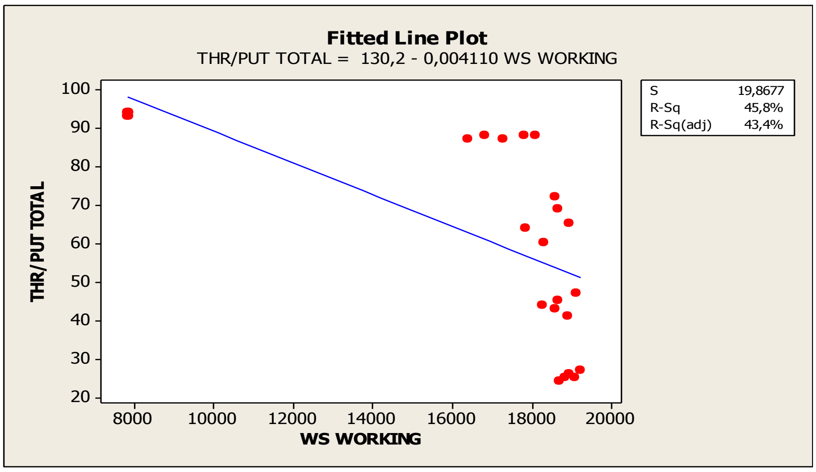
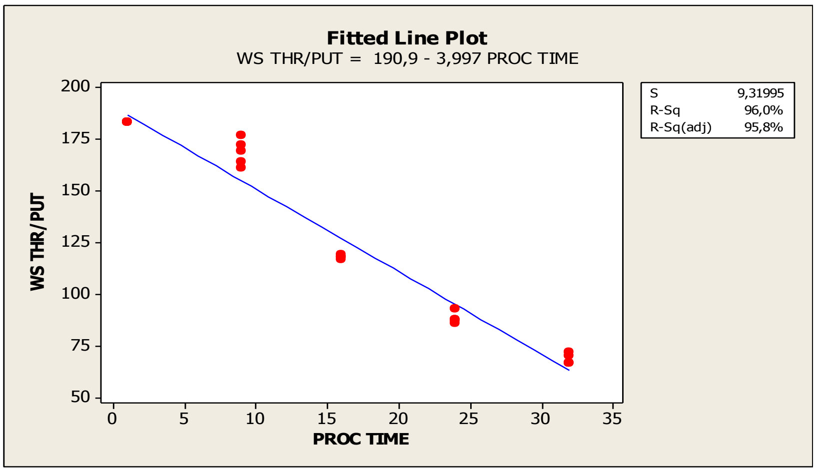


Figure 15

Marking workstation Results



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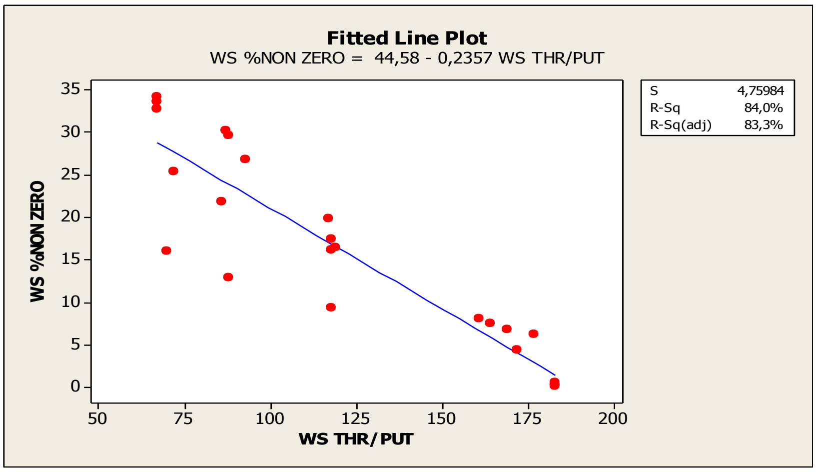

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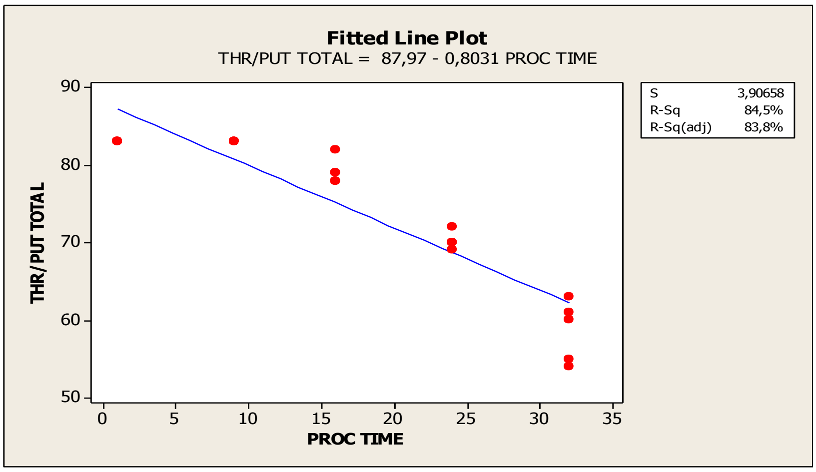

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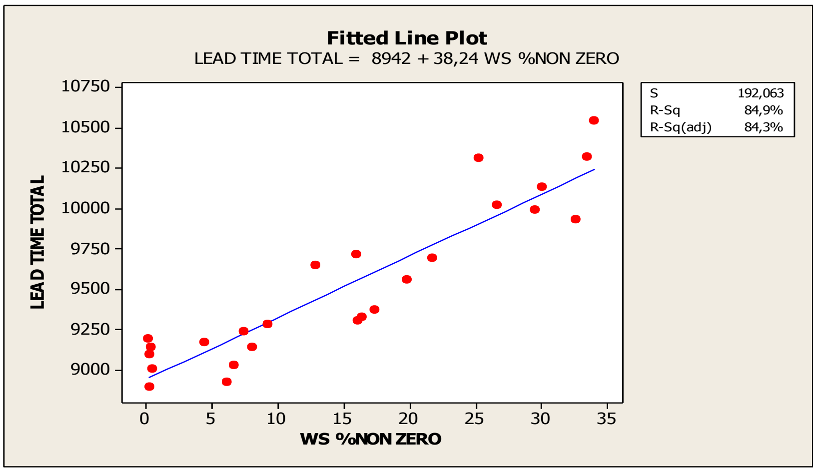

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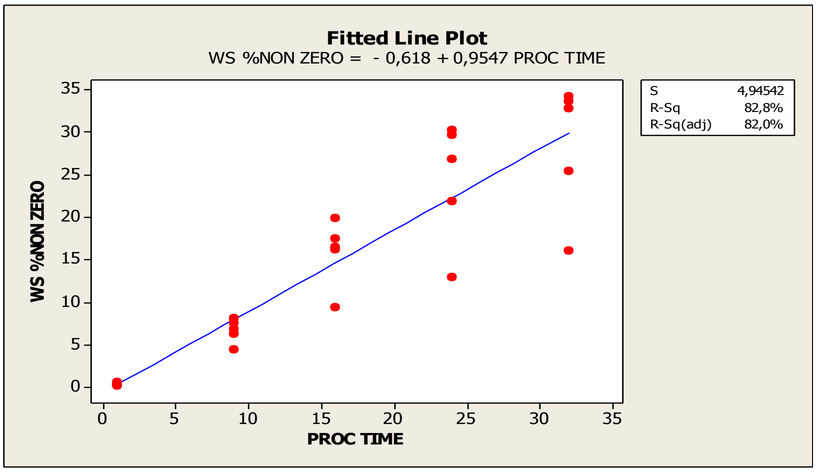

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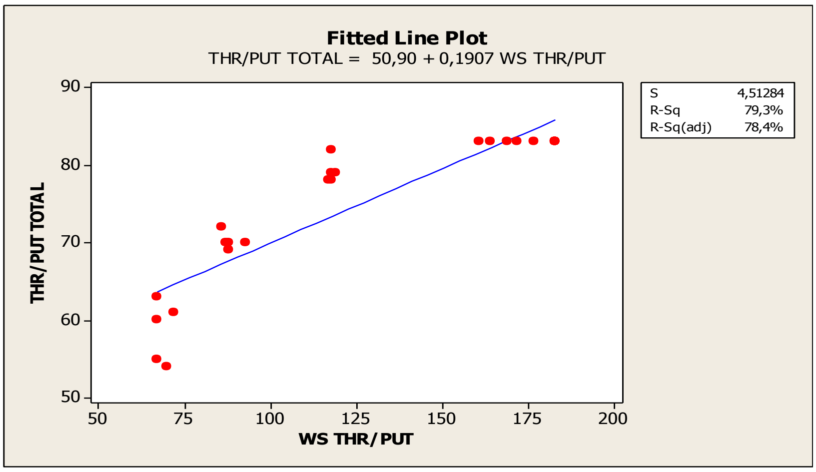

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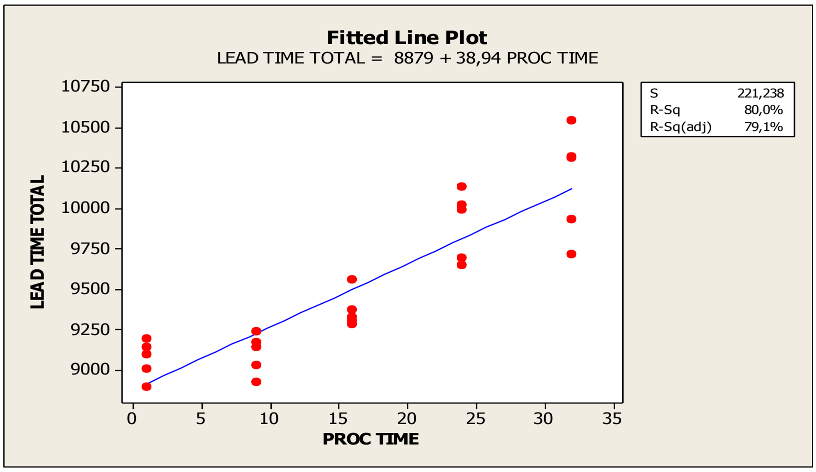

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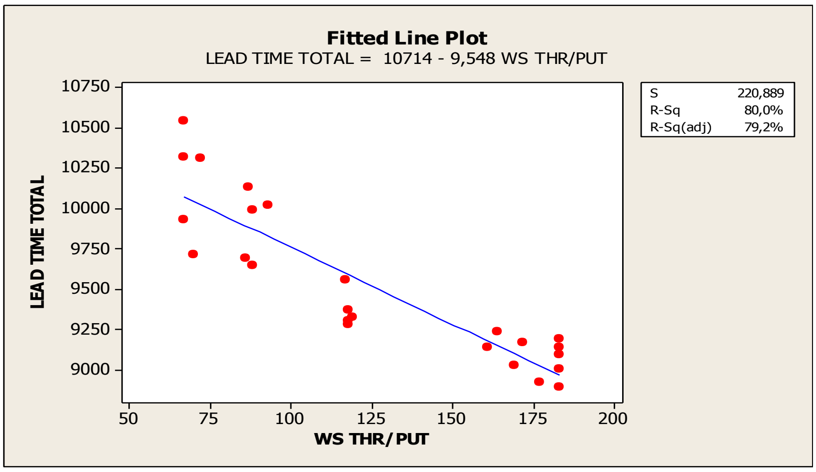

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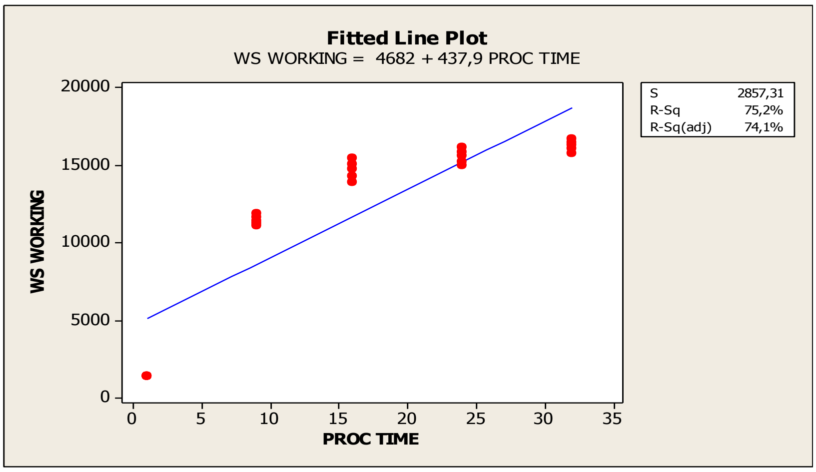

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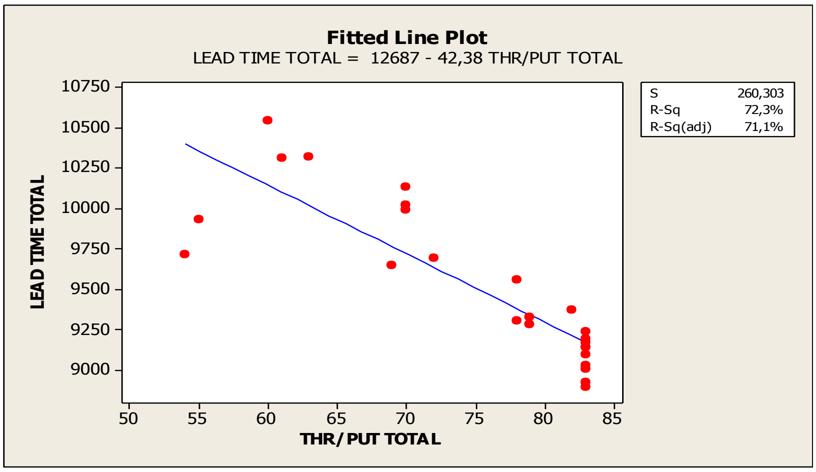

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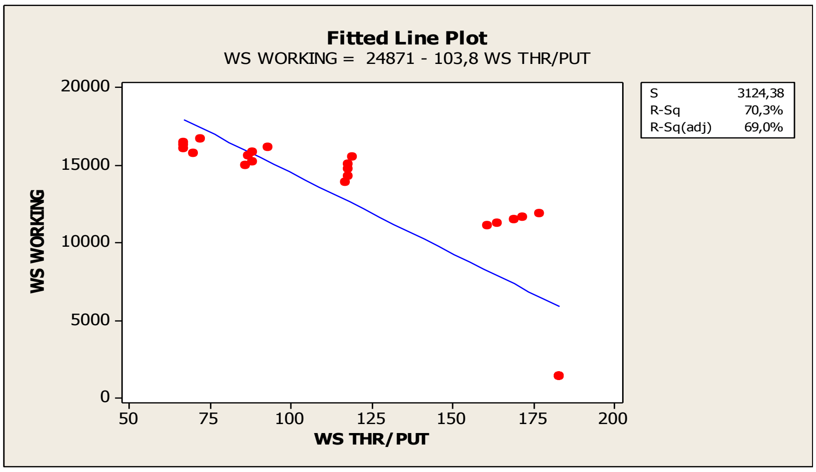

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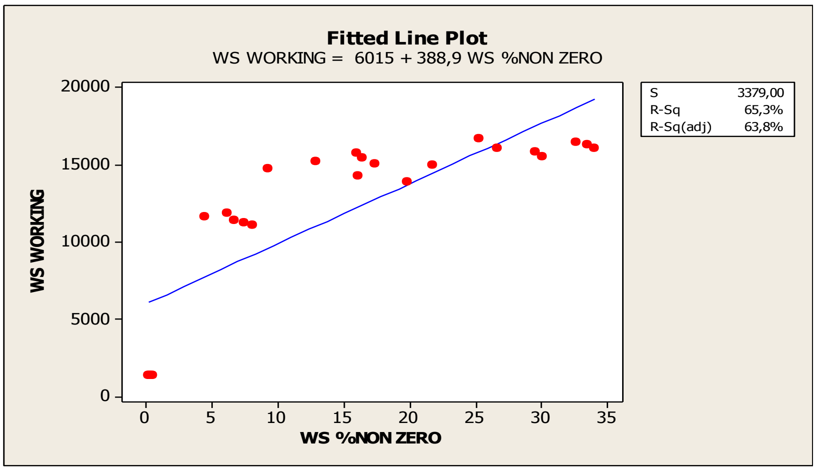

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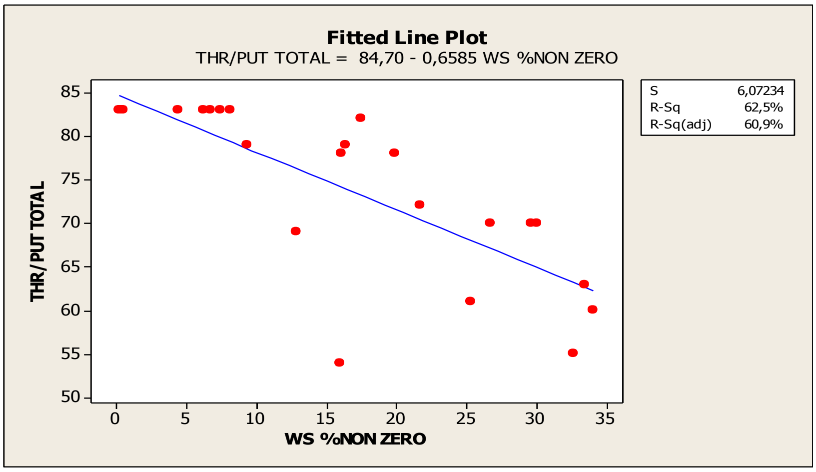

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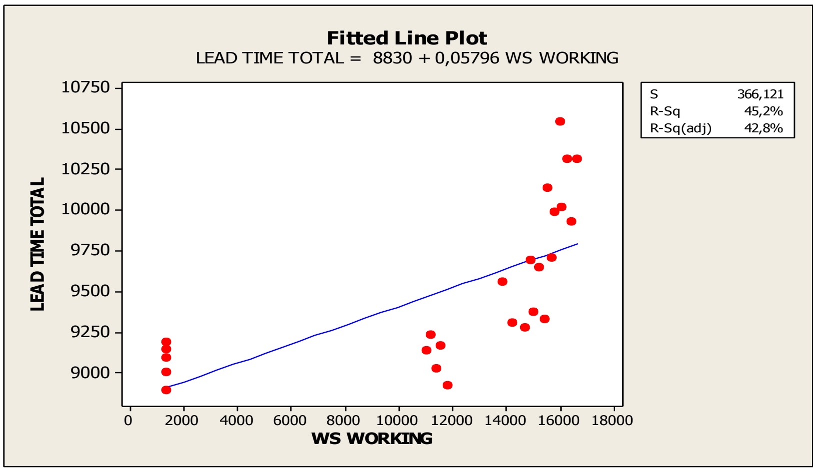
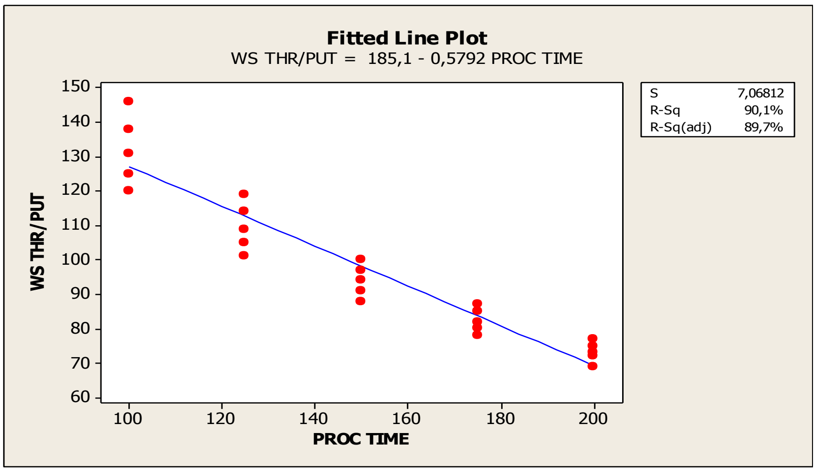


Figure 29

Primer workstation Results



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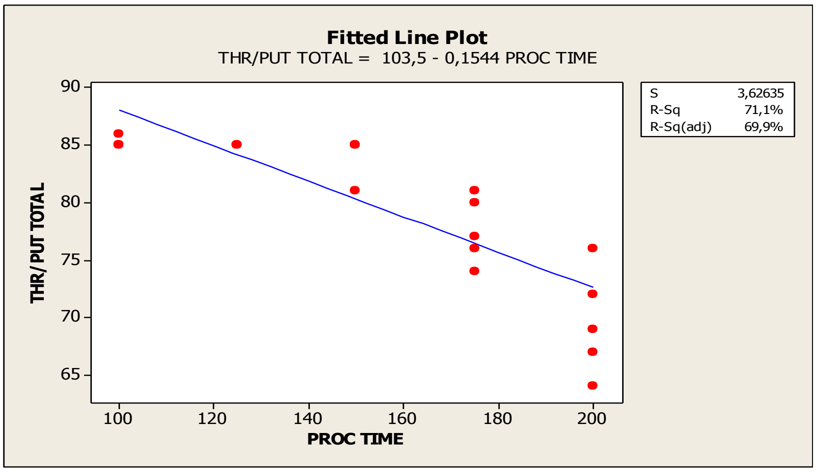

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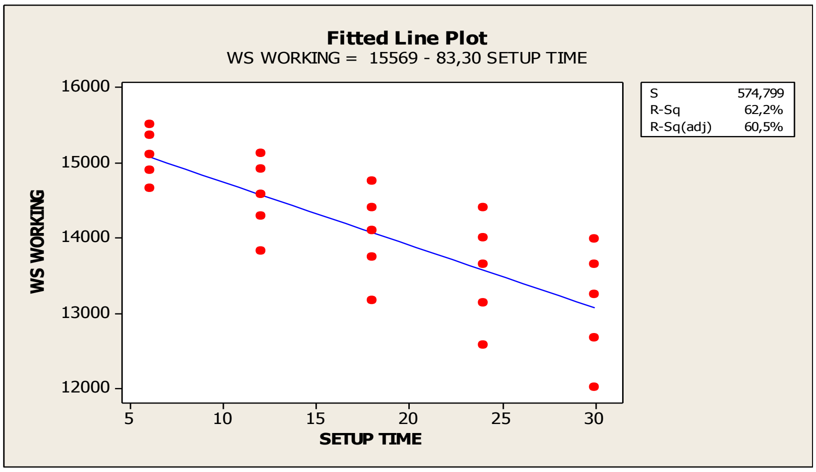

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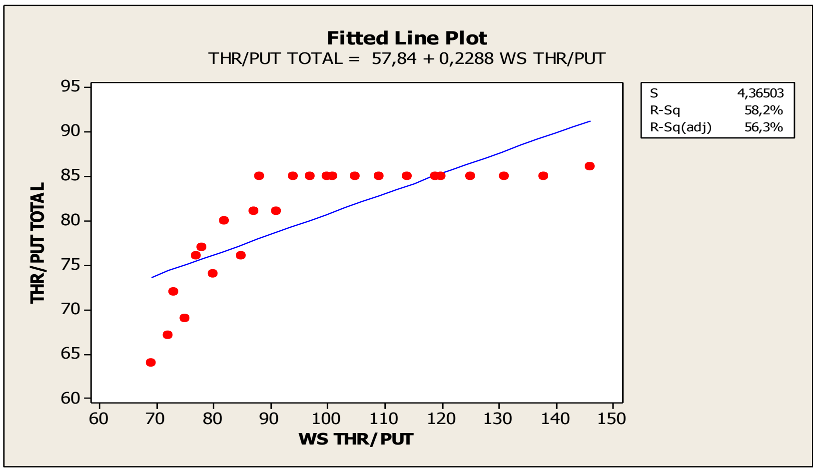

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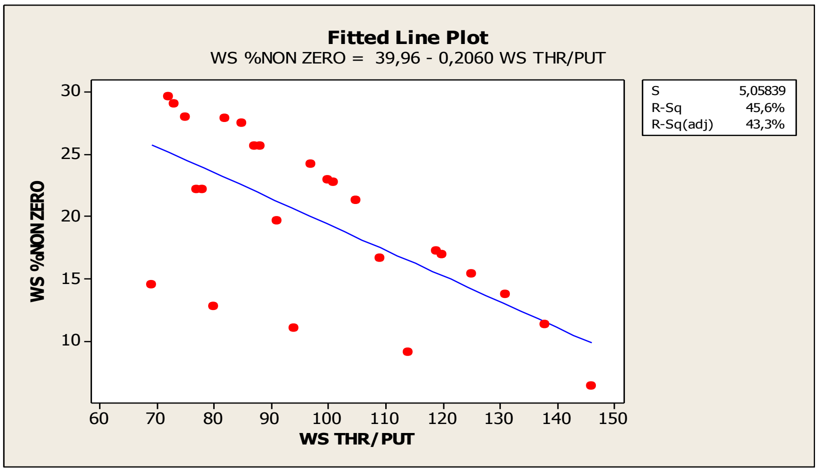

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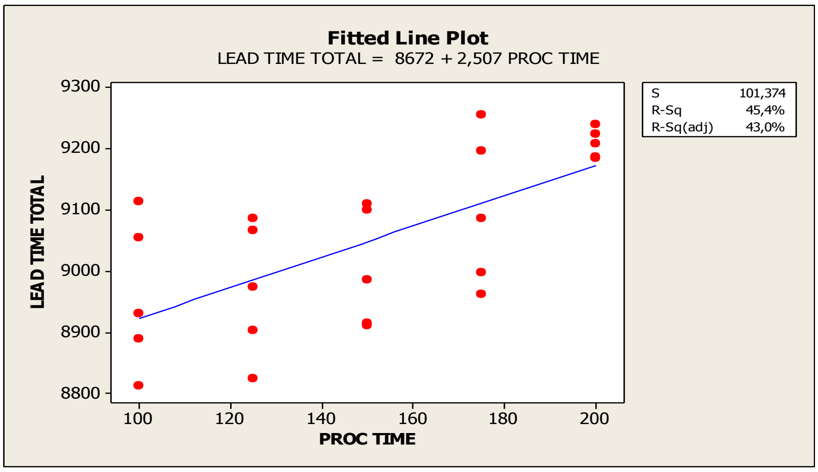

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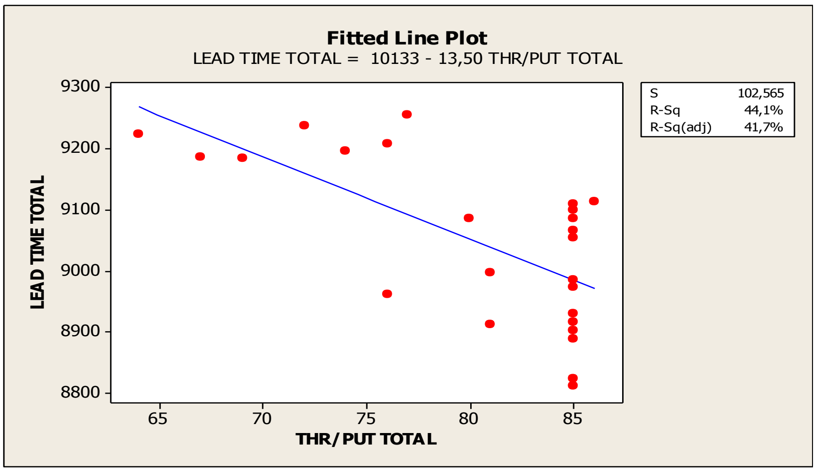

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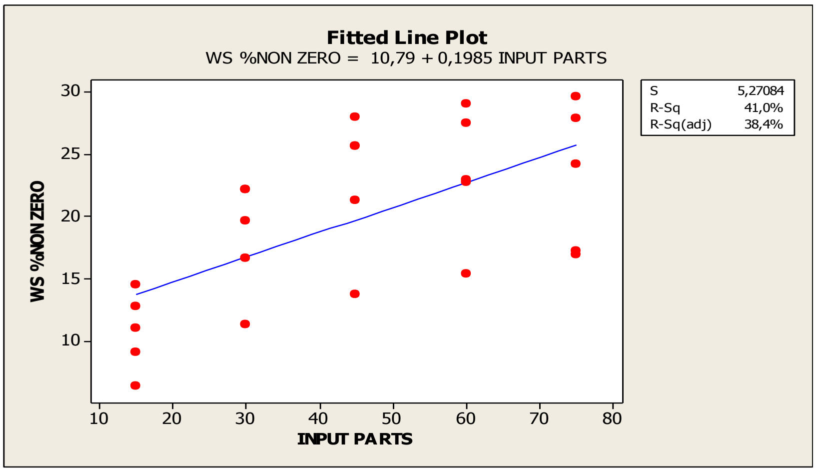

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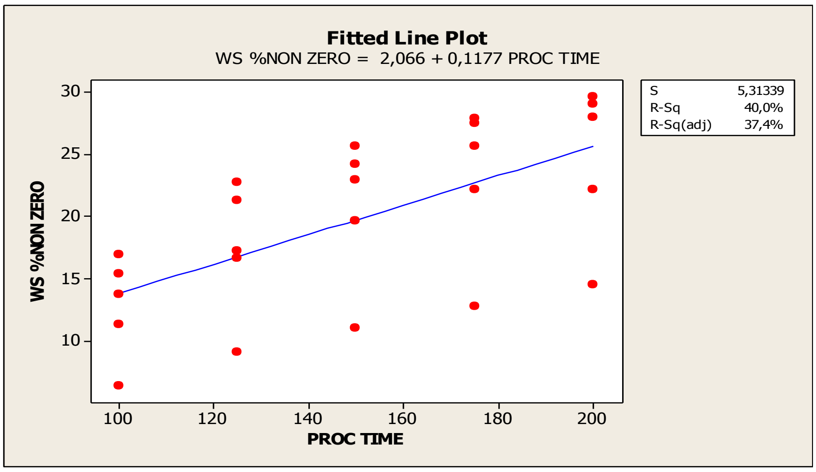

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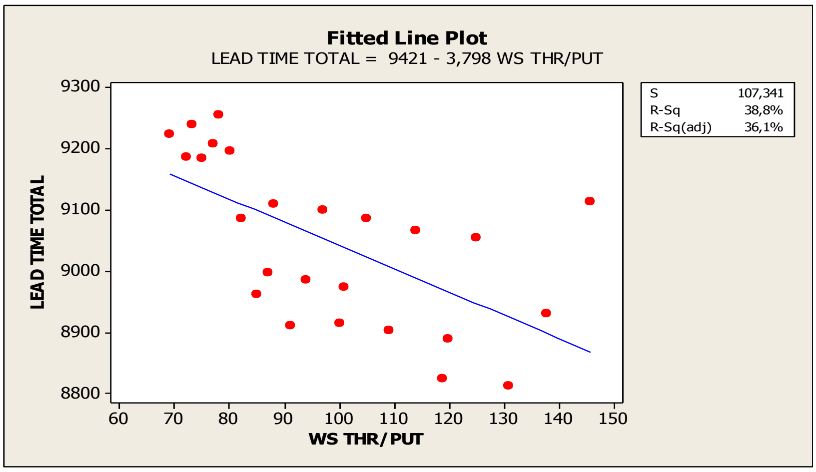

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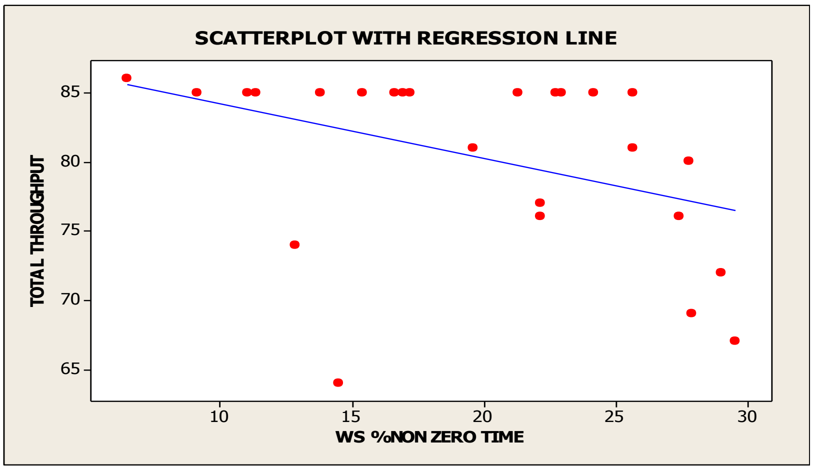

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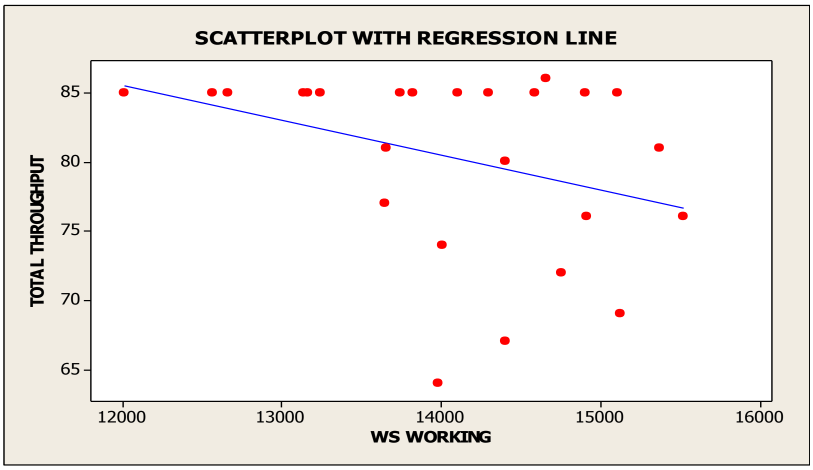

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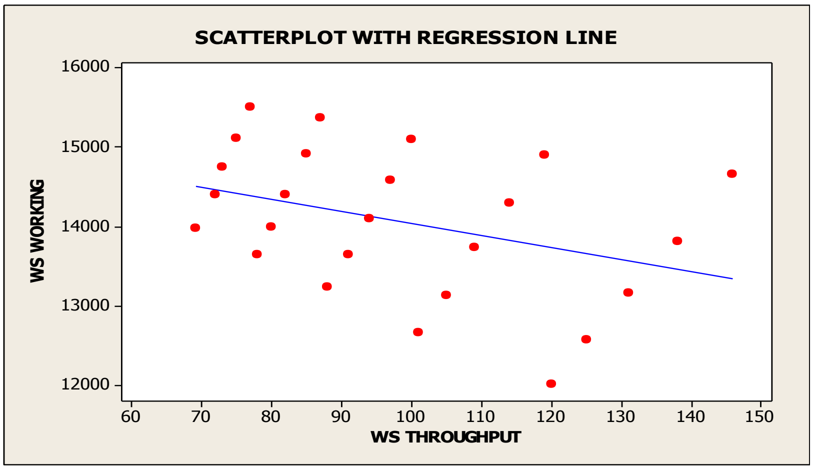

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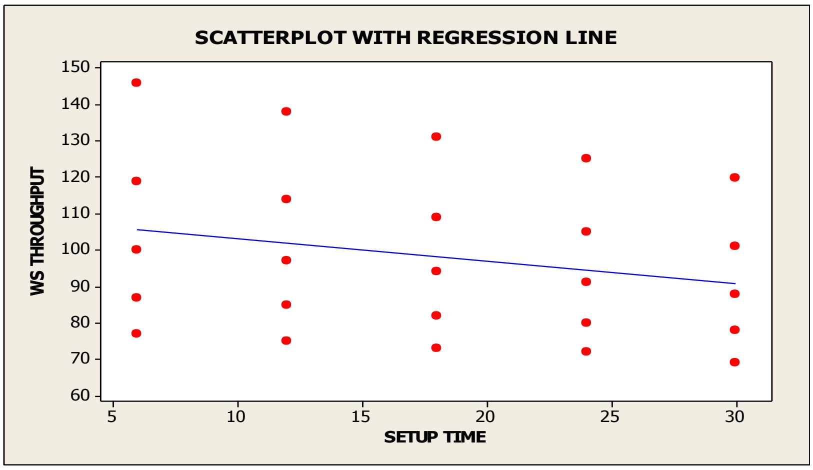
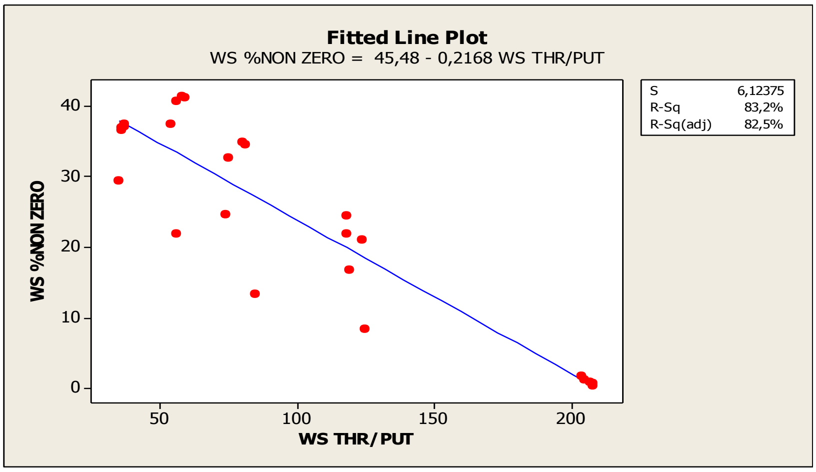


Figure 43

Painting Workstation Results



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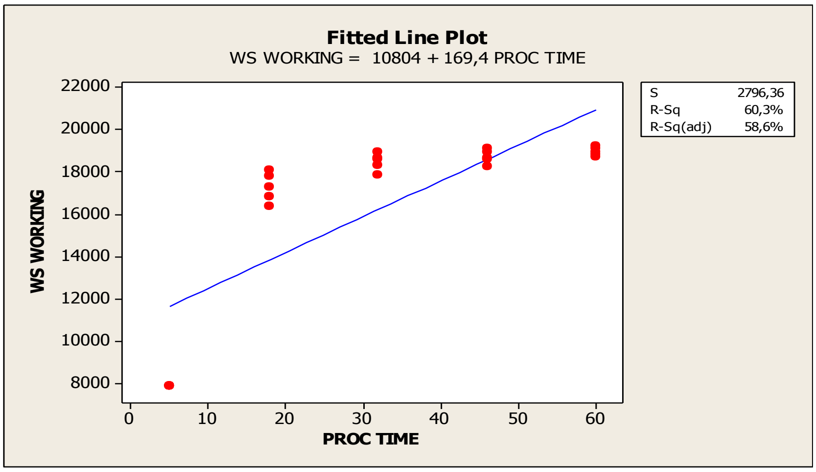

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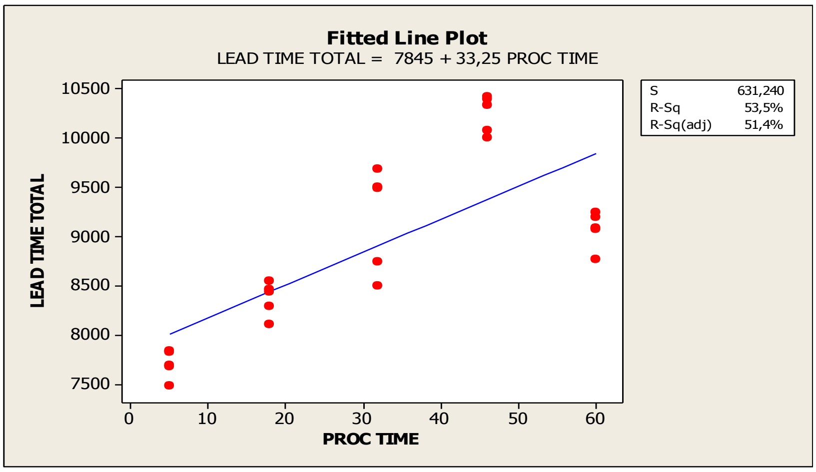

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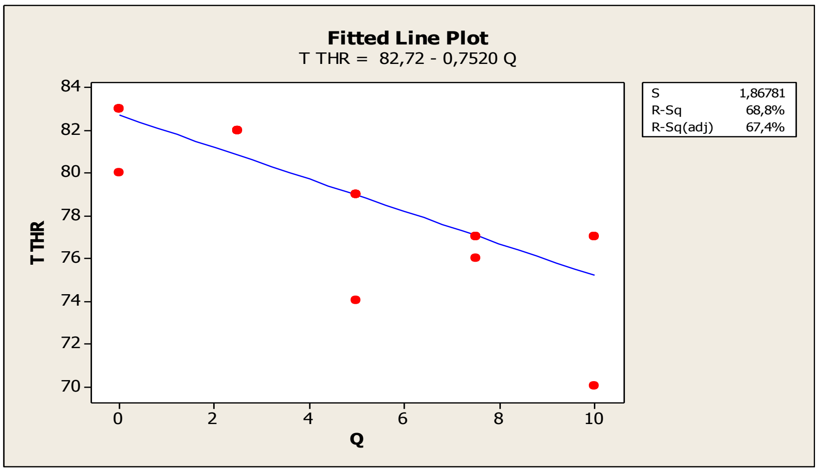

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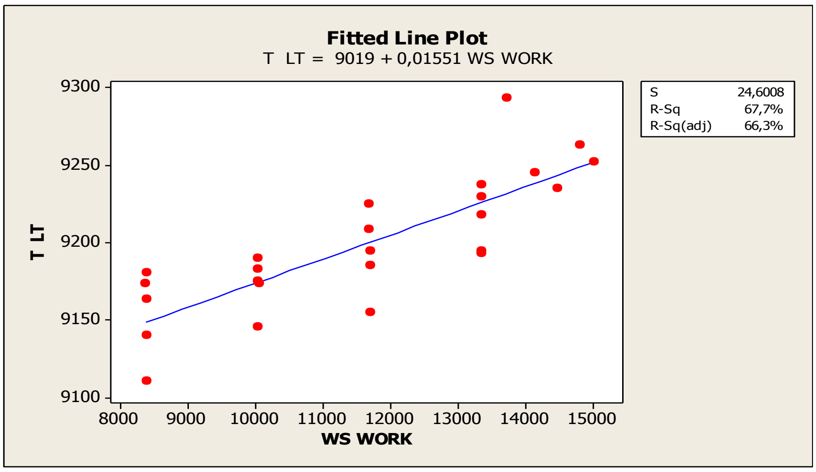

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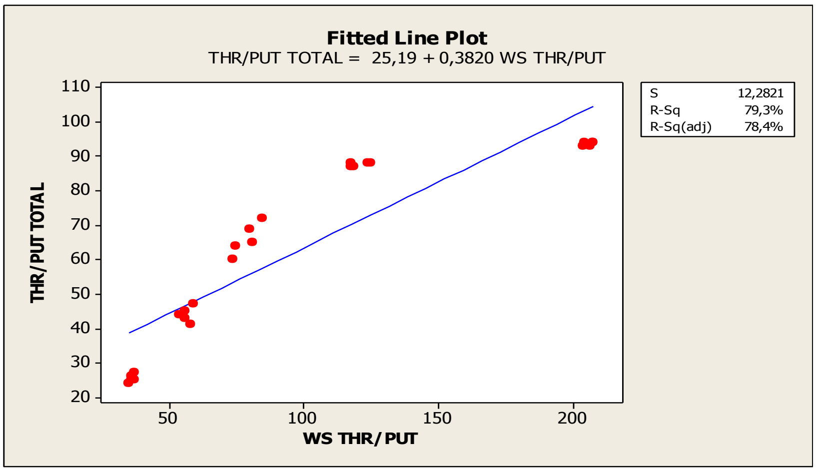

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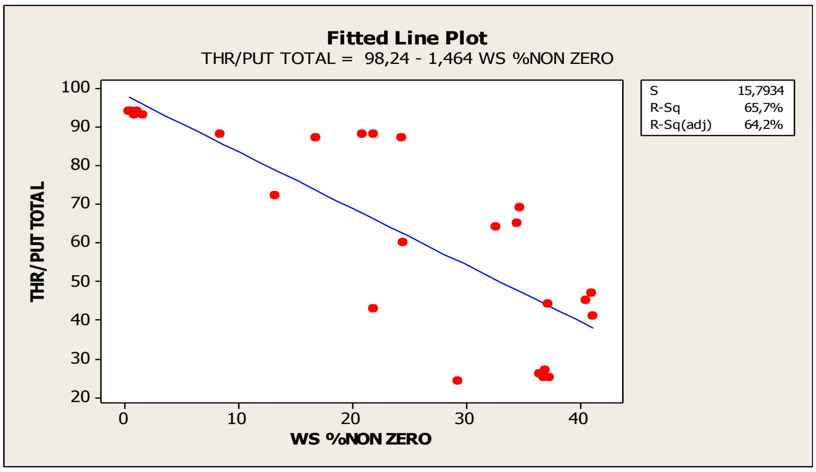

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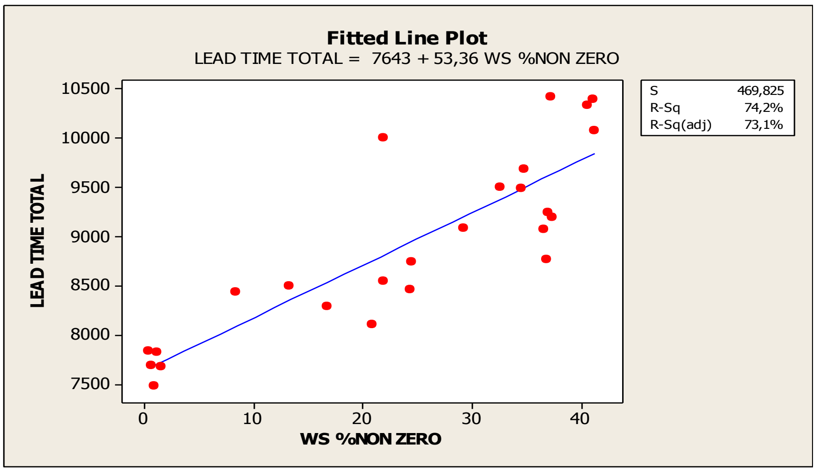

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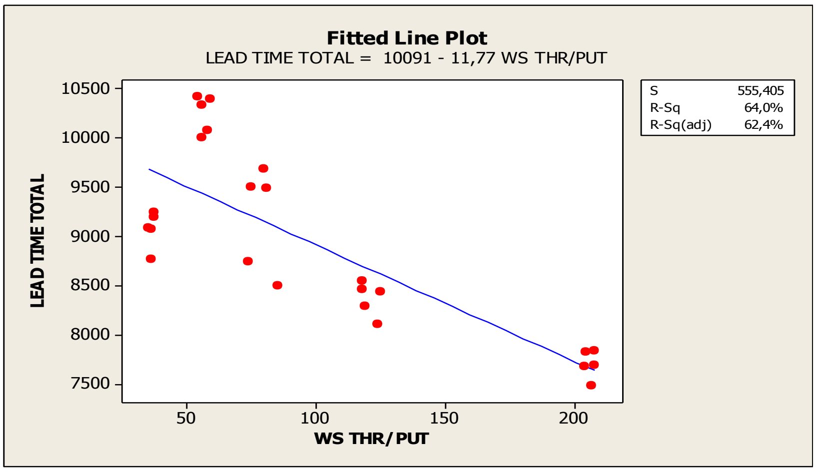

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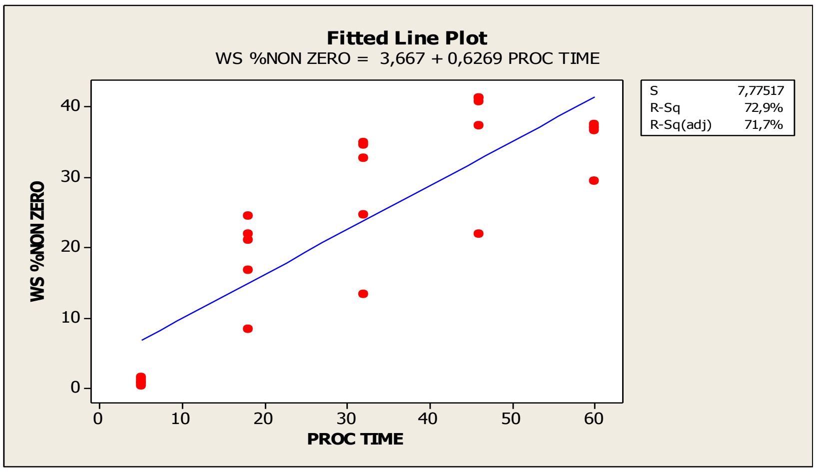
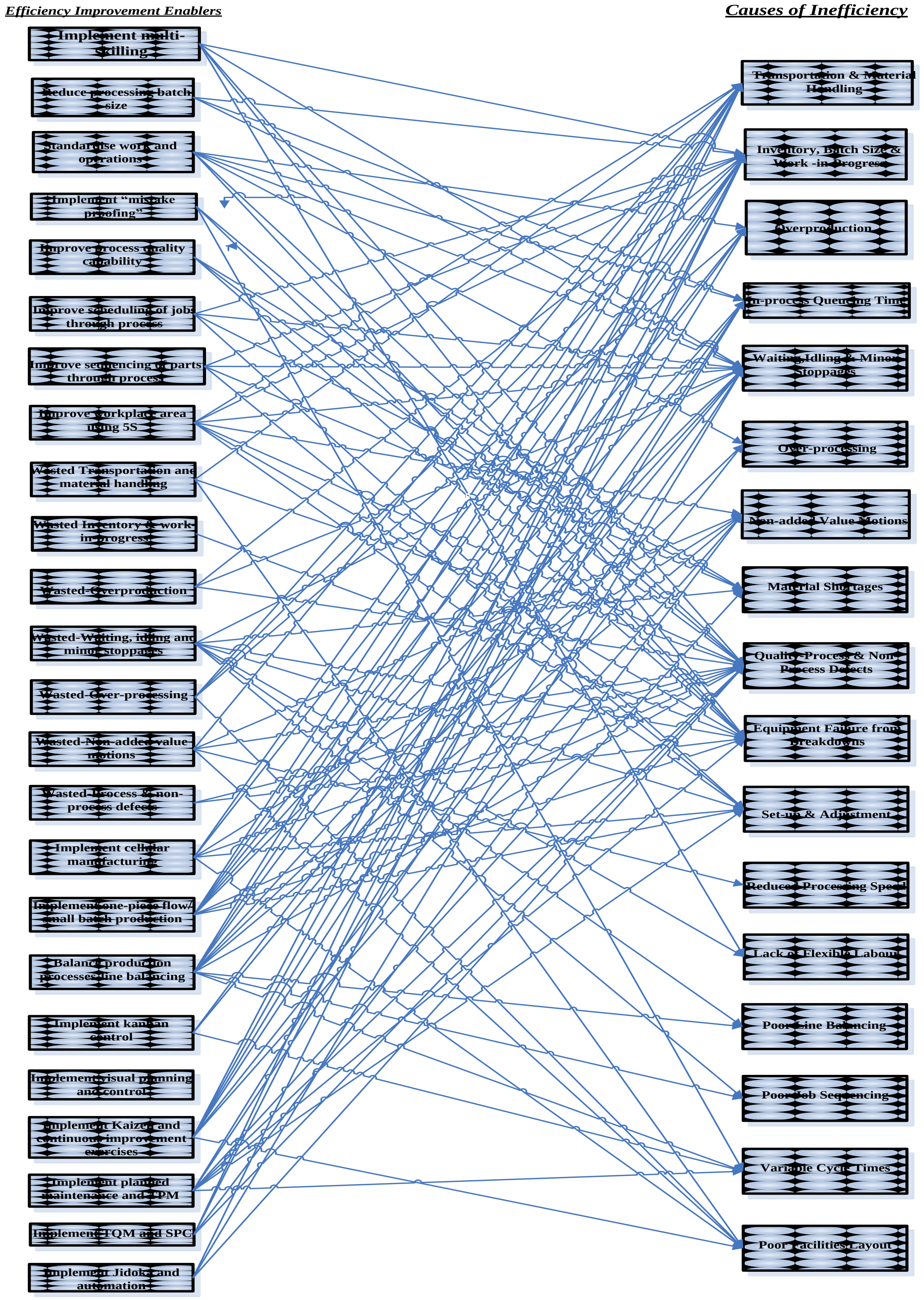
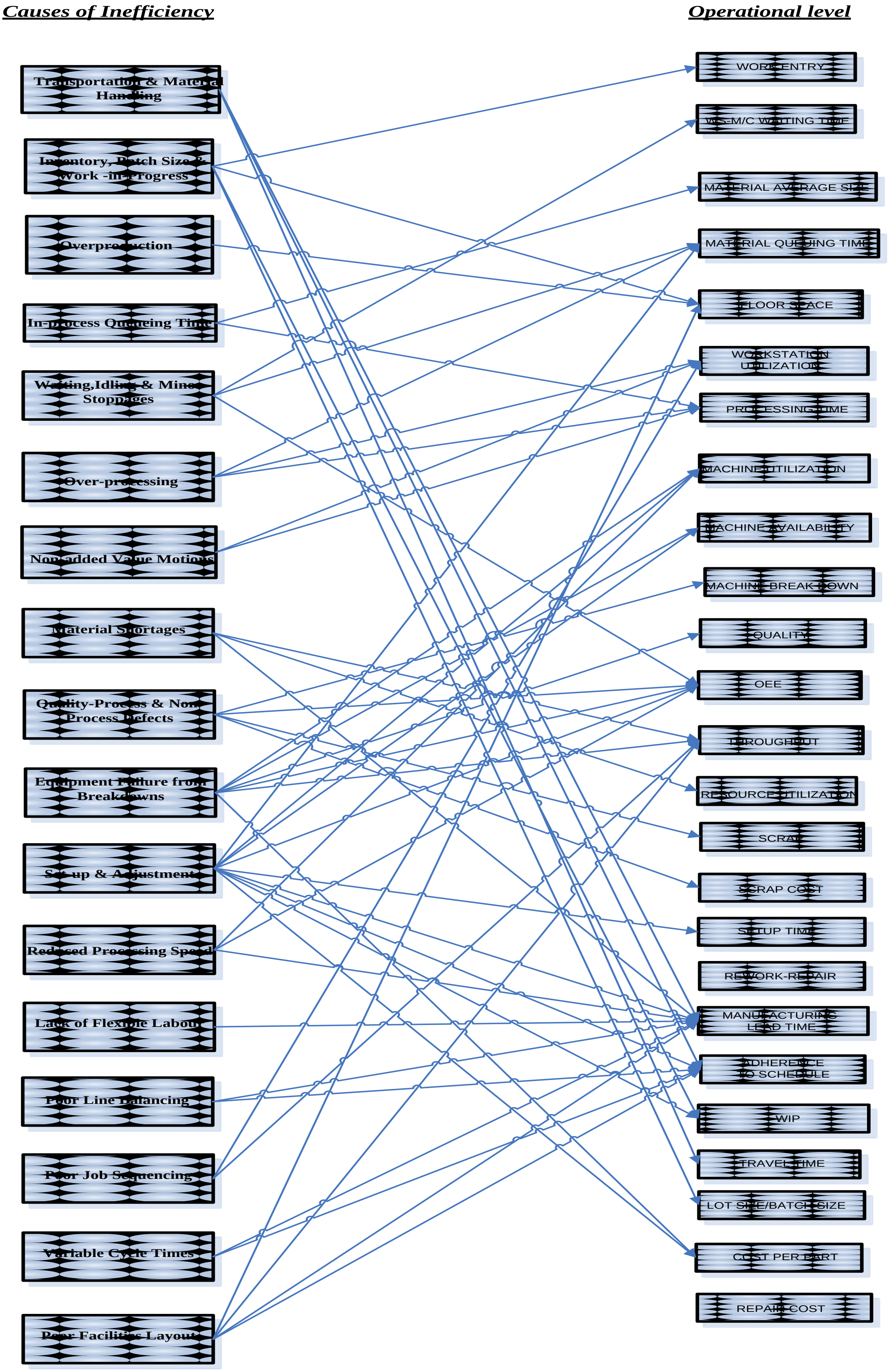
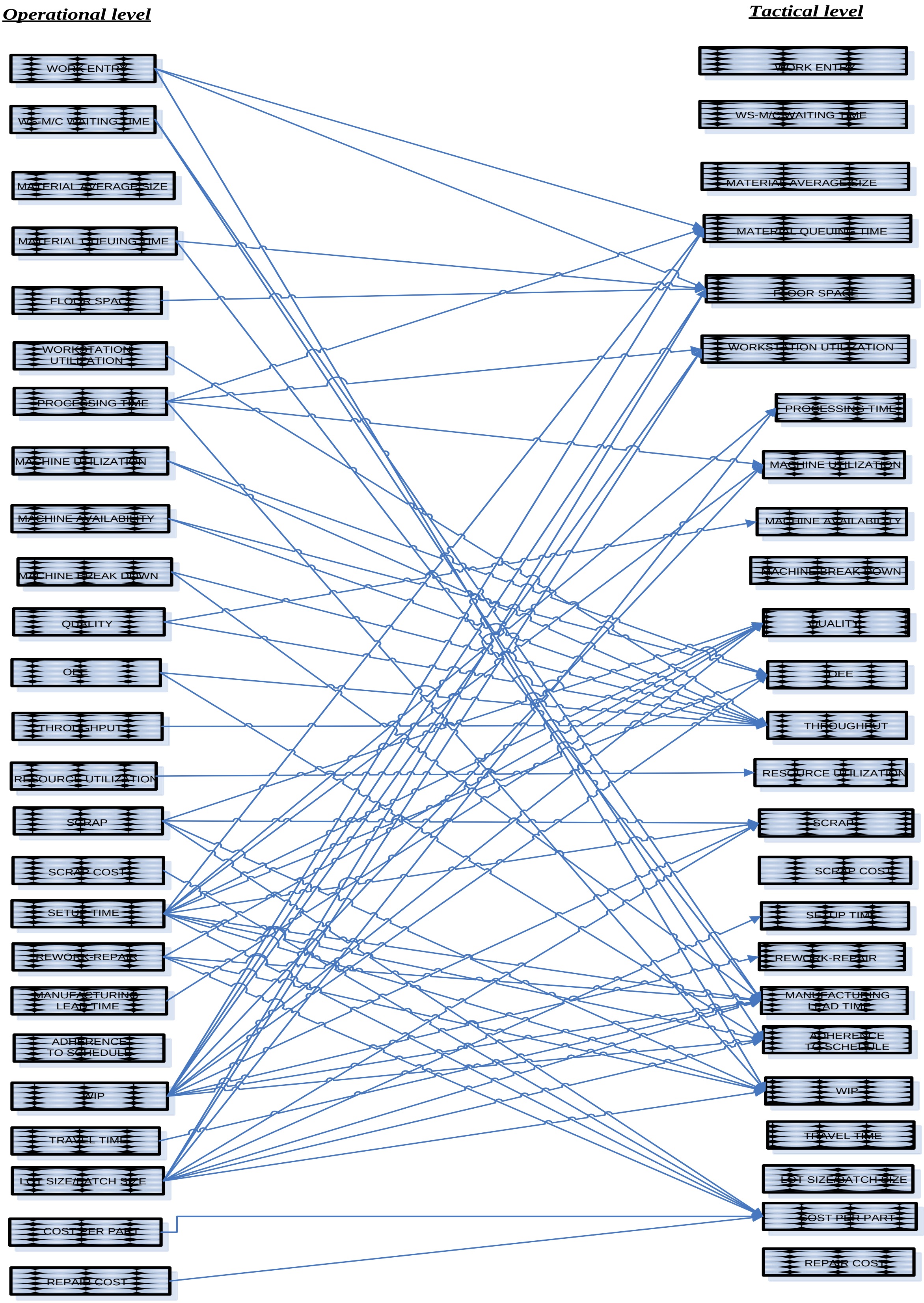

Fitted Line Plot
WS %NON ZERO = 3,667 + 0,6269 PROC TIME
S 7,77517
R-Sq 72,9%
R-Sq(adj) 71,7%
WS %NON ZERO
0
10
20
30
40
PROC TIME
0
10
20
30
40
50
60

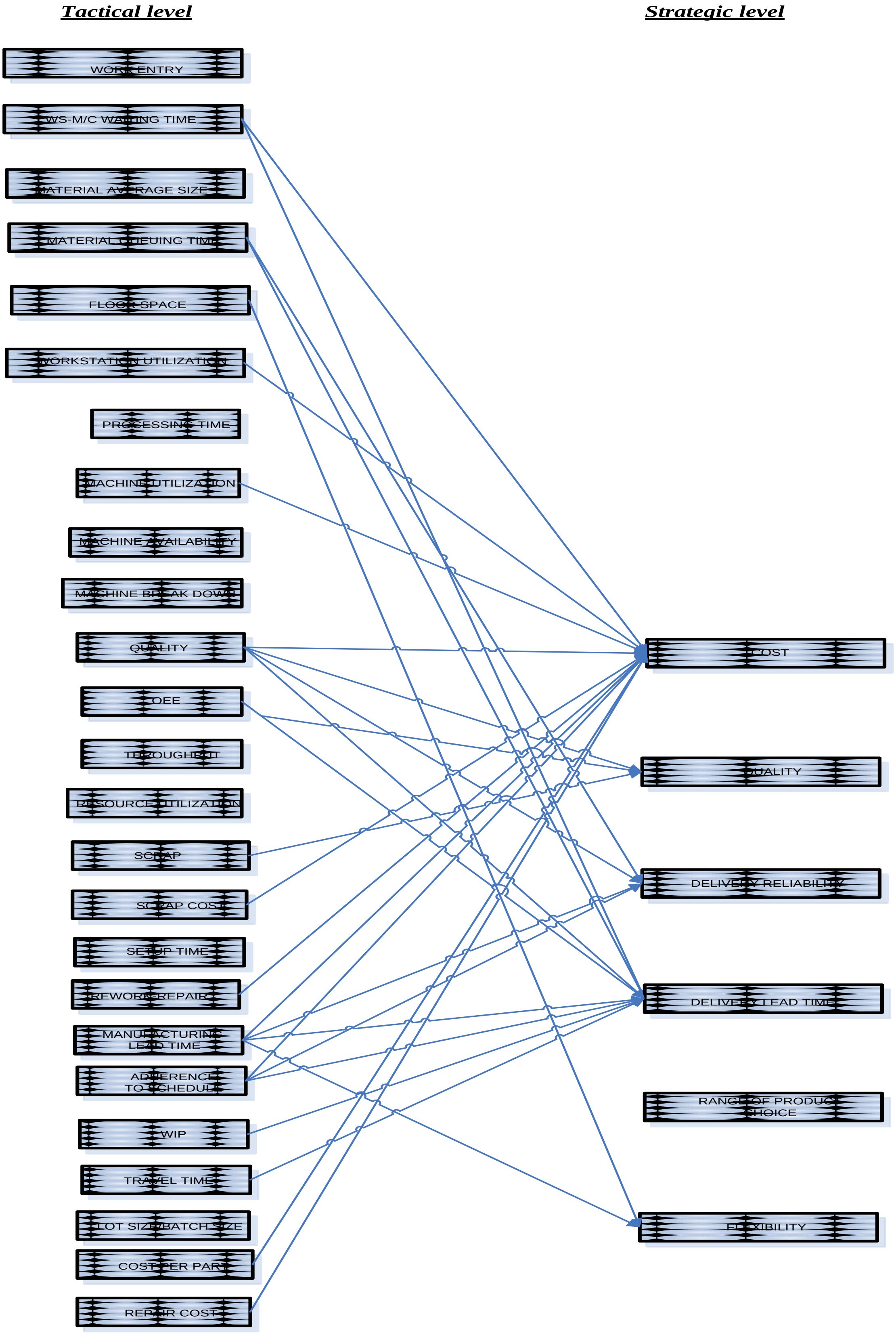
Figure 53

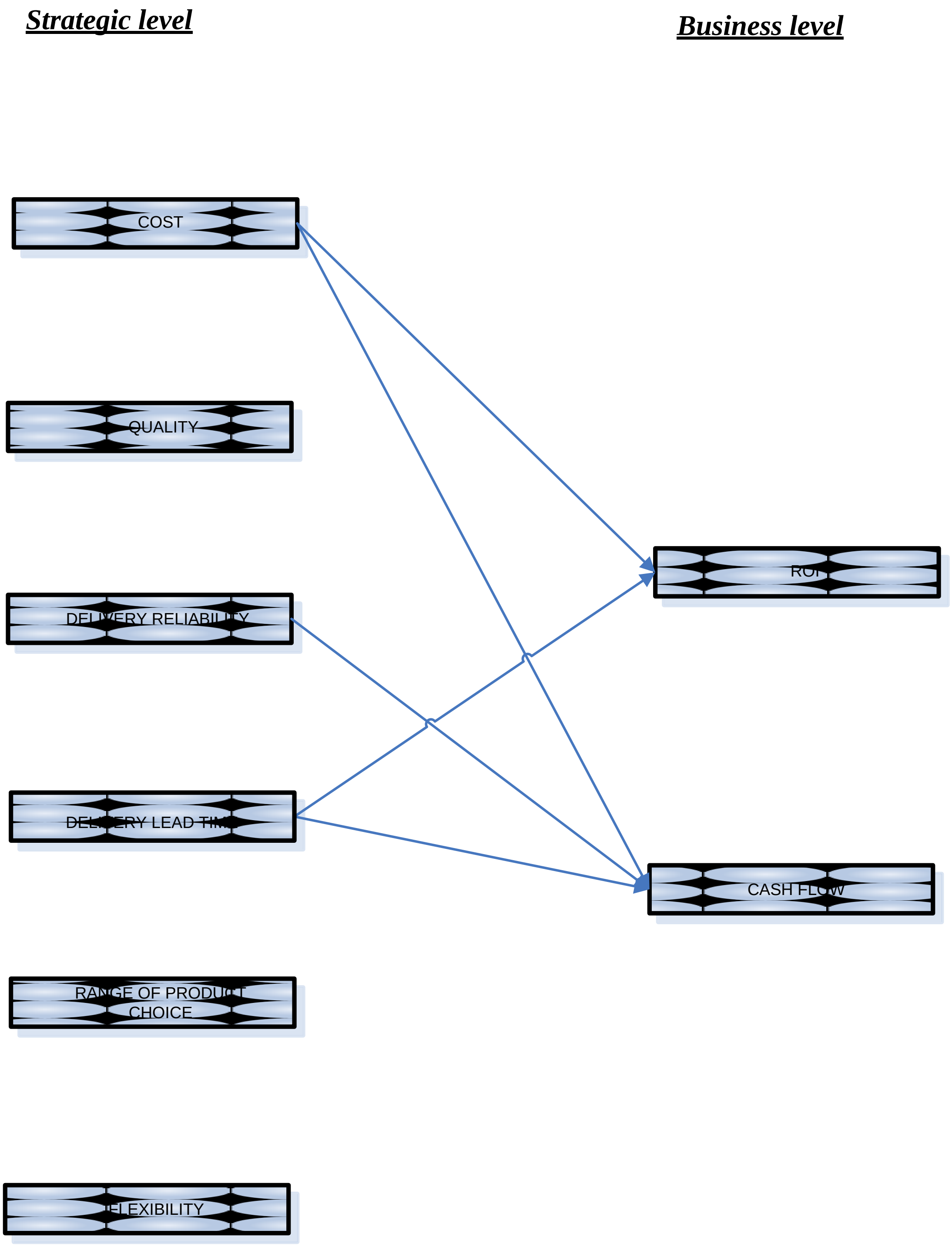
APPENDIX C RELATIONSHIPS




Causes of Inefficiency
Operational level
Transportation & Material Handling
Inventory, Batch Size & Work -in-Progress
Overproduction
In-process Queueing Time
Waiting,Idling & Minor Stoppages
Over-processing
Non-added Value Motions
Material Shortages
Quality-Process & Non-Process Defects
Equipment Failure from Breakdowns
Set-up & Adjustments
Reduced Processing Speed
Lack of Flexible Labour
Poor Line Balancing
Poor Job Sequencing
Variable Cycle Times
Poor Facilities Layouts
WORK ENTRY
WS-M/C WAITING TIME
MATERIAL AVERAGE SIZE
MATERIAL QUEUING TIME
FLOOR SPACE
WORKSTATION UTILIZATION
PROCESSING TIME
MACHINE UTILIZATION
MACHINE AVAILABILITY
MACHINE BREAK DOWN
QUALITY
OEE
THROUGHPUT
RESOURCE UTILIZATION
SCRAP
SCRAP COST
SETUP TIME
REWORK-REPAIR
MANUFACTURING LEAD TIME
ADHERENCE TO SCHEDULE
WIP
TRAVEL TIME
LOT SIZE/BATCH SIZE
COST PER PART
REPAIR COST


Operational level
Tactical level
WORK ENTRY
WS-M/C WAITING TIME
MATERIAL AVERAGE SIZE
MATERIAL QUEUING TIME
FLOOR SPACE
WORKSTATION UTILIZATION
PROCESSING TIME
MACHINE UTILIZATION
MACHINE AVAILABILITY
MACHINE BREAK DOWN
QUALITY
OEE
THROUGHPUT
RESOURCE UTILIZATION
SCRAP
SCRAP COST
SETUP TIME
REWORK-REPAIR
MANUFACTURING LEAD TIME
ADHERENCE TO SCHEDULE
WIP
TRAVEL TIME
LOT SIZE/BATCH SIZE
COST PER PART
REPAIR COST
WORK ENTRY
WS-M/C WAITING TIME
MATERIAL AVERAGE SIZE
MATERIAL QUEUING TIME
FLOOR SPACE
WORKSTATION UTILIZATION
PROCESSING TIME
MACHINE UTILIZATION
MACHINE AVAILABILITY
MACHINE BREAK DOWN
QUALITY
OEE
THROUGHPUT
RESOURCE UTILIZATION
SCRAP
SCRAP COST
SETUP TIME
REWORK-REPAIR
MANUFACTURING LEAD TIME
ADHERENCE TO SCHEDULE
WIP
TRAVEL TIME
LOT SIZE/BATCH SIZE
COST PER PART
REPAIR COST


Tactical level
Strategic level
WORK ENTRY
WS-M/C WAITING TIME
MATERIAL AVERAGE SIZE
MATERIAL QUEUING TIME
FLOOR SPACE
WORKSTATION UTILIZATION
PROCESSING TIME
MACHINE UTILIZATION
MACHINE AVAILABILITY
MACHINE BREAK DOWN
QUALITY
OEE
THROUGHPUT
RESOURCE UTILIZATION
SCRAP
SCRAP COST
SETUP TIME
REWORK/REPAIR
MANUFACTURING LEAD TIME
ADHERENCE TO SCHEDULE
WIP
TRAVEL TIME
LOT SIZE/BATCH SIZE
COST PER PART
REPAIR COST
COST
QUALITY
DELIVERY RELIABILITY
DELIVERY LEAD TIME
RANGE OF PRODUCT CHOICE
FLEXIBILITY


Strategic level
Business level
COST
QUALITY
DELIVERY RELIABILITY
DELIVERY LEAD TIME
RANGE OF PRODUCT CHOICE
FLEXIBILITY
ROI
CASH FLOW