

Implementing Flow Processing with Product End of Life Remanufacturing

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Abstract

This research focuses on improving the remanufacturing process efficiency by estimating the workstation utilization through identifying percentage of %Blocking and %Waiting on individual workstations within a remanufacturing flow line. It attempts to achieve this aim such that improved use of methods to overcome the effect of variability can be employed.

Extensive literature review revealed the requirement of strategies to recover End of Life products due to the introduction and implementation of legislative directives demanding manufacturers to recover the End of Life resources. Upon analyzing the range of product recovery strategies, End of Life product remanufacturing has emerged as an appropriate and suitable strategy to be used since it extends the operational life of existing products without the need for the new resources required when making products.

Remanufacturing is a process in which a product is disassembled to component level. Each of the components will be thoroughly examined for defects. Upon identifying defects, they will either be repaired or components will be replaced. This process in turn increases the product life span. However, remanufacturing is not widely used process applied into various industry sectors due to the fact that it is labour intensive and expensive process compared to new products. Although remanufacturing process is in infancy where small number of industry such as Automotive and Aerospace are deriving benefit from it by making effective use of remanufacturing.

Ideally, the suitable manufacturing methods i.e. flow processing system, should be used to remanufacture products. However when flow processing is deployed, it is found that there are a number of factors affecting the process that if not tackled, will result in poor performance and poor efficiency of the overall remanufacturing system. This inefficiency is primarily due to the number of sources of variation found in terms of supply, product design, parts specification, operation and demand variability. Further investigation led to the characterizing the remanufacturing variability and identified ways the effect of this variability can be removed or reduced using Lean principles e.g. Single Minute Exchange of Dies and use of an appropriate manufacturing system.

Based on the information revised in literature and experimental design, novel equations were developed along with a set of rules that accurately measures the workstation utilization in terms of %Blocking and %Waiting on individual workstation.

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Declaration

I declare that the work described within this thesis was originally undertaken by myself, (Sajid Khalifa) between the dates of registration for the degree of doctor of philosophy at De Montfort University:

Full-time: October 2004 to October 2006

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Glossary

%Waiting	It is the waiting time for succeeding workstation that is waiting for the preceding workstation to finish the job (Khalil, 2005)
%Blocking	It is the waiting time for the preceding workstation that is waiting for the succeeding workstation to finish the jobs. (Khalil, 2005)
Product EoL	Product End of Life
Skewness	Skewness is an attribute of a distribution. A distribution that is symmetric around its mean has skewness zero, and is 'not skewed'.
PERT	The Program Evaluation and Review Technique (PERT) is a network model that allows for randomness in activity completion times.
Variance	The variance is a numerical value used to indicate how widely individuals in a group vary. If individual observations vary greatly from the group mean, the variance is big; and vice versa.
Mode	The mode is the number that appears most often in a set of numbers (Khalil, 2005)
Standard Deviation	In statistics and probability theory, standard deviation shows how much variation exists from the average value

Coefficient of Variation	It is a normalized measure of dispersion of a probability distribution.
Mean	The mean is a particular informative measure of the "Central Tendency" of the variable if it is reported along with its confidence interval.
Median	The Median is the value half way through the ordered data set, below and above which there lies equal number of data set.
GT	Group Technology
PSCL	Process Sequence Cell Layout
HVFL	High Variability Flow Line
SMED	Single Minute Exchange of Dies
TAKT	TAKT mean "Rhythm" in German. TAKT time is the allowable time to produce one product.
TPM	Total Protective Maintenance
TQM	Total Quality Management
JIT	Just in Time
HV/LV	High Variety/Low Volume

DBR	Drum-Buffer-Rope
DFM	Design For Manufacturing (This is a Manufacturing terminology)
DfR	Design for Recycle (This is a Recycling terminology)
DfD	Design for Disassembly
DfReman.	Design for Remanufacturing
DfE	Design for Environment
DFPR	Design for Product Retirement

Chapter 1 Introduction

Product End of Life issue has been widely discussed in the industry and academia. Number of attempts have been made to complement the issue with major success such as in the Automotive industry. Although the issue remains open for further work, this research focuses on a specific industry area that covers domestic products. When domestic products such as Washing machine reaches their End of Life, they were at large initially recycled and also directed to the landfill sites. As the Climate change appear to be a major global issue, more emphasis were put on recycling the majority of the End of Life products and material.

1.1 State of the Art

State of the Art technology such as Remanufacturing may suit and fulfil the needs of today's resource recovery demand. Although Remanufacturing is seen as labour intensive process that is currently applicable to limited number of industries such as Aerospace and Automotive; its further use in general industries would make it a viable and environmental friendly process.

1.2 Environmental Legislation

European environmental legislation is forcing manufacturers to become more responsible for the level of waste created by the "End of Life" (EoL) disposal of the products they have sold once. These products reach the stage where customers wish to replace them. Industries that are particularly being affected are those that manufacture

in large volumes, complex products such as road vehicles and household appliances (Howells, 1999; King, et al, 2004).

A cleaner and safer environment is a necessity for society. Primarily, the impact on climate due to environmental pollution has become a major global issue. In this respect legislative directives are being aimed at reducing waste generation and disposal activities through making manufacturers more responsible for recycling of their products, e.g.:

- (i) **The Landfill Directive** transposed into UK law through the Landfill Regulations 2002 bans disposal of various materials including liquid waste, explosive or flammable waste, hospital and clinical waste, and used tyres (Bywaters, 2007).
- (ii) **The Waste Electrical and Electronic Equipment (WEEE) Directive** restricts the use of hazardous substances in electrical and electronic equipments (Otto, 2007).
- (iii) **The End of Life Vehicles (ELVs)** directive increases the level of parts and material recovery and recycling from EoL vehicles by setting laws demanding the use of authorised treatment facilities (ATFs) for their vehicle dismantling and reprocessing (Waste-Online, 2007).
- (iv) **The Batteries Directive** bans disposal of those batteries that contain a trace of elements cadmium or mercury, i.e. recycling of these batteries will become obligatory from 2008.

- (v) **The Packaging Waste Directive** maintains safety and hygiene by keeping the volume and weights of packaging to minimum necessary (Bywaters, 2007; Otto, 2007).
- (vi) **The Hazardous Materials** directive sets the rules for identifying hazardous materials and controlling their management, reprocessing and responsible disposal (Bywaters, 2007).

1.3 Product End-of-Life Strategies (King, et al, 2004)

These examples of major environmental legislation clearly show that EoL recycling and recovery of products and components is becoming increasingly important. There exist a number of product retirement strategies that focus on recovering material resources used within products that have reached their end-of-life. Here, three basic strategies exist, i.e.

- a) Dispose the entire product or part of product.
- b) Shred the product to its basic material level and recycle these materials.
- c) Undertake activities that will enable the components, component assemblies and/or the complete product to be reused.

1.3.1 Disposal

This is the final solution for remaining waste that cannot be recycled. This is the least favourable option since it has the greatest potential effect on environmental safety (King, et al, 2004).

1.3.2 Recycling

The basic recycling activity involves shredding a product into small fragments and separating these fragments according to their material specifications. Varying levels of recycling activity are possible, i.e.:

- i. **Primary recycling** which supplies the base material to be used in high value products. For example, recycled cans can be used to make new cans, or used within such products as building materials, car parts, bicycles, fishing poles, and baseball bats (Barlow, 2007).
- ii. **Secondary recycling** which supplies material for low value products, such as polymer materials for household products (Barlow, 2007).
- iii. **Tertiary recycling** involves the decomposition or chemical breakdown of EoL materials which are then re-utilised to make new products (Barlow, 2007).
- iv. **Quaternary recycling** utilises waste normally through an incineration process to produce energy as electricity and heat (Barlow, 2007).

1.3.3 Reuse

As the term implies, the retired product or its parts are reused. Only those parts that have failed are replaced resulting in minimum repair effort and the reuse of the maximum original product content. However, the resulting product some time may not retain its original functionality (King, et al, 2004; Sofa, 2005; Barlow, 2007).

1.3.4 Refurbish or Recondition

Here, the retired product may be upgraded by adding modules or components to match the latest product specification; this approach may merely involve the restoring components to their basic functionality with additional non-technical processes such as re-painting (King, et al, 2004).

1.3.5 Remanufacturing

Remanufacturing involves separating a product into its constituent parts and/or sub-assemblies such that both reusable and repairable items can be recovered and repaired to meet customer cost, quantity, quality and delivery requirements. Remanufactured products are then supplied with as new product warranties (Caterpillar-Remanufacturing, 2006). Typical examples of remanufactured products are aircraft engines and domestic goods such as washing machines (Law, 1996; King, et al, 2004).

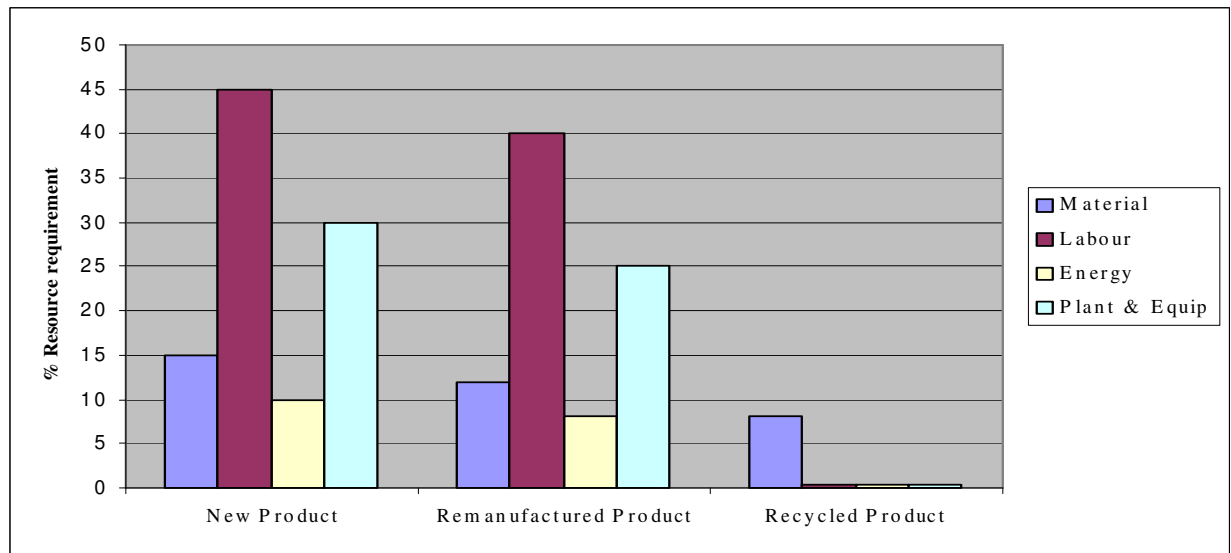
The remanufacturing solution has significant environmental advantages but is currently less cost effective due to the labour intensive process steps and hence less used, than high volume, capital intensive, recycling operations. Improving the competitiveness of Remanufacturing process is, therefore, essential to its increased usage. Here the adoption of a suitable production system is essential to achieving these aims of improving the Remanufacturing process efficiency (Gaudette, 2003).

The market potential for remanufacturing within UK and Europe can be estimated through examining the current size of the US remanufacturing sector due to the success of remanufacturing in number of sectors listed in Table 1.1 (Gaudette, 2003).

	Automotive	Electrical apparatus	Toner Cartridge	Tyre Retreader
No of Companies	50,000	13,000	6,500	< 6,500
Employee	330,000	50,000	30,000	< 3,000
Sales	\$ 36b	\$ 4.6b	\$ 2.5b	\$ 4.3b

Table 1.1 US Remanufacturing Market (Lund, 2003)

The advantages of remanufacturing, when compared with other End of Life retirement strategies are significant conservation in terms of material, labour, energy and equipment resources.



Relative cost of new Product Manufacture

Conservation of value in product Remanufacturing and Recycling

Figure 1.1 Value Conservation through Remanufacturing and Recycling (Lund, 2003)

Figure 1.1 represents the comparison of product remanufacturing and product recycling against new product development. Clearly, Recycling process require less resources and energy in order to recycle End of Life products, however it will only supply raw material at the end of the recycling process that will involve further treatment if new

product is to be produced from the recycled material. In comparison, remanufacturing will use less new resources and energy and will offer 'like' new product and this is why this research looks into remanufacturing variability.

1.4 Remanufacturing Strategies

At one end of the remanufacturing spectrum are domestic products such as washing machines that will only be tested for safety run and non-functional components. When remanufacturing aero-engines, the entire product is disassembled to its basic components. Each component is inspected and either repaired or replaced depending on its condition. The main issues involved in ensuring a structured remanufacturing of a complex product, such that the retrieval and repair of useful components is possible, are shown in Figure 1.2 (Caterpillar-Remanufacturing, 2006).

Caterpillar remanufacturing plant remanufactures some of their products including engines and its components, drive trains, hydraulic systems and under carriages of rollers. As an engine enters the plant, it will be disassembled into main modules, cleaned and the depth of repair will be identified followed by an inspection process. Figure 1.2 lists number of stages and their significance in terms of cost. As the complexity of component remanufacturing increases from Buffering to Basic machining and Advanced machining to Welding and Remanufacturing, the cost of the product will reach to sixty per cent (60%) compare to new product (Caterpillar-Remanufacturing, 2006). If the work content goes beyond Remanufacturing, then Line boring cost goes over seventy seven per cent (77%) which then becomes financially unviable (Caterpillar-Remanufacturing, 2006).

Caterpillar Remanufacturing schematic: unique for every part

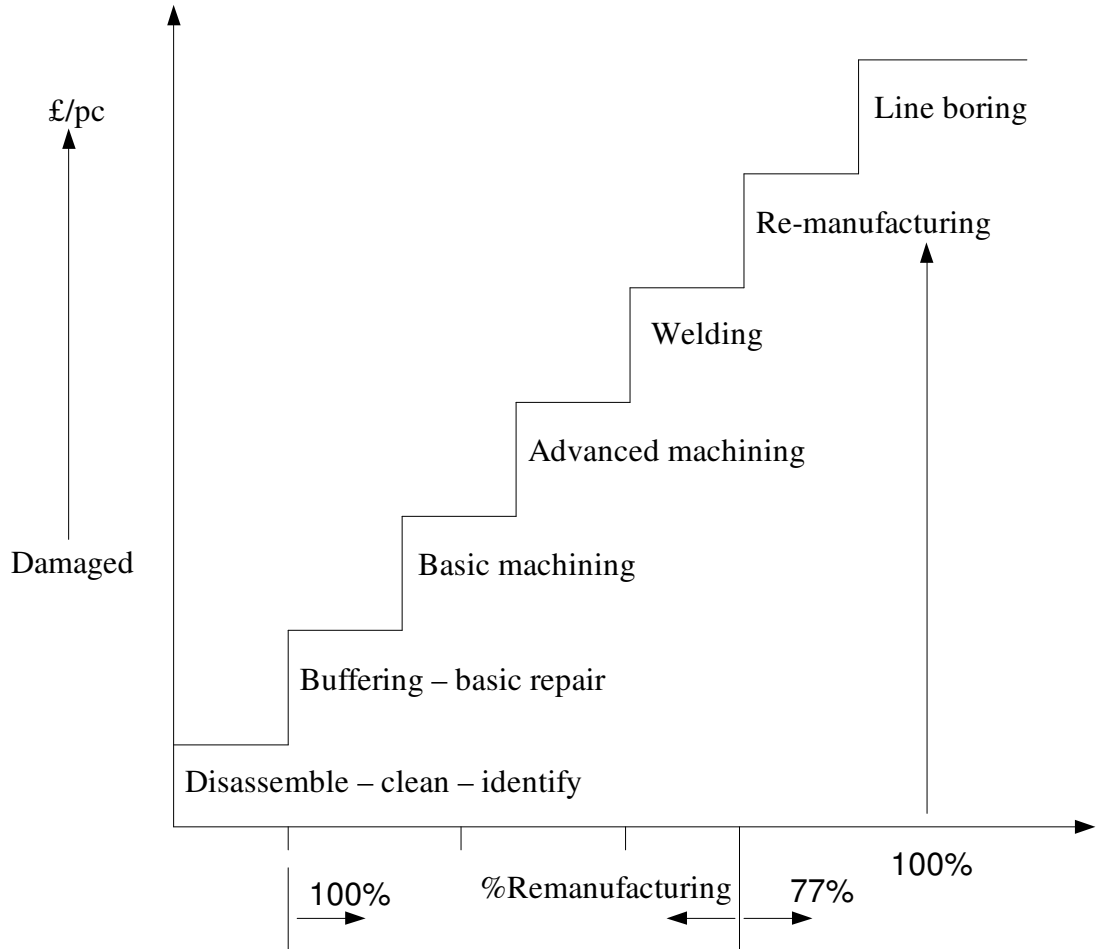


Figure 1.2 Structured flow of remanufacturing: Caterpillar-Remanufacturing example (Caterpillar-Remanufacturing, 2006)

1.5 Remanufacturing Issues

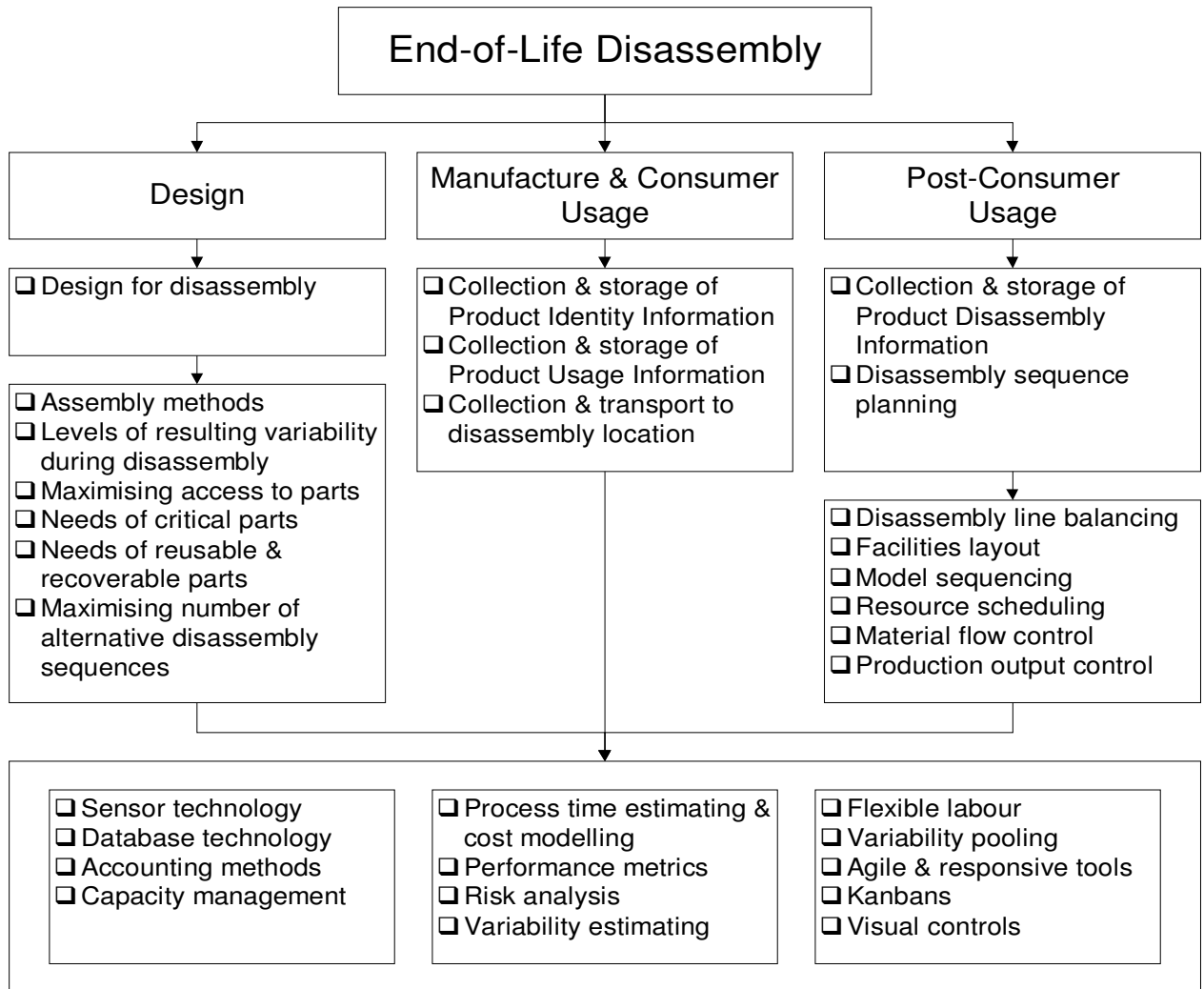


Figure 1.3 Illustration of Various Issues Involved in Remanufacturing
(Stockton, 2006)

Stockton (2006) considered number of options in terms of End of Life product disassembly, which is a major part of remanufacturing process. In the area of product design, defining assembly method that also complements disassembly of the same product at the end of its life is important. Other issues such as maximum access for disassembly operation, and maximising number of alternative dismantling sequences

are some of the important factors to be taken into account when designing environmental friendly products.

Collection of part identity information and product usage information will help to identify the product components and age of the product that helps in making disassembly decision. In addition, Stockton (2006) looks into the area of reverse logistic, which is another issue where collection and transport of End of Life products become extremely important issue due to the cost of collection from multiple sites and storage of End of Life products.

If the product is designed with disassembly guidelines, the third phase of the product lifecycle “Post-Consumer Usage” will have less impact on remanufacturing process. At this point, important information can be collected and stored in terms of disassembly process sequence and the process planning of remanufacturing including detailed steps on material flow, process scheduling, facility lay out and the remanufacturing process efficiency.

Furthermore, latest technology will ease and simplify the process by integrating sensor technologies, database technology on product design phase while cost-modelling, variability estimating will ease the manufacturing process. Flexible labour, variability pooling and lean engineering tools can be integrated to the remanufacturing and disassembly operations.

1.6 Design for Remanufacturing

Gaudette (2003) recognised the need to design products for both, ease of disassembly and remanufacturing to eliminate problems that arise during remanufacturing. Of importance are the levels of process and product variability that arise that may be reduced by designing for:

- (i) **Ease of disassembly** modularity, joining/fastening methods and appropriate material use will greatly ease the disassembly operation (Gaudette, 2003).
- (ii) **Ease of identification:** product and components can be easily identified and segregated or the material information can be traced through trade marking system that ease the recycling operation (Bras, 2005; Caterpillar-Remanufacturing, 2006).
- (iii) **Ease of access and separation** involves servicing and repair needs and therefore, if the design is complex that is difficult to disassemble in service, it will increase the labour cost and also the complex design may require complete module to be replaced which further raises the repair cost (Bras, 2005).
- (iv) Improved wear resistance associates the use of sustainable material within product (Hanafiah, 2003; Bras, 2005).

In order to address these issues, a variety of design philosophies have arisen which includes, Design for Recycle (DfR), Design for Disassembly (DfD), Design for Remanufacturing (DfReman.), Design for Environment (DfE), Design for Product Retirement (DFPR) (Parlikad, 2004; Kosuke and Ishii, 1994; Hammond, 1996; Srinivasan, 1997; Okada, Ono and Yamano, 1999). These philosophies provide

guidelines to assist designers to design more environment friendly products that ease the remanufacturing operation. The guidelines provided center on providing design solutions to difficulties faced on remanufacturing products.

1.7 Aims and objectives of research

Remanufacturing process can become a means to recover the product end of life resources as well as bring benefits to the community and environment. The main reason for decline of remanufacturing process is the variability encountered during the process due to its uncertain nature in terms of End of Life product wear condition, life span of the product and skills requirement to undertake the remanufacturing process.

Previous research Khalil (2005) identified the need to improve the efficiency of high variability flow lines within manufacturing processes by enabling the use of methods that can help to overcome the effect of variability. In order to achieve this objective, number of equations were developed that quantitatively measures the level of workstation utilisation. Khalil (2005) identified mixed level of variability as one of the areas for further work which complements the remanufacturing environment.

The aim of the current research is to identify a suitable strategy to recover the End of Life resources from a domestic product.

- Carrying on from the previous research (Khalil, 2005), the remanufacturing environment presents mixed level of variability that requires further investigation.

- Identify and **investigate different types of variability** encountered during the remanufacturing process.
- Based on (Khalil, 2005) research, further identify ways to reduce the unfavourable effect of **remanufacturing variability** that directly affect the remanufacturing process efficiency.
- Develop a novel mathematical equation based on process time that estimates the variability effect on individual workstation.

In order to achieve the objectives of the research, a **framework of research method** was considered that identified the need to design virtual remanufacturing environment where all the remanufacturing process conditions can be associated with the models developed. It was equally necessary to identify the relationships between three important parameters, process cycle time, %Blocking and %Waiting that allows development of rules and mathematical equation to estimate the effect of %Blocking and %Waiting on individual workstations.

1.8 Structure of the Thesis

CHAPTER 1: This chapter identifies the main issues relating to current environmental problems caused by End of Life products and the EU and UK legislation relating to these products. The chapter also addresses the strategies to help resolve these environmental problems and in this respect examines a suitable product End of Life solution i.e. 'remanufacturing' for its feasibility and usefulness.

CHAPTER 2: Upon identification of remanufacturing as the most suitable product End of Life strategy, the issues that present challenges within remanufacturing process have been addressed in terms of the presence of a large amount of, and wide range, of sources of variability at different phases, of products and processes. These different types and levels of variability are investigated in terms of their significance in effecting process efficiency and effectiveness. Which are respectively defined as “doing the thing right” and “doing the right thing” (Chaffey D, 2011).

CHAPTER 3: In order to achieve high levels of system throughput and efficiency, this chapter analyses the characteristics of remanufacturing system. In this chapter, remanufacturing variability characteristics have been identified along with the most appropriate manufacturing systems, which are suitable to deploy in remanufacturing environments. From this the flow processing structure was found to be the most appropriate for remanufacturing End of Life products, as was the application of lean principles to reduce the effects of variability.

CHAPTER 4: High level of remanufacturing variability presents greater difficulties in End of Life product remanufacturing. Such uncertain remanufacturing process also requires a suitable method to estimate individual workstation utilisation. In order to investigate this hypothesis, a framework of experiments were put together which identified the need of appropriate set of data to be used. Visits to the remanufacturing sites and literature together offered estimated cycle time data. To support the experimental design process, “Simul8” was identified as a means to undertake experiment that allows designing real-time process environment. This led to important

results, which was further analysed and important parameters that control the process efficiency were synchronised to improve the process efficiency and effectiveness.

CHAPTER 5: Simulation runs presented vast amount of data in terms of different parameters that further filtered to derive main parameter. Two main parameters, %Blocking and %Waiting are identified as the main drivers that determine the remanufacturing process variability. In this chapter, the results were further analysed and some logic was put together in the form of equation, relationships, and graphical representation. Numbers of statistical measures were tested against simulation results to identify the most suitable statistical measure that resulted minimum error.

CHAPTER 6: This chapter primarily looks at the main issue revolving around remanufacturing process and variability within process. Here, the hypothesis, experimental framework and results are critically analysed. It identifies possible ways and avenues that may have been adopted or used and critically looks at the applicability of equations and taking experimental analysis further through detailed discussion.

CHAPTER 7: The thesis concluded with making statements that responds to the research questions. The novel investigation which contributes to the body of knowledge is reviewed.

CHAPTER 8: Specifies the area of further work in line with End of Life Remanufacturing.

Chapter 2 Remanufacturing Variability

2.1 Introduction

Engineering manufacturing operations tend to work between limits, upper limit and lower limit. There is no process exists that is not subject to variation. Variation can be defined as change or difference in condition. Manufacturing processes present variation between processing equipment or workstations. One process can finish the operation earlier or later than others. This situation offers a great challenge in planning the production process.

This chapter examines remanufacturing in terms of the sources and levels of process time variability. Here, product and process variability can exist at all stages of the remanufacturing process, i.e. from variability in the initial supply of 'end of life' OEM products to variability in the final demand for the remanufactured products (Hopp, 1996; Mohan, 2006)

The individual remanufacturing processes have been grouped in the following variability categories:

- (a) Supply variability, (Dimitrios, 2007)
- (b) Product design variability, (Sofa, 2005)
- (c) Part specification variability, (Moroni and Polini, 2002)
- (d) Operation variability, (Guide, 1999)
- (e) Sales demand variability (Daniel, 1997)

The individual sources of variability arising within each of these categories have been identified and their effects on the design and efficient operation of remanufacturing system is critically examined. The operation variability is the one that directly refers to the remanufacturing process and therefore it will be further discussed.

2.2 Supply variability

Krupp (1993) stated that individual product units returned to a remanufacturing facility are termed “Cores” because the components within each returned unit are primarily those that will be removed via a disassembly process, repaired and / or refurbished and reassembled to form remanufactured unit.

There are several reasons why “process variability” can be associated with “core”, i.e.

- The year, in which cores were originally manufactured and first entered service, can vary greatly.
- The number of years a product unit has been in service can vary greatly as can the usage conditions, e.g. number of washes per week for a washing machine.
- The condition of returned product can vary greatly depending on at what stage the owner decides to replace the products; e.g. when repair costs begin to outweigh the cost of purchasing a new unit, when fashion dictates the purchase of a new model or the impact of new technology makes the product inferior.

As a result of OEMs continually improving product designs, i.e. changing model types and/or component design specifications (Dimitrios, 2007). Here the continuous decrease

in product development cycle times required to maintain competitive advantage is leading to higher levels of product and component variability (Ahmed and Fujimoto, 2001). Direct design changes will incur variation in following tasks of remanufacturing operation:

- a. Disassembly methods (Gungor, 1998)
- b. Disassembly work content (Gungor, 1998)
- c. Tooling requirements to undertake disassembly (Parlikad and McFarlane, 2004)
- d. Required skills set to undertake disassembly work on new design (Parlikad and McFarlane, 2004)
- e. Requirement of replacement components with identical specification (Sullivan, 2007)
- f. Variation in inspection times – identification of component specification; remanufacturing according to these specifications (Parlikad and McFarlane, 2004).

Product owners also vary in their approach to product service failure, i.e. whether to repair or replace End of Life units.

The growing importance of OEMs developing “product service” systems in which they no longer focus on selling “physical products” to their customers but the functions these products carryout is tending to lead higher levels of servicing, overhaul and remanufacturing rather than the traditional approach of scrap and replace with new

units. Such activities will also be undertaken after defined periods of service and/or defined usage conditions have taken place. A typical example of product-service system is that of Rolls Royce who provide “Power By The Hour” through product leasing (Sundin, Bjorkman and Jacobsson, 2000).

“Power By The Hour” is one of the Rolls-Royce aero engine maintenance programs available to the operators. The program provides operators with a fixed engine maintenance cost over an extended period of time. The operators are assured of an accurate cost projection and avoid the costs associated with unscheduled maintenance actions, (RollsRoyce, 2012); however this research will focus on remanufacturing variability.

The adoption of these “service related” functions – that mean leasing product for a defined period of time and then take it back at the end of the contract; are having significant influence on the product development process where they are leading to the design of products that minimise “whole life” costs as opposed to merely the development and manufacturing costs which form only part of these ‘Whole Life’ costs (Hanafiah, 2002).

In summary, the above effects generate variability in terms of fluctuation in supply rate, product and component mixes, i.e. both specification and quantities.

Marx-Gómez et al, (2000) attempted to develop forecasting model for the rate of returns of products for remanufacturing. In addition, fluctuations in the “reverse logistics”

process is a further source of supply variability (Guide, Kraus and Srivastava, 1996). This process involves the management of End of Life product collection from users and its transportation to a remanufacturing facility. Effective management of this process must take into consideration the variation in initial collection points, i.e. initially from consumers' homes.

The frequency of collections, quantities collected, transportation methods and frequencies of deliveries to remanufacturing units may also affect the levels of variability experienced by the remanufacturing process (Skerlos, et al, 2003).

It is impossible to guarantee the required supply rate due to the uncertain nature of the recovery environment (Lewis, 2005). Product manufactured of the same type may have different life spans because of their varied level of usage, e.g. a washing machine will be used by user 'A' four times a week, while user 'B' will use for daily one wash and user 'C' will have three washes a day in a week. All three users demonstrate three different levels of usage, therefore concluding from the example, the washing machine that is been used by user 'C' will have a shorter lifecycle than user 'A' washing machine. However, there is a greater possibility of 'A' having defects in material or manufacturing for whatever reason it may reach its end of life before washing machine 'C'. Nakashima et.al. (2004) examined the remanufacturing cost management problem in the light of different types of variability involved within remanufacturing, e.g. variability in demand rate, remanufacturing rate, and discard rate. They considered both, actual inventory and virtual inventory, i.e. those items still being used by consumers in their homes. The outcome of the research was based on numerical representation that represented the remanufacturing management of actual and virtual inventory.

Due to the increasing market demand for higher quality, aesthetic and ergonomic quality products, manufacturers are striving to introduce products using the latest technology with upgraded higher functionality (Ahmed and Fujimoto, 2001; Oakdene-Hollins-Ltd, 2004). This trend is also affecting the supply of End of Life products. Due to higher variety of different products with their associated models, supply rates constantly fluctuate. For example, domestic product washing machine manufacturer 'Hotpoint' have a variety of models, which vary depending upon their levels of functionality such that product price increases with the levels of functionality such as number of spins and additional drier options hence products arriving at the remanufacturing facility will not be of the same make or model, i.e. the strong possibility exists that they will be of different makes or different models.

Necati, Tamer, and Vedat (2004) presented an approach for assessing the impact of quality-based categorisation of returned EoL products. Here product cores arriving at a remanufacturing facility, are assessed for quality and a disposal decision made immediately in order to better deal with stochastic returns. They found that savings are cost amplified as the return quality decreases and the return rate increases. Hence prioritising those returned End of Life products for remanufacturing with greater number of good components within was a feasible strategy to adopt.

Dimitrios, Patroklos and Eleftherios (2007) scrutinised capacity planning for remanufacturing economical and environmental issues such as, "Take Back" and "Green Image" to complement with remanufacturing. "Take Back" is one of the initiatives

implemented and run by OEM's to take their products back at the end of their functional lives to recycle and recover useful parts while "Green Image" forces OEMs to maintain their "green manufacturer" image by creating environmental friendly products.

2.3 Product design variability

It was identified in Section 2.2 that the specification of the core components within returned products can vary greatly. Various sources of 'Process Variability' associated with returned End of Life products are related to:

- a. variability in component specification both between and within model types,
- b. variability in the wear and failure state of individual components between successive cores,
- c. variability in relative volumes of each model entering the remanufacturing system, and
- d. variability in terms of ease with which products can be disassembled and repaired.

In addition, the possible presence of identical model types containing different component specifications results in significant variation in the time required to determine each components identification code and hence its replacement parts or repair specifications. Also, variation in remanufacturing work content and specification results in mixed volumes between production periods of each unique product/component type.

The flow of returned products/cores from varying sources in different product ranges, ages and quality are other challenges to an effective remanufacturing industry (Ahmed and Fujimoto, 2001). Lack of workforce skills and complex product design along with non-standardised joining methods are among the factors that also makes high levels of remanufacturing efficiency difficult to achieve (Gaudette, 2003).

Returned cores have finished their first lifecycle. Whether they were used to their full capacity and efficiency, or due to the specific failure of capital component not economically viable to replace, they were scrapped and replaced with alternative products (Caterpillar-Remanufacturing, 2006). This is where the product variability identified. At the stage of planning the remanufacturing process, the extent of remanufacturing required to the product is not known, e.g. some product may require only one part/component replacing, while the other product may require several parts to get it into the working order. This will also have direct effect on disassembly operation. The depth or extent to which the disassembly operation to be performed, becomes challenging task. Different products with their different models have lifecycle options. Now in the era of designing environmentally conscious products, many products come with eco-friendly components design. These components may have shorter lifespan as at the end they are going to be recycled and reused (Kroll, 1995; Gupta and Gungor 2001).

Due to large differences in customer demand for individual product models, returned product volumes can fluctuate significantly. These large differences between product model volumes returned for remanufacturing makes, balancing, restructuring,

scheduling and processing the product in order to remanufacture them, a challenging and unpredictable environment (Lewis, 2005).

In addition, product mixes can have other highly unpredictable factor such as "different ages" of the cores. In this respect products may have been initially used only for several days and due to warranty return policy, taken back and replaced with a new product due to a single major component failure (Souza G, Ketzenberg M, and Guide V., 2002). In these circumstances all components within such products will be requiring merely one or two components replacing before the product can be resold. In comparison, products may have been used for several years, during which multiple services have been carried out and components replaced or repaired. Hence products will have mixed aged components. Cores of these types are more complex to remanufacture and when remanufactured, will have higher level of uncertainty in their lifespan; this situation represents higher level of remanufacturing variability within 'cores' of different component ages. The continual change in product specifications over time will result in mismatches of fixing and joining methods which in turn brings variability to the remanufacturing process by extending the process time to find the appropriate component and/or modify components to fit older version of a product.

Dimitrios (2007) stated that increasing the number of product offering, the rapid increase in new product development levels and reduced operational life cycle makes the supply of cores extremely uncertain.

- Products made of non-recyclable materials and components with single life spans become obstacles to remanufacturing efficiency.

- Products intended for reuse should be durable for a period equal to two functional lives by the mean of remanufacturing.
- Materials in new product development should be excessively utilised so that it can have enough strength; with the use of scenario, first functional life may be extended due to extra strength given in first manufacture (Susumu, Toshimitsu, and Norio, 2003).

2.4 Parts specification variability

Over the course of time the new product development process results in constant development of new product models and model revisions each with differences in component design specifications. As a result, a single component with a product, over a period of time will end up having many different changes in product design specification (PDSs), hence resulting increase in component variability at the remanufacturing process stage (Gupta and Gungor, 2001).

In addition, due to the introduction of updated manufacturing methodologies, such as Design for Manufacturing (DFM) which seeks to reduce the number of components within a product to reduce the total cost of the product and material usage, the component design becomes increasingly complex due to the component integration; again increasing the level of variability during the remanufacturing process (Corbett, Meleka and Pym, 1991).

In addition, the introduction of environmental initiatives such as Design for Disassembly (DfD), Design for Environment (DfE) and Design for Remanufacture,

forces designers to change the component specification, in order to adhere to changing government directives and environmental targets for recycling. This has a direct effect on such design aspects as joining methods and material usage. These types of product component changes again increase the effect of parts variability within remanufacturing operation (Lewis, 2001).

Changing component specification also changes the size and the shape of the part, which again become obstacles to efficient remanufacturing since for example the latest version of a component will not fit earlier product module and vice versa.

Gungor and Gupta (1999) identified that the state-of-wear of the individual components in End of Life products also varies dramatically as the level of operational usage depends upon individual end users. For example,

- Some users use products to their full design capacity, whilst other users use products to less than this capacity. Hence the states-of-wear can vary considerably between components from heavily worn parts to parts with little wear.
- Some parts may have only minor levels of damage during normal service while others may have major failures; this is again leading to variability in remanufacturing process, when components have differing levels of wear, damage or failure.

This type of circumstance will require constant need to provide alternative process routes; for example, out of two similar parts, one may require cleaning operation only with inspection for damage whilst the other may require many more repair process.

Component state can also represent a major source of variability within remanufacturing. End of Life products can have components with varying levels of functional quality. They may or may not have been serviced or repaired during their operational use. Depending upon the component specification, products may be made up of different quality components with specification variation levels between them. This may result in remanufactured products having uncertain lifespan. Where these indications occur, parts and quality variability greatly effect the remanufacturing operation (Gupta and Gungor, 2001).

Retrieved component volume can also have effects on the levels of variability within the remanufacturing process. Returned products requiring remanufacturing have high variety but also very low volume (HVLV) with frequent changes in product and model mixes. Therefore remanufacturing systems must have characteristics to enable them to cope with such situations. A chaotic remanufacturing environment can be created when higher levels of variability occur along the process sequence (Gupta and Gungor, 2001).

2.5 Operation variability

In terms of variability during remanufacturing operations, there are many sources, i.e. since out of a thousand returned products, identical products need to be processed, these components may have completely different refurbishment requirements as listed below (Gupta and Gungor, 2001).

- I. no refurbishment, use as is
- II. minor refurbishment
- III. major refurbishment
- IV. scrap and replace

Based on above conditions, taking example of washing machine, one machine may have only the need for a motor replacement whilst other may require a new door seal and refurbishment of the washing drums. Such requirements result in the need for variability segregation prior to operations planning. An efficient hybrid manufacturing system facilitates with remanufacturing such types of remanufacturing customisation where a high level of uncertainty is experienced in repair needs (Lewis, 2005; Sofa, 2005).

In order to remanufacture products using Flow Line manufacturing method, certain conditions need to be considered to ensure the smooth flow of the work along the line, i.e.

1. Specific products may have minimal refurbishing work than others therefore; such products need to be allocated to leave the production line earlier than others.
2. Specific products may not require certain operations as they flow, in which case, they would need to skip these operations.
3. Products may need to re-visit previous operations because of a missed task or partly performed activity.
4. Products may need to leave the line for additional operations to be performed that returns to the line, (Kizilkaya and Gupta 2001).

Within remanufacturing, disassembly operations also play a large part in providing a significant source of variability. In addition, creating the optimum sequence for disassembly, is often a complex task specifically during the non-destructive disassembly of complex products. A number of approaches to the disassembly sequence problem have been identified by Zhang and Kuo (1997); Gungor & Gupta; (1998); Huang, Wang and Johnson, (2000); McGovern and Gupta (2003) that includes Petri-Net, mathematical algorithm, graph-based disassembly neural network modelling that creates feasible disassembly sequences. This body of research investigated and modelled different types of variation that occurs during part remanufacturing, (such as corroded screws and surfaces, welded joints, broken springs and/or fasteners), which increase the levels of process time variability. When such variability arises during the remanufacturing process, additional and/or alternative disassembly steps will be considered, to cope with the effects of this variation.

According to Guide (1996) scheduling within the remanufacturing environment is more complex than in traditional manufacturing environments. Scheduling within remanufacturing environments must be able to cope with complicating factors that increase operations variability. Such factors include conditional routing and dependent events; e.g. routing that may or may not be taken due to the condition of the product 'Core' and the sequential dependency of operations. Hence the Drum-Buffer-Rope (DBR) control methodology has been identified as the robust scheduling method for remanufacturing environment that effectively deals with such factors as conditional routing and dependent events.

Drum-Buffer-Rope is a planning and scheduling solution that identifies the scarce resource within a manufacturing process and protects that resource against disruptions through the use of time buffers that continuously feeds the resource to improve the efficiency. The development of Drum-Buffer-Rope is derived from the philosophy of “Theory of Constraint” that basically teaches how to identify and focus the critical resources that affects the throughput, Hopp and Spearman (2001).

2.6 Demand variability

According to a study of the remanufacturing industry report by Oakdene (2004), the UK remanufacturing industry is still in its infancy and gradually developing through initiative such as "the Centre for Remanufacturing and Reuse". Although remanufacturing is gathering pace in the UK as an environmentally feasible and profit making sector it still lacks significant demand for remanufactured products. Consumer support is needed for remanufactured products to become successful in the UK market. Hence, the variability associated with demand is currently not a significant factor affecting the efficiency of remanufacturing operations. In terms of remanufactured products, typically potential customers are not in favour of buying such products due to new products being available at reasonable prices. Overseas market also compete with remanufactured products by offering lower priced new products with all required design standards and similar or higher functionality (Oakdene, 2004).

There are also warranty issues affecting the sales of remanufactured products. New products normally have a full one-year service warranty whilst remanufactured products

would normally come with three or six months warranty. This warranty period is devised by the individual company or remanufacturers. One obvious reason for shorter warranty period is that the remanufactured products are going through their second life and the chances of failure are greater. In addition, remanufactured products are more likely to contain components or modules of differing quality which may malfunction, (Sofa, 2005). However, the trend is, for OEM remanufactured products to be sold with one year warranties, e.g. CatReman, engines remanufactured by Caterpillar, come with full warranty (Caterpillar-Remanufacturing, 2006). Local authority run project 'SOFA' supplies remanufactured products to low-income families unable to afford from superstores, (Sofa, 2005). Furthermore, according to Sofa representative, those households with average or above average income who could afford to buy a new product are not interested in buying remanufactured product whereas low-income households were more interested which represents low demand for remanufactured products. Hence the demand variability sometime grows high when specific product-models are envisaged by customers. Also, due to the uncertain nature of the process there is no certainty of specific product arrival therefore promising customer of a specific product that might arrive in future will hold-up the sales.

There is no higher demand for remanufactured parts/components that might possibly be used at the servicing/overhaul stage, (Lewis, 2005). There is a growing demand for service industry where yearly subscription of service/repair plan are taken by customer where, if product stops functioning, an engineer will be called out and product will be repaired, replacing non-functional components. As remanufacturing industry have not yet developed to a greater extent in the UK, the effect of demand variability is not

explicitly observed as other variability of remanufacturing. It may experiences high variability in demand rate when the remanufactured products are demanded for overseas market. Developing countries welcome remanufactured products as they value the European products and brands due to their quality and reliability. Pricing the remanufactured product is difficult as it involves unpredictable work content that is difficult to cost at initial stages of remanufacturing (Ling, 2001).

Chapter 3 Remanufacturing systems

3.1 Introduction

Chapter 2 highlighted the high levels of variability that exists within the remanufacturing process caused by varying supply and demand conditions and the variable and unknown condition of the actual components being remanufactured. This chapter addresses the effect this variability has on the selection of an appropriate manufacturing system design philosophy.

3.2 Characteristics of Remanufacturing Variability

Khalil (2005) identified two basic strategies of dealing with variability within manufacturing environments, i.e.:

- i. Reduce or remove the levels of variability that arise.
- ii. Respond to changes arising from variability.

3.2.1 Reducing or Removing the Levels of Variability

In terms of reducing or removing variability, a number of strategies have emerged as follow.

3.2.1.1 Establishing balanced workloads between items of processing equipment through effective allocation of tasks to items of processing equipment

Here, the same flow line may be used to produce mixed model or multi model products with the average workstation time being used to allocate tasks to the workstations such that a 'balanced' line is obtained.

In order to overcome stochastic workstation cycle time situations, several strategies have been developed which includes transforming the stochastic manufacturing situation into a deterministic situation normally adopted in mixed-model and multi-model flow lines, where the highest workstation cycle time that is used as the task time (time to process one component) to control the throughput rate.

Where individual workstations along a flow line exceed the "TAKT time", then adjustments must be made by stopping the lines to complete any unfinished operations. "Takt time" is a method that sets the pace within manufacturing line to balance the movement of products being manufactured or assembled. It is also possible to provide a dedicated area for unfinished operations to be completed offline, hence preventing line stoppages. If finance and organization policy allows, additional resources or mobile resources can also be allocated to heavily loaded workstations in order to maintain the flow of material.

According to Kottas and Lau (1973), who examined manufacturing flows, idle time must be allocated to workstations within flow line in order to avoid potential incompleteness costs. In this method, a workstation simply waits for the next job once it

finishes its current tasks and therefore stays idle until the successive workstation has completed its tasks.

Further methods involve intentionally unbalancing the work allocation along flow line to mirror the 'bowel phenomenon' (Hiller and Boling, 1966), ensuring that the majority of the variability sources are centred on a specific workstation hence reducing its effects on the remaining workstations within flow line. These approaches result in additional resources being allocated to specific workstations and/or opportunities for variability reducing through use of lean tools and techniques. This will also result in reduced effect of %Blocking and %Waiting on other workstations while one or more other workstations will experience high levels of waiting or blocking.

3.2.1.2 Effective finite capacity scheduling of work items through the remanufacturing system

The effective launch sequence of models onto a flow line has been used to improve workstation utilization, which requires appropriate ordering of models onto the line and predetermining time intervals for model launches (Yano and Bolat, 1989). This shows mixed-model approach where production for a day is evenly distributed to workstations within flow line for a specific day. The most utilized sequence is repeated until the demand changes. This will reduce the level of interruption to present flow that occurs due to changeovers.

3.2.1.3 Removing the causes of variation through set-up reduction, lean practices and total quality management activities

Here a number of methodologies have evolved that seek, in part, to reduce sources and levels of variability, i.e.:

Set-up reduction

SMED (Single Minute Exchange of Dies) is a Lean manufacturing method used in reducing waste on the set-up phase of the production. SMED was initially implemented in the injection moulding industry for changing moulding tools from one product to another in single minute steps. The concept arose in the late 1950s and early 1960s, when Shigeo Shingo, was consulting various companies including Toyota and was contemplating their inability to eliminate bottlenecks at car body-molding presses. Application of the SMED improves productivity and reduces downtime by implementing discipline on the shop-floor, which includes pre-kitting, prior to set-up execution that results in flow-less execution. Also, SMED looks into set-up method improvements by dividing work into manageable chunks as well as seeks to reduce motions during set-up process (Shingo, 1985).

Total Productive Maintenance (TPM)

This considers maintaining the plant machinery to highest level where at a regular time interval, formal check is undertaken of all the primary and secondary functions of a scheduled machine. It helps in reducing the repair work during the production run while maintains quality and cost by preventing major breakdowns. TPM mainly focuses on processing equipment, employee participation and waste elimination (Wireman, 2004).

Total Quality Management (TQM)

TQM is a management approach focuses on customer relationship and it involves all members of an organisation. Everyone participates in delivering the highest standard product by performing their relevant responsibilities to their best ability. It helps companies to meet customer quality requirements whilst simultaneously placing emphasis on process measurement and control through collective effort from all employees as well as suppliers which results in continual improvement. It primarily focuses on quality, in terms of output and its effect in helping management to achieve quality levels measured in Part Per Million (PPM). PPM is quality measure used by many automotive companies which means that the manufacturers and suppliers will be rated as tier one supplier if their scrap rate or non-conformance rate is one scrap part per batch of one million components produced (Mukherjee, 2006)

3.2.1.4 Combining sources of variation, i.e. through variability pooling and buffering

Combining various sources of variability in terms of time and place is referred to as variability pooling. This method reduces the overall effect of variability within flow lines; while individual workstation variability will be more visible and will represent greater idle time within a flow line, however, if the same workstation is grouped with other workstations having variability, together they will have less overall effect.

Kahlil (2005) identified that multiple items of processing equipment is fed through one queue, where if one station is taking longer than others, the other stations will still be fed through while the bottleneck workstation will not heavily affect the flow line. The

batches will have less variability in terms of cycle time than single component cycle time. In addition, inventory, capacity and time may also be used as buffers to offset variability within a flow line.

With all the methods and techniques, that is used to reduce the effect of variability, adequate knowledge of remanufacturing process and flow manufacturing is necessary. Information in terms of requirements of additional resources, appropriate allocation of resources, level and types of resources required.

3.3 Comparison of Alternative Remanufacturing System Strategies

The remanufacturing process needs to cope with high levels of process and product variability. In consequence Kekre (2003) points out that it is an unorganized and uncertain process that requires better management of returned cores and process activities. Defining the best facilities layout and organising the process so that products flow at a smooth pace is hence essential (Kekre, 2003).

Mixed-model flow and Process Sequence Cell Layout, are two main systems that enable flow environment to be designed (Stockton and Lindley, 1994).

Mixed-model flow lines involve several models of a product being processed on one assembly flow line. Models are similar in their set-up requirements and hence require no long time setup between models. The main objective of such systems are to smooth the demand on upstream workstations or suppliers which helps reduce changeover, inventory and avoids difficult assembly line set-ups. A range of terms are used to

describe such cells including Cellular manufacturing (Wemmerlov, 2002), Group technology (Suresh and Kay, 1998) and Flexible manufacturing system (Horst and Kuhn, 1993).

Further in detail, it is a kind of set-up where a group of different types of processing equipments and supportive tools for producing a complete or part sub-assembly are arranged. In the cell, the raw material is processed to the stage in a sequence, moving from one machine to another until it reaches the phase where it becomes part of assembly or sub-assembly. Through integration of Just in Time (Pull system), number of components, raw material and other resources can be kept to minimum level that helps reduce the inventory level. Flow line is able to move work quickly from one station to another, which in turn reduces waste. Furthermore, this Pull system will pull the material as required or as demanded by the workstations and also the products can be manufactured on customer demand with cost effective inventory and storage. “Kanban” signal method that signals the next operator or workstation through different colours labelling system of process stages, will further improve the process efficiency.

Process Sequence Cell Layout (PSCL)

In order to support High Variety Low Volume (HVLV) manufacturing environment, (Stockton and Lindley, 1995) developed Process Sequence Cell Layout. Each cell is designed according to manufacturing requirement where item of processing equipment is allocated according to their position in the process route. When designing such cells, there is a specific requirement of product and process data, in terms of number of operations to be performed and item of processing equipment to be used.

When selecting a suitable production environment for remanufacturing, the following factors are important to consider, i.e.

- (i) **Volume:** system should be able to handle possible return of 'cores' in higher or lower volume, depending on product life and usage. Variability in supply of cores frequently prevents optimum batch size from being formed. Due to the uncertain incoming cores, the system should be able to process the higher to lower product volumes (Klausner, Grimm and Horvath, 1999; Sundin and Ostlin, 2005).
- (ii) **Lead time:** the system should have shorter lead-time specifically in such environment where input is highly variable / uncertain. The process lead-time will dramatically effect the storage and WIP inventory, therefore it is desirable that the system does not hold queues before processing in front of the work-stations; in effect, shorter lead time will increase the productivity and efficiency of the process. Also in terms of **Variable process time**, system should be able to handle variable cycle time as to cope with variable part condition (Tang and Grubbstrom 2005; Tang, Grubbstrom and Zanoni, 2007).
- (iii) **Variety:** the system should be able to handle high product variety, as there is strong possibility of receiving different product with their respective model variety. The ideal system will be implemented in recovery environment, in which, the incoming flow of material is in mixed variety. If a washing machine for example, is taken, then there are vast number of

manufacturers found with very high variety of product models. In this situation, if products are sorted to their relevant make and models, they may end-up having fewer number in which case, the volume becomes very low. Therefore, the ideal system must be able to handle both, higher and lower volume production, (Klausner and Grimm, 1999).

- (iv) **Flexibility:** system should be flexible in order that a component/module may be able to skip the operation or can re-visit previous workstation within the flow. Flexibility within a process adds value and on certain occasions, reduces processing cost. If the facility is flexible in terms of terminating process at any stage would help reducing processing cost. If the processing equipments are arranged in a way that different product variety can be processed without re-arrangement of processing equipments, (Gupta and Gungor, 2001).
- (v) **Cost:** the overall cost is the main driver within a product management and keeping manufacturing cost down is the main aim of producers. In terms of product manufacturing, the system should be such that does not take larger share of product cost. The system implementation and re-arrangement of processing equipments are some of the factors that increase the overall cost (Luh, et al., 2005).

Manufacturing systems	Volume			Lead time			Cost		Flexibility			Variety		
	H	M	L	H	M	L	H	L	H	M	L	H	M	L
Mixed Model Flow	X	X				X	X			X			X	
Process Sequence Cells	X	X	X		X			X	X			X		X
Ideal Manufacturing system	X		X			X		X	X			X		X

Table 3.1 Most suitable production system characteristics for remanufacturing

From Table 3.1, it is evident that the ideal production system should possess following characteristics, i.e.

- a. **Volume:** enable varying batch sizes to be processed efficiently,
- b. **Lead time:** provide short lead-time
- c. **Cost:** lower overall operating cost without requiring new equipments
- d. **Flexibility:** allow multi-tasks to be performed in between process operations
- e. **Variety:** enable sorting method and process variety of product with ease

Further analysis

Upon analysing these manufacturing systems against the required characteristics, flow manufacturing fulfils most of the requirements and seems to be more suitable manufacturing system to be employed in remanufacturing environment.

Justification for flow line

In section 3.3, through comparing other available methods suitable for remanufacturing environment, the flow line is identified as the most appropriate method to be deployed in remanufacturing. As discussed in Section 3.2, number of Workstations are placed in the sequence in which the majority of the products can be processed without needing to re-arrange processing equipment layouts between models. The production process starts from the first workstation, and moves forward onto succeeding processing equipment. This movement can be regulated using Kanban material movement control systems along with the integration of TAKT time, which would further smooth the process flow (Rolls-Royce, 2006). Furthermore sorting the products into different categories according to their make and model will further simplify the process.

Chapter 4 Experimental Design

4.1 Introduction

Chapter 3 identified a suitable manufacturing system that could be deployed for product EoL remanufacturing. However the challenge of removing or reducing the effect of various sources of variability within remanufacturing environment needs to be thoroughly assessed in a structured manner where main variables that controls the variability are identified and their causes removed. Khalil (2005) stated that the improved use of planning and control methods would help overcome the detrimental effect of such variability.

Aims and objectives

Reducing or removing the effect of remanufacturing variability is the primary aim of the research. In order to achieve the research goals, there is a need for methods that provide the required knowledge that will allow estimation of the effects of variability along a flow processing line.

Data collection method is an integral part of the experimental process where important decisions are made in terms of how to collect data and how to identify the main parameters effecting %Blocking and %Waiting inefficiencies along the line.

4.2 Research Methodology

4.2.1 Data Collection Methods

The main types of data collection methods available are:

- I. Observing and recording well-defined operations or processes.
- II. Obtaining data from management information system, e.g. legacy data.
 - a. For example, actual process information/data from remanufacturing facility with a flow line setting; e.g. remanufacturing facility in Leicester such as Remploy, who implemented flow line environment.
- III. Administering surveys with close ended questions.
- IV. Mathematical and graphical representation reveals causes and effects relationships by manipulating independent variables to see the correspondent effect on a dependant variables.
- V. Real experiments, where prototype of the process may be developed with all the required resources in uncontrolled/controlled remanufacturing environment.
- VI. Modelling techniques such as queuing theory or discrete event simulation, where actual process would be designed, executed and data will be collected.

Of the above methods, the only practical method was the use of data generation technique, using data collection through other methods could not provide sufficient type and detail of data required.

Observing and recording the well-defined process and obtaining legacy data is not possible since such information is not yet published in the literature or seen in the industry because fully operational remanufacturing flow line is not yet available.

Administering surveys and mathematical / graphical representation can give inaccurate results due to stochastic process nature. Real experiments where building prototypes of actual remanufacturing process will be very expensive to set-up.

4.2.2 Data Generation Methods

Two methods were considered, i.e. discrete event simulation (DES) and queuing theory. Queuing theory could not be used since the resulting models would only be able to measure the utilisation and non-utilisation levels of the complete High Variability Flow Line (HVFL), and the restriction of queuing theory to exactly model real-world situation, will add further complexity to such chaotic remanufacturing process. Therefore performance for individual workstations could not be measured and non-utilisation could not be split into 'Blocking' and 'Waiting'.

For generating data, discrete event simulation was therefore, selected because of its ease in changing numbers of workstations within flow lines. Also, it is able to record number of variables that is responsible for process efficiency including %Blocking and %Waiting. In addition various scenarios may be designed and options may be included to make the experimental design robust and comprehensive.

4.2.3 Selection of Experimental Methodology

When designing the discrete event simulation models from which to generate data, care was taken to ensure that these models provided suitable data for subsequent analysis. The washing machine example is used for flow line experimentation. The reason for this specific product selection is, due to having medium level of complexity in disassembly and remanufacturing operation because of limited number of components and modules.

Khalil (2005) identified and used manufacturing tasks with shorter cycle times and greater number of workstations, e.g. 21 workstations. Khalil (2005) stated there is a need to develop methods to estimate %Blocking and %Waiting on individual workstations when mixed levels of variability exist between workstations. This situation directly corresponds to remanufacturing operations that present mixed levels of variability due to unknown conditions of components within end of life products.

In order to recognise whether relationships existed between workstation variability levels and workstation blocking and waiting levels, it was, therefore, decided to undertake experimental work in three basic stages with the results at one stage directing experimentation at the next.

Stage I Experimentation

Undertake experiments using a fixed cycle time at each workstation but variation in cycle times between workstations to enable examination of the effect of differences in variability levels between workstations. Here it was necessary to isolate the effect of

variability between workstations by removing variability within workstations through the effective use of methods discussed in Section 3.2.1.

Use visual analysis to identify potential cycle time variability and Blocking and Waiting relationship and convert this relationship into equation.

Stage II Experimentation

Introduce intra-workstation variability and test the idea/model developed. Identify how mathematical relationship identified in stage I. Modify where necessary these relationships to take effect of Intra-workstation cycle time variability, Khalil (2005)

Stage III Experimentation

Undertake range of experiments to identify limits to the applicability of the modified relationships identified in stage II, in terms of:

- i. Number of workstations
- ii. Levels and ranges of variability
- iii. Relative position within the HVFL of Stage II and Stage III variability

The experimental stages were designed using variability levels that are carefully selected to include:

- i. Sudden decrease in the middle position of flow line.
- ii. Gradual 'upstream' increase in variability levels between workstations.
- iii. A range of workstations variability.

- iv. Varying number of workstation within flow line.
- v. Largest cycle time in first and last workstations.

Each experiment consisted of one simulation run and all experiments used the same random number stream. Khalil (2005) adopted this strategy since multiple simulation runs would tend to provide a false impression of the accuracy of results, i.e. use of the triangular distribution is a trade off between ease of use and accuracy of probability distribution.

4.2.4 Selecting the Distribution Type

The various types of probability distributions applicable to manufacturing have been identified by Khalil (2005). From these, the Triangular distribution has been chosen as the basic distribution to be used in this experimentation. Triangular distributions have been selected, since these are used, particularly within project management, when actual probability distribution types are unknown because of the relative ease with which the values that define the triangular distribution can be estimated. They are flexible in terms of being able to approximate a wide range of other distribution types including both skewed and non-skewed distribution types.

Khalil (2005) stated “If the variability associated with individual workstation task cycle times (TCT) is represented by the triangular distribution shown in Figure 4.1 then the mode is represented by the most likely t_{TCT} and the median, mean and standard deviation of the triangular distribution and can be calculated using equations 1 to 4”, i.e.:

If $t_{TCT} - a_{TCT} \geq 0.50(b_{TCT} - a_{TCT})$ then

$$\text{Median} = a_{TCT} + \sqrt{0.50(t_{TCT} - a_{TCT})(b_{TCT} - a_{TCT})} \quad (\text{Khalil 2005}) \quad (1)$$

If $t_{TCT} - a_{TCT} < 0.50(b_{TCT} - a_{TCT})$ then

$$\text{Median} = b_{TCT} + \sqrt{0.50(b_{TCT} - a_{TCT})(b_{TCT} - t_{TCT})} \quad (\text{Khalil 2005}) \quad (2)$$

$$\text{Mean} = \frac{a_{TCT} + t_{TCT} + b_{TCT}}{3} \quad (\text{Khalil 2005}) \quad (3)$$

Standard Deviation =

$$\sqrt{\frac{a_{TCT}^2 + t_{TCT}^2 + b_{TCT}^2 - (a_{TCT} \cdot t_{TCT} + a_{TCT} \cdot b_{TCT} + t_{TCT} \cdot b_{TCT})}{18}} \quad (\text{Khalil 2005}) \quad (4)$$

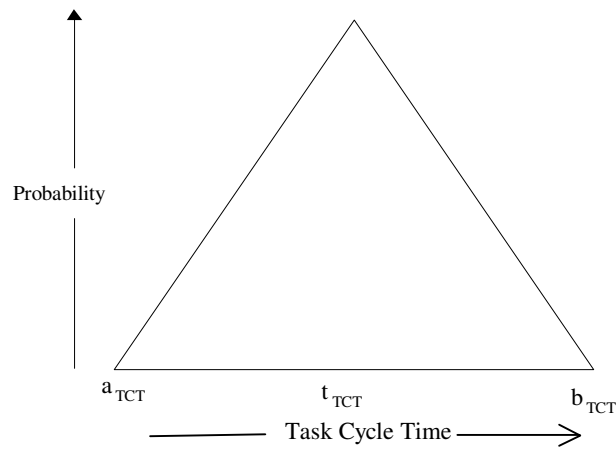


Figure 4.1 Triangular Distribution for Cycle Time (Khalil 2005)

Where:

a_{TCT} = shortest likely time required to complete a task,

b_{TCT} = longest likely time required to complete a task, and

t_{TCT} = most likely time required to complete a task.

4.2.5 Simulation modelling

Simul8 was selected as a tool to design experiments to develop flow lines. This is a commercial, computer-based simulation-modelling package that will be used at all three experimental stages due to its comprehensive nature that allows designing various remanufacturing scenarios with ease.

Basic lay out design of flow line was planned and simulated with standard estimated cycle times that produced initial data in terms of:

- Workstation %Blocking
- Workstation %Waiting
- Number of completed products
- Number of changeovers
- Minimum Workstation use
- Average Workstation use
- Maximum Workstation use
- Number of parts entered to the system
- Number of parts lost

The aim of the experimentation was to make use of workstation cycle time variability distributions to develop models by which the effects on the remanufacturing flow line of differences in workstation variability can be determined. The essential question to be answered is illustrated in Figure 4.2, i.e. how do differences in levels of variability

within and between workstations affect the levels of blocking and waiting experienced by individual workstations along the flow line.

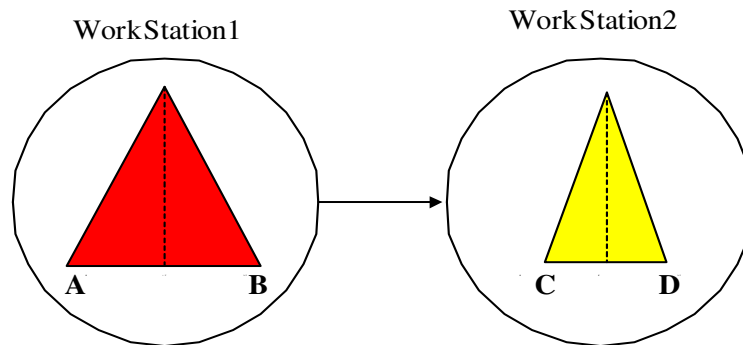


Figure 4.2 Sequential Workstations of Flow Line exhibiting Different Workstation Variability Levels (Khalil 2005)

Figure 4.2 represents two workstations within a flow line. Workstation 1 has longer cycle time than Workstation 2. This establishes the fact that while Workstation 1 is working, Workstation 2 will be waiting for preceding workstation to finish. In addition, Figure 4.2 represents the ranges of cycle time (A and B; C and D) where 'A' and 'C' are the Shortest range that an operation will take and 'B' and 'D' are the Longest range of time that an operation can take.

Stage I Experimentation: Zero Intra-Workstation Cycle Time/Variable, Inter-Workstation Cycle Times

These experiments were designed to identify the basic manner in which %Blocking and %Waiting of individual workstations varied along a flow line when zero cycle time variability existed at individual workstations and cycle times between workstation

varied, i.e. removing workstation cycle time variability is designed to enable the effects of inter- workstation cycle time variability to be isolated and, therefore, better observed.

Exp. No.	Workstation Cycle Time (Min)				
	1	2	3	4	5
1	7	2	2	2	7
2	7	2	2	4	7
3	7	2	4	4	7
4	7	4	4	4	7
5	7	4	2	2	7
6	7	4	4	2	7
7	7	4	2	4	7
8	2	7	7	7	2
9	2	7	7	4	2
10	2	7	4	4	2
11	2	4	4	4	2
12	2	4	7	7	2
13	2	4	4	7	2
14	2	4	7	4	2
15	4	7	7	7	4
16	4	7	7	2	4
17	4	7	2	2	4
18	4	2	2	2	4
19	4	2	7	7	4
20	4	2	2	7	4
21	4	2	7	2	4

Exp. No.	Workstation Cycle Time (Min)				
	1	2	3	4	5
22	49	4	4	4	49
23	49	4	4	16	49
24	49	4	16	16	49
25	49	16	16	16	49
26	49	16	4	4	49
27	49	16	16	4	49
28	49	16	4	16	49
29	4	49	49	49	4
30	4	49	49	16	4
31	4	49	16	16	4
32	4	16	16	16	4
33	4	16	49	49	4
34	4	16	16	49	4
35	4	16	49	16	4
36	16	49	49	49	16
37	16	49	49	4	16
38	16	49	4	4	16
39	16	4	4	4	16
40	16	4	49	49	16
41	16	4	4	49	16
42	16	4	49	4	16

Group - A

Group - B

Four different types of data set





-  Largest Cycle-Time (CT) in first and last position
-  Largest Cycle-Time (CT) in middle position (WS: 2,3,4)
-  Largest and Shortest Cycle-Time (CT) in varying position
-  Largest and Shortest Cycle-Time (CT) in varying position

Table 4.1 Stage I Experimentation, 5 Workstations: Zero Intra Workstation Cycle Time Variable/Inter Workstation Cycle Time Variability

Four different types of data sets were generated and used for experimentation purposes. These data set was obtained based on the variety of situations arising during remanufacturing operation as defined by (Gupta and Gungor, 2001; Caterpillar-Remanufacturing, 2006). These data sets have various patterns of Cycle-Time (CT) mirroring the actual operations' duration or length of CT; where largest CT and shortest CT was moved to different positions, starting from first to last Workstations.

To further verify and justify the task of comprehensive experimentation using the simulation tool to develop a real-time process environment, two groups of data set, Group - A and Group - B (Table 4.3) are developed. One group (Group - A) having CT under 10 minutes while the other group (Group - B) having maximum CT of 49 minutes. This use of two groups of CT justifies that the simulation models have been tested for situations consisting of both, larger and smaller CT. The experimental input data shown in Table 4.3 was used to undertake the actual simulation modelling of which results are discussed in Chapter 5. When setting the remanufacturing environment in the simulation application, fixed value CTs are allocated to each WS.

Stage II Experimentation - 9 Workstations: Inter and Intra Workstation Cycle Time Variability

Results from Stage I experimentation (Chapter 5) indicated that, zero intra-workstation variability relationship existed between workstation cycle time, %Blocking and %Waiting. This relationship is organized in mathematical form, producing two equations, Equation 5 and Equation 6, in section 5.2, that can be used to estimate %Blocking and %Waiting on individual workstations along a flow line.

Here, reality practical remanufacturing operations can have dissimilar cycle times on individual workstations, therefore, the data to be used for Stage III experimental purposes had individual workstation variable CTs. At Stage II experimentation, therefore variability has been introduced in terms of CT and in addition, the number of workstations to be utilized in remanufacturing flow line is varied.

In Stage II experimentation, 9 workstations flow-line have been used with CT variability in middle position of the flow-line; i.e. Fifth WS No. 5, Table 4.4 demonstrates the individual CTs that are used at Stage II experimentation. In the simulation environment, the CT parameter for individual WS are defined as Triangular Distributions with Lower, Upper and Most likely (mode) cycle-time values in minutes. Stage II experiments were designed to examine the effect of individual workstations cycle-time variability and to identify the suitable statistical measure to be used in Stage III experiments, i.e. Pert Mean, Mode, Standard Deviation, Coefficient of Variation, Median, Pert Variance and Skewness, where differing levels of variability between workstations are introduced.

Exp. No.	WORK STATION VARIABILITIES																										
	1			2			3			4			5			6			7			8			9		
	a	t	b	a	t	b	a	t	b	a	t	b	a	t	b	a	t	b	a	t	b	a	t	b	a	t	b
43	0	1	2	0	1	3	0	1	4	0	1	5	0	1	6	0	1	5	0	1	4	0	1	3	0	1	2
44	0	1	6	0	1	5	0	1	4	0	1	3	0	1	2	0	1	3	0	1	4	0	1	5	0	1	6
45	0	1	2	0	1	4	0	1	6	0	1	4	0	1	2	0	1	4	0	1	6	0	1	4	0	1	2
46	0	1	6	0	1	4	0	1	2	0	1	4	0	1	6	0	1	4	0	1	2	0	1	4	0	1	6
47	0	1	2	1	2	3	2	3	4	3	4	5	4	5	6	3	4	5	2	3	4	1	2	3	0	1	2
48	4	5	6	3	4	5	2	3	4	1	2	3	0	1	2	1	2	3	2	3	4	3	4	5	4	5	6
49	0	1	2	2	3	4	4	5	6	2	3	4	0	1	2	2	3	4	4	5	6	2	3	4	0	1	2
50	4	5	6	2	3	4	0	1	2	2	3	4	4	5	6	2	3	4	0	1	2	2	3	4	4	5	6
51	0	1	2	0	2	3	0	3	4	0	4	5	0	5	6	0	4	5	0	3	4	0	2	3	0	1	2
52	0	5	6	0	4	5	0	3	4	0	2	3	0	1	2	0	2	3	0	3	4	0	4	5	0	5	6
53	0	1	2	0	3	4	0	5	6	0	3	4	0	1	2	0	3	4	0	5	6	0	3	4	0	1	2
54	0	5	6	0	3	4	0	1	2	0	3	4	0	5	6	0	3	4	0	1	2	0	3	4	0	5	6
55	0	5	9	1	5	9	2	5	9	3	5	9	4	5	9	3	5	9	2	5	9	1	5	9	0	5	9
56	4	5	9	3	5	9	2	5	9	1	5	9	0	5	9	1	5	9	2	5	9	3	5	9	4	5	9
57	0	1	1	0	1	3	0	1	5	0	1	7	0	1	9	0	1	7	0	1	5	0	1	3	0	1	1
58	7	8	9	6	8	9	5	8	9	4	8	9	3	8	9	4	8	9	5	8	9	6	8	9	7	8	9
59	0	1	9	0	1	1	8	8	9	0	1	9	0	1	1	8	8	9	0	1	9	0	1	1	8	8	9
60	3	6	8	6	9	9	0	9	9	0	6	7	0	7	9	4	5	6	0	5	9	0	4	7	4	8	9
61	2	5	8	0	3	7	6	6	8	4	5	8	4	6	9	0	1	6	2	5	7	0	2	2	0	4	9
62	1	2	7	0	4	7	0	1	2	0	2	4	0	6	7	3	4	6	1	3	8	1	4	5	4	7	9
63	2	3	4	1	3	5	0	3	6	1	3	5	2	3	4	1	3	5	0	3	6	1	3	5	2	3	4
64	0	3	6	1	3	5	2	3	4	1	3	5	0	3	6	1	3	5	2	3	4	1	3	5	0	3	6

Table 4.2 Stage II Experimentation - 9 Workstations: Inter and Intra Workstation Cycle Time Variability

Stage - III Experimentation: Inter and Intra Workstation Variability

In these experiments both the cycle time variability and the cycle time between individual workstations varied. Here, no same cycle time variability defined in any particular workstation but all the cycle time variability are different than each other. The main difference in these experiments is all the cycle time variability is overlapping each other covering certain area of the triangular distribution ranges; which interpreted as the effect of %Blocking or %Waiting being distributed amongst these workstations resulting in the proportion of each workstation waiting or blocking unless they are running to their full efficiency.

Results from Stage II experimentation did not represent a significant differences from Stage I experimentation. However, in Stage II experimentation, number of statistical measures have exhibited various strength of relationship between %Blocking and %Waiting to represent Inter and Intra workstation cycle time variability.

Cycle time variability was grouped according to the relative levels of variability that existed between workstations. If AB and CD represent the range of variability of sequential workstations as shown in Figure 4.2, then the relative values of A, B, C and D used with the experimentation were as follows (Khalil 2005):

Following relationship should be seen in conjunction with Figure 4.2.

- (i) $A < C < B < D$
- (ii) $A < C < B = D$
- (iii) $A < B < C < D$
- (iv) $A = C < B < D$

Exp.No.	Cycle time with Variability in Individual Workstation														
	1			2			3			4			5		
	a	t	b	a	t	b	a	t	b	a	t	b	a	t	b
65	0	6	18	0	6	18	6	8	24	0	6	18	0	6	18
66	0	8	22	0	8	22	8	22	30	0	8	22	0	8	22
67	4	16	20	4	16	20	16	20	40	4	16	20	4	16	20
68	2	5	7	4	7.5	11	6	7.5	21	12	18.5	23	20	22.5	25
69	2	5.5	13	10	12.5	15	6	13.5	21	17	19.5	22	20	25.5	31
70	2	4.5	7	4	11.5	19	6	11.5	17	8	15.5	23	20	22.5	25
71	2	9.5	17	13	15.5	18	8	13.5	19	15	17.5	20	18	23.5	29
72	2	9.5	17	10	15.5	21	17	19.5	22	12	17.5	23	20	22.5	25
73	2	7.5	13	10	12.5	15	11	13.5	16	12	19.5	27	20	25.5	31
74	3	5.5	8	6	11.5	17	9	16.5	24	12	17.5	23	19	21.5	24
75	3	8.5	14	11	13.5	16	9	16.5	24	21	23.5	26	19	24.5	30
76	3	5.5	8	6	13.5	21	11	16.5	22	12	17.5	23	19	21.5	24
77	3	10.5	18	15	17.5	20	11	16.5	22	21	23.5	26	19	24.5	30
78	3	10.5	18	11	16.5	22	18	20.5	23	13	18.5	24	21	23.5	26
79	3	8.5	14	11	13.5	16	18	20.5	23	12	19.5	27	19	24.5	30
80	2	4	7	4	6	11	6	9	21	12	17	23	20	21	25
81	2	8	13	10	11	15	6	10	21	17	18	22	20	27	31
82	2	6	7	4	15	19	6	13	17	8	12	23	20	23	25
83	2	11	17	13	16.5	18	8	17	19	15	19	20	18	21	29
84	2	7	17	10	12	21	17	20	22	12	15	23	20	24	25
85	2	9	13	10	13.5	15	11	12	16	12	22	27	20	27	31
86	2	9	16	6	22	38	7	30	53	22	38	54	43	50	57
87	2	18	34	21	28	35	22	45	68	55	62	69	56	72	88
88	2	9	16	6	29	52	22	38	54	23	39	55	43	50	57
89	2	25	48	45	47	49	22	38	54	41	48	55	43	59	75
90	2	25	48	21	37	53	40	47	54	41	57	73	60	67	74
91	2	18	34	21	28	35	22	29	36	23	46	69	43	59	75
92	2	12	16	6	16	38	7	40	53	22	28	54	43	46	57
93	2	25	34	21	33	35	22	50	68	55	67	69	56	83	88
94	2	5	16	6	20	52	22	32	54	23	45	55	43	54	57
95	2	40	48	45	46	49	22	45	54	41	52	55	43	50	75
96	2	10	48	21	30	53	40	50	54	41	70	73	60	62	74

Table 4.3 Stage - III Experimentation: 5 Workstation - Inter and Intra Workstation variability

Where: **a** = shortest likely time : **t** = most likely time : **b** = longest likely time

At stage III experimentation, most comprehensive set of CT data with different levels of variability have been used. Closely observing the data in Table 4.5 displays variety of different patterns where in majority of the CT value, the Lower CT value remains same

on first WS but the Upper and Most likely CT dramatically changes as different stages of remanufacturing operation takes place (Güngör and Gupta 2001).

Chapter 5 Analytical Results

5.1 Introduction

In chapter four, three stages of experimentation were introduced. Varying designs of flow processing system and simulation models using different levels of cycle time variability to determine the effect of blocking and waiting on workstations.

In this chapter, key results were extracted to identify the relationship between three main variables, e.g. %Blocking, %Waiting, and Workstation cycle time. A number of relationships between these variables were derived that can be used in combination with graphical representation to establish quantitative relationships for estimating individual workstation utilizations.

5.2 Stage I Experimentation: Inter workstation Variability: Zero Intra Workstation Variability

These trials used visual examination of the outputs from simulation models to identify the basic manner in which %Blocking and %Waiting of individual workstations varied and behave along a flow line.

The complete set of results from Stage I simulation experiments listed in Table 4.3 are provided in Table 5.7, Table 5.8 and Appendix 1, where Simulated results that presents %Blocking and %Waiting are those obtained through Simulation package, Simul8 while the estimated results are the one that are obtained through using the equation developed

in this research. Representative results, Table 5.1, from each of the four types of cycle time patterns were selected, and graphically represented in Figures 5.1 to 5.5

Exp. No.	Workstation Cycle Time					% Blocking (Simulation)					% Waiting (Simulation)				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
3	7	2	4	4	7	0.0	0.0	0.0	0.0	0.0	0.0	71.5	43.0	43.2	0.8
11	2	4	4	4	2	49.9	0.0	0.0	0.0	0.0	0.0	0.1	0.3	0.5	50.3
17	4	7	2	2	4	42.8	0.0	0.0	0.0	0.0	0.0	0.2	71.5	71.6	43.2
19	4	2	7	7	4	42.6	71.1	0.0	0.0	0.0	0.0	0.3	0.3	0.6	43.3
20	4	2	2	7	4	42.5	70.9	71.0	0.0	0.0	0.0	0.4	0.4	0.4	43.2

Table 5.1 Results for %Blocking obtained from Simulation for Stage I

As stated in Section 4.2.3, parameters of remanufacturing flow line were defined into simul8 and remanufacturing flow line was designed with individual workstations. The simulation package automatically calculated the results based on the condition defined before running the experiments.

These graphs were then used to establish the relationships between workstation cycle time, %Blocking and %Waiting. The remaining Stage I results provided in Appendix 1 were used to validate the relationships visually identified from Figures 5.1 to 5.5.

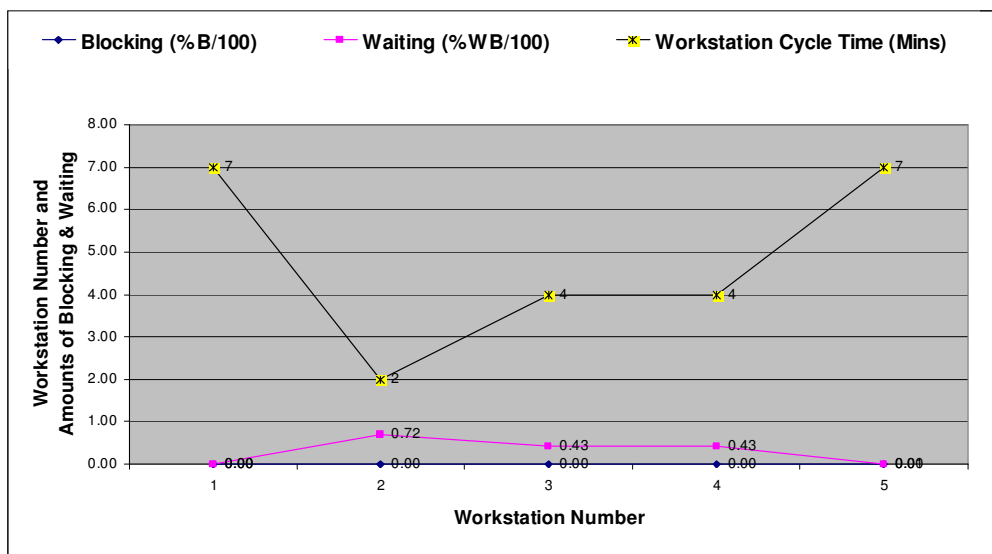


Figure 5.1 Experiment No. 3 Result

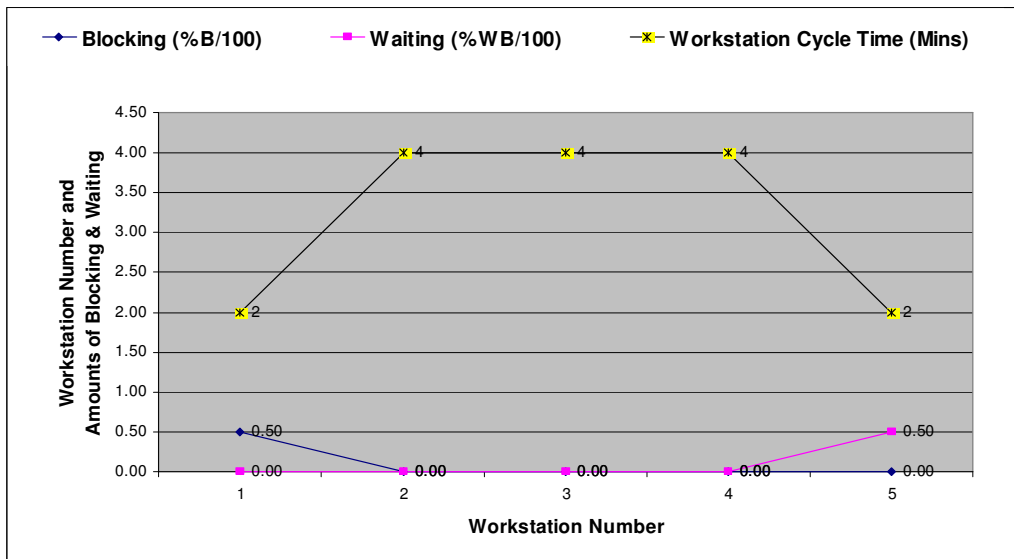


Figure 5.2 Result for Experiment No. 11 Result

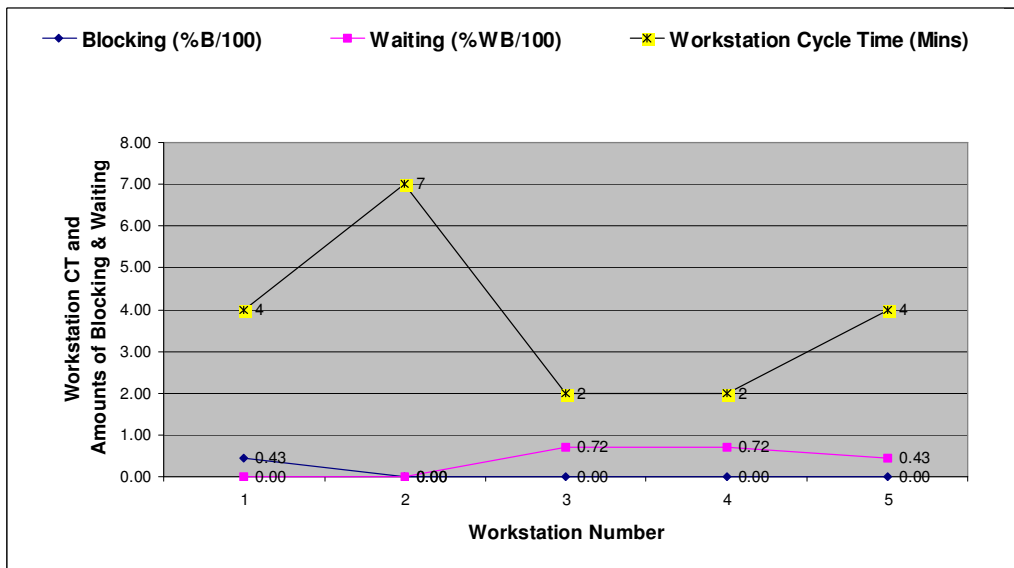


Figure 5.3 Experiment No. 17 Result

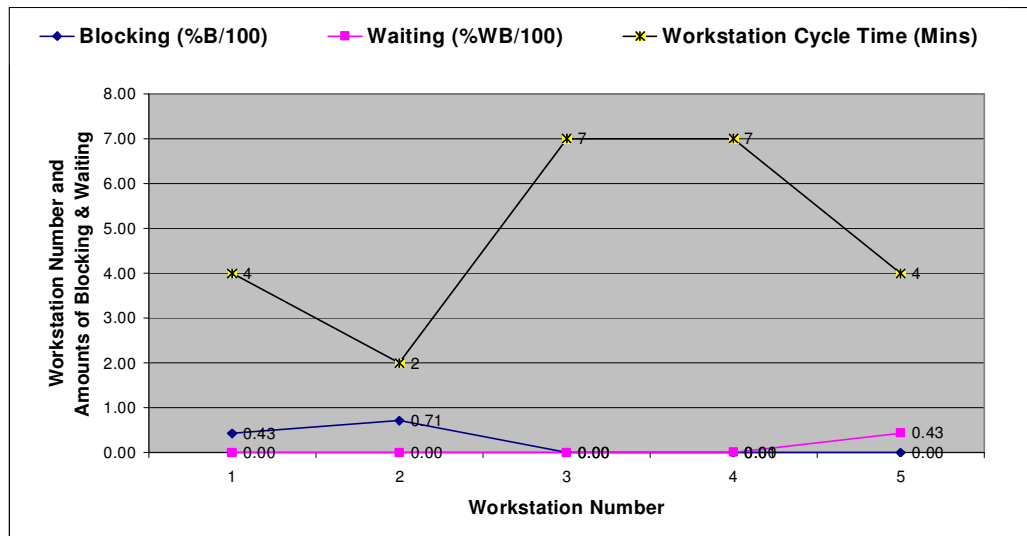


Figure 5.4 Experiment No. 19 Result

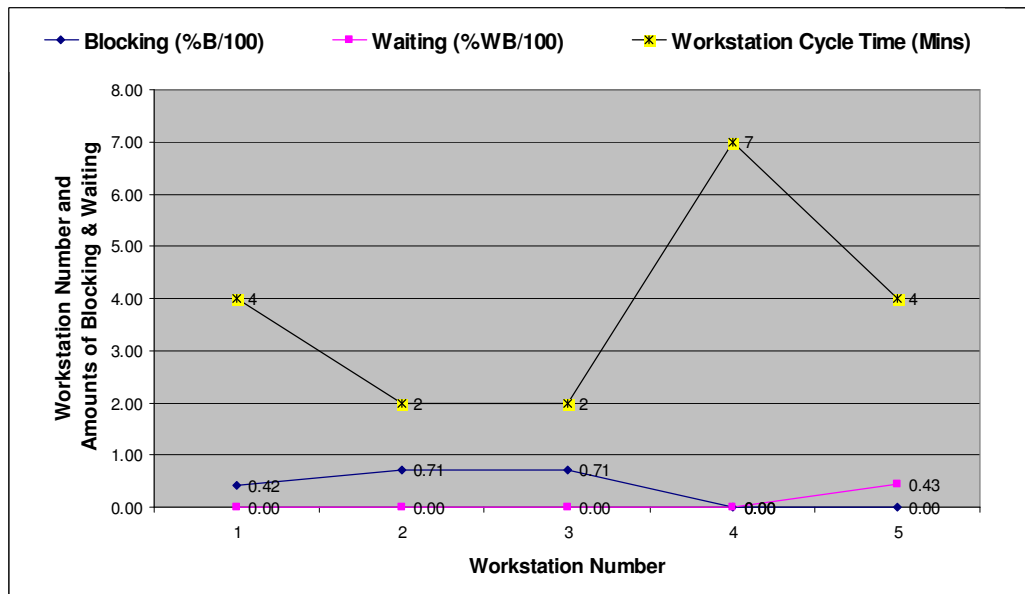


Figure 5.5 Experiment No. 20 Result

Visual examination of Figure 5.1 - 5.5 revealed the following relationships, i.e.

R1:	WS1	always	0% W
R2:	WS1	always	Varying level B
R3:	WS last	always	0% B
R4:	WS last	always	Varying level W

***R1** – First Workstation within a flow line will always have zero %Waiting and varying level of %Blocking.*

***R2** - Last Workstation within a flow line will always have zero %Blocking and varying level of %Waiting.*

***R3** - Workstations upstream of the Workstation with Longest cycle time exhibits varying level of %Blocking.*

***R4** - Workstations Downstream of the Workstation with Longest cycle time exhibits varying level of %Waiting.*

Based on visual examination of Figure 5.1 to Figure 5.5 that present most common results and represents generic patterns across all first stage experiments. It revealed a strong relationship between workstation cycle time, %Blocking and %Waiting. It has also emerged that the Longest cycle time and Shortest cycle time are affecting the process variability in terms of %Blocking and %Waiting. Figures 5.1 to Figures 5.5 also assisted in development of rules R1 to R4. These rules demonstrate the fundamental behaviour of a remanufacturing flow line.

Rule 1 focuses on the first workstation as the visual observation analysis of Figure 5.1 to 5.5 suggest that first workstation will always have no waiting effect. This is because

there is no existence of a preceding workstation before first workstation and so it cannot experience any waiting time.

Rule 2 focuses on the last workstation as the visual observation analysis of Figure 5.1 to 5.5 suggest that last workstation will always have no blocking effect. This is because there is no existence of a succeeding workstation after last workstation and so it cannot experience any blocking time.

Rule 3 focuses on the upstream workstations in conjunction with longest cycle time as the visual observation analysis of Figure 5.1 to 5.5 suggest that workstations upstream of the workstation with Longest cycle time exhibits **varying level of %Blocking effect**. This is because all the preceding workstations before the workstation with longest cycle time cannot be utilised until the workstation with longest cycle time completes its task.

Rule 4 focuses on the downstream workstations in conjunction with longest cycle time as the visual observation analysis of Figure 5.1 to 5.5 suggest that workstations downstream of the workstation with Longest cycle time exhibits **varying level of %Waiting effect**. This is because all the succeeding workstations after the workstation with longest cycle time cannot be utilised as they will be waiting for the workstation with longest cycle time to complete its task.

This observation inspired to randomly combine the cycle time to identify further relationship between three parameters, Workstation Cycle time, %Blocking and

%Waiting, on which bases equations 7 to 10 were developed and tested to investigate the significance.

$$((CT_{i,n} - CT_{k,n}) / (CT_{i,n})) \times 100 \quad (5)$$

$$((CT_{i,n} - CT_{k,n}) / (CT_{i,n})) + ((CT_{i,n} - CT_{k,n+1}) / (CT_{i,n})) \times 100 \quad (6)$$

$$((CT_{i,n} + CT_{k,n}) / (CT_{i,n} - CT_{k,n})) + ((CT_{i,n} - CT_{k,n+1}) / (CT_{i,n} - CT_{k,n})) \times 100 \quad (7)$$

$$((CT_{i,n} - CT_{k,n}) / (CT_{k,n})) + ((CT_{i,n} - CT_{k,n+1}) / (CT_{k,n})) \times 100 \quad (8)$$

Where:

$CT_{i,n}$ = Longest cycle time in flow line

$CT_{k,n}$ = Individual WS cycle time to be estimated

k = Position of workstation

n = Number of workstation

Visual observation and rules development concluded the Longest cycle time (CT_{max}) as the key driver and controlling factor to estimate the %Blocking and %Waiting on individual workstation within a flow line. As a result, Equations 5 and 6 are developed based on the observation supported by rules 1 to 4.

$$\%W_{i,j} = \frac{CT_{max\ i,j} - CT_{i,j}}{CT_{max\ i,j}} \quad (9)$$

If Longest cycle time is on the Left side of the actual workstation

Where,

W_{i,j} = % Waiting on actual workstation

CT_{max i,j} = Longest cycle time within flow line

CT_{i,j} = Cycle time on the workstation to be estimated (actual workstation)

i = Position of the workstation

j = Number of workstation

$$\%B_{i,j} = \frac{CT_{max\ i,j} - CT_{i,j}}{CT_{max\ i,j}} \quad (10)$$

If Longest cycle time is on the Right side of the actual workstation

Where,

B_{i,j} = % Blocking on actual workstation

CT_{max i,j} = Longest cycle time within flow line

CT_{i,j} = Cycle time on the workstation to be estimated (actual workstation)

i = Position of the workstation

j = Number of workstation

Experiment No. 3			
WS	% B (Sim)	% B (Est)	% B (Err)
1	0.0	0.0	0.0
2	0.0	50.0	-50.0
3	0.0	0.0	0.0
4	0.0	42.9	-42.9
5	0.0	0.0	0.0

Experiment No. 3			
WS	% W (Sim)	% W (Est)	% W (Err)
1	0.0	0.0	0.0
2	71.5	71.4	0.1
3	43.0	42.9	0.2
4	43.2	42.9	0.3
5	0.8	0.0	0.8

Table 5.2 Results for Experiment 3 showing Simulated and Estimated %B and %W using equations 5 and 6

From graphical representation, one of the most obvious pattern identified in all results is, “if longest cycle time is followed by shortest cycle time, then, the workstation with shortest CT will always have relatively high %Waiting effect. This can be seen in Experiment No 3, in Table 5.2. The Longest cycle time is in the first position of the flow line (Table 5.1) and according to Equation 5, if the Longest cycle time is to the Left side of the Actual workstation, the resulting variability will be %Waiting; the equation is still valid however it is not programmed in the Excel with all the conditions therefor it is unable to determine the position of Longest cycle time which as a result produces large error. Table 5.7 and Table 5.8 present results for Experiments 1 to 21.

Experiment No. 11			
WS	% B (Sim)	% B (Est)	% B (Err)
1	49.9	50.0	-0.1
2	0.0	0.0	0.0
3	0.0	0.0	0.0
4	0.0	0.0	0.0
5	0.0	0.0	0.0

Experiment No. 11			
WS	% W (Sim)	% W (Est)	% W (Err)
1	0.0	0.0	0.0
2	0.1	0.0	0.1
3	0.3	0.0	0.3
4	0.5	0.0	0.5
5	50.3	50.0	0.3

Table 5.3 Results for Experiment 11 showing Simulated and Estimated %B and %W using equations 5 and 6

Experiment No. 17			
WS	% B (Sim)	% B (Est)	% B (Err)
1	42.8	42.9	-0.1
2	74.8	0.0	74.8
3	24.9	0.0	24.9
4	24.9	50.0	-25.1
5	0.0	0.0	0.0

Experiment No. 17			
WS	% W (Sim)	% W (Est)	% W (Err)
1	0.0	0.0	0.0
2	0.2	0.0	0.2
3	71.5	71.4	0.1
4	71.6	71.4	0.2
5	43.2	42.9	0.3

Table 5.4 Results for Experiment 17 showing Simulated and Estimated %B and %W using equations 5 and 6

Experiment No. 19			
WS	% B (Sim)	% B (Est)	% B (Err)
1	42.6	42.9	-0.2
2	71.1	71.4	-0.3
3	0.0	0.0	0.0
4	0.0	0.0	0.0
5	0.0	0.0	0.0

Experiment No. 19			
WS	% W (Sim)	% W (Est)	% W (Err)
1	0.0	0.0	0.0
2	0.3	50.0	-49.7
3	0.3	0.0	0.3
4	0.6	0.0	0.6
5	43.3	42.9	0.5

Table 5.5 Results for Experiment 19 showing Simulated and Estimated %B and %W using equations 5 and 6

Experiment No. 20			
WS	% B (Sim)	% B (Est)	% B (Err)
1	42.5	42.9	-0.4
2	70.9	71.4	-0.5
3	71.0	71.4	-0.4
4	0.0	0.0	0.0
5	0.0	0.0	0.0

Experiment No. 20			
WS	%W (Sim)	%W (Est)	%W (Err)
1	0.0	0.0	0.0
2	0.4	50.0	-49.6
3	0.4	50.0	-49.6
4	0.4	0.0	0.4
5	43.2	42.9	0.3

Table 5.6 Results for Experiment 20 showing Simulated and Estimated %B and %W using equations 5 and 6

Equations 5 and 6 were used to estimate % Blocking and % Waiting of all remaining Stage I experiments with the results being shown in Table 5.7, Table 5.8 and Appendix 1. The values estimated for %Blocking and %Waiting using Equation 5 and Equation 6 are in close agreement with those values obtained from the simulation models. Mean errors that ranged between 0.0 % and -0.5%.

In number of experiments, larger errors have been noted because of the programming restriction on Excel to determine the position of longest cycle time. For example, Experiments 16, 17 and 18 for their % Blocking.

Exp. No.	Workstation Cycle Time					Workstation % Blocking					Estimated % Blocking					% Error				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
1	7	2	2	2	7	0.0	0.0	0.0	0.0	0.0	0.0	71.4	71.4	71.4	0.0	0.0	-71.4	-71.4	-71.4	0.0
2	7	2	2	4	7	0.0	0.0	0.0	0.0	0.0	0.0	71.4	71.4	42.9	0.0	0.0	-71.4	-71.4	-42.9	0.0
3	7	2	4	4	7	0.0	0.0	0.0	0.0	0.0	0.0	71.4	42.9	42.9	0.0	0.0	-71.4	-42.9	-42.9	0.0
4	7	4	4	4	7	0.0	0.0	0.0	0.0	0.0	0.0	42.9	42.9	42.9	0.0	0.0	-42.9	-42.9	-42.9	0.0
5	7	4	2	2	7	0.0	0.0	0.0	0.0	0.0	0.0	42.9	71.4	71.4	0.0	0.0	-42.9	-71.4	-71.4	0.0
6	7	4	4	2	7	0.0	0.0	0.0	0.0	0.0	0.0	42.9	42.9	71.4	0.0	0.0	-42.9	-42.9	-71.4	0.0
7	7	4	2	4	7	0.0	0.0	0.0	0.0	0.0	0.0	42.9	71.4	42.9	0.0	0.0	-42.9	-71.4	-42.9	0.0
8	2	7	7	7	2	71.3	0.0	0.0	0.0	0.0	71.4	0.0	0.0	0.0	0.0	-0.1	0.0	0.0	0.0	0.0
9	2	7	7	4	2	71.3	0.0	0.0	0.0	0.0	71.4	0.0	0.0	0.0	0.0	-0.1	0.0	0.0	0.0	0.0
10	2	7	4	4	2	71.3	0.0	0.0	0.0	0.0	71.4	0.0	0.0	0.0	0.0	-0.1	0.0	0.0	0.0	0.0
11	2	4	4	4	2	49.9	0.0	0.0	0.0	0.0	50.0	0.0	0.0	0.0	0.0	-0.1	0.0	0.0	0.0	0.0
12	2	4	7	7	2	71.3	42.7	0.0	0.0	0.0	71.4	42.9	0.0	0.0	0.0	-0.1	-0.1	0.0	0.0	0.0
13	2	4	4	7	2	71.2	42.6	42.6	0.0	0.0	71.4	42.9	42.9	0.0	0.0	-0.2	-0.2	-0.2	0.0	0.0
14	2	4	7	4	2	71.3	42.7	0.0	0.0	0.0	71.4	42.9	0.0	0.0	0.0	-0.1	-0.1	0.0	0.0	0.0
15	4	7	7	7	4	42.8	0.0	0.0	0.0	0.0	42.9	0.0	0.0	0.0	0.0	-0.1	0.0	0.0	0.0	0.0
16	4	7	7	2	4	42.8	0.0	0.0	0.0	0.0	42.9	0.0	0.0	50.0	0.0	-0.1	0.0	0.0	-50.0	0.0
17	4	7	2	2	4	42.8	0.0	0.0	0.0	0.0	42.9	0.0	50.0	50.0	0.0	-0.1	0.0	-50.0	-50.0	0.0
18	4	2	2	2	4	0.0	0.0	0.0	0.0	0.0	0.0	50.0	50.0	50.0	0.0	0.0	-50.0	-50.0	-50.0	0.0
19	4	2	7	7	4	42.6	71.1	0.0	0.0	0.0	42.9	71.4	0.0	0.0	0.0	-0.2	-0.3	0.0	0.0	0.0
20	4	2	2	7	4	42.5	70.9	71.0	0.0	0.0	42.9	71.4	71.4	0.0	1.0	-0.4	-0.5	-0.4	0.0	-1.0
21	4	2	7	2	4	42.6	71.1	0.0	0.0	0.0	42.9	71.4	0.0	50.0	0.0	-0.2	-0.3	0.0	-50.0	0.0

Table 5.7 %Blocking Estimated using Equation 8 compared to Simulation results with Mean %Error

Exp. No.	Workstation Cycle Time					Workstation % Waiting					Estimated % Waiting					% Error				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
1	7	2	2	2	7	0.0	71.5	71.5	71.5	0.6	0.0	71.4	71.4	71.4	0.0	0.0	0.1	0.1	0.1	0.6
2	7	2	2	4	7	0.0	71.5	71.5	43.1	0.7	0.0	71.4	71.4	42.9	0.0	0.0	0.1	0.1	0.3	0.7
3	7	2	4	4	7	0.0	71.5	43.0	43.2	0.8	0.0	71.4	42.9	42.9	0.0	0.0	0.1	0.2	0.3	0.8
4	7	4	4	4	7	0.0	43.0	43.1	43.2	0.8	0.0	42.9	42.9	42.9	0.0	0.0	0.1	0.3	0.3	0.8
5	7	4	2	2	7	0.0	43.0	71.5	71.6	0.7	0.0	42.9	71.4	71.4	0.0	0.0	0.1	0.1	0.2	0.7
6	7	4	4	2	7	0.0	43.0	43.1	71.6	0.8	0.0	42.9	42.9	71.4	0.0	0.0	0.1	0.3	0.2	0.8
7	7	4	2	4	7	0.0	43.0	71.5	43.2	0.8	0.0	42.9	71.4	42.9	0.0	0.0	0.1	0.1	0.3	0.8
8	2	7	7	7	2	0.0	0.1	0.4	0.7	71.7	0.0	0.0	0.0	0.0	71.4	0.0	0.1	0.4	0.7	0.2
9	2	7	7	4	2	0.0	0.1	0.4	43.1	71.7	0.0	0.0	0.0	42.9	71.4	0.0	0.1	0.4	0.3	0.2
10	2	7	4	4	2	0.0	0.1	43.0	43.2	71.6	0.0	0.0	42.9	42.9	71.4	0.0	0.1	0.2	0.3	0.2
11	2	4	4	4	2	0.0	0.1	0.3	0.5	50.3	0.0	0.0	0.0	0.0	50.0	0.0	0.1	0.3	0.5	0.3
12	2	4	7	7	2	0.0	0.1	0.3	0.6	71.7	0.0	0.0	0.0	0.0	71.4	0.0	0.1	0.3	0.6	0.2
13	2	4	4	7	2	0.0	0.1	0.3	0.5	71.6	0.0	0.0	0.0	0.0	71.4	0.0	0.1	0.3	0.5	0.2
14	2	4	7	4	2	0.0	0.1	0.3	43.2	71.6	0.0	0.0	0.0	42.9	71.4	0.0	0.1	0.3	0.3	0.2
15	4	7	7	7	4	0.0	0.2	0.5	0.8	43.5	0.0	0.0	0.0	0.0	42.9	0.0	0.2	0.5	0.8	0.6
16	4	7	7	2	4	0.0	0.2	0.5	71.6	43.3	0.0	0.0	0.0	71.4	42.9	0.0	0.2	0.5	0.2	0.5
17	4	7	2	2	4	0.0	0.2	71.5	71.6	43.2	0.0	0.0	71.4	71.4	42.9	0.0	0.2	0.1	0.2	0.3
18	4	2	2	2	4	0.0	50.1	50.1	50.2	0.5	0.0	50.0	50.0	50.0	0.0	0.0	0.1	0.1	0.2	0.5
19	4	2	7	7	4	0.0	0.3	0.3	0.6	43.3	0.0	50.0	0.0	0.0	42.9	0.0	-49.7	0.3	0.6	0.5
20	4	2	2	7	4	0.0	0.4	0.4	0.4	43.2	0.0	50.0	50.0	0.0	42.9	0.0	-49.6	-49.6	0.4	0.3
21	4	2	7	2	4	0.0	0.3	0.3	71.6	43.2	1.0	50.0	0.0	71.4	42.9	-1.0	-49.7	0.3	0.2	0.3

Table 5.8 % Waiting Estimated using Equation 8 compared to Simulation results with Mean %Error

5.3 Stage II Experimentation: Inter and intra workstation Variability

Stage I experimentation identified the basic relationships between three variables, %Blocking, %Waiting, and Workstation Cycle Time. In order to obtain more realistic outcomes, stage II experimentation examines the effect of variable CTs. Three ranges of CT have been used to undertake simulation studies, Higher, Most likely and Lower range of a WS cycle time in a triangular distribution form. Also the number of WSs has been increased to nine, where in previous trials in stage I, five WS flow lines were simulated.

Statistics is the discipline of data management in terms of collecting, organising and representing data in logical format in the form of charts or diagrams to identify relationships between variables. Statistical measures are set of parameters that assist in data analysis process to derive logical solution to a problem. Within Stage II experimentation, various statistical measures were introduced to identify one suitable statistical measure that enables estimation of %Blocking and %Waiting with higher accuracy on individual workstations. Once, this statistical measure is identified, it will be used in further experiments. Using this statistical measure, cycle time with three levels (Longest-Most likely-Shortest) will be reduced to one single level. This is because the cycle times are in triangular distribution format; and the most effective statistical measure will be used to perform correlation analysis. The correlation analysis identifies a suitable statistical measure that shows stronger relationship between workstation cycle time, %Blocking and %Waiting.

In the correlation analysis, the closer the value of the correlation coefficient to either +1 or -1 the greater the possibility that strong positive or negative relationships exists between them and hence, their ability for estimating levels of blocking and waiting.

Results from the simulation experiments listed in Table 4.4 are shown in Appendix 2. For each of the variability categories, nine workstation flow lines were modelled and simulated in which first four and last four workstations in the flow line possessed the same levels of variability whilst the 5th workstation possessed a different level of variability. Correlation coefficients were used to compare the actual workstation %Blocking and %Waiting levels arising from the simulation models with the Pert Variance, Skewness, Pert mean, Median, Standard Deviation, and the Coefficient of Variation of the workstation cycle time variability. The reason these statistical parameters are used because they are the most common ones primarily used in the industrial project management and academic research. The summary results of these comparisons are shown in Table 5.9 whilst the detail individual statistical results are shown in Fig 5.10 to Fig 5.16.

Figure	Statistical Measure	Minimum	Average	Maximum
5.10	Pert Mean	-0.82	-0.18	+0.6
5.11	Mode	-0.79	-0.18	+0.58
5.12	Standard Deviation	-0.54	-0.05	+0.68
5.13	Coefficient of Variation	-0.35	+0.14	+0.54
5.14	Median	-0.82	-0.18	+0.61
5.15	Pert variance	-0.48	0.05	+0.61
5.16	Skewness	-0.48	0.05	+0.61

Table 5.9 Identification of most suitable statistical measure to be used for further experimentation

Table 5.4 shows the correlation analysis for Pert Mean. This is one of the strongly related statistical measures and is correlated with both %Blocking and %Waiting. In Table 5.6, the summary of Min, Max and Average of the all workstations which represents the strength of the relationship. The closest value identified for this particular analysis was -0.82(Min), 0.60(Max) and -0.18(Average); as it is mentioned earlier, that if either value comes closer to +1 or -1, which represents variable relationship in terms of strong positive or negative relationship, then the statistical measure that is being tested would be most suitable to be used for further analysis.

PERT MEAN									PERT MEAN	
1	2	3	4	5	6	7	8	9	MIN	MAX
1.00	1.17	1.33	1.50	1.67	1.50	1.33	1.17	1.00	1.00	1.67
1.67	1.50	1.33	1.17	1.00	1.17	1.33	1.50	1.67	1.00	1.67
1.00	1.33	1.67	1.33	1.00	1.33	1.67	1.33	1.00	1.00	1.67
1.67	1.33	1.00	1.33	1.67	1.33	1.00	1.33	1.67	1.00	1.67
1.00	2.00	3.00	4.00	5.00	4.00	3.00	2.00	1.00	1.00	5.00
5.00	4.00	3.00	2.00	1.00	2.00	3.00	4.00	5.00	1.00	5.00
1.00	3.00	5.00	3.00	1.00	3.00	5.00	3.00	1.00	1.00	5.00
5.00	3.00	1.00	3.00	5.00	3.00	1.00	3.00	5.00	1.00	5.00
1.00	1.83	2.67	3.50	4.33	3.50	2.67	1.83	1.00	1.00	4.33
4.33	3.50	2.67	1.83	1.00	1.83	2.67	3.50	4.33	1.00	4.33
1.00	2.67	4.33	2.67	1.00	2.67	4.33	2.67	1.00	1.00	4.33
4.33	2.67	1.00	2.67	4.33	2.67	1.00	2.67	4.33	1.00	4.33
4.83	5.00	5.17	5.33	5.50	5.33	5.17	5.00	4.83	4.83	5.50
5.50	5.33	5.17	5.00	4.83	5.00	5.17	5.33	5.50	4.83	5.50
0.83	1.17	1.50	1.83	2.17	1.83	1.50	1.17	0.83	0.83	2.17
8.00	7.83	7.67	7.50	7.33	7.50	7.67	7.83	8.00	7.33	8.00
2.17	0.83	8.17	2.17	0.83	8.17	2.17	0.83	8.17	0.83	8.17
5.83	8.50	7.50	5.17	6.17	5.00	4.83	3.83	7.50	3.83	8.50
5.00	3.17	6.33	5.33	6.17	1.67	4.83	1.67	4.17	1.67	6.33
2.67	3.83	1.00	2.00	5.17	4.17	3.50	3.67	6.83	1.00	6.83
3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00

	WS	Work station Cycle Time PERT MEAN Correlation Values									PERT MEAN		POSITION	
	No.	1	2	3	4	5	6	7	8	9	MIN	MAX		
%Blocking	1	-0.82	-0.49	-0.06	-0.27	-0.30	-0.07	-0.12	-0.54	-0.58	-0.43	-0.20	MIN	-0.82
	2	-0.67	-0.63	0.04	-0.25	-0.22	0.10	-0.23	-0.64	-0.30	-0.46	-0.05	MAX	0.60
	3	-0.28	-0.32	-0.72	-0.32	0.19	-0.21	-0.50	-0.23	-0.18	-0.33	-0.28	Average	-0.18
	4	-0.22	-0.25	-0.77	-0.42	0.07	-0.33	-0.46	-0.14	-0.13	-0.35	-0.29		
	5	-0.29	-0.20	0.06	-0.46	-0.72	-0.04	0.01	-0.06	-0.04	-0.29	-0.05		
	6	-0.11	-0.02	-0.22	-0.42	-0.56	-0.38	0.04	0.12	-0.14	-0.21	-0.22		
	7	0.17	0.02	-0.47	-0.43	-0.23	-0.31	-0.28	0.14	0.18	-0.17	-0.17		
	8	0.15	-0.05	-0.03	-0.31	-0.08	0.28	-0.31	-0.09	0.60	-0.23	0.34		
	9													
%Waiting		Zero % Blocking												
	1	-0.42	-0.35	-0.27	-0.18	-0.08	-0.20	-0.28	-0.35	-0.43	-0.23	-0.33		
	2	0.30	-0.06	-0.45	-0.28	-0.13	-0.33	-0.46	0.04	0.10	-0.21	-0.20		
	3	0.38	0.19	-0.25	-0.25	-0.18	-0.31	-0.30	0.13	0.20	-0.11	-0.09		
	4	0.03	0.05	0.42	-0.23	-0.52	0.15	0.02	-0.11	0.28	-0.17	0.27		
	5	-0.08	-0.03	0.35	-0.29	-0.60	0.04	-0.02	-0.17	0.12	-0.19	0.11		
	6	0.13	-0.06	-0.14	0.11	0.34	-0.40	-0.26	-0.33	-0.13	-0.19	-0.09		
	7	-0.12	-0.34	-0.11	-0.09	0.14	0.06	-0.53	-0.49	0.00	-0.31	0.01		
	8	-0.50	-0.39	0.11	0.02	-0.01	-0.18	-0.08	-0.58	-0.50	-0.32	-0.13		
9	-0.61	-0.45	-0.25	-0.15	-0.16	-0.37	-0.20	-0.46	-0.74	-0.29	-0.48			

Table 5.10 Results for Stage II Experimentation: Inter and intra workstation Variability - Pert Mean of Cycle time Correlated with % B and % W

The 'Pert Mean' was correlated with %Blocking and %Waiting in Table 5.10. The decisive value, that helps make decision of whether the correlated variables have stronger or weaker relationship, came to (Min: -0.82, Max: +0.60, Average: -0.18). Therefore this stats measure will also not be used for further analysis.

MODE									MODE	
1	2	3	4	5	6	7	8	9	MIN	MAX
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1.00	2.00	3.00	4.00	5.00	4.00	3.00	2.00	1.00	1.00	5.00
5.00	4.00	3.00	2.00	1.00	2.00	3.00	4.00	5.00	1.00	5.00
1.00	3.00	5.00	3.00	1.00	3.00	5.00	3.00	1.00	1.00	5.00
5.00	3.00	1.00	3.00	5.00	3.00	1.00	3.00	5.00	1.00	5.00
1.00	2.00	3.00	4.00	5.00	4.00	3.00	2.00	1.00	1.00	5.00
5.00	4.00	3.00	2.00	1.00	2.00	3.00	4.00	5.00	1.00	5.00
1.00	3.00	5.00	3.00	1.00	3.00	5.00	3.00	1.00	1.00	5.00
5.00	3.00	1.00	3.00	5.00	3.00	1.00	3.00	5.00	1.00	5.00
5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
1.00	1.00	8.00	1.00	1.00	8.00	1.00	1.00	8.00	1.00	8.00
6.00	9.00	9.00	6.00	7.00	5.00	5.00	4.00	8.00	4.00	9.00
5.00	3.00	6.00	5.00	6.00	1.00	5.00	2.00	4.00	1.00	6.00
2.00	4.00	1.00	2.00	6.00	4.00	3.00	4.00	7.00	1.00	7.00
3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00

	WS No.	Work station Cycle Time MODE Correlation Values									MODE		POSITION	
		1	2	3	4	5	6	7	8	9	MIN	MAX		
%Blocking	1	-0.79	-0.47	-0.08	-0.30	-0.32	-0.11	-0.16	-0.53	-0.56	-0.41	-0.21	MIN	-0.79
	2	-0.70	-0.61	-0.03	-0.36	-0.25	0.03	-0.31	-0.61	-0.30	-0.45	-0.09	MAX	0.58
	3	-0.27	-0.31	-0.70	-0.30	0.16	-0.23	-0.48	-0.22	-0.16	-0.31	-0.27	Aver	-0.18
	4	-0.22	-0.25	-0.75	-0.37	0.06	-0.33	-0.45	-0.14	-0.12	-0.34	-0.28		
	5	-0.33	-0.19	0.03	-0.45	-0.64	-0.03	-0.04	-0.07	-0.06	-0.26	-0.04		
	6	-0.11	-0.03	-0.22	-0.34	-0.49	-0.34	0.05	0.10	-0.15	-0.20	-0.19		
	7	0.14	0.02	-0.43	-0.34	-0.17	-0.27	-0.25	0.13	0.17	-0.16	-0.13		
	8	0.04	-0.02	-0.02	-0.32	-0.01	0.27	-0.37	-0.06	0.58	-0.21	0.33		
	9	Zero % Blocking												
%Waiting	1	-0.37	-0.35	-0.30	-0.25	-0.19	-0.26	-0.30	-0.37	-0.40	-0.21	-0.39		
	2	0.32	-0.06	-0.42	-0.22	-0.11	-0.27	-0.38	0.04	0.11	-0.21	-0.15		
	3	0.40	0.19	-0.19	-0.14	-0.14	-0.25	-0.22	0.12	0.21	-0.10	-0.03		
	4	-0.01	0.09	0.44	-0.22	-0.43	0.15	-0.02	-0.08	0.28	-0.16	0.28		
	5	-0.10	0.01	0.36	-0.28	-0.53	0.04	-0.04	-0.14	0.13	-0.18	0.13		
	6	0.19	-0.07	-0.13	0.10	0.26	-0.43	-0.19	-0.30	-0.10	-0.24	-0.10		
	7	-0.11	-0.32	-0.11	-0.15	0.09	0.02	-0.53	-0.47	0.01	-0.30	-0.01		
	8	-0.45	-0.38	0.07	-0.05	-0.08	-0.23	-0.09	-0.56	-0.48	-0.34	-0.16		
	9	-0.53	-0.45	-0.27	-0.17	-0.23	-0.38	-0.16	-0.47	-0.72	-0.29	-0.47		

Table 5.11 Results for Stage II Experimentation: Inter and intra workstation Variability - Mode of Cycle time Correlated with % B and % W

The 'Mode' was correlated with %Blocking and %Waiting in Table 5.11. It did not represent stronger relationship than 'Pert Mean'. The decisive value, that helps make decision, whether the correlated variables have stronger or weaker relationship, came to (Min: -79, Max: +0.58, Average: -0.18). Therefore this statistical measure will not be used for further analysis.

STANDARD DEVIATION									STD DEV	
1	2	3	4	5	6	7	8	9	MIN	MAX
0.41	0.62	0.85	1.08	1.31	1.08	0.85	0.62	0.41	0.41	1.31
1.31	1.08	0.85	0.62	0.41	0.62	0.85	1.08	1.31	0.41	1.31
0.41	0.85	1.31	0.85	0.41	0.85	1.31	0.85	0.41	0.41	1.31
1.31	0.85	0.41	0.85	1.31	0.85	0.41	0.85	1.31	0.41	1.31
0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41
0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41
0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41
0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41
0.41	0.62	0.85	1.08	1.31	1.08	0.85	0.62	0.41	0.41	1.31
1.31	1.08	0.85	0.62	0.41	0.62	0.85	1.08	1.31	0.41	1.31
0.41	0.85	1.31	0.85	0.41	0.85	1.31	0.85	0.41	0.41	1.31
1.31	0.85	0.41	0.85	1.31	0.85	0.41	0.85	1.31	0.41	1.31
1.63	1.43	1.25	1.25	1.08	1.25	1.43	1.63	1.84	1.08	1.84
1.08	1.25	1.43	1.63	1.84	1.63	1.43	1.25	1.08	1.08	1.84
0.24	0.62	1.08	1.55	2.01	1.55	1.08	0.62	0.24	0.24	2.01
0.41	0.62	0.85	1.08	1.31	1.08	0.85	0.62	0.41	0.41	1.31
2.01	0.24	0.24	2.01	0.24	0.24	2.01	0.24	0.24	0.24	2.01
1.03	0.71	2.12	1.55	1.93	0.41	1.84	1.43	1.08	0.41	2.12
1.22	1.43	0.47	0.85	1.03	1.31	1.03	0.47	1.84	0.47	1.84
1.31	1.43	0.41	0.82	1.55	0.62	1.47	0.85	1.03	0.41	1.55
0.41	0.82	1.22	0.82	0.41	0.82	1.22	0.82	0.41	0.41	1.22
1.22	0.82	0.41	0.82	1.22	0.82	0.41	0.82	1.22	0.41	1.22

	WS	Workstation Cycle time STANDARD DEVIATION Correlation Values									STANDARD DEVIATION		POSITION	
	No.	1	2	3	4	5	6	7	8	9	MIN	MAX		
%Blocking	1	-0.31	-0.24	0.06	0.15	-0.02	0.04	0.19	-0.25	-0.45	-0.26	0.05	MIN	-0.54
	2	0.01	-0.20	-0.25	0.35	-0.06	0.08	0.29	-0.48	-0.35	-0.31	0.23	MAX	0.68
	3	-0.12	0.09	-0.27	-0.12	0.37	0.13	-0.22	-0.09	-0.07	-0.13	-0.08	Aver.	-0.05
	4	-0.09	0.18	-0.31	-0.25	0.34	0.06	-0.28	-0.06	0.01	-0.15	-0.14		
	5	0.02	-0.19	-0.17	-0.12	-0.47	-0.38	0.09	-0.21	-0.31	-0.20	-0.21		
	6	-0.10	0.16	-0.03	-0.47	-0.38	-0.24	-0.13	0.08	-0.01	-0.04	-0.33		
	7	0.32	0.33	-0.21	-0.36	-0.08	-0.23	-0.21	0.25	0.35	-0.01	-0.14		
	8	0.68	0.02	-0.38	0.17	-0.08	-0.51	0.24	-0.04	0.17	-0.20	0.16		
	9													
%Waiting	1	-0.41	-0.28	0.01	0.13	0.27	0.27	-0.12	-0.25	-0.36	-0.23	0.02		
	2	0.16	-0.05	-0.35	-0.43	-0.21	-0.26	-0.54	0.00	0.24	-0.03	-0.39		
	3	0.19	0.00	0.00	-0.32	-0.14	-0.35	-0.30	0.25	0.29	-0.03	-0.22		
	4	0.33	-0.22	0.14	0.19	-0.43	-0.53	0.39	0.02	-0.07	-0.21	0.13		
	5	0.25	-0.13	0.28	0.25	-0.38	-0.34	0.45	0.11	-0.09	-0.18	0.23		
	6	0.00	0.15	0.01	-0.02	0.32	0.27	-0.20	-0.02	0.37	-0.08	0.18		
	7	0.05	-0.40	-0.19	0.31	0.16	-0.02	-0.03	-0.32	-0.16	-0.25	0.13		
	8	-0.31	-0.17	0.09	0.21	0.10	0.27	0.11	-0.32	-0.22	-0.22	0.18		
	9	-0.51	-0.09	0.24	0.02	0.07	0.39	-0.03	-0.09	-0.30	-0.10	0.03		

Table 5.12 Results for Stage II Experimentation: Inter and intra workstation Variability - Standard Deviation of Cycle time Correlated with % B and % W

The 'Standard Deviation' was correlated with %B and %W in Table 5.12. It did not represented stronger relationship than 'Pert Mean' or 'Mode'. The decisive value, that helps make decision of whether the correlated variables have stronger or weaker relationship, came to (Min: -54, Max: +0.68, Average: -0.05). Therefore this stats measure will also not be used for further analysis.

COEFFICIENT OF VARIATION									C of V	
1	2	3	4	5	6	7	8	9	MIN	MAX
0.41	0.53	0.64	0.72	0.79	0.72	0.64	0.53	0.41	0.41	0.79
0.79	0.72	0.64	0.53	0.41	0.53	0.64	0.72	0.79	0.41	0.79
0.41	0.64	0.79	0.64	0.41	0.64	0.79	0.64	0.41	0.41	0.79
0.79	0.64	0.41	0.64	0.79	0.64	0.41	0.64	0.79	0.41	0.79
0.41	0.20	0.14	0.10	0.08	0.10	0.14	0.20	0.41	0.08	0.41
0.08	0.10	0.14	0.20	0.41	0.20	0.14	0.10	0.08	0.08	0.41
0.41	0.14	0.08	0.14	0.41	0.14	0.08	0.14	0.41	0.08	0.41
0.08	0.14	0.41	0.14	0.08	0.14	0.41	0.14	0.08	0.08	0.41
0.41	0.34	0.32	0.31	0.30	0.31	0.32	0.34	0.41	0.30	0.41
0.30	0.31	0.32	0.34	0.41	0.34	0.32	0.31	0.30	0.30	0.41
0.41	0.32	0.30	0.32	0.41	0.32	0.30	0.32	0.41	0.30	0.41
0.30	0.32	0.41	0.32	0.30	0.32	0.41	0.32	0.30	0.30	0.41
0.34	0.29	0.24	0.23	0.20	0.23	0.28	0.33	0.38	0.20	0.38
0.20	0.23	0.28	0.33	0.38	0.33	0.28	0.23	0.20	0.20	0.38
0.28	0.53	0.72	0.84	0.93	0.84	0.72	0.53	0.28	0.28	0.93
0.05	0.08	0.11	0.14	0.18	0.14	0.11	0.08	0.05	0.05	0.18
0.93	0.28	0.03	0.93	0.28	0.03	0.93	0.28	0.03	0.03	0.93
0.18	0.08	0.28	0.30	0.31	0.08	0.38	0.37	0.14	0.08	0.38
0.24	0.45	0.07	0.16	0.17	0.79	0.21	0.28	0.44	0.07	0.79
0.49	0.37	0.41	0.41	0.30	0.15	0.42	0.23	0.15	0.15	0.49
0.14	0.27	0.41	0.27	0.14	0.27	0.41	0.27	0.14	0.14	0.41
0.41	0.27	0.14	0.27	0.41	0.27	0.14	0.27	0.41	0.14	0.41

	WS	Workstation Cycle time COEFFICIENT OF VARIATION Correlation Values									COEFFICIENT OF VARIATION		POSITION	
	No.	1	2	3	4	5	6	7	8	9	MIN	MAX		
%Blocking	1	0.38	0.28	0.21	0.37	0.31	0.19	0.30	0.28	0.24	0.21	0.37	MIN	-0.35
	2	0.51	0.34	0.06	0.54	0.20	0.23	0.49	0.20	0.08	0.05	0.61	MAX	0.54
	3	0.06	0.29	0.48	0.18	0.22	0.17	0.20	0.17	0.07	0.30	0.12	Avr.	0.14
	4	0.06	0.31	0.49	0.15	0.29	0.19	0.13	0.16	0.09	0.32	0.10		
	5	0.35	0.04	-0.06	0.25	0.22	-0.15	0.15	-0.01	-0.01	0.05	0.15		
	6	0.05	0.12	0.12	-0.07	0.16	0.01	-0.13	0.05	0.16	0.22	-0.08		
	7	0.13	0.20	0.19	0.02	0.12	-0.02	-0.02	0.13	0.14	0.28	-0.07		
	8	0.45	0.00	-0.11	0.31	-0.10	-0.35	0.36	-0.03	-0.23	-0.16	0.20		
	9	Zero % Blocking												
%Waiting	1	-0.02	0.23	0.37	0.37	0.50	0.42	0.25	0.24	0.07	0.17	0.38		
	2	-0.09	-0.01	0.10	-0.15	-0.03	-0.04	-0.07	-0.02	0.07	0.16	-0.12		
	3	-0.12	-0.06	0.09	-0.13	0.03	-0.09	-0.08	0.07	0.05	0.15	-0.16		
	4	0.30	-0.11	-0.21	0.25	0.00	-0.25	0.27	0.04	-0.14	-0.11	0.17		
	5	0.29	0.03	-0.05	0.35	0.14	-0.08	0.34	0.18	-0.06	0.09	0.23		
	6	-0.21	0.20	0.15	-0.06	0.08	0.50	0.01	0.21	0.22	0.11	0.25		
	7	0.12	0.07	0.13	0.33	0.07	0.12	0.43	0.14	-0.09	-0.01	0.38		
	8	0.10	0.26	0.10	0.22	0.20	0.46	0.21	0.25	0.23	0.09	0.46		
	9	0.04	0.40	0.40	0.22	0.33	0.51	0.16	0.40	0.36	0.45	0.29		

Table 5.13 Results for Stage II Experimentation: Inter and intra workstation Variability - Coefficient of Variation of Cycle time Correlated with % B and % W

The 'Coefficient of Variation' was correlated with %B and %W in Table 5.13. It did not represented stronger relationship than 'Pert Mean'. The decisive value, that helps make decision of whether the correlated variables have stronger or weaker relationship, came to (Min: -0.35, Max: +0.54, Average: +0.14). So this stats measure will not be used for further analysis.

MEDIAN									MEDIAN	
1	2	3	4	5	6	7	8	9	MIN	MAX
1.00	1.27	1.55	1.84	2.13	1.84	1.55	1.27	1.00	1.00	2.13
2.13	1.84	1.55	1.27	1.00	1.27	1.55	1.84	2.13	1.00	2.13
1.00	1.55	2.13	1.55	1.00	1.55	2.13	1.55	1.00	1.00	2.13
2.13	1.55	1.00	1.55	2.13	1.55	1.00	1.55	2.13	1.00	2.13
1.00	2.00	3.00	4.00	5.00	4.00	3.00	2.00	1.00	1.00	5.00
5.00	4.00	3.00	2.00	1.00	2.00	3.00	4.00	5.00	1.00	5.00
1.00	3.00	5.00	3.00	1.00	3.00	5.00	3.00	1.00	1.00	5.00
5.00	3.00	1.00	3.00	5.00	3.00	1.00	3.00	5.00	1.00	5.00
1.00	1.73	2.45	3.16	3.87	3.16	2.45	1.73	1.00	1.00	3.87
3.87	3.16	2.45	1.73	1.00	1.73	2.45	3.16	3.87	1.00	3.87
1.00	2.45	3.87	2.45	1.00	2.45	3.87	2.45	1.00	1.00	3.87
3.87	2.45	1.00	2.45	3.87	2.45	1.00	2.45	3.87	1.00	3.87
5.00	5.26	5.54	5.54	5.84	5.54	5.26	5.00	4.74	4.74	5.84
5.84	5.54	5.26	5.00	4.74	5.00	5.26	5.54	5.84	4.74	5.84
0.71	1.27	1.84	2.42	3.00	2.42	1.84	1.27	0.71	0.71	3.00
8.00	7.73	7.45	7.16	6.87	7.16	7.45	7.73	8.00	6.87	8.00
3.00	0.71	8.29	3.00	0.71	8.29	3.00	0.71	8.29	0.71	8.29
5.74	8.12	6.36	4.58	5.61	5.00	4.74	3.74	7.16	3.74	8.12
5.00	3.26	6.59	5.55	6.26	2.13	4.74	1.41	4.26	1.41	6.59
3.13	3.74	1.00	2.00	4.58	4.27	3.82	3.45	6.74	1.00	6.74
3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00

	WS No.	Workstation Cycle time MEDIAN Correlation Values									MEDIAN		POSITION	
		1	2	3	4	5	6	7	8	9	MIN	MAX		
%Blocking	1	-0.82	-0.50	-0.05	-0.23	-0.28	-0.04	-0.09	-0.54	-0.58	-0.43	-0.19	MIN	-0.82
	2	-0.63	-0.64	0.10	-0.14	-0.18	0.15	-0.16	-0.66	-0.29	-0.48	0.00	MAX	0.61
	3	-0.29	-0.32	-0.72	-0.32	0.21	-0.20	-0.50	-0.22	-0.19	-0.32	-0.27	Avr.	-0.18
	4	-0.22	-0.25	-0.77	-0.45	0.07	-0.32	-0.46	-0.14	-0.13	-0.35	-0.29		
	5	-0.25	-0.20	0.07	-0.45	-0.77	-0.05	0.06	-0.05	-0.02	-0.29	-0.05		
	6	-0.11	-0.01	-0.23	-0.47	-0.60	-0.41	0.02	0.14	-0.13	-0.20	-0.25		
	7	0.18	0.03	-0.49	-0.48	-0.27	-0.33	-0.29	0.14	0.19	-0.16	-0.20		
	8	0.22	-0.07	-0.04	-0.28	-0.14	0.29	-0.25	-0.11	0.61	-0.23	0.33		
	9	Zero % Blocking												
%Waiting	1	-0.45	-0.34	-0.24	-0.11	0.01	-0.14	-0.26	-0.33	-0.44	-0.24	-0.26		
	2	0.28	-0.07	-0.47	-0.33	-0.13	-0.36	-0.51	0.05	0.10	-0.21	-0.24		
	3	0.35	0.18	-0.30	-0.32	-0.21	-0.34	-0.34	0.13	0.19	-0.10	-0.13		
	4	0.05	0.02	0.40	-0.22	-0.57	0.14	0.05	-0.12	0.28	-0.18	0.25		
	5	-0.07	-0.06	0.33	-0.28	-0.64	0.03	0.01	-0.18	0.11	-0.19	0.08		
	6	0.08	-0.07	-0.15	0.11	0.39	-0.37	-0.31	-0.35	-0.14	-0.20	-0.09		
	7	-0.12	-0.36	-0.11	-0.03	0.18	0.10	-0.51	-0.50	-0.01	-0.32	0.03		
	8	-0.53	-0.39	0.14	0.08	0.04	-0.13	-0.07	-0.59	-0.51	-0.34	-0.10		
	9	-0.66	-0.44	-0.24	-0.14	-0.10	-0.35	-0.23	-0.45	-0.75	-0.29	-0.47		

Table 5.14 Results for Stage II Experimentation: Inter and intra workstation Variability - Median of Cycle time Correlated with % B and % W

The 'Median' was correlated with %B and %W in Table 5.14. This Statistical measure showed stronger positive and negative relationship between %Blocking, %Waiting and workstation cycle time, compared to 'Pert Mean' and out of other measures. The decisive value, that helps make decision of whether the correlated variables have stronger or weaker relationship, came to (Min: -82, Max: +0.61, Average: -0.18). So this statistical measure can be used for further analysis.

PERT VARIANCE									PERT VARIANCE	
1	2	3	4	5	6	7	8	9	MIN	MAX
0.00	0.43	0.54	0.58	0.60	0.58	0.54	0.43	0.00	0.00	0.60
0.60	0.58	0.54	0.43	0.00	0.43	0.54	0.58	0.60	0.00	0.60
0.00	0.54	0.60	0.54	0.00	0.54	0.60	0.54	0.00	0.00	0.60
0.60	0.54	0.00	0.54	0.60	0.54	0.00	0.54	0.60	0.00	0.60
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	-0.61	-0.93	-1.11	-1.23	-1.11	-0.93	-0.61	0.00	-1.23	0.00
-1.23	-1.11	-0.93	-0.61	0.00	-0.61	-0.93	-1.11	-1.23	-1.23	0.00
0.00	-0.93	-1.23	-0.93	0.00	-0.93	-1.23	-0.93	0.00	-1.23	0.00
-1.23	-0.93	0.00	-0.93	-1.23	-0.93	0.00	-0.93	-1.23	-1.23	0.00
0.00	0.26	0.61	0.61	1.01	0.61	0.26	0.00	-0.19	-0.19	1.01
1.01	0.61	0.26	0.00	-0.19	0.00	0.26	0.61	1.01	-0.19	1.01
-1.70	0.43	0.58	0.60	0.60	0.60	0.58	0.43	-1.70	-1.70	0.60
0.00	-1.53	-1.77	-1.75	-1.66	-1.75	-1.77	-1.53	0.00	-1.77	0.00
0.60	-1.70	5.09	0.60	-1.70	5.09	0.60	-1.70	5.09	-1.70	5.09
-0.52	-3.96	-1.70	-1.30	-1.03	0.00	-0.19	-0.25	-1.75	-3.96	0.00
0.00	0.21	2.26	1.03	0.48	0.60	-0.46	-1.70	0.17	-1.70	2.26
0.69	-0.25	0.00	0.00	-1.30	0.79	0.56	-1.10	-0.57	-1.30	0.79
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

	WS	Workstation Cycle time PERT VARIANCE Correlation Values									PERT VARIANCE		POSITION	
	No.	1	2	3	4	5	6	7	8	9	MIN	MAX		
%Blocking	1	-0.07	0.11	0.16	0.19	0.08	0.22	0.21	0.11	0.07	-0.02	0.13	Min	-0.48
	2	0.04	0.15	0.61	0.41	-0.04	0.57	0.29	-0.19	0.43	-0.06	0.59	Max	0.61
	3	-0.09	0.30	-0.11	0.09	-0.02	-0.09	0.31	0.18	-0.30	0.14	-0.21	Average	0.05
	4	-0.03	0.34	-0.18	0.10	-0.02	-0.14	0.32	0.19	-0.35	0.18	-0.28		
	5	0.24	0.07	0.19	0.10	-0.11	0.28	0.13	-0.01	0.35	0.20	0.18		
	6	0.13	0.21	-0.22	0.00	0.12	-0.18	-0.01	0.14	-0.12	0.29	-0.27		
	7	0.09	0.12	-0.19	-0.02	-0.03	-0.11	0.10	0.07	-0.16	0.18	-0.21		
	8	0.24	-0.27	0.41	0.09	-0.45	0.57	0.31	-0.33	0.42	-0.18	0.49		
	9	Zero % Blocking												
%Waiting	1	-0.42	0.24	0.06	0.27	0.34	0.07	0.29	0.32	-0.23	0.03	-0.06		
	2	-0.15	0.11	-0.13	-0.06	0.08	-0.19	-0.02	0.11	-0.12	0.26	-0.24		
	3	-0.19	-0.17	-0.27	-0.19	0.03	-0.21	-0.05	0.15	-0.24	0.01	-0.29		
	4	0.02	-0.48	0.28	-0.05	-0.22	0.43	0.01	-0.22	0.38	-0.30	0.39		
	5	-0.07	-0.41	0.21	-0.04	-0.09	0.36	-0.04	-0.17	0.30	-0.28	0.34		
	6	-0.38	-0.01	0.03	0.15	0.29	-0.14	-0.03	-0.02	-0.35	-0.27	-0.03		
	7	-0.26	-0.12	0.37	0.16	-0.06	0.34	0.23	-0.03	0.17	-0.19	0.32		
	8	-0.23	0.07	0.27	0.27	0.23	0.15	0.07	-0.01	-0.01	-0.19	0.22		
	9	-0.25	0.29	-0.09	0.14	0.38	-0.17	-0.01	0.28	-0.21	0.09	-0.17		

Table 5.15 Results for Stage II Experimentation: Inter and intra workstation Variability - Pert Variance of Cycle time Correlated with % B and % W

The 'Pert Variance' was correlated with %Blocking and %Waiting in Table 5.15. It did not represented stronger relationship than other measures. The decisive value, that helps make decision of whether the correlated variables have stronger or weaker relationship, came to (Min: -48, Max: +0.61, Average: 0.05). Therefore this stats measure will not be used for further analysis.

SKEWNESS									SKEWNESS	
1	2	3	4	5	6	7	8	9	MIN	MAX
0.00	0.43	0.54	0.58	0.60	0.58	0.54	0.43	0.00	0.00	0.60
0.60	0.58	0.54	0.43	0.00	0.43	0.54	0.58	0.60	0.00	0.60
0.00	0.54	0.60	0.54	0.00	0.54	0.60	0.54	0.00	0.00	0.60
0.60	0.54	0.00	0.54	0.60	0.54	0.00	0.54	0.60	0.00	0.60
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	-0.61	-0.93	-1.11	-1.23	-1.11	-0.93	-0.61	0.00	-1.23	0.00
-1.23	-1.11	-0.93	-0.61	0.00	-0.61	-0.93	-1.11	-1.23	-1.23	0.00
0.00	-0.93	-1.23	-0.93	0.00	-0.93	-1.23	-0.93	0.00	-1.23	0.00
-1.23	-0.93	0.00	-0.93	-1.23	-0.93	0.00	-0.93	-1.23	-1.23	0.00
0.00	0.26	0.61	0.61	1.01	0.61	0.26	0.00	-0.19	-0.19	1.01
1.01	0.61	0.26	0.00	-0.19	0.00	0.26	0.61	1.01	-0.19	1.01
-1.70	0.43	0.58	0.60	0.60	0.60	0.58	0.43	-1.70	-1.70	0.60
0.00	-1.53	-1.77	-1.75	-1.66	-1.75	-1.77	-1.53	0.00	-1.77	0.00
0.60	-1.70	5.09	0.60	-1.70	5.09	0.60	-1.70	5.09	-1.70	5.09
-0.52	-3.96	-1.70	-1.30	-1.03	0.00	-0.19	-0.25	-1.75	-3.96	0.00
0.00	0.21	2.26	1.03	0.48	0.60	-0.46	-1.70	0.17	-1.70	2.26
0.69	-0.25	0.00	0.00	-1.30	0.79	0.56	-1.10	-0.57	-1.30	0.79
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

	WS	Workstation Cycle time SKEWNESS ratiion Correlation Values									SKEWNESS		POSITION	
	No.	1	2	3	4	5	6	7	8	9	MIN	MAX	MIN	MAX
%Blocking	1	-0.07	0.11	0.16	0.19	0.08	0.22	0.21	0.11	0.07	-0.02	0.13	MIN	-0.48
	2	0.04	0.15	0.61	0.41	-0.04	0.57	0.29	-0.19	0.43	-0.06	0.59	MAX	0.61
	3	-0.09	0.30	-0.11	0.09	-0.02	-0.09	0.31	0.18	-0.30	0.14	-0.21	Average	0.05
	4	-0.03	0.34	-0.18	0.10	-0.02	-0.14	0.32	0.19	-0.35	0.18	-0.28		
	5	0.24	0.07	0.19	0.10	-0.11	0.28	0.13	-0.01	0.35	0.20	0.18		
	6	0.13	0.21	-0.22	0.00	0.12	-0.18	-0.01	0.14	-0.12	0.29	-0.27		
	7	0.09	0.12	-0.19	-0.02	-0.03	-0.11	0.10	0.07	-0.16	0.18	-0.21		
	8	0.24	-0.27	0.41	0.09	-0.45	0.57	0.31	-0.33	0.42	-0.18	0.49		
	9	Zero % Blocking												
%Waiting	1	-0.42	0.24	0.06	0.27	0.34	0.07	0.29	0.32	-0.23	0.03	-0.06		
	2	-0.15	0.11	-0.13	-0.06	0.08	-0.19	-0.02	0.11	-0.12	0.26	-0.24		
	3	-0.19	-0.17	-0.27	-0.19	0.03	-0.21	-0.05	0.15	-0.24	0.01	-0.29		
	4	0.02	-0.48	0.28	-0.05	-0.22	0.43	0.01	-0.22	0.38	-0.30	0.39		
	5	-0.07	-0.41	0.21	-0.04	-0.09	0.36	-0.04	-0.17	0.30	-0.28	0.34		
	6	-0.38	-0.01	0.03	0.15	0.29	-0.14	-0.03	-0.02	-0.35	-0.27	-0.03		
	7	-0.26	-0.12	0.37	0.16	-0.06	0.34	0.23	-0.03	0.17	-0.19	0.32		
	8	-0.23	0.07	0.27	0.27	0.23	0.15	0.07	-0.01	-0.01	-0.19	0.22		
	9	-0.25	0.29	-0.09	0.14	0.38	-0.17	-0.01	0.28	-0.21	0.09	-0.17		

Table 5.16 Results for Stage II Experimentation: Inter and intra workstation Variability - Skewness of Cycle time Correlated with %B and %W

The 'Skewness' was correlated with %B and %W in Table 5.16. It also did not represented stronger relationship than other measures. The decisive value, that helps make decision of whether the correlated variables have stronger or weaker relationship, came to (Min: -48, Max: +0.61, Average: 0.05). Therefore this stats measure will also not be used for further analysis.

Close observation and examination of all the correlation analysis performed using statistical measures revealed that the Median is the most suitable statistical measure that can be used for further experimentation purpose because the correlation analysis result seeks stronger positive or negative relationship that numerically represented as +1 or -1. The result for Median comes to -0.82 and +0.61. This is presented in comparison to other statistical measures in Table 5.9.

Most statistical measures have not confirmed strong relationship in Stage II experiments because every statistical measure arranges the calculating factors differently as shown in Section 4.2.4, equations 1 to 4. These equations are arranged in conjunction with the Longest, Most likely and Shortest cycle time.

5.4 Stage III Experimentation: Inter and Intra Workstation Variability

In Stage II trials, variability in Cycle Time was introduced in middle position but in Stage III, Cycle Time variability is assigned to all workstations in these flow lines. Use of Median also justified in Stage II experiments that showed strong correlation between %Blocking, %Waiting and Median CT for which reason, Median CT is used for Stage III experiments. The length of remanufacturing flow line has been again restricted to five workstations so that it becomes possible to establish the fundamental theory with reference to stage I experimentation. At this final stage of experimentation, larger ranges of CT have been allocated to make the trial more realistic to remanufacturing process stages. In addition, the maximum error acceptable for estimation was restricted to $\pm 10\%$.

Exp No.	W S Cycle Time - Median				
	1	2	3	4	5
68	4.7	7.5	10.9	18.0	22.5
77	10.5	17.5	16.5	23.5	24.5
86	9.0	22.0	30.0	38.0	50.0
95	31.6	46.6	41.2	49.8	55.0

Table 5.17 Median Cycle Time for Stage III

Exp	Workstation % Blocking (Simulation)					Workstation % Waiting (Simulation)				
	1	2	3	4	5	1	2	3	4	5
68	78.68	66.52	47.68	20.44	0.00	0.04	0.25	0.52	1.11	1.92
77	57.93	28.86	33.07	6.49	0.00	0.04	0.60	1.38	2.07	4.57
86	80.79	53.43	41.75	23.30	0.00	0.04	0.45	1.19	2.73	4.36
95	45.11	16.80	26.78	11.68	0.00	0.04	1.67	3.59	5.59	9.48

Table 5.18 Results for % Blocking obtained from Simulation for Stage III

Exp	Workstation % Blocking (Estimated)					Workstation % Waiting (Estimated)				
	1	2	3	4	5	1	2	3	4	5
68	78.94	66.67	51.39	20.09	2.00	0.00	0.00	0.00	0.00	0.00
77	57.14	28.57	32.65	4.08	11.00	0.00	0.00	5.71	0.00	0.00
86	82.00	56.00	40.00	24.00	20.00	0.00	0.00	0.00	0.00	0.00
95	42.61	15.36	25.12	9.50	29.00	0.00	0.00	11.53	0.00	0.00

Table 5.19 Results for % Waiting obtained from Simulation for Stage III

Exp	% Error (Blocking)					% Error (Waiting)				
	1	2	3	4	5	1	2	3	4	5
68	-0.26	-0.15	-3.71	0.35	-2.00	0.04	0.25	0.52	1.11	1.92
77	0.79	0.29	0.42	2.41	-11.00	0.04	0.60	-4.33	2.07	4.57
86	-1.21	-2.57	1.75	-0.70	-20.00	0.04	0.45	1.19	2.73	4.36
95	2.50	1.44	1.66	2.18	-29.00	0.04	1.67	-7.94	5.59	9.48

Table 5.20 % Error between Simulation and Estimated results for Stage III

“Median” was further used to analyse the mixed level of cycle time using equations 5 and at stage III to estimate the %Blocking and %Waiting on individual WS. With further development of these equations in terms of introduction of constraint and taking certain condition into account that arise during the remanufacturing operation. This process demonstrates the initial step taken to identify %B on a WS having highest CT within flow line.

- a. Identified maximum %B and %W in the flow line to form benchmark.
- b. Identify maximum and minimum cycle times within flow line.
- c. Estimate maximum %Blocking or %Waiting, using equation 3.
- d. Replacing maximum and minimum CT in equation estimates the maximum %Blocking or %Waiting.
- e. The maximum error generated at this stage remains under $\pm 10\%$.

The equation was further developed to suite the maximum number of workstations within a flow line. In this order, following constraint were introduced:

If

Maximum CT within a flow line (from *Actual* to n^{th}) is greater than the CT on Actual WS (for which %B is being estimated)

Then

$\frac{\text{MaxCT (within flow line)} - \text{CT on the Workstation being estimated}}{\text{MaxCT (within flow line)}}$

$$((CT_{i,n} - CT_{k,n}) \div (CT_{i,n})) \times 100$$

$$\text{Otherwise } \%B = 0.0$$

Where:

$CT_{i,n}$	=	Longest cycle time in flow line
$CT_{k,n}$	=	Individual WS cycle time to be estimated
k	=	Position of workstation
n	=	Number of workstation

This equation works on flow line with maximum number of workstations to investigate the amount of %Blocking and %Waiting on individual workstations. The %Error falls within the range of $\pm 10\%$. From this, it is proven that the methodology developed in this research to estimate %Blocking and %Waiting can work in remanufacturing environment. Equations and rules developed in this research can prove to be a very useful at planning and scheduling stages of remanufacturing process.

Chapter 6 Discussion

6.1 Introduction - Product End of Life (EoL) strategies

The Government is striving to reduce the amount of waste produced by products reaching their End of Life. In response to this, hierarchy, categorizing different stages for resource recovery has been developed by the UK Government and is described in Appendix – 3.

A number of strategies, including, recycling, reusing, refurbishing and remanufacturing are now widely employed with remanufacturing being identified as most suitable in terms of its effectiveness.

However, remanufacturing does have limitations which include, labour intensiveness, a requirement of high levels of product and process knowledge, appropriate remanufacturing skill set and tooling requirements. A major advantage, however is ability to provide like-new products at greatly reduced levels of new material and at much reduced costs, (Sofa, 2005).

Due to the uncertain nature of End of Life returned product supply, it is difficult to use flow processing principles within a remanufacturing environment. (Gupta & Gangor, 2004; Sundin, 2005) identified the various individual remanufacturing process operation stages.

There is a significant difference between direct manufacturing of a new product and remanufacturing of EoL product. The latter involves initial disassembly of the EoL

product to component level with each component potentially having to visit or re-visit more than one workstations due to the uncertain condition of component wear and nature of the remanufacturing process involved.

This research, through review of literature in the area of manufacturing systems engineering has identified number of systems in Section 3.3, that include Flexible Manufacturing Systems, Process Sequence Cell Layouts, Flow Processing and Mixed Model Flow Processing. One of which directly responds to facilitate flow processing within remanufacturing environment.

6.2 Product and process variability

In chapter 3, a critical assessment of these alternative manufacturing systems revealed that implementing flow processing is feasible only if the variability associated with remanufacturing can be managed such that high levels of resource efficiency and throughput can be achieved.

In addition to cycle time and operations variability arising from variation in wear states of components there are other potential issues that may occur during the operations of a flow line in remanufacturing including:

- a. Flow of material may be halted due to lack of new components
- b. Variable task times may be generated
- c. Refurbished components may not become available in which case the product may have to be removed from the flow line
- d. Supply variability

- e. Product design variability
- f. Parts specification variability
- g. Operations variability
- h. Demand variability

Companies such as Caterpillar (Caterpillar-Remanufacturing, 2006) have successfully adopted flow line to remanufacture EoL diesel engines products but the throughput effectiveness and resource usage efficiency is limited

The variability for supply arises because of the fluctuations in the rate of which products reach their End of Life state. The number of End of Life cores entered a remanufacturing facility, on a daily or weekly basis, may therefore vary directly affecting flow line effectiveness. Depending upon product make and model factors, product design variability will also have a dramatic effect by segregating products such that various 'batch sizes' need to be processed along the flow line.

Such features are identified by Gungor (1998) who emphasised that process variability can be associated with End of Life cores through variation in terms of:

- year in which original product was manufactured.
- the age of the product.
- required level of repair or remanufacturing, and
- the level of design change taking place since first manufacture.

Considering the levels of product and process variability and their sources that can arise, it is apparent that the management of remanufacturing flow processing systems could be a highly chaotic process that will require significant attention and thorough planning.

In order to overcome or reduce the overall effect of variability, methods used have included:

- allocation of balanced workload between all workstations.
- effective finite capacity scheduling, and
- removing causes of variation through implementing lean practices.

Within remanufacturing flow processing environments it is difficult to determine and/or manage task times due to parts and product design variability. Therefore, balancing flow line in such an environment is difficult and frequently ineffective. Methods used to achieve balanced lines that are applicable to remanufacturing and that help improve process efficiency are:

- Providing offline work areas for completing tasks not possible on the main flow line.
- Allocating operators to multi-work stations.

These methods improve flow efficiency but add extra cost to the process.

Removing causes of variation through lean implementation would assist the remanufacturing process in the areas of maintenance, quality and process time. Set-up

time reduction may assist in setting up workstations/fixtures, loading and disassembly methods, e.g. a standard way of performing certain task, using a set of standard tools will tend to reduce processing times.

6.3 Estimating workstation utilization

There are several ways of estimating process time and efficiency which in turn can be used to understand the behaviour of a process. These methods include, data collection through observation, legacy data retrieval, operator's interview, and use of published information in reliable sources, e.g. reputed journals and simulation.

Through close examination, it is revealed that observation and interview methods are time and cost consuming while there is a lack of such specific data in academic journals and due to the recent emergence of remanufacturing, legacy data is not available. In which case, Simulation software becomes the most viable option due to its availability, ease of use, data output, repeatability, and reliability of data. Hence, Simulation application, Simul8 has been used for this research in order to estimate process times and hence levels of variability.

Khalil (2005) examined flow lines in direct-manufacturing environment with the aim of investigating the effect of variability and offering suitable solution to maintain the flow processing efficiency with the identification of various causes and types of variability on flow line. Also the previous research developed a method to categorise sources of variability to overcome the effect. The current research extends this work by including remanufacturing characteristics to flow lines in which workstations have differing

amount of variability, which is more appropriate to the remanufacturing process. As discussed in the literature review, several approaches have been used in the area of disassembly and non-destructive part removal to estimate the sequence and time, i.e. Petri-Net approach and Neural Networks but a systematic estimation method to estimate individual workstation efficiency does not exist. In which context, this research will fill this gap and offer a constructive methods of estimating variability.

In terms of the cycle times allocated to each workstation these were based on information gathered from visits to remanufacturing facilities at Remploy (Lewis, 2005) and from Sofa project (Sofa, 2005).

But the novelty or main feature of this research is that it offers two methods to validate the end result. Primarily, %Blocking and %Waiting will be estimated using equations 5 and 6. Secondly, can double-check through visual observation of graphical representation in conjunction with relationships developed.

In experiment 3 results, Table 5.2, shows high amount of %Blocking error. The cycle time for these specific workstations are 2, 4 and 4 minutes respectively for WS 2, 3 and 4. According to the rule developed, if the longest cycle time is to the left side of the actual workstation, then the result will be %Blocking and if the longest cycle time is to the right side of the actual workstation, then the result will be %Waiting. Here equation is automatically unable to determine the position of the longest cycle time and this is why it generates errors.

For further validation, experiment 7 is randomly picked and selected where cycle times for individual workstations are as below:

WS	1	2	3	4	5
CT (min)	7	4	2	4	7

Table 6.1 Workstation and Cycle time for Experiment 7

Applying the basic formula of equation to above Experiment 7 cycle times:

Estimated %Blocking or %Waiting = $(CT_{max} - CT_{act}) / CT_{max}$

WS 1: $100 \times (7 - 7) / 7 = 0 \% B, \%W$

WS 2: $100 \times (7 - 4) / 7 = 0 \% B, 42.8\%W$

(Because of the Longest cycle time in first position)

WS 3: $100 \times (7 - 2) / 7 = 0 \% B, 71.4\%W$

(Because of the Longest cycle time in first position)

WS 4: $100 \times (7 - 4) / 7 = 0 \% B, 42.8\%W$

(Because of the Longest cycle time in first position)

WS 5: $100 \times (7 - 7) / 7 = 0 \% B, 0\%W$

From experiment 7 estimates, it has emerged that one equation is applicable to all situations. The estimated value is either %Blocking or %Waiting is determined by longest cycle time. If the WS cycle time is Longer than succeeding workstation then estimated values are most definitely the % Waiting for following workstations.

It would be noted that it may be confusing and misleading way of estimating sensitive parameters that help in planning the stochastic remanufacturing process. However the positive side of the methodology is that the equation will be used in parallel with graphical representation. Therefore, each remanufacturing flow line will be scheduled with its relative estimates obtained through equation as well as graphical representation to quickly double check the Blocking and Waiting on individual workstations.

6.4 Stage II: Inter and Intra workstation variability

At this second stage, the complexity added to the experimental design in terms of cycle time in the format of Triangular Distribution, i.e. Higher, Most likely and Lower ranges, as well as the number of workstations are increased to nine and variability introduced in the middle position of the flow line.

In order to technically analyse the data and achieve the most effective measure, a number of statistical measures were introduced, i.e. Pert mean, Mode, Standard deviation, Coefficient of Variation, Median, Pert variance and Skewness. These measures were correlated with %Blocking and %Waiting to test which statistical measure will be most suitable for correlation analysis.

6.5 Stage III: Inter and Intra workstation variability

Since the Median value presented the strongest correlation between cycle time , %Blocking and %Waiting for individual workstation, further variability is assigned to all the workstation cycle time at Stage III. Also, in order to keep the experiments to a manageable level and resemble the Stage I experiments to establish basic relationship, the flow line length were restricted back to five workstations.

Randomly picking an experiment, i.e. Experiment 91, of which Median cycle time for all workstations and Simulation results are presented below.

WS	1	2	3	4	5
CT (min)	18	28	29	46	59
%B (Sim)	67.44	50.10	50.17	21.27	0.0
%W (Sim)	0.04	0.75	1.99	3.1	6.85

Table 6.2 Experiment 91 Cycle time and Simulation results

As established at Stage I experimentation, if the Shortest CT is in the beginning workstation, then Blocking effect will occur at first workstation but if, Longest CT encountered in first workstation, then higher levels of waiting will be seen at succeeding workstations.

Applying the equation to estimate variability on Workstation 3:

$$\text{WS 3: } 100 \times (59 - 29) / 59 = 50.84 \%B$$

The equation itself will not determine whether it is %Blocking or %Waiting. This will be determined by looking at the workstation cycle time. The longest cycle time is in the last position in Experiment 91 and so all the preceding workstations are assumed to be having %Waiting.

Some of the basic understanding gained through these rules were the fundamental behaviour of the flow line, where, for example:

- First workstation will always have varying level or zero level of %Blocking
- Last workstation will always have varying level of zero level of %Waiting

Further work on relationship/rules is required as it may propose a better way of accurately estimating %Blocking and %Waiting, even without the use of equations. Close observation and analysis revealed the relationship between %Blocking, %Waiting and workstation cycle time.

These basic observation helped identify relationship, which formed equation to find the %Blocking and %Waiting on individual workstation within a flow line. The application of equation requires additional information in terms of the position of the workstation with longest cycle time. As stated earlier, longest cycle time governs blocking and waiting effect within a flow line. Workstations before the workstation with longest cycle time will most probably be blocked and will have varying level of blocking effect while, workstations after the workstation with longest cycle time will be waiting and will have varying level of waiting effect.

Although the relationship shows the applicability to certain situation, further analysis and tests using other experiments undertaken showed some of the shortfall.

It is evident that remanufacturing is a non-deterministic and stochastic process environment. During the period of high demand and supply, it will present more complications in scheduling and planning the process. The equations and relationship developed in this research would help to improve the situation and ease the planning process. But the solution presented here does have its limitations, i.e.

- Where estimated results were compared to simulation results, it presented error, in which case, relationships and graphical representations must be referred to.
- There is a need of two separate equations to estimate two main parameters, i.e. %Blocking and %Waiting.
- For the purpose of this research, simulation was used to generate and compare the data and as a result, %error was estimated. Many small organizations, due to financial circumstances, are unable to get access to such industrial high-end simulation software. The outcome of this research, in terms of equations will help such organisations to estimate the workstation utilization.

Chapter 7 Conclusion

The main aim of this research was to identify a suitable strategy to recover product End of Life resources from a typical domestic product.

The intention was to:

- Carrying on from the previous research (Khalil, 2005); the remanufacturing environment presents mixed level of variability that requires further investigation.
- Identify and **investigate different types of variability** encountered during the remanufacturing process.
- Based on (Khalil, 2005) research, further identify ways to reduce the unfavourable effect of **remanufacturing variability** that directly affect the remanufacturing process efficiency.
- Develop a novel mathematical equation based on process time that estimates the variability effect on individual workstation.

Based on above aims, this research has revealed and identified following key findings and issues related to Product End of Life remanufacturing:

- i. **A novel mathematical equations developed** for Product End of Life remanufacturing environment that presents mixed level of variability to estimate workstation utilisation in terms of %Blocking and %Waiting.

- ii. Remanufacturing can offer cost effective solution to recover End of Life resources. The main difficulty experienced during the process is the variability; that if removed or reduced will result in improved process efficiency. This research has **identified remanufacturing variability** in terms of product, process, supply and demand of remanufactured products.

- iii. Competitive challenging remanufacturing environment requires rapid changeover from one process to another. Planning such process requires cost effective user friendly method to identify bottle necks within process and reduce the effect of such at the remanufacturing production planning stage. In order to complement to such requirement, this research has developed some basic rules to investigate the workstation utilisation at initial stages.

Chapter 8 Further Work

1. The equation developed in this research estimates the %Blocking or %Waiting for an individual workstation but it requires human input in terms of identifying which side the longest cycle time is. Here, improved version of such equation is envisaged where, automatic detection of longest cycle time is possible.
2. Triangular distribution is the main distribution type that is used in this research to estimate the cycle time however, other probability distribution types could be considered and tested within existing model.
3. Development of a database that holds legacy data for remanufacturing processes in terms of process cycle time will help develop remanufacturing process cost models. This will also help in identifying generic process problems within remanufacturing strategies applied in this research.
4. Domestic product example used in this research could be extended to investigate the application of equations developed as part of this research to other products. The equation can benefit universal remanufacturing scenarios as mixed levels of variability have been tested.

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Appendices

Appendix – 1

Stage I experiments results (Experiments: 22 – 42)

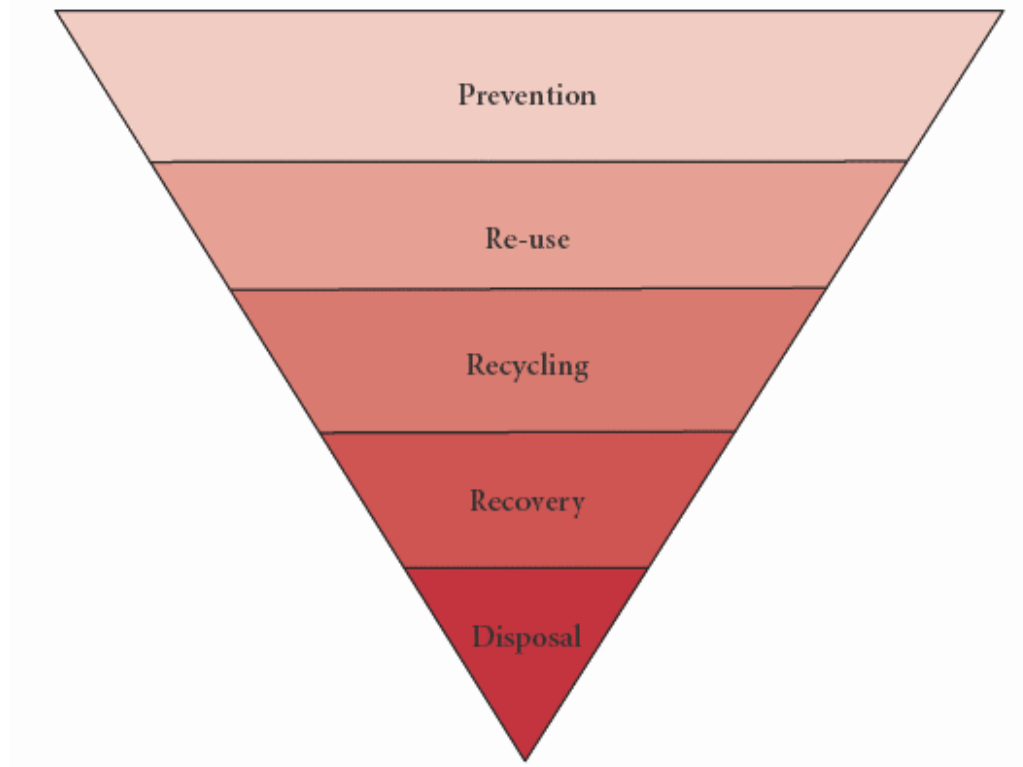
Exp. No.	Simulation										Estimated										% Error (% B)					% Error (% W)				
	% Blocking					% Waiting					% Blocking					% Waiting														
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
22	0.0	0.0	0.0	0.0	0.0	0.0	92.0	92.0	92.0	2.6	0.0	91.8	91.8	91.8	0.0	0.0	91.8	91.8	91.8	0.0	0.0	-91.8	-91.8	-91.8	0.0	0.0	0.2	0.2	0.2	2.6
23	0.0	0.0	0.0	0.0	0.0	0.0	92.0	92.0	68.0	3.1	0.0	91.8	91.8	67.3	0.0	0.0	91.8	91.8	67.3	0.0	0.0	-91.8	-91.8	-67.3	0.0	0.0	0.2	0.2	0.7	3.1
24	0.0	0.0	0.0	0.0	0.0	0.0	92.0	68.0	68.0	3.6	0.0	91.8	67.3	67.3	0.0	0.0	91.8	67.3	67.3	0.0	0.0	-91.8	-67.3	-67.3	0.0	0.0	0.2	0.7	0.7	3.6
25	0.0	0.0	0.0	0.0	0.0	0.0	68.0	68.0	68.0	4.1	0.0	67.3	67.3	67.3	0.0	0.0	67.3	67.3	67.3	0.0	0.0	-67.3	-67.3	-67.3	0.0	0.0	0.7	0.7	0.7	4.1
26	0.0	0.0	0.0	0.0	0.0	0.0	68.0	92.0	92.0	3.1	0.0	67.3	91.8	91.8	0.0	0.0	67.3	91.8	91.8	0.0	0.0	-67.3	-91.8	-91.8	0.0	0.0	0.7	0.2	0.2	3.1
27	0.0	0.0	0.0	0.0	0.0	0.0	68.0	68.0	92.0	3.6	0.0	67.3	67.3	91.8	0.0	0.0	67.3	67.3	91.8	0.0	0.0	-67.3	-67.3	-91.8	0.0	0.0	0.7	0.7	0.2	3.6
28	0.0	0.0	0.0	0.0	0.0	0.0	68.0	92.0	68.0	3.6	0.0	67.3	91.8	67.3	0.0	0.0	67.3	91.8	67.3	0.0	0.0	-67.3	-91.8	-67.3	0.0	0.0	0.7	0.2	0.7	3.6
29	91.6	0.0	0.0	0.0	0.0	0.0	0.2	2.3	4.3	92.3	91.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	91.8	-0.2	0.0	0.0	0.0	0.0	0.0	0.2	2.3	4.3	0.5
30	91.6	0.0	0.0	0.0	0.0	0.0	0.2	2.3	68.7	92.2	91.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	67.3	91.8	-0.2	0.0	0.0	0.0	0.0	0.0	0.2	2.3	1.3	0.3
31	91.6	0.0	0.0	0.0	0.0	0.0	0.2	68.0	68.0	92.0	91.8	0.0	0.0	0.0	0.0	0.0	0.0	67.3	67.3	91.8	-0.2	0.0	0.0	0.0	0.0	0.0	0.2	0.7	0.7	0.2
32	74.8	0.0	0.0	0.0	0.0	0.0	0.2	0.9	1.5	75.5	75.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	75.0	-0.2	0.0	0.0	0.0	0.0	0.0	0.2	0.9	1.5	0.5
33	91.5	66.5	0.0	0.0	0.0	0.0	0.2	0.9	2.9	92.2	91.8	67.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	91.8	-0.4	-0.9	0.0	0.0	0.0	0.0	0.2	0.9	2.9	0.3
34	91.3	66.0	66.0	0.0	0.0	0.0	0.2	0.9	1.5	92.0	91.8	67.3	67.3	0.0	0.0	0.0	0.0	0.0	0.0	91.8	-0.5	-1.3	-1.3	0.0	0.0	0.0	0.2	0.9	1.5	0.2
35	91.5	66.5	0.0	0.0	0.0	0.0	0.2	0.9	68.0	92.0	91.8	67.3	0.0	0.0	0.0	0.0	0.0	0.0	67.3	91.8	-0.4	-0.9	0.0	0.0	0.0	0.0	0.2	0.9	0.7	0.2
36	66.6	0.0	0.0	0.0	0.0	0.0	0.7	2.8	4.8	69.3	67.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	67.3	-0.7	0.0	0.0	0.0	0.0	0.0	0.7	2.8	4.8	2.0
37	66.6	0.0	0.0	0.0	0.0	0.0	0.7	2.8	92.2	68.7	67.3	0.0	0.0	75.0	0.0	0.0	0.0	0.0	91.8	67.3	-0.7	0.0	0.0	-75.0	0.0	0.0	0.7	2.8	0.3	1.3
38	66.6	0.0	0.0	0.0	0.0	0.0	0.7	92.0	92.0	68.0	67.3	0.0	75.0	75.0	0.0	0.0	0.0	91.8	91.8	67.3	-0.7	0.0	-75.0	-75.0	0.0	0.0	0.7	0.2	0.2	0.7
39	0.0	0.0	0.0	0.0	0.0	0.0	75.2	75.2	75.2	1.2	0.0	75.0	75.0	75.0	0.0	0.0	75.0	75.0	75.0	0.0	0.0	-75.0	-75.0	-75.0	0.0	0.0	0.2	0.2	0.2	1.2
40	65.9	90.5	0.0	0.0	0.0	0.0	1.2	0.9	2.9	68.7	67.3	91.8	0.0	0.0	0.0	0.0	0.0	75.0	0.0	0.0	67.3	-1.4	-1.4	0.0	0.0	0.0	-73.8	0.9	2.9	1.3
41	65.3	89.8	90.3	0.0	0.0	0.0	1.7	1.4	1.0	68.0	67.3	91.8	91.8	0.0	0.0	0.0	75.0	75.0	0.0	67.3	-2.1	-2.0	-1.5	0.0	0.0	0.0	-73.3	-73.6	1.0	0.7
42	66.0	90.5	0.0	0.0	0.0	0.0	1.2	0.9	92.0	68.0	67.3	91.8	0.0	75.0	0.0	0.0	75.0	0.0	91.8	67.3	-1.4	-1.4	0.0	-75.0	0.0	0.0	-73.8	0.9	0.2	0.7

Appendix – 2

Stage III experiments results

Exp. No.	WS Cycle Time - Median					Workstation % Blocking					Estimated % Blocking					% Error				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
65	7.6	7.6	12.0	7.6	7.6	41.68	39.51	5.56	7.93	0.00	36.6	36.6	0.0	0.0	-1.0	5.1	2.9	5.6	7.9	1.0
66	9.6	9.6	20.4	9.6	9.6	48.31	50.79	0.63	3.07	0.00	53.0	53.0	0.0	0.0	0.0	-4.7	-2.2	0.6	3.1	0.0
67	13.8	13.8	24.5	13.8	13.8	46.32	48.88	0.13	0.90	0.00	43.7	43.7	0.0	0.0	1.0	2.6	5.2	0.1	0.9	-1.0
68	4.7	7.5	10.9	18.0	22.5	78.68	66.52	47.68	20.44	0.00	78.9	66.7	51.4	20.1	2.0	-0.3	-0.1	-3.7	0.3	-2.0
69	6.6	12.5	13.5	19.5	25.5	72.80	50.72	46.98	23.35	0.00	74.2	51.0	47.1	23.5	3.0	-1.4	-0.3	-0.1	-0.2	-3.0
70	4.5	11.5	11.5	15.5	22.5	80.75	47.38	49.95	31.11	0.00	80.0	48.9	48.9	31.1	4.0	0.8	-1.5	1.1	0.0	-4.0
71	9.5	15.5	13.5	17.5	23.5	59.08	33.96	41.73	25.30	0.00	59.6	34.0	42.6	25.5	5.0	-0.5	-0.1	-0.8	-0.2	-5.0
72	9.5	15.5	19.5	17.5	22.5	60.71	30.20	13.88	22.04	0.00	57.8	31.1	13.3	22.2	6.0	2.9	-0.9	0.5	-0.2	-6.0
73	7.5	12.5	13.5	19.5	25.5	69.56	50.12	46.96	24.67	0.00	70.6	51.0	47.1	23.5	7.0	-1.0	-0.9	-0.1	1.1	-7.0
74	5.5	11.5	16.5	17.5	21.5	74.06	46.23	23.08	17.71	0.00	74.4	46.5	23.3	18.6	8.0	-0.4	-0.3	-0.2	-0.9	-8.0
75	8.5	13.5	16.5	23.5	24.5	66.81	44.35	32.35	7.40	0.00	65.3	44.9	32.7	4.1	9.0	1.5	-0.5	-0.3	3.3	-9.0
76	5.5	13.5	16.5	17.5	21.5	74.28	36.13	22.27	17.54	0.00	74.4	37.2	23.3	18.6	10.0	-0.1	-1.1	-1.0	-1.1	-10.0
77	10.5	17.5	16.5	23.5	24.5	57.93	28.86	33.07	6.49	0.00	57.1	28.6	32.7	4.1	11.0	0.8	0.3	0.4	2.4	-11.0
78	10.5	16.5	20.5	18.5	23.5	54.69	29.92	12.34	20.86	0.00	55.3	29.8	12.8	21.3	12.0	-0.6	0.1	-0.4	-0.4	-12.0
79	8.5	13.5	20.5	19.5	24.5	65.22	45.43	17.51	21.90	0.00	65.3	44.9	16.3	20.4	13.0	-0.1	0.5	1.2	1.5	-13.0
80	4.3	6.8	11.5	17.3	21.8	79.59	67.94	44.35	20.88	0.00	80.5	68.8	47.3	21.0	14.0	-0.9	-0.8	-2.9	-0.1	-14.0
81	7.7	11.8	11.9	18.8	26.2	69.87	53.63	52.23	26.54	0.00	70.4	54.8	54.5	28.1	15.0	-0.6	-1.2	-2.3	-1.6	-15.0
82	5.2	13.1	12.2	13.9	22.7	78.68	42.54	48.32	36.76	0.00	77.3	42.5	46.3	38.8	16.0	1.4	0.1	2.0	-2.0	-16.0
83	10.2	16.0	15.0	18.2	22.4	55.10	30.07	34.56	20.56	0.00	54.3	28.7	32.8	18.8	17.0	0.8	1.4	1.8	1.8	-17.0
84	8.3	14.0	19.7	16.4	23.2	64.99	36.69	14.89	27.26	0.00	64.0	39.7	14.8	29.3	18.0	1.0	-3.0	0.1	-2.1	-18.0
85	8.2	13.0	12.8	20.7	26.2	68.30	49.92	49.90	23.03	0.00	68.7	50.6	51.0	21.2	19.0	-0.4	-0.6	-1.1	1.9	-19.0
86	9.0	22.0	30.0	38.0	50.0	80.79	53.43	41.75	23.30	0.00	82.0	56.0	40.0	24.0	20.0	-1.2	-2.6	1.8	-0.7	-20.0
87	18.0	28.0	45.0	62.0	72.0	71.30	59.42	39.94	13.85	0.00	75.0	61.1	37.5	13.9	21.0	-3.7	-1.7	2.4	0.0	-21.0
88	9.0	29.0	38.0	39.0	50.0	82.40	37.62	24.64	21.76	0.00	82.0	42.0	24.0	22.0	22.0	0.4	-4.4	0.6	-0.2	-22.0
89	25.0	47.0	38.0	48.0	59.0	54.12	19.32	35.35	18.89	0.00	57.6	20.3	35.6	18.6	23.0	-3.5	-1.0	-0.2	0.2	-23.0
90	25.0	37.0	47.0	57.0	67.0	63.62	40.05	28.89	16.30	0.00	62.7	44.8	29.9	14.9	24.0	0.9	-4.7	-1.0	1.4	-24.0
91	18.0	28.0	29.0	46.0	59.0	67.44	50.10	50.17	21.27	0.00	69.5	52.5	50.8	22.0	25.0	-2.1	-2.4	-0.7	-0.8	-25.0
92	10.4	19.2	34.5	33.6	48.2	78.12	59.61	33.95	29.31	0.00	78.5	60.1	28.4	30.3	26.0	-0.4	-0.5	5.6	-1.0	-26.0
93	21.2	30.2	47.4	64.2	76.8	72.99	57.75	38.95	15.71	0.00	72.4	60.7	38.3	16.4	27.0	0.6	-3.0	0.7	-0.7	-27.0
94	7.2	24.9	35.2	41.8	51.8	83.92	42.85	30.92	19.20	0.00	86.0	52.0	31.9	19.3	28.0	-2.1	-9.1	-1.0	-0.1	-28.0
95	31.6	46.6	41.2	49.8	55.0	45.11	16.80	26.78	11.68	0.00	42.6	15.4	25.1	9.5	29.0	2.5	1.4	1.7	2.2	-29.0
96	18.4	33.8	48.4	62.5	64.8	66.26	48.60	25.50	7.03	0.00	71.6	47.8	25.4	3.5	30.0	-5.3	0.8	0.1	3.5	-30.0
97	23.2	26.6	29.5	52.6	61.8	61.44	56.18	51.92	20.39	0.00	62.5	56.9	52.3	14.9	31.0	-1.1	-0.7	-0.3	5.5	-31.0

Appendix – 3



The Waste Hierarchy

Courtesy: House of Lords – Science and Technology – Sixth report

<http://www.publications.parliament.uk/pa/ld200708/ldselect/ldsctech/163/16305.htm>

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