

**CRANFIELD UNIVERSITY**

**RYAN MARSDEN**

**GENERIC PROPOSALS TO INCREASE PRODUCTIVITY USING DISCRETE  
EVENT SIMULATION FOR FORD MOTOR COMPANY**

**SCHOOL OF INDUSTRIAL AND MANUFACTURING SCIENCE**

**MRes THESIS**

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MRes THESIS

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RYAN MARSDEN

Generic proposals to increase productivity using discrete-event simulation for Ford  
Motor Company

Supervisor: Dr Benny Tjahjono

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## ABSTRACT

The research project was carried out in conjunction with Ford Motor Company and Cranfield University. This research project has demonstrated partial fulfilment of the requirements for the Master Degree of Science. The project uses discrete simulation techniques to carry out experimentation with an aim of developing generic solutions to increase productivity and output of manufacturing transfer lines within the Ford group.

In this highly competitive era for manufacturing where the profit margins tighten each year, Ford and other automotive companies are striving to ensure they produce products that are not only desirable to the consumer but also profitable.

Every year senior management at Ford expect an increase in output for each line. This means that investigations must be carried out using simulation to formulate generic ideas and proposals to optimise and increase the output of a number of machining lines. Increasing manufacturing outputs reduces the unit cost per part; therefore there is an increase on the profit margin for each unit sold.

Based on the experimental data collected from the research project, three manufacturing lines have been optimised to maximise their productivity. The solutions were then developed into business cases which were produced in line with Ford's strict investment criteria and as a result each of the three lines should have its annual output increased by more than 5%, with a pay back period of under a year for the required capital investment. A generic solution was found which can potentially optimise any manufacturing line in the Ford Motor Company, providing large increases in annual output to Ford's manufacturing lines. These solutions will help Ford to maximise its profit contribution per unit sold, securing its place as a leading global automotive manufacturer.

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## GLOSSARY OF TERMS

|       |                                                      |
|-------|------------------------------------------------------|
| CNC   | Computer Numerical Control                           |
| CT    | Cycle Time                                           |
| FAST  | Ford Assembly Simulation Tool                        |
| FIRST | Fast Interactive Replacement Simulation Tool         |
| JPH   | Jobs per Hour                                        |
| KPI   | Key Performance Indicator                            |
| MTBF  | Mean Time Between Failure                            |
| OEMs  | Original equipment manufacturers                     |
| OP    | Operation (project context: a manufacturing process) |
| PRN   | Pseudo random number                                 |
| RMS   | Re-Configurable Manufacturing Systems                |
| ROCE  | Return On Capital Employed                           |
| RRP   | Recommended Retail Price                             |
| SMART | Self-Monitoring Analysis and Reporting Technology    |
| UK    | United Kingdom                                       |
| USA   | United States Of America                             |
| WIP   | Work In Progress                                     |

# 1 INTRODUCTION

## 1.1 *Overview of the industrial problem*

Ford Motor Company is one of the oldest and most established automotive manufacturing companies in the world and has become one of the world's most iconic brands. The Ford Motor Company was founded in 1903 by Henry Ford and 11 business associates and within ten years Henry Ford had designed and built the first moving assembly line in Michigan (United States) housed within the Piquette Manufacturing Plant.

In recent times Ford has branched out into new automotive markets, by using its purchasing power to acquire smaller car manufacturers. Presently Ford sells cars under its umbrella corporation using the following branding names: Lincoln, Mercury, Mazda, Jaguar, Land Rover, Aston Martin and Volvo

In this highly competitive era for automotive manufacturing where the profit margins tighten each year, Ford and other automotive companies are striving to ensure they produce products that are not only desirable to the consumer but are also profitable to ensure the future prosperity of the Ford motor company. Thirty years ago Ford and other large American companies such as General Motors, would not have questioned their dominance in the automotive sector. Now each of the large American Automotive companies is driven by the goal to survive and expand in one of the most competitive markets in the world.

Every year senior management expect an increase in jobs per hour (JPH) (i.e. the number of parts produced per hour) for each line. This means that investigations must be carried out to formulate generic ideas and proposals of changes to optimize and increase the output of a number of machining lines. Increasing manufacturing outputs reduced the fixed costs on each unit and therefore increases the profit margin on each unit sold. The simplest way in which to increase JPH is to enhance the existing manufacturing system by increasing the number of machines, adding new technologies or reducing non-value adding activities. Each of these enhancements of the existing system will produce certain benefits to a system with an associated cost of implementation, thus the question is "How to make strategic operational decisions, based on investment proposals to maximise JPH for a number of manufacturing lines".

Ford needs to accurately predict the effects of possible alterations to a real system without experimenting with the real system. If experiments were carried out on a real system and damage occurred to the line, it could produce a significant amount of downtime which could carry significant cost implications.

Simulation techniques can be used without the risk of experimenting with the real system. Simulation can be used as a decision support tool that can help engineers to redesign new and existing machining lines. All of the large automotive companies including Ford use simulation as a tool to plan and optimise their machining and assembly lines. Ford has used Witness (a common simulation software) to run these type of experiments before and this has given key stake holders (senior management) in Ford the knowledge to make a strategic decision on how capital should be invested.

The simulation team in Ford led by the industrial sponsor has developed an Excel package called FIRST to interface with Witness to produce a simulation model. This interface has been verified and proven to accurately produce models that can be used to model machining and assembly lines.

The industrial sponsor at Ford has stated that the industrial problem which is the basis for the project should be centred on a number of machining lines including one known as the Lion transfer line based in Dagenham. This line is felt by the management to be a prime candidate for adjustment or alteration to increase its JPH value. Once this line has been optimised, generic solutions will be proposed for optimising other machining lines within Ford Europe.

## **1.2 *Summary of thesis aim, objectives and programme***

The aim of this project is to:

“Develop a number of proposals that can be potentially used to increase productivity (JPH) in a number of different machining lines using simulation as a decision support tool, in order to increase Ford’s future profitability”.

To achieve the general aim stated above, the following research objectivities have been established:

- Learn how to experiment with the FIRST decision support tool and carry out preparatory experimentation.
- Develop generic proposals for Ford via experimentation with WITNESS and FIRST
- Apply previously developed generic proposals to different manufacturing
- Summarise the proposals to senior Ford management detailing: cost, risk, feasibility, benefits and payback period for Ford’s investment.

### **1.3 Summary of scope of the project**

In the sections below the key stages of the project will be introduced. These stages could be viewed as the overall methodology of how to successfully carry out an optimisation project on a number of real manufacturing systems using simulation as a consultation device.

#### **Stage 1 – Development of preparatory work needed pre-experimentation**

This stage will introduce the preparatory work (training and familiarisation) that was needed to carry out the simulation experimentation. It will then consider the experimental strategy and the experimental methodology that was used in all of the experiments. It will also discuss the preparatory experimentation that was needed before simulation experiments could be carried out.

#### **Stage 2 – Development of generic proposals via simulation**

Once a comprehensive understanding of the default model has been fashioned, the main experimentation can start using the simulation model to develop generic proposals which could increase the productivity (JPH) of a number of manufacturing lines. This process of identifying possible generic improvements will start with very broad areas and these will become more defined as the experiments begin to show positive results.

#### **Stage 3 – Application of previously developed generic proposals to different manufacturing lines**

Once a number of generic proposals have been shown to increase the productivity on the default manufacturing line, other lines will be optimised using the previously developed generic proposals. This will show the proposals are truly generic and can be used in future productivity projects.

#### **Stage 4 – Development of business cases**

This stage will take into account the financial information and the benefits of the proposals to Ford for each of the lines. A number of other important types of information will also be documented, such as time period needed for implementation and effects of proposals on maintenance to the existing line.

### **1.4 Thesis structure**

This thesis has been structured to include the following chapters:

#### **Chapter 2 Industrial Context**

In this chapter the industrial problem will be defined and the project will be put into perspective with the background information relevant to this project.

### **Chapter 3 Literature review**

This chapter reviews the current literature and academic knowledge which will form the foundations on which this project will be built. The purpose of the chapter is to acknowledge the existing work in the areas that the research project will cover and to produce a general overview of the subjects that will be investigated.

### **Chapter 4 Research Aim and Programme**

This chapter introduces the aims and objectives of this project. In the last section of this chapter the research methodology will be presented with the deliverables from the project. The research methodology will show how the project will be structured to successfully complete the projects aims and deliverables.

### **Chapter 5 Stage 1: Development of preparatory work needed pre-experimentation**

This chapter describes the preparatory work that was needed in the research project to competently simulate a manufacturing production line.

### **Chapter 6 Stage 2: Develop generic proposals via simulation**

The aim of this chapter is to document the experiments that were carried out and their findings. A number of proposals that meet Ford's selection criteria will be correlated together to produce the chapter's deliverable, which is generic solutions to increase the JPH for potentially any Ford manufacturing line.

### **Chapter 7 Stage 3: Application of previously developed generic proposals to different manufacturing lines**

The aim of this chapter is to document the process of running experiments on different machining lines using generic proposals documented in chapter 6.

### **Chapter 8 Stage 4: Development of business cases**

In this chapter the solutions to increase productivity (JHP) for each of the three lines will be evaluated against a series of recognised benefits and drawbacks. Each solution will be structured as a business proposal which will be presented to the senior management at Ford. The aim of this chapter is to produce an impartial business case for each of the solutions to meet Ford's requirements based on the results of the simulation and also information gathered for Ford personnel.

### **Chapter 9 Discussion**

The aim of this final chapter of the project is to discuss, analyse and evaluate the project, based on the project aims and objectives stated in chapter 4. As part of this chapter there are sections detailing recommendations to Ford, further work, limitations of the research project and contributions to knowledge.

## **1.5 Chapter summary**

This chapter introduces the research project and provides a summary of the aims and objectives that this project will be evaluated against. This chapter has also provided an introduction to each of the chapters stating their purpose and detailing what should be found within them.

## 2 Industrial Context

This chapter gives an overview of the company's history, current products and market sector, all of which provide the industrial background for the project. This chapter then acknowledges the industrial problem which forms the foundation of the research project.

### 2.1 *The Company history*

Henry Ford started Ford Motor Company on the 16<sup>th</sup> June 1903 with 11 business associates. Within ten years (1913) Henry Ford had designed and built the first moving assembly line in Michigan (United States) housed in the Piquette Manufacturing Plant to produce the first mass produced car named the 'Model T' which can be seen in Figure 1.

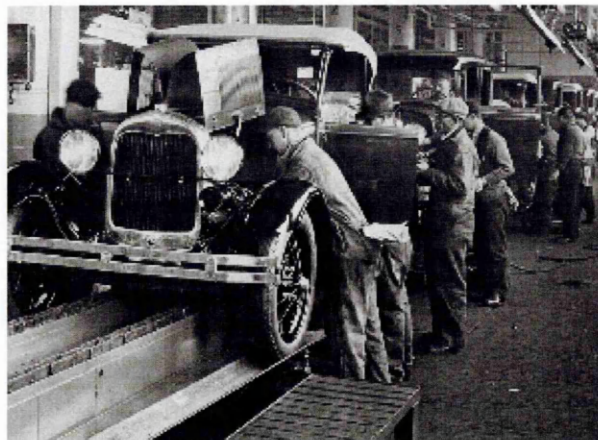


**Figure 1: Ford Model T assembly line circa 1917 (source: University of California, Irvine)**

Henry Ford gave birth to the first fully mass produced car which for the first time gave average income homes within the USA the possibility of owning a car. Henry Ford wanted to reduce the price of a car so that people working in his factories could afford the car that they helped to produce.

The Ford empire expanded in the post war development era with a succession of popular new models such as the Thunderbird (1955), Ford Falcon (1960) and Mustang (1965). This new wave of development allowed Ford to expand into Europe, developing Ford of Europe in 1967.

Since the mid 1990s Ford has lost roughly 25% of its market share in the USA to other automotive competitors. It has also suffered financial problems with the effects of 9/11 on the stock market lowering its share value and pension scheme cash reserve.

Currently Ford employs around 14,200 personnel at 10 locations around the UK. Ford has had many success stories within the UK, still remaining the number one automotive retailer and

the Ford Focus has been the UK's favourite car for six successive years. Ford has also become renowned for its commercial vehicles such as the Ford Transit which in 2005 had its 40<sup>th</sup> anniversary of production.

## **2.2 *Current products and market position***

Ford wanted to branch out into other automotive markets that it could not currently do well in. To achieve this Ford set up a number of new companies that began to produce a new range of cars. Although new sister companies such as Edsel and Merkur were selling similar cars to Ford, they failed to gain market share and the brands were scrapped. The problem was that a new company would have no existing customer base. To combat this Ford used its purchasing power to acquire many other smaller car manufacturers and today Ford sell cars under the umbrella corporation using the following existing branding names: Lincoln, Mercury, Mazda, Jaguar, Land Rover, Aston Martin, and Volvo

The Ford Motor Company Annual Report 2005 states that its USA market share in 2005 was 18.2% of the market which fell from 19.3% in 2004. The European market share was valued at 10.8% falling by 0.1% from 2004. Ford's sales went up by \$5.5 billion from \$171 billion in 2004 to \$177 billion in 2005, but its net income fell from \$3.5 billion in 2004 to \$2 billion in 2005.

## **2.3 *Dagenham Engine plant***

The Ford automotive plant in Dagenham is still one of the major assembly and manufacturing sites in the UK. Historically Dagenham produced and assembled cars but it now only manufactures and assembles diesel engines. A list of the engines produced in Dagenham can be seen below:

- Diesel engines and 2.0-litre and 2.3-litre Dual Overhead Cam (DOHC) engines.
- 1.8-litre 4-cyl. Diesel: Ford Escort, Fiesta and Focus.
- 2.0-litre 4-cyl. Diesel: Ford Mondeo.
- 2.4-litre 4-cyl. Diesel: Ford Transit.
- 2.5-litre 4-cyl. Diesel: Ford Transit.
- 2.0-litre 4-cyl. DOHC: Ford Galaxy and Transit.
- 2.3-litre 4-cyl. DOHC: Ford Focus and Fiesta

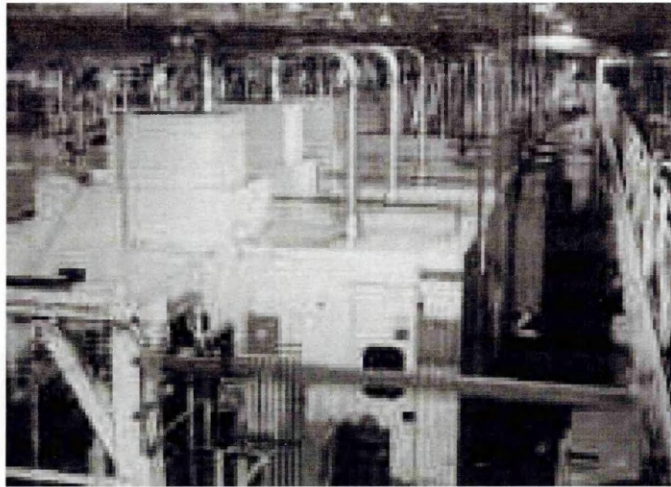


**Figure 2: A typical Ford CNC machining line**

Figure 2 shows a typical CNC transfer line within Ford. Each of these transfer lines is operated slightly differently, and the CNC milling and turning machines are usually large white boxes capable of housing all of the systems required for them to be fully automatic.

### 2.3.1 Parts machined in Dagenham

Ford only manufactures key components for its engines. They are typically base units from which the assembly starts. These base units are normally the parts that make up the main percentage of engine mass, which are cylinder block shown in Figure 3 and cylinder head shown in Figure 4.



**Figure 3: Cylinder block**

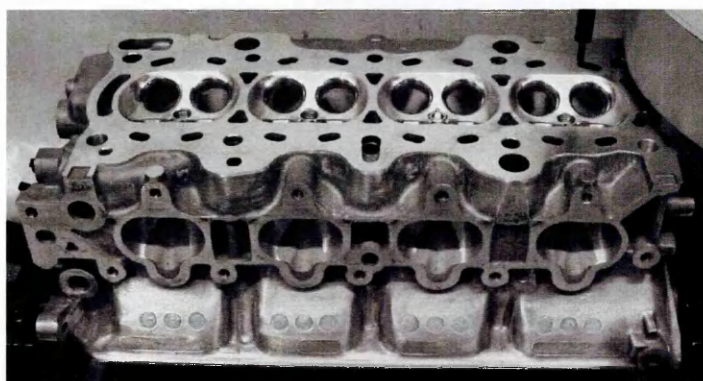


**Figure 4: Cylinder Head**

### 2.3.2 Typical operations needed to manufacture cylinder heads and blocks

After the basic shape of the component has been cast, machining is used to complete the manufacturing of the component. A typical machining line will carry out the following operations:

- Deburring
- Drilling and tapping
- Vertical and horizontal milling
- Assembly
- Washing
- Inspection

Each one of these operations will be carried out by one or a series of machines which are also known as machining lines. There are a small number of manual operations which are predominantly assembly and inspection activities.

#### 2.3.3 How a machining line works

Each of the machining lines in Dagenham is highly automated using a material transferring system known as a transfer line. The transfer line uses a system of fixtures called “platens” (Figure 5) to move parts between operations. Platens are effectively reusable clamps that can be used to precisely position work pieces and transport Work In Progress (WIP) between CNC machines without losing accuracy. This is achieved by providing the work piece with a referencing point to enabling accurate machining to take place. Once this datum has been established the work piece can move between CNC machines without losing any precision.

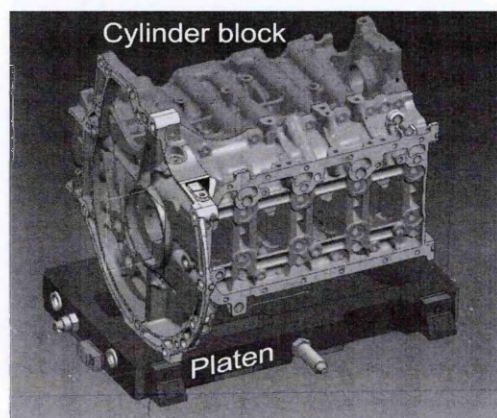


**Figure 5: Platen diagram**

To load the machines a gantry system is used to pick up the parts for the conveyor and insert them into the correct machine. Gantryes are also used to unload parts from machines in a similar way.

#### 2.3.4 Definition of JPH

Jobs per hour (JPH) is the Ford terminology for the productivity of a manufacturing system or parts produced per hour. JPH is effectively the output of a manufacturing line. It can be used to compare or benchmark different manufacturing systems

JPH is calculated by the following equation:

$$\text{JPH} = \frac{60\text{mins}}{\text{Cycle time of the systems bottleneck operation (mins)}}$$

As shown above JPH of a system is in fact the productivity of the system which is governed by the Cycle time of the bottleneck operation in the system. Thus to increase JPH the cycle time of the bottleneck operation must be reduced by some means.

#### 2.4 *Ford interface development*

Ford originally developed a simulation program using Witness, a FORTRAN-based package from the Lanner group. This program acted as a user interface for engineers to build and simulate machining lines without needing to understand how to construct the FORTRAN logic. In 1986 the first version of Witness was released which Ford has used to this day.

FIRST (Fast Interactive Replacement Simulation Tool) is Ford's latest simulation interface which is used to simplify the model building process shown in Figure 6. Using FIRST, simulation parameters can be easily input into the Excel spreadsheet. When the user is ready to run a simulation experiment, an execution code is sent to the Visual Basic start-up macro. Visual Basic then opens the Witness program and loads the data from the spreadsheet. Witness then executes the logic and carries out the simulation. FIRST does not provide a visual display of the simulation, but it is a facilitation tool which allows anyone with knowledge of the manufacturing process and basic Excel skills to carry out simulation experiments.

| FIRST - User Data (Machines) - Line2 |                    |                  |            |              |                     |            |          |                      |                    |                       |             |         |  |                     |  |
|--------------------------------------|--------------------|------------------|------------|--------------|---------------------|------------|----------|----------------------|--------------------|-----------------------|-------------|---------|--|---------------------|--|
| Line Pull From:                      |                    | Always Available |            | Line Type:   |                     | Machining  |          | Menu                 |                    | Print                 |             | Help    |  | Insert Distribution |  |
| Line Push To:                        |                    | Ship             |            | Line Number: |                     | Op number: |          | Customised Breakdown |                    |                       |             |         |  |                     |  |
| Operation number                     | Number of Machines | Pieces per Cycle | Cycle Time | Breakdown %  | Breakdown n Lockout | Assem hly  | Reject % | ct to Line           | Reject to Op       | Time Between Failures | Repair Time |         |  |                     |  |
| mtpalret                             | 1                  | 1                | 0.51       |              |                     |            |          |                      |                    |                       |             |         |  | 117.9               |  |
| 60                                   | 1                  | 1                | 0.51       |              |                     | 1          | 0.2      | 6 ra60               | Negexp(1098.96,15) | Erlang(5.233,6,16)    | 117.6       |         |  |                     |  |
| g70                                  | 1                  | 1                | 0.5        |              |                     |            | 100      | 2                    | 71                 | Negexp(6306.53)       | dg(54)      | 120     |  |                     |  |
| g70                                  | 1                  | 1                | 0.5        |              |                     |            |          |                      |                    | Negexp(6306.53)       | dg(54)      | 120     |  |                     |  |
| 70                                   | 5                  | 1                | 5.415      |              |                     |            | 100      | 6 ra70               | Negexp(190.27,53)  | dc(18)                | 55.4        |         |  |                     |  |
| 71                                   | 5                  | 1                | 5.415      |              |                     |            | 0.2      | 6 rb71               | Negexp(190.27,53)  | dc(18)                | 55.4        | 110.8   |  |                     |  |
| g80                                  | 1                  | 1                | 0.500      |              |                     |            | 100      | 2                    | 81                 | Negexp(7422,17)       | dg(60)      | 120     |  |                     |  |
| g80                                  | 1                  | 1                | 0.500      |              |                     |            |          |                      |                    | Negexp(7422,17)       | dg(60)      | 120     |  |                     |  |
| 80                                   | 5                  | 1                | 5.215      |              |                     |            | 100      | 6 ra80               | Negexp(190.27,19)  | dc(20)                | 57.53       |         |  |                     |  |
| 81                                   | 5                  | 1                | 5.215      |              |                     |            | 0.2      | 6 rb81               | Negexp(190.27,19)  | dc(20)                | 57.53       | 115.053 |  |                     |  |
| g90                                  | 1                  | 1                | 0.500      |              |                     |            | 100      | 2                    | 91                 | Negexp(7422,21)       | dg(22)      | 120     |  |                     |  |
| g90                                  | 1                  | 1                | 0.500      |              |                     |            |          |                      |                    | Negexp(7422,21)       | dg(22)      | 120     |  |                     |  |
| 90                                   | 4                  | 1                | 4.867      |              |                     |            | 100      | 6 ra90               | Negexp(190.27,29)  | dc(30)                | 49.31       |         |  |                     |  |
| 91                                   | 5                  | 1                | 4.867      |              |                     |            | 0.2      | 6 rb91               | Negexp(190.27,29)  | dc(30)                | 61.64       | 110.951 |  |                     |  |
| g110                                 | 1                  | 1                | 0.500      |              |                     |            |          |                      |                    | Negexp(20412,69)      | dg(70)      | 120     |  |                     |  |
| 110                                  | 1                  | 1                | 0.5        |              |                     |            | 0.2      | 6 ra110              | Negexp(29563.8,23) | Erlang(105.6,6,24)    | 120         |         |  |                     |  |
| 120                                  | 2                  | 1                | 1.02       |              |                     |            | 0.2      | 6 ra120              | Negexp(10776,25)   | Erlang(68.4,6,26)     | 117.6       |         |  |                     |  |
| g130                                 | 1                  | 1                | 0.500      |              |                     |            |          |                      |                    | Negexp(12186,71)      | dg(72)      | 120     |  |                     |  |
| 130                                  | 2                  | 1                | 1          |              |                     |            | 0.2      | 6 ra130              | Negexp(29563.8,27) | Erlang(105.6,6,28)    | 120         |         |  |                     |  |
| 132                                  | 1                  | 1                | 0.4        |              |                     | 1          |          |                      |                    |                       | 150         |         |  |                     |  |
| retmtpal                             | 1                  | 1                | 0.51       |              |                     |            |          |                      |                    |                       |             |         |  | 117.9               |  |

Figure 6: FIRST interface

## 2.5 Industrial problem

In this highly competitive era for manufacturing where the profit margins tighten each year, Ford and other automotive companies are striving to ensure they produce products that are not only desirable to the consumers but also profitable, to ensure the future prosperity of the company. A few decades ago Ford and other large American companies such as General Motors would not have thought that their dominance in the automotive sector would ever come into question. Now each of the large American automotive companies is driven by the goal to survive and expand in one of the most competitive markets in the world.

Each year automotive companies try to cut their costs by a certain percentage in order to keep up with their competitors around the world. The might of the Japanese automotive community with its lean principles and cost reduction incentives is the major threat to Ford's customer base.

Companies such as Toyota can produce cars that are at a higher standard than US products but at a lower recommended retail price. This threat is what is driving Ford to reduce its costs to compete with companies such as Toyota. One of the ways Ford seeks to achieve cost reductions is by increasing productivity of existing factories and production lines. Although the amount of cost reduction over these kinds of exercises is small for each part, when implemented over large volumes, these small cost reductions become extremely sizeable, running into the millions of dollars.

Every year senior management expect an increase in JPH (parts produced per hour) for each line. This means that investigations must be carried out to formulate generic ideas and proposals of changes to optimise and increase the output of a generic machining line.

The most common way in which to increase JPH is to enhance the existing manufacturing facility by increasing the number of machines, adding new technologies or reducing non-value adding activities. Each of these enhancements to the existing system will produce certain benefits to a system with an associated cost of implementation. Therefore the question is “how make strategic investment decisions based on generic proposals formulated to maximise JPH”.

The problem is that Ford wants to increase JPH but cannot experiment with the real system to quantify the benefits of possible changes. Thus Ford needs to accurately predict the effects of possible alterations to a real system. At present many of the machining lines are the bottlenecks for car production in Ford Europe; therefore any delay in parts will delay all subsequent operations, including final assembly. This makes the engine machining lines critical operations for Ford and is the main reason that it needs to continually produce engines and engine components. If experiments were carried out on a real system and damage occurred to the line, it could produce a significant amount of downtime which could equate to significant cost implication.

Without corporate visibility of how the alterations will affect the system, irreparable damage could be inflicted on the real system which could potentially destabilise Ford as a company. Ford cannot afford to invest in new manufacturing technology to alter the current system, unless it is sure that the investment will produce the maximum benefit.

Simulation techniques can potentially be used to answer this question without the risk associated with experimenting with the real system. Simulation can be used as a decision making tool that can help engineers to redesign machining lines. All of the large mass production automotive companies including Ford use simulation as a tool to plan and optimise their machining and assembly lines. If the representation of a real system can be accurately built, then the model can then be used to experiment and ask “what if” questions that cannot be answered by experimenting with the real system due to the cost or complexity issues. Ford has used Witness, to run these types of experiments before and this has given key stakeholders in Ford (senior management) the knowledge to make strategic decisions on how capital should be invested in Ford.

Ford has a system of overhead electric display boards. They can indicate which machines are stopped and which machines have a breakdown. The major problem is that this is a generic system that does not provide detailed information about the stoppage and does not alert the maintenance staff to the problem immediately. This system has been said to be only 50% effective by the team leader at identifying there is a problem and alerting the correct maintenance personnel to the incident.

The research projects industrial supervisor at Ford, John Ladbrook (hereafter referred to as the 'industrial sponsor') is a simulation expert working in the manufacturing and engineering department at Ford's Dunton technical centre.

The simulation team in Ford led by the industrial sponsor has developed an Excel package (FIRST) to interface with Witness to produce a simulation model. This interface has been verified and proven to accurately produce models that can be used in the modelling of machining lines. FIRST gives engineers with a limited understanding of how to build a simulation model a quick way of inputting information into a familiar application which will then build the model for the user.

The industrial sponsor has recommended that FIRST is used in the experimentation as it could potentially allow Ford to determine whether there any generic solutions to increase the JPH of existing manufacturing lines.

The industrial sponsor at Ford has stated that the industrial problem which is the basis for this project should be centred on a number of machining lines, including the Lion transfer line based in Dagenham. This line is felt by the management to be a prime candidate for adjustment or alteration to increase the line's JPH value. Once this line has been optimised the solutions will be put forward as generic solutions for optimising two other machining lines within Ford Europe.

## **2.6 Chapter summary**

From 1903 the Ford Motor Company has evolved into one of the world's largest companies and has spread to every continent. Ford has become one of the leading organisations in the automotive industry but in recent years it has lost market share to competitors.

One of Ford's strategies is to reduce manufacturing cost to enable it to reduce the selling cost of its products whilst ensuring each unit sold provides an acceptable profit margin. To enable Ford to do this senior management expect manufacturing lines to be optimised every year, increasing their output so that the overall cost can be spread over more units.

Simulation can potentially be used to devise new, innovative generic solutions to optimise machining lines. This will then enable Ford to reduce its overall costs and become more competitive in the automotive industry.

### 3 LITERATURE REVIEW

This chapter reviews the current literature and academic knowledge which will form the foundations on which this project has been built. The purpose of literature review is to acknowledge existing work in the areas that the research covers and produce a general background into the subjects that will be investigated. This chapter will also provide a critical appraisal of academic and commercial literature to date and will compare and contrast these works to provide a balanced view as to what extent the problem has been solved previously.

According to Andersen (1997) a researcher conducts a literature review in order “to establish the status quo, define the value of pursuing the line of enquiry established, and compare the findings and ideas with his or her own.”

The literature review has been categorized into the following areas:

- Transfer lines
- Ways of increasing output from transfer lines
- Simulation
- Cases studies of simulation
- Warm up period and pseudo random numbers
- Design for experiments

#### 3.1 *Transfer line*

According to Dallery (1989), a transfer line is a series of machines that are separated by buffers. These buffers could be store areas but are more likely to be transportation devices such as conveyors which by their nature can have a work in progress (WIP) capacity. Parts enter the transfer line and at each station work is carried out on the part. Each machine will have a cycle time, the length of time of an operation such as a machining operation. The machine with the longest cycle time will be the bottleneck of the whole transfer line. Dallery (1989) states “the performance of the transfer line is highly influenced by machine failures”. This means that even if a transfer line is completely balanced, when breakdowns and failures occur the line can quickly become blocked pre failure and post failure the line could enter starvation (starvation is where a machine is ready to produce but has no work) mode. Both blocking (blocking is where a machine cannot unload its finished work thus cannot start more work) and starvation of the transfer line will spread throughout the line unless the failure or break down is quickly addressed. The major problem with blocking and starvation is it reduces line efficiency of machines that are perfectly capable of higher output.

Masood (2006) has defined a transfer line as an autonomous production line with a number of sequential operations with an automatic material transfer system. Masood (2006) states that transfer lines are widely used in mass production and large quantity products with little variability, such as the automotive industry, due to the large capital investment needed to purchase a transfer system.

Therefore for this research project a transfer line can be defined as a manufacturing system that is highly automated and is used for mass production of similar parts for a long demand period.

To summarise a transfer line is a manufacturing technique of automating the material transfer from operation to operation. It allows machines and operations to run with minimal human interaction with the system. A transfer line is normally used in high volume industries such as the automotive industry.

### **3.2 *Ways of increasing output from transfer lines***

Buzacott (1987) defines two main types of failure that could affect the productivity of transfer lines, these are:

- Operational dependent failure: is when the machine failure is due to a breakdown when in use.
- Time dependent failure: is blocking or starvation of the machine which prevents the machine from producing.

Although Buzacott says “most failures of transfer lines are operational dependent rather than time dependent”, starvation and blocking can be detrimental to the whole line. If the whole transfer line is affected by one breakdown this must be identified and quickly rectified.

Buzacott (1987) defines bottlenecks as the slowest process or operation in a machining or assembly line. The bottleneck operation determines the output and productivity of the whole line, so identifying the bottlenecks within a manufacturing line can highlight processes that need to be investigated and optimised.

Roser (2001) has developed a novel method for detecting the bottleneck using discrete event simulation techniques. Roser uses the simulation to examine the average duration of all machines in the following three states: busy, idle and blocked. The machine with the longest average uninterrupted active period is considered the bottleneck of the system. Sometimes it is unclear which machine is the bottleneck of a system due to the complex interactions between buffers and machines. Roser’s method gives a definitive answer to which machine is the bottleneck of the process.

Roser (2001) has also stated his bottleneck detection method has many advantages compared to conventional bottleneck detection methods. The method utilises information contained in the standard simulation data files, describing the change in the status of each of the machines against time. No knowledge is needed of the logic for the system and its structure. The results of the bottleneck detection method also yield a high level of confidence due to the results coming directly out of the simulation package. This means that not only is the method simple to use but the data that is needed is readily available from any machine and the confidence in the finding of the bottleneck is much higher.

The next paragraphs details a number of conventional and novel ways in which to increase the output of a manufacturing transfer line.

### 3.2.1 Line balancing

Balancing of a manufacturing line is important to increase output. Once processes have been identified as bottlenecks they then can be isolated and examined for possible improvements.

Sung-Yong et al (2001) describes why line balancing is so important and states that “a balanced manufacturing line provides maximum resource utilisation of a transfer line or assembly system”. Sung-Yong et al (2001) states that even if a system is completely balanced then there will still be inherent waste within the system since real world manufacturing systems never run at 100% capacity. Sung-Yong et al (2001) concludes that although it is important to balance a manufacturing line, the financial implications of achieving this must be taken into account and sometimes it is not financially viable to balance a transfer line completely.

Yeung (2003) has identified the importance of optimisation of computer numerical control (CNC) programming and the reduction of bottlenecks. Yeung (2003) states that one of the major bottlenecks of CNC machining is the CNC programming code. The code relies on the skill of the CNC programmer and also the competency of the computer program that is used to optimise the CNC code in post processing. To reduce the cycle time of a manufacturing operation that is controlled by CNC coding, optimal tool paths can be created that enable safe, and most importantly, quick cutting. A lot of work has been done to document how to effectively produce CNC code and Yeung (2003) and many others have investigated the possibility of using artificial intelligence to produce optimal CNC code. Although potentially significant cycle time reductions could be made by optimising CNC coding, the industrial sponsor has stated that this is outside the project boundaries. This paragraph therefore highlights a potential solution to increasing output, but this avenue will not be investigated further in this research project.

### 3.2.2 Adding new machines to operations

Kattan (2005) has stated that adding new machines to bottleneck operations may solve the bottleneck effects. Also Jayaraman and Agarwal (1996) have argued that duplication of machines within bottleneck operations could increase throughput. There are many papers and academics such as Masood (2006), Rajakumar et al (2006) and Cheng and Gen (1995), which agree that once a bottleneck operation has been found, new machines could be added to the operation. This would effectively reduce the cycle time of the operation and increase the output of the operation, which should increase the output of the transfer line. Adding new machines to a transfer line is a sure way to increase output assuming the bottleneck operation has been correctly identified. The reason why this is not common practice is due to the costs involved in buying a new machine tool. Machine tools can be expensive and cannot always increase the output of the system to a level that allows a realistic pay back period on the capital invested in the transfer line.

### 3.2.3 Buffer allocation

Buffer allocation can affect throughput on a manufacturing line. According to Roser (2003) increased buffer space can potentially increase manufacturing output.

Roser (2003) states that allocating buffers in manufacturing systems is one of easiest ways to improve the throughput of the system, as alterations can be quickly implemented and the costs of the changes are low. Roser (2003) also warns that increasing buffer capacity can lead to increased levels of WIP within the transfer line. In fact, the trade off between throughput and WIP is an area of significant academic research with many academics writing articles on this problem such as Lloyd (1999), Altiparmak et al (2002), Enginarlar et al (2002) and Gershwin and Schor (2000).

Increasing buffer sizes will ensure that parts are available for processing when machines are waiting, which will increase productivity of the system. However, this does not address the inherent problems of the manufacturing line. It also increases the WIP of the line, which will tie up lots of additional capital, which means that this important asset is not being fully utilised by the company. This goes against the principle of just in time JIT and lean manufacturing.

Roser (2003) states that increased buffer allocation should only be used when bottleneck operations have a period of idleness due to starvation of WIP. If this is true then increasing the buffer size before the operation will indeed increase the output of the bottleneck operation.

### 3.2.4 Reducing breakdowns

Breakdowns affect the productivity of transfer lines; in fact any complex system has a higher likelihood of developing a complication. Ozbavrak et al (2004) has stated that manufacturing systems are often affected by unpredictable stoppages of production. Ozbavrak et al (2004) also states that breakdowns are frequently random occurrences in a manufacturing system, which can greatly affect the productivity of the system as breakdowns are the most important random factor that affects the productivity of the manufacturing line.

Reduction of the impact of breakdowns is critical to the performance of the transfer line and one way to do this is to use constant real time monitoring of the system. SMART is an acronym for Self-Monitoring Analysis and Reporting Technology, which as it suggests is a technology that can monitor itself, analyse its own data and report on its status. SMART automatically makes any course of action that might be required known to the maintenance manager. It is the equivalent of a patient knowing they are ill, diagnosing their illness and then actively seeking help to regain their health. This is the current level of web-based maintenance that is now available for manufacturing machines. Although this system would be a high investment to the existing transfer line, if breakdowns were shown to be significantly affecting the productivity of the transfer line then the investment could be an astute decision. Web-based maintenance is still in its infancy states Yang and Xue (2003) but this area of web based maintenance will be used to monitor and evaluate and run the manufacturing systems of the future.

### 3.2.5 Mean time between failures and breakdowns

According to Palmer (1999) mean time between failures (MTBF) is a calculation of the average time between failures of a piece of equipment carrying out an operation over a period of time. Palmer (1999) states that equipment that has a lower MTBF is more susceptible to breakdowns thus will subject the system to longer periods of down time. If an operation is a critical bottleneck of a system then the longer the MTBF is for the operation the smaller the effect on the rest of the line. Palmer (1999) states MTBF of all operations within a transfer line becomes critical; if one operation breaks down the effects could potentially starve and block the rest of the operations within the line decreasing the whole lines efficiency and output.

## 3.3 *Simulation*

### 3.3.1 What is simulation?

Banks (2000) defines simulation as “the imitation of the operation of a real-world process or system over time. Simulation is used to describe and analyze the behaviour of a system, ask

"what if" questions about the real system, and aid in the design of real systems. Both existing and conceptual systems can be modelled with simulation."

Law et al (1979) defines a simulation model as, a representation of a system or process. A discrete event simulation model is a representation of a system that incorporates time and certain events occur over a period of time. A discrete model is one that changes only at discrete points in time, not continuously.

According to Law et al (1979) "a good simulation model provides not only numerical measures of system performance, but provides insight into system performance".

This definition of a model takes into account the main benefits of a discrete event model versus a mathematical model. The benefits of a discrete event model can include embedded logic such as a machine break down or labour variations. This logic makes the model a more realistic representation of the system's actual performance. Mathematical models can give quick estimations of system performance, but with limited inputs and no logic the data generated will be averaged and therefore an inaccurate prediction of the actual result.

### 3.3.2 Why use simulation

Ülgen et al (1997) stated that simulation can provide the empowerment needed for manufacturing engineers and managers to avoid and negate "costly mistakes" that can be involved in installing the wrong type of machinery into a system. Norman, (1995) also stated that computer simulations allows an engineer to experiment with a "virtual factory" which allow engineers to experiment with different types of automation to find the optimum type of equipment which will best fit the companies needs.

Ülgen et al (1997) also stated that discrete event simulation allows engineers to produce models of production lines, which could be used as a "Test-bed To Improve Design and Operational Rules and Implement New Systems". This means that once a credible model of a real system has been produced it can be used to test and modify the simulation to increase the productivity of the model. Ülgen et al states "Simulation can be used to answer "what if" questions in concept and design phases of the project". This means that accurate simulation models can answer question about the real production line without needing to interfere with the real manufacturing process.

Simulation is a safe way in which an interested party can investigate questions and assumptions without the associated risk of experimenting with the real system. Simulation techniques can be used to model the impossible which can generate new ideas and lines of thought to investigate further. Having created a "virtual factory" there is no risk to the real system through "costly mistakes" or damages to the real system.

Chaharbaghi (1990) has stated the three reasons for a simulation project to be undertaken:

1. A system is already in existence but has many undesirable effects such as variable output and frequent breakdowns.
2. A system that is already in existence is acceptable but it is perceived that there is possible improvement that can be made to increase its productivity.
3. A system does not currently exist, simulation can be used to design and plan a new system.

This thesis project can be clearly identified as point 2 above. There has been significant work carried out on this transfer line by teams of production engineers. Therefore it would be safely stated that there are no problems with the line but senior management perceive that improvements could be done to optimise the line and increase productivity.

### 3.3.3 Steps taken in normal simulation project

Splanemann, (2001) has produced a list of stages that normally make up a simulation study and these are shown below:

Clarification of the problem: the questions to be answered as well as the system boundaries for the analysis have to be defined.

System analysis: definition of included system objects, organisational structure and sequence structure.

- Data acquisition: collection of all relevant data regarding the included system objects.
- Model construction: modelling the system objects with purchasable simulation software.
- Model validation: comparison between model and reality.
- Simulation experiments: simulation runs with different parameter values.
- Evaluation of results: simulation results are to be interpreted in regard to included conclusions. To obtain the goals of the project iterative continuous improvement loops are necessary, as shown overleaf.

These stages of a simulation study can be shown in a diagrammatic format, which has been produced by Splanemann, (2001) and can be seen in Figure 7.

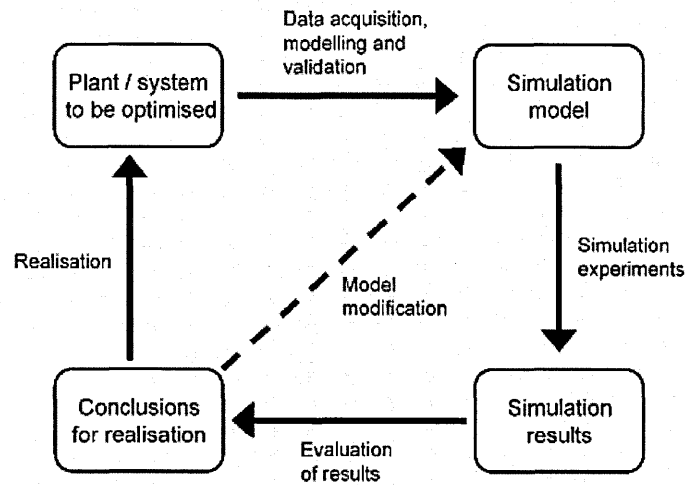


**Figure 7: Typical stages in a simulation project**

### 3.3.4 Producing improvements

Once possible improvements have been formulated they can then be investigated using a feasibility study or analysis. This is carried out with production engineers and also suppliers. Ideas that have been investigated in the simulation may work well in theory but they may be impractical or just too costly to implement on the real system. To achieve a continuous improvement loop shown in Figure 8 the research project must be able to continuously develop to improve the results of the simulation process. The simulation process is inherently accepting of any alteration, and any modification can be made without the consequences for the real system being taken into account. This can be counterproductive much of the time can be wasted on infeasible experiments. Therefore it is very important to test simulations frequently with real data. This will ensure that the benefits have not been lost and identify any possible additional improvements that could increase output of the system.

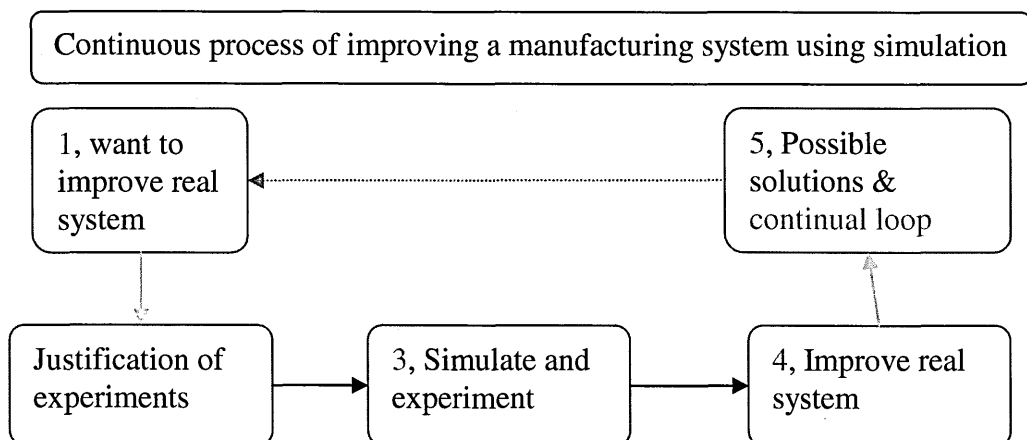


**Figure 8: Logic needed for improving manufacturing system using simulation**

### 3.3.5 Benefit of simulation

Kochhar and Ma (1989) has defined one of the major benefits of simulation: simulations can be done when experimentation cannot be carried out on the actual system. This could be because it is extremely costly to give up production time to experimentation on an existing system, or because a system does not yet exist. This benefit makes simulation suitable for carrying out experiments which are relatively cheap and do not influence the real system in any way.

Schrage, (2000) has produced a paper investigating “How the World’s Best Companies Simulate to Innovate”. Schrage makes it very clear that manufacturing systems are growing in complexity to the extent that the interaction between the elements is very difficult to comprehend and only with simulation can these interactions be fully understood. Many companies previously made decisions based on “gut instinct” with no real understanding of the consequences of these designs on the future prosperity of the company. Schrage argues that simulation of proposed investment solutions allows experiments to be conducted in a short time, enabling senior management to make informed choices based on tangible experimental results.

### 3.3.6 Types of simulation groups

Mehta et al (1999) states that manufacturing businesses generally pursue two major routes for simulation. The first is to form a new department of internal consultants that specialises in simulations and works throughout the business simulating different systems. Mehta et al (1999) states the benefits of this are:

- The internal consultants become expert simulation users, which shortens the building and experimentation stages of simulation.
- They are more likely to stick to best practices such as warm up periods and use of statistical data and would ensure a correct methodology was followed.

The disadvantages are:

- The internal consultants would not know the system well. Time would be needed to study, which would extend the model building process.
- Data is often needed from the customer, in this case the engineers that work with the machine, and this takes a lot of time to collect and can take time away from the engineers’ primary role.

The second route is called distributed modelling; this is when any engineer that wants to propose modification to a manufacturing line produces a simple simulation model. This

approach ensures that the model builder knows the system well, but the model will be limited and might take a long time to produce and might yield limited benefits.

A compromise between these is called “wrapping Witness” as shown in Figure 9, Mehta et al (1999) states that the technique lets the simulation designer wrap the completed model within a shell or interface that allows the users to change the data, thereby creating varied business scenarios without needing the simulation and logic skills to build a full simulation model.

This means that an interface is produced by internal consultants to allow engineers with little or no simulation or logic experience to build and experiment with simulation models using programs such as Microsoft Excel. This is the strategy that Ford has adopted, which effectively brings simulation to the general population of engineers. This technique allows complex simulation models to be built within a familiar spreadsheet package. This enables the engineers to concentrate their efforts on inputting the correct data and running the experiment without the need to write or debug any complex simulation logic.

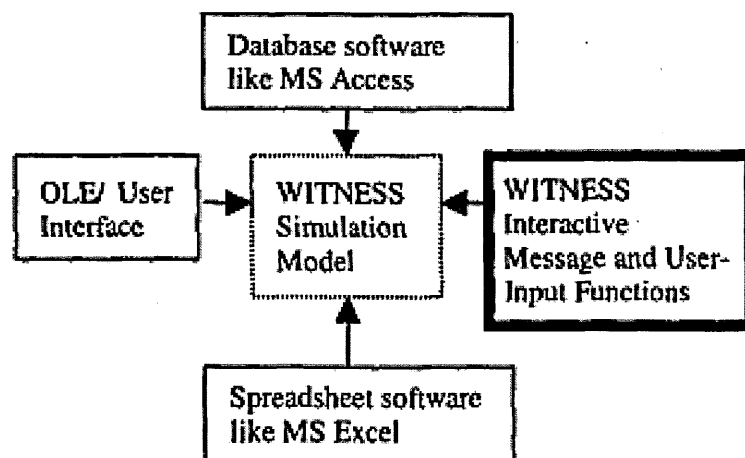


**Figure 9: Wrapping witness, typical interfacing techniques**

### **3.4 Case studies simulation use in industry**

There are two case studies in Appendix A, showing the potential benefits of simulation studies, focusing on two businesses. In both companies it was infeasible to experiment with the real system, thus simulation was used to modify/optimize two existing manufacturing lines and produce proposals that were implemented to make both companies more profitable and productive. Both of the case studies show the importance of simulation to businesses in today's manufacturing sector and demonstrate how successful simulation projects have enabled companies to invest strategically to maximize their productivity.

### **3.5 Warm-up period and pseudo random numbers**

It has been recognised by Robinson (1994) that simulations as with any new manufacturing lines need a period of time to reach normal manufacturing capacity. Robinson (1994) has been quoted in saying “for the results of a simulation to be correct, they should only be collected once a steady state has been reached”. Robinson (1994) argues that the simulation must pass through an initial transient period effectively a warm-up period in which no results should be collected. Robinson states it is therefore important that the simulation is run for a period of time that negates the initial transient period of warm up before any results are collected.

When a simulation model is built then the inputted data must also be validated. Pseudo random number (PRN) streams are used in simulation models to add variability to the system. PRN are used to govern any aspect of the simulation this is random such as a breakdown or tool change. Bradford and Martin (1993) state that tool change and down-time are the two greatest effects of randomness of a simulation model. Therefore if a model is unpredictable then they recommend that these are the most likely areas that should be investigated to remove the random aspect to production. PRN must be used to govern these types of random activities that can affect the output and performance of the simulation model. Kleijnen (1979) states that if randomness is ignored when using simulation then it becomes as useful as tossing a coin. When using simulations Pawlikowski (1990) has stated that average results must be obtained from simulation results, these averaged results will reduce the effects of PRN variation and give a result which is clustered around the mean of the actual result. Pawlikowski (1990) states there are two ways to achieve this, the first is to run multiple experiments and average the results the second is to run a simulation until it reaches its statistical equilibrium at which time the simulation will produce a steady result.

### **3.6 Design of experiments**

Design of experiments (DOE) is very important as it ensures that experiments are carried reliably and that data can be collected with the minimum amount of time and resources.

According to Barton (2004), the bulk of time and resources are usually spent on building and validating a simulation model, leaving little time to carry out the actual experimentation. This is risky, since poorly executed simulation projects can produce misleading results. By this Barton is trying to stress that time should be evenly distributed over the whole of the project, ensuring the construction and validation and experimentation have a fair percentage of the project time plan. Although the model has already been created for the present research experiment, Barton (2004) does indicate how easy it is to get bogged down with a small part of the project, leaving insufficient time for testing other hypotheses.

Barton (2004) has developed a cyclic process that can be used in the development and design of experiments which has been specifically designed for use in design discrete event simulations. The main steps are shown below:

- A. State a hypothesis to be evaluated.
- B. Plan an experiment to test the hypothesis.
- C. Conduct the experiment.
- D. Analyze the data from the experiment, this will likely lead to modification of the original hypothesis and a return to step one for the next cycle.

Barton (2004) then expanded activity B, stating that “careful planning in B can simplify the remaining activities”. Barton (2004) broke down activity B to five steps, which can help define the experiment:

- 1. Define the goals of the experiment.
- 2. Identify and classify independent and dependent variables.
- 3. Choose a probability model for the behaviour of the simulation model.
- 4. Choose an experiment design.
- 5. Validate the properties of the chosen design.

These five steps have been highlighted as being important to any simulation project. Effective planning of experiments based on formed hypothesis allowed experiments to be carried out only when a certain question needed to be answered. Once there is a question then the experiment can be tailored to answer it.

### **3.7 Chapter summary**

The purpose of this chapter was to review the current academic knowledge relevant to the industrial problem in which is the basis of this project. This chapter has concentrated on two main areas of investigation. The first was the definition of a transfer line from the academic community and alternatives for increasing the output or productivity of a transfer line. According to research into other projects in this area, a number of potential solutions were found for increasing the output of a manufacturing line. Although each manufacturing line is different, some of these solutions could potentially be transferable to solve the industrial problem being considered in this project. The second avenue of investigation was to gain an understanding of ‘simulation’ and put into context where and how simulation should be used to solve an academic or industrial problem. Using simulation to ask ‘what if’ questions and carry out experiments which are infeasible on the real system is a new technique that is enabling manufacturing companies to maximise their profitability by giving better insight into the manufacturing production and assembly lines. To illustrate this, two cases studies are

presented, each involving manufacturing enterprises using simulation to gain insight into how they could potentially optimise their manufacturing lines when experimentation with the real manufacturing system is infeasible. At the end of the chapter a section about design of simulation experiments shows a typical methodology that could be used to effectively carry out a simulation project. A variation on this will be used in this project.

## **4 Research Aim and Programme**

This chapter introduces the following information regarding the project. First the industrial problem that is the basis of this project is reiterated from chapter 2 and combined with the literature review in chapter 3 to form the aims and objectives for this project. The aims and objectives will constrain the project scope and ensure the project has defined boundaries. In the last section of this chapter the research methodology will be presented with the deliverables from this project. The research methodology will show how the project will be structured to successfully complete the project's aim and produce its deliverables.

### **4.1 *Problem definition***

As stated in chapter 2, the industrial problem which is the basis for the project is that, at present, Ford does not understand how to increase output (JPH) or productivity on a number of transfer machining lines. Although similar projects have been carried out previously in this area by Ford employees and other manufacturing engineers, each one of these projects has different constraining elements that combine together to form an individual problem that has not been encountered before. Hence to tackle each of the individual problems, generic solutions could potentially be found, which could enable Ford to increase productivity using generic solutions on a number of manufacturing lines.

In chapter 3 a review of academic and industrial literature was produced to put the problem into context and provide potential solutions to the industrial problem. As literature was investigated and the current understanding of the problem became apparent, a gap in knowledge was found which related to how a manufacturing engineer can produce generic solutions to increase productivity (JPH) for a number of Fords machining transfer lines.

The results from this research project could be used to guide future research to use the generic solutions produced within this project to increase the output in other manufacturing lines within Ford. The lack of industrial and academic knowledge on how to generically increase output in a manufacturing line is a key driving force behind this project. Once these "generic solutions" have been documented they can be used to simulate the effects they would have on the manufacturing line under investigation. If they are successful they could form the basis of a proposal to senior management on where Ford should strategically invest its capital, to maximise output (JPH). Finding the "generic" solutions is the major gap in academic and industrial knowledge that this project endeavours to fill.

### **4.2 *Scope of the project***

Ford senior management have agreed that, increasing productivity within Ford's manufacturing lines is an essential business strategy. This strategy will not be questioned

within this project scope, neither will the issue of whether Ford should invest nor whether Ford has correctly predicted its customer's requirements will not be considered for this project. The project will be confined to producing proposals for increasing productivity within three of Ford's manufacturing lines via creation of generic solutions to increase output (JPH) of each line.

### **4.3 Aims and objectives**

The aim of this research project is to:

“Develop a number of proposals that can be potentially used to increase productivity (JPH) in a number of different machining lines using simulation as a decision support tool, in order to increase Ford's future profitability”.

To achieve the general aim stated above, the following research objectivities have been established:

- Learn how to experiment with FIRST and carry out preparatory experimentation.
- Develop generic proposals for Ford via experimentation FIRST
- Application of previously developed generic proposals to different manufacturing lines
- Summarising the proposals to senior Ford management detailing: cost, risk, feasibility, benefits and payback period for Ford's investment.

### **4.4 Programme**

In the following section, the key stages of the project summarised in Table 1 will be introduced, and these will form the main stages undertaken in the research project. These stages could be viewed as the overall methodology for an optimisation project on a number of real manufacturing systems using simulation as a consultation device.

#### **Stage 1 – Development of preparatory work needed pre experimentation**

This stage will introduce the preliminary work (training and familiarisation) that was needed to carry out the simulation experimentation. It will then consider the experimental strategy and the experimental methodology that was used in all of the experiments. It will also discuss the preparatory experimentation that was needed before the main simulation experiments could be carried out.

#### **Stage 2 – Develop generic proposals via experimentation with discrete event simulation**

Once a comprehensive understanding of the default model had been developed, the main experimentation could be undertaken using the simulation model to develop generic proposals which could increase the productivity (JPH) of a number of manufacturing lines. This process of identifying possible generic improvements will start with very broad areas and these will become more defined as the experiments begin to show positive results.

### **Stage 3 – Application of previously developed generic proposals to different manufacturing lines**

Once a number of generic proposals have been shown to increase the productivity on the default manufacturing line, a number of other lines will be optimised using the previously developed generic proposals. This will show which proposals are truly generic and can be used in future productivity projects.

### **Stage 4 - Development of business cases**

This stage will take account of financial information and the benefits of the proposals to Ford for each of the lines. A number of other important types of information will also be documented, such as: time period needed for implementation and effects of proposals on maintenance to the existing line. All relevant information will be compiled into a business case for each of the lines.

**Table 1: Methodology of project split into stages**

| Stage   | Title                                                                                  | Purpose                                                                                                                                                                        | Method                                                                                                | Deliverable                                                                                                                          |
|---------|----------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------|
| Stage 1 | Development of preparatory work needed pre-experimentation                             | Familiarise with experimental software, plan experiments, identify possible improvements and carry out preparatory experimentation before main experimentation                 | Run numerous experiments and collaborate with the industrial sponsor to define experimental strategy. | Initial experiments using FIRST simulation and understanding of experimental software                                                |
| Stage 2 | Develop generic proposals via experimentation with discrete event simulation           | Carry out main experiment and devise a number of generic solutions to increase JPH over a number of different lines                                                            | Follow the experimental methodology developed in stage 1                                              | A group of proposals that increase JPH by circa 5% of the default line and could potentially be generic to other manufacturing lines |
| Stage 3 | Application of previously developed generic proposals to different manufacturing lines | Use the generic proposals to increase JPH on two different manufacturing lines. Prove if the generic solutions are indeed generic and whether they can be used on other lines. | Follow the experimental methodology developed in stage 1                                              | A number of solutions that will increase the JPH of two lines and prove or disprove if the generic solutions are indeed generic.     |
| Stage 4 | Development of business cases                                                          | Understand the costing and risk analysis and benefits of each of the proposals                                                                                                 | Communication with process engineers and OEMs                                                         | Business case for each validated proposal.                                                                                           |

## 5 Stage 1: Development of preparatory work needed pre-experimentation

In this stage of the research programme an experiment will be carried out using the FIRST simulation interface. This chapter will allow the reader to understand the preparatory work that was needed in the research project to competently simulate a production line. This chapter is broken down into the following key headings:

- Default manufacturing line
- Familiarisation
- Developing hypotheses
- Experimental strategy
- Experiment methodology
- Preparatory experiments
- Deliverable discussion
- Chapter conclusion

### 5.1 *Default manufacturing line*

The Lion V6/V8 line (henceforth referred to as the “default line”) is a machining line that produces core engine parts for Ford, its subsidiaries and one of its collaborators (PSA, Peugeot Citroen). The default line produces cylinder head and cylinder blocks for V6 and V8 engines in a variety of different configurations (see Appendix H for details on Ford engine manufacturing tree) which will fit the following cars:

- Ford
- Land Rover
- Jaguar
- PSA

The default line has been modelled using the FIRST interface, from Ford’s work standard for the default line. This default model has the following characteristics:

- Number of machines: 64
- Number of operations: 21
- Default value of: **94.59 JPH**

The default line will be used in majority of the experiments within this research project unless otherwise stated.

## **5.2 *Familiarisation with FIRST***

Familiarisation stage is essential for the understanding of any software package. When using any type of software there must be a certain level of knowledge before research and experimentation can be carried out to an effective level. Many researchers that use software programs for research undertake their familiarisation process within the research itself. This means that their early experimental work cannot be considered acceptable. This project wanted to clearly separate the learning and understanding needed to effectively carry out simulation from the main body of experimentation.

The familiarisation took place over a period of three weeks; a number of these days were spent with the industrial sponsor at Ford. The industrial sponsor, whom is also the software developer, gave an introduction of the FIRST interface by giving a brief introduction on how the program worked and basic operating procedures. The industrial sponsor then highlighted a previous Cranfield thesis by Canero (2004). The project described by Canero (2004) was based on training engineers to use FIRST interface for simulation. The thesis provided an electronic manual on how to build and run simulation experiments using the FIRST simulation interface. This manual was also used to gain enough knowledge to effectively simulate and experiment. For the next two weeks all free time was spent on familiarisation with the FIRST simulation interface. This produced a list of queries and problems which were then raised with the industrial sponsor at the next meeting.

The time allocated for familiarisation produced the necessary confidence to ensure consistency and credibility for all of the experiments. It also provided a good insight into the working of the simulation, which was important for later stages of the project when debugging was needed.

## **5.3 *Identification of experimental Hypotheses to be tested***

Below are is a list of the main hypotheses that will be investigated within this project. These hypotheses were developed and designed within this project and took into account current academic thought, similar projects and preparatory experimentation. Preparatory experimentation is the most important activity which produces a level of understanding of the system which was used to formulate new hypotheses.

1. The effects of pseudo random number streams on simulations have been well documented but presently no research has been carried out into their effects on the FISRT interface package. It is assumed that they significantly alter the results of short run time experiments, therefore experiments could be carried out to quantify their effects and understand how they can be negated.

2. Identifying bottlenecks in the model and reducing their impact on the throughput of the line should increase productivity. All manufacturing lines have a bottleneck as they can never be perfectly balanced. Normally bottlenecks are the slowest machine in the line, which would dictate the production rate of the whole line. If these bottlenecks can be identified as having the highest utilisation, then steps can be taken to reduce their effects on the productivity of the line. Introducing new machinery or technology into a transfer line at key strategic bottlenecks could increase the productivity of the system.
3. One of the bottlenecks of the system could be the number of platens the system uses. If there are too few platens in the system, then an increase in platens could boost the output of the system, reducing the time that machines have to wait for platens.
4. Experiments with the gantry system showed that improving the loading/unloading of the CNC machines could increase their productivity. In most of the cases there is one robotic gantry system for a number of CNC machines, if this gantry fails the whole line could stop manufacturing, therefore an investigation should be undertaken to understand the effects of gantry break downs.
5. Combining operations is when similar operations are combined together to produce a larger cell of machines with a longer cycle time. This combining of operations could potentially lessen the effects of individual machine breakdowns as more machines are producing the same part.
6. Buffer allocation could be increased at strategic bottlenecks in the system, which could reduce the effects of these bottlenecks on the rest of the system by reducing the idle time of the bottleneck operations.

#### **5.4 *Experimental Strategy***

The simulation models that will be used have been shown to be an accurate representation of the real system. For this project each of the simulations was validated based on the industrial supervisor's knowledge and experience, this is known as face validation. Therefore each of the models used has been verified to give a high level of confidence that it will produce an accurate representation of the real system. Appendix C is a flow diagram that can be used as a justification for the benefits of each simulation experiment. To ensure that the experiments are a fair test, each experiment will alter one of the model input variables at one time. Thus any possible results can be directly attributed to the change in results.

Below is a list of the areas of experimentation:

#### **Preparatory experiments**

- EXP: 1 Familiarisation experimentation
- EXP: 2 Warm-up period
- EXP: 3 Run length experiments
- EXP: 4 Random numbers experiments

#### **Main experiments**

- EXP: 5 Experimentation designed by researcher and Ford
- EXP: 6 Number of patterns
- EXP: 7 Buffer allocation
- EXP: 8 Number of machines
- EXP: 9 Combining operations and their cycle times
- EXP: 10 Gantry Break downs
- EXP: 11 Investigating effects of single machine operations on the system

### **5.5 *Experiment methodology***

Before any experiments were carried out a standard methodology was created to ensure that each experiment was designed in the optimum way. It was decided when conversing with the industrial sponsor that the following methodology would be used in the design and execution of the experiments in this research project. The methodology also takes into account academic literature about the best way in which to carry out a simulation experiment. The main influences were Barton (2004) and Law (2003) from which a flow diagram was produced which can be found in Appendix C, which can be used as a justification of each of the experiments that will be carried out within the project. The flow diagram will ensure that each of the experiments has been correctly thought through to maximise its benefits of the understanding of the problem that needs to be investigated.

#### **5.5.1 Purpose**

This is where a hypothesis is defined which led to a question that could potentially be answered using the simulation model.

#### **5.5.2 Method**

The experimental method is where the experiment is detailed and defined in order to show interested parties how it was conducted and what steps are needed to replicate the experiment. Each experiment must be designed to isolate the relationship between the factors (X) which will be varied to affect the simulation productivity (Y). To maximise the likelihood of the

results being a genuine representation of how the actual machining line would vary the productivity (Y), only one variable should be changed in each experiment. If more than one variable is changed then the results cannot be conclusively attributed to the variable value. Therefore whenever possible only one variable will be changed and its effects monitored.

### 5.5.3 Conclusion of experiment

When the results have been collected, they must be compared to the original hypothesis. The hypothesis that was originally formulated should try to be understood compared to the experimental data collected. Experimentation methods and results and conclusions made for each experiment should be documented to ensure that all information is retained for future analysis. In cases where the hypothesis was clearly wrong a new hypothesis could be devised based on the results of the experiment and academic knowledge.

## 5.6 *Preparatory experiments*

Preparatory experiments were used to define some of the experimental variables which could affect the results of each of the following experiments. All of the preparatory experiments have been summarised within this chapter but for each experiment in full with the experimental results see Appendix D.

- EXP1: Familiarisation experimentation
- EXP2: Warm-up period
- EXP3: Run length experiments
- EXP4: Random numbers experiments

### 5.6.1 EXP: 1 Familiarisation experimentation

#### **Purpose**

The main purpose of these experiments was to gain an understanding of the simulation interface and to comprehend interactions within the default model. The secondary objective of these experiments was to familiarise and understand how to carry out simulation experiments and potentially provide some further avenues to investigate.

Once this was fully understood, the model then started to identify possible improvements which could potentially increase the productivity by circa 5%. This process of identifying possible improvements will start with very broad areas and these will become more defined as the experiments begin to show positive results.

## **Findings**

The familiarisation experiments have shown that breakdowns and increasing the number of machines can alter the JPH of manufacturing lines. These experiments have highlighted that when using simulation many experiments have to be carried out in order to gain the best result and that experimenting with an unrealistically high value can produce erroneous results. There was a total of 6 experiments carried out in this section which generated ideas that could potentially be carried on and developed further. From the 6 experiments carried out there were two results that stood out. The first was when each of the operations increased the number of their machines to 10. This showed that increasing the number of machines in the system could increase the systems productivity. The other productivity increase was shown when all breakdowns were removed from the system. Although removing all breakdowns from a system would be very costly it does show that breakdowns play a significant role in the productivity of the system thus should be investigated further.

### **5.6.2 EXP 2: Warm-up period**

#### **Purpose**

The warm up period was also investigated. Robinson (1994) argues that the simulation must pass through an initial transient period known as a “warm-up” period in which no results should be collected. This period must be long enough to negate the time at the start of the simulation when the model is running but has not yet reached normal output levels.

#### **Findings**

From the results of this experiment the warm-up period can be said to have little effect on the output of the simulation model. As shown in the results the standard deviation of the results was less than 0.2 deviations from the mean which can be shown in Table 18. There is also no sign of correlation between increasing the number of warm up days and the JPH level that could be seen in this experiment. A correlation would have been predicted by the research prior to running of the experiment. This experiment is not an extensive investigation into the effects of a warm-up period on the output of the simulation model; but this demonstrates that the correct result has been obtained from the experiments run. This study reveals the reason for not being able to identify a linear correlation between the variable “warm-up period in days” and the simulation output is due to the long run time that was fixed at the start of the experiment. The run time for this experiment was 200 days which potentially could negate the effects of the initial transient period. Thus this experiment was stated that using a high run time of over 200 days a warm up period makes little impact on the output value of the experiment.

**Purpose**

Both of these experiments have been combined together as they share the same question which is stated below:

Research by Pawlikowski (1990) and Kleijnen (1979) has demonstrated that the effects of random numbers on simulation experiments reduce as the run time of the models increases. Pawlikowski (1990) states that after a certain run time the effect of different random numbers is negligible. This means that experiments must be carried out to ensure that random number streams do not adversely affect the result of the experimentation. Once the experiments have been run a random number stream will be selected and this value will not change throughout the research project. These experiments will also identify the optimum experimental run length. Once this experiment has been conducted a run length will be selected and will be made a constant for all following experiments.

**Findings**

The results of this experiment show two distinctive areas of results, the first is that when an experiment is run for a sufficient time for stabilisation to occur, the longer the run time, the tighter the results cluster around the mean. If run time continues to increase, this will eventually result in a straight line and any further increase in the length of experimentation would not make any difference as all effects of randomness would be lost. This experiment has proven a link between longer run times and increased system output. As stated in the purpose of the experiment, longer run times increase the experimental accuracy, thus a balance must be struck between accuracy and time taken per experiment. The original value that was used in experiments was “30 days”. For these results this can be shown to produce instability and thus the pseudo random numbers have a considerable effect on the outcome of the experiment.

The experimental data was used to define a run length that was adequate for the required accuracy of this research project. There is no optimum run length for this research project but from a discussion with the industrial supervisor was held to confirm the interpretations of the results. From this discussion a run time of 200 days was selected. 200 days can be shown from the experimental results to be an adequate number to gain the benefits of long run times without taking too long to conduct the experiments. As a direct result of this simulation experiment a run time of “200 days” will be recommended for future Ford research projects using FIRST.

It can be shown from EXP3 that the 200 day run length allows the simulation experiment to stabilise. This is evident from the differences in standard deviation from the mean. Each experiment fixed the 200 day run time, which gave the lower standard deviation from the mean. This means that the simulation is more stable and less affected by the random number

streams that are used within the simulation. From these experiments it can be stated that although simulation might sometimes be run quickly for fast results, these simulations are being affected by an external variable that may give a misleading result. These simulations are effectively a step up from the probability of rolling dice. A good analogy is a short run time might be equivalent to 10 rolls of a die; this could lead a researcher to believe 5 is the most probable number but each dice roll is independent of all other die rolls. If this experiment was run again 1 million times the randomness would have been negated and it would show that each of the six sides has a equal change to being picked, thus giving the researcher the correct understanding of the system. To conclude, a longer run time has shown to better negate the effects of random numbers, so this will be used as a standard approach for the rest of the experiments.

## 5.7 Chapter summary

This chapter shows how an understanding was gained that was necessary to carry out the simulation project. The experiments described in this chapter also started to identify experiments and hypotheses that could be used to increase the JPH of a generic manufacturing line. An experimental strategy with a list of the proposed experiments has been created as well as an experimental methodology which will be used in future experiments throughout this project. As a result of these experiments into long run times and random number streams, it has demonstrated that longer run times stabilise the effects of pseudo random numbers. Therefore a run time of 200 days will be adopted from this point on. With this 200 day was experimental period the effects of system warm-up are also negated therefore a warm-up of 3 days will be used which will be sufficient time to allow the system to become fully loaded. The Preparatory experiments have also highlighted two areas for further investigation which are breakdowns of key operations and increasing the number of machines in bottleneck operations. All of the preparatory experiments have been summarised within this chapter but for each experiment in full details and experimental results see Appendix D. A summary of the Preparatory experiments can be seen in Table 2.

**Table 2: summary of Preparatory experiments**

| EXP name and number                   | Description                                                                                                                         | Result                                                                                                           |
|---------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------|
| EXP1: Familiarisation experimentation | The aim was to better understand the simulation process using FIRST and potentially produce further experimental avenues to explore | Increase in JPH was found when removing breakdowns and increase the number of machines in the line.              |
| EXP2: Warm-up period                  | The aim was to find a warm up period suitable for the main experiments                                                              | There is no need for a warm up period when a long run time is used as there is little difference in output.      |
| EXP3: Run length experiments          | The aim was to find a run length suitable for the main experiments                                                                  | After interpellation of results "200 days" was selected as the optimum run length for all further experiments    |
| EXP4: Random numbers experiments      | The aim was to quantify the effects of random numbers on long and short run times                                                   | The result clearly demonstrated that random number affected the results of simulation less with longer run times |

## **6 Stage 2: Develop generic proposals via simulation**

Once a complete understanding of the model was developed, experiments were designed with the default simulation model. The aim of these experiments was to develop generic proposals which could increase the productivity (JPH) on a number of manufacturing lines. This process of identifying possible generic improvements will start with very broad areas and these will be defined further as the experiments begin to show positive results.

The aim of this chapter is to document the experiments that were carried out and their findings. These findings will then be assessed against Ford criteria which will be documented below. A number of proposals that meet Ford selection criteria will be correlated together to produce the overall deliverable, which is generic solutions to increase the JPH for any Ford manufacturing line.

### **6.1 *Assessment criteria for experiments***

Each year Ford expects to increase the JPH of each of its lines by a certain percentage. In many cases this percentage is circa 5%. This target JPH increase will allow Ford to remain competitive against other manufacturers. Each of the experiments will be judged against an increase to the default value of circa 5%. The current default value for the default model is 94.59 JPH therefore the aim of each of these experiments is to reach or surpass a JPH of 99.30. Solutions that achieve this percentage increase must also be feasible in terms of implementation, risk to business and cost. These techniques for increasing JPH will then progress to the next stage which is the correlation of potential solutions and further refinement via defined testing.

### **6.2 *General experimentation***

In this section the general experimental work is documented along with the findings for each of the experiments and a decision on whether further investigations are appropriate or whether the line of inquiry should be closed. The general experiments that were carried out are listed below:

- EXP 5: Experimentation designed by researcher and Ford
- EXP 6: Number of platens
- EXP 7: Buffer allocation
- EXP 8: Number of machines
- EXP 9: Combining operations and their cycle times
- EXP 10: Gantry breakdowns
- EXP 11: Investigating effects of single machine operations on the system

All of the general experiments have been summarised within this chapter but for each experiment in full with the experimental results see Appendix E.

#### 6.2.1 EXP 5: Experimentation designed by researcher and Ford

##### **Purpose**

After the familiarisation experiments were carried out, a list of possible experimental strategies were defined and investigated. A meeting was setup with the industrial sponsor to discuss the familiarisation experiments and other hypotheses for increasing the JPH value for the default line. After a number of experiments had been defined and run, a better understanding was gained of how to produce new hypotheses for increasing the JPH of a line.

##### **Findings**

This list of initial experiments produced an understanding of how variations to the machining line would affect the JPH level. This information was then used to understand which areas to investigate further and which experiments were more likely to produce beneficial results. The investigation has shown that gantries do affect the output of the line, thus further investigations should be done to understand the benefits of altering the loading system. These experiments also show that increasing buffers at bottleneck operations does indeed increase the throughput of the line. Also it was shown that better placed machines in bottleneck operations can produce a larger increase in JPH per machine. All these points will be further investigated.

#### 6.2.2 EXP 6: Number of platens

##### **Purpose**

The aim of this experiment is to investigate the effects of platen availability on the productivity of the machining transfer line. A platen is effectively a precision jig that is used to constrain the work piece when machining takes place. They are reusable and effectively govern the amount of WIP that is within the transfer line at any time. A shortage of platens can produce a bottleneck of the system by starving key operations. Therefore, increasing the number of platens will allow more WIP which will allow starved operations to increase their output. After a certain number of platens, the system reaches a point at which new platens will not increase the output of the line and a plateau effect will form. The aim of this experiment is to find the starting point of the plateau and thus the maximum JPH for the minimum number of platens. The system in question has two platen loops which will be independently investigated for optimisation.

### Findings

The result of this experiment has produced an unexpected outcome. Within both loops there were a significant number of excess platens, which were used within the two loops. From the data collected, the number of platens in the loop gave two results: a maximum JPH value created by an optimum number of platens and also a minimum platen level for manufacturing without losing more than 0.5 JPH. The latter provides an acceptable JPH value with a slightly reduced platen count. Both of these values are interesting to Ford, but the minimum number of platens can be found when the JPH level plateaus (see Figure 23 and Figure 24). The maximum JPH value for loop one is 94.72 with 160 platens, whilst the start of the minimum platen level is 100 with a JPH of 94.24. This gives a benefit of 0.008 JPH increase per extra platen on top of 100 platens needed as a minimum value. This information can be shown in Table 3 for both loop1 and loop2.

For this small increase in output Ford would not invest millions of extra pounds unless it would meet Ford’s strict pay back period of less than 1 year which this would not. From this experiment it can be shown that Ford has 95 extra platens than the minimum values which means they have a combined value of -0.35 JPH.

**Table 3: Findings from platen optimisation experiment**

|        | Current platen level | minimum platen level for circa 94JPH | Optimum platen level for JPH | MAX JPH value | Increase in JPH |
|--------|----------------------|--------------------------------------|------------------------------|---------------|-----------------|
| loop 1 | 250                  | 100                                  | 160                          | 94.72         | 0.13            |
| loop 2 | 40                   | 15                                   | 35                           | 94.7          | 0.11            |

### 6.2.3 EXP 7: Buffer allocation

#### Purpose

After establishing a number of bottleneck operations in the transfer line by using the bottleneck detection technique from Roser (2001), the aim of this experiment was to investigate if an increase in pre-operation buffer capacity could increase the JPH value in the bottleneck operations and thus increase the JPH of the manufacturing line.

#### Findings

The results of this experiment show that increases in buffer sizes pre-bottleneck operations does not increase the JPH value in a significant way. The experiments only managed to increase the output of the line by 2 JPH, which is seen to be a small increase for the increase in buffer capacity. The likely explanation for this insignificant increase in JPH is that the bottleneck operations are idle less than 2% of their operating time. Therefore buffers could only increase the JPH of the line by a maximum of 2% of the running time; this 2% running time would also take into account of a period of warm-up time which would reduce the 2% time further. If the bottlenecks were idle for a longer period, such as 15%, then increase in buffer size would have more of an impact on JPH.

Increasing buffer capacity would only help if, for instance, one operation (op1) had a high blockage percentage and the next operation (op2) had a high idle percentage. In this case increasing buffer capacity would increase both operations throughput and JPH. This however would not guarantee an increase in the line JPH as op1 and op2 might not be the bottleneck of the line. Increasing buffer capacity can be a cheap and simple way of increasing JPH providing the previous assumptions are shown to be true and an increase in WIP is acceptable.

#### 6.2.4 EXP 8: Number of machines

##### **Purpose**

The purpose of this experiment was to remove the bottlenecks from the line to increase JPH of the system by adding new machines to bottleneck operations. After the running the default program and analysing the results it was clear that some operations were busier than others. This information was used to strategically place new machines into the default model. The method of bottleneck detection can be seen in the experimental methodology.

##### **Findings**

This method of identifying bottlenecks within the system produced some significant results. Experiment 8A increases the output of the model by >5% to 99.32 JPH. This increase would meet the aim of the project brief to increase the output by at circa 5%. Experiment 8B also increased output by nearly 10% from the base model to 104 JPH. Experiment 8B has doubled the required output for the project; the bottleneck reduction in this experiment has balanced the to an acceptable level. Experiment 8C did not increase the output rate from its base model of experiment 8B. The output rate actually fell by 0.2 JPH. This shows that Experiment 8B is the optimum system using this experimentation method and without changing other parameters. Experiment 8B increases the number of machines by 6 from the base model. This increase could be very costly and also might not be possible due to space restrictions on the factory floor.

#### 6.2.5 EXP 9: Combining operations and their cycle times

##### **Purpose**

This experiment aims to understand if there are benefits in changing the manufacturing strategy of the machining line from “AS IS” to “TO BE” shown in Figure 10. At present the manufacturing strategy that has been adopted is the transfer line. This continuous flow manufacturing technique is quick and very fluid but when machines break down blockages and starvations occur throughout the line reducing its overall efficiency. To combat these

breakdowns, it has been suggested that many stand alone machines which are independent of the line could be used to negate the effects of the blocking and starvation throughout the line.

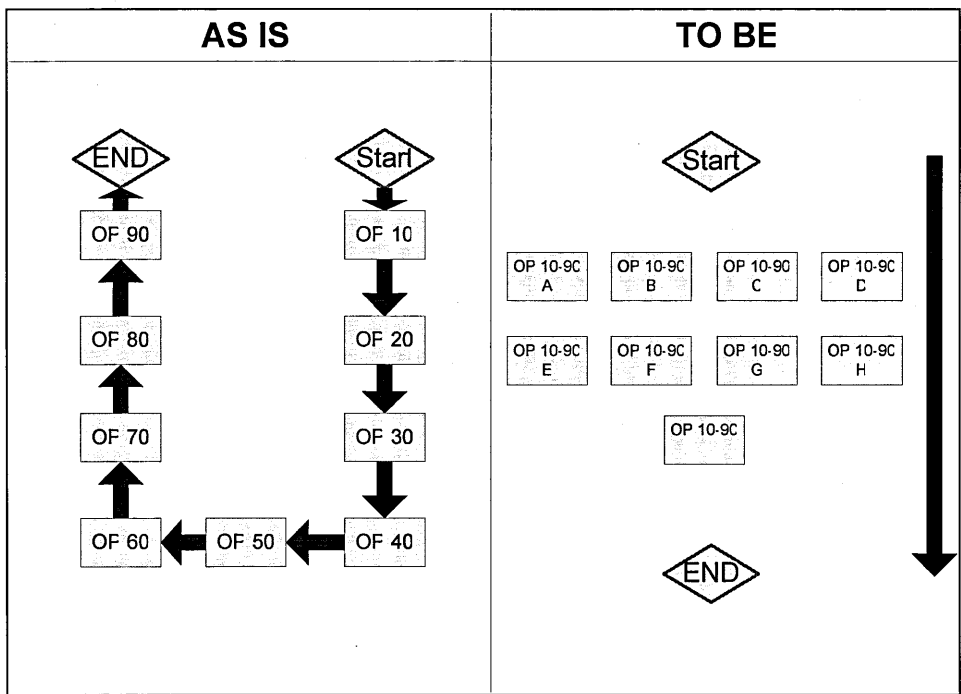


Figure 10: Example of combining operation

### Findings

This experiment has shown that significant benefits can be produced when operations are combined together to form a machining centre capable of carrying out all 180 operations. The output of 112.74 JPH is an increase of 18.15 JPH, which is a **19%** percentage increase. As stated in the industrial problem, this project aimed to find ways in which to increase JPH value by 5%. This experiment shows that this is a possibility. However, a major problem with simulation experiments is that they can lack real-world constraints and this can affect the outcome of the result. A good example of this is experiment 9D, where the likelihood of finding machine tooling that is capable of carrying out 18 different operations within one work centre is very low. None of the machine tools that Ford currently possesses could combine all of these operations together. The amount of investment needed to change manufacturing strategy in this way would be prohibitive.

Although combining all operations together is infeasible, more experiments are needed to investigate the benefits of combining similar operations together on a smaller scale.

From investigating the different states of the machines, combining operations can be seen as a way of reducing operational bottlenecks. Therefore, when possible, instead of increasing the number of machines within the operation, combining similar operations could remove the need to invest in new machines. This technique could be very popular with Ford management

as increases to JPH could be found without the need to invest in a number of expensive machine tools.

#### 6.2.6 EXP 10: Gantry Break downs

##### **Purpose**

The Purpose of this experiment is to investigate the effects of mean time between failures (MTBF) of gantries on the JPH levels in the transfer line. Palmer (1999) states MTBF of all operations within a transfer line becomes critical and so the loading system needs to be investigated to understand its effect on the output of the line. The transfer line is almost fully automated and the CNC machines are fed automatically by gantries. If gantries have a short time between break downs then there would be a high percentage of inactive CNC milling machines in the transfer line. This experiment will increase the mean time between failures for gantries and monitor the effect this has on the JPH of the transfer line.

##### **Findings**

The results of this experiment show the effects of the gantry loading system on JPH for the transfer line. The relationship between the two shows that the increased mean time between failures results in less gantry breakdowns so that the CNC machines can be fed more frequently. This increases their individual JPH and also the overall JPH of the transfer line. This increase in JPH assumes that the gantries will become more resilient to breakdowns, or even have no breakdowns. However, having no breakdowns is highly unrealistic even if system maintenance is resourced at a ratio of one maintenance man to each gantry. Therefore a new type of load/unload system would have to be implemented that would be affected by fewer breakdowns than the current level. This would be expensive and would not be worth the required capital investment. Therefore gantry optimisation could produce good increases in the JPH, but there would always be gantry breakdowns which would affect the JPH of the line.

#### 6.2.7 EXP 11: Investigating effects of single machine operations

##### **Purpose**

The aim of this experiment is to investigate the effects on all single machine operations on the transfer line. The simulation has two types of single machine operation which can be seen below:

**Real operations:** are actual operations that are part of the real system but only use one machine.

**Dummy operations:** are used to help construct the simulation model. They are not present in the real system, but they can help construct the complex logic needed to accurately simulate the system.

## Findings

This experiment was used to gauge the effects of real and dummy operations that had only 1 machine present in them. From the results of doubling each of the single machine operations and removing the breakdown data and tool change data, only a small increase of 1 JPH has been observed. Therefore it can be stated that these operations do not have a significant effect on the overall throughput or JPH of the line. Conversely in experiment 11C breakdowns and tool changes were removed for operations which all have more than one machine within them, (this result can be found in Table 43) which shows a large increase in JPH. These operations are where the majority of the machining is carried out and therefore made a significant change to the output of the model.

**Table 4: summary of General experiments**

| EXP name and number                                                      | Description                                                                                                                             | Result                                                                                                                                                       |
|--------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------|
| EXP 5: Experimentation designed by researcher and Ford                   | A number of experiments that could potentially lead on to further investigation using simulation.                                       | The gantry system has been shown to adversely affect the JPH. Also increasing buffer capacity at pre bottleneck operations has increased JPH.                |
| EXP 6: Number of platens                                                 | The aim was to investigate if the current level of platens hindered the default line in any way.                                        | The result showed there was an abundance of platens in both loops. Reducing the platen level would increase JPH of the line but not significantly.           |
| EXP 7: Buffer allocation                                                 | Understand if increasing buffers to bottleneck operation could increase JPH                                                             | No significant increase in JPH was found when increase buffer capacity to known bottleneck operations.                                                       |
| EXP 8: Number of machines                                                | Understand if increasing number of machine in bottleneck operation can increase JPH of the line                                         | 6 strategically placed machines increase the JPH by circa 10% to 104.72 JPH.                                                                                 |
| EXP 9: Combining operations and their cycle times                        | Understand if combining all or some operations together would increase JPH of the line by reducing effects of single machine breakdowns | Combining operations has increased JPH and has proven the hypothesis that single machine breakdowns can greatly effect out of a manufacturing line.          |
| EXP 10: Gantry breakdowns                                                | Understand if the gantry breakdowns affect the JPH of the default system adversely.                                                     | Increasing the MTBF of the gantry system and removing it completely showed that the current gantry system effects the productivity of the manufacturing line |
| EXP 11: Investigating effects of single machine operations on the system | Understand if single machine operations affect the JPH of the default system adversely.                                                 | The results of this experiment show that single machine operations do not significantly alter the effects of the default system.                             |

### 6.3 *Defined experimentation*

After the general experimentation was completed there were a number of further questions that had been developed from the previous set of experiments. These defined experiments were then carried out to fully understand the implications of all of the experimental findings.

EXP 12: Varying new machine locations

- EXP 13: Combining operations with /without gantries
- EXP 14: Combining effects of previous buffer experiments
- EXP 15: Increasing the number of gantries
- EXP 16: Gantries breakdown on balanced line
- EXP 17: Testing the combining process

All of the defined experiments have been summarised within this chapter but for each experiment in full with the experimental results see Appendix F.

#### 6.3.1 EXP 12: Varying new machine locations

##### **Purpose**

This experiment follows on from the general experiments that were carried out which stated that there could potentially be large benefits in increasing the number of machines in strategic bottleneck operations. The experiment will determine whether adding new machines to the line will increase their individual and combined JPH. This will change the aim of the experiment from maximising JPH to a more realistic target of maximising JPH per machine investment.

##### **Findings**

After many variations of adding new machines to bottleneck operations, it has been found that this does not only increase the JPH value to above the 104 JPH, as shown in experiment 8B. Adding new machines following this methodology also produces better increases in JPH per extra machine. This process of adding new machine to bottlenecks has been found to be a repeatable methodology. For the first few bottlenecks, new machines should be placed in operations with the highest busy rate, but as the system becomes more balanced this methodology changes. After this point it could be better to put a machine in other operations which may not have the highest busy rate. Although the operation may not be the largest bottleneck of the system, adding a machine can enable the system to balance other operations pre and post, which could have a combined effect greater than any individual bottleneck operation. Finding such operations is a matter of trial and error; this is why many experiments

were run to identify such operations. This technique has proven that increasing machines in bottleneck operations can increase the JPH value of the line.

### 6.3.2 EXP 13: Combining operations with /without gantries

#### **Purpose**

The aim of this experiment is to investigate combining operations with and without the effects of the gantry loading system. When combining operations together a gantry system becomes highly expensive, so this experiment will try to evaluate the benefit to the transfer line.

#### **Findings**

The findings of this experiment have been shown before in EXP: 10, where removing the effects of gantries increased the JPH by circa 6%. When combining operations together without gantries, the JPH increases and is then offset by the removal of the gantry system. Therefore it can be stated that both combining operations and removal of gantry breakdowns increases the JPH of the system and together they increase the JPH considerably. The findings from this experiment show that the current transfer system has some disadvantages when it comes to breakdowns and unexpected stoppages. This experiment has also shown that enhancing the gantry system can be added to another optimisation technique to further balance the manufacturing line and maximise the JPH.

### 6.3.3 EXP 14: Combining effects of previous buffer experiments

#### **Purpose**

Although no significant benefits were found in experiment 7, increasing strategic buffer sizes, it was decided that certain combinations of the increased buffer sizes could produce more noticeable results. Thus the aim of this experiment is to understand if combinations of increased buffers can potentially change the transfer line output.

#### **Findings**

As shown in the previous experiment 7 and within this experiment, there was no significant benefit from increasing buffer capacity for bottleneck operations. The best result was 97.23 with an extra 400 buffer capacity spread over the four major bottlenecks. This experiment and its predecessors have proven that in this instance buffer capacity does not increase the JPH sufficiently to merit the investment required from the default model. Another observation was that at a highest buffer capacity there was no difference between the experiment with or without extra platens. This could be because the increase in buffer capacity was so large, the length of time a platen was in the conveyor removed the need for extra platens. This finding though cannot be substantiated on these experiments alone.

#### 6.3.4 EXP 15: Increasing the number of gantries

##### **Purpose**

As shown in previous experiment (EXP: 10) gantry systems can have a profound effect on the JPH of the line. In previous experiments the breakdown data has been altered to produce increases in reliability. This experiment investigates increasing the number of gantry systems in operations that are known bottlenecks or have potential gantry issues.

##### **Findings**

Increasing the number of gantries in the system does not have the same effects as removing all of the gantry breakdowns. The increase in gantries has been shown to increase the JPH by circa 5%. This would potentially incur a large investment cost that would not balance any of the benefits in doubling up the gantry loading systems. Doubling gantry systems in bottleneck operations produced an increase in JPH but it does not address the root cause of operations that are bottlenecks in the system. An analogy for this would be buying ice to cool beverages rather than tackling the root cause which could be that the fridge is broken. Therefore increasing the number of gantries in any situation should not be used unless there are significant idle periods which could be reduced by adding extra gantry operations to increase the JPH of bottleneck operations.

#### 6.3.5 EXP 16: Gantry breakdowns on balanced lines

##### **Purpose**

This experiment follows on from the general experiment (EXP: 10) detailing the effects of gantry breakdowns. This experiment will investigate the same effects of gantry breakdowns but on a balanced line. This experiment was designed in the same way as the original but with all operations balanced. This experiment could show if the gantry loading system affects the line or if breakdowns just magnify the existing bottleneck operations.

##### **Findings**

The results from the experiment clearly showed that gantry breakdowns do influence the JPH of the line, but the significance of this must be questioned. In the original experiment in the unbalanced line there was an increase of 6% in JPH between running the experiment with no breakdowns and running the system with gantry breakdowns. Conversely, in this experiment, when the line has been balanced, removing breakdowns increased the JPH by 3%. This seems to suggest that gantry breakdowns can affect bottleneck operations and thus the whole line can suffer as a result. When balancing the line a higher than average cycle time was used which significantly reduced the JPH of the system. Therefore it can be said that gantry breakdowns affect the whole system and especially individual bottleneck operations.

6.3.6 EXP 17: Testing the combining process

Purpose

The goal of this experiment is to investigate the effects of combining operations which have equal cycle times. A cycle time of 5 and 0.5 was used in this experiment to understand if combining operations can be used to increase JPH on balanced line with higher and lower average cycle times than the mean of the system. This experiment will evaluate the technique of combining operations, comparing its benefits on balanced and non balanced lines.

Findings

From the results of this experiment, it can be shown that combining operations with equal cycle times does not produce the same increases in JPH as found in previous experiments (EXP: 9) with an unbalanced line. This can be attributed to the fact that combining operations effectively balances an area of the line, which could reduce the bottleneck operations cycle time. When all operations have equal cycle times the increase in JPH can be seen as minimal. It seems that the longer cycle times have a greater effect when combining operations together. This could be due to decreasing the likelihood of breakdown effects on subsequent operations.

Table 5: summary of Defined experiments

| EXP name and number                                      | Description                                                                                                                                   | Result                                                                                                                                                                                         |
|----------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| EXP 12: Varying new machine locations                    | To further investigate the benefits of placing machines in strategic bottlenecks.                                                             | The method produced in this experiment has been proven to increase JPH with a limited number of more optimally placed machines                                                                 |
| EXP 13: Combining operations with /without gantries      | To understand if combining operations is affected by the gantry system. Does the gantry system still affect the JPH of the system?            | When combining operations without the effects of gantries, a large increase in JPH is observed. Therefore the gantry system is still affecting the JPH of the system.                          |
| EXP 14: Combining effects of previous buffer experiments | To understand if increasing buffer capacity in more than one operation at once increase the JPH significantly.                                | This experiment shows that increasing buffer capacity makes little difference to the JPH of the line.                                                                                          |
| EXP 15: Increasing the number of gantries                | Identify if increasing number of gantries will reduce the effects of the current gantry system on the default line.                           | If each gantry system is increased then benefits can be seen similar to reducing MTBF. This shows that MTBF is a problem for gantry system.                                                    |
| EXP 16: Gantries breakdown on balanced line              | Identify if gantry system is a bottle neck of the system on its own or is the gantry system affecting the output of the bottleneck operations | This experiment shows that although the gantry system is a small bottleneck of the system it affects the output of the bottlenecks. This produces the largest effect on the JPH of the system. |
| EXP 17: Testing the combining process                    | Identify if combining operations increases JPH via balancing line or by other means                                                           | This experiment shows that combining operations increasing JPH by balancing the line operation, thus combining operations should be concentrated on bottleneck operation to maximise benefits. |

## 6.4 *Correlate potential solutions*

In this section a list of solutions will be compiled which could potentially be used as generic solutions for optimising other manufacturing lines. Producing these potential solutions will allow future projects to build upon the work that has been achieved in this research project and may allow simple and quick optimisation of further manufacturing and assembly lines.

From the solution matrix shown in Table 15 within Appendix B, 3 solutions were identified as being potential generic solutions that have been proven to increase the JPH on this line and could feasibly be implemented in the real system. The fourth solution “platen optimisation” has been used in a number of previous Ford optimisation projects for different lines with a substantial success rate in increasing JPH. In the experiments that were carried out in this research project, “platen optimisation” did not produce any large increase in JPH. For this reason and also because this is a known generic solution, platen optimisation will not be put forward as a generic solution. Therefore the three generic solutions are:

- Varying new machine locations
- Combining operations and their cycle times
- Reducing gantry breakdowns thus improving reliability of gantries

## 6.5 *Chapter Summary*

This chapter has developed several different hypotheses and has also produced a number of general and defined experiments, the purpose and findings of each of which are summarised in Table 4 (general) and Table 5 (defined). These experiments have produced a large increase in the JPH and have shown where and how certain optimisation techniques can increase a system’s JPH. As a result of these experiments a number of possible solutions have been shown to produce the type of increase in JPH which is required for this project. For stage three of the project, 3 generic solutions have been put forward, each of which could potentially increase the JPH of any line. They have been tried and tested on the current default manufacturing line and should be transferable to other manufacturing lines throughout Ford. All of the general and defined experiments have been summarised within this chapter, but for each experiment in full with the experimental results see Appendix E and F respectively.

## **7 Stage 3: Application of previously developed generic proposals to different manufacturing lines**

The aim of this chapter is to document the process of running experiments on different machining lines using generic proposals to potentially increase the JPH values of the machining lines. The three generic proposals which were defined in stage 2 can be seen below:

- Varying new machine locations
- Combining operations and their cycle times
- Reducing gantry breakdowns

This process could potentially show that generic solutions can be created to increase productivity on a variety of different manufacturing lines. This process will also show whether the proposals are actually generic or specific to a number of manufacturing lines. Using the three generic proposals the aim of the following experiments is to optimise each of the new lines and increase the JPH of both new lines by circa 5%.

### **7.1 *New lines***

Two new simulation models were obtainable via the industrial sponsor. Both simulation models are representations of two different manufacturing lines within Ford Europe. For more information on both lines see Appendix H for details on Ford engine manufacturing tree.

Both new simulation models have been created by the industrial sponsor using the FIRST interface developed by Ford. The two models simply employ different input variables for their respective Ford work standards. This enabled the research to transition seamlessly between the different simulation models. Each of the models have been face validated via the industrial sponsor and a number of process engineers who work with the machining lines in question. The two manufacturing lines are detailed below:

#### **7.1.1 Line 1 REP**

Line 1 is a machining line called LYNX, henceforth referred to as “REP”. REP is a machining line that produces core engine parts for the Ford automobiles including the following brands:

- Transit connect
- Courier
- Fiesta pickup
- Focus

REP is a machining line which produces cylinder heads and cylinder blocks for diesel engines with a 1.8 litre capacity. The machining line also has many assembly operations embedded in it. These operations are carried out at this stage of production for simplicity. This REP simulation model has the following characteristics:

- Number of machines: 80
- Number of operations: 25
- Default value of: **138.40 JPH**

Benchmarking REP against the default line there is a significant difference in JPH. The REP line has a throughput of 138.4JPH, 43JPH more than the default line. This large throughput will make it much easier to find a solution to increase the output by a significant number. The REP simulation model was used in experiment numbers EXP: 18, EXP: 20 and EXP: 22.

#### 7.1.2 Line 2 Only Block

Line 2 is called OnlyBlock\_V8, which henceforth will be referred to as “Only Block”. Only Block is a variation of the Lion head machining line, which, as the name suggests, only produces cylinder blocks for V8 engines. Only Block is a standalone machining line that has been produced to meet the increased demand for V8 engines in two models of Ford’s most popular subsidiary luxury automotive brand Jaguar. Only Block simulation model has the following characteristics:

- Number of machines: 45
- Number of operations: 17
- Default value of: **42.74 JPH**

The Only Block has a lower JPH than the default model, almost half of the defaults JPH. This low throughput will make it very difficult to produce solutions which will meet Ford’s strict pay back period. The Only Block simulation model was used in experiment numbers EXP: 19, EXP: 21 and EXP: 23.

### 7.2 *Experiments using the three generic proposals*

The three potentially generic solutions will be used for both the REP and Only Block machining lines. Each experiment will be carried out using the same methodology as the original experiment. All of the experiments using the three generic proposals for lines REP and Only Block have been summarised within this chapter but for each experiment in full with the experimental results see Appendix G.

### **7.3 Experiments on REP line**

Below is a list of the three experiments that were carried out on the REP simulation model:

#### **7.3.1 Varying new machine locations EXP: 18**

##### **Purpose**

In this experiment the major bottlenecks of the line were first identified using the Roser, (2001) bottleneck detection method and then a series of experiments were carried out adding new machines to operations seen to be potential bottlenecks.

##### **Findings**

20 experiments were carried out to find the optimum number of machines placed in different operations. As stated previously creating the best solution cannot only be found by investigating the busiest operations. Finding the optimum solution required many variations on the basic experiment. One experiment in particular showed one operation (OP50) to be a major bottleneck of the line. Once this operation was identified as being the key to balancing the line, significant increases in JPH were established. In this instance increasing the number of machines in the bottleneck operation increased the JPH output by roughly 10%; this was seen to result in a considerable increase in the overall output of the manufacturing line.

#### **7.3.2 Combining operations and their cycle times EXP: 20**

##### **Purpose**

Combining operations allows a number of operations to be combined which will reduce the impact of individual machines' breakdown and cycle times on the JPH of the line in question. Operations were only combined together if they were shown to be CNC machines that were close together (i.e. in the same loop). In a system there would be a number of separate loops and operations can only be combined when they are in the same loop, this generally means they will be close to each other.

##### **Findings**

This experiment did not produce any large increases in JPH. The only large JPH increase was produced when combining operations and adding extra machines to known bottleneck operations. This was done because some bottleneck operations were not suitable to be combined with other key operations but they still posed a major bottleneck for the system. When combining operations which could be shown to have bottleneck properties no measurable increase was produced. One hypothesis for this was that the line was generally more balanced than the default model and from findings of previous experiments combining operations does not show the same increase in JPH when a line is fully balanced. It has also

been shown that OP50 is a key operation that greatly affects the output of the line which seems to contradict the hypothesis that the line is balanced. Potentially the line could be in a state of balance compared to the default line; this however is difficult to prove as the two lines are very different.

When combining operations a standard method had been created which always combines operations in the first operation, the operation with the lowest identification number. After some unsatisfactory results this method was changed to again combine operations and house the new operation in the operation with the highest busy percentage. This new method gave significantly better results compared to the original experiments, but the significance of this can not be quantified from the limited number of experiments that were carried out. Certainly when combining operations together any researcher must think very carefully where the new operations are placed to give the correct result.

### 7.3.3 Reducing Gantry Break downs EXP: 22

#### **Purpose**

The experiment into reducing the effects of gantry breakdowns on the system followed the previous experimental methodology which increases the mean time between failures so that the breakdowns to the gantry system occur less frequently.

#### **Findings**

All of the experiments were carried as in the previous gantry experiments, but no increase in JPH was recorded. In fact the most significant increase that was produced from the experiments showed less than 1.5% increase in JPH (EXP: 22M). This increase was produced by removing all of the effects of a gantry system, thus no gantry break downs or cycle times for each gantry operation, this effectively removed any effect of the gantry system on the manufacturing line.

Other experiments were carried out including equal ratio between machine to gantry and no cycle times for gantries. The reason for no increase in JPH can be found when looking in detail at the systems' work standard log. It can be clearly shown that gantries in the simulation that were supplying key and bottleneck operations had little effect on the productivity of the operations. On closer inspection of each of the gantries a number of gantries loading operations had been doubled up, to reduce the effects of the gantry system on key operations. Thus the understanding developed within this research project suggests that the gantry system had already been optimised to negate the effects of the gantry breakdowns within this line. This hypothesis was later confirmed by the industrial sponsor; therefore the gantry system does not affect the output of this manufacturing line.

## **7.4 Experiments on Only Block line**

Below is a list of the three experiments that were carried out on the Only block simulation model.

### **7.4.1 Varying new machine locations EXP: 19**

#### **Purpose**

In this experiment the major bottlenecks of the line were first identified and then a series of variations of adding new machines to operations seen to be potential bottlenecks were investigated.

#### **Findings**

This experiment produced a variety of results which were tightly clustered around the default JPH for the system. This led to the hypothesis that the system could have been previously optimised. This statement was later confirmed by the industrial supervisor who confirmed there had been a previous optimisation project based on this line.

As before, one operation (operation 130) seemed to be a key operation in increasing JPH. Adding one machine to this operation increased the JPH by circa 5%, which made this the largest single increase in JPH within this line, with just one extra machine added to the system.

In the end there was a list of 4 potential solutions that would increase the JPH of the system but each one of these would have to be costed to find the most cost-effective solution to the optimisation problem.

### **7.4.2 Combining operations and their cycle times EXP: 20**

#### **Purpose**

Combining operations allows a number of operations to be combined which will reduce the impact of individual machines on the JPH of the line. Operations were only combined together if they were shown to be CNC machines that were close together. In a system there would be a number of separate loops and operations can only be combined when they are in the same loop.

#### **Findings**

This experiment produced very insignificant results. There were potentially many operations that could have been prime candidates for combining, but when combined together the results

did not increase JPH beyond 1%. The main reason for this is the line has been highly balanced in the design stage and as shown in experiment (EXP: 17) lines that are balanced show little increase in JPH when operations are combined. Many of the operations have the same cycle time which means that only operations with a high cycle time could potentially be improved. These operations unfortunately only produced small increases in JPH which would not have been large enough to warrant the improvements from a strategic investment standpoint. These experiments were then tried again without breakdowns. Again, insignificant increases in JPH resulted.

As stated in the previous experiment, operation (OP130) was shown to be one of the major bottlenecks in the system, thus combining it with other operations seems like a sensible move. At first there was little improvement, and then another machine was added to the combined operation. This produced a 5% increase in JPH. The last experiment was combining the same operations again but housing the one large operation in op130. This produced the highest JPH increase of more than 5%. This again shows that when combining operations together it is very important to include the operation with the highest percentage busy in order to gain the maximum increase in JPH.

#### 7.4.3 Reducing Gantry Break downs EXP: 23

##### **Purpose**

The experiment into reducing the effects of gantry breakdowns on the system followed the previous experimental methodology which increased the mean time between failures so that the breakdowns to the gantry system happen less frequently.

##### **Findings**

After the problems with the REP gantry breakdowns where the gantry system had been clearly optimised previously, the experiments started by comparing no breakdowns with the original value. With no breakdowns the increase was a fraction over 1%, therefore it was decided that any other experiments between the normal value and no breakdowns would not produce significant results. Further experiments were carried out increasing the number of gantries and zero cycle times and breakdowns for the gantries. None of the experiments produced any significant results with the highest increase of JPH being circa 1%. This clearly shows that in case of the Only Block manufacturing line the output of the lines is not affected by the gantry loading system.

#### **7.5 Summary of proposals**

In this section each of the three proposals will be evaluated based on their original generic potential for increasing JPH and their future applications will be summarised.

### 7.5.1 Varying new machine locations

Increasing the number of machines in strategic operations throughout different manufacturing lines has proven successful in three different manufacturing lines. Each of the lines JPH increased, using the method of adding a number of new machines to the lines in key bottleneck operations. As long as a line is not 100% balanced then adding new machines to operations, when done correctly, will increase the JPH of the line. This technique has certainly produced some mixed results and can be very time consuming. Many experiments must be carried out to understand which operations will benefit the most from additional machines.

In both REP and Only Block, one operation yielded a significant increase in JPH for both lines when the bottleneck was addressed. This however was not the case in the default line. Only when a number of machines were added to the line were real increases in JPH observed. It cannot be taken for granted that in every line there will be an operation that once optimised will increase the line's JPH so dramatically.

There was also no logical way to document how to find the optimum arrangement of new machines in a line, but if future researchers take the approach of increasing JPH per machine added to the line, this will ensure that justifying the cost of additional machines becomes the main objective rather than simply maximising overall JPH. In summary, this technique can potentially be used in any line and if sufficient experimental resources are available significant increases productivity can be produced.

### 7.5.2 Combining operations and their cycle times

Combining operations was found to work well in the original model due to the unbalanced nature of the line. It has worked in both subsequent lines but only when a bottleneck operation was found and operations were combined within the key bottleneck operation. From the experiments that have been carried out in this project, combining operations can be said to work less well when a line is balanced. This can be attributed to the fact that combining operations effectively balances a small piece of the line, thus lowering the average cycle time.

Combining operations when correctly identified can produce significant JPH increases without problematic cost implications and most importantly no large capital investments such as new CNC machines.

### 7.5.3 Reducing Gantry Break downs

Gantries systems should only be investigated when they are amplifying the bottlenecks within the system. Gantries are only the loading/unloading system used to automate the machining operations. Therefore if the gantries' busy percentage is affecting the idle time of the CNC

machine they are servicing then investigation of gantry systems should be undertaken. In REP this optimisation had already taken place with a number of double gantries servicing one operation. Only Block had not been optimised but there were no operations that were being starved by the gantry system. If gantry systems increase the output of key bottlenecks within a line, adding new gantries or reducing the MTBF could be used to increase the output of the line, but this was not the case in REP and Only Block lines.

## **7.6 *Experimental research findings***

This section will discuss the findings of the research which are not correlated to the aims and objectives of this project but are important findings that have resulted from the process of experimentation.

### **Long run time**

One of the findings from this research project is that longer run times enable simulations to negate the effects of the pseudo random number streams that can have a significant effect on the output of the simulation experiment. These findings prove for the first time that the FIRST interface is also affected by pseudo random numbers. These experiments had not been carried out prior to this project. Therefore it can be said that the FIRST interface is susceptible to the effects of its random number streams and experiments EXP: 3 and EXP: 4 have shown that a 200 day run time will give more accurate results.

### **Warm-up period**

When running experiments that are 200 days long there is no need to add an additional warm up period as shown in EXP: 2. From this experiment the result suggests there is no real difference between running an experiment with zero or 30 days of warm up for the system. This is because the long 200 day run time is large enough to negate the first couple of days when the system is not running a full capacity.

### **Individual operation**

Experiment EXP: 11 has shown in the case of the default experiment that the single machine operations that are 'Dummy operations' (which are used to simplify the model building), do not affect the result of the simulation in a significant way. This means that although these dummy operations are fabricated only to simplify the building of the simulation, they do not have any undesirable effect on the simulation. This point, although simple, has been highly contested within Ford with engineers posing this question to the designer of FIRST, therefore the result of EXP: 11 should finally settle this debate.

### **Platens optimisation**

In the experiment EXP: 6 the default experiment was shown to have surplus platens for its requirement in both loops.

The default model experiment showed no significant benefits by reducing the platen levels. However, when interviews were carried out to potentially sell excess platens to other Ford facilities, to offset any potential optimisations cost for the default line, it was pointed out that the platen pool cannot be reduced as new lines that are in development will share the current platen pool. Platen optimisation has been a successful technique and although not able to increase JPH significantly in this project it should not be underestimated for future optimisation projects.

## **7.7 Chapter Summary**

To summarise this chapter, each of the three generic proposal solutions have been simulated for the two European machining lines with varying results. All of the experiments using the three generic proposals for lines REP and Only Block have been summarised within this chapter but for each experiment in full with the experimental results see Appendix G. Each of the lines has had its JPH value increased by at least 5% using the three generic proposals for increasing productivity. The other objective of this chapter was to test each of the three generic proposals to understand whether they were generic or specific to the default simulation. It can be said that “Varying new machine locations” and “Combining operations and their cycle times” from experiments in this chapter have been shown to be generic methods to increase JPH. Conversely, “Reducing Gantry Break downs” has been shown to be specific to manufacturing lines with bottleneck operations which are affected by their gantry loading system. Finally a number of experimental research findings have been documented which are not linked to the aim and objectives of this research project but are relevant to Ford.

## 8 Stage 4: Developing a business case

In this chapter options for increasing productivity (JHP) for each of the three lines will be evaluated against a series of recognised benefits and drawbacks. Each solution will be shaped into a business proposal which can be presented to the senior management at Ford. The aim of this chapter is to produce business cases for each of the potential solutions, based on the results of the simulations carried out within this research project as well as information gathered from Ford personnel.

### 8.1 *Creation of the solution matrix*

Once all of the data was collected, it needed to be presented in a way which enabled senior management at Ford to see it holistically and easily understand its ramifications. The management would then be equipped with all of the data needed to make an informed decision on the correct course of action to fit with Ford's productivity mission statement.

### 8.2 *Evaluation of benefits*

The evaluation of the benefits of each proposal will be done in a way most appropriate for each proposal. All of the evaluation techniques will centre around two variables: *cost of implementation* and *increase in JPH*.

Payback period is one of Ford's main investment criteria for its productivity projects. Ford's normal payback period is only a year, which is quite short compared to other manufacturing business (e.g. BOC Edwards' payback period is 2 years). The reason for the very short payback period is that Ford cannot allow itself to significantly reduce its liquid capital as this could increase commercial vulnerability.

Increase in JPH per new machine is an evaluation technique that was produced within this project to emphasise value for money as the overriding factor when evaluating and comparing proposals for increasing the number of machines. It also allows senior Ford management to understand the real benefit each machine will give to the existing line in terms of the number of extra parts that can be produced per year.

### 8.3 *Cost*

Each of the proposals will be fully costed to the level that is needed for the first level of senior management appraisal. As stated before costing information was collected from a Ford cost expert who has costed similar projects previously.

Table 6 shows a breakdown of the generic costs that will be used for each of the proposals.

**Table 6: Breakdown of generic costs for key manufacturing products**

| Product                 | Cost             |
|-------------------------|------------------|
| CNC machine             | £500,000         |
| Gantry system           | £100,000         |
| CNC machine tooling set | £50,000          |
| Increase in gantry MTBF | Circa £1,000,000 |

Below are some of the assumptions that have been made when calculating these costs with help from the Ford costing expert.

#### 8.3.1 Varying new machine locations

If a new machine is needed the cost would be circa £500,000. This price is based on the previous projects Ford has undertaken which involve buying CNC machines from their main supplier Cross Huller. The £500,000 covers the machine, its installation and all other associated costs that are external to Ford. Therefore this is the only external cost to Ford when they purchase a new machine.

#### 8.3.2 Combining operations and their cycle times

When combining operations it is assumed that each of the machines that will be combined does not need to be replaced, but they would only need extra machining tooling sets. Each machine in the new combined operation would need a set of tools for each of the newly combined operations with an average cost of £50,000. An example of this is shown below.

If 3 operations were to combine together, each with 3 machines, there would be a need for  $2 \times 9 = 18$  new tooling sets, thus 18 sets of tools would need to be bought @ a cost of £50,000 each, costing a total of £900,000.

#### 8.3.3 Reducing Gantry Break downs

Reducing gantry breakdowns had never been costed prior to this project, so brainstorming was carried out with several Ford engineers. The following cost breakdown is understood to be quite generous, which ensures that the benefits identified for each proposal are conservative. The cost has been set at £1,000,000 which has been broken down into the components shown in Table 7.

**Table 7: Cost breakdown of expenditure for reducing gantry breakdowns**

| Description                                               | Cost in £        |
|-----------------------------------------------------------|------------------|
| Extra mechanics @ £70,000 each, 5 in total                | 350,000          |
| Increase training budget for maintenance crews            | 200,000          |
| Preventative maintenance                                  | 150,000          |
| Self-Monitoring Analysis and Reporting Technology (SMART) | 300,000          |
| <b>Total</b>                                              | <b>1,000,000</b> |

**Extra mechanics@ £70,000 each 5 in total**

The five extra mechanics will be split over the existing shift systems to allow each shift to have another mechanic on standby throughout the shift to reduce machine down time. £35K will be used for an annual salary. The other £35K takes into account all of the essential training costs each of the mechanic, national insurance, pension contribution and all other human resource costs of employing each new mechanic. This cost of £350K is an annual cost, **not** a one off payment.

**Increase training budget for maintenance crews**

This will allow all of the existing maintenance personnel to be retrained with the latest preventative maintenance techniques. Hour slots of training could be started before each shift started. This cost would also take into account of an overtime allowance needed for working an hour before their shift.

**Preventative maintenance**

This cash allocation will be spent on the line in areas that are thought to be potential breakdown bottlenecks. The cash will be used to buy, replace and install new technologies.

**Self-Monitoring Analysis and Reporting Technology (SMART)**

As stated in the literature review the alert system in Ford's manufacturing lines has a limited success rate. Installing a SMART system would give all mechanics a pager with allows each mechanic to be informed and allocated to breakdowns as soon as they occur.

Jerry Kumba, a manufacturing engineer who works with a number of the transfer lines discussed within this project, stated that the current maintenance system within the lines he works on are a large problem for production. He stated that "there is not enough maintenance labour for the number of breakdowns that occur". He has also stated that lots of production time is lost in maintenance staff responding to stoppages and that he would certainly champion the SMART system throughout Ford.

**8.4 Implementation/ time frame**

This section will document the timeframes for implementing each of the three generic proposals. This section will also take account of Ford's track record with implementing similar projects and whether the proposal fits with Ford's current strategy for increasing productivity.

**8.4.1 Varying new machine locations**

Varying new machine locations has long been the standard way for Ford to increase the JPH in a manufacturing line. In fact all Ford transfer lines are built with additional spaces to enable additional machines to be added if the demand of the line increases.

#### 8.4.2 Combining operations and their cycle times

Combining operations is not normally done by Ford after the design stage as once a line has been built this has been found to be problematic. If the proposal for combining operations is implemented then each of the operations would warrant a capability survey to ensure that the combined operations are compatible with the machines. Once this has been confirmed the machines would then have to be reconfigured to enable the operations to be combined. As this normally happens at the design stage, this task could take a significant amount of time during which the transfer line would have to be stopped. To avoid long periods of downtime, changes could be made on single machines to enable a smooth transition between the current state and the proposed combination of operations. Another idea for implementation would be to gradually combine operations in individual machines. Both of the above techniques could potentially be used together to de-risk implementation, but this would extend implementation time.

#### 8.4.3 Reducing Gantry Break downs

Reducing gantry breakdowns has never been done so the implementation time is uncertain. Also, unlike buying a new machine, which will deliver a predictable JPH increase, it is not possible to predict when the benefits from reducing gantry breakdowns will be realised. A Ford gantry expert estimated that it could take up to six months before benefits are seen.

### 8.5 *Feasibility*

Within this project, work was carried out with a number of Ford production engineers. Before each experiment was carried out the hypothesis and the intention was presented to a number of Ford production engineers, using their combined experience each experiment was analysed to ensure that the understanding of the problem and the solution was potentially feasible. Below the three generic solutions will be briefly described and their feasibility will be examined based on current best practise at Ford and also results of previous projects.

#### 8.5.1 Varying new machine locations

Adding new machines into bottleneck operation is one of Ford core optimisation techniques. Ford produces manufacturing lines with additional spaces for machine in case added output is required. Therefore this technique is highly feasible.

#### 8.5.2 Combining operations and their cycle times

Combining operations together is normally carried out at the design stage and so is certainly a recognised form of increasing productivity in a manufacturing line. A number of Ford production engineers raised the point that if possible to combine operations it would have

been done at the design stage of the manufacturing line. The production engineers also stated that if the operations were close together and were made up of similar operations then combining operations could be a feasible solution to increase JPH.

### 8.5.3 Reducing Gantry Breakdowns

Reducing gantry breakdowns is a feasible option to increase JPH. The problem is there can be no guarantee that the investment put into the manufacturing line, will increase the JPH to the level that can be shown in the experimental results. The problem is there is no definitive link between investment in maintenance and an increase in productivity. Therefore the technique is feasible but the benefits cannot be quantified.

## 8.6 *Problems*

To give a balanced view of the potential solutions, the list of possible implementation problems below was identified via brainstorming with Ford engineers:

- Training
- How will the current line altered
- Impact on breakdowns
- Complexity

Table 8 shows the potential problems that could effect each of the generic solutions.

Table 8: Potential problems with generic solutions

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Varying new machine locations</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |
| <ul style="list-style-type: none"> <li>• <b>Training:</b> no new training will be required</li> <li>• <b>How will the current line altered:</b> the line will not be adversely effected</li> <li>• <b>Impact on breakdowns:</b> there will be a number of extra machines which would potential decrease the MTBF of the transfer line in question; this is due to added complexity.</li> <li>• <b>Complexity:</b> this adds no complexity to the systems logic or operations apart from increased maintenance.</li> </ul>                                                                                                                                                                                                           |
| <b>Combining operations and their cycle times</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
| <ul style="list-style-type: none"> <li>• <b>Training:</b> a small amount of extra training will be required to load/ unload the tooling sets</li> <li>• <b>How will the current line altered:</b> in the implementation stage there could be problems affecting the whole line. This solution could fundamentally change the way the transfer line would operate, see Figure 10 for details.</li> <li>• <b>Impact on breakdowns:</b> the MTBF of the line should stay the same but the effects of the JPH should reduce so that the MTBF becomes less critical.</li> <li>• <b>Complexity:</b> Would add some complexity to the system, this would cause an increase in loading of tooling sets, as more would be needed.</li> </ul> |
| <b>Reducing Gantry Breakdowns</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
| <ul style="list-style-type: none"> <li>• <b>Training:</b> new training will be required but this will be budgeted for in the cost of proposal</li> <li>• <b>How will the current line altered:</b> the line will not be adversely affected - in fact other operations will increase their MTBF, as a result of extra maintenance staff.</li> <li>• <b>Impact on breakdowns:</b> potentially a large increase in the MTBF</li> <li>• <b>Complexity:</b> this adds no complexity to the system</li> </ul>                                                                                                                                                                                                                             |

**Table 9: Proposals for Default simulation line**

| Name of generic solution                   | experiment number | description                                                                                                 | Benefit (Default JPH:94.59)      | Extra JPH per machine | Extra parts annually | Cost                                                                                                                 | Pay back period              |
|--------------------------------------------|-------------------|-------------------------------------------------------------------------------------------------------------|----------------------------------|-----------------------|----------------------|----------------------------------------------------------------------------------------------------------------------|------------------------------|
| Varying new machine locations              | 8B                | add 6 machines, one each to following operations: op20,op70, op71, op80,op81,op90                           | JPH: 104.72<br>Increase of 10.7% | 1.68                  | 54702                | <b>£3,000,000</b><br>for 6 machines @ £500K each                                                                     | 13.1 months<br>Or 1.1 years  |
| Varying new machine locations              | 12C-6             | add 2 machines, one each to following operations op70,op90                                                  | JPH: 99.62<br>Increase of 5.2%   | 2.09                  | 22572                | <b>£1,000,000</b><br>for 2 machines @ £500K each                                                                     | 10.6 months<br>Or 0.88 years |
| Varying new machine locations              | 12C-13            | add 4 machines, one each to following operations op20,op70,op80,op90                                        | JPH: 103.13<br>Increase of 9.0%  | 2.13                  | 46116                | <b>£2,000,000</b><br>for 4 machines @ £500K each                                                                     | 10.4 months<br>Or 0.86 years |
| Combining operations and their cycle times | 13C               | Combining op70,op80, in total 20 machines                                                                   | JPH: 97.41<br>Increase of 2.9%   | N/A                   | 15228                | <b>£2,000,000</b> 40 new tooling sets required @ 50K each                                                            | 31.5 months<br>Or 2.6 years  |
| Combining operations and their cycle times | 13E               | Combining op70,op80 and op90, in total 29 machines                                                          | JPH: 99.19<br>Increase of 4.8%   | N/A                   | 24840                | <b>£2,900,000</b> 58 new tooling sets required @ 50K each                                                            | 28.0 months<br>Or 2.3 years  |
| Reducing Gantry Break downs                | 10G               | Increase MTBF by 3.5* for gantry break downs                                                                | JPH: 99.22<br>Increase of 4.9%   | N/A                   | 25002                | <b>£1,000,000</b> based on an estimated cost of implementation                                                       | 9.5 months<br>Or 0.7 years   |
| Reducing Gantry Break downs                | 10I               | Removing all gantry break downs                                                                             | JPH: 100.65<br>Increase of 6.4%  | N/A                   | 32742                | <b>£1,000,000</b> based on an estimated cost of implementation                                                       | 7.3 months<br>Or 0.6 years   |
| Combining EXP: 12C-13 with EXP: 10I        | 24B               | add 4 machines to operations op20, op70, op80, op90 <b>and</b> Increase MTBF by 3.5* for gantry break downs | JPH: 108.5<br>Increase of 14.7%  | 3.47                  | 75114                | <b>£2,000,000</b><br>for 4 machines @ £500K each and <b>£1M</b> for gantry estimated<br><b>TOTAL COST £3,000,000</b> | 9.5 months<br>Or 0.79 years  |

**Table 10: Proposals for REP simulation line**

| Name of generic solution                   | experiment number | description                                                                                     | Benefit Default JPH:138.40       | Extra JPH per machine | Extra parts annually | Cost                                                                          | Pay back period              |
|--------------------------------------------|-------------------|-------------------------------------------------------------------------------------------------|----------------------------------|-----------------------|----------------------|-------------------------------------------------------------------------------|------------------------------|
| Varying new machine locations              | 18.5              | add 1 machines to operation op50                                                                | JPH: 145.5<br>Increase of 5.1%   | 7.1                   | 38340                | <b>£500,000</b><br>for 1 machines @<br>£500K each                             | 3.1 months<br>Or 0.26 years  |
| Varying new machine locations              | 18.14             | add 7 machines plus one gantry to following operations<br>op10,op50,op20W,op3R,op100,op110,120g | JPH: 152.49<br>Increase of 10.2% | 1.8                   | 76086                | <b>£3,600,000</b><br>for 7 machines @<br>£500K each and<br>#100K for 1 gantry | 11.3 months<br>Or 0.94 years |
| Varying new machine locations              | 18.16             | add 5 machines, one each to following operations<br>op10,op50,op100,op110,op200W                | JPH: 151.37<br>Increase of 9.3%  | 2.6                   | 70038                | <b>£2,500,000</b><br>for 5 machines @<br>£500K each                           | 8.5 months<br>Or 0.71 years  |
| Combining operations and their cycle times | 20.7              | Combining op10,op50 in total 13 machines                                                        | JPH: 146.38<br>Increase of 5.7%  | N/A                   | 43092                | <b>£650,000</b> 13 new tooling sets required @ 50K each                       | 3.6 months<br>Or 0.3 years   |
| Reducing Gantry Break downs                | 22.M              | No gantries, thus no break downs and cycle times                                                | JPH: 140.57<br>Increase of 1.5%  | N/A                   | 11718                | <b>£1000000</b> based on an estimated cost of implementation                  | 20.48 months<br>Or 1.7 years |

**Table 11: Proposals for Only Block simulation line**

| Name of generic solution                   | experiment number | description                                                          | Benefit<br>Default JPH: 42.74   | Extra JPH per machine | Extra parts annually | Cost                                                         | Pay back period              |
|--------------------------------------------|-------------------|----------------------------------------------------------------------|---------------------------------|-----------------------|----------------------|--------------------------------------------------------------|------------------------------|
| Varying new machine locations              | 19.2              | add 1 machine to following operation op130                           | JPH: 44.98<br>Increase of 4.9%  | 2.1                   | 11448                | <b>£500,000</b><br>for 1 machines @ £500K each               | 10.4 months<br>Or 0.87 years |
| Varying new machine locations              | 19.7              | add 2 machines plus one gantry to following operations op110 and 130 | JPH: 45.02<br>Increase of 5.33% | 1.14                  | 12312                | <b>£1,000,000</b><br>for 2 machines @ £500K each             | 19.5 months<br>Or 1.62 years |
| Combining operations and their cycle times | 21.27             | Combining op120,op130,op140, in total 9 machines                     | JPH: 44.96<br>Increase of 5.2%  | N/A                   | 11988                | <b>£900,000</b> 19 new tooling sets required @ 50K each      | 18.01 months<br>Or 1.5 years |
| Reducing Gantry Break downs                | 23.M              | No gantries, thus no break downs and zero cycle times                | JPH: 43.47<br>Increase of 1.7%  | N/A                   | 3942                 | <b>£1000000</b> based on an estimated cost of implementation | 60.8 months<br>Or 5.0 years  |

## **8.7 *Summarising proposals***

The solutions were produced using the highest increases in JPH as the overriding factor in the choice of which result could potentially meet the capital investment pay back period. For each of the three transfer lines numerous experiments were carried out, thus not all of the experimental data was used in this chapter. A number of experimental results were identified as likely to meet Ford's selection criteria for new capital investments. Due to the amount of time that was taken developing the generic proposals, and the fact that the majority of experiments were based on the default manufacturing line, more proposals were developed for the default line than for Rep or Only Block lines

## **8.8 *Chapter Summary***

This chapter considers potential productivity increasing solutions for three different manufacturing lines and summarises these solutions in tabular form in Table 9, Table 10 and Table 11. These proposals have been costed and their benefits have been quantified in terms of increase in parts produced annually, the predicted JPH and the percentage increase in JPH that this represents. This information will enable senior management to understand the costs, feasibility, pay back period, benefits and implementation risks associated with each proposal.

## **9 Discussion and conclusions**

In this final chapter of the project the research will be discussed, analysed and an evaluation will be undertaken of the fulfilment of the research aims and objectives of each of the stages of the project. The aim of the project as stated in Chapter 4 was to:

“Develop a number of proposals that can be potentially used to increase productivity (JPH) in a number of different machining lines using simulation as a decision support tool, in order to increase Ford’s profitability”. This aim was then broken down into a number of stages which have been summarised below:

### **Stage 1 – Development of preparatory work needed pre experimentation**

This stage introduced the experimental strategy and the experimental methodology that was used in all of the experiments. It also documented the preparatory experimentation that was needed before main simulation experiments could be carried out.

### **Stage 2 – Develop generic proposals via experimentation with discrete event simulation**

This stage’s objective was to carry out the bulk of the experimentation and identify possible generic solutions to increase JPH to a number of manufacturing lines.

### **Stage 3 – Application of previously developed generic proposals to different manufacturing lines**

Using the generic solutions apply these techniques to a number of different manufacturing lines and gauge whether they are in fact generic.

### **Stage 4 - Development of business cases**

Use the experimental data and financial information from Ford to produce business plans for the implementation of the proposals for all lines that were experimented on. In the business case for each proposal there must be a summary of benefits, costs, feasibility, payback period and also potential issues associated with the proposal.

#### **9.1 *Research findings compared to research objectives***

In this section the research findings for each stage will be assessed against the objectives stated for each stage. The aim of this section is to evaluate the success and completion of each of the stages objectives and to discuss where appropriate why these objectives might not have been met.

### **Stage 1 – Development of preparatory work needed pre-experimentation**

As stated in the introduction to this chapter the purpose of this stage was to define the experimental strategy and carry out a number of preparatory experiments. These objectives were completed successfully and this stage was completed without any problems.

### **Stage 2 – Develop generic proposals via simulation**

The stages objective was to carry out the bulk of the experimentation and identify possible generic solutions to increase JPH to a number of manufacturing lines. All of the experiments that are identified were run without any problems. After the defined experiments had been run, 3 experiments had proven to increase the JPH of the default system and thus could potentially produce generic solutions to increase JPH of other manufacturing lines. Therefore all of the objectives were completed, although time permitting, more generic proposals should have been developed to take into the next stage. Only producing three generic proposals might not have been sufficient to find a number of generic solutions to increase JPH.

### **Stage 3 – Application of previously developed generic proposals to different manufacturing lines**

Using the generic solutions developed in stage 2, each was tested on two different manufacturing lines to prove if the generic solution would indeed increase JPH. It became apparent that adding new machines to bottleneck operations from the experimental results is a generic solution to increase the JPH in any manufacturing line. Combining bottleneck operations produced acceptable results in both lines but the results were difficult to obtain. Combining operations could therefore also be said to be a generic solution applicable to all manufacturing lines. The gantry optimisation 'generic' solution was shown in both lines not to be a generic solution. The reason for this is in both cases the gantry system did not influence the bottleneck operations of the line, which had been the case in the default model. Therefore it can be said from the experimental results that adding new machines and combining operations are generic solutions based on the experiments carried out within this research project. Gantry optimisation has been found to be not a generic solution and is only applicable when the gantry system influences the bottleneck operations' output. In retrospect, finding truly generic solutions that can be used on every manufacturing line seems unrealistic. It would be more feasible to have a number of solutions and depending on the manufacturing line one of these solutions could be used to optimise the JPH of the line.

### **Stage 4 - Development of business cases**

Using the experimental data and financial information from Ford, business plans were produced for the three generic solutions. In each case the cost was shown against the

potential benefit and potential problems were identified. This stage was not intended to identify which business case was the optimum choice for Ford so the objective of was fully completed, with a number of different business cases being produced from the generic solutions.

9.2 Recommendations to Ford

This section lists the recommendations made based on the result of the business cases within chapter 4 for the three manufacturing lines. These recommendations are based on the information gathered within this project and therefore the following recommendations are based solely on the information obtained in this project.

Default manufacturing line

There are four potential solutions for the default manufacturing line, which have been listed in Table 9. Each of the four potential solutions has been shown to increase the JPH by a significant level and to do so within the one year pay back period that Ford adheres to. Of the four potential solutions, two are for adding new machines into strategic bottleneck operations and the other two are increasing the MTBF for gantry operations, thereby reducing the effects of the gantry system on the output of the system. Although combining operations produced a significant increase in JPH, the payback period was too long, so this option was not recommended. With four potential solutions, it was important to weigh up the merits and drawbacks of each proposal in order to pick the optimum solution.

Table 12: Default line: merits and drawbacks for four potential solutions

| Experiment number | Merits                                                                                                                                                                                                      | Drawbacks                                                                                                                                           |
|-------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------|
| 12C-6             | This solution has a small capital investment of £1M for 2 extra machines. This solution tackles the root cause of the bottlenecks within the line.                                                          | A fairly lengthy pay back period of 10.6 months and a relatively small increase in JPH of 99.62, which is an increase of 5.2% from the default.     |
| 12C-13            | Delivers a JPH of 103.13, which is an increase of 9.0% from the default. The pay back period is 10.4 months with 2.13 JPH per extra machine.                                                                | The solution requires 4 extra machines which is a large capital investment of £2M.                                                                  |
| 10I               | Delivers a high JPH of 100.65, which is an increase of 6.4% from default. The capital investment of £1M has a short pay back period of 7.3 months.                                                          | This solution is highly unrealistic as it cannot remove all breakdowns. This technique reduces blocking, but does not tackle root cause.            |
| 10G               | This solution is potentially attractive as an increase in MTBF is possible with additional maintenance procedures and staff. There is an investment of £1M. Reasonably short pay back period of 9.5 months. | The solution cannot guarantee the increase shown in the experimental results. This technique only reduces blockage, and does not tackle root cause. |

From the results in There are four potential solutions for the default manufacturing line, which have been listed in Table 9. Each of the four potential solutions has been

shown to increase the JPH by a significant level and to do so within the one year pay back period that Ford adheres to. Of the four potential solutions, two are for adding new machines into strategic bottleneck operations and the other two are increasing the MTBF for gantry operations, thereby reducing the effects of the gantry system on the output of the system. Although combining operations produced a significant increase in JPH, the payback period was too long, so this option was not recommended. With four potential solutions, it was important to weigh up the merits and drawbacks of each proposal in order to pick the optimum solution.

Table 12, the clear favourite can be seen to be EXP: 12C-13. This experiment has an increase in JPH of 9%, which is the highest of all of the proposals and has a short pay back period of 10.4 months. Also this experiment involves adding additional machines to bottleneck operations which is a proven technique for increasing the JPH in unbalanced lines within Ford Europe. The only problem with this experiment is it does require a high capital investment of **£2M**.

Experiment 10I shows the result of having no gantry breakdowns; it would be infeasible to achieve zero breakdowns due to the complexity of the current gantry system. Although it does give a good increase in JPH, the increase could not be achieved for £1million. The gantry breakdowns could potentially be removed from the system by buying a new loading system that could be more resilient to breakdowns but this would cost in excess of £1million.

Experiment 10G is an experiment which increases the MTBF by 3.5 times. This is a highly feasible result based on the investment of £1 million which has been broken down in section 8.3.3. The increase in MTBF cannot be guaranteed by the investment on £1million, but having extra maintenance staff will reduce the effects of breakdowns on the manufacturing line but this increase is difficult to quantify.

Experiment 12C-6 increase the JPH by circa 5% and has a capital investment of only £1million. This proposal although cheap and within the pay back period will not be recommended to Ford as similar experiments have produced proposals that increase the JPH more significantly than in Experiment 12C-6. This proposal should only be implemented if Ford can only invest circa £1 million due to financial constraints.

One other potential solution would be to combine EXP: 12C-13 with an optimised gantry solution to significantly increase the JPH of the line. Although EXP: 10I has the highest increase in JPH, it is unrealistic as removing all breakdowns from any system is practically impossible. Conversely EXP: 10G has real potential of increasing the MTBF of the gantry system by a significant amount which could increase the JPH of the line and complement the benefits shown in EXP: 12C-13.

EXP: 24B combined EXP: 12C-13 (adding four machines at strategic bottlenecks) with EXP: 10G (increasing the MTBF of the gantry system by 3.5). This experiment increased the JPH by 14.7% to 108.5 JPH. Combining these two solutions together significantly increases the JPH of the line. Also a major point to consider is although a total investment of **£3M is required**; the payback period is one month less than EXP: 12C-13 due to the increase in JPH per machine. The increase in MTBF cannot be guaranteed by the investment on £1million, but having extra maintenance staff and newer systems to detect breakdowns will benefit the whole line. According to Palmer (1999) MTBF is highly important for operations within a transfer line so this investment should increase the productivity of the transfer line, though as stated previously this is difficult to quantify.

Another potential solution is to add 14 new gantries (Exp: 15.3) into the system with EXP: 12C-13. Although this combination would increase the JPH above the value of EXP: 24B doubling the gantry system could bring the solution over the pay back period. Another point is the amount of experimental data that has been produced cannot guarantee the potential benefits, for these reasons this will not be recommended to Ford but is certainly another potential avenue to explore.

In summary, for the default line, the researcher recommends EXP: 24B, as a solution to significantly increase the JPH of the line. An alternative is, if management do not find the benefits of 10G to be convincing, then the solution identified by EXP: 12C-13 would be recommended. Both EXP: 24B and EXP: 12C-13 recommend buying four machines and placing them within known bottleneck operations to balance the line, but both solutions also depend on increasing the MTBF of the gantry system.

### **REP manufacturing line**

Of the generic proposals produced via experimentation for the REP line which have been summarised in Table 10, three met the payback period set by Ford. Each of these proposals involved adding new machines to different bottleneck operations. Each of the three proposals has different merits and drawbacks, as shown in Table 13.

**Table 13: REP line, merits and drawbacks for three potential solutions**

| Experiment # | Merits                                                                                                                                                                                            | Drawbacks                                                                                                                                                                                                                             |
|--------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 18.5         | Only <b>£0.5M</b> investment needed and a fast pay back period of 3.1 months. This should be seen as a short term investment, requiring minimal work for increase in JPH.                         | Only 5.1% increase in JPH for the system.                                                                                                                                                                                             |
| 18.14        | This experiment predicts a large increase in JPH of 10.2%, increasing to 152.49.                                                                                                                  | The experiment needs a large investment of <b>£3.6M</b> to buy 7 machines and an extra gantry. It also has a lengthy pay back period of 11.3 months. It is a significant investment. The increase in JPH per machine = <b>1.8 JPH</b> |
| 18.16        | This experiment predicts a JPH: 151.37 which is a significant increase of 9.3%. This is achieved with 5 new machines at a cost of <b>£2.5M</b> . The increase in JPH per machine = <b>2.6 JPH</b> | The payback period of 8.5 months is not particularly short.                                                                                                                                                                           |

Based on the assumption that Ford wants the largest increase in JPH per machine, the researcher recommends the solution in experiment 18.16. This recommendation looks at the increase in JPH per machine as a decisive factor between experiments 18.16 and 18.14. Although 18.14 has the highest JPH it also has the longest pay back period. Experiment 18.16 therefore appears more financially attractive.

### **Only Block manufacturing line**

From the business cases produced via experimentation, and using the generic proposals summarised in Table 11 based on the Only Block line, there was only one potential business case which would meet the payback period of less than one year for Ford. This was experiment 19.2: buying an extra machine for operation 130. This would increase the JPH by 4.9% to 44.98 JPH with a pay back period of 10.4 months with an investment of £500,000.

The main reason for only one solution being produced for the Only Block manufacturing line is that this line has a low default JPH of 44.74, which means that the pay back period for this line will take a lot longer as less parts are produced on the line compared to the default manufacturing line and REP manufacturing line, both of which have more than double the JPH of Only Block. It seems short sighted to impose the same pay back period on all manufacturing lines within Ford. Insisting that proposals for low output lines like Only Block meet the 12 month pay back period requirement significantly limits Ford's investment options. This means that these low output lines will never reach their full production potential.

### 9.2.1 Summary of recommendation for each line

A summary of the recommendation for Ford has been compiled in Table 14. Table 14 shows the basic information needed to understand the benefits and cost of the proposals for each line. For a more detailed understanding of each proposal please see the experimental number and chapter 4.

**Table 14: summary of the recommendation for each line**

| Line name  | Experiment number | Description                                                                     | Cost to implement | Pay back period | Benefit                                                                                                        |
|------------|-------------------|---------------------------------------------------------------------------------|-------------------|-----------------|----------------------------------------------------------------------------------------------------------------|
| Default    | EXP: 24B          | adding four machines at bottlenecks and Increase MTBF by 3.5* for gantry system | <b>£3,000,000</b> | 9.5 months      | 75114 annual increase in parts<br>14.7% increase in output<br>Additional income:<br><b>£3,755,700</b> annually |
| REP        | EXP:18.16         | add 5 machines at bottleneck operations                                         | <b>£2,500,000</b> | 8.5 months      | 70038 annual increase in parts<br>9.3% increase in output<br>Additional income:<br><b>£3,501,900</b> annually  |
| Only block | EXP:19.2          | add 1 machines at a bottleneck operation                                        | <b>£500,000</b>   | 10.4 months     | 11448 annual increase in parts<br>4.9% increase in output<br>Additional income:<br><b>£572,400</b> annually    |

### 9.3 Contributions to knowledge

This section draws together a number of findings that have been mentioned elsewhere in the thesis. These findings have been found as a direct result of experimentation within this project. These findings are not seen to be common knowledge within the academic community; therefore these findings have furthered the collective knowledge within the academic community and Ford motor company.

#### **Adding machines**

Adding machines to bottleneck operations using the method described in experiment EXP: 8 has so far proven to be a generic solution to increase the JPH. This technique has been used experimentally on three different manufacturing lines and each has produced a number of solutions that increase JPH. Any researcher carrying out further optimisation projects within Ford motor company or the wider industrial community would be advised to consider this technique. The technique was developed from the bottleneck detection method in Roser (2001), together with Microsoft Excel conditional formatting which was used to identify the major bottleneck of a system using the data from Witness. This method allows Witness data output to show the key

bottlenecks of the line and highlights operations which need to be optimised for any manufacturing line.

### **Producing generic solutions**

Producing generic solutions to increase JPH in a number of machining lines is a difficult task. Each machine line is highly complex with a variety of complex interactions which affect the JPH of the line. A large pool of different generic solutions will allow a researcher to select a generic solution from the pool that can be used to optimise the system. The contribution to knowledge is that it's difficult to find generic solutions to increase JPH which are applicable to every manufacturing line, so the more "generic" solutions a manufacturer has, the higher the likelihood of possessing the solution needed to optimise any systems.

#### **9.3.1 Contributions to Fords internal knowledge**

The following information has been compiled with the intention of advancing Ford's understanding of its manufacturing operations. These findings may be more readily acknowledged in the academic community, but they are not applicable to other companies and so have only been partially covered previously within the academic world. For any further optimisation project in Ford these contributions to knowledge should be recognised.

### **Combining operations**

Combining operations together seems to be a feasible way to reduce the effects of bottleneck operations without the need to invest in new machine tools such as vertical CNC milling machines. This is done by reducing the effects of single machines on a transfer line. It has been proven to help balance a manufacturing line and thus increase the JPH. The major problem with this technique is that there is significant tooling set costs (tooling bits) for its implementation.

### **Gantry optimisation**

This technique works best on unbalanced lines when their bottlenecks are affected by their loading system (gantry), giving a higher than average idle time. In the default model benefits were gained by increasing the MTBF for the loading system. This will reduce the idle time of the bottleneck operations and increase the JPH of the line.

### **Buffer capacity**

When increasing buffer capacity on transfer lines an equal number of platens and buffer capacity should be added to the system in order to model this experiment correctly. Increasing the buffer capacity alone effectively creates a space within the

buffer that cannot be filled as no new platens have been added to the platen pool to fill the space.

#### **9.4 *Limitations of research***

One of the limitations of the research is that the quantity and relevance of information available to an external researcher is obviously less than would be available to an employee, so the researcher needs to look elsewhere for the information required to carry out the necessary experimentation.

Another limitation of the research findings may be the costing data. Ensuring the proposals have met Fords pay back period has been a critical part of this project and therefore if the data collected from Ford is not accurate it could alter the recommendation of this project. The costing data within this project was provided by the industrial supervisor and other senior Ford employees, therefore it is assumed to be correct. However if not accurate then the recommendations should be reassessed.

There was a finite amount of resources available for this research project. If more funding had been available, more research would have been accomplished. If research funds had been provided, a team of researchers could have been engaged to run a more extensive list of experiments. This would then produce more generic solutions, which in turn could have been tested on twenty to thirty different lines, instead of just three as within this project. Additional resources would have enabled the production of more generic solutions, as together with the execution of the future projects recommended in section 9.5.

The experimentation that was carried out within the research project forms a major part of the work that was carried out. The following problems could be associated with the experimental results and hence the finding and conclusions of this research project.

- The generic solutions should have been tested on other lines, which would have increased the level of confidence that adding new machines to bottleneck operations is a generic solution to increase the JPH;
- The contributions to knowledge could have been tested further and critics of the benefits of simulation (FIRST) within Ford could have been consulted. Experiments could have then been devised to prove/disprove their reservations.
- The default model was sourced for this project from the industrial sponsor. The researcher was asked to accept that it was a verified representation of the

real system. With extra time this could have been verified by comparing the model to the real system at the beginning of the project.

The major limitation with this project, as with other research projects, is there is a limited amount of time to carry out the project and write a comprehensive thesis. Putting a cap on a piece of research limits the outcome of the research immediately so that it can never be more than a Masters Research project. Additional research time would have allowed more experimentation to be done and avoided the following limitations:

- A lot of time was lost due to the research project only having access to one specialist - the industrial supervisor - that worked approximately 3 hours by car from the research base.
- The project will end before the proposals are implemented by Ford, so the results of this implementation will not be known.
- Some experiments were carried out which did not shed any light on the real problem. They did, however take up valuable experimental time. With a longer research period these erroneous results would have had less impact on the time available for experimentation and analysis.

#### 9.4.1      How the limitations should have been retrospectively negated

In retrospect the research project should have differed in these ways:

##### **Communications with industrial sponsor**

Poor communication between the student and the industrial sponsor meant that little work was carried out in the first few months of the project. With the benefit of hindsight, better communication between the industrial sponsor and the student at the outset would have made the whole project a lot easier for both parties. This is the most significant change that would be made if this project were to be repeated and this sentiment will stay with the student through his industrial career.

##### **In-house experimentation at Ford**

Following on from the previous point, it would have greatly benefited the research project if the experimental work had been carried out in-house at Ford Dunton. This would allow continuous progress reports on the status of the experimentation and also quick resolution of any simulation problems. Unfortunately, basing the experiments within the company would have been very difficult due to other academic commitments during most of the experimentation period.

### **Better planning of experiments**

A number of experiments that were carried out were not managed in the most efficient way. This project has been made up of 80 percent of experimental data, so to maximise the time allocated to experimentation, each experiment should have been carefully planned to deliver the maximum output of data with the minimum input of resources. In a certain number of cases this did not happen and some experiments had to be repeated. Also, some experimental work did not add value to the project. For future simulation projects the following planning should be adhered to:

Before any experiments are carried out, the purpose of the experiment must be clearly defined. Also the influencing factors which will be manipulated to carry out the experiment should be identified. Taking an initial period of approximately 30 minutes, to run through the reason for the experiments and validating what needs to be done before starting the experimental process is a simple planning technique which should reduce the number of wasted experiments and make the research project more resource efficient.

#### **9.4.2 Measurement of success**

The overriding objective of this research project was to increase the JPH to a number of manufacturing lines. Increasing the JPH of a manufacturing line means that the fixed costs that are incurred when manufacturing the engine parts (cylinder head and block) on each of the lines is now lower (per unit). This allows Ford to reduce its total cost per part, which in turn increases its profit margin. This increase of annual profits (which can be seen in Table 14) was the high level aim for this research project, and this aim can be seen to have been achieved.

The other major objective was to develop a number of generic solutions to increase the JPH on a number of lines with the potential to increase the output of every manufacturing line within Ford. This aim has been less clearly achieved. Currently one out of the three potential generic solutions (increasing MTBF for gantry system) has been identified as having limited genericity. Adding new machines to strategic bottleneck operations has been proven to increase JPH over three different machining lines and therefore can be said to be a completely generic solution from the experimental results carried out. Finally the “combining operations” solution increased JPH; it does not always meet Ford’s pay back period. This highlights the difficulty of identifying completely generic solutions that fit every manufacturing line. It would be more feasible to identify a number of reasonably generic solutions from which one could be selected to optimise the JPH of a specific manufacturing line.

As well as completing all of the planned work before the project end date, the project time plan has been able to factor-in an element of continuous improvement, despite the tight timescales. The planning of this project could therefore be said to have been very successful, with a 100 percent achievement of internal and external (Ford) milestones and deliverables.

## **9.5 *Future work***

In this section further research will be discussed which could be carried out to expand and complement this research project. The ideas for future work have all been formulated as a result of this research project.

### **Additional experiments**

Additional experiments could be carried out in the following areas:

- Further experimentation to increase JPH of manufacturing lines and produce more generic solutions to increase JPH over a number of manufacturing lines.
- Testing the generic solutions on a number of different lines (20-30) to definitively determine if the generic solutions are indeed generic for any manufacturing transfer lines.

Potentially there is enough further work here for a number of different Masters Projects (or a PHD research thesis), which could be relevant for a number of manufacturing businesses that use high automation or transfer lines in their manufacturing systems.

### **Implementation of simulation results**

Further work from this project would be to gain approval by Ford management and then to drive forward with implementation of the recommended solutions on each of the three manufacturing lines. In any large company, implementing changes can be very difficult due to the tendency for such organisations to strive to maintain the status quo. A successful change agent would need sufficient political power within Ford to be able to champion the benefits of the proposals and oversee the implementation of the recommendations.

### **Toolbox of generic solutions**

As stated previously although a solution might appear to be generic it might not always fit every manufacturing line. It would therefore be useful to have a number of solutions so that, depending on the manufacturing line, one of these could be used to optimise the JPH of the line. Once a number of solutions have been found to work on more than one line they could be classed as “generic”. These solutions could then be

incorporated into an optimisation “tool box” which could be used by a process engineer to optimise any manufacturing line. Not all of the solutions would be applicable but the tool box could be structured in a way that there would always be a solution that could be used in any situation. Such a toolbox would be an invaluable asset to any manufacturing company.

### **Toolbox manual**

Once a number of solutions have been found and a toolbox has been established, a subsequent toolbox manual should be produced. This manual would take the form of a flow diagram or (road map) that would guide an engineer through the optimisation process based on best practice techniques which could have been previously established. This would guide an engineer on the order in which solutions should be investigated. The manual could potentially be interactive and evaluate the results of experiments and suggest the next course of action. Another potential solution is if enough experiments are carried out using the generic solutions on a large number of different lines, then a matrix could be produced which would link the line characteristics with the solution that was used to optimise it. When a line needs to be optimised, the characteristics could be entered into the matrix, and based on previous experimental results, the matrix could identify a generic solution for that line.

### **Design of simulation “play-list”**

When running multiple experiments a researcher must be present to formulate the experiment, run the experiment and collect the results. This process could take up to 40 minutes per experiment. A novel idea would be to design a “play-list”, a piece of software that would effectively control FIRST and be capable of formulation, starting and collecting experimental data direct from FIRST and compiling the information into an executive report. The “play-list” could therefore load a large number of different experiments and then be left for a number of days to solve a series of experiments. This would dramatically increase the number of experiments that could be carried out in any research project, and minimise man hours on the project experimentation.

## **9.6 Chapter conclusion**

The aim of this final chapter of the project has been to discuss, analyse and evaluate the project based on the project aims and objectives stated in chapter 4. This chapter has endeavoured to objectively evaluate the work that has been carried out within the project and also the overall success of the project. For each of the three manufacturing lines, recommendations have been made to Ford based on the experimental data and also the business cases that were produced for each of the proposals. As a result of this research project a number of contributions to knowledge

have been documented which should be used in any further simulation projects at Ford. To objectively evaluate this research project a number of limitations were stated which must be taken into account when reviewing the work carried out within this project. As part of the limitations, a number of lessons learnt have been compiled which could be used for any further research project. Finally, future work that should be carried out to build on the work done in this research project was documented.

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## **11 Appendix A - Case studies of manufacturing companies using simulation**

### **11.1 Case study 1: Simulation project for a large enterprise.**

O'kane (2003) produced three cases studies of manufacturing enterprises of different sizes. Each of these businesses used simulation as guidance to alter a part of their business strategy in order to increase productivity with the minimum investment. One case study was based on a large automotive engineering manufacturing enterprise, very similar to Ford. The company was not named in this report for reasons of competitiveness, but it can be assumed that the company is one of the major engine producers around the world. The case study stated that the company wanted to maximise the output from their machine shop. The company produced a list of alterations that could be made to the machine line but these needed to be investigated before a decision was made. The company then ranked them in cost of implementation and likelihood of increased output of the model. The resulting list of alterations can be seen below:

- additional machines;
- shift alterations;
- optimisation of labour;
- re-jigging of machines; and
- re-routing parts by moving machines.

Their conclusion from the experiments was that bottleneck reduction only moved the bottleneck to another part of the line. It was concluded that to increase the output of the line significant modification of machine shop layout could be achieved by splitting of certain operations without the need for large capital investment. This showed that simulation of low cost changes to the factory layout could indeed increase productivity.

### **11.2 Case study 2: Manufacturing company investigating increasing output**

Greasley (2004) produced a case study that investigated increasing output levels of a large manufacturing company that produces wheel and axle sets for the railway industry. The process of production can be grouped into 6 sequential groups, each of which were investigated to identify improvements to the overall productivity of the line's output. The simulation study was undertaken to investigate the effects of altering each of the 6 groups. It was very important that the interaction between the

groups of operations was fully understood to ensure that any investment maximised the output from the factory.

In the optimisation process the first area of investigation was the balancing of the line by reducing cycle times of each individual group of operations. All cycle times were investigated and two out of the six were identified as being the bottlenecks of the production line. In both cases investments were made to reduce the cycle times which balances the line to an acceptable level.

The next investigation was to assess the random effects of breakdowns to the production line's performance. From historical data that had been collected it was found that breakdown lost on average 3% of the output per day. This was felt to be an acceptable level of breakdowns.

Finally the production line layout was considered, changing the layout was simulated and different designs were tested without the routing times. It was found that modification of the current production layout delivered no benefits. Without taking into account the routing times, the simulation seems to miss the point of investigating the layout out of the production line. Reducing the time taken to transport between groups of operations could potentially provide large cycle time reductions, thereby increasing the output of the production line.

## 12 Appendix B - Generic solution matrix

Table 15: Solution matrix to define generic solutions

| Solution name                              | Cost   | Increase in JPH | Expert opinion                                                 | Concurrent with Ford strategy | Generic solution |
|--------------------------------------------|--------|-----------------|----------------------------------------------------------------|-------------------------------|------------------|
| Number of machines                         | Medium | high            | the transfer system is set up to add new machine to operations | Yes                           | Yes              |
| Combining operations and their cycle times | Low    | high            | although feasible difficult to implemented correctly           | No                            | Yes              |
| Gantry Breakdowns                          | Low    | high            | could be used to increase reliability of loading system        | No                            | No               |
| Platen optimisation                        | Low    | Low             | cannot remove platens from platen pool                         | Yes                           | Yes              |
| Buffer allocation                          | High   | Low             | not worth investment                                           | Yes                           | No               |
| Varying new machines                       | Medium | high            | the transfer system is set up to add new machine to operations | Yes                           | Yes              |
| Combining operation                        | Low    | high            | Potentially feasible must be implemented carefully, in stages  | No                            | No               |
| Combining effects of buffer experiments    | High   | Low             | not worth doing                                                | Yes                           | No               |
| Increasing the number of gantries          | High   | Low             | not worth doing                                                | Yes                           | No               |
| Gantry Breakdown on balanced line          | medium | Low             | not worth doing                                                | No                            | No               |

### 13 Appendix C - Justification of experiments

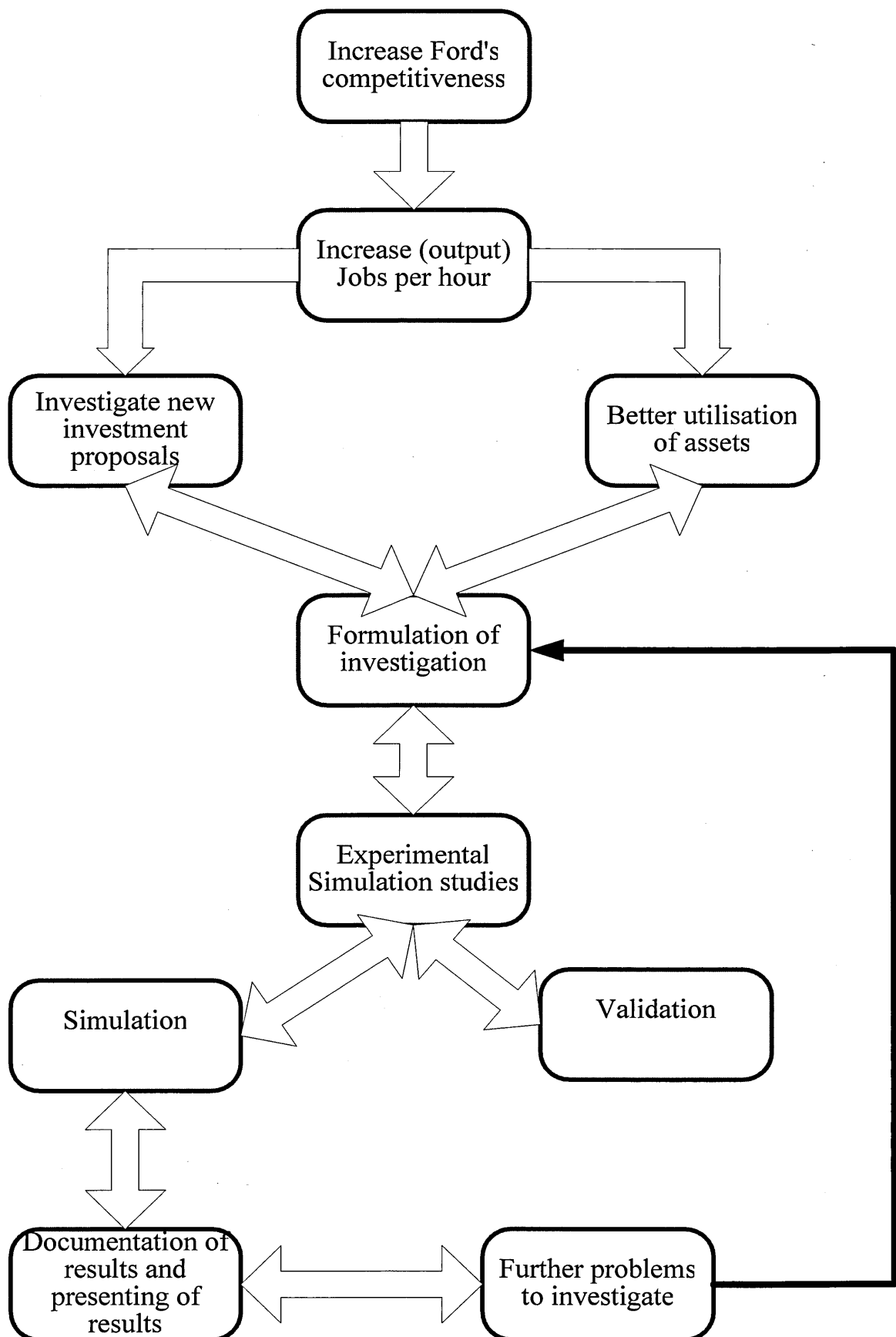


Figure 11: flow diagram for justification of experiments

## 14 Appendix D - Proprietary Experiments

### 14.1 Introduction to preparatory experiments

The preparatory experiments were carried out before the bulk of the main and defined experimentation, with a purpose to develop an understanding of a number of issues that could potentially affect the result of the core experimentation within this project. Therefore these experiments although not directly associated with the aim of the project, were needed to ensure the validity of the main experiments within this project.

### 14.2 EXP: 1 Familiarisation Experimentation

Below are a number of experiments that were carried out at the start of the project. The main purpose of these experiments was to understand the basic mechanics of the simulation interface and also gain an understanding of the interactions between the inputs and the default model. The secondary objective of these experiments was to understand how to scientifically carry out simulation experiments and potentially provide some further avenues to investigate.

#### Results of Familiarisation Experimentation

**Table 16: results for EXP: 1 Familiarisation Experimentation**

| Experiment # | Description                 | JPH    | Default value |
|--------------|-----------------------------|--------|---------------|
| Experiment1a | Increase the platens        | 93.06  | 94.59         |
| Experiment1B | Increase buffer capacity    | 78.87  | 94.59         |
| Experiment1C | Increase number of machines | 113.93 | 94.59         |
| Experiment1D | Zero cycle times            | 76.28  | 94.59         |
| Experiment1E | No tool changes             | 94.98  | 94.59         |
| Experiment1F | No breakdowns               | 110.31 | 94.59         |

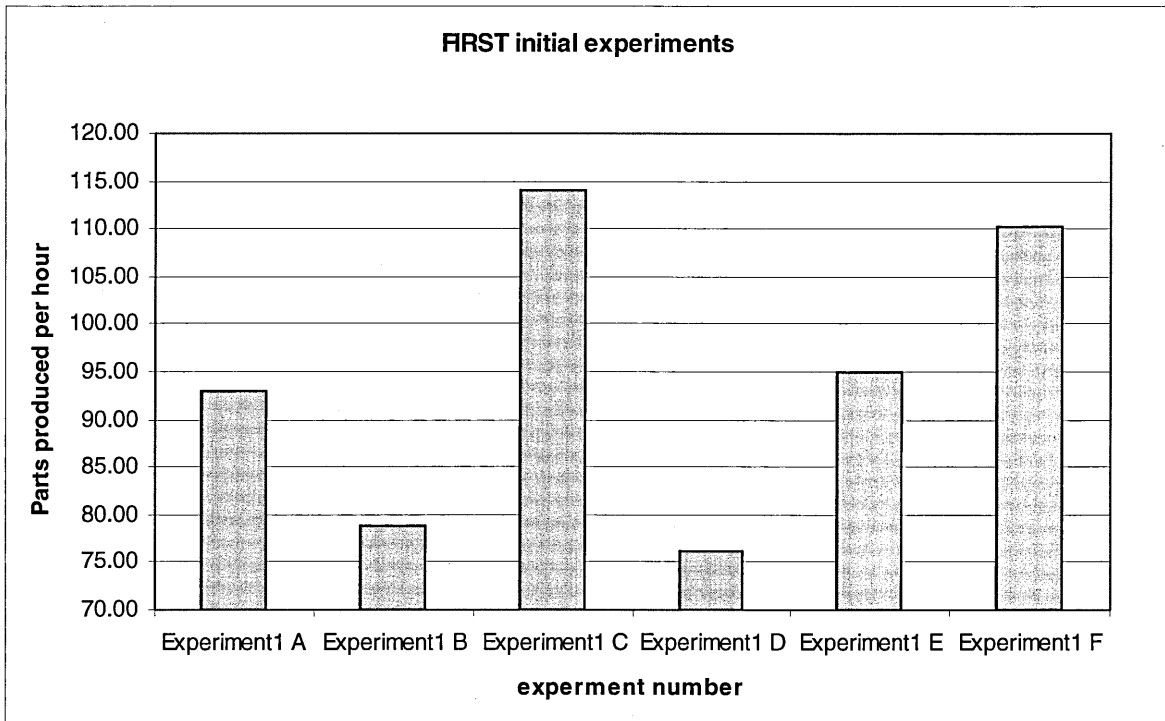


**Figure 12: Graph for EXP: 1 Familiarisation Exp Results**

#### 14.2.1 Findings of Familiarisation Experimentation

##### **Experiment 1A Increase the Platens**

The level of platens was increased from 250 to 1000. This increase in platens slightly reduced the JPH of the line from 94.59 to 94.26. This was not expected but this experiment was only carried out once and thus the reasons for the decrease in JPH are hard to quantify.

##### **Experiment 1B Increase Buffer Capacity**

Each of the buffers pre machining operations where increased from their default to 1000 capacity. This would potentially increase JPH as there would be less blocking within the manufacturing line. The JPH after this experiment actually fell, one possible reason for this could be the buffers have a cycle time for each unit of buffer moved, thus the larger the buffer the longer it takes before the part reaches the machine.

##### **Experiment 1C Increase Number of Machines**

Each operation was set up to have 10 machines within it. This experiment was carried out for a period of over 140 minutes without solving completely. After this time the experiment was stopped and the result was taken. There was however a large increase in JPH. This is because the experiment effectively doubled and in some cases tripled the number of machines within each operation; therefore you would expect an increase in JPH to be significantly higher than the default value.

### **Experiment 1D Zero Cycle Times**

All the operations had their cycle times set to zero. This actually reduced the JPH of the line. This must be due to the fact that hidden operations or operations that have been viewed as dummy operations are altering the JPH value of the manufacturing line, when all operations have zero cycle times.

### **Experiment 1E No Tool Changes**

This experiment removed all of the tool changes from the default model and ran the experiment. The results show a small increase in the JPH level but this was insignificant. To get rid of all tool changes would be impossible, therefore tool changes is an external factor that cannot be negated. If tool changes could be negated the cost of removing them from the real manufacturing system would be far too expensive for only a small increase in JPH shown in graphical form in Figure 12 and in Table 16 .

### **Experiment 1F No Breakdowns**

This experiment removed all of the breakdown data from the simulation model. This effectively meant that the system would run with no failures that would affect the system. This removing of breakdowns showed a considerable increase in JPH which means that breakdowns, although not bottlenecks of the system, themselves impede the JPH of the system.

## **General findings of Familiarisation Experimentation**

The familiarisation experiments have shown that breakdowns and increasing the number of machines can potentially increase the JPH of manufacturing lines. These experiments have highlighted that when using simulation you must carry out many experiments in order to gain the best result and that experimenting with an unrealistically high value can produce erroneous results. There was a total of 6 experiments carried out in this section which generated ideas that could potentially be carried on and developed further. From the 6 experiments carried out there were two results that stood out. The first was when each of the operations increased the number of their machines to 10. This showed that increasing the number of machines in the system could increase the systems productivity. The other productivity increase was shown when all breakdowns were removed from the system. Although removing all breakdowns from a system would be very costly it does show that breakdowns play a significant role in the productivity of the system thus should be investigated further.

14.3 EXP: 2 Experiment Warm up Period

Purpose

The aim of this experiment was to investigate the effects of a “warm-up” period on the JPH of the simulation model. Warm-up periods are used to allow a simulation model to go through an initial transient period from running empty. A warm-up period acts to negate the effects of the initial transient period on the output of the model. Therefore the aim of this experiment is to understand if varying the warm-up period can find an optimum or stable warm-up period for the simulation model which allows the simulation to negate the initial warm-up period.

Method

The method used for this experiment was to modify the warm-up period in numbers of days from a value of 0 to 40 days and record the variances in the JPH values. It was assumed that an increment of plus two days would give a good understanding of the hypotheses. The experiment was carried out by running the default experiment for a period of 200 days altering the warm-up period in the FIRST interface shown in Figure 13. Each time the model was run the results where collected in the tabular form shown in Table 17 and also graphical form Figure 14.

| FIRST Version 2.4 - Main Menu |         |
|-------------------------------|---------|
| Experimentation (in Days):    |         |
| Warm-Up Period                | 1.0000  |
| Experimentation Period        | 20.0000 |
| First Random Number Stream    | 3       |

Figure 13: Screenshot of First Interface Showing Warm-Up Period

**Table 17: Warm-Up Period Experiments**

| Warm-up<br>period | JPH   |
|-------------------|-------|
| 0                 | 94.55 |
| 2                 | 94.65 |
| 4                 | 94.59 |
| 6                 | 94.55 |
| 8                 | 94.77 |
| 10                | 94.81 |
| 12                | 94.71 |
| 14                | 94.72 |
| 16                | 94.73 |
| 18                | 94.56 |
| 20                | 94.65 |
| 22                | 94.75 |
| 24                | 94.81 |
| 26                | 94.85 |
| 28                | 94.83 |
| 30                | 94.72 |
| 32                | 94.52 |
| 34                | 94.41 |
| 36                | 94.34 |
| 38                | 94.26 |
| 40                | 94.25 |

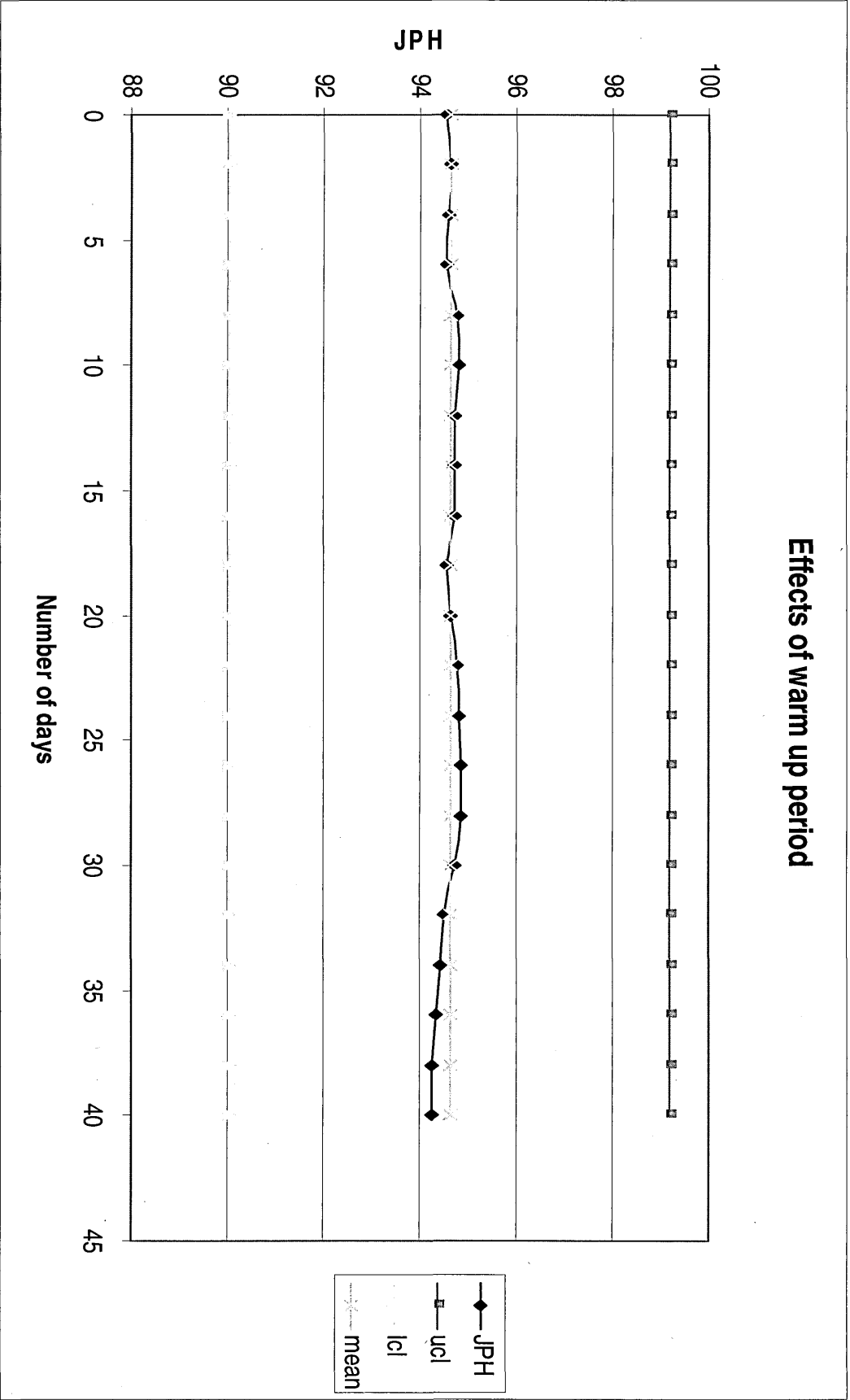


Figure 14: Graph for EXP: 2 Effects of Warm-Up Period

**Table 18: Results For Exp: 2 Warm-Up Experiment**

|                    |       |
|--------------------|-------|
| Default JPH        | 94.59 |
| Average JPH        | 94.62 |
| Standard deviation | 0.18  |

### **Findings**

From the results of this experiment the warm-up period can be said to have little effect on the output of the simulation model. As shown in the results the standard deviation of the results was less than 0.2 deviations from the mean which can be shown in Table 18. There is also no sign of linear correlation between increasing the number of warm up days and the JPH level that could be seen in this experiment. A linear correlation would have been predicted by the research prior to running of the experiment. This experiment is not an extensive investigation into the effects of a warm-up period on the output of the simulation model; but this demonstrates that the correct result has been obtained from the experiments run. This study reveals the reason for not being able to identify a linear correlation between the variable “warm-up period in days” and the simulation output is due to the long run time that was fixed at the start of the experiment. The run time for this experiment was 200 days which potentially could negate the effects of the initial transient period. Thus this experiment was stated that using a high run time of over 200 days a warm up period makes little impact on the output value of the experiment.

## **14.4 EXP: 3 Experiment Run Length Analysis**

### **Purpose**

The aim of this experiment is to investigate the variation within the output (JPH) when increasing the run time of the simulation. This experiment investigates the effects of random numbers on the output of the model when the run time is altered.

### **Objectives**

The objective of this experiment was to determine if a longer cycle time would significantly change the output (JPH) of the model. This experiment should be able to quantify the variation in output that a longer run time produces. This information will become valuable when running experiments to ensure that the most realistic results are collected.

### **Problems with the models run time**

The model that was originally handed over for the project could not be used to simulate run times over 58 days. Once this error was made apparent to the industrial

sponsor, he provided a model that did not have this error. This model was then used to debug the model that was given to the research project. There could not have been a straight swap as Cranfield University and FORD use different operating systems and also different network setups, which makes it impossible to transfer working files between the two groups. When debugging the model, the problem was identified as the rejection of platens. Within the model there was a finite amount of platens, which are used in one of the assembly operations. At certain operations part rejections would occur pushing a small percentage out of the model, roughly 1% of platens. This model loss over a cumulative time stopped the model from working, thus the model would run out of its platen pool. The model was altered so that the platens were not lost from the model but instead were rejected to the platen storage buffer.

The altered model was saved as a new base model that was used to experiment with run times over 58 days. The base model was modified with the same methods that had been documented in the previous experiments.

## **Method**

This experiment was carried out in two parts.

- EXP: 3A takes the default simulation and increases the run time in increments of 10 from a starting value of 10 days to 300 days. Each of the simulations has its JPH value recorded and the results can be seen in Table 19 and the graphical form in Figure 15.
- EXP: 3B compared a number of the main experiments with run times of 30 days and 200 days. This experiment was carried out after the preliminary experiments but has been located within this section as it clearly shows the difference between long and short run times.

Below are the results for the EXP: 3A.

**Table 19: results For Exp: 3A Run Length Experiments**

| Run length in days | JPH   |  | Run length in days | JPH   |
|--------------------|-------|--|--------------------|-------|
| 10                 | 92.46 |  | 160                | 94.73 |
| 20                 | 93.12 |  | 170                | 94.52 |
| 30                 | 93.24 |  | 180                | 94.7  |
| 40                 | 94.77 |  | 190                | 94.44 |
| 50                 | 94.79 |  | 200                | 94.59 |
| 60                 | 95.6  |  | 210                | 94.63 |
| 70                 | 95.31 |  | 220                | 94.5  |
| 80                 | 94.77 |  | 230                | 94.44 |
| 90                 | 94.52 |  | 240                | 94.28 |
| 100                | 94.41 |  | 250                | 94.36 |
| 110                | 94.83 |  | 260                | 94.39 |
| 120                | 94.73 |  | 270                | 94.43 |
| 130                | 94.73 |  | 280                | 94.51 |
| 140                | 94.93 |  | 290                | 94.49 |
| 150                | 94.87 |  | 300                | 94.48 |

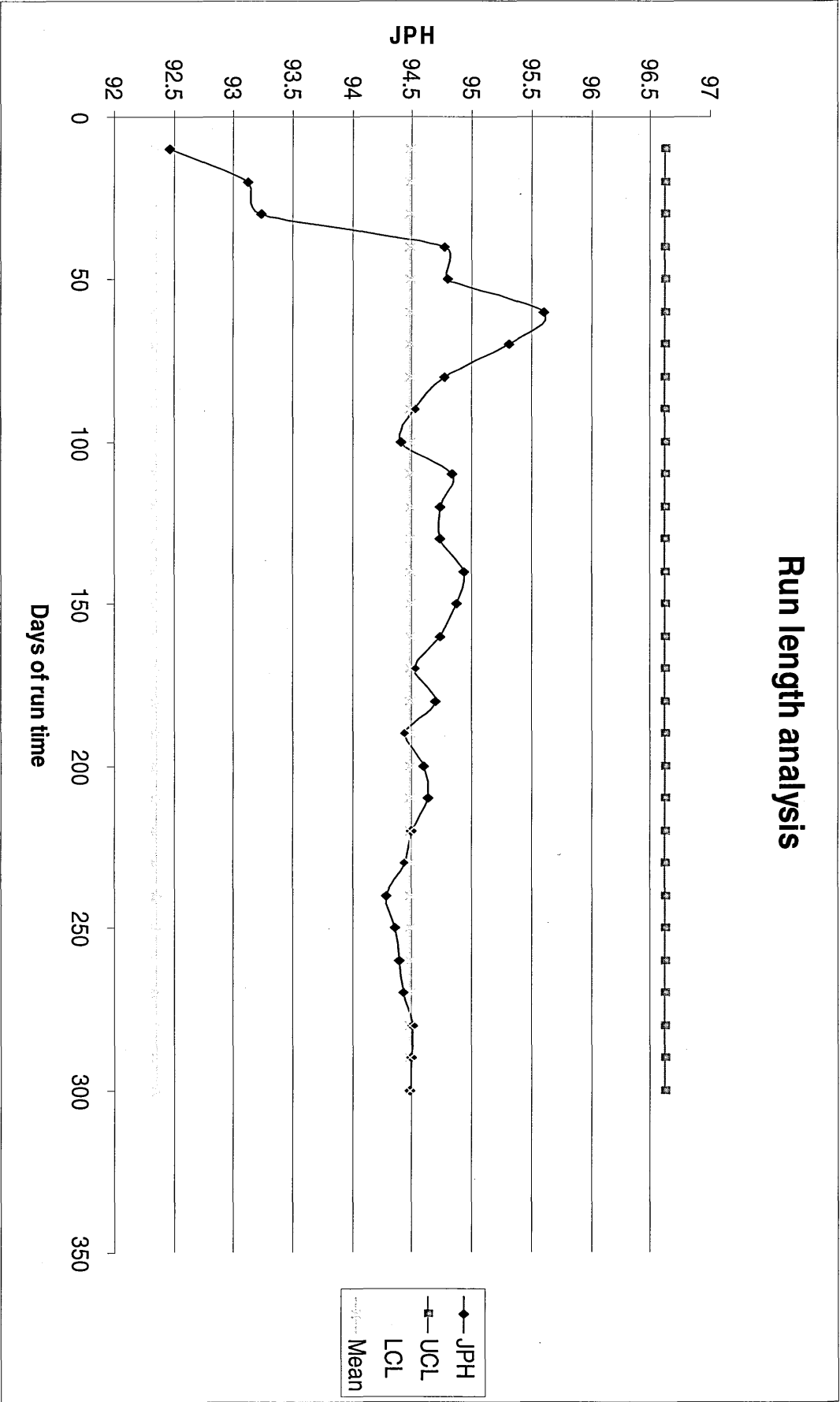


Figure 15: Graph for EXP: 3A Run Length Experiment Results

Below are the results for the EXP: 3B.

Table 20: results for EXP: 3B Varying Run Time 200 And 30 Days

| Exp name | 200 days | 30 days | variance |
|----------|----------|---------|----------|
| exp 1    | 99.88    | 99.32   | 0.56     |
| exp 2    | 104.72   | 104.34  | 0.38     |
| exp 3    | 99.12    | 99.51   | -0.39    |
| exp 4    | 100.11   | 99.25   | 0.86     |
| exp 5    | 94.72    | 93.35   | 1.37     |
| exp 6    | 104.82   | 103.53  | 1.29     |
| exp 7    | 104.65   | 105.03  | -0.38    |

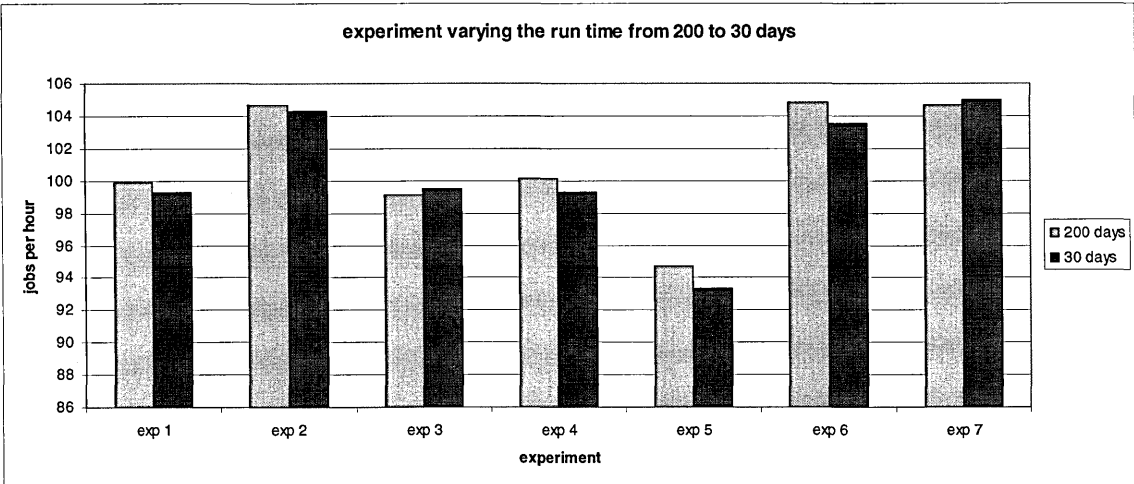


Figure 16: Graph for EXP: 3B Run Length Experiment Results

**Findings for EXP: 3A**

As shown in Figure 15 the results show that the longer the run time of the experiment the tighter the results are packed around the mean of the results. The results of this experiment show two distinctive areas of results, the first is the warm-up period (initial transient period), this is when the run time is not long enough to stabilise the experiment to gain the normal output level by fully loading the system. After this point when an experiment is run for a sufficient time for stabilisation to occur, the longer the run time the tighter the results centre on the mean. This would eventually result in the run time (number of days) producing a straight line at which point any further increase in the length of experiments would not make any difference thus all pseudo randomness would be lost and the simulation would have been normalised. This experiment has proven a link between longer run times and results which are less affected by the initial transient period. As stated in the aim, longer run times increase the experimental time, thus a median must be found between accuracy and time taken per experiment.

200 days seems an adequate number to gain the benefits of long run times without taking too long to compute the experiments. As a direct result of this simulation 200 days was defined as an acceptable run time length and is used in other Ford experiments using the similar first simulation of a manufacturing line. 200 days was also chosen as it is almost a whole year of

production day and it was presumed that this the average time between full line shut downs for maintenance activities.

### **Findings for EXP: 3B**

These experimental results shown in graphical form in Figure 16 and tabular form in Table 20, shows that there is a variance between the output of 30 days and 300 days. This link cannot be quantified from the current number of experiments that have been done but it can be stated that 200 day run times is less effected by the warm-up period. The variance itself is not large therefore for rough or initial experiments so a 30 day run time is acceptable. Any experiment that is needed to be accurate or will have some work or assumptions made on it must be as accurate as possible.

## **14.5 EXP: 4 Random Number Experiments**

### **Introduction**

The previous experiment was devised due to the uncertainty of the random number streams of the output of the model. This uncertainty is due to the effects of the pseudo random number on a model that has a short run time. Originally the concept of this study aimed to experiment with a run time of 30 days, this run time was suggested by the industrial supervisor. He felt that it was short enough to show the difference between pseudo random number streams. Thus this experiment is needed to confirm if different random number streams effect output of the system at a low run time (30 days) and also a high run time of (200 days).

### **Methodology**

The experiment was carried out in two stages. Both stages used the same methodology. Stage one, altered the random number streams of three experiments (including the default model) that where chosen for their high output rates or JPH of more than 99 JPH. Each of the three models where experimented on within low run times (30 days). Stage two is a direct copy of stage one but with the longer run time of (200 days)

### **Choosing number streams**

Using the Microsoft Excel, a formula was used to produce a list of random numbers between 1 and 99 these numbers could then be used in the simulation experiment. The formula that was used to create the ten experiments was: “=int(rand()\*100)”

Each experiment was run for the same period of time and only the one variable was changed which was the pseudo random number stream.

Experimental results for EXP: 4A for 30 days

The experimental results were completed from the preparatory work which is shown in Table 5.

**Table 21 results for EXP: 4A Showing Random Number Stream 1 and 2**

| Random numbers     | Results experiment 8b | Results experiment 1C |
|--------------------|-----------------------|-----------------------|
| 3                  | 104.34                | 99.97                 |
| 97                 | 104.41                | 100.72                |
| 74                 | 103.91                | 99.63                 |
| 84                 | 104.33                | 100.28                |
| 66                 | 104.65                | 99.86                 |
| 95                 | 103.26                | 99.36                 |
| 16                 | 104.53                | 99.9                  |
| 23                 | 103.35                | 100.19                |
| 36                 | 104.18                | 99.85                 |
| 2                  | 103.50                | 99.57                 |
| Average            | 104.05                | 99.93                 |
| Standard deviation | 0.508909227           | 0.39049968            |

The same method was used for the next experiment but the random number streams were again changed to ensure there was no drastic change in results, the results from this experiment can be found in Table 22. Graphical representations of the results for the three experiments can be found in Figure 17, Figure 18 and Figure 19.

**Table 22: results for EXP: 4A showing random number stream 3**

| Random numbers     | Results experiment default |
|--------------------|----------------------------|
| 3                  | 94.59                      |
| 16                 | 94.56                      |
| 58                 | 94.47                      |
| 54                 | 93.08                      |
| 75                 | 94.55                      |
| 68                 | 93.63                      |
| 46                 | 94.66                      |
| 43                 | 93.25                      |
| 94                 | 94.7                       |
| 13                 | 94.28                      |
| Average            | 94.14                      |
| STANDARD deviation | 0.636928393                |

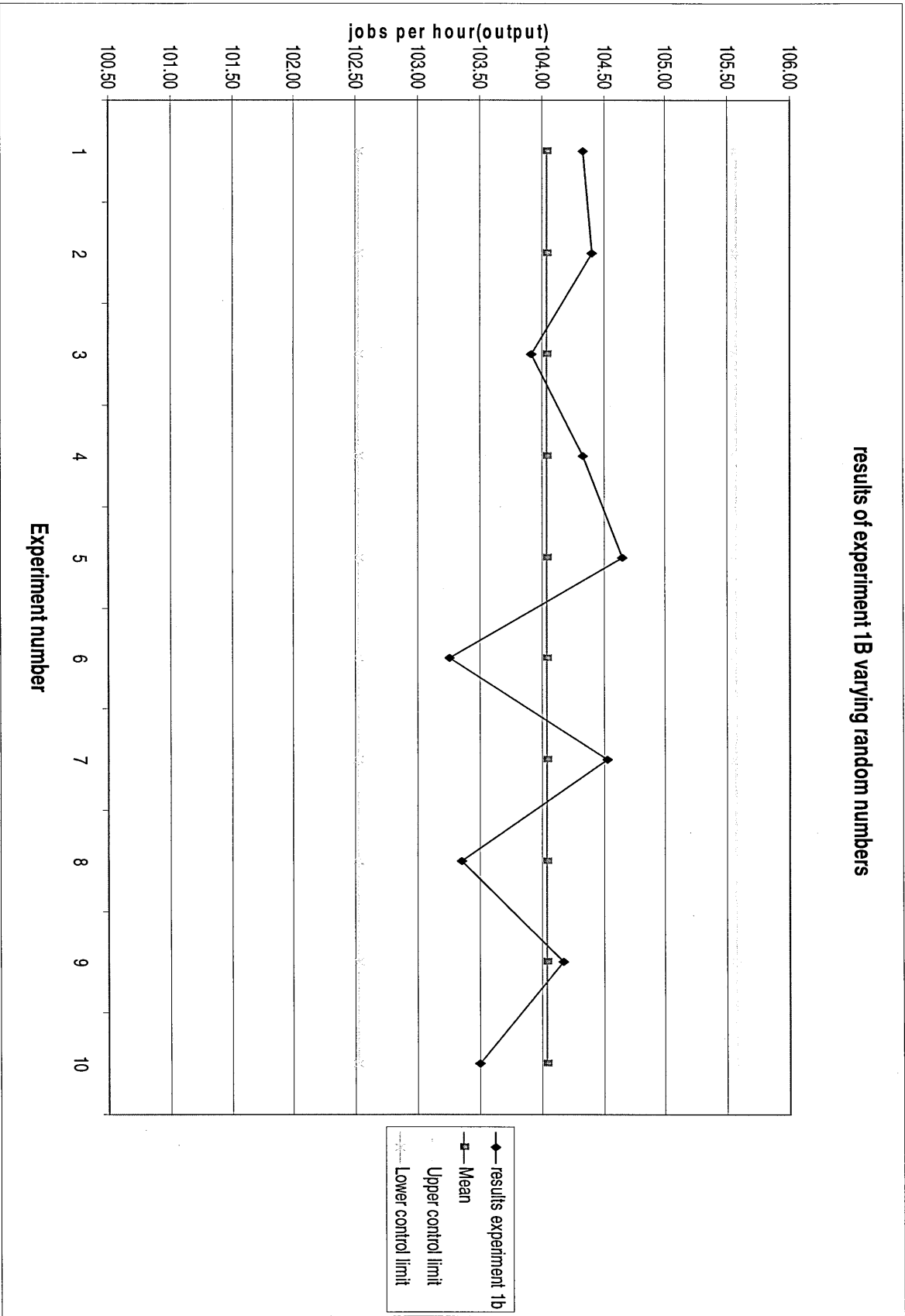


Figure 17: Graph for EXP: 4A showing random number stream 1

Results of experiment 6 varying random numbers

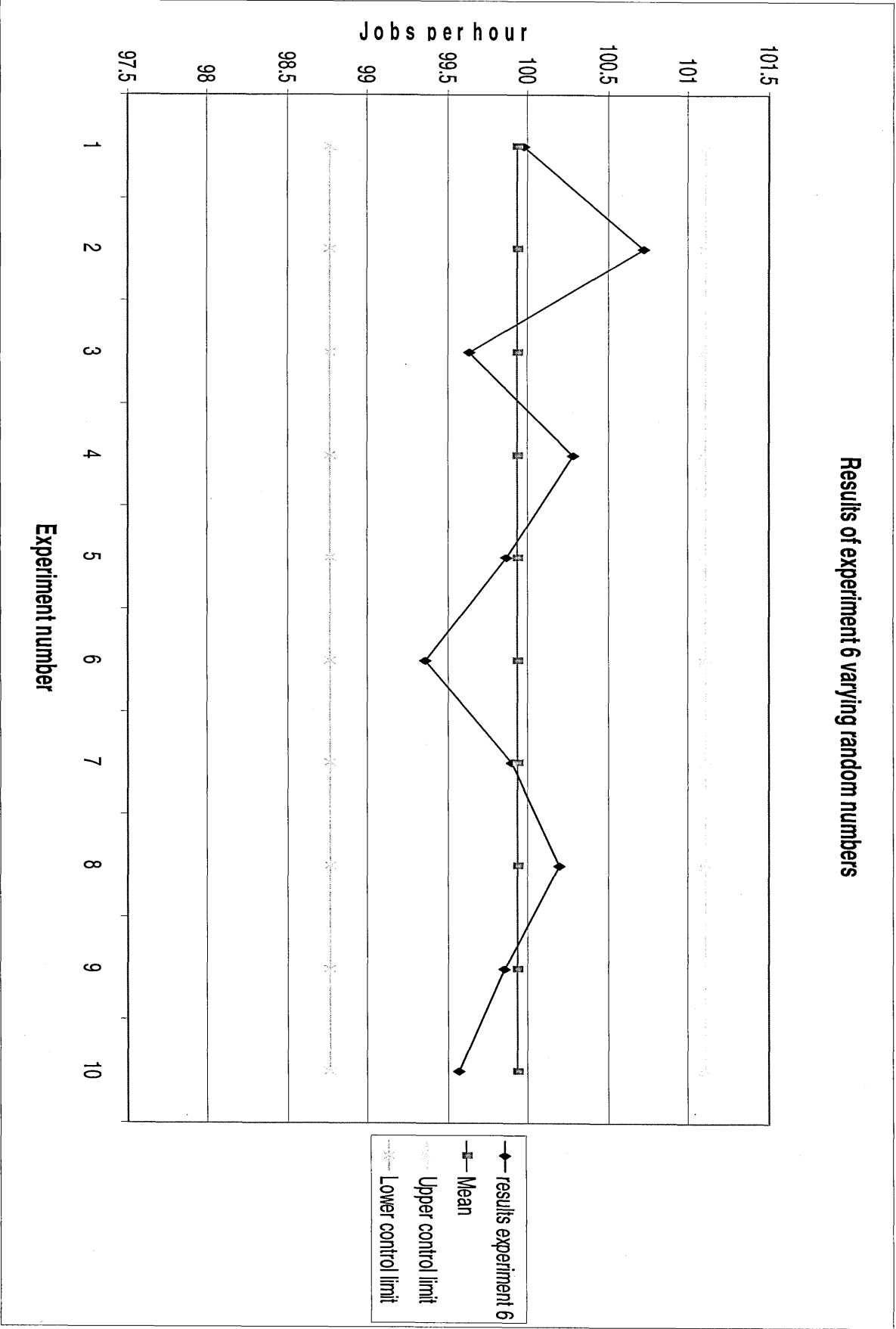


Figure 18: Graph for EXP: 4A Showing Random Number Stream 2

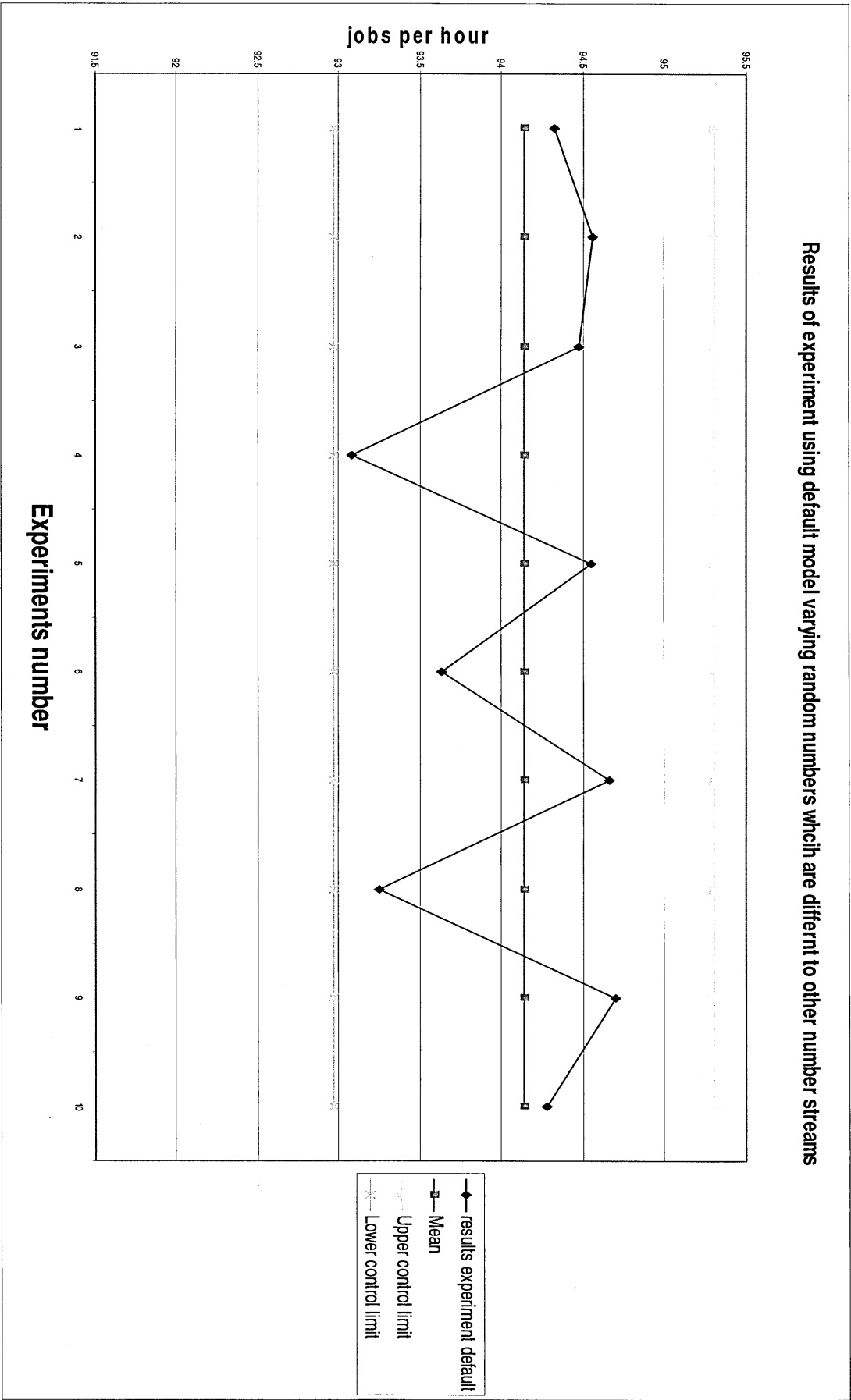


Figure 19: Graph for EXP: 4A Showing Random Number Stream 3

#### Findings for EXP: 4A

From the results in Table 21 and Table 22 it can be said that the random number streams do somewhat alter the output of the model, thus the run time is adequate for initial simulations but not experimentation where accurate conclusions need to be drawn. The random number streams can be said to produce less than one standard deviation shift from the mean value which is acceptable for initial experiments.

#### EXP: 4B. Random Number Experiments Run For 200 Days

##### Purpose

The link between longer run times and output (JPH) needs to be investigated further therefore the experiment below will investigate the effects of longer run times and random number streams. These experiments are needed to understand the implications of run times on the output of the default simulation model. The length of run time might play a significant role in the modification of any outputted results and for this reason the optimum run time must be understood. The industrial supervisor has confirmed from previous experiments that a 200 day run time taking approximately 28 – 32 minutes produces an acceptable run time for experiments. In this experiment a question was produced which was is there a difference between a 30 day run time which takes 3-5 minutes and the recommended cycle time from the industrial supervisor.

##### The method

The method used was the same as in the pervious experiment (4A). Three experiments were run using a selection of pseudo random numbers.

**Table 23: results for EXP: 4B showing random number stream 1**

| exp number | random number stream      | 200 days experiment 1b<br>JPH | 30 days results experiment<br>1b |
|------------|---------------------------|-------------------------------|----------------------------------|
| 1          | 3                         | 104.72                        | 104.34                           |
| 2          | 97                        | 105.02                        | 104.41                           |
| 3          | 74                        | 104.8                         | 103.91                           |
| 4          | 84                        | 104.59                        | 104.33                           |
| 5          | 66                        | 104.7                         | 104.65                           |
| 6          | 95                        | 104.2                         | 103.26                           |
| 7          | 16                        | 104.42                        | 104.53                           |
| 8          | 23                        | 104.4                         | 103.35                           |
| 9          | 36                        | 104.64                        | 104.18                           |
| 10         | 2                         | 104.69                        | 103.50                           |
|            | <b>Mean</b>               | <b>104.62</b>                 | <b>104.05</b>                    |
|            | <b>Standard Deviation</b> | <b>0.230882365</b>            | <b>0.508909227</b>               |

**Table 24: results for EXP: 4B showing random number stream 2**

| exp number | random number stream      | 200 days experiment 6<br>JPH | 30 days results experiment<br>6 |
|------------|---------------------------|------------------------------|---------------------------------|
| 1          | 3                         | 99.19                        | 99.97                           |
| 2          | 97                        | 99.29                        | 100.72                          |
| 3          | 74                        | 99.52                        | 99.63                           |
| 4          | 84                        | 99.6                         | 100.28                          |
| 5          | 66                        | 99.56                        | 99.86                           |
| 6          | 95                        | 99.44                        | 99.36                           |
| 7          | 16                        | 99.21                        | 99.9                            |
| 8          | 23                        | 99.29                        | 100.19                          |
| 9          | 36                        | 99.29                        | 99.85                           |
| 10         | 2                         | 99.36                        | 99.57                           |
|            | <b>Mean</b>               | <b>99.38</b>                 | <b>99.93</b>                    |
|            | <b>Standard Deviation</b> | <b>0.146609837</b>           | <b>0.39049968</b>               |

**Table 25: results for EXP: 4B showing random number stream 3**

| exp number | random number stream      | 200 days experiment default<br>JPH | 30 days results experiment<br>default |
|------------|---------------------------|------------------------------------|---------------------------------------|
| 1          | 3                         | 94.59                              | 94.59                                 |
| 2          | 16                        | 94.39                              | 94.56                                 |
| 3          | 58                        | 94.75                              | 94.47                                 |
| 4          | 54                        | 94.73                              | 93.08                                 |
| 5          | 75                        | 94.52                              | 94.55                                 |
| 6          | 68                        | 94.8                               | 93.63                                 |
| 7          | 46                        | 94.57                              | 94.66                                 |
| 8          | 43                        | 94.54                              | 93.25                                 |
| 9          | 94                        | 94.68                              | 94.7                                  |
| 10         | 13                        | 94.7                               | 94.28                                 |
|            | <b>Mean</b>               | <b>94.63</b>                       | <b>94.15</b>                          |
|            | <b>Standard Deviation</b> | <b>0.1263197</b>                   | <b>0.602236572</b>                    |

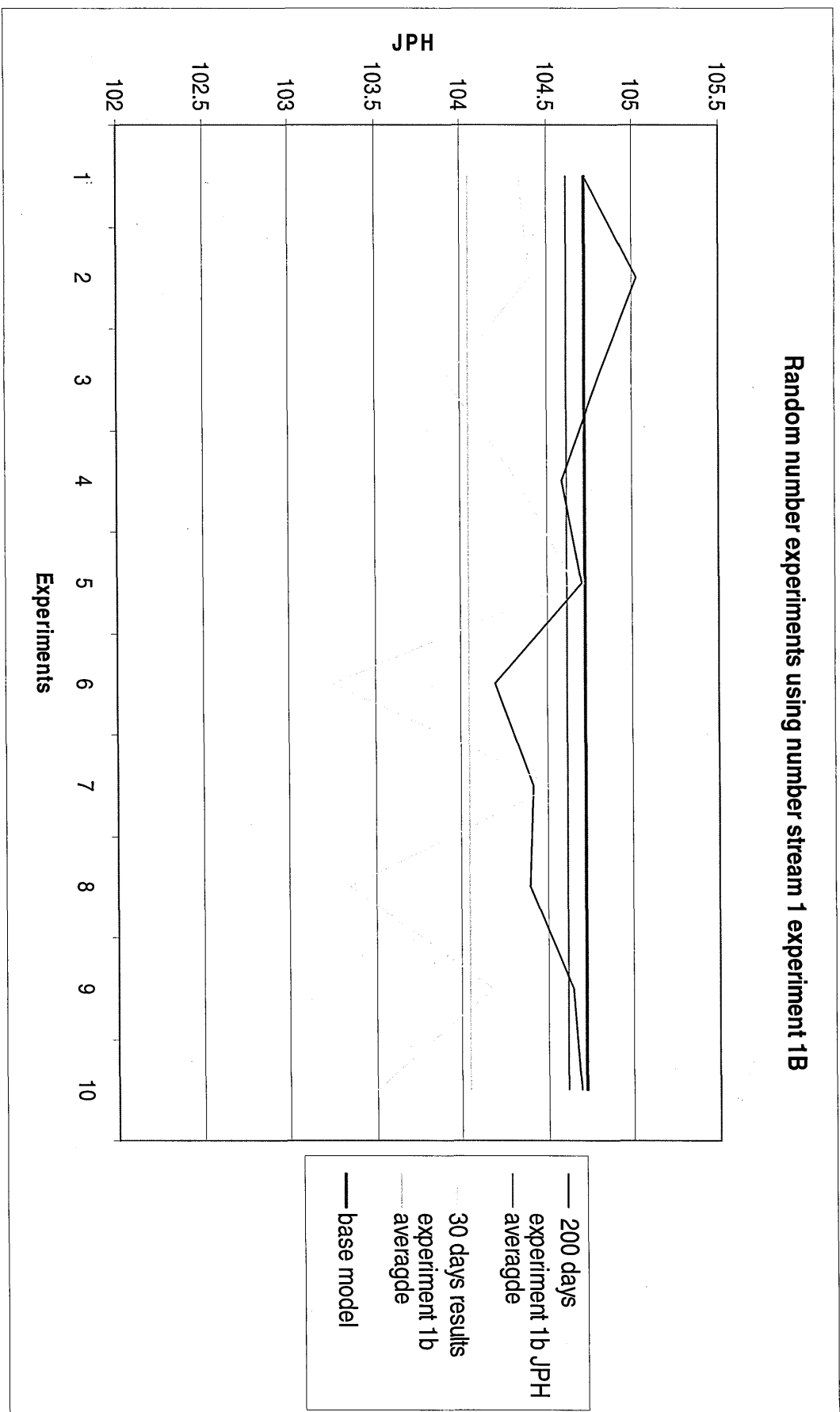


Figure 20: Graph for EXP: 4B showing random number stream 1

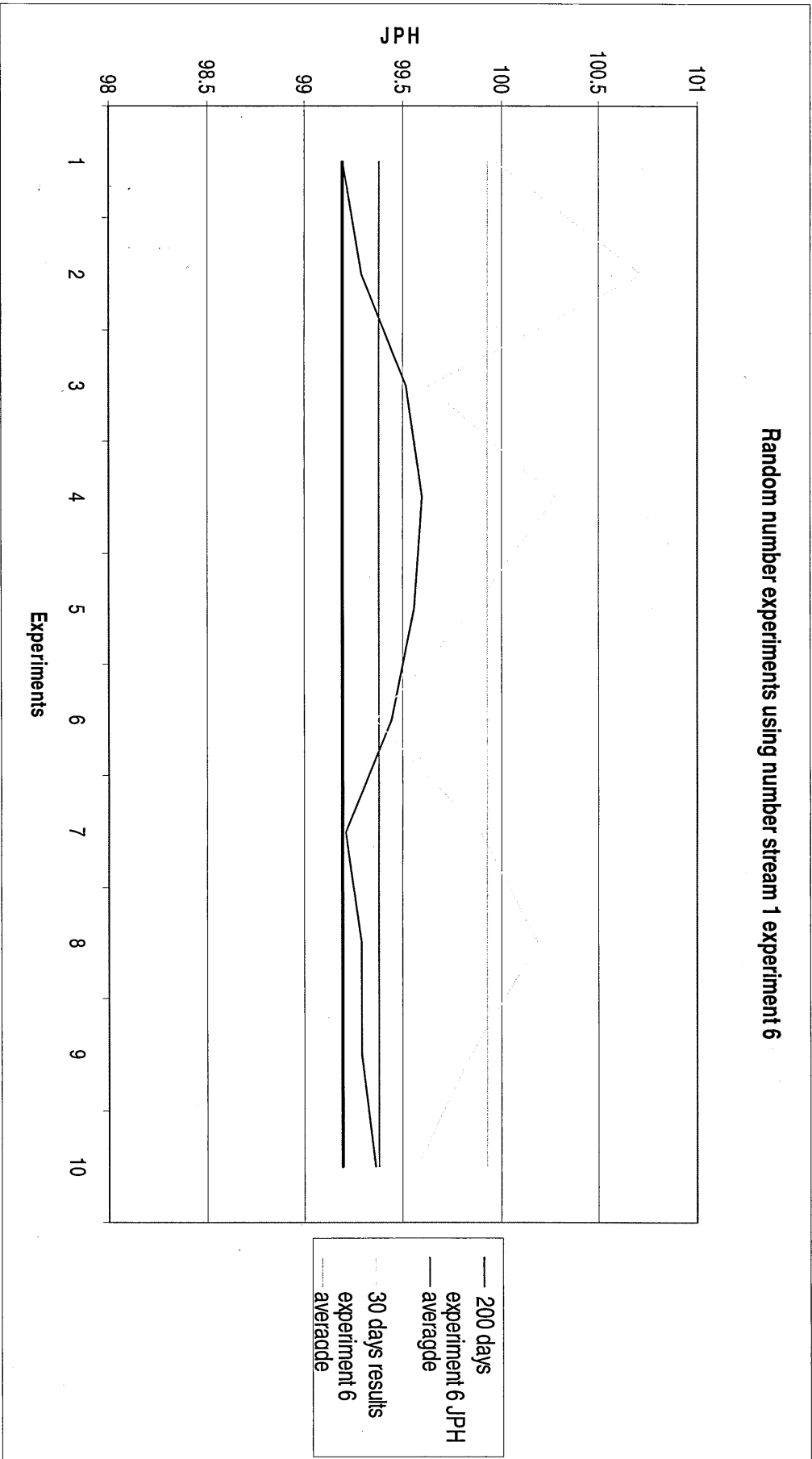


Figure 21: Graph for EXP: 4B showing random number stream 2

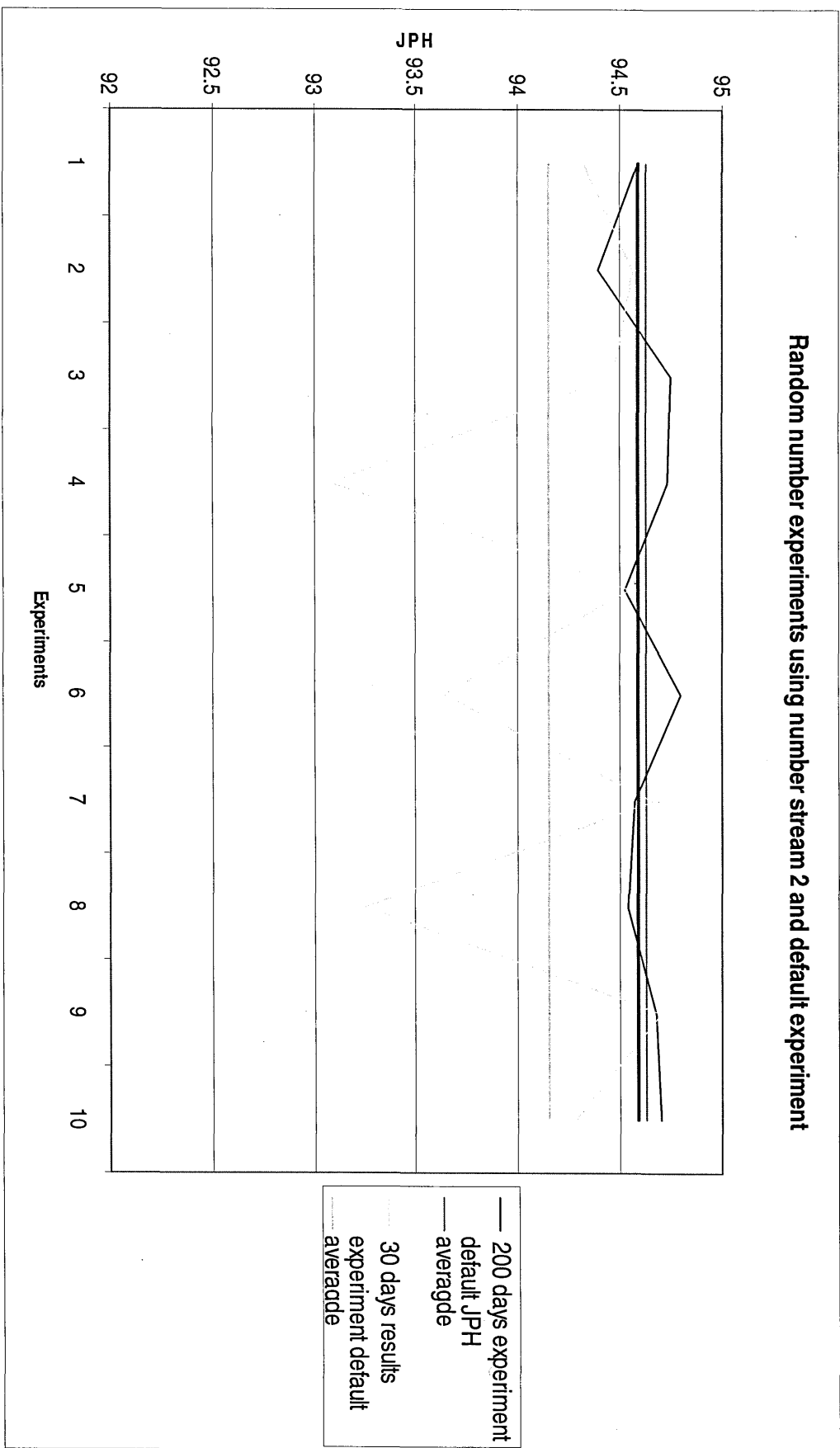


Figure 22: Graph for EXP: 4B showing random number stream 3

## Findings

From the result that have been produced in graphical (Figure 20, Figure 21 and Figure 22) and tabular (Table 23, Table 24 and Table 25) form, have been compared with the previous pseudo random number experiment 4A with the shorter run length. It can be shown that the 200 day run length allows the simulation experiment to stabilise. This can be shown by the differences in standard deviation from the mean. In each experiment set, the 200 day run time gave the lower standard deviation from the mean which states that the simulation is more stable and less effected by the random number streams that are used in the simulation.

From these experiments it can be stated that although simulation might sometimes be run quickly to gain faster results, the result can be affected by the random number streams. Therefore these simulations are being effected by an external variable that may give a misleading result.

To conclude, a longer run time has been shown to negate the effects of random numbers. Therefore this will be used as a standard for the rest of the experiments.

## 15 Appendix E - Main Experiments

### 15.1 *Introduction to Main Experiments*

This section has the bulk of the experiments that were carried out on the default simulation. There are a number of experimental hypotheses that have been produced in previous chapters and they will be tested and understood in this section.

### 15.2 *EXP: 5 Experimentation designed by researcher and FORD*

After the familiarisation experiments were carried out, a list of varying directions were defined. This was one via meetings with the industrial sponsor to discuss the previous experiments and other academic ways in which to increase the JPH for the default line.

#### Exp: 5.1 Optimisation of EXP: 8B

##### **Purpose**

The aim of this experiment is to optimise EXP: 8B and investigate the potential to remove machines from the system to reduce the impact of increasing the system by six machines in EXP: 8B. This will reduce the capital investment needed to make the changes to increase the output by a significant amount.

##### **Method**

The method used in this experiment was similar to that done in EXP: 8B using conditional formatting, but in this experiment the task was to identify operations that were underutilised which could then be investigated and potentially remove machines from the operation. Conditional formatting was used to identify operations which were underutilised <30%, <40%, <50% and <60%. At <60% operation 10 was highlighted as a possible underutilised operation and so the machines in this operation were reduced from 3 to 2.

##### **Findings of experiment**

This experimental method identified many underutilised operations but all operations excluding one, had only one machine present within their operation. This made it impossible to remove any other machines from the operations. This experiment did identify the possibility of combining operations together which were underutilised.

Although the output of this experiment actually reduced, the experiment can be still seen as a success. As shown below Exp: 5.1 had slightly less increase in output but the increase in

output per machine was greater. This reduction of only one machine is therefore more economical even though there is slightly less total output this can be shown in Table 26.

**Table 26: results for EXP: 5.1 optimisation of experiment 8**

| experiment    | Increase in output from base model | increase per machine |
|---------------|------------------------------------|----------------------|
| experiment 8B | 10.618                             | 6 machine = 1.769666 |
| Exp: 5.1      | 9.79194                            | 5 machine = 1.958388 |

Exp: 5.2 Optimising of Exp: 5.1 by investigating system blocking

### Purpose

The aim of this experiment was to increase output of the system by investigating system blocking using Exp: 5.1 as a base model. This experiment was conducted to understand if there were any other benefits that could be gained by increasing the size of strategic buffers to relieve blockages which could potential increase the overall output of the system.

This experiment was split into five separate experiments which build on each other to achieve the aim of this experiment.

### Exp: 5.2A

### Method

Using the conditional formatting rule imbedded within Microsoft Excel each operation was investigated to show which operations were blocked for more of time. This information was then used to increase buffer sizes post operation. Using this method the following changes were made:

**Table 27: results for EXP: 5.2A optimisation of OP10 buffers**

| operation | Buffer changed | Original buffer size | Current buffer size |
|-----------|----------------|----------------------|---------------------|
| Gantry 10 | Pre10          | 3                    | 6                   |
| Gantry 10 | Pre10          | 3                    | 6                   |
| Gantry 20 | Pre20          | 3                    | 6                   |
| Gantry 20 | Pre20          | 4                    | 7                   |
| RA10      | Preg20         | 1                    | 4                   |

Both Gantry 10 and Gantry 20 appear twice as they feed two separate operations called the same name. This is because the operations are modelled separately and show slight differences in breakdowns between machine types. RA10 is a buffer that is used to load Gantry 20; this is used to simulate the areas before the Gantry.

## Exp: 5.2B

### Method

This experiment used Experiment 5.1A as a base model. As in the experiment previously described, conditional formatting was used to identify operations that were blocked a high percentage of the time. All operations were investigated and the operations that were revealed to have with the lowest output were investigated further and highlighted. Combining both sets of information together it was shown that OP 10 was still blocked a high proportion of the time. They also were shown to be the bottleneck of the system. Armed with this information both operation 10 had its post operations buffers increased by a factor of two shown in Table 28, this increase can be seen in the table below:

**Table 28: results for EXP: 5.2B optimisation of OP10 buffers**

| operation | Buffer changed | Original buffer size | Current buffer size |
|-----------|----------------|----------------------|---------------------|
| Gantry 10 | Pre10          | 6                    | 12                  |
| Gantry 10 | Pre10          | 6                    | 12                  |

## Exp: 5.2C

### Method

The method is the same as experiment 2.12, the only change is the increase in buffer size which can be seen in Table 29

**Table 29: results for EXP: 5.2C optimisation of OP10 buffers**

| operation | Buffer changed | Original buffer size | Current buffer size |
|-----------|----------------|----------------------|---------------------|
| Gantry 10 | Pre10          | 12                   | 18                  |
| Gantry 10 | Pre10          | 12                   | 18                  |

## Exp: 5.2D

### Method

Using the conditional formatting method of identification on blocked operations, RA10 and RB10 were highlighted as possible buffers that could be strategically increased. Each of these buffers was increased from 10 to 20 storage spaces which can be shown in Table 30.

**Table 30: results for EXP: 5.2D optimisation of OP10 buffers**

| operation    | Buffer changed | Original buffer size | Current buffer size |
|--------------|----------------|----------------------|---------------------|
| operation 10 | RA10           | 10                   | 20                  |
| operation 10 | RB10           | 10                   | 20                  |

## Exp: 5.2E

**Method**

Using the conditional formatting method of identification on blocked operations, 20 and 21 were highlighted to be possible buffers that could be strategically increased. The buffers were increased by a factor of 2, Table 31 shows which buffers were increased:

**Table 31: results for EXP: 5.2E optimisation of OP20 buffers**

| operation | Buffer changed | Original buffer size | Current buffer size |
|-----------|----------------|----------------------|---------------------|
| 20        | Pre20          | 6                    | 12                  |
| 21        | Pre21          | 7                    | 14                  |

**Table 32: results for EXP: 5 summarised**

| Experiment | Result | Default value | Needed value |
|------------|--------|---------------|--------------|
| Exp: 5.2A  | 103.53 | 94.59         | 99.04        |
| Exp: 5.2B  | 105.03 | 94.59         | 99.04        |
| Exp: 5.2C  | 103.63 | 94.59         | 99.04        |
| Exp: 5.2D  | 103.63 | 94.59         | 99.04        |
| Exp: 5.2E  | 104.08 | 94.59         | 99.04        |

**Findings**

The results from experiment 5.2 are listed in Table 32

Experiment 5.2A did not increase the output of the system but the reduction was a small amount less than 1 part per hour. This experiment did obviously increase that amount of WIP in the system which is an unfortunate downside of the experiment.

Experiment 5.2B increased the output of the whole system to a value of 105.03 JPH. This is an increase of 1.5 JPH. The only problem with this experiment is the increase in WIP within the system. This is one thing that mass production industries including automotive industries have worked hard to reduce in recent decades to ensure that they remain lean to reduce costs. Experiment 5.2B shows that indeed buffer manipulation can increase the output of the machining line and therefore further experiments should be carried out to maximise any new alteration to the machining line.

Experiment 5.2C has proven that increasing buffer size to 18 units does not increase the output of the system. In fact the output level from the system dropped by 1.5 JPH to the

equivalent value of Experiment 5.2A. This experiment shows that an increase in buffer size can be counter productive to the machining line.

Experiment 5.2D did not change the output from Experiment 5.2C at all. There was an increase in the amount of WIP within the system which did not add any value to the system. This line of experimentation was shown to be without any positive benefits and so RA10 and RB10 buffers should not be increased in further experimentations.

Experiment 2.3E increased the JPH by a small amount. The increase could not be justified by the increase in WIP in the system. This experiment does not show if this increase in buffer size has produced the maximum output.

### **Exp: 5.3: removing of gantries.**

#### **Purpose**

The aim of this experiment was to remove the effects of the gantries on the default model. Gantries are used on the machining line to load and unload the parts from the CNC machines. Gantries could potentially affect the output of individual machines and thus the JPH of the line.

#### **Method**

The method used to negate the effect of gantries included removing the gantry's from the system. This was done by removing the breakdowns in each gantry and also setting the gantry cycle time to zero. This meant that the gantries were still within the logic of the simulation but their effects had been negated.

#### **Findings of experiment**

The negation of the gantries on the system was sizeable. The output increase by >5% to **99.51** JPH this reached the target increase of output for the system. This is certainly an area of further investigation but the possibility of having no cycle times for the gantry's is infeasible.

#### **Findings of initial experiment EXP: 5**

This list of initial experiments was produced to understand how variations to the machining line would affect the JPH level. This information can then be used to understand were to investigate further and which experiments are more likely to produce results. From these experiments it is clear that increasing the number of machines in operations that are bottlenecks has a dramatic effect on the JPH of the line. The investigation into gantry breakdowns has shown that gantries effect the output of the line, thus further investigations should be done to understand the benefits of altering the loading system.

15.3 EXP: 6 Number of platens

Purpose

The aim of this experiment is to investigate the effects of platen availability on the optimisation of the machining transfer line. A platen is effectively a precision jig that is used to constrain the work piece when machining takes place. They are reusable and effectively govern the amount of WIP that can be within the transfer line. After a certain number of platen the system reaches a point at which new platens will not increase the output of the line and a plateau effect will form. The aim of this experiment is to find the starting point of the plateau, thus the maximum JPH for the minimum number of platen. The default line has two platen loops which will be independently investigated for optimisation.

Method

The both platen loops from the default experiment will be run only changing the number of platens in one loop at a time. In each platen optimisation the number of platens will be reduced in units of 10, until a stable plateau has formed. The experiments will start at a higher value than the current platen level and reduce until the number of platens does not allow the simulation to run. At this point the simulation results will be collected if the results don't produce a stable plateau then further experiments will be carried to ensure the correct result has been found.

Optimum results

Table 33: results for EXP: 6 platen optimisation

|        | Current platen level | minimum platen level for circa 94JPH | Optimum platen level for JPH | MAX.JPH value | Increase in JPH |
|--------|----------------------|--------------------------------------|------------------------------|---------------|-----------------|
| loop 1 | 250                  | 100                                  | 160                          | 94.72         | 0.13            |
| loop 2 | 40                   | 15                                   | 35                           | 94.7          | 0.11            |

KEY

The below Key is for Figure 23 and Figure 24 and highlights the following points.

-  Brown diamond = minimum platen level
-  Orange diamond = optimum platen level for JPH
-  Pink diamond = current platen level

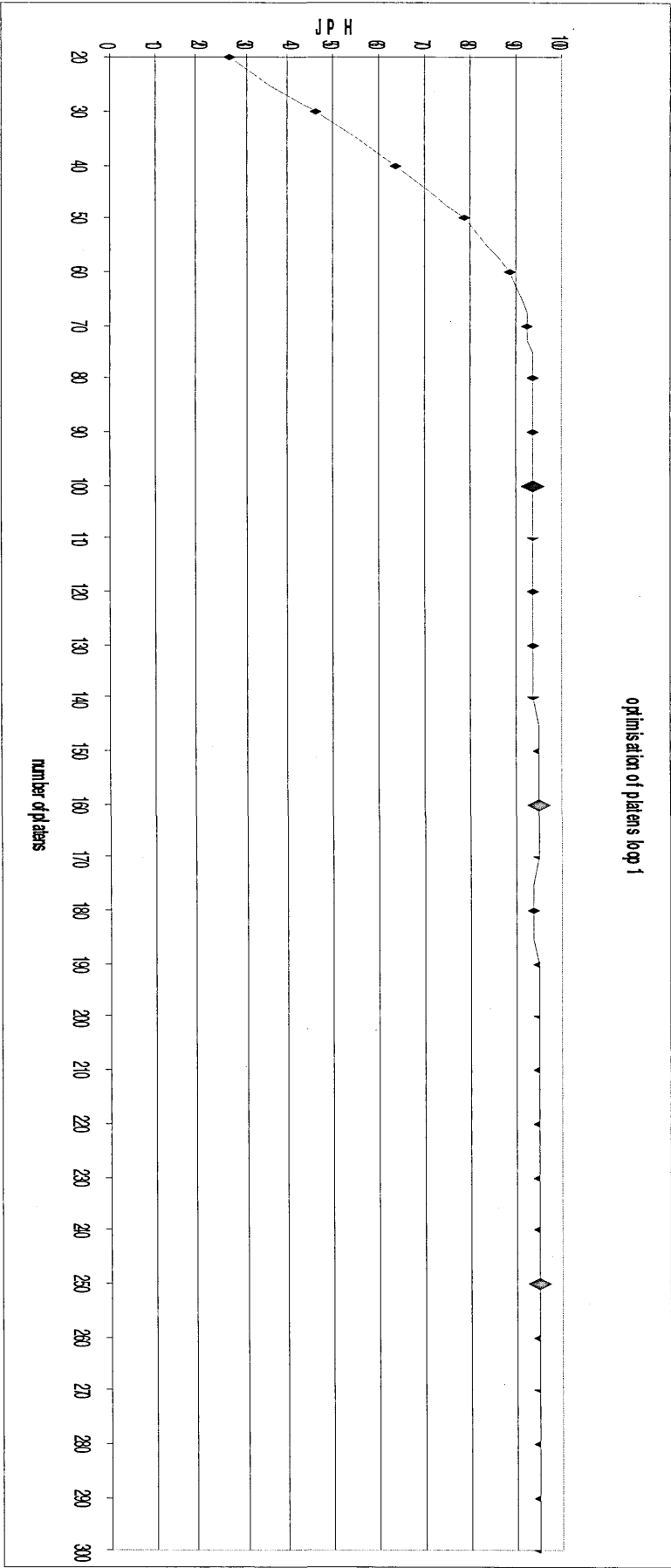


Figure 23: Graph for EXP: 6 Platen Optimisation Experiment Loop 1

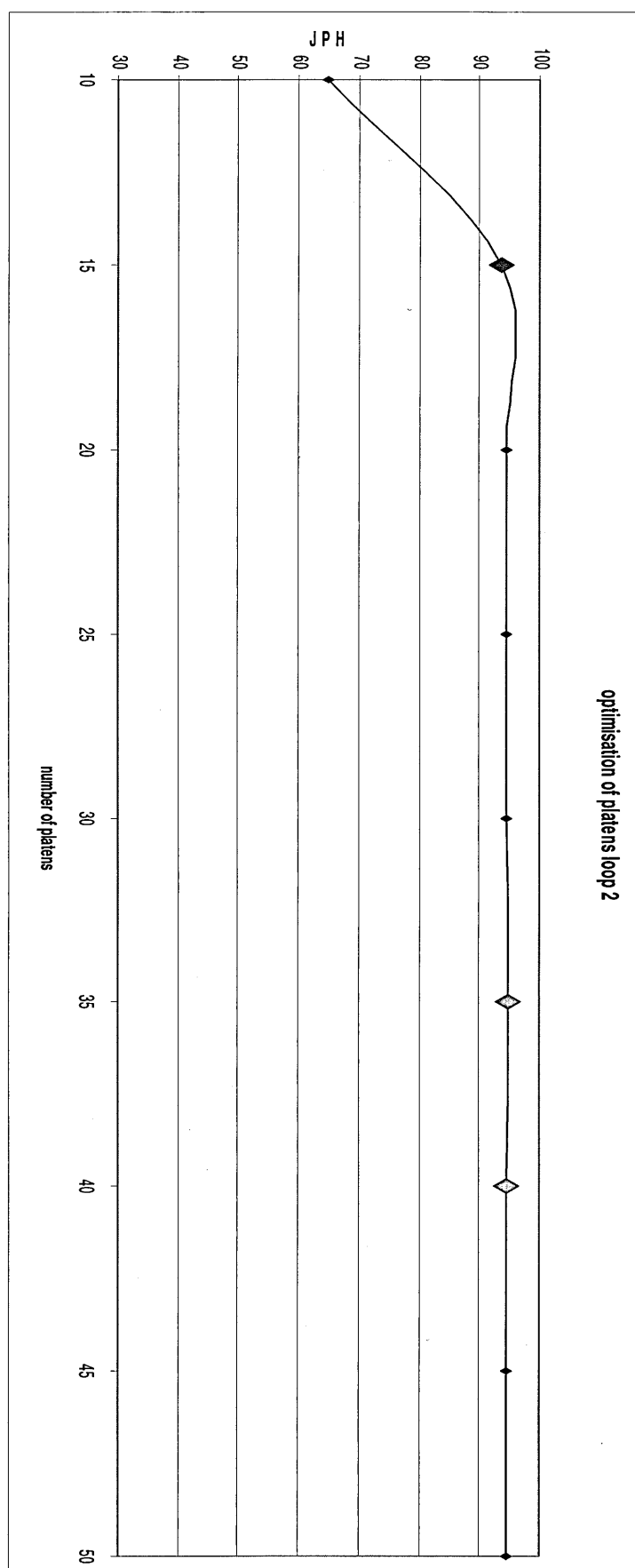


Figure 24: Graph for EXP: 6 Platen Optimisation Experiment Loop 2

**Findings**

The results of this experiment have produced interesting results shown in Table 33. With both loops there were a significant number of excess platens, which were used within the two loops. From the data collected, the number of platens in the loop gave two results: a maximum JPH value created by an optimum number of platens and also a minimum platen level for manufacturing without loosing more than 0.5 JPH. The latter provides an acceptable JPH value with a slightly reduced platen count. Both of these values are interesting to Ford, but the minimum number of platens should be when the JPH level plateaus. The maximum JPH value for loop one is 94.72 with 160 platens, whilst the start of the minimum platen level is 100 with a JPH of 94.24. This gives a benefit of 0.008 JPH increase per extra platen on top of 100 platens needed as a minimum value. This information can be shown in Table 34 for both loop1 and loop2.

**Table 34: benefits in JPH per platen**

|        | minimum number of platens | Optimum platen level for JPH | increase JPH between min and op | Increase in JPH per extra platen |
|--------|---------------------------|------------------------------|---------------------------------|----------------------------------|
| loop 1 | 100                       | 160                          | 0.48                            | 0.008                            |
| loop 2 | 15                        | 35                           | 0.96                            | 0.048                            |

For this small increase in output Ford would not invest millions of extra pounds unless it would meet Fords strict pay back period of less than 1 year which this would not.

**15.4 EXP: 7 Buffer Allocation**

**Aim**

After establishing a number of bottleneck operations in the transfer line using Roser (2001) bottleneck detection technique the aim of this experiment was to, investigate if increasing pre operation buffer capacity could increase the JPH value in the bottleneck operations and thus increase the JPH of the default line.

**Method**

Once bottleneck operations were found in previous experiments the buffer before these operations were increased. The operations that will be investigated in this experiment are listed in Table 35.

**Table 35: current buffer capacity for operations in EXP: 7**

| Operation | Current buffer capacity |
|-----------|-------------------------|
| 70        | 10                      |
| 90        | 3                       |
| 20        | 3                       |
| 80        | 3                       |

## EXP: 7A

The original experiment increased the buffer capacity by one unit at a time and also did not take into account of the additional platens needed to fill the new buffer capacity.

## EXP: 7B

In the second buffer experiment the capacity was increased in multiples of 10 units of capacity and for each new buffer space an additional platen was added to the platen storage pool.

## Results

**Table 36: results for EXP: 7A optimisation of buffer capacity**

| op70 | JPH  | extra jph per buffer space | op90 | JPH  | extra jph per buffer space | op20 | JPH | extra jph per buffer space |
|------|------|----------------------------|------|------|----------------------------|------|-----|----------------------------|
| 10   | 94.6 |                            | 3    | 94.6 |                            | 3    | 95  |                            |
| 11   | 94.5 |                            | 4    | 94.9 |                            | 4    | 95  |                            |
| 12   | 94.6 |                            | 5    | 94.7 |                            | 5    | 95  |                            |
| 13   | 94.6 |                            | 6    | 94.5 |                            | 6    | 95  | 0.016666667                |
| 14   | 94.6 |                            | 7    | 94.5 |                            | 7    | 94  |                            |
| 15   | 94.7 | 0.026                      | 8    | 94.5 |                            | 8    | 94  |                            |
| 16   | 94.6 |                            | 9    | 94.6 |                            | 9    | 94  |                            |
| 17   | 94.6 |                            | 10   | 95   | 0.058571429                | 10   | 94  |                            |

**Table 37: results for EXP: 7B optimisation of buffer capacity**

| op70 | JPH   | extra jph per buffer space | op90 | JPH   | extra jph per buffer space | op20 | JPH   | extra jph per buffer space | op80 | JPH   | extra jph per buffer space |
|------|-------|----------------------------|------|-------|----------------------------|------|-------|----------------------------|------|-------|----------------------------|
| 10   | 94.59 |                            | 3    | 94.59 |                            | 3    | 94.59 |                            | 3    | 94.59 |                            |
| 20   | 94.52 |                            | 13   | 94.72 |                            | 13   | 94.76 | 0.017                      | 13   | 94.97 |                            |
| 30   | 94.8  |                            | 23   | 94.91 |                            | 23   | 94.42 |                            | 23   | 95.04 |                            |
| 40   | 95.02 |                            | 33   | 95.02 |                            | 33   | 94.35 |                            | 33   | 95.62 |                            |
| 50   | 94.92 |                            | 43   | 95.12 |                            | 43   | 94.6  |                            | 43   | 95.59 |                            |
| 60   | 95.09 |                            | 53   | 95    |                            | 53   | 94.72 |                            | 53   | 95.71 |                            |
| 70   | 95.07 | 0.008                      | 63   | 95.31 | 0.012                      | 63   | 94.68 |                            | 63   | 95.91 | 0.022                      |

## Findings

The results of this experiment shown in tables Table 36 and Table 37, show that increases in buffer sizes pre bottleneck operations does not increase the JPH value in a significant way. The experiments only managed to increase the JPH by 2 which is a small increase based on the increase in buffer capacity. This insignificant increase in JPH is due the bottleneck operations are idle less then 2% of their operating time. Therefore buffers would only increase the JPH to the line for 2% of the running time, this 2% running time would also take into account of a period of warm-up time which would reduce the 2% time even more. If the bottlenecks where idle for a longer period such as 15% then increase in buffer size could be more applicable in the situation.

Increasing buffer capacity would only help in the following situation, if op 1 had a high blockage percentage and the next operation op 2 had a high idle percentage then increasing buffer capacity would increase both operations thought put or JPH. This however would not guarantee an increase in the line JPH as op1 and op2 might not be the bottleneck of the line. Increasing buffer capacity can be a cheap and simple way of increasing JPH providing the previous assumptions are shown to be true.

### **15.5 EXP: 8 Number of machine**

After running the default program and analysing the results it was clear that some operations were busier than others this means that they were in fact the bottlenecks of the line.

#### **Purpose**

The aim of this experiment was to remove the bottlenecks from the line to increase output of the system by adding new machines to bottleneck operations.

#### **Method**

This experiment was split into three sub experiments which built on each other to increase output of the system. Each of the three experiments used the same method of data analysis which leads to possible solutions. In experiment 8A results from the default model were used to investigate the largest bottlenecks in the system. At the operations results page within the FIRST program there are columns of operation percentage utilisation which are named idle, busy and blocked. Busy is the columns which can tell you which machines have the highest busy time thus the bottleneck of the system. Using Microsoft Excels conditional formatting tool a rule was produced that highlighted operations that were busy. These operations were then investigated. This bottleneck identification technique was pioneered by Roser (2001) and has been used throughout these experiments to first identify bottleneck operations and then investigate ways of negating them.

EXP: 8A the conditional formatting was set to highlight operations with greater than 84% busy. The rule highlighted operations 20, op70, op71 and op90 where busy more than 84% of the time. Each one of these operations was then increased by one additional machine which should reduce their interference to the output of the line.

EXP: 8B used the same principles used in EXP: 8A but used experiment EXP: 8A as a base model to experiment with instead of the default model. Due to the reduction of some of the bottlenecks within the previous experiment the value of conditional formatting was raised to more than 85%. This rule highlighted two operations that could be investigated and optimised, these were operations op80 and op81. As in experiment EXP: 8A one new machine was added to both operations to reduce the operations bottleneck effects.

EXP: 8C was a development of EXP: 8B with the same aims and method as the two previous experiments. Due to the two previous reductions in bottlenecks the conditional formatting was set at 89% to identify operations that could be investigated. This rule highlighted three operations which were operations op40, op50 and op55. Again as in the two previous experiments each operation was increase by another machine.

## Results

The results from the previous experiment can be seen in Table 38.

**Table 38: results for EXP: 8 adding new machines**

| Experiment | Number of new machines | Result     | Default value | Required value |
|------------|------------------------|------------|---------------|----------------|
| EXP: 8A    | 4                      | 99.32 JPH  | 94.59 JPH     | >99.0 JPH      |
| EXP: 8B    | 6                      | 104.72 JPH | 94.59 JPH     | >99.0 JPH      |
| EXP: 8C    | 9                      | 104.09 JPH | 94.59 JPH     | >99.0 JPH      |

## Findings

As shown in Table 38, the experiments produced results that exceeded the “needed value” of the project. These three experiments have shown that adding new machines into the existing machining line can produce the benefits that are required in this project. Experiment 8B shows the largest increase in JPH with an increase in 6 new machines.

There is a significant increase in JPH between experiment 8A and 8B although only 2 machines are added to the existing machining line. This could be due to better balancing or more likely due to the operations (80 and 81) being key bottlenecks in the machining line. Experiment 8C increases the number of new machines to 9 but the JPH result falls, this could be due to unbalancing the machining line.

This method of identifying of bottleneck in the system produced some significant results. Exp: 8A increased the output of the model by >5% to 99.32 parts per hour. This increase would meet the aim of increasing the project brief to increase the output by at least 5%. Exp: 8B also increased output by nearly >10% from the base model to 104 parts per hour. This effectively has doubled the required output for the project. The bottleneck reduction in this experiment has levelled the line out to an acceptable level. Exp: 8C did not increase the output rate from its base model of Exp: 8B. The output rate actually fell by .2 parts per hour. This means that trying to balance the line any further than Exp: 8B does not add any values to the system. This shows that Exp: 8B is the optimum system using this experimentation method and without changing other parameters. Exp: 8B increases the amount of machine by 6 from the base model this increase could be very costly and also might not be possible due to space restrictions on the factory floor.

To conclude this Exp: 8B shows real potential in terms of the benefits of adding new machines to existing operations and also shows potential for further work.

## 15.6 EXP: 9 combining operation within lines

### Purpose

This experiment aims to understand if there are benefits in changing the manufacturing strategy of the machining line. At present the manufacturing strategy that has been adopted is the transfer line. This continuous flow manufacturing technique is quick and very fluid but when machines breakdown, blockages and starvations occur throughout the line reducing the overall efficiency of the line. To combat these breakdowns within the line it has been hypothesized that many standalone machines which are part of the transfer line could be used to negate the effects of the blocking and starvation throughout the line, this concept can be seen in Figure 25.

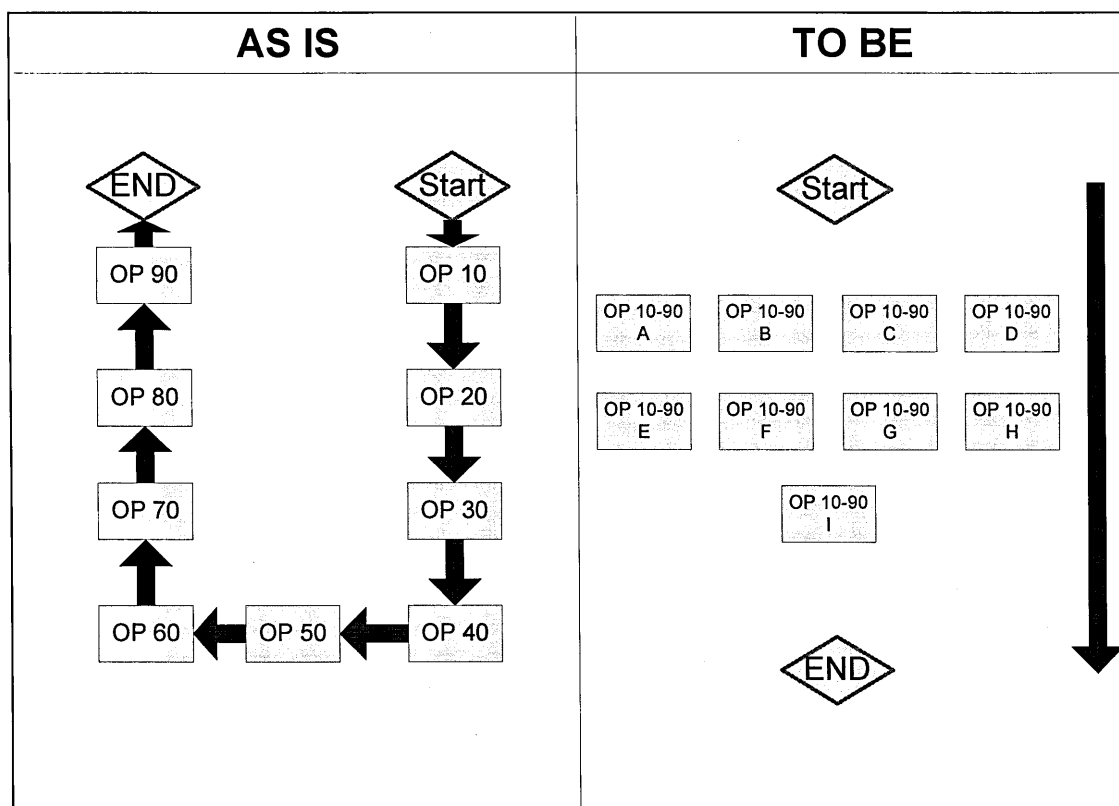


Figure 25: Diagram showing logic of combining operations

### The method

As discussed in previous experiments there are different sections within the whole transfer line. The experiment will first individually combine operations together within sections and inthen will combine all operations in the transfer line. The method that will be used will take a number of operations add the number of machines in each operation together and do the same with the cycle times. The combined cycle time and number of machines is then inputted into the first operation ensuring that the breakdown data is associated with it and it is not an assembly operation. For the rest of the combined operations, the cycle times will be set to zero. The number of machines will not be changed.

**Table 39: Results For Exp: 9 Combining Lines**

| Experiment name        | EXP: 9A<br>line 1 | EXP: 9B<br>line 2 | EXP: 9C<br>line 3 | EXP: 9D<br>combination | total |
|------------------------|-------------------|-------------------|-------------------|------------------------|-------|
| total cycle time       | 20.338            | 34.424            | 2.73              | 57.492                 |       |
| # of machines combined | 22                | 36                | 6                 | 64                     |       |
| ops combined           | 5 to 55           | 60 to 132         | 135 to 180        | 5 to 180               |       |
| result                 | 95.31             | 101.9             | 94.79             | 112.74                 |       |

### Findings

These results show that significant benefits can be produced when operations are combined together to form a machining centre capable of carrying out all 180 operations. This produced large result of 112.74 JPH which is an increase of 18.15 JPH which is a percentage increase of **19%**. As stated in the industrial problem this project wanted to find ways in which to increase JPH value by 5% these experiments show that this is a possibility.

The major problem with simulation experiments is that there are no constraints which affect the outcome of the result. A good example of this is experiment 9D the likelihood of finding a machine tool that is capable of carrying out 30 different operations within one work centre is very low. It could certainly be stated that none of the existing machine tools that Ford possesses could combine all of these operations together. The amount of investment needed to change manufacturing strategy in this way would be massive.

Although this combining all operations together is infeasible, this experiment does show that combining operations can make a large difference in terms of increase JPH. Therefore more experimentation needs to be carried out to show the benefits of combining similar operations together which use the same machine tooling.

From investigating the different states of the machines the combining of operations can be seen as a way of reducing operational bottlenecks. Therefore when possible, instead of increasing the number of machines within the operation, combining similar operation could remove the need to invest in new machines.

## 15.7 EXP: 10 Gantry Breakdowns

### Purpose

The aim of this experiment is to investigate the effects of mean time between failures (MTBF) of gantries on the JPH levels in the transfer line. The transfer line is almost fully automated thus the CNC milling machines are fed automatically by gantries. If gantries have a short time between breakdowns then there would be a higher percentage of inactive CNC milling machines in the transfer line. Thus this experiment will increase the mean time between failures for gantries and the effect on the JPH of the transfer line being monitored.

### Method

In the default simulation model the MTBF is calculated using this statistical distribution equation:

$\text{Negexp}(7392,41)$

To increase the mean time between failures, the same statistical distribution equation was used with the addition of a multiplying factor, an example of which can be seen below:

$(X * \text{Negexp}(7392,41))$

The multiplying factor was changed 7 times until 4 times MTBF had been reached. At this point the statistical distribution equation was deleted to show the effects of no mean time between failures.

### Results

#### Table of results

**Table 40: Results For Exp: 10 Gantry Breakdowns**

| experiment # | variation in break down  | JPH    | Default JPH | increase in JPH |
|--------------|--------------------------|--------|-------------|-----------------|
| 10A          | Default system           | 94.59  | 94.59       | 0               |
| 10B          | 1.25 * normal breakdowns | 96.07  | 94.59       | 1.48            |
| 10C          | 1.5 * normal breakdowns  | 95.84  | 94.59       | 1.25            |
| 10D          | 2 * normal breakdowns    | 98.21  | 94.59       | 3.62            |
| 10E          | 2.5 * normal breakdowns  | 98.55  | 94.59       | 3.96            |
| 10F          | 3 * normal breakdowns    | 98.92  | 94.59       | 4.33            |
| 10G          | 3.5 * normal breakdowns  | 99.22  | 94.59       | 4.63            |
| 10H          | 4 * normal breakdowns    | 99.46  | 94.59       | 4.87            |
| 10I          | No break downs           | 100.65 | 94.59       | 6.06            |

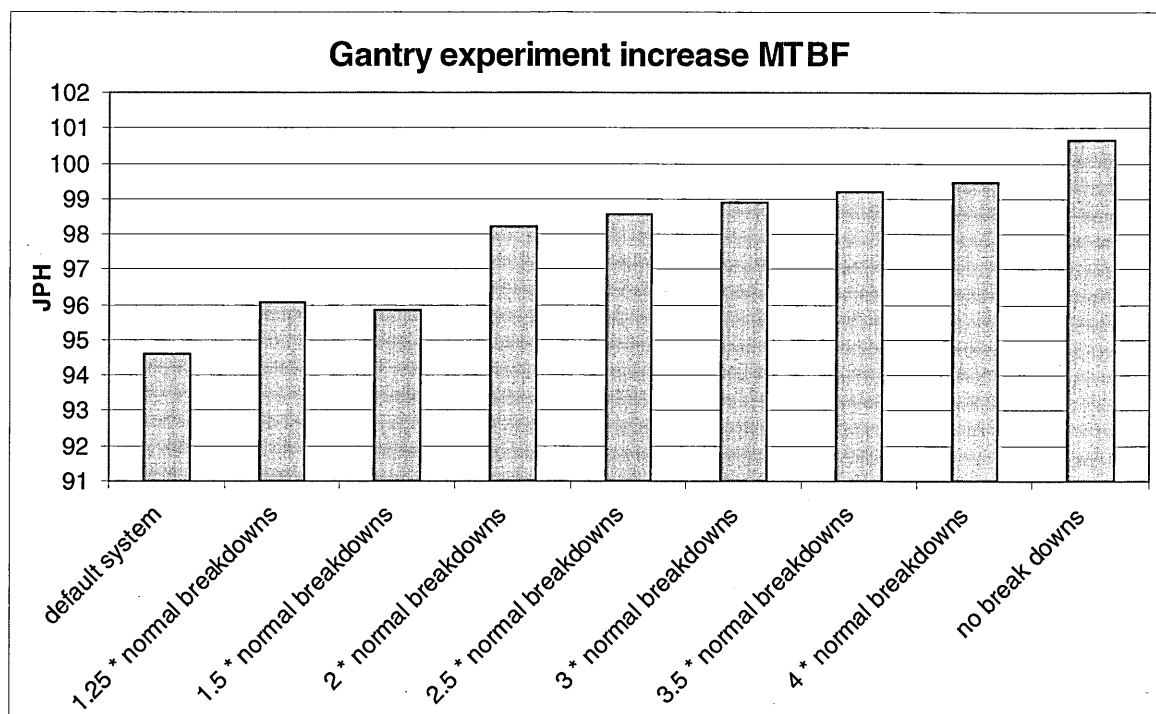


Figure 26: Graph for EXP: 10 Gantry Breakdowns experimental results

## Findings

The results of this experiment shown in Table 40 and Figure 26 show the effects of the gantry loading system on JPH for the transfer line. This relationship between the two can be shown from the increase in MTBF, resulting in less gantry breakdowns. Thus the CNC machines can be attended to more frequently. This will increase their machining rate increasing the overall JPH of the transfer line. This increase in JPH assumes that the gantries will become more resilient to breakdowns or even have no breakdowns. This is highly unrealistic even if the system is maintained at 1 to 1 ratio, maintenance man to gantry. Therefore a new type on load/unload system would have to be implemented if zero breakdowns were required. This would be expensive and would not be worth the required capital investment. Therefore gantry optimisation could produce credible increases in the JPH but only at a 2-4 times MTBF if new maintenances schemes are set up.

## 15.8 EXP: 11 Investigating effects of single machine operations on the system

### Purpose

The aim of this experiment is to investigate the effects all single machine operations in the rest of the transfer line. The simulation has two types of single machine operations which can be seen below:

- **Real operations** are actual operations that are part of the real system but only possess one machine.

**Dummy operations** are used to help construct the simulation model, they are not present in the real system as operations with single machines but they do help construct the complex logic needed to accurately simulate the model.

Both of these types of operation must be investigated to quantify their effects on the simulation.

**Method**

A list of operation was defined for the simulation model and operations were then split into their respective types “**Real or Dummy**” operations, a list of these can be found in Table 41:

**Table 41: list of real and dummy operations**

| <b>Real operations</b> | <b>Dummy operations</b> | <b>Dummy operations</b> | <b>Dummy operations</b> |
|------------------------|-------------------------|-------------------------|-------------------------|
| 5                      | ra10                    | rb71                    | rb160                   |
| 30                     | rb10                    | rc71                    | ra170                   |
| 40                     | rc10                    | ra80                    | rb170                   |
| 50                     | rb11                    | rb80                    | ra180                   |
| 55                     | rc11                    | rc80                    | rb180                   |
| mtpalret               | ra20                    | rb81                    | ra10A                   |
| 60                     | rb20                    | rc81                    | rb10A                   |
| 132                    | rc20                    | ra90                    | ra20A                   |
| retmtpal               | rb21                    | rb90                    | rb20A                   |
| mtpalet                | rc21                    | rc90                    | ra30A                   |
| 135                    | ra30                    | rb91                    | rb30A                   |
| 140                    | rb30                    | rc91                    |                         |
| 150                    | ra40                    | ra110                   |                         |
| 160                    | rb40                    | rb110                   |                         |
| 170                    | ra50                    | ra120                   |                         |
| 180                    | rb50                    | rb120                   |                         |
| 182                    | ra55                    | ra130                   |                         |
| retmtpal               | rb55                    | rb130                   |                         |
| 5A                     | ra60                    | ra140                   |                         |
| 10A                    | rb60                    | rb140                   |                         |
| 20A                    | ra70                    | ra150                   |                         |
| 30A                    | rb70                    | rb150                   |                         |
| 200                    | rc70                    | ra160                   |                         |

The experiment then split into two sections the first would investigate increasing the number of machines in the single machine operations. The second part would remove the tool change and breakdown data from the single machine operations.

## Results

**Table 42: results for EXP: 11A effects of single machine operations**

| Exp number | JPH   | Description                                         |
|------------|-------|-----------------------------------------------------|
| Exp 1      | 95.52 | ops 5-200 without gantries, pallet and A ops        |
| Exp 2      | 95.19 | all ops                                             |
| Exp 3      | 94.32 | RA AND RB PLUS 1                                    |
| Exp 4      | 94.07 | RA AND RB PLUS 2                                    |
| Exp 5      | 95.35 | ops 5-200 without gantries, pallet and A ops PLUS 2 |

**Table 43: results for EXP: 11B effects of single machine operations**

| Exp number | JPH    | Description                                                                            |
|------------|--------|----------------------------------------------------------------------------------------|
| Exp A      | 95.19  | ops 5-200 remove breakdown, no tool change to remove                                   |
| Exp B      | 95.41  | all ops remove breakdown, no tool change to remove                                     |
| Exp C      | 102.94 | remove breakdown and tool change for ops with more than 1 machine, 10,20, 70,80,90,130 |

## Findings

This experiment was used to gauge the effects of real and dummy operations, the results of which can be found in Table 42 and Table 43. The operations that had only 1 machine present in them. From the results of doubling each of the single machine operations and removing the breakdown data and tool change data a small increase of 1 JPH has been observed. Therefore it can be stated that these operations do not have a significant effect on the overall throughput or JPH of the line. Conversely in experiment 11C breakdowns and tool changes were removed for operations which all have more than one machine within them, this result can be found in Table 43. These operations are where the majority of the machining is carried out and therefore made a significant change to the output of the model.

## **16 Appendix F - Defined experiments**

### **16.1 *Introduction to defined experimentation***

In this section the defined experimentation will be carried out. Questions from previous experiments will be further investigated and understood. Once all of the questions have been answered by the experimental results a number of generic proposals will be produced predominantly from the defined experimentation.

### **16.2 *EXP: 12 varying new machine locations***

#### **Purpose**

One of the possible ways in which to increase the output rate of the transfer line is to increase the number of machines that are in the transfer line at strategic bottlenecks. This was first done in Exp: 8B which needed 6 extra machines and increased the output from the default value of 94.59 to 104.72 JPH. The aim of this experiment is to understand where a number of machines would be best placed throughout the line to reduce bottlenecks and increase the JPH value. A machine tool is a large investment therefore if one is needed it must be placed within the transfer line in an operation that most requires a new machine.

For this experiment the experiment assumes Ford has the capital to buy 6 new machines which is the maximum amount of money that can be invested within the transfer line. Cost is a key driving factor and therefore each financial investment will be evaluated on the productivity gains based in the investment cost (increase in JPH per new machine).

This experiment is split into 3 main sub experiments each of these experiments follows the above aim but tries to get to the answer in different ways.

#### **EXP: 12A Operation by operation**

In this sub experiment 6 machines were added to each operation in turn to establish which if any operations could be shown to have a significant benefit of having 6 extra machines imbedded in the operation. The experiment also was used to identify key operations that were previously over utilised.

The method for this experiment was to start with a default model and add 6 machines to each operation in turn. Where operations have been split such as 10 and 11 which are the same production operation they have been combined together and the six machines has been split equally between both. This experiment concentrates on operations OP10 to OP130 operation. Operations post OP130 were not considered for this experiment as none of these operations

had high busy percentages, thus these operations are not considered as bottlenecks of the manufacturing system. The following results have been obtained which are shown in Table 44.

**Table 44 : Results For Exp: 12A varying new machine locations by operation**

| Operation number | Original number of machines in op | Result | Increase per new machines |
|------------------|-----------------------------------|--------|---------------------------|
| 10+11            | 3+3                               | 94.51  | -0.013333333              |
| 20+21            | 5+6                               | 94.76  | 0.028333333               |
| 30               | 1                                 | 94.57  | -0.003333333              |
| 40               | 1                                 | 94.64  | 0.008333333               |
| 50               | 1                                 | 94.68  | 0.015                     |
| 55               | 1                                 | 94.49  | -0.016666667              |
| 60               | 1                                 | 94.53  | -0.01                     |
| 70+71            | 5+5                               | 96.52  | 0.321666667               |
| 80+81            | 5+5                               | 96.05  | 0.243333333               |
| 90+91            | 4+5                               | 96.02  | 0.238333333               |
| 110              | 1                                 | 94.84  | 0.041666667               |
| 120              | 2                                 | 94.7   | 0.018333333               |
| 130+132          | 2+1                               | 94.43  | -0.026666667              |

**Findings**

These experiments have not produced favourable results, but it has highlighted a number of operations such as (70+71, 80+81 and 90+91) where an increase of machines has increased the number of JPH in the transfer line. Therefore these operations can be shown to need a number of new machines but how many new machines is still unclear.

**EXP: 12B Line by Line**

The experiment investigates where to introduce machines in operations within areas of the model. In the transfer line there are 3 main loops 1, 2 and 3. Each one of these areas was investigated for bottlenecks and new machines were placed within operations shown to be heavily utilised.

**Method**

Each area was investigated for operations that were heavily utilised using conditional formatting. Understanding that 6 machines were available the machines were strategically situated to maximise the JPH of the transfer line. The results can be seen in Table 45.

**Table 45: Results For Exp: 12b varying new machine locations by loop**

| Experiment                 | Loop 1            | Loop 2            | Loop 3     |
|----------------------------|-------------------|-------------------|------------|
| New machines added to op # | op 20+ 2 machines | op 70+ 1 machines | op 150 + 2 |
| New machines added to op # | op 21+ 1 machines | op 71+ 1 machines | op 160 + 2 |
| New machines added to op # | op 40+ 1 machines | op 80+ 1 machines | op 170 + 2 |
| New machines added to op # | op 50+ 1 machines | op 81+ 1 machines |            |
| New machines added to op # | op 55+ 1 machines | op 90+ 1 machines |            |
| New machines added to op # |                   | op 91+ 1 machines |            |
| Results                    | 94.92             | 100.29            | 94.68      |
| Benefit per new machine    | 0.055             | 0.95              | 0.015      |

## Findings

From this experiment the results have shown that more machines are needed in loop 2 of the transfer line. This is where the most bottlenecks are. Thus any new investment in machines should concentrate the new machines in this area of the transfer line. This experiment has also again identified operations 70, 80 and 90 as being key bottleneck operations. This is also part of the 9A experimental findings.

## EXP: 12C Optimisation Of Machine Placement

Using conditional formatting and also the Roser (2001) bottleneck detection technique a number of experiments were carried out placing up to six machines in operation shown to be potential bottlenecks from previous experimentation and conditional formatting .

## EXP: 12C Results

**Table 46: Results For Exp: 12C varying new machine locations by known bottlenecks**

| experiment                   | 12C-1     | 12C-2     | 12C-3     | 12C-4     | 12C-5     | 12C-6     | 12C-7     | 12C-8     |
|------------------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| new machines added to op #   | op 70 + 1 | op 20 + 1 | op 70 + 1 | op 70 + 1 | op 70 + 1 | op 70+1   | op 90+1   | op 70+1   |
| new machines added to op #   | op 81 + 1 | op 70 + 1 | op 71 + 1 | op 71 + 1 | op 20 + 1 | op 90+1   |           |           |
| new machines added to op #   | op 90 + 1 | op 71 + 1 | op 81 + 1 | op 81 + 1 | op 81 + 1 |           |           |           |
| new machines added to op #   |           | op 90 + 1 | op 90 + 1 | op 90 + 1 | op 90 + 1 |           |           |           |
| new machines added to op #   |           | op 91 + 1 | op 20 + 1 |           |           |           |           |           |
| total number of new machines | 3         | 5         | 5         | 4         | 4         | 2         | 1         | 1         |
| results                      | 99.72     | 99.96     | 104.18    | 100.09    | 103       | 99.62     | 95.76     | 96.01     |
| JPH benefit per new machine  | 1.710     | 1.074     | 1.918     | 1.375     | 2.103     | 2.515     | 1.170     | 1.420     |
|                              |           |           |           |           |           |           |           |           |
| experiment                   | 12C-9     | 12C-10    | 12C-11    | 12C-12    | 12C-13    | 12C-14    | 12C-15    | 12C-16    |
| new machines added to op #   | op 70+1   | op 70+1   | op 90+1   | op 70+1   | op 70+1   | op 70 + 1 | op 71 + 1 | op 71+1   |
| new machines added to op #   | op 20+1   | op 20+1   | op 71+1   | op 21+1   | op 20+1   | op 20 + 1 | op 20 + 1 | op 20+1   |
| new machines added to op #   |           | op 90+1   |           |           | op 90+1   | op 81 + 1 | op 81 + 1 | op 90+1   |
| new machines added to op #   |           |           |           |           | op 80 + 1 | op 90 + 1 | op 90 + 1 | op 80 + 1 |
| new machines added to op #   |           |           |           |           |           |           |           |           |
| total number of new machines | 2         | 3         | 2         | 2         | 4         | 4         | 4         | 4         |
| results                      | 95.3      | 99.62     | 98.4      | 96.1      | 103.13    | 103       | 102.88    | 102.49    |
| JPH benefit per new machine  | 0.355     | 1.677     | 1.905     | 0.755     | 2.135     | 2.103     | 2.073     | 1.975     |

### **Findings EXP: 12C Results**

There are two optimum experiments of which the results can be shown in Table 46, the first is EXP: 9C-3 this has the highest JPH per new machine. This is optimum for the return on capital investment and also has the best chance to meet the pay back period. This is certainly the safest of the two strategies. The second EXP: 9C-6 is to go for maximum increase in JPH; this will be more of a gamble and will be less likely to meet the pay back period but if a major increase in JPH is needed then perhaps Ford might take this option even though there would be more capital investment.

After many variations of adding new machines to bottleneck operations it has been found that less machines better placed, can not only increase the JPH value to above the 104 JPH level, it can do this with a smaller number of machines. This process of adding new machines to bottlenecks has not been found to have a repeatable formula. For the first few bottleneck the highest busy rate is where a new machine should be placed but as the system becomes more balanced this changes. In this case it could be better to put a machine in another operation which would produce a more beneficial result rather than always the busiest operation of the line. This could be due to the operation although not be the largest bottleneck of the system it can enable the system to balance other operations pre and post, which could have a combined effect greater than any benefit to the individual bottleneck operation. This technique has proven that increase machine in bottleneck operations can increase the JPH value of the line.

### **16.3 EXP: 13 Combining Operations With /Without Gantries**

#### **Purpose**

The aim of this experiment is to investigate combining operations with and without the effects of the gantry loading system. When combining operation together, a gantry system becomes highly expensive thus this experiment will try and evaluate its benefit of the transfer line method of manufacturing.

#### **Method**

A number of operations were picked that were within the same line and had low outputs, thus the bottlenecks of the lines. The experiment was run first combining the operations together by summing the total cycle time for the operations and increasing the number of machines accordingly.

The experiment was run again with no gantry cycle times or breakdown data. This eliminated the effects of the gantries on the output of the simulation model.

**Table 47: results for EXP: 13 combining operations with /without gantries**

| Experiment # | combining operations | JPH with gantry | JPH without gantry |
|--------------|----------------------|-----------------|--------------------|
| 13A          | default value        | 94.59           | 100.76             |
| 13B          | op 80, 90            | 96.03           | 101.8              |
| 13C          | op 70,80             | 97.41           | 102.34             |
| 13D          | op 70, 90            | 97.41           | 102.34             |
| 13E          | op 70,80, 90         | 99.19           | 104.13             |

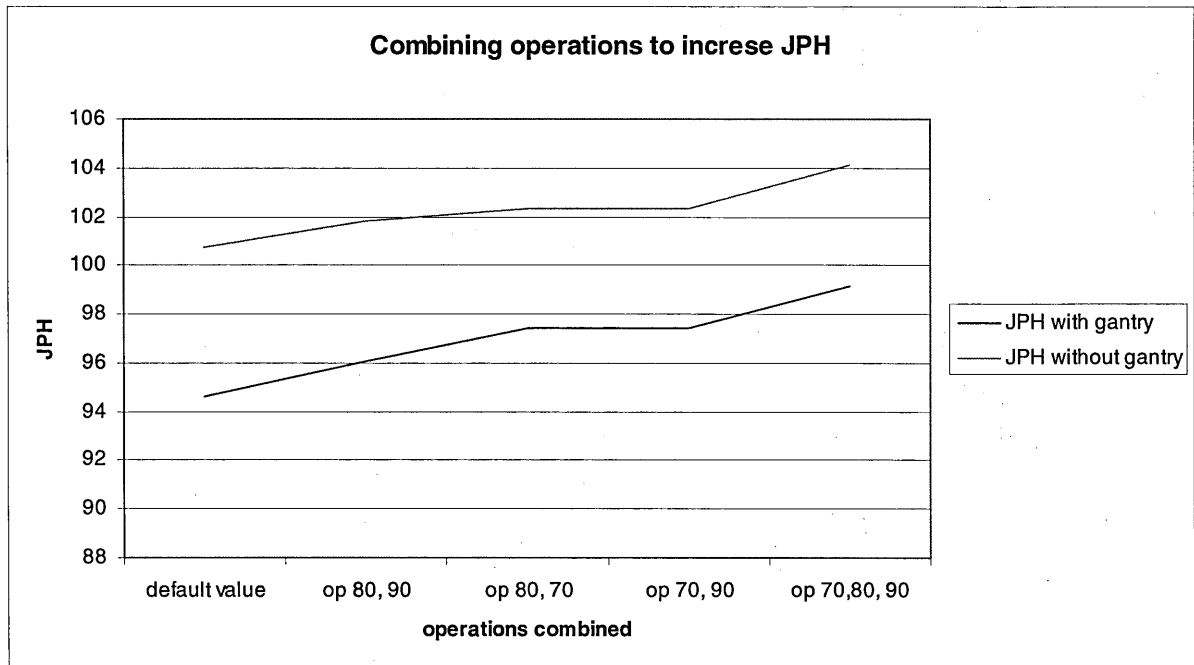
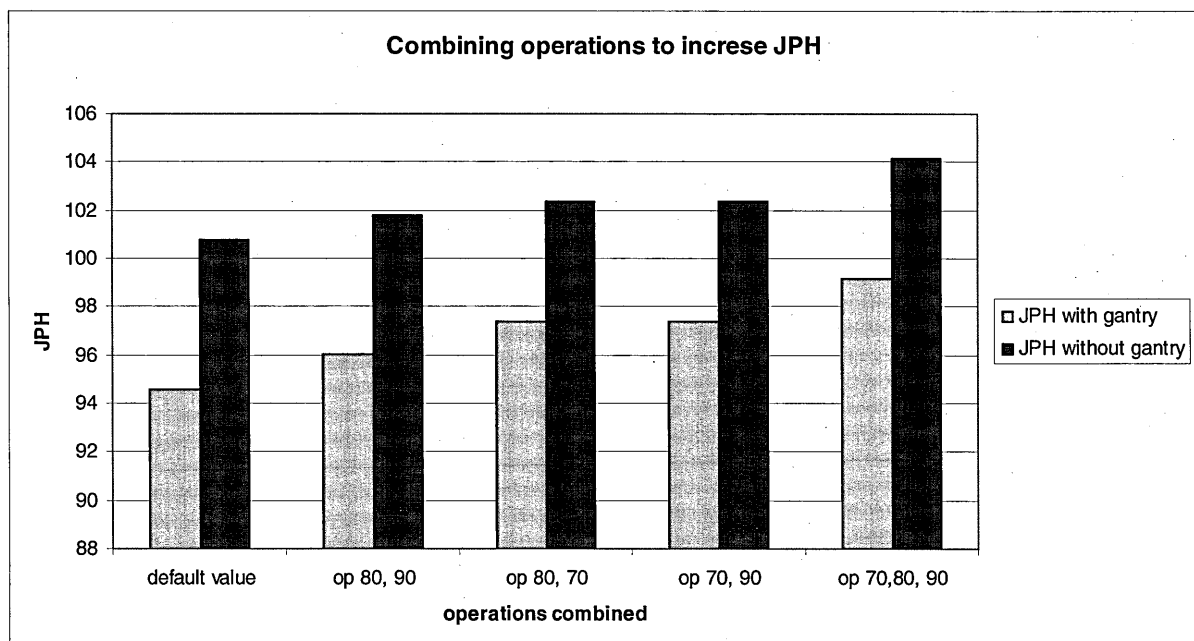


**Figure 27: Graph for EXP: 13 Combining Operations with Effects of Gantries**

## Findings

The findings of this experiment shown in Figure 27 and Table 47 are similar to those shown revealed in other experiments removing gantry breakdowns. Removing the effects of gantries increases the JPH by circa 6%. When combining operations together without gantries, the JPH increase from the combining process and is then offset by the removal of the gantry system. Therefore it can be stated that both combining operations and removal of gantry breakdowns increases the JPH of the system and together they increase the JPH dramatically. The findings from this experiment show that the current transfer line system has many disadvantages when it comes to breakdowns and unexpected stoppages. This experiment has also shown that the enhancing the gantry system can be added to another optimisation technique to further balance the manufacturing line and maximise the JPH.

### 16.4 EXP: 14 combining effects of previous buffer experiments

#### Purpose

Although no significant benefits were found Exp: 7, increasing strategic buffer sizes. It was decided that certain combinations of the increased buffer sizes could produce more noticeable results. Thus the aim of this experiment is to understand if combinations of increased buffers can change the transfer line output.

#### Method

This experiment followed the same method as Exp: 7, increase pre operation buffer capacity and in some experiments increasing the number of extra platens. Only four operations were seen as potential bottlenecks which could benefit from buffer allocation.

#### Results

**Table 48: results for EXP: 14 extended buffer capacity experiments**

| Exp number | Experiment                                    | buffer capacity for ops |      |      |      | JPH   |
|------------|-----------------------------------------------|-------------------------|------|------|------|-------|
|            |                                               | op20                    | op70 | op80 | op90 |       |
| 1          | combining best no extra platens               | 60                      | 60   | 10   | 60   | 96.54 |
| 2          | combining best adding platens                 | 60                      | 60   | 10   | 60   | 96.46 |
| 3          | each op has + 60 capacity with extra platens  | 60                      | 60   | 60   | 60   | 96.82 |
| 4          | each op has + 60 capacity no extra platens    | 60                      | 60   | 60   | 60   | 96.47 |
| 5          | each op has + 100 capacity with extra platens | 100                     | 100  | 100  | 100  | 97.23 |
| 6          | each op has + 100 capacity no extra platens   | 100                     | 100  | 100  | 100  | 97.23 |

**Table 49: increase in JPH per extra buffer capacity**

| Experiment number | best result | number of extra buffer cap | JPH per new buffer capacity |
|-------------------|-------------|----------------------------|-----------------------------|
| 6                 | 97.2        | 400                        | 0.006525                    |

## **Findings**

Increasing the number of gantries in the system does not have the same effects as removing all of the gantry breakdowns which can be shown in Table 48. The increase in gantries has been shown to increase the JPH but by less than 5% and with an additional 400 extra buffer capacity shown in Table 49. This would also incur a large investment cost that would not balance any of the benefits in doubling up the gantry loading systems. Doubling gantries systems in bottleneck operations produced an increase in JPH but it does not address the root cause of operations that are bottlenecks in the system. An analogy for this would be buying ice to cool beverages rather than tackling the root cause which could be that the fridge is broken. Therefore increasing the number of gantries in any situation should not be used unless there are significant idle periods which could be reduced by adding extra gantry operations to increase the JPH of bottleneck operations.

## **16.5 EXP: 15 Increasing the number of gantries**

### **Purpose**

As shown in previous experiments Exp: 10 gantry systems can have a profound effect on the JPH of the line. In previous experiments the breakdown data has been altered to produce increases in reliability as if the loading system is not operational then machines cannot manufacture parts. This experiment investigates increase in the number of gantry systems in operations that are bottlenecks or have potential gantry issues.

### **Method**

To carry out these experiments two different techniques were used, the first was increasing the number of gantries; this was done by selecting the relevant gantry operation and increasing the number of gantries in the spreadsheet. The second technique was removing the breakdown data from individual operations. This was carried out via searching for the correct gantry operation and then deleting the gantry data.

### **Results**

**Table 50: results for EXP: 15 increase number of gantries to operations**

| experiment # | description                                         | # of new gantries | JPH    | benefit per gantry |
|--------------|-----------------------------------------------------|-------------------|--------|--------------------|
| 1            | each machine has own gantry                         | 50                | 98.84  | 0.0850             |
| 2            | each machine has own gantry without break down data | 50                | 101.2  | 0.1322             |
| 3            | double existing gantries                            | 14                | 100.88 | 0.4493             |
| 4            | double existing gantries without breakdown data     | 14                | 100.87 | 0.4486             |
| 5            | increase gantries to ops20,70,80,90                 | 4                 | 95.76  | 0.2925             |
| 6            | increase gantries to ops 10,21,71,90 and 91         | 5                 | 95.97  | 0.2760             |

### Findings

This experiment was conducted to understand if the gantry system could be increased rather than optimised, the results of this experiment can be found in Table 50. It was shown in previous experiments that the current gantry system certainly affects the output of the system. It seems that 50 extra gantries, one for each of the machines did not massively increasing the loading and unloading of the CNC operations. Doubling the gantry system seems to be the optimum choice when it comes to benefits per gantries. Doubling the existing gantry system could be potentially a solution to increasing the JPH in this line. EXP: 15.4 actually reduces the JPH of the line, this result does not make any sense as removing all breakdown data means that there would be no breakdowns to effect the JPH of the line, which would then increase the JPH of the line. More experiments must be run to understand this result.

### 16.6 EXP: 16 Gantries breakdown on balanced line

#### Purpose

This experiment follows on from the general experiment about the effects of gantry breakdowns on a balanced line. This experiment was designed in the same way as the original but with balanced operations. This experiment would show if the gantries loading system affects the line or if breakdowns just magnify the existing bottleneck operations.

#### Method

All operations were set to a cycle time of 2, this was carried out via manually changing the cycle time of each operation; this effectively balanced the whole line. Once the line was balanced the following steps were taken to experiment with the system.

In the default simulation model the MTBF is calculated using this statistical distribution equation:

$\text{Negexp}(7392,41)$

To increase the mean time between failures, the same statistical distribution equation was used with the addition of a multiplying factor, an example of which can be seen below:

$(X * \text{Negexp}(7392,41))$

The multiplying factor was changed 7 times until 4 times the MTBF was reached. At this point the statistical distribution equation was deleted to show the effects of no mean time between failures.

**Results**

**Table 51: results for EXP: 16 gantry breakdowns on balanced line**

| variation in break down  | JPH   | Default JPH | increase in JPH |
|--------------------------|-------|-------------|-----------------|
| default system           | 28.34 | 28.34       | 0               |
| 1.25 * normal breakdowns | 28.55 | 28.34       | 0.21            |
| 1.5 * normal breakdowns  | 28.77 | 28.34       | 0.43            |
| 2 * normal breakdowns    | 28.9  | 28.34       | 0.56            |
| 2.5 * normal breakdowns  | 28.94 | 28.34       | 0.6             |
| 3 * normal breakdowns    | 29.05 | 28.34       | 0.71            |
| 3.5 * normal breakdowns  | 29.16 | 28.34       | 0.82            |
| 4 * normal breakdowns    | 29.23 | 28.34       | 0.89            |
| No break downs           | 29.31 | 28.34       | 0.97            |

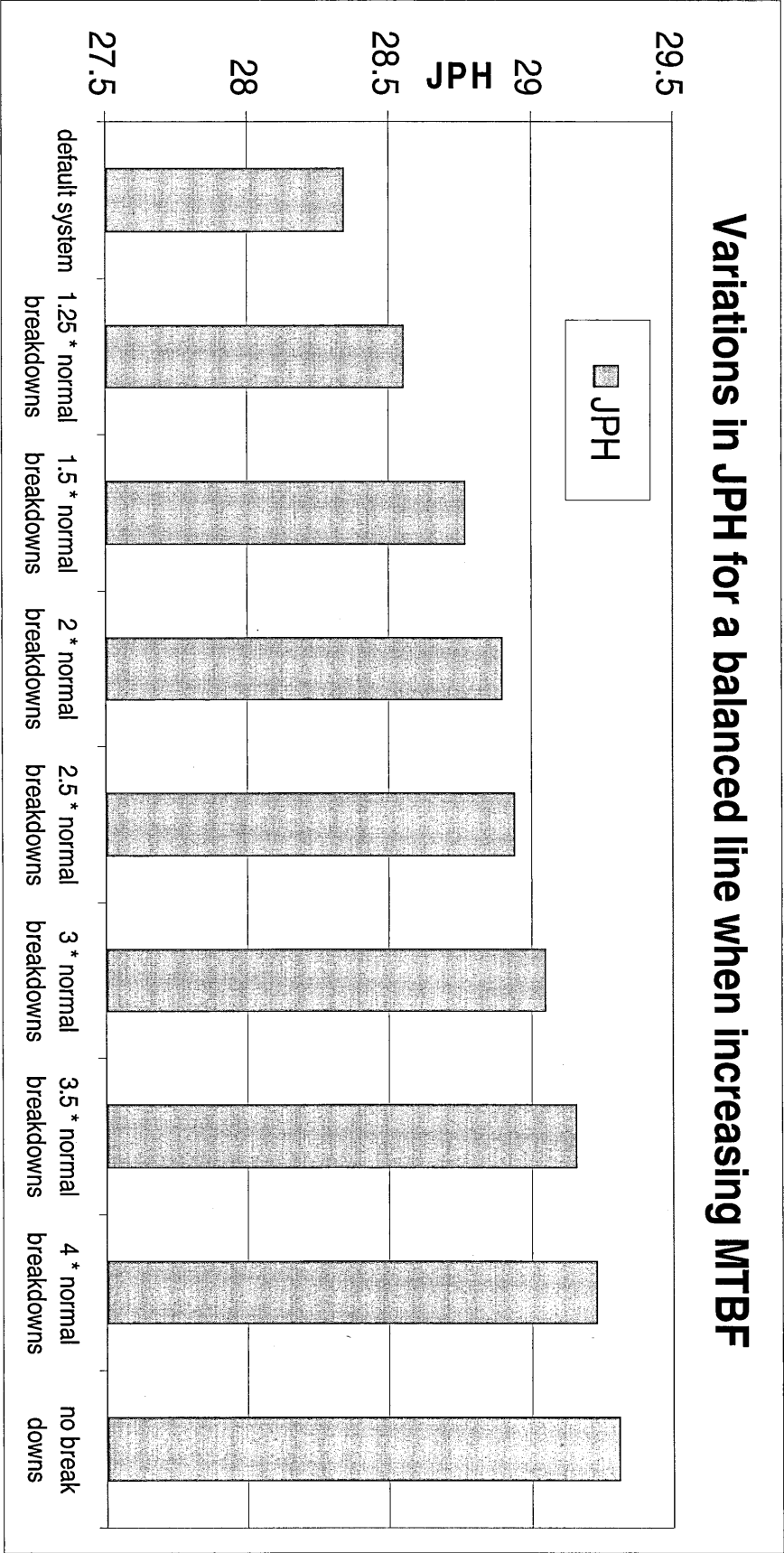


Figure 28: Graph for EXP: 16 increasing gantry MTBF with balanced line

## **Findings**

The results from the experiment shown in Figure 28 and Table 51 clearly show that the gantries breakdowns do play a role in the JPH of the line, but the significance of this must be questioned. In the original experiment in the unbalanced line from breakdowns to no breakdowns, there was an increase in JPH of 6% in the balanced line from breakdowns to no breakdowns there was an increase of just JPH of 3%. This seems to suggest that gantry breakdowns can effects bottled neck operations and thus the whole line can suffer as a result. When balancing the line, a higher than average cycle time was used which significantly reduced the JPH of the system. Therefore it can be said that gantry break downs affects the whole system and especially individual bottleneck operations.

This experiment follows on from the general experiment about the effects of gantry break downs on a balanced line. This experiment was designed in the same way as the original but with all balanced operations. This experiment could show if the gantries loading system affects the line or if breakdowns just magnify the existing bottleneck operations.

## **16.7 EXP: 17 Testing the combining process**

### **Purpose**

The aim of this experiment is to investigate the effects combining operations which have equal cycle times. A cycle time of 5 and 0.5 was be used in this experiment to understand if combining operations can be used to increase JPH on balanced line with higher and lower average cycle times, the mean of the system.

### **Method**

The method that was used will take a number of operations, add the number of machines in each operation together and do the same with the cycle times. The combined cycle time and number of machines is then inputted into the first operation ensuring that is has breakdown data associated with it and it is not an assembly operation. For the rest of the combined operations, the cycle times will be set to zero. The number of machines will not be changed. This was done for a number of bottleneck operations and also certain loops within the system. Each experiment was first run with an operation in question, balanced at either a value of 5 or 0.5 and then the operations that were to be investigated would be combined and the results would then be compared.

Results

Table 52 : results for EXP: 17 testing the combining process

| experiment # | CT  | description                     | Un combined | combined |
|--------------|-----|---------------------------------|-------------|----------|
| 1            | 0.5 | CT 0.5: line 1 all ops balanced | 94.77       | 96.22    |
| 2            | 0.5 | CT 0.5: op70,op80,op90          | 101.98      | 101.85   |
| 3            | 0.5 | CT 0.5: op70,op80               | 98.63       | 98.78    |
| 4            | 0.5 | CT 0.5: op10,11,20,21           | 95.06       | 95.02    |
| 5            | 5   | CT 5: op70,op80                 | 96.19       | 98.02    |
| 6            | 5   | CT 5: op70,op80,op90            | 94.18       | 101.64   |
| 7            | 5   | CT 5: op10,11,20,21             | 94.88       | 94.96    |

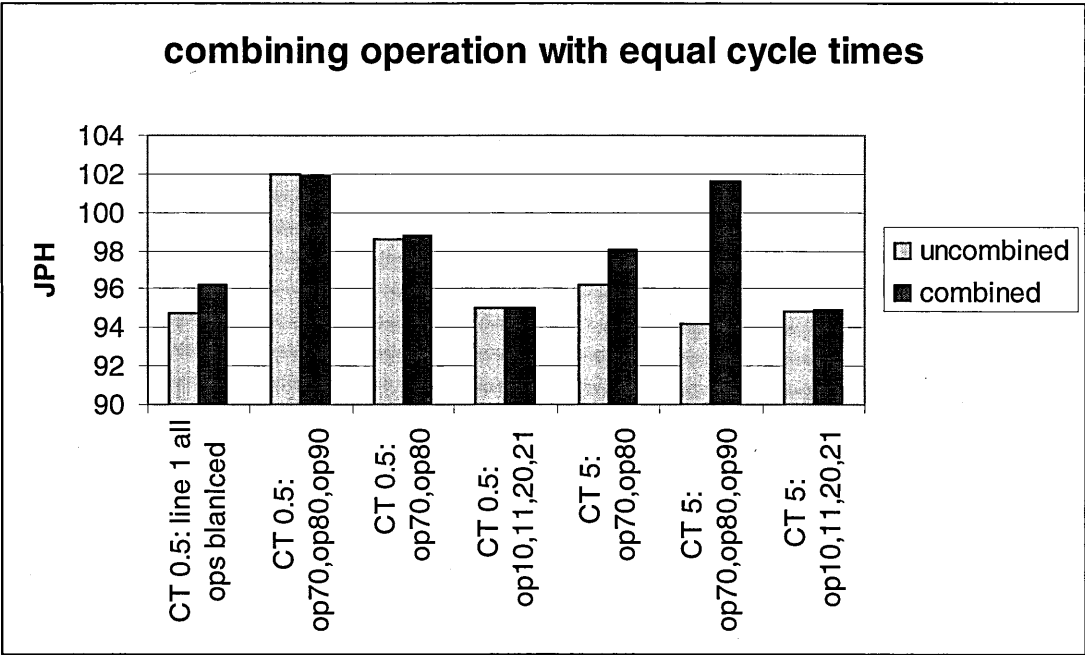


Figure 29: Graph for EXP: 17 Combining Operations with Equal Cycle Times

Findings

From the results of this experiment shown in Table 52 and Figure 29 of the experimentation it can be shown that combining operations with equal cycle times does not produce the same increase in JPH that can be found in previous combining experiments such as Exp: 9 and Exp: 13. This can be attributed to combining operations effectively balancing an area of the line which could reduce the bottleneck operation cycle time. When the operations have equal cycle times, the increase in JPH can be minimal. It seems that the longer cycle times have a greater effect when combining operations together. This could be due to decreasing the likelihood of a breakdown, effects the subsequent operations.

## **17 Appendix G - Application of previously developed generic proposals to different manufacturing lines**

### **17.1 *Introduction to Applying developed generic proposals***

In this section the generic solution to increase JPH will be tested on two new manufacturing line simulations named REP and Only Block. The first objective is to increase both of the new lines JPH level by circa 5%. The second objective is to understand if the three generic solutions can be said to be generic solutions to increase JPH for any manufacturing line or were just ways to increase the default simulation values.

### **17.2 *EXP: 18 varying new machine locations for REP***

### **17.3 *EXP: 19 varying new machine locations for Only Block***

#### **General Purpose**

The primarily aim of these experiments (18 and 19) was to remove the bottlenecks from the line to increase output of the system by adding new machines to bottleneck operations. The secondary aim was to confirm whether adding new machines to a manufacturing system in key operations could be seen to be a generic solution to increasing the output of the line.

The below method was used for both REP (EXP: 18) and Only Block (EXP: 19) manufacturing lines. After running the default program for each manufacturing line and analysing the results using Roser (2001) bottleneck detection method, it was clear that some operations were busier than others. Roser (2001) stated that this means that they are in fact the bottleneck of the lines, the most prolific bottlenecks were noted and they were then optimised in sequential order.

#### **General Method**

Each of the experiments used the same method of data analysis which leads to possible solutions. A number of the major bottlenecks of the line were tackled first in descending order of busy percentage. After a certain number of new machines were added to bottleneck operations, this logic changes as the line becomes more balanced. Then machines were placed in busy operations but it was more trial and error to get the most optimum position of machines to bottleneck operations.

**Table 53 of Results for EXP: 18 varying number of machines for REP**

| experiment                   | 2           | 3           | 4           | 5        | 6        | 7        | 8        | 9        | 10       |
|------------------------------|-------------|-------------|-------------|----------|----------|----------|----------|----------|----------|
| new machines added to op #   | op 200w + 1 | op 200w + 1 | op 200w + 1 | op 50cnc | op 50cnc | op 50cnc | op 50cnc | op 50cnc | op 50cnc |
| new machines added to op #   |             | op 50cnc    | op 50cnc    |          | 110      | 100      | 10       | 10       | 10       |
| new machines added to op #   |             |             | 20w         |          |          |          |          | op 200w  | op 200w  |
| new machines added to op #   |             |             |             |          |          |          |          | 20w      | 20w      |
| new machines added to op #   |             |             |             |          |          |          |          |          | 003r     |
| new machines added to op #   |             |             |             |          |          |          |          |          |          |
| new machines added to op #   |             |             |             |          |          |          |          |          |          |
| total number of new machines | 1           | 2           | 3           | 1        | 2        | 2        | 2        | 4        | 5        |
| results                      | 138.63      | 147.57      | 147.99      | 145.5    | 145.74   | 145.89   | 146.01   | 149.38   | 149.53   |
| JPH benefit per new machine  | 0.230       | 4.585       | 3.197       | 7.100    | 3.670    | 3.745    | 3.805    | 2.745    | 2.226    |
|                              |             |             |             |          |          |          |          |          |          |
| experiment                   | 11          | 12          | 13          | 14       | 15       | 16       | 17       | 18       | 19       |
| new machines added to op #   | op 50cnc    | op 50cnc    | op 50cnc    | op 50cnc | op 50cnc | op 50cnc | op 50cnc | op 50cnc | op 50cnc |
| new machines added to op #   | 10          | 10          | 10          | 10       | 10       | 10       | 10       | 10       | 10       |
| new machines added to op #   | op 200w     | op 200w     | op 200w     | op 200w  | 100      | 100      | 100      | 100      | 100      |
| new machines added to op #   | 20w         | 20w         | 20w         | 20w      | 110      | 110      | 110      | 110      | 110      |
| new machines added to op #   | 110         | 100         | 100         | 100      |          | 200w     | 20w      | 033r     | 200w     |
| new machines added to op #   |             |             | 003r,       | 003r,    |          |          |          |          | 033r     |
| new machines added to op #   |             |             | 110         | 110, 120 |          |          |          |          |          |
| total number of new machines | 5           | 5           | 7           | 8        | 4        | 5        | 5        | 5        | 6        |
| results                      | 150.38      | 150.71      | 151.95      | 152.49   | 146.99   | 151.37   | 147.07   | 147.01   | 151.58   |
| JPH benefit per new machine  | 2.396       | 2.396       | 1.936       | 1.539    | 3.388    | 2.818    | 1.734    | 1.722    | 2.197    |

**Table 54 of Results for EXP: 19 varying number of machines for only block**

| Experiment                   | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     | 10    | 11    |
|------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| new machines added to op #   | 130   | 130   | 130   | 130   | 130   | 130   | 130   | 130   | 130   | 130   |
| new machines added to op #   |       | 80    | 80    | 80    | 80    | 110   | 20    | 70    | 110   | 110   |
| new machines added to op #   |       |       | 20    | 20    | 120   |       |       |       | 90    | 90    |
| new machines added to op #   |       |       | 110   | 110   |       |       |       |       |       | 120   |
| new machines added to op #   |       |       | 70    | 70    |       |       |       |       |       |       |
| new machines added to op #   |       |       |       | 30    |       |       |       |       |       |       |
| new machines added to op #   |       |       |       |       |       |       |       |       |       |       |
| total number of new machines | 1     | 2     | 5     | 6     | 3     | 2     | 2     | 2     | 3     | 4     |
| JPH results                  | 44.86 | 44.97 | 45.53 | 45.63 | 45.51 | 45.02 | 44.98 | 44.98 | 45.32 | 45.86 |
| JPH benefit per new machine  | 2.120 | 1.115 | 0.558 | 0.482 | 0.923 | 1.140 | 1.120 | 1.120 | 0.860 | 0.780 |

## Findings for REP EXP: 18

20 experiments were carried out and the results can be seen in Table 53. As stated previously, creating the best solution cannot only be found investigating the highest percentage busy operations. Finding the optimum solution took many variations based on some key experiments. One operation in particular was shown to be a major bottleneck of the line. Once the operation was identified as being the key to balance the line significant increasing in JPH where seen. In this case increasing the number of machines in bottleneck operations increased the JPH output by circa 10%, this could be seen as a significant increase in the overall output of the line.

## Findings for Only Block EXP: 19

This experiment produced a variety of results (shown in Table 54) which were certainly more finely distributed around the default value of the system. Having a tightly packed group of results with no real standout results demonstrates that the system has been previously optimised. This statement was later confirmed by the industrial supervisor who confirmed there had been previous optimisation projects based on this line. As before there was one operation that seemed to be a key operation in increasing JPH which was operation 130. Adding one machine to this operation increased the JPH to circa 5%, which made this operation the largest single increase in JPH when one extra machine was added to the system.

In the end there was a list of 4 potential solutions that would increase the JPH of the system but each one of these would have to be costed to find the most cost effect solution.

#### **17.4 EXP: 20 Combining operations and their cycle times for REP**

#### **17.5 EXP: 21 Combining operations and their cycle times for Only Block**

##### **General Purpose**

The primary aim of these experiments (20 and 21) was to remove the bottlenecks from the line to increase output of the system by combining bottleneck operations together, which should reduce the effects of the bottlenecks on the system. The secondary aim was to confirm whether the process of combining operations in manufacturing systems is a generic solution to increasing the output of the line.

The below method was used for both REP and Only Block manufacturing lines. After running the default program for each manufacturing line and analysing the results using Roser (2001) bottleneck detection method, it was clear that some operations were busier than others. Roser (2001) stated that this means that they are in fact the bottleneck of the lines, the most prolific bottlenecks were noted and they there then optimised in sequential order.

##### **General Method**

Once bottleneck operations had been found then different assortments of combining operations were carried out until a number of solutions became apparent. The method that will be used will take a number of operations, add the number of machines in each operation together and do the same with the cycle times. The combined cycle times and number of machines is then inputted into the first operation ensuring that it has breakdown data associated with it and it is not an assembly operation. For the rest of the combined operations the cycle times will be set to zero. The number of machines will not be changed.

Table 55: results for EXP: 20 combining operations for REP

| experiment # | discription                                                                      | JPH    |
|--------------|----------------------------------------------------------------------------------|--------|
| 1            | op 100-110                                                                       | 138.68 |
| 2            | op 120-140                                                                       | 138.37 |
| 3            | op 10-50                                                                         | 138.97 |
| 4            | 100-110-120                                                                      | 138.68 |
| 5            | 110-120-140                                                                      | 138.64 |
| 6            | op 10-50 +3 extr machines                                                        | 146.72 |
| 7            | op 10-50 combined in op 50                                                       | 146.38 |
| 8            | op 100-110-120-140 comibied in op 100                                            | 138.64 |
| 9            | op 100-110-120-140 comibied in op 110                                            | 138.63 |
| 10           | op 100-110-120-140 comibied in op 120                                            | 138.38 |
| 11           | op 100-110-120-140 comibied in op 140                                            | 138.43 |
| 12           | op 100-110-120-140 comibied in op 100 plus extra machine in 200w                 | 138.89 |
| 13           | op 100-110-120-140 comibied in op 100 plus extra machine in 003r                 | 138.77 |
| 14           | op 100-110-120-140 comibied in op 100 plus extra machine in 200w and 003r        | 139.03 |
| 15           | op 100-110-120-140 comibied in op 100 plus extra machine in 200w and 003r and 50 | 145.95 |

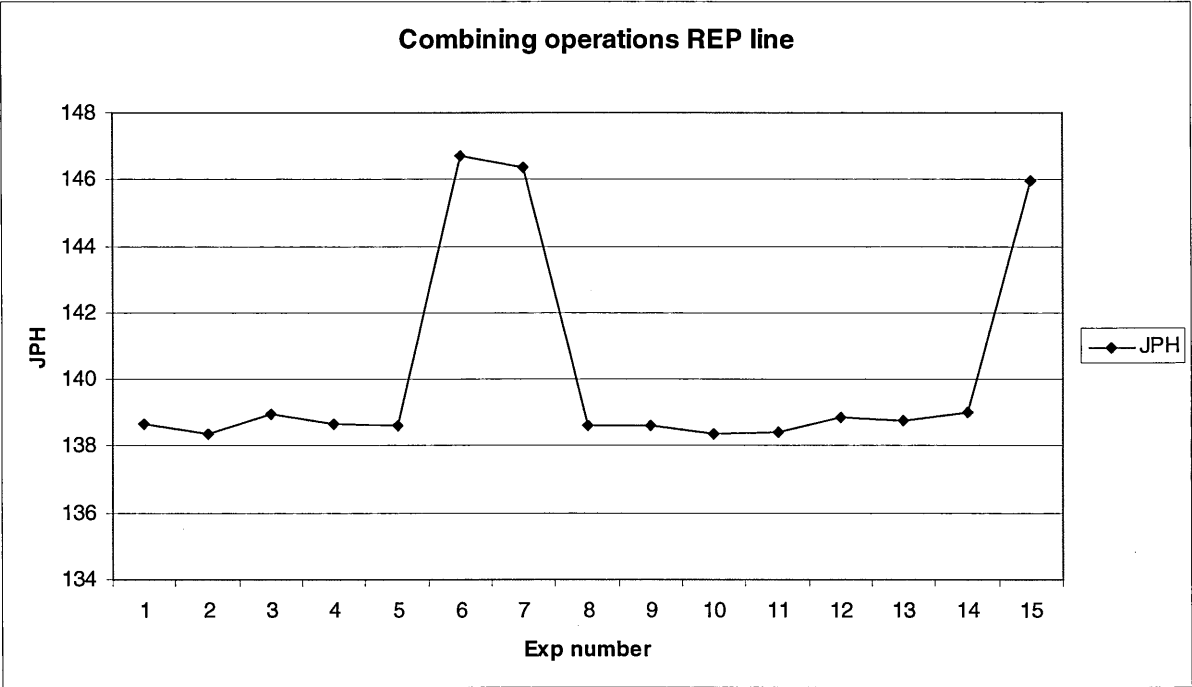


Figure 30: Graph for EXP: 20 effects combining operations on REP line

Results for Only Block EXP: 21

Table 56 : results for EXP: 21 combining operations for Only Block

| experiment # | discription                     | with breakdown | without breakdown |
|--------------|---------------------------------|----------------|-------------------|
|              |                                 | JPH            | JPH               |
| 1            | default                         | 42.74          | N/A               |
| 2            | op 20-30                        | 42.74          | 42.8              |
| 3            | op 30-40                        | 42.74          | 42.7              |
| 4            | op 80-90                        | 42.68          | 42.75             |
| 5            | op 100-110                      | 42.76          | 42.74             |
| 6            | op 120-130                      | 42.86          | 42.68             |
| 7            | op 130-140                      | 42.91          | 43.65             |
| 8            | op 20-30-40                     | 42.7           | 42.73             |
| 9            | op 20-30-41 + one extra gantry  | 42.75          | 42.79             |
| 10           | op 80-90-100                    | 42.67          | 42.76             |
| 11           | op 80-90-100 + one extra gantry | 42.77          | 42.75             |
| 12           | op 90-100-11                    | 42.73          | 42.69             |
| 13           | op 90-100-11 + one extra gantry | 42.76          | 42.79             |
| 14           | 120-130-140                     | 42.92          | 43.85             |
| 15           | 120-130-140 + one extra gantry  | 42.93          | 43.89             |
| 16           | 70-80                           | 42.74          | N/A               |
| 18           | 70-80-90                        | 42.73          | N/A               |
| 19           | 70-80-91 with extra machine     | 42.71          | N/A               |
| 20           | 20-30-40 with extra machine     | 42.73          | N/A               |
| 21           | 120-130-140 with extra machine  | 44.92          | N/A               |
| 22           | 70-80-90 in op 80               | 42.74          | N/A               |
| 23           | 80-90-100 with extra machine    | 42.75          | N/A               |
| 24           | 90-100-110 with extra machine   | 42.75          | N/A               |
| 25           | 150-160-166 with extra machine  | 42.92          | N/A               |
| 26           | 177-178 with extra machine      | 42.68          | N/A               |
| 27           | 120-130-140                     | 44.96          | N/A               |

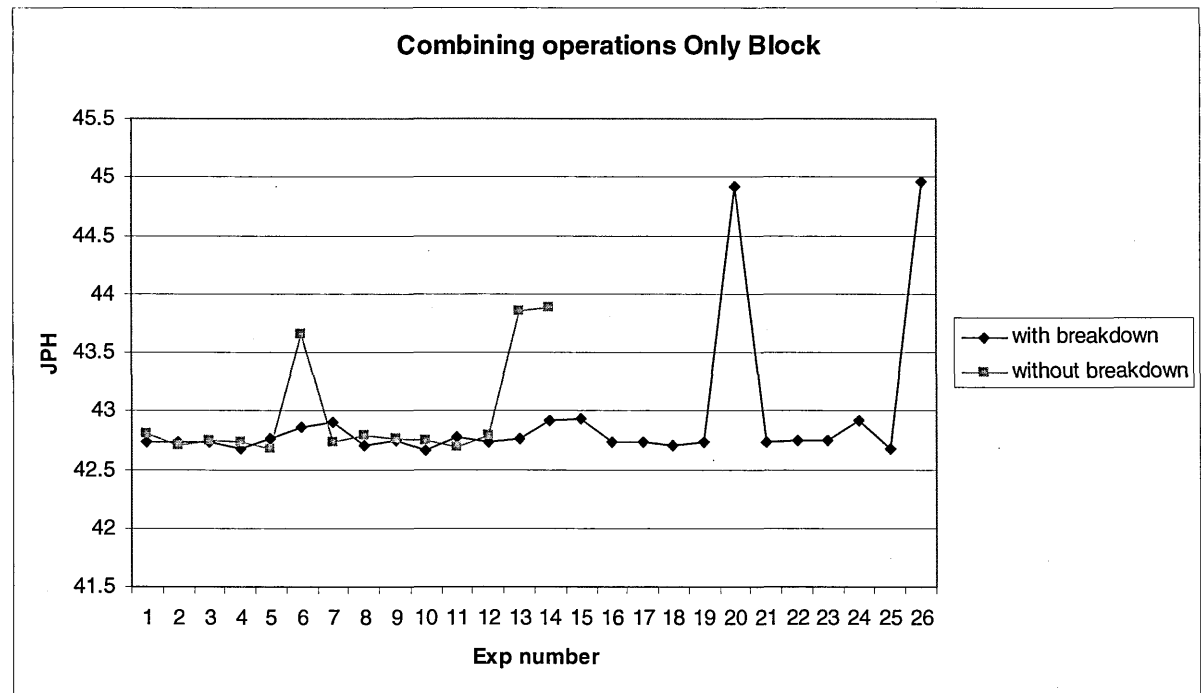


Figure 31: Graph for EXP: 21 showing effects combining operations on Only Block line

### **Findings from REP EXP: 20 combining operations**

This study produced the following results which are shown in Figure 30 and Table 55. This experiment did not produce any large increases in JPH from any of the experiments. The only large increases were produced when combining operations and adding extra machines to known bottleneck operation was carried out. This was done because some bottleneck operations could not be combined with other operations but they were still some of the most utilised operations present within the line.

When combining operations which could be shown to have bottleneck properties no measurable increase was produced. One hypothesis for this was that the line was well balanced and from findings of previous experiments combining operations does not show the same increase in JPH when a line is fully balanced. Thus combining operations is not applicable in this instance of optimisation.

### **Findings from Only Block EXP: 21 combining operations**

This experiment produced insignificant results shown in Table 56 and in graphical form shown in Figure 31. There were potentially many operations that could have been prime candidates for combining but when combined together the results did not increase beyond 1%. The main reason for this is the line has been highly balanced in the design stage. Many of the operations have the same cycle time which means that only operations with a high cycle time could be potentially improved. These operations unfortunately only produced the smallest increase in JPH which would not have been a large enough improvement. These experiments were then tried again without breakdown on the operations that had been combined with again insignificant increases in JPH.

When combining operations, a standard method was created which always combined operation within the first operation. After some disappointing results this method was changed to combine operations and housing them within the operation the highest busy percentage. This new method gave significantly better result (EXP: 20.27), but the significance of this cannot be quantified from the limited number of experiments that were carried out. Certainly when combining operations together a researcher must think very carefully where the new operation is placed to give the optimum result.

## 17.6 EXP: 22 Reducing Gantry Break downs for REP

## 17.7 EXP: 23 Reducing Gantry Break downs for Only Block

### General Purpose

The primary aim of this experiment is to reduce the effects of gantry breakdowns or the (MTBF) of the gantry system. If the current gantry system hinders any of the bottleneck operations within the line in question, then increasing the MTBF should increase the JPH of the line. This has been proven to work in experiment Exp: 10, and therefore the secondary aim of this experiment is to understand if this experiment can produce generic solution to any lines JPH.

### General Method

In all simulation models, the MTBF is calculated using a similar statistical distribution equation:

$$\text{Negexp}(7392,41)$$

To increase the mean time between failures the same statistical distribution equation was used with the addition of a multiplying factor, an example of which can be seen below:

$$(X * \text{Negexp}(7392,41))$$

The multiplying factor was changed 7 times, every time the simulation was run and results were collected. At this point the statistical distribution equation was deleted to show the effects of no mean time between failures.

### Results for REP EXP: 22

**Table 57: results for EXP: 22 increase MTBF for gantry on REP**

| experiment # | variation in break down        | JPH    | Default JPH | increase in JPH |
|--------------|--------------------------------|--------|-------------|-----------------|
| 22.A         | default system                 | 138.4  | 138.4       | 0               |
| 22.B         | 1.25 * normal breakdowns       | 138.82 | 138.4       | 0.42            |
| 22.C         | 1.5 * normal breakdowns        | 139.1  | 138.4       | 0.7             |
| 22.D         | 2 * normal breakdowns          | 139.4  | 138.4       | 1               |
| 22.E         | 2.5 * normal breakdowns        | 139.52 | 138.4       | 1.12            |
| 22.F         | 3 * normal breakdowns          | 139.59 | 138.4       | 1.19            |
| 22.G         | 3.5 * normal breakdowns        | 139.69 | 138.4       | 1.29            |
| 22.H         | 4 * normal breakdowns          | 139.84 | 138.4       | 1.44            |
| 22.I         | 5 * normal breakdowns          | 139.89 | 138.4       | 1.49            |
| 22.J         | no break downs                 | 140.29 | 138.4       | 1.89            |
| 22.K         | all gantries +1                | 140.49 | 138.4       | 2.09            |
| 22.L         | equal gantry machine ratio     | 140.53 | 138.4       | 2.13            |
| 22.M         | no break downs, no cycle times | 140.57 | 138.4       | 2.17            |

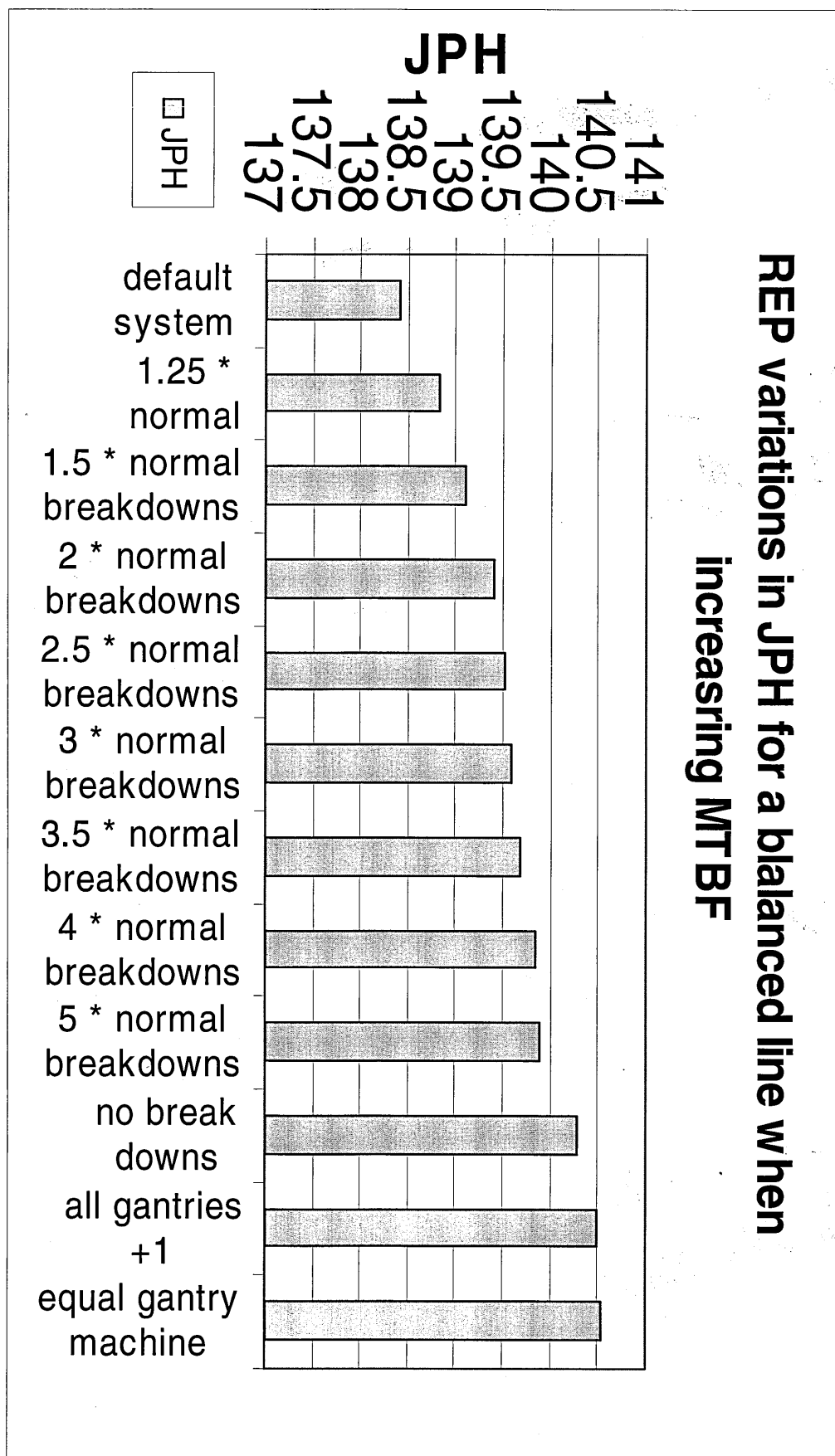


Figure 32: Graph for EXP: 22 showing effects of increasing MTBF of gantry

**Results for Only Block EXP: 23**

**Table 58 results for EXP: 23 increase MTBF for gantry on Only Block**

| experiment # | variation in break down        | JPH   | Default JPH | increase in JPH |
|--------------|--------------------------------|-------|-------------|-----------------|
| 23.A         | default system                 | 42.74 | 42.74       | 0               |
| 23.B         | 1.25 * normal breakdowns       | N/A   | 42.74       | N/A             |
| 23.C         | 1.5 * normal breakdowns        | N/A   | 42.74       | N/A             |
| 23.D         | 2 * normal breakdowns          | N/A   | 42.74       | N/A             |
| 23.E         | 2.5 * normal breakdowns        | N/A   | 42.74       | N/A             |
| 23.F         | 3 * normal breakdowns          | N/A   | 42.74       | N/A             |
| 23.G         | 3.5 * normal breakdowns        | N/A   | 42.74       | N/A             |
| 23.H         | 4 * normal breakdowns          | N/A   | 42.74       | N/A             |
| 23.I         | 5 * normal breakdowns          | N/A   | 42.74       | N/A             |
| 23.J         | no break downs                 | 43.31 | 42.74       | 0.57            |
| 23.K         | all gantries +1                | 43.55 | 42.74       | 0.81            |
| 23.L         | equal gantry machine ratio     | 43.52 | 42.74       | 0.78            |
| 23.M         | no break downs, no cycle times | 43.47 | 42.74       | 0.73            |

**REP Findings EXP: 22**

All the experiments were carried out with no success see Table 57 and Figure 32 for experimental results. Looking at the REP model in detail it seemed that the model had already been optimised with a number of double gantries servicing one operation. This was confirmed later by the industrial supervisor, that the REP line had previously had its gantry system optimised at the design stage using simulation. Further experiments were carried out increasing the number of gantries and no cycles times and breakdowns for the gantries. None of the previous experiments produced any significant results with the highest increase of JPH was circa 1%.

**Only Block Findings EXP: 23**

After the previous problems with the REP gantry break downs were the gantry system had been clearly optimised which can be demonstrated by the results shown in Table 58. The experiments started with comparing no breakdowns with the original value. With no breakdowns the increase was a fraction over 1%, therefore it was decided that any other experiment between the normal value and no breakdowns would not produce important results. Gantry systems should only be investigated when they are hindering the bottlenecks within the system. Gantry are only the loading/unloading systems used to automate the machining operations. Therefore if the gantries busy percentage is effecting the idle time of the CNC machine they are servicing, then investigation of gantry systems should be undertaken. Only Block had not been optimised but there was no operation that was being starved from its gantry system.

## 17.8 EXP: 24 combining other experiments

### Purpose

The aim of this experiment is to combine a number of previous experiments together to produce an optimum solution that can be given to senior management at Ford. The default line has a number of potential solutions that could be mutually beneficial to each other. The new base model will be (EXP: 12C-13) the increase of four machines at strategic bottlenecks. Added to this will be three variation on optimising the gantry system base on (EXP 10.G), (EXP 10.I) and (EXP 15.3).

### Method

The method that was used for this experiment followed and combined two methodologies, first recreated (EXP: 12C-13) using its method and then each of the three methods was added to it. For more information please see all of these previous methodologies.

### Results

**Table 59: results of experiment 24 combining benefits of experiments**

| Experiment number | Description                                                              | JPH    |
|-------------------|--------------------------------------------------------------------------|--------|
| 24A               | EXP: 12C-12 combining with no gantry breakdowns (EXP 10.G)               | 110.26 |
| 24B               | EXP: 12C-12 combining no gantry breakdowns 3.5 times the MTBF (EXP 10.I) | 108.50 |
| 24C               | EXP: 12C-12 combining with double gantries (EXP 15.3)                    | 110.95 |

### Findings

Experiment 24A (results shown in Table 59) was done for comparison only as stated previously it is not possible to remove all breakdown from any system, especially on a budget of only £1million. From the results of Experiment 24B which combined (EXP: 12C-13) the increase of four machines at strategic bottlenecks with (EXP: 10G) increased the MTBF of the gantry system by 3.5 times. This experiment increased the JPH by 14.7% to 108.5 JPH. Adding these two solutions together has massively increased the JPH of the line compared to both of the individual solutions. Also a major point to consider is although more money is needed to be invested (an extra £1million more than EXP: 12C-13) the payback period is less than EXP: 12C-13 due to the increase in JPH per machine. The increase in MTBF cannot be guaranteed by the investment on £1million but having extra maintenance staff and newer systems to detect breakdowns, the whole line should, in theory, benefit from this capital investment. Experiment 24C produced the highest value but there are concerns over the cost of implementation and this would increase the pay back period significantly. Also some of the results within experiment 15 are inexplicable and for this reason exp24C will not be recommended.

18 Appendix H – Tree diagram of ford machining facilities within Europe

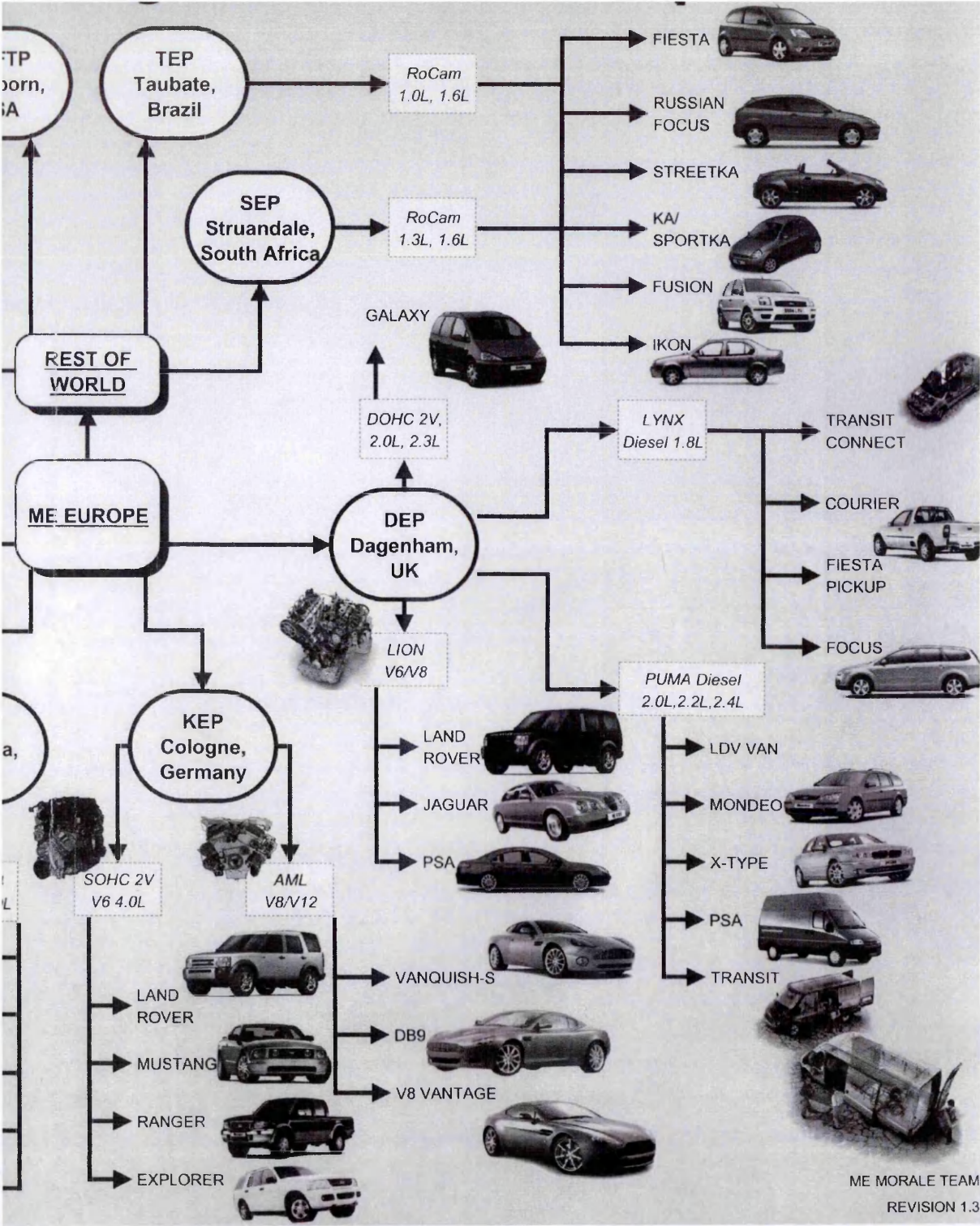


Figure 33: Tree diagram of ford machining facilities within Europe