

Autonomous Finite Capacity
Scheduling using Biological Control
Principles

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Abstract

The vast majority of the research efforts in finite capacity scheduling over the past several years has focused on the generation of precise and almost exact measures for the working schedule presupposing complete information and a deterministic environment. During execution, however, production may be the subject of considerable variability, which may lead to frequent schedule interruptions.

Production scheduling mechanisms are developed based on centralised control architecture in which all of the knowledge base and databases are modelled at the same location. This control architecture has difficulty in handling complex manufacturing systems that require knowledge and data at different locations. Adopting biological control principles refers to the process where a schedule is developed prior to the start of the processing after considering all the parameters involved at a resource involved and updated accordingly as the process executes.

This research reviews the best practices in gene transcription and translation control methods and adopts these principles in the development of an autonomous finite capacity scheduling control logic aimed at reducing excessive use of manual input in planning tasks. With autonomous decision-making functionality, finite capacity scheduling will as much as practicably possible be able to respond autonomously to schedule disruptions by deployment of proactive scheduling procedures that may be used to revise or re-optimize the schedule when unexpected events occur.

The novelty of this work is the ability of production resources to autonomously take decisions and the same way decisions are taken by autonomous entities in the process of gene transcription and translation. The idea has been implemented by the integration of

simulation and modelling techniques with Taguchi analysis to investigate the contributions of finite capacity scheduling factors, and determination of the ‘*what if*’ scenarios encountered due to the existence of variability in production processes. The control logic adopts the induction rules as used in gene expression control mechanisms, studied in biological systems. Scheduling factors are identified to that effect and are investigated to find their effects on selected performance measurements for each resource in used. How they are used to deal with variability in the process is one major objective for this research as it is because of the variability that autonomous decision making becomes of interest.

Although different scheduling techniques have been applied and are successful in production planning and control, the results obtained from the inclusion of the autonomous finite capacity scheduling control logic has proved that significant improvement can still be achieved.

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DEDICATION

Special dedication of this work goes to:

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end of the journey;

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beautiful angels, who are a great source of strength and inspiration to me, grow to

become great scholars.

Declaration

I declare that this research report is my own work and every effort has been made to indicate clearly the contributions from others by providing due reference to the literature, and acknowledgement. It has not been submitted before for any degree or examination in any other University. I further declare that I obtained the necessary authorisation and consent to carry out this research.

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Abbreviations and Glossary

% Blocking	It is the waiting time for preceding machine which is waiting for the succeeding workstation to finish the jobs.
% Stoppages	It the time work is paused for either short or long term interruptions such as breakdown or scheduled maintenance.
% Waiting	It is the waiting time for succeeding workstations that are waiting for the proceeding workstations to finish the jobs.
% Working	It is the percentage of time when the machine is working
AFCS	Autonomous Finite Capacity Scheduling
APS	Advanced Planning Systems
AVG	Automatic Guided Vehicles
BMS	Bionic Manufacturing System
BOM	Bill of Material
CRP	Capacity Requirement Planning
CVM	Committee on Visionary Manufacturing
DES	Discrete-Event Simulation
DOE	Design of Experiments
ERP	Enterprise Resource Planning
FCS	Finite Capacity Scheduling
JIT	Just-in-Time

LT	Lead Time
MES	Manufacturing Execution System
MRP	Material Requirement Planning
MRPII	Manufacturing Resources Planning
MTO	Make to Order
MTS	Make to Stock
MTTF	Mean Time To Failure
MTTR	Mean Time To Repair
NOP	Number of Operations due date rule
OA	Orthogonal Array
OPT	Optimised Production Technology
PPW	Processing Plus Waiting due-date rule
RCCP	Rough Cut Capacity Planning
SLK	Equal Slack due-date rule
TOC	Theory of Constraint
TWK	Total Work Content due-date rule
WIP	Work in Progress

Chapter 1: Introduction

1.1 Overview

Many manufacturing facilities generate and update schedules, which are plans that state when certain controllable activities such as processing of jobs by machine, take place. Today's manufacturing is faced with a rising global competition, challenging customers and employees, decreasing product lifecycles and response times.

Within this highly dynamic environment, variability becomes inherent characteristic of manufacturing systems. As stated by Bogle (2000), "*variability in operating conditions is becoming the norm, rather the exception*" and the traditional strategy of operating a manufacturing system independently of its environment is not appropriate any more. Rather, flexibility and responsiveness of manufacturing processes are important features to be considered and explored to deal with the eventual effects of variability quickly and effectively.

The systematic treatment of variability is widely recognised as a real problem and one of the main challenges in the area of manufacturing (Grossmann, 2004; Floudas, 2005). George Dantzig once said, "*I am working on planning under variability; that's the big field as far as I'm concerned. That is the future*", (Horner, 1999).

There is need to develop tools capable of solving problems caused by variability quickly and efficiently. Many of these problems are characterised by a number of finite solutions as well as a value of performance measurements assigned to each solution. Many solution algorithms have increasingly been used in solving most of these problems. The successful application of emergent techniques based on natural

comparisons, such as genetic algorithms and neural networks, to manufacturing problems is certainly encouraging; it most definitely points to the natural systems as a source of ideas and models for the development of various artificial systems such as manufacturing.

1.2 Problem Statement

With the evolving mass customisation, the competitiveness in manufacturing is increasingly dependent on the ability to adapt to the novel requirements for on-demand manufacturing. Such adaptation requires increased flexibility in manufacturing capacity and quick response to variability induced by unpredictable operating conditions. Scheduling problem has usually been seen as a function of known and reliable information, providing solutions based on actual or estimated values for all the parameters, and totally assuming that a predictive schedule will be carried out exactly as planned.

A wide range of manufacturing and service work environments are characterised by uncertainty. The environment in which a human expert (controller) makes decisions is often complex, making it difficult to formulate modelling of some kind; hence the development of autonomous finite capacity scheduling control logic seems justified in such situations. Developing models for solving difficult finite capacity scheduling problems characterised by variability is a very important and challenging research task.

Finite capacity scheduling techniques need to be combined with control principles adopted from biological systems to improve the level of autonomous decision-making functionality of machines under unpredictable conditions of system variability. As can be learnt in biological systems, survival is not for the fittest but for the most adaptive;

hence firms better prepared to survive are those that better respond to variability by adapting dynamically their operations.

Responding to this variability in the system is related with the having capability of autonomous decision-making functionality as encountered in biological processes. The decision-making requires the ability to maintain performance in face of *internal* and *external* variability. Inability to respond quickly to different types of variability leads to deviations from initial plans and causes delays and generally unwarranted stoppages.

Most of the organisations operating in the traditional way suffer from the centralised and hierarchical control that has weak response to variability. In this regard, the challenge is to develop an autonomous finite capacity scheduling control logic adopting biological control principles founded in gene transcription and translation – a control method displaying immense capabilities of dealing with system variability.

A response to customer needs, input and process variability, recovery capability and autonomous decision-making could facilitate the smooth operation of manufacturing firms. A practical solution is possible through the application of the control principles in gene transcription and translation – the concept of biological manufacturing systems – by considering a number of control factors. Such manufacturing operations could be seen as individual genes that are responding to their environmental stimulus by either assembling the processing mechanisms or processing parts through production of required proteins for gene expression. Potential genetic information such as customer requirements could describe the manufacturing system variability required to adapt or process more efficiently the given tasks.

The potential of variability continuously appearing in manufacturing processes and equipment (machine, tools, and operators) and raw materials or parts resulting, require an autonomous system that aims at reducing excessive highly skilled manual input in finite capacity scheduling activities. The work presented here makes use of biologically inspired approach based on gene transcription and translation control principles which localise their decision-making at respective production machines using reduction rules.

By adopting this idea taken from natural gene transcription and translation control processes and by taking into account changes in systems parameters occurring in time at each machine levels, modelling the way the system may respond is still an open question. Many other methods such as those discussed in Section 2.7 have been explored but in this thesis the final decision on how the machine responds to variability among available options will be made based on some reduction rules to guide the system autonomy. Specific comparative cases between manufacturing and biological systems are presented. A modelled validation is developed and explained. This work attempts to contribute towards increased adaptability of a production line affected by variability.

1.3 The Aims and Objectives of Research

This research seeks to develop an autonomous finite capacity scheduling control logic that makes use of biological control gene transcription and translation control logic, for designing autonomous operations planning and control system within manufacturing and service work environments. The developed biologically inspired logic mechanisms can be used for controlling individual types of operations planning and control the activities of manufacturing.

To achieve this aim, this research undertook the following objectives:

- a. to perform literature review to understand the relationships between manufacturing and biological system and learn from it to improve finite capacity scheduling (sections 2.6 – section 2.10);
- b. to integrate the biological control principles in discrete event simulation to provide autonomous decision making functionality;
- c. to identify finite capacity scheduling control factors to be incorporated in the logic development;
- d. to develop process mapping for customer order to provide the step-by-step events for modelling in the simulation;
- e. to integrate Taguchi Design of Experiment and biological control principles for the development of autonomous control logic;
- f. to develop logic to offer a quick response to variability and then fulfil customer order requirements whether a product or a service; and
- g. integrate discrete event simulation model with the different logic rules to provide autonomous finite capacity scheduling functionality to model manufacturing system.

1.4 Structure of the Thesis

This thesis begins with Chapter 1 that lays the ground for the general information of the scope of this research. The general trend in modern manufacturing environment is introduced, and a problem statement is specified. This chapter states the aim and

objectives of this research that provide milestones for attaining the aim are given. The chapter concludes with the structure of the thesis.

Chapter 2 reviews the relationships between manufacturing and biological systems to provide the understanding and the applicability of biological control principles into manufacturing systems. The chapter introduces the importance of inclusion of variability in the scheduling of manufacturing tasks to improve on autonomous decision-making functionalities. Issues of lean are also discussed aiming at ensuring the information adopted from biological systems fits well with existing systems. Different manufacturing systems are discussed in this chapter of which one of them (manufacturing flow lines) was selected for use with this method since it displays similarities with biological processes. Finite capacity scheduling factors are discussed preparing way for the investigation of the variability associated with them. This chapter also looks at some of the methods used to model biological control principles and some examples of manufacturing control systems with inspiration from biological processes.

Chapter 3 presents the explanation of rules for finite capacity scheduling where the proposed autonomous finite capacity scheduling logic can be developed around manufacturing flow lines as described in Section 2.4 which exhibit similar characteristics with biological systems. Components of finite capacity scheduling, some existing planning and scheduling systems, benefits of finite capacity scheduling and types or categories of scheduling problems are discussed.

Chapter 4 describes the steps undertaken to develop the research methodology. The methodology combined both quantitative and qualitative types. Taguchi's Orthogonal Arrays is applied in the Design-of-Experiment. Based on the aims and objectives of the

research, the experimental design is chosen to investigate expected improvements to achieving the research aims.

Chapter 5 reports the results of the simulation experiments after running the required number of experiments according to Taguchi's Orthogonal Arrays. Additionally, it draws attentions to the variability in the finite capacity scheduling factors and how they determine the process variability at machines and hence the set system performance measurements are investigated to justify the logic. This chapter analyses the results obtained and lays down the procedures for the development of the AFCS control logic.

Chapter 6 discusses the results and major findings obtained in chapters 4 and 5. The chapter proceeds by listing the difference between the proposed method and other existing scheduling methods. It then discusses the results and answers some questions based on the proposed steps for the development of autonomous finite capacity scheduling control logic.

In addition, the chapter highlights some major points related to the AFCS:

- a. how proposed method fits into existing planning and scheduling methods;
- b. the useful lessons from biological methods and contribution of the proposed method; and
- c. how to apply AFCS.

Chapter 7 draws the conclusions of the research and the contributions of this research to the knowledge base.

Chapter 8 lays out the ground for further work in this area to provide an enhanced solution to manufacturing problems. Inclusion in future work is the capability to provide a learning capability so as to continuously improve the decision-making rules.

Chapter 2: Manufacturing and Biological Systems

2.1 Introduction

Many recent studies in manufacturing systems have reported continuous changes in the production processes caused by variability of many kinds (Perminova et al., 2008). Consideration of this variability during planning and scheduling is a vital undertaking to ensuring quick response to customer demands and also remaining competitive to the ever-changing business environment. The inclusion of variability in scheduling in manufacturing and service work environments may be improved further by adopting some principles of biological control providing highly autonomous decision-making functionalities, as founded in gene transcription and translation processes.

Scheduling has become a core manufacturing tool both on strategic and operational levels. In fact, any activity that is perceived as significant and necessary from the customer perspective could be variability, which may be taken into consideration during the scheduling process or after schedule, has already been constructed. Consequently, such developments change the way manufacturing systems are controlled, such that future scheduling of activities will have to adopt strategies and methods founded outside manufacturing as in biological systems.

This chapter provides the useful similarities between biological systems and manufacturing systems. Some basic principles of biological control are underscored in line with the fundamental principles of autonomous decision-making functionalities of these systems with a possible application to manufacturing is presented.

2.2 Overview of Modern Manufacturing Operations

Hopp and Spearman, (2001) define manufacturing system as an *objective*-oriented *network* of *process activities* through which *flow of material* occurs. In this definition several aspects are highlighted:

- a. *objectives* help to know the direction the organisation takes to meet customer demands and to sustain itself, which are viewed as performance measurements in this research;
- b. *process activities* may include the usual physical processes or steps taken during manufacturing or other steps that support the direct taken in manufacturing processes, such as kitting, shipping, maintenance etc.;
- c. *flow of materials* for the parts being manufactured move from machine to machine that is used to make the product;
- d. *flow of information* describing how information about orders, activities being executed, products in-production, products made, operators, work process etc. is gathered, stored, transferred, processed, used for manufacturing or decision making processes (Petrauskas, 2006), and;
- e. *network* of interacting parts as well as information which when managed will establish good synchronisation in production activities, to the betterment of the customer.

Modern manufacturing operations are accomplished by mechanised, automated equipment supervised by operators and they include assembly and almost always

the activities are carried out as a sequence of operations (Ahmed et al., 2005). Manufacturing is therefore concerned with the transformation of materials into items of greater value by means of one or more processing and/or assembly operations. It adds value to the material by changing its shape or properties, or by combining it with other materials, hence having variety of inputs and outputs. Figure 2.1 shows the general structure of a manufacturing system, where inputs are scheduling factors acting as sources of variability, having effect on process variability and finally outputs being products, services or both.

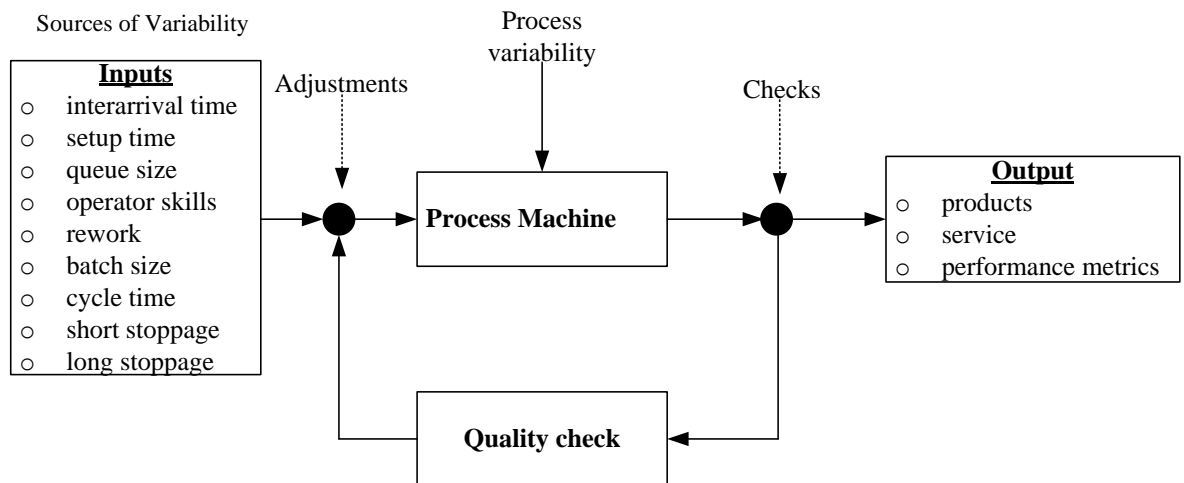


Figure 2.1: Manufacturing system inputs and outputs

Increased challenges from global competitors have prompted many manufacturing firms to adopt a number of manufacturing approaches (Shah and Ward, 2003). Of particular significance among these approaches is the concept of lean production (Womack and Jones, 1996) as introduced in Section 2.3 in pursuance of continuous improvement in manufacturing processes.

2.3 Definition of Lean

Lean production is a multi-dimensional approach that includes a variety of practices such as just-in-time, quality systems, work teams, cellular manufacturing supplier management, etc., (Shah and Ward, 2003). In modern manufacturing systems, adoption of lean principles plays an important role in ensuring that there is systematic approach towards identification of waste through continuous improvement; flowing the product at the pull of the customer in pursuit of perfection (Abdulmalek and Rajgopal, 2007). Five lean principles have been identified to help meet the customer requirements and helping manufacturing firms to remain competitive (Kilpatrick, 2003):

- i. ***Understanding customer value*** – only what the customer perceives as value is important;
- ii. ***Value stream analysis*** – having understood the value of the customer, the next step is to analyse the process to determine which ones actually add value. If action does not add value, it may be modified or eliminated from the process;
- iii. ***Flow*** – focus on organising a continuous flow through the production or supply chain rather than moving commodities in large batches;
- iv. ***Pull*** – demand chain management minimise producing commodities to stock, i.e. customer demand pulls finished products through the system, and hence no work is carried out unless the results of it are required downstream.
- v. ***Perfection*** – the elimination of non-value-adding elements (waste) is a process of continuous improvement, and hence there is no end to reducing time, cost, space, mistakes and effort (McCurry and McIvor, 2001)

Lean manufacturing uses less, or the minimum, of everything required to produce a product or perform a service. Additionally, lean identifies seven wastes that are experienced in manufacturing, service and project work environments (Womack and Jones, 2003; Bhasin and Burcher, 2005) as follows:

- a. ***over-production*** – This is the most deceptive waste in today’s variable demand scenario and it leads to unnecessary utilization of machines and operators. Overproduction includes making more than what is required and making products earlier than required. The rationale behind this just-in-case thinking is undue use of automation (Bicheno, 2000);
- b. ***waiting*** – this is the time spent waiting for raw material, the job from the preceding work station, machine downtime, and the operator engaged in other operations and schedules (Hicks, 2007). Waiting causes long lead times which make a business become less competitive.
- c. ***transport*** – this consumes huge capital investment and time in terms of equipment required for material movement, storage devices, and systems for material tracking. Labour cost associated with the material movement also comes under this category of waste. Transportation does not add value towards the final product (Shah and Ward, 2003);
- d. ***over-processing*** – efforts that add no value to the desired product from a customer’s point of view are considered as non-value added processing. Vague picture of customer requirements, communication flaws, inappropriate material or machine selection for the production are the reasons behind this type of waste (Bhasin and Burcher, 2005), e.g. reworking, inspection and deburring;

- e. **inventory** – higher inventory is not beneficial for any company in today's varied-demand business environment. The danger associated with high inventory is the chances of obsolescence. In the case of obsolete inventory, all costs invested in the production of a part are wasted (Shah and Ward, 2003);
- f. **motion** – any motion that does not add value to the product or service comes under non-value added cost; it may include operator or machine movement. Time spent by the operators looking for a tool, extra product handling and heavy conveyor usage are the typical example of the motion waste, resulting from improper design of the workplace, inconsistent work methods or lack of standard operations, and poor workplace organization and housekeeping (Khalil et al., 2006) and;
- g. **defects** – most companies give much emphasis on defects reduction, however, defects still remain the major contributors towards the non-value added activities. The effect of defects is quality and inspection activities, provision of extra service to the customer, warranty cost and loss of customer fidelity (Hicks, 2007; Shah and Ward, 2003).

Identification of wastes helps to develop procedures that can minimise them. If lean is well implemented, manufacturing time may considerably be reduced leading to a reduction in operational costs acquired due to unnecessary utilisation of machines and operators. In this research lean production is adopted to:

- i. improve flow of material and information across the entire manufacturing system;

- ii. emphasise on customer pull rather than organisational push enabled on the shop floor by considering all the process variability;
- iii. show commitment to continuous improvement enabled by the flexibility reached by the operator skills where they can switch from machine to machine in response to observed variability;
- iv. consider the effects of variability in decision-making by identifying their levels on different finite capacity scheduling factors and their effect on process variability, to determine the machine availability slots to process activities, and;
- v. adopt feedback links between machines and operators to increase the performance and flexibility in responding quickly to variability.

Additionally, biological processes have been found to display a great deal of lean in their operations and based on these findings, it became important to adopt biological control principles in this research for the development of an autonomous finite capacity scheduling control logic.

2.4 Types of Manufacturing Systems

Generally, the word manufacturing will conjure up many pictures of production and assembly lines making very large numbers of products, such as vehicles, clothes, electronics, and so on. Because of the wide range of products manufactured, several different types of manufacturing systems are identified each meeting unique demands and characteristics of the product and the market in which the product will eventually be sold. Govil and Fu (1999) have classified a number of manufacturing systems based on

the physical layout in Table 2.1 of the manufacturing resources and, hence, the types of material flow in the systems.

The parts arrive at different machines and wait in queues based on the machine availability. In this research, the manufacturing type of interest is flow lines because it exhibits similarities with biological processes in gene transcription and translation processes and in this flow lines operations lead to a final product in terms of goods or services. The variability in the factors mentioned in the next section are important ingredients in developing an autonomous finite capacity scheduling control logic

Table 2.1: Basic Types of Manufacturing Systems

- | |
|--|
| <p>i. Job shop systems – is a type of manufacturing process structure where small batches of many custom products are made. Job shop process flow has most of the products produced that require unique setups and sequencing of processing steps (Khalil, 2005). Material movement is achieved through transporters and has high work-in-progress (WIP). Factors associated with this system include: <i>the job arrival patterns, service pattern of machines, the breakdown and repair of machines, the routing of parts, and the queuing rules at buffers.</i></p> <p>ii. Flexible Manufacturing Systems – is a manufacturing system that has some amount of flexibility present to react in the case of predictable or unpredictable changes. It offers an advantage for the firms in this quickly changing manufacturing environment. Flexible manufacturing systems consist of automated machines and material handling system to move jobs between machines; and their controllers to control the machines and the material handling system (Krajewski and Ritzman, 2001; Malhotra et al., 2009). This system is</p> |
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characterised by: *service rates at different resources, routing of the parts, number of pallets in the material handling system, unreliability of the machines, and size of buffers.*

iii. **Assembly/Disassembly Systems** – characterised by parts waiting not only for the resource to become available but also for the other parts of the assembly to arrive before processing can begin (Nof and Chen, 2003). The system is associated with a set of input and output buffers. The station becomes starved if at least one of the input buffers is empty, and it is blocked if at least one of the output buffers is full. This system suffers from synchronisation constraints bringing about dependencies between stations. This is a low-volume production environment in which the machines tend to have a functional layout, and parts from different products may be routed to the same set of machines.

iv. **Reconfigurable Manufacturing Systems** – this is a machining system which can be created by incorporating basic process modules – both hardware and software – that can be rearranged or replaced quickly and reliably (Mehrabi et al., 2000). This type manufacturing system will allow adding, removing, or modifying specific process capabilities to adjust production capacity in response to variability of whatever kind. Reconfigurable manufacturing system provides customised flexibility for a particular part family, and will be open-ended, so that it can be improved, upgraded, and reconfigured, rather than replace. According to Mehrabi et al. (2000), permits (i) reduction of lead time for launching new systems and reconfiguring existing systems, and (ii) rapid production modification and quick integration of new technologies and/or new functions into

existing systems.

v. **Manufacturing Flow Lines** – they consist of stations with buffers where parts route in specified sequence. Khalil (2005) identified three types of flow lines in manufacturing based on the type of parts transfer method: (a) synchronous, (b) asynchronous and (c) continuous. *Flow lines with synchronous part transfer are called transfer lines and flow lines with asynchronous parts transfer are called production line.* Flow lines are high-volume production systems, and layout of the machines and buffers is dedicated to a few families of products. Flow lines are affected by the reliability of machines and buffer sizes.

vi. **Cellular Manufacturing System**—this is a methodology for organising the design and operation of a wide range of manufacturing systems so that the advantage of mass production and flexibility of job shop manufacturing can be derived from the production system. This kind of system processes a wide variety of parts that have common features (Solimanpur et al., 2004). Cellular manufacturing has the following advantages (Shankar and Vrat, 1999): (i) low production cost, (ii) low material handling cost, (iii) low production time, (iv) reduction in work-in-progress (WIP) inventories, (v) simple production control, (vi) reduction in scrap and waste, (vii) decentralisation of responsibility, and (viii) saving manufacturing space.

vii. **Agile Manufacturing Systems**— this is a dynamic manufacturing setting which allows rapid reconfiguration and is highly adaptive to quick market changes through widespread use of information technology (Gunasekaran and Yusuf, 2002). This requirement for manufacturing to be able to respond to unique demands moves the balance back to the situation prior to the introduction of lean

production, where manufacturing had to respond to whatever pressures were imposed upon it, with the risks to cost, speed and quality. Agility as a concept increases the emphasis on speed of response to new market opportunities. Agile manufacturing enables an efficient product development system to: (i) meet the changing market requirements, (ii) maximize customer service level and (iii) minimize the cost of goods, with an objective of being competitive in a global market and for an increased chance of long-term survival and profit potential. One way to model agile manufacturing environments can be through the following four variables:

- I. Rate of new product introduction.
- II. Length of PLC for each type of product.
- III. Demand per period for each type of product.
- IV. Production time per unit for each type of product.

viii. Sustainable manufacturing system – involves taking into account both economic and ecological constraints in designing a system (Heilala et al., 2008). Veleva and Ellenbecker (2001) define sustainable manufacturing as the creation of goods and services using processes and systems that are non-polluting, conserving of energy and natural resources, economically viable, safe and healthful for employees, communities, consumers and socially and creatively rewarding for all working people.

2.5 Identifying the Finite Capacity Scheduling Factors

Identification of scheduling factors is a major component of this research and their inclusion in planning and scheduling is important because of how they are used to

manage different types of variability within the manufacturing. Reducing system variability improves the final performance.

From literature, different factors or variables have been identified that can be used to provide control for schedule development. Pongcharoen et al. (2004); Pisinger and Ropke (2005); Sarimveis et al. (2008) identified stoppages, queue time, operator skills, batch size as major causes of different kinds of variability experienced in production systems. Several other researchers have identified a variety of factors that affect a manufacturing system. In this research the following list provides some variability that can affect processing at a machine:

- i. **Batch Size:** is a specific quantity of material produced according to a single manufacturing order during the same cycle of manufacturing and intended to have uniform characteristics, quality and with specific limits (Sarker et al., 2001). An optimal batch size quantity depends on the demand pattern and the production rate of the system. Historically, manufacturing has operated with large batch sizes in order to maximise machine utilisation, assuming that changeover times are fixed and could not be reduced (Kilpatrick, 2003; Meng and Heragu, 2004; Schmidt and Rose, 2008; Mukhongo et al., 2010), as well as reduced work-in-progress (WIP), and reduced cycle time (Chen and Chen, 2004).
- ii. **Cycle Time:** this is the time allotted for each task at a machine. It can also refer to the processing time of an individual machine (e.g., the time for a drilling machine to go through one cycle) (Hopp and Spearman, 2000; Haller et al., 2003).

- iii. **Inter-arrival Time:** this is the rate at which parts or jobs enter the manufacturing system, and whenever the system is finite there is the possibility that the system will be full and arriving parts will be lost; hence, the actual rate of parts entering the system may not be the same as the arrival rate (Hopp and Spearman, 2000). Also, when machines are fed by upstream stations whose processing times have different distributions; inter-arrival times are also unlikely to be with the same distributions, causing queues to develop (Hopp and Spearman, 2000). Variability in the arrival process means that the time between arrivals at the machine is a random variable.
- iv. **Operator Skills:** refers to the operational ability to use knowledge about the manufacturing system, tools to carry out the work, adhering to set standards or specifications, techniques and logic that are needed to finish the processing of activities (Grabot and Letouzey, 2000). The higher the skills level, the quicker the processing or the faster the setup, and the faster the understanding of the customer order specification. Operators work at different rates in the sense that one operator simply does a better job than others, because of the experience or skills, manual dexterity, or just sheer discipline. Differences in operator skill levels beyond simple variations in work pace can also have consequences for operation decisions.
- v. **Queue Time:** is the time jobs spend waiting for processing at the machine or to be moved to the next machine. Schmidt and Rose (2008) quantified how the queue time changed with lot size reductions by means of queuing theory and single-operation simulation, by analysing factors shaping queue time change and

how their influence changed for different availability characteristics. Queue time is determined by change in batch size and cycle time since the longer the cycle time, the more the WIP and hence the longer the queue time.

- vi. **Rework:** is necessary to convert the defects into finished goods since the system is not perfect, some scrap is produced as well. Rework provides the correction process of the defective items produced during normal production. Rework robs capacity and contributes greatly to the variability of the lead time (Flapper et al., 2002). The traditional reason for reducing rework is to prevent a loss of capacity (that is, reduce waste) since more rework implies more variability and more congestion, WIP, and long lead time. When defects become known, the production sequence is interrupted while the defects are corrected and may also cause unexpected workloads for repair or replacement.
- vii. **Setup Time:** is the time required for changeover of machines from making one product to making another (Hopp and Spearman, 2000). It is therefore the total time elapsed for changing a piece of equipment over from making the last part of a production batch to making the first good part of the following production batch. Shortening setup times and making them more consistent leads to reduced manufacturing costs and improved flexibility to meeting customer demands and help increase the overall output (Schmidt and Rose, 2008).
- viii. **Short Stoppages:** is the elapsed time when a machine is not capable of operating to specification for short periods of time (Brall et al., 2002). They include operators' unavailability, parts shortage and machine breakdowns (Ichikawa, 2009). The numerous stoppages that occur which do not require the

replacement or repair of a machine component falls under this category of short stoppages. Setups can contain short stoppages when they occur due to changes in the production process (such as changing a blunt tool) as opposed to changes in the product (Wu et al., 2008).

- ix. **Long Stoppages:** is the elapsed time when a machine is out of normal operation (Wu et al., 2008). They include machine breakdowns, operator accidents or even running out of consumables. Since they have similar effect on the behaviour of production lines, they are combined and treated as machine breakdowns in this research. When long stoppage (breakdowns) is frequent, inventory builds up.

This research undertakes to develop an autonomous finite capacity scheduling control logic adopting biological control principles founded in gene transcription and translation processes. The variability in the identified finite capacity scheduling factors cause interruptions in the flow of material and hence become important for autonomous decision-making for machine allocation to production activities in all types of manufacturing systems.

2.6 Similarities Between Manufacturing and Biological Processes

Biological processes have been found to display a number of similarities with manufacturing systems and in particular, production lines. Because of these similarities, attempts have been made to learn the structures and behaviours of biological systems with the aim of establishing the possibility of adopting biological control principles into manufacturing. It is based on this background that this research develops an autonomous finite capacity scheduling control logic adopting biological control principles founded in gene transcription and translation processes.

The structure and behaviours observed in biological processes from the cell level to the whole system expose some important principles of control applicable to manufacturing. For example, flow production can be likened to biological systems, where each machine will have certain abilities and functions to make its only decisions independently, but, with cooperation with other machines, can achieve the overall goal of the manufacturing systems (intermediate goals or finished products) responding to variability at all times (Christo and Cardeira, 2007).

Raw materials, parts and control information circulate in predefined ways, and the products and information from the processes are sent again by corresponding mechanisms to the machines that initiated the need. The properties of biological systems and manufacturing units uncover a lot of similarities (Anderson and Bartholdi III, 2000).

Two groups of similarities have been identified between biological and manufacturing systems as listed below, but in this research, we undertake to adopt the operational similarities to enable the development of the autonomous finite capacity scheduling control logic:

- i. Structural
- ii. Operational

2.6.1 Structural Similarities

Some structural similarities between manufacturing and biological cell have been identified (Stockton et al., 2007; Demeester et al., 2002; Wolkenhauer and Mesarovic 2005; and Szallasi et al., 2006) and are tabulated in Table 2.2.

Table 2.2 Structural Similarities between Biological cell and Manufacturing

Manufacturing	Function	Cell Organelle	Function
Plant/Factory facility	Factory premises	Cytoskeleton	Provides shape and gives (mechanically) structural support. Also serves as a monorail to transport substances around the cell.
Planning and scheduling logic	Manages activities, initiates production and controls different activities	Nucleus	Coordinates activities, including growth and reproduction.
Receive Inspection/Entry Point	Receiving goods and ready to be processed at different machines	Cell membrane	Defines and compartmentalizes space, regulates the flow of materials, detects external signals, and mediates interactions between cells
Shop floor	Factory floor where products are assembled, finished and shipped	Cytoplasm	Holds the cell organelles which are basically the components of the cell which control all the activities of the cell.
Machine/working area	Machines which can include conveyor belts and robots that make parts	Ribosomes	Make proteins for the cell
Assembly Line	Machines, tools and operators that	Endoplasmic reticulum	Used in the manufacture, process and transport of

	assemble different parts		chemical compounds
Storage area/buffer	Store different levels of inventories for later use, or if the succeeding is not ready to accept work	Vacuole	Maintains fluids, removes wastes, stores ingested food
Energy Producer/Generator, boiler room or furnace	Produces energy for the factory	Mitochondrion	Generates energy required for metabolism and cellular activities
Transportation	Move the material among different machines/area via forklift, AVGs etc.	Centrioles	Used to organise cell organelles by moving or pulling replicated chromosomes during cell division
Packaging and Dispatch	Packs products for distribution	Golgi bodies	Sorts the proteins and packs them into membrane wrapped structures called vesicles.
Scrap Area	Scrap parts that are out of specification	Lysosome	Breakdown unwanted cell organelles

2.6.2 Operational Similarities

These show the operational similarities between biological and manufacturing systems which make use of the structures identified in Table 2.2. They comprise the control features that run the structures identified to achieve the set goals. Table 2.3 list some of the operational similarities identified in this research.

Table 2.3: Operational Similarities

- i. flow of information and material among different machines in production flow lines (Tharumarajah et al., 1998). In biological system, this translates to systematic series of actions directed to the achievement of a goal;
- ii. in manufacturing, there is a structured measured set of activities designed to produce a specified output for a particular customer or market. Biological systems, generate highly ordered and complex structures from simple options, stores information for making choices between different options, and transmitting adequate instructions to the correct places;
- iii. comprise of a large number of different machines (as enzymes for biological systems) where many events take place such as assembling, processing, breakdowns, planned and unplanned maintenance. This was introduced in this research as sources variability which include, mean time to repair (MTTR), mean time to failure (MTTF), and % rework and change over (Stockton et al., 2007) as explained in section 2.5;
- iv. ability to measure completed job represented as throughput, equivalent to metabolic flux through a certain pathway in biological systems (Szallasi et al., 2006);
- v. degree of flexibility to manufacture mixed products which is the need of nowadays successful manufacturing system (Slack, 2005). Gene transcription and translation regulatory proteins can have different roles for different genes, and this is one mechanism by which cells can coordinate the regulation of many genes at once;

2.7 Methods Used for Biological Control Modelling

Biological processes can be considered at many levels of detail, ranging from molecular mechanism to general processes such as cell division and transcription and translation. The representation of hierarchical process knowledge in biology has been approached by a variety of methods:

- a. **Bayesian Network** – this method represents independence and dependence relationships between variables and the links represent conditional relationships in the probabilistic sense (Ghahramani, 2001). Bayesian network method assumes that expression of some entity is a function of only expression of level of other entities in the system. However, this is not always the case since some entities do not interact directly with each other, instead they do so by means of mediating factors or agents are represented by the introduction of hidden variables, making the method hard to explain and follow (Djebbari and Quackenbush, 2008).
- b. **Neural Network** – unlike the Bayesian networks, neural networks have no relationship, dependent or independent between variables and in fact the intermediate nodes are discovered features, instead of having any predicate associated with them in their own right (Dudek et al., 2006).
- c. **Stochastic Network** – provides an intelligent design and control method to describe the potential for coherence among several processes and characterise the control strategies that achieve it (Harrison, 2002).

d. **Boolean Logic** – Boolean logic is a building block for modelling complex, large-scale and dynamical networks of genetic interactions where the expression level of each involved factor in the process is functionally related to the expression states of some other entities using logical rules (Shmulevich et al., 2002). The expression of an entity corresponds to the entities being expressed with the required inputs being present. Time is viewed as proceeding in discrete steps; the new state of a node is Boolean function of the prior states of the nodes together with other required inputs. Boolean network are in the form $G(V, F)$ defined by a set of nodes (gene) $V = \{x_1, \dots, x_n\}$ and a list of Boolean functions $F = (f_1, \dots, f_n)$. Each $x_i \in \{0, 1\}$, $i = 1, \dots, n$ is a binary variable and its value at time $t + 1$ is completely determined by the values of other nodes or products at time t by means of Boolean functions.

This section has highlighted some of the methods used to express gene expression control mechanisms, though the method of choice for this research is the Boolean logic because of a number of reasons: the ease of modelling involved with it; fits well with the experiment; the rules of Boolean logic fit well with Simul8; and provides autonomous decision-making without issues with fitness functions etc.

2.8 Example of Manufacturing Control Methods Adopting Biological Reorganisation

For timely response to the rapidly changing manufacturing environment and markets, future manufacturing systems tends towards flexibility, adaptability, and self-organising. Bionic, holonic and fractal manufacturing systems have been discussed as potential candidates for the next generation manufacturing systems (Ryu and Jung,

2003). In this research, these methods are used to show how biological systems have inspired control methods in manufacturing. This study focuses on developing logic adopting biological control principles as observed in gene transcription and translation processes. The main issue here is to determine the scheduling factors and their variability level and how they cause the process variability used to determine machine availability.

Accordingly, this section briefly examines the emerging concepts of Bionic Manufacturing Systems (BMS), Holonic Manufacturing Systems (HMS) and Fractal Manufacturing System (FrMS). Table 2.4 highlight the comparison aspects of FrMS, HMS, and BMS (Okino, 1993; Tharumarajah et al., 1998; Christo and Cardeira, 2007; Babiceanu and Chen, 2006; Leitao and Restivo, 1999; Warnecke, 1993; Ryu and Jung, 2003).

The three systems presented in Table 2.4 are examples of systems adopting the functionalities of biological systems but tend to be very hierarchical in operation. Although the control is easy to understand and has less redundancy, they are not fast responding to variability affecting all levels in the hierarchy. Furthermore, these methods face difficulties in handling the ever-changing customer needs, since the hierarchical control architecture is not flexible in reconfiguring the shop layout. In this research we approach the control of machines based on the variability observed in each of the finite capacity scheduling factors identified and adopting biological control principles enabling decision-making at machines independently and autonomously. To be able to adopt the control principles in biological systems, characteristics of interest to manufacturing from biological systems are identified as discussed in Section 2.9.

Table 2.4: Comparison of Fractal, Holonic and Bionic Manufacturing Systems (Ryu and Jung, 2003)

Features	Fractal Manufacturing System	Holonic Manufacturing System	Bionic Manufacturing System
Basic unit	fractal (BFU): autonomous	holon: autonomous & cooperative entity	cell (Modelon): biological entity using DNA and Enzyme concepts
Creation of unit	predefined but dynamically reproduced or reorganised by the self-organisation	predefined and dynamic but limited to rule & functional decomposition at design time	predefined but dynamically reproduced by the evolution & self-organisation
Unit function	predefined but can be dynamically reassigned as new functions during operating time	predefined, new holons (or set of holons) with functions can be defined at design time	new modelons with required functions can be defined at design time, or can be divided or merged during operating time
Flexibility of unit	flexibly react to the environmental status through the dynamic restructuring process, self-optimization, and self-organization	flexibly react to the change of status of other holons through cooperation and negotiation	flexibly react to the changes in operating environment following the biological approach
Group creation	dynamically redefined as a fractal (an individual or a set of fractals)	holons in holarchy to support specific functions are define	as an organ through cell division to support required functionality dynamically
Reconfiguration	change fractal structure by constructing new fractals or reassigning new functions to existing fractals	change resources by re-allocating resources to holons subject to fixed canons with stable intermediate forms	change process flows by re-arranging flow lines of live (available) cells

2.9 Characteristics of Biological Systems

There has been no identified research that has studied gene transcription and translation control principles adopted for manufacturing control processes. In this research, we explore the circumstances occurring at the machine level as a result of the variability in finite capacity scheduling factor, which cause process variability that are used to determine machine availability profiles for allocation to production activities.

The following are some of the characteristics of biological systems that may be of relevance to manufacturing:

- i. ***self-organisation*** – freedom of the machine and other resources in organising and executing tasks by choosing their own methods of problems solving (Frei and Barata, 2010). In manufacturing systems, autonomous machines and resources can self-organise into assembly lines that can re-configure themselves as requirements change or machines break down (Tharumarajah et al., 1998), with the objective of meeting customer demands. Self-organising manufacturing system evaluating its own behaviour and changes behaviour when the evaluation indicates that it is not accomplishing what the objectives intends to achieve or when better functionality of performance is possible (Ghosh et al., 2007);
- ii. collection of biological entities that ***work together*** to achieve the organisms overall aims (through achieving their own individual ones) and they interact, collaborate, communicate and interrupt each other (Gatti and Lucena, 2007; Gordon, 2007). This characteristic is similar to a manufacturing system made up of several different machines working independently and cooperatively to achieve the firm's objectives

(Mills and Sherlock, 2000). This ensures that quality is maintained at the source such that no defective parts leave the station that produced it until it is corrected;

- iii. ***coordination*** (Gatti and Lucena, 2007; Gordon, 2007) – the coordination mechanisms are based on the specialization of certain cells, which will become able to interact and activate their specific working when activated by the direct interaction with other considered factors or controllers. In manufacturing, this characteristic is likened to the operator skills needed at various points in the production line, identified based on the activities and required processes. This will enable movement of operators from one part of the manufacturing system to the other when their need become known;
- iv. ***locality*** is a fundamental feature of biological systems where decisions are taken considering only the local conditions and not the global average. In manufacturing this characteristic gives each machine the capability to take its own decisions considering the variability of the finite capacity scheduling controller factors. The processing decisions are moved towards runtime to control dynamic behaviour and that an individual machine or resource reasons about its availability based on controller factor variability;
- v. ***recovery from disturbance*** where the biological system evolves to handle the recovery of the failure(Gatti and Lucena, 2007) – applying this characteristic in manufacturing will initiate the procedures to roll the machine back to a working condition. The recovery procedure may be invoked when failure is detected automatically approximating recovery time as mean-time-to-repair (MTTR)

determined based on the level of variability identified and may apply a combination of active recovery and re-scheduling techniques.

2.10 Autonomous Processing Based on the Concept of Biological Control

In gene transcription process decisions are taken autonomously based on prevailing circumstances by, (i) evaluating the process' own performance, (ii) adjusting accordingly and (iii) sending synchronisation signals to other units of the mechanism. This is done to ensure that the gene expresses at the right time thereby not causing any harmful effects to the biological cell. Autonomous decision-making processes as evidenced in gene transcription and translation are characterised by a shift of control capabilities from the total system to its elements (distributed control) (Demeester et al., 2004).

Watson and Scheidt (2005) define autonomous system as a system that can change its behaviour in response to unanticipated events during operation with ability to:

- a) develop a well-defined, yet modifiable action plan;
- b) execute the action plan, modifying it if necessary;
- c) react appropriately, if not optimally, to variability and;
- d) coordinate with human controllers (just by extension or indirectly)

In developing the finite capacity Scheduling control logic in this research, some of these abilities of autonomous system are used so as to aid in reducing the excessive use of highly skilled manual input in manufacturing planning and scheduling. Some of the additional capabilities of autonomous systems may include:

- a) improvement of performance through learning; and
- b) coordination with other autonomous systems in collaborating to execute a wider objective.

In this research every machine or resource is autonomous and has limited knowledge of the whole objective of manufacturing system, the control emerges, as a whole, from the interaction among the distributed machines and resources of the system with each contributing with its actions based on local optimisations as shown in Figure 2.2.

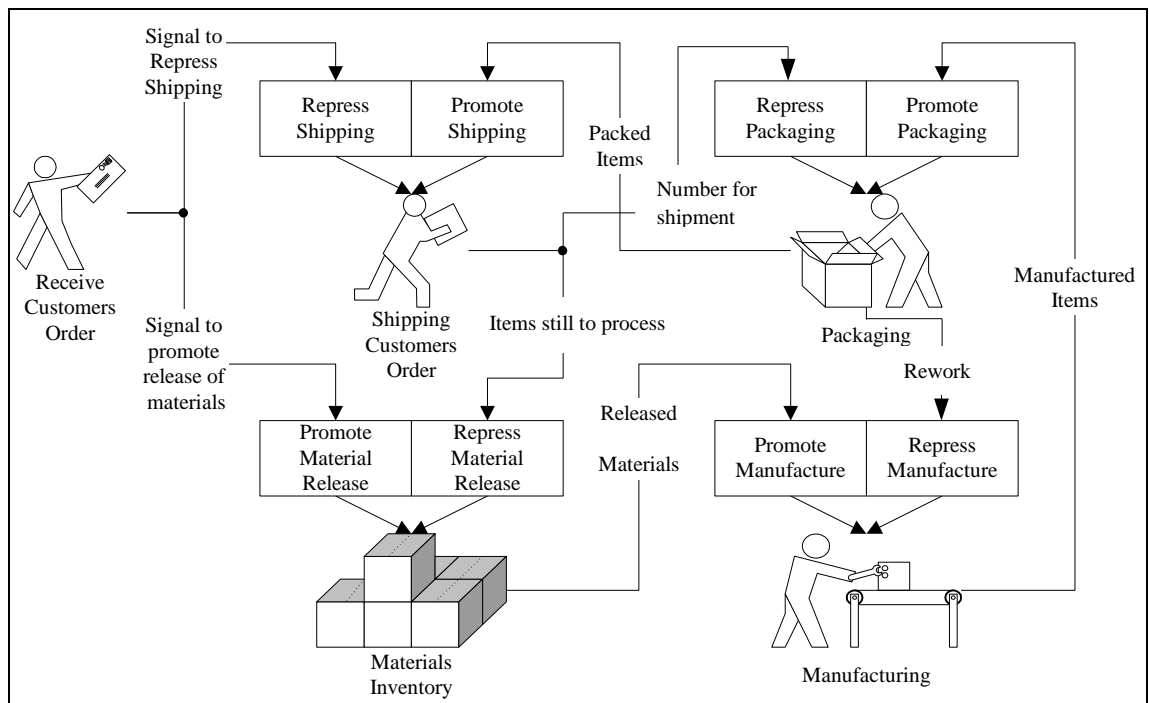


FIGURE 2.2: The idea of Regulated Finite Capacity Scheduling Approach (Stockton et al., 2008)

The autonomous decision-making in finite capacity scheduling may be transferred to individual machines and other resources in an effort to control production activities at each machine according to the objectives set for that machine based on the processing

factors of that machine and the prevailing interactions with other machines, as shown in Figure 2.2. In these interactions the machines may depend on the following factors:

- a) **Objectives:** each machine or resource has specific goals, which may not be compatible between themselves, leading to conflicts, such as activities and performance measurements.
- b) **Decision-making process:** machine may have difficulties to reach the best decision within a required recovery time, due to the local knowledge only
- c) **Manufacturing system:** depending on the manufacturing type, such as make-to-stock, make-to-order etc., different factors are considered and different relationships may be required.

Biologically inspired control methods are characterised by sets of rules for autonomous decision-making and indirect communication of the machines and other resources (Scholz-Reiter, 2008a; Scholz-Reiter, 2008b). From literature, modelling of finite capacity scheduling assumes that all the production requirements (such as cycle time, setup time, inter-arrival times, etc.) from customer orders are available to contribute to an optimal solution with consideration of the variability in these requirements. In this research, the variability of production requirements or factors is taken into consideration to determine the process variability of machines which contribute to the determination of the whole system set performance measurements. Also from the process variability determine the finite capacity availability of the processing machines.

By adopting biological control principles in this research, three different interaction mechanisms are identified:

- a) determination of variability in input finite capacity control factors;
- b) determination of machine variability, such as % waiting, % blocking, % stopped and % working, caused by variability of input control factors; and
- c) estimation of the recovery time (which in this case is the mean time to repair (MTTR)) from the disturbance that caused the variability and hence taking the appropriate processing action.

These interactions are modelled using Simul8 - a decision support simulation tool which the manufacturing industry uses to deliver improved performance through analysis of their processes. The variability in scheduling factors is simulated in the model to determine the process variability of the machines. This information together with principles learnt in biological control are then used to develop an autonomous finite capacity scheduling control logic to be used to manage resource allocation to manufacturing activities, thereby reducing excessive manual input involved in scheduling. The steps towards the experimental design are explained in *chapter four*.

Chapter 3: Finite Capacity Scheduling

3.1 Introduction

This chapter presents the explanation of rules for finite capacity scheduling where the proposed autonomous finite capacity scheduling logic can be developed around manufacturing flow lines as described in Section 2.4 which exhibit similar characteristics with biological systems. Capacity is viewed through each individual machine with consideration to all identified types of variability that affect the machines' availability. In other words, the sequencing process is done by considering the current load and capacity on the shop floor, i.e., when a set of orders is to be scheduled, and there are already orders in process, the arriving orders will adapt themselves to the capacity resultant from already approved schedules. Rules for finite capacity scheduling are presented in Table 3.1 and different existing planning and scheduling systems are briefly explained and some benefits of manufacturing scheduling are explained.

3.2 Overview of Manufacturing Planning and Scheduling

Planning and scheduling are often used interchangeably; however, they are quite different in the manufacturing sense. Planning is used to determine the long term requirements for manufacturing and considers diverse conditions that may occur such as overtime, capacity changes, and changing due dates (Pinedo, 2007).

Krajewski and Ritzman (2002) define scheduling as a process of allocating appropriate machines for the required manufacturing activities and to identify the sequence and timing parameter values to accomplish these activities. Scheduling therefore, determines

in what fashion manufacturing will be accomplished by determining the timing and location of particular activities to meet customer demand (Pinedo, 2007).

Omar et. al, (2007) defined scheduling as a decision-making process of allocating limited machines over time in order to perform a number of activities, for the purpose of optimising certain objective functions. Scheduling may allow for pre-emption of jobs by others released at a later point in time, based on differences in their priority levels, ready time, and processing times. Scheduling of customer orders differ in terms of:

- a. the number of machines per each process stage of the manufacturing facility;
- b. the link between orders and customer requests such as make-to-order or make-to-stock; and
- c. the level of uncertainty imposed on the scheduling activity (variability) as explained in *Section 3.9*.

The generalisation about the consistency and coordination of decisions as well as the availability of information may not hold true, especially in complex manufacturing systems.

Agrawalet.al (2000) studied planning in manufacturing facilities that produce large and complex assemblies, for which cycle times ranged between two months to two years. They employed a lead-time evaluation and scheduling algorithm for performing detailed backward scheduling of operations with cycle time minimisation as their sole performance measurement. The approximated lead times were scaled to account for capacity sharing effects by multiple products layouts and were used by a Material Requirement Planning (MRP)-based system to release work-orders to the shop floor.

Yoo and Martin (2001) explained several heuristics for a single-machine scheduling problem with the objective of minimizing the number of late jobs for a single due date and the number of early to late jobs for a due date window case. They developed backward scheduling procedure yielding satisfactory experimental results for a general class of early to late jobs ratio problems. Nonetheless, there was no consideration for the variability that caused lateness in jobs in this case, making the method hard to apply. Additionally in this work, relationships between machines were not considered as well.

Manufacturers can plan their processes based on customer orders, determined on the basis of the level of finished goods inventory, or the combination of the two. Serving customers from inventories is known as make-to-stock (MTS), whereas moving the decoupling point of customer orders to raw materials is called make-to-order (MTO) (Olhager and Rudberg, 2002). The difference between these two methods is that MTS focuses on projecting inventory levels and assuring promised customer service levels, while MTO pays more attention to product specifications and adjustment of manufacturing capacity to the requirements of customers.

In manufacturing scheduling, the power of mathematical methods and the benefits of management approaches such as lean practices are emphasised. There can, however, be scheduling of tasks/activities for which different types of disciplines are needed, especially if there are several types of variability being considered. Hence, this research studies and develops a control logic for finite capacity scheduling, making use of types of variability experienced in a manufacturing environment, and applying biological control principles as discussed in *Chapter two* to reduce much of the existing many highly skilled manual inputs in planning of activities . The research has

investigated different types of variability that may affect manufacturing processes as identified in Section 2.5. Attention is drawn to the effects developed on the process variability as a result of the different sources of variability as shown in Figure 2.1.

Sequencing of customer orders also involves determination of the direction in which jobs are to be run at a machine and thus determines the schedule. The assumption is that each job is started at the machine as soon as the machine has finished all predecessor operations and it has completed all earlier jobs in the sequence following the scheduling rules in Table 3.1. Scheduling does not entail creating information, but instead it incorporates, organises, and legitimises information already available from the logical sequences, time estimates and the prior experience (Framinan et al., 2011 and Omar et al., 2007), and therefore is the end result of the ideas and knowledge put into it during development.

Table 3.1 Rules for Finite Capacity Scheduling

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| <p>i. <i>Next job starts when the previous one ends and the previous operation on the machine is also finished</i> (Pongcharoen et al., 2004; Demeulemeester and Herroelen, 2011; Ebben et al., 2004);</p> <p>ii. <i>The next job starts on the first available machine</i> – schedule the next job on the list on a machine which is available first (i.e. the job starts its processing as early as possible (Hurink and Knust, 2001));</p> <p>iii. <i>The next operation starts when the first transfer batch is complete</i>. The process batch corresponds to the number of products that have to be produced consecutively on a machine before a next batch can be started on that machine (Demeulemeester and</p> |
|--|

Herroelen, 2011). The transfer batch specifies a number of products to be transferred to the next machine;

iv. ***The next operation of the same transfer batch cannot end before the previous operation*** (Dastidar and Nagi, 2007); the succeeding machine cannot start the job except the preceding one has completed its activities ensuring that the successor operation cannot end before the last unit from the predecessor operation has been finished. If the successor operation is faster than the predecessor operation, after every transfer batch completed, the successor operation will have to wait. Although it is faster, you cannot finish painting, for example, until the last frame of the next transfer batch is welded;

v. ***An assembly can start when the first batch of the last component is complete*** (Demeulemeester and Herroelen, 2011) and this translates into, and whenever the transfer batch size is smaller than the process batch size, processing on the succeeding machine does not have to await the completion of all products on the preceding machine and activities may overlap. When a batch equivalent to the transfer batch has been processed, the next operation will have to be done on that transfer batch;

vi. ***Processing does not start before it has to*** (pull system), such that an activity cannot be started earlier than its start time and must be completed by its deadline (Xue et al., 2001). Manufacturing occurs only when triggered by a downstream shortage removing the possibility of accumulating inventories and manages the workflow in the manufacturing flow lines. Therefore pulling is used to limit the amount of inventory that can be placed between processing machines;

vii. ***Apply three pass logic at all times*** (push, pull and push again) (Ozbayrak et al., 2004; Cheraghi et al., 2011). Forward scheduling (push) tries to schedule orders as soon as possible and may result in early or late completion of some finished products. Backward scheduling (pull) tries to complete all orders on their due dates and may result in early completion and an infeasible release date of some orders (an operation may be started in the past). With application of push – pull – push, the objective is to reduce the earliness associated with the forward (or first push) pass only of the system by delaying some early completion orders; and removing the infeasible completion or release date associated with the pull (backward scheduling). The idea is *push – pull – and – push again*.

Scheduling determines standardisation to handle machines, tools, planned maintenance, breakdowns, and other. (Stevenson et al., 2005), and have been identified by this research as different levels of variability that if they occur may result in:

- a. the schedule being revised;
- b. some procedures being developed that will force manufacturing to return to the original, planned schedule as soon as possible; or
- c. a new schedule being developed

These adjustments allow the operation to achieve the objectives that the plan has set, even when the assumptions on which the plan was based do not hold true.

In this research, the manufacturing system has been viewed as a set of interacting elements incorporating:

- i) a set of components that work together for the overall objective of the whole;
- ii) a set of variables that influence one another; and,
- iii) a series of functions or activities within the system that works together for the aim of the organisation.

Figure 3.1 shows how interacting the manufacturing system is in providing a variety of control points or many points of regulations.

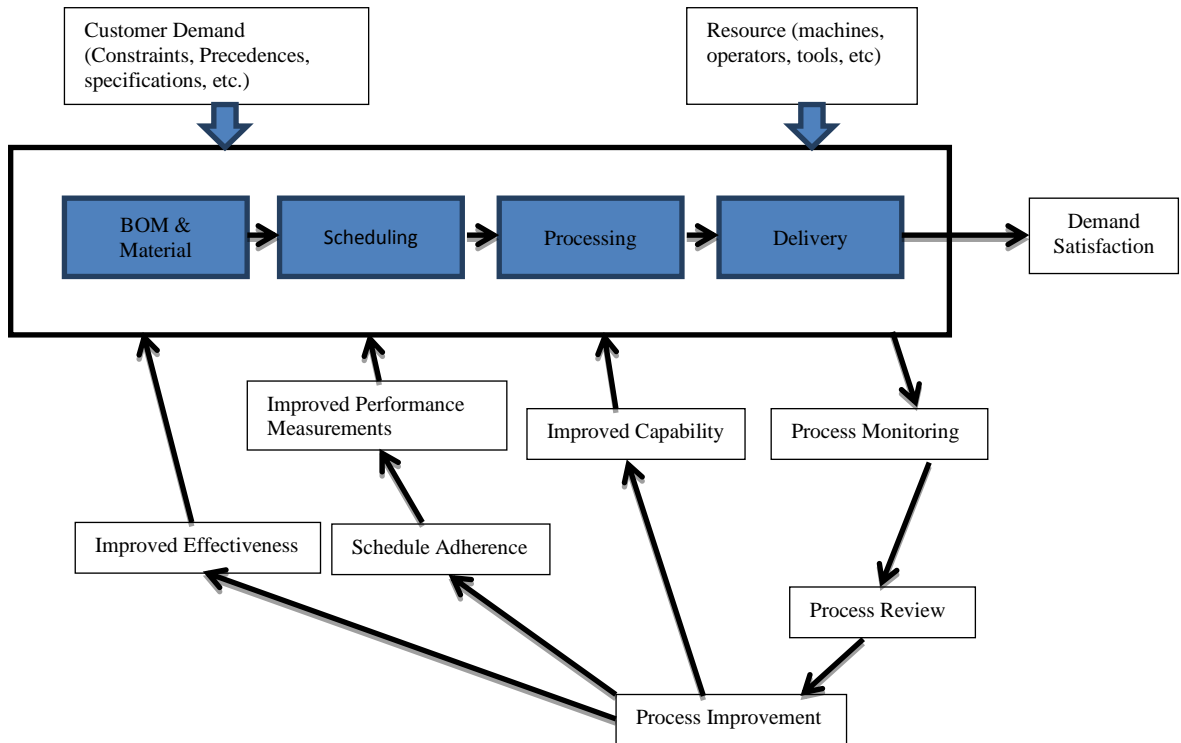


Figure 3.1: Manufacturing Process with Many Points of Regulation

The inputs are expressed as demand or customer requirements that include goals for the output and constraints on how those objectives are achieved. The outputs therefore become satisfied demands or customer orders. There are also process objectives and measures and process checking to determine if the objectives are being achieved followed by process reviews that determine whether process improvement is necessary. This ensures that the manufacturing process is going on well or if the processes need

changing; if there can be a better way of carrying out the process, and whatever is being produced is right as per the customer specifications.

3.3 Definition of Finite Capacity Scheduling

Finite capacity scheduling removes the assumption that sufficient capacity is available for processing when required, that is, removes the assumption that machines have infinite capacity. Material requirements planning (MRP) system, for example, (as will be explained in section 3.5) typically takes the orders, breaks them down into component parts and calculates when to start making them based on the individual lead times (Ho and Chang, 2001); however, no account is taken of the currently available capacity of the machine.

Saad et al., (2004) developed an integrated model for order release and due date management. Orders were scheduled by a horizontal backward finite scheduling method in a planning horizon that was broken into time buckets. The following five assignment rules were employed to determine their due dates:

- i. Total work content due-date rule (TWK);
- ii. The number of operations due-date rule (NOP);
- iii. Total work and number of operations due-date (TWK and NOP);
- iv. Equal slack due-date rule (SLK);
- v. The processing plus waiting due-date rule (PPW).

These rules estimate the flow time of the arriving order and then add the flow time allowance to the order release time (or the order's arrival time) and effectively determines the order due-date as the sum of the order flow time allowance and order release time. The fundamental difference among these rules is how to estimate the order flow time allowance.

Additionally, during the calculation of the customer order start times, the materials required in the manufacturing are ordered to arrive in time for the work to start. If there is a delay in the processing upstream of a particular operation then the materials may be ordered too early (Agrawal et al., 2000). Without concept of different source of variability such as bottlenecks available to the scheduling personnel, machines becoming overloaded, queues of work get longer and inventories of work-in-progress increasing.

Finite capacity scheduling methods vary substantially with respect to their scheduling algorithms and the performance measures they attempt to improve. It is therefore important to survey some of the definitions proposed by several authors for finite capacity scheduling so as to have a clear understanding of what it really is.

Srinoi (2002) defined finite capacity scheduling as the process of organising, choosing and timing machine usage to carry out all the activities necessary to produce the desired outputs. In finite capacity scheduling, the schedules and/or the capacity is adjusted as much as its rules can allow ensuring all the work is realistically planned and executed (Nafthal, 2000). In this case operations of each manufacturing processes are scheduled in relation with other processes based on the available capacity, and if there is any idle time that the job can start.

Sauer (2001) defined finite capacity scheduling as the creation of schedules which are temporal assignment of activities to machines with a number of performance measurement and variability considered. Nishioka (2005) defined it as an activity of allocating actions and operations to particular machines at particular times, taking into account various actual constraints and to minimise the errors and give the best solutions on several sources of variability. FCS therefore, calculates a schedule that does not exceed the machine capacity during the scheduling process, but does not account for the situations when operations are on-going sudden capacity unavailability occurs, such as breakdowns, operator absence, delayed arrival of parts and so on.

Finite capacity scheduling involves the determination of the sequence of operations to satisfy several conditions and goals concurrently, where limited machines, material and tooling, are allocated over the scheduling period among both parallel and sequential activities (Xiao-Feng et al., 2004). Often, finite capacity scheduling deals with differing objectives, multiple constraints, different configurations of shop floor, various simultaneous orders, the machines, etc. In many cases, the combination of multiple goals and constraints results in an exponentially growing scheduling problem.

Khalil et al. (2009) defined finite capacity scheduling as the process of allocation – over time – of the machines, within a short time of operation (possibly daily or weekly) and according to a specific criterion, such as due-date, tardiness and machine utilisation. In these definitions, the issues of capacity availability, manufacturing uncertainties and manufacturing constraints have been implied extensively as being the major inputs in finite capacity scheduling.

In summary, this research defines finite capacity scheduling as method to investigate and measure the effects of variability and solve problems regarding the allocation of machines to perform activities in manufacturing including:

- i. acquisition of relevant information relating to past, current and anticipated future events, such as when the current order will finish processing, scheduled maintenance, routing, setup times, machine speeds, and capacities (sources of variability);
- ii. breaking up the customer order and respectively scheduling each activity of the order to processing machines within available capacities; and
- iii. making decisions on how to meet the customer orders and organisation's set goals, such as performance measurements.

One of the key advantages of finite capacity scheduling (FCS) is the scheduling capability in which activities are never scheduled if the necessary parameters to produce a product are not fulfilled and process synchronisation enforced such that parts consumed by downstream machines are produced just-in-time by upstream machines. A machine in this case is viewed as a customer that gets materials from an upstream machine that acts as a store which replenishes the supply to the downstream machine. In this case, each machine acquires the required materials from upstream machine precisely as needed, or just-in-time. If materials are not available when a machine requires them, the entire system may be disrupted (MTTR).

From the above definitions it can be noted that finite capacity scheduling recognises the capacity of the machine – based on its scheduling rules (Table 3.1) – as being limited

and therefore it is a process whereby a sequence of orders is generated based on the real capacity of machines, operators, tooling or any constraint on the manufacturing process and informs the scheduler by indicating:

- i. which jobs are going to be late;
- ii. how late they are going to be;
- iii. what revised delivery dates can be provided, and;
- iv. how all these would change if the jobs were undertaken in a different manner.

Finite capacity scheduling enables responsiveness to the uncertainties which occur from time to time within the manufacturing system such as market conditions and customer demands to finish goods at the right time with the same available machines at the lowest cost, so as to remain competitive in the ever increasing challenges in economic conditions (Saad et al., 2004; Merkuryeva and Shires, 2004).

Finite capacity scheduling can be implemented either in *forward* or *backward* way, where:

- ***forward scheduling*** will schedule all operations of a job from the schedule start date to actual finite capacity, commencing with the first operation in its routing sequence, with the objective of completing the job as early as possible, and can be used to examine whether the earliest feasible completion time will meet a customer's requirements (Zhang et al., 2009);
- ***backward scheduling*** will schedule all activities to complete customer order from the due date, starting from the last operation in its routing sequence, with

the objective of completing the job on or as close as possible to its due date (Kolisch and Hartmann, 2006).

3.4 Components of Finite Capacity Schedule

Once the activities have been defined as shown in *Section 4.3* (identifying order requirements), and the details of finite capacity schedule have been determined based on the milestone dates and phasing information developed in the conceptual plan (based on the FCS rules as listed in Table 3.1), the detailed schedule is developed to model the processes used in product development. Briefly, some of the components of finite capacity schedule include:

- i. **Resources** – are the basic units of manufacturing system input (Figure 2.1) as well as for scheduling. Leitao and Restivo (2002) defined resource as an entity that can execute a range of jobs, when available, as long as its capacity is not exceeded. Based on this definition, a resource then includes machines, operators, tools, and storage space; however, in this research we take resources to mean *machines* so that we can differentiate them from *operators* for modelling purposes. Allocation of a machine to manufacturing activities will involve assignment of the required number of the machines identified to each activity of the job order. More than one machine may be linked to an individual activity.
- ii. **Constraints** – play the role of controlling or regulating how, when, and if an activity is performed and which outputs are obtained and hence provide the direction of process flow for efficient utilisation of machines. Examples of constraints include machine capacity availability, precedence relationship, and flow control. A number of constraints and their modelling features have been

identified (Martin and White, 2003) such as, (i) temporal (precedence and synchronisation); (ii) machine related (availability and utilisation), and; (iii) work order related (pre-emption or non-pre-emption).

- iii. **Activities** – these are the portions of the job that consume time and machines or at least time, has definable beginning and ending, and requires operators, machines, storage spaces, etc. (Bardak et al., 2006). An activity is the smallest element or building block and is obtained from decomposing the customer order, giving the opportunity to accurately schedule as compared to a manufacturing plan (Omar et. al, 2007). Assignment of activities to machines ought not to overlap (as explained in Table 3.1) such that two different activities cannot be assigned to the same machine at the same time. An activity may be logically linked with other activities to form the schedule. Creating viable activities for a schedule is necessary to achieving the set objectives of a manufacturing system as well as customer satisfaction.
- iv. **Variability** – different types of variability can interrupt the manufacturing activities and production as a whole. According, to Aytug et al., (2005), there is myriad variability that occurs in a manufacturing system, hence this research approaches manufacturing scheduling by focusing on local control policies determined by variability in some identified scheduling factors.
- v. **Calendar** – used to number working periods so that the components and work order scheduling may be done based on the actual number of periods available. The calendars indicate the cycle of shifts concerning each machine in the plant.

According to Alvarez and Diaz (2004), a calendar can use several working shifts, while a given shift can be applied to several calendars.

- vi. **Schedule Logic** - this is the basis behind scheduling such that it plays an important role in producing viable, completed schedule. Once the planning process is complete, the data is recognised and analysed by use of logic, which dictates the sequence of activities, the viability and the accuracy of the schedule (Stevenson et al., 2005). If any data becomes incorrect or the logic utilised is inaccurate, the controlling and managing process might adapt and amend the schedule to keep the process on time to the satisfaction of the customer. Scheduling depends fully on the *data*, *logic* and *experience*.

A schedule is therefore a planned effort to complete the manufacturing successfully within the constraints and the set organisational goals (Khalil et al., 2009), by identifying sequences of the manufacturing activities and allocating them to available machines while observing the variability of controlling factors. Once the right mix of manufacturing parameters is specified, the goal of scheduling becomes clear – to make efficient use of machines to complete activities in a timely manner (Chan, 2003).

Manufacturing scheduling normally involves jobs that travel along some fixed routes through various machines for processing. To get a better understanding of the complexity involved, Nanvala and Awari (2011) note some of the important characteristics observed and included in scheduling decisions:

- i. variety of products may be produced in batches, and some other jobs may be produced simultaneously;

- ii. jobs can arrive all at once or at varying times, and their due dates may be tight;
- iii. highly capital-intensive processing and material handling equipment may be employed;
- iv. processing equipment may be functionally versatile such that it can perform more than one activity;
- v. real-time control of scheduling decisions is required to respond to the dynamic behaviour of the system and to attain an effective utilisation of machines;
- vi. decisions about various manufacturing machines are required to be coordinated in order to exploit the flexibilities provided by alternate substitutes for some of the machines;
- vii. jobs are capable of travelling through different routings; and,
- viii. changes in customer demand.

It is important to note that due to the complexity involved in scheduling, no single approach to scheduling is best for all situations due to variability.

3.5 Existing Planning and Scheduling Systems

Planning and control concerns with managing the on-going activities of the operation so as to meet customer demand. All manufacturing activities require plans and control although the complexity of planning and controlling may vary greatly from order to order. This section provides overview of some planning and scheduling systems in use in manufacturing systems.

3.5.1 Material Requirement Planning (MRP)

This is an inventory control and manufacturing planning system that calculates demand for component items of products while keeping track of their work orders and purchase orders (Russell and Taylor, 2003). The MRP system informs on what product is processing and how much is needed to fill the order and stay on schedule (Ake et. al, 2004). MRP gets its information from the Master Production Schedule for demand, inventory status, open orders from the shop floor, planned orders from the shop floor, and Bill of Materials (BOM) to ensure the plant has the right quantities of the right parts at the right time and affects many functions of manufacturing (Langenwalter, 2000). MRP system assumes infinite capacity for both the manufacturing system and its suppliers (Langenwalter, 2000), scheduling with no regard to their capacity constraints (Russell and Taylor 2003). As a solution to this problem of infinite capacity, manufacturing systems have incorporated Capacity Requirement Planning (CRP) module that predicts capacity problems, however, it does not handle any scheduling but provides a means by which decisions can be taken (Mula et al., 2008).

3.5.2 Manufacturing Resource Planning (MRPII)

MRPII system combines the material planning and the shop floor with the business functions such as accounting and purchasing (Ake et al., 2004; Langenwalter, 2000). It is a hierarchical planning tool where the decisions made at one level impose constraints within which more detailed decisions are made at the lower level. Because of the existence of feedback from lower level to higher level, the decisions made at higher levels might be revised (Abdinnour-Helm et al., 2003; Hopp and Spearman, 2000).

MRPII provides a closed loop system by taking into account capacity when developing manufacturing schedules

3.5.3 Enterprise Resource Planning (ERP)

ERP system combines more functions such as logistics and distribution, operators, manufacturing engineering, maintenance management, manufacturing execution systems and advanced planning and scheduling systems (Bartels, 2004). An ERP system has a number of advantages including:

- i. achievement of a high level of functionality;
- ii. integrating systems at the plant and corporate levels, and;
- iii. improved information flow between the plant and the ERP system and vice versa.

When ERP systems are fully realised in an organisation, they can yield many benefits: reduce cycle time, enable faster information flow, facilitate better financial management, lay groundwork for e-commerce, and make hidden knowledge explicit (Abdinnour-Helm et al., 2003).

3.5.4 Manufacturing Execution Systems (MES)

These systems are used as online, integrated systems to communicate to the shop floor and to help make decisions about manufacturing. Orders are managed, use of material is maintained and information concerning material status, and collection of data to be put into the context for real-time decision making as well as historical analysis (Russell and Taylor, 2003). These systems can relay minute-by-minute changes on the plant floor,

where the traditional MRP or ERP respond less frequently. The difference between MRP and MES systems is that where MRP is more of planning tool, MES may include changing order priorities, assigning and reassigning inventory, moving inventory to and from machines, managing the manufacturing process, and scheduling and rescheduling machines (Langenwarter, 2000). MES systems have exceptional management where the systems have the ability to respond to raw material shortages and machine breakdowns. When an exception occurs, the MES system will reschedule orders and re-route the product flow.

3.5.5 Just in Time (JIT)

The Just-in-Time (JIT) manufacturing system, also called the *kanban* system, was developed in the 1960s by Toyota. In JIT system, work is only performed when a subsequent machine expresses the need for the work, making it a pull system as shown in Figure 3.1. The communication is accomplished by sending card, (kanban), to the previous machine to request another piece of work. In this case therefore, inventory is controlled by controlling the number of *kanbancards* in the system (Zhou et al., 2006).

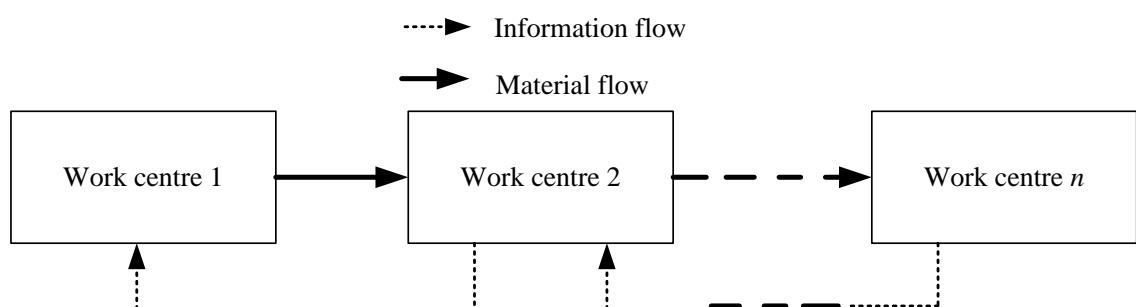


Figure 3.2 Material and kanban flow in JIT system

3.5.6 Scheduling by Theory of Constraints (TOC)

This provides planning and scheduling facilities for batch manufacturing environments, where it generates schedules using primary rules that enable machines to contribute towards achieving optimum values of throughput, inventory and operating expenses (Krajewski and Ritzman, 2002). The principal objective of constraint management is to establish a process of continuous improvement through synchronised processing, i.e. a systematic method of moving material quickly and smoothly through the manufacturing system in response to customer demand (Steyn, 2002). Theory of constraints then focuses on the constraint that blocks the achievement of goals of the manufacturing system, ignoring the capacity of all non-constraint machines which makes it difficult to apply the input and output buffers. In this research, however, the availability of both constrained and un-constrained machines are considered before scheduling can be implemented.

3.5.7 Advanced Planning and Scheduling (APS)

Advanced planning and scheduling systems are used to help manufacturers optimise schedules for either the plant floor of a single plant or they may have the ability to schedule multiple plants and warehouses. APS uses finite capacity scheduling that assumes a fixed capacity for machines and will not load more work than the machine's capacity (Russell and Taylor, 2003). They use many techniques such as linear programming, advanced mathematical formulae, heuristics and rules to create the best schedule for the manufacturing processes (Langenwalter, 2000). APS systems have the ability to simultaneously take into account capacity and material constraints when generating the manufacturing schedule. In APS systems, schedules are generated

considering the capacity of machines and the availability of materials, rather than the availability of machines only as is the case in finite capacity scheduling systems (Preactor, 2003).

3.6 Capacity

Krajewski and Ritzman, (2002) define capacity as the maximum rate of output for a process. Therefore there may be enough capacity provided to meet current and future demand to remain competitive in the global economy. Customer order need not be released into the system at or above the capacity as this will cause the system to become unstable (i.e., build up WIP without bound) (Hopp and Spearman, 2000).

According to Scholz-Reiter et al. (2002) capacity is divided into three important aspects:

- a) **Capacity of space**(buffers) – describing the physical space to store and manufacture raw material, sub-assemblies, and final products;
- b) **Capacity of time** – the working time in a day or week; and,
- c) **Capacity of manufacturing** – the volume of manufacturing, product variety, quality measures and other parameters depending on machine parameters and structure.

In this research when issues of capacity are mentioned such as availability of capacity, the three types of capacity will be in consideration such that capacity of space for manufacturing purpose will be issues of buffer capacity, capacity of time identifies whether the work presented can be done within the stated time of the calendar and

capacity of manufacturing addressing the issue of whether the manufacturing systems can process the presented work.

Sequence rules may be used to control the use of capacity as the schedule evolves from new information about operating conditions and so important decisions are made to determine which activity to process next the scheduler assigns the work to the right amount of capacity available. These rules handle the processes although they need to be defined in details for modelling and control purposes as listed in Table 3.1, used to ensure that the capacity of a machine is not exceeded at any given time.

Finite capacity scheduling therefore regards capacity in terms of the manufacturing workload and availability levels within a given time slot, and if necessary, the time slot may be extended in time to accommodate the manufacturing activity Krajewski and Ritzman (2001).

3.7 Benefits of Manufacturing Scheduling

Herrmann (2006); Leung (2004); Gupta et al., (2012); and Brucker (2007) identified some benefits of scheduling:

- i. monitors variability so as to adhere to customer order requirements;
- ii. the manufacturing system can be more *responsive to unexpected system change or change in demand* for the product requirements that would manifest themselves as updates on the execution status of activities as well as monitored conditions and machine status;

- iii. *helps to plan* for material procurement, preventive maintenance and committing to shipping due dates to customers (Horroelen and Leus, 2004);
- iv. provides *avenues or strategies* aimed at reducing total manufacturing lead time by working together with suppliers and customers on a continuous basis; and
- v. *vital for cash flow projections and provides a standard by which to measure the performance* of both management and shopfloor personnel enabling the organisation to estimate the completion times of their customer orders and take corrective action when needed. By doing this, it improves scheduling decisions and in turn allows for quoting of competitive and reliable due dates.

3.8 Finite Capacity Scheduling Factors

This research has identified scheduling factors and how they affect different types of processes within a manufacturing system. Reducing system variability improves the final performance.

From literatures, different factors or variables have been identified as introduced in section 2.5 and explain in Table 4.1, provide control for schedule development. (Pongcharoen et al., 2004; Chen and Chen, 2004; Pisinger and Ropke, 2005; Sarimveis et al., 2008); identified stoppages, queue time, operator skills, batch size as major causes of different kinds of variability experienced in manufacturing systems. Several of researchers have identified a variety of factors but for the sake of this research the variability explained in Section 2.5 have been selected for the development of the autonomous finite capacity scheduling logic. The identified scheduling factors are presented in Table 4.1.

3.9 Types of Scheduling Problems

The following is a brief of scheduling problems based on Ruiz et al., (2008):

- i. ***requirements generation*** – these are related to make-to-stock (MTS) where order generation is directly or indirectly based on the inventory replenishment decisions, or requirements generation could be directly from the customer as in make-to-order (MTO).
- ii. ***processing complexity*** – concerned with the number of process steps associated with each activity or item. This dimension is broken down into:
 - *One-stage, one-processor problem* – also termed one machine problem where all activities require one processing step which is to be done on the one manufacturing facility (Moghaddam, 2005);
 - *One-stage, multi-process* – means one stage and multi-processors that can be carried out in one or several machines (Oguz et al., 2004);
 - *Multi-stage manufacturing flow lines* – each activity requires processing at a set of facilities where typically there is a strict precedence ordering of the processing steps for a particular activity (Ruiz et al., 2008); and
 - *Multi-stage, job shop manufacturing* - it is possible to allocate a number of machines and route of operations to one job which may create a situation used for producing different types of products.

In this research we concentrate on the multi-stage manufacturing flow lines.

- iii. ***Scheduling with consideration to some performance measurements*** – describes the considered objectives that need to be taken into account in resolving the problem; often these criteria are many, complex and with interaction effects. For example, some of the scheduling criteria are to decrease the total time of late jobs, to increase machine utilisation, to decrease work-in-progress, and so on. Under this criterion the scheduling solution may contribute to the improvement of the manufacturing by providing feedback to enable decision making (Chan, 2003).
- iv. ***Consideration of variability*** – includes the degree of uncertainty of different variability in scheduling problems. This variability includes such factors as the characteristics, operation process times, sequencing, precedence constraints, delivery times as explained in Section 2.5 if the variability is not significant to the problem, then the scheduling problem is deterministic one, otherwise the problem may be considered stochastic one.
- v. ***Scheduling environment*** – can be identified in two categories static or dynamic. The scheduling problem with the identified number of jobs and a ready time for them is a static problem; otherwise a scheduling problem with variable number of jobs and a number of sources of variability considered is dynamic. In this research consideration is made to dynamic scheduling problems.

Manufacturing scheduling may generally involve moving activities around searching for optimal solutions in whichever type of manufacturing system and may encounter one or more classes of problems as explained above. As introduced in Section 3.2, scheduling will operationalise selected plans at the shop-floor level by determining exactly what each manufacturing facility has to do to complete the operations.

3.10 Properties of Successful Schedule

Schedules appear at various points and periods in the manufacturing process and are maintained to report on progress and forecast trends, work progress and completion (Fleischmann and Meyr, 2003). A manufacturing plan is modelled by a schedule using machines and execution strategy or logic, and accommodates and accounts for changes as they occur to exhibit the properties of successful schedules (Bacheldor, 2004).

A completed schedule is therefore a dynamic living document that adapts to modifications of the work and adjusts to changes in the duration of the manufacturing process. It may be revised and updated to reflect changes to the scope and methodology and provides ways to document all major changes to the process in order to communicate them to all appropriate parties.

Properties of a schedule are the foundations of the schedule that do not change since they form the basic make-up and concrete attributes of the schedule. Poncharoen et al. (2002) identified some properties of a good schedule as relates to the flow chart in Figure 4.2:

- i. being able to check and rearrange activities and precedence;
- ii. check capacity and adjust timing; and
- iii. identify and avoid deadlock

The success of a well-developed and implemented schedule is dependent on a solid plan and reflects the physical manufacturing and planning effort and has the ability to properly suggest achievable goals as implemented in the flow chart of Figure 4.4.

Chapter 4: Research Methodology and Experimental Design

4.1 Introduction

This chapter will discuss the methodology for the development of an autonomous finite capacity scheduling logic applying biological control principles. Biological control principles make use of ‘promoters’, and ‘repressors’ which are factors used to control system activities in an efficient and effective way, providing means of improving system synchronisation.

This research applies both qualitative and quantitative research approaches as discussed by Neuman (2000) and Babbie and Mouton (2001). The two research approaches when used together constitute a very important research approach, *triangulation*.

The main aim of the current research is to develop logic for autonomous finite capacity scheduling that will introduce proposed steps to improve the decision making functionality and reduce excessive skilled manual input control of production line activities.

The current research identifies four tasks as means to achieving the above aim:

- i. identifying scheduling factors that control process activities and determining appropriate performance measurements;
- ii. understanding biological control principles of application to manufacturing systems that will help to develop an autonomous decision-making in finite capacity scheduling;

- iii. developing the relationships between manufacturing and biological processes, to identify the scheduling factors, and develop rules for autonomous finite capacity scheduling control logic
- iv. integration of the simulation model with Design of Experiment (DOE) and biological control principles to test the new control logic in scheduling a customer order to attain the identified performance measurements. DOE is an experimental strategy that determines the solution with minimum effort or steps. It determines the inputs for running the process taking the option to take HIGH and LOW values of each, to obtain the best way of manufacturing.

The research here used a single product customer order as a case study to manufacture a souvenir clock as an example of any manufacturing processes. Nevertheless, the proposed method can be used for any service and manufacturing sectors as explained in Section 6.4.

4.1.1 Qualitative Research

Qualitative research studies things in their natural settings, attempting to make sense of, or interpret, phenomena in terms of the meanings people bring to them, as well as giving priority to what the data contribute to important research question or existing information (Denzin, 1994). In qualitative research, a range of philosophies, research designs and specific techniques, including: in-depth qualitative interviews; participant and non-participant observation; focus groups; document analyses; and a number of other methods of data collection (Pope et al., 2007; Olsen, 2003) are applied. A variety of methodological and theoretical approaches have been employed in qualitative research to study, design and analyse such as phenomenology; ethnography; grounded

theory; action research; case studies; and a number of others. Qualitative research includes a number of activities:

- i. historical research and qualitative research;
- ii. collection of narrative data to gain insights into phenomena of interest;
- iii. data analysis which includes the coding of the data and production of a verbal synthesis.

4.1.2 Quantitative Research

Quantitative research is a process of inquiry based on testing a theory composed of variables, measured with numbers, and analysed using statistical techniques and aims at determining whether the predictive generalisation of a theory holds true (Creswell and Maitta, 2002).

A number of activities identified for quantitative research (Bryman, 2004):

- i. categorisation of descriptive research, correlational research, causal-comparative research and experimental research;
- ii. collection of numerical data in order to explain, predict and or control phenomena of interest; and
- iii. statistical data analysis.

Johnson and Christensen (2004) identified various types of quantitative research in use:

- i. ***Descriptive***: involving collecting data in order to test hypotheses or answer questions concerning the current status of the subjects of the study and determines and reports the way things are.
- ii. ***Correlational***: attempts to determine whether and to what degree a relationship exists between two or more quantifiable variables, however, it never establishes a cause-effect relationship.
- iii. ***Cause-comparative***: establishes the cause-effect relationship compares the relationship, but the cause is not manipulated.
- iv. ***Experimental***: establishes the cause-effect relationship and does the comparison, but the cause is manipulated.

4.1.3 Triangulation

According to Bryman (2001) and Johnson and Onwuegbuzie (2004), the combination of different methodologies will generally lend to have a leading strategy for starting out the research, and a follow-up strategy for rounding out and widening the inquiry. Thurmond (2001) discusses five types of triangulation:

- i. **Data triangulation**: data sources can vary based on the data collected, the place or setting and from whom the data were obtained. Time triangulation means the collection of data at different times to determine if similar findings occur.
- ii. **Investigator triangulation**: this involves using more than one observer, interviewer, coder or data analyst in the study.

- iii. **Methodology triangulation:** uses multiple methods, which strive to reduce the deficiencies and biases that stem from any single method, creating the potential for counterbalancing the weaknesses of one method with the strengths of another.
- iv. **Theoretical triangulation:** uses multiple theories to support or refute findings.
- v. **Data-Analysis triangulation:** combines two or more methods for analysing data.

4.1.3.1 Benefits of Triangulation

Triangulation refers to the use of more than one approach to the investigation of a research question in order to enhance confidence in the ensuing findings. Triangulation offers the prospect of enhanced confidence and is one of the several rationales for multi-method research. The main objectives of this strategy include the following (Lincoln and Guba, 2000) and Cobb, 2000)):

- i. increasing confidence in research,
- ii. creating innovative ways of understanding a phenomenon,
- iii. revealing unique findings,
- iv. challenging or integrating theories, and
- v. providing a clearer understanding about the problem.

4.2 Research Methodology

As it has been found in literature, assembly of processes to produce proteins in a gene is a highly autonomous process involving a number of conditions to be fulfilled, and it is this characteristic ability to self-regulate protein production that is of important interest

to the industrial operations which will increase levels of autonomous decision-making and control manufacturing process in order to ensure that they respond effectively to changes in the increasingly competitive market and service environments.

This research is based on the information that useful insights can be gained for the future design of industrial and manufacturing systems from the study of biological systems like gene transcription and translation which display functionalities of autonomous decision-making.

From the operation point of view, production of a single protein requires a well regulated and coordinated assembly pathway. There are several checkpoints, which are vital in ensuring that some processes cannot be begun until some processes have been started or finished. This research describes the factors, and their interactions associated with the production process; including control of various activities in the production line processes, causing important checkpoints, which act as measures of the performance during the process and eventual completion of the process.

In order to achieve the research objectives, data was obtained from two different sources:

- i. from literature review of published work on finite capacity scheduling and biological control principles (as discussed in chapters two and three) to describe the core elements of the process.
- ii. data generation using a discrete event simulation technique to visualise the effects of variability in the finite capacity scheduling factors identified in (i) and how biological control principles can be adopted to improve system performance.

4.2.1 Discrete Event Simulation

Discrete event simulation is used in this research to integrate the finite capacity scheduling factors, collected data from literature and biological control principles to develop an autonomous decision-making in finite capacity scheduling. Despite this integration, several assumptions were made during the building of the model and these were necessary as variability still affects the idea of autonomous decision-making. The selected factors were considered input variability used to determine the process variability at machine levels and determine the machine availability.

According to Gupta and Sivakumar (2006); and Law and Kelton (2000), experimenting with a model as opposed to the real system, has the following benefits:

- i. the element of time can be accelerated so that long-term effects of the system can be understood in a much shorter time. In this research, the experiments were run for 21,000 minutes or two months of 8-hours a day;
- ii. the ability to study much larger or smaller versions of a system (physical scaling);
- iii. facilitates understanding of the real system and its behaviour by knowing what factors affect the system and how to go about resolving the many problems encountered in a real system (Abdulmalek and Rajgopal, 2007);
- iv. facilitates communication information about the process and provide a basis for discussion on the improvement of the manufacturing process (Abdulmalek and Rajgopal, 2007);

- v. what-if analyses can be carried out allowing the testing of the effects of different alternative scenarios before having to make changes in the real system (Semini et al., 2006).

Discrete event simulation lends itself to incorporation of additional details about the manufacturing system and therefore, may give more accurate estimates of manufacturing system behaviour. In general, DES is a practical methodology for understanding the high-level dynamics of a manufacturing system (Yücesan and Fowler, 2000).

Several simulation software are available for manufacturing modelling reported by different researchers; however, in this research, simulation software of choice is Simul8, which is a computer-based modelling package. The software supports the following functionalities some of which will be used in this research (Concannon et al., 2003):

- a. provides an easy-to-use, discrete-event simulation package that is used for supporting numerous decisions (Mustafee and Taylor, 2006);
- b. incorporates programming language (visual logic) and model visualisation capabilities that enable it to create accurate, flexible, and robust simulations more rapidly;
- c. provides helpful defaults to allow quick initial model building;
- d. performance data is collected automatically as required;
- e. models can be run at any speed so one can choose whether to see the dynamic animation or not;
- f. there is no limit to model size and number of work items (entities) in the model; and

- g. distribution choice can be set to depend on the time of day.

4.2.2 Design of Experiment (DOE)

Design of experiments (DOE) technique:

- a. tests different values of input factors and their effects on the outputs (Antony et al., 2006);
- b. identifies significant input factors affecting an output/response by separating the vital few from the trivial many;
- c. provides means for reducing variability by finding ways of changing the process but producing the same product;
- d. DOE provides a full insight of interaction between finite capacity scheduling factors of a manufacturing system and hence more responsive to changes in their values (Kwak and Choi, 2002).
- e. DOE uses specially constructed tables to make the design of experiments easy and consistent and requires relatively lesser number of experimental trials to study the entire parameter space (Mehat and Kamaruddin et al., 2011).

Each factor is a variable in this research and is selected with three levels due to the depth of the analysis of the current research, and according to Taguchi orthogonal array, L27, employed for the experimentation. There were 27 runs of experiments as presented in Table 4.6.

4.3 Research Steps

The following steps were proposed to support the attainment of the research objectives in this work. They are developed with a precedence such that, step 1 occurs first before step 2 occurs and so on up to step 8. Figure 4.1 presents the proposed research steps and are explained below:

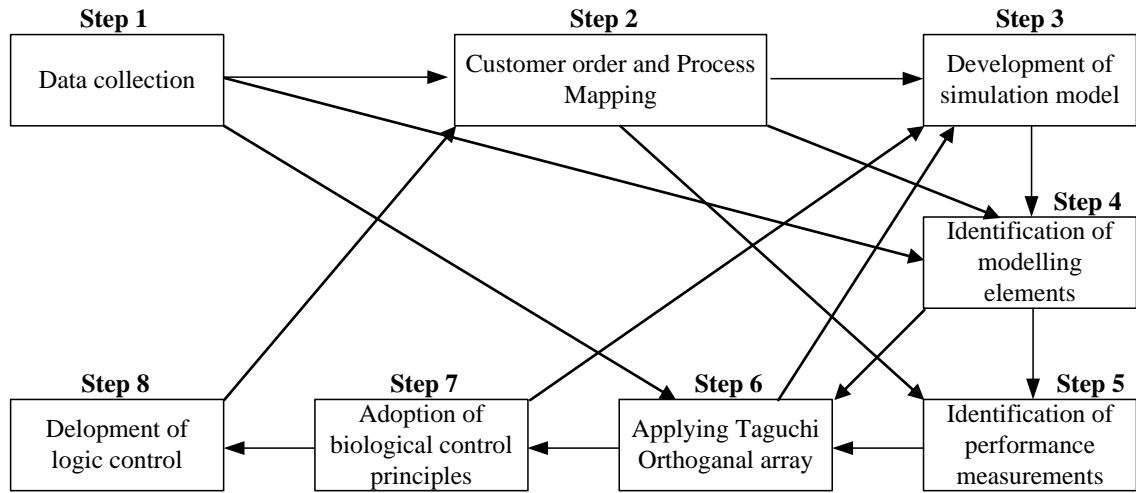


Figure 4.1: Proposed Research Steps

Step 1: Data Collection

Data collection is the first objective of this research, which is to derive a set of factors and effects concerning finite capacity scheduling. The factors and their effects are derived in a similar way, by reviewing the literature within the field of finite capacity scheduling. The collected data provided insight into the complexities of finite capacity scheduling, giving information regarding the control factors involved throughout the process.

Machines in a manufacturing system are subject to many sources of variability such as batching, rework, setup, and operator availability. All together introduce a substantial amount of variability in the inter-arrival and operational times of the parts during their flow through the system. Queue times are mainly influenced by variability and

utilisation; however, high utilisation leads to large cycle times for the parts (Jacobs et al., 2003). Therefore, relationships between the collected factors (input variability) were investigated to show their effect on finite capacity scheduling and identified performance measurements. The eighteen (18) factors initial identified scheduling factors are as listed in Table 4.1.

Table 4.1 Finite Capacity Scheduling Factors

Inter-arrival time	time between work items entering the system i.e. arrival time.
Throughput	completed items and ready to be dispatch to the customer.
Setup time	the period of time required to prepare a device, machine, process, or system for it to be ready to function or accept a job.
Batch size	number of work items of the same type to be processed at the same time
Transfer batch	the number of parts moved at the same time to the next workstation. In this research this factor has not been investigated and therefore has not been used.
WIP	unfinished items that can be found at different machines or storage/buffer
Job sequence	the order in which jobs or tasks are processed.
Due date	the date when material and or products are due to be available or required for use by the customer.
Rework	recycle defects item
Machine availability	the percentage of time that a machine is actually able to produce parts out of the total time that it may be able to produce.
Precedence relationships	specifies the order in which tasks may be performed to complete a product or a project.
Queue time	the amount of time work spends before being attended to, or before value adding work is performed on it.
Production calendar	used to number only working days so that the components and work order scheduling may be done based on the actual number of days available.
Capacity availability	the capability of a system or resource to produce a quantity of output in a particular time period.
Material/parts availability	raw materials that are actually ready to be worked on as opposed to scheduled work that may not yet be physically on hand.
Cycle time	this is time allocated for each machine to complete a specified task, e.g. the time for a punch press to cycle.
Lead Time	the time designated for a job to traverse a designated portion of the production process. Customer lead times are the times allotted to fulfill a customer request. Notice that lead times are management constants (i.e., set by policy), while cycle times are attributes of the system itself.
Utilization	the utilization of a station is defined as the ratio of the rate into the

	machine and the machine capacity.
Operator skills	determines the skill of the operator if they are non or multi-task that can allow operators to move down and upstream the production line

In modelling the customer order fulfilment, the research has identified nine scheduling factors/controllers for finite capacity scheduling as shown in Table 4.4 and explained in Section 2.5. Factors relate to each other in some way such as some factors feed into other or depend on others as illustrated in Table 5.1 in the following chapter.

Step 2: *Customer Order and Process Mapping*

From literature reviews the most time-consuming element in manufacturing control is identification of requirements for a customer order.

Clearly, finding a known solution appears to be the simplest and fastest method. Because of the variability in the production line, this research integrates a rule induction process learnt from biological processes for autonomous decision-making to cope with this dynamic environment. In the event of gathering information for modelling purposes, there was partial ordering of processes based on a customer order describing the product to be produced where some processes may precede others in time.

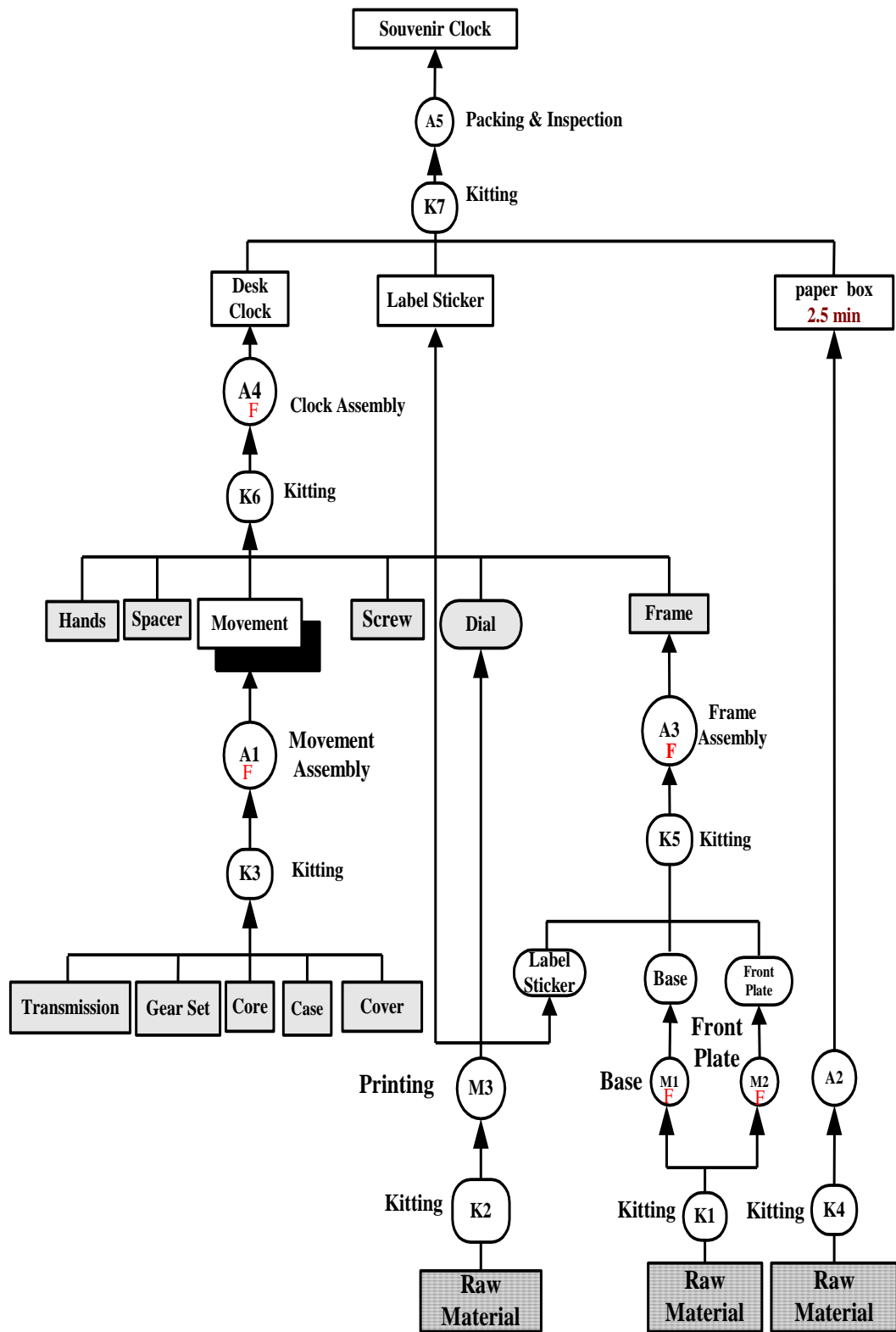


Figure 4.2: Flow Chart for Customer Order (Jiao et al. 2000)

Under this arrangement, the following information is collected indicating the general and initial specification decisions obtained from a customer order, as indicated from the flow chart in Figure 4.2:

- a. determining the range or families of components of part types to be produced or supplied – for all the part types to be produced, there may be identification of parts to be manufactured and /or assembled;
- b. determining how these part types shall be manufactured – check consideration for a number of and types of machine tools required;
- c. specifying types of variability in parts produced and the amounts of each; and
- d. specifying the type, capacity, and frequency of material supply in line with the cycle time for each machine (JIT considered).

Step 3: *Developing the Simulation Model*

The simulation model was developed based on customer order using Simul8 selected as an experimental tool because of the expertise in use of this tool at the Centre for Manufacturing. The model was developed for single product manufacturing process within 15 machines, and the discrete event simulation model was run for 21,000 minutes of manufacturing time as listed in Table 4.2. This run time was considered long enough to properly reduce any transient periods or conditions during production, as well as the conditions of parameters not considered during system initialisation. The finite capacity control factors were modelled as Boolean values with biological control principles.

Table 4.2: Simulation Parameters

Simulation Parameters	Value
Results Collection Period	It represented the result collection of 21,000 minutes.
Travel Time	It was set to Zero, as the model represent a real production process and evade the effect of any other factors that may change final results.
Random Time	No randomness as it represents a customer order as a case study.
Warm up time	It was set up to zero
Shift Pattern	8am-4pm equivalent to 8hrs per day , 5 days per a week
Probability Distribution	Triangle distribution was chosen because of the stochastic nature of the inter-arrival times and other control factors (Khalil, 2005).
Resources	Machines and operators are modelled with each having precondition factors before they can be used.

Step 4: Modelling Elements

The modelling elements were selected based on the customer order decomposition steps. Information on the relationships among components, logical information flow and input factors for each machine were modelled. The general planning and control objectives determining the factor variability were considered; all obtained from a customer order and the manufacturing routine as identified in Figure 4.2 and table 4.3 shows the modelling elements.

Table 4.3: Modelling Elements

Activity	Machine(s), Operators and Material used	Output Parts
Base & Front plate fabrication	K1 M1 M2 Operators Raw materials	Base Front plate Quantity
Printing	K2	Label stickers

	M3 Operators Raw materials	Dial Quantity
Frame assembly	K5 A3 Operators Base Front plate Label Sticker	Frame Quantity
Movement assembly	K3 A1 Operators Gear set Core Case Transmission Cover	Movement Quantity
Paper box preparation	K4 A2 Operators Raw material	Paper box Quantity
Clock assembly	K6 A4 Dial Frame Operators Hands set Movement Screws Spacers	Desk clock Quantity
Packaging & inspection	K7 A5 Operators Label sticker Desk clock Paper box	Souvenir clock Quantity

Step 5: Identifying Performance Measurements

Performance measurements are means by which a manufacturing system assesses its effectiveness in its operations to deal with the effect of any uncertainty or variability that can occur within customer order fulfilment (Kasunic, 2008). Performance measurements make systems responsive to demand changes, monitoring quality and

quantity variability, plan for material supply, improve material delivery and help in production decision-making in a variety of situations (Chan, 2003).

The performance measurements provide feedback information from the system with respect to meeting customer expectations and strategic objectives, reflecting the need for improvement in areas with unsatisfactory performance.

Step 6: *Minimising Factors and Applying Taguchi Orthogonal Array*

a) Minimisation of Design Factors

The initial eighteen (18) finite capacity scheduling factors, were reduced to nine (9) listed in Table 4.4, since some were well represented in others while others were identified to be hard to measure.

Table 4.4 Factors Identified for Modelling.

Scheduling Factors	Modelling Parameter
Inter-arrival time	Numbers
	Distribution
Cycle time	Time
	Distribution
Batch size	Time
	Distribution
Operator skills	Skills level (High [3], Medium [2] & Low [1])
	Distribution
Queue time	Time
Rework	% Rework
	Distribution
Setup time	Time
	Distribution
Short stoppage	Time
	Distribution
Long stoppage	Time
	Distribution

All these factors are considered as different types of variability that can be measured in the form of %working, %waiting, %blockage, and %stoppage. Accordingly, determines the overall performance measurements for the production line, that is, they affect *throughput*, *throughput rate*, *queue time* and *lead time*. In this research, the design undertook to use nine factors identified in experimental data in Table 4.4, each of which was set at three levels as shown in Table 4.5.

b) Applying Taguchi Orthogonal Arrays

Taguchi techniques were used because a number of reasons; first, it is a structured method of experiments for investigating the types of variability among factors, and uses experiments to establish that subset of those factors which has the greatest influence on the performance measurements. Taguchi techniques include a set of tables that enable main variables/factors and interactions to be investigated in a minimum number of trials. Minitab was used to determine which factor had significant effect and the contribution of each factor towards the identified process variability and selected production line performance measurements. L-27 was chosen for this experiment because of the nine (9) factors at different levels of variability.

Each one of the manufacturing activities was controlled by each factor in the Table 4.4 varying within three levels as shown in Table 4.5. The three levels have been chosen because of the application of the triangular distribution introduced in section 4.1.3. According to Khalil (2005):

- i. triangular distribution provides an acceptable trade-off between accuracy of results and ease of estimation of the distribution parameters;

- ii. its functions can be completely defined by estimating for an activity, its absolute minimum value, likely value and absolute maximum value; and,
- iii. both the absolute minimum and maximum values can be skewed about the most likely value to provide a skewed distribution if appropriate.

The interactions among the parameters offer the required input to control the production line activities, significantly saving on resource usage, material and other requirements that can then be used in times of excessive need.

Table 4.5: Finite Capacity Scheduling Factors with their Variability Levels

Factor Level	Batch size (units)	Cycle time (min)	Inter-arrival time (min)	Operator skills (level)	Queue time (min)	Rework (%)	Setup time (min)	Short stoppage (min)	Long stoppage (min)
1	1	4.5	60	1	5	2	5	5	50
2	5	5.5	120	2	10	4	10	10	150
3	9	6.5	180	3	15	6	15	15	200

Level: 1 = low; 2 = medium; and 3 = high

Table 4.6: L27 Experimental data for the model and the units used

Run No.	Batch size (items)	Cycle time (Minutes)	Inter-arrival time (Minutes)	Operator skills (Level)	Queue time (Minutes)	Rework (%)	Setup time (Minutes)	Short stoppage (Minutes)	Long stoppage (Minutes)
1	1	4.5	60	low	5	2%	5	5	50
2	1	4.5	60	low	10	4%	10	10	150
3	1	4.5	60	low	15	6%	15	15	200
4	1	5.5	120	medium	5	2%	5	10	150
5	1	5.5	120	medium	10	4%	10	15	200
6	1	5.5	120	medium	15	6%	15	5	50
7	1	6.5	180	high	5	2%	5	15	200
8	1	6.5	180	high	10	4%	10	5	50
9	1	6.5	180	high	15	6%	15	10	150
10	5	4.5	120	high	5	4%	15	5	150
11	5	4.5	120	high	10	6%	5	10	200
12	5	4.5	120	high	15	2%	10	15	50
13	5	5.5	180	low	5	4%	15	10	200
14	5	5.5	180	low	10	6%	5	15	50
15	5	5.5	180	low	15	2%	10	5	150
16	5	6.5	60	medium	5	4%	15	15	50
17	5	6.5	60	medium	10	6%	5	5	150
18	5	6.5	60	medium	15	2%	10	10	200
19	9	4.5	180	medium	5	6%	10	5	200
20	9	4.5	180	medium	10	2%	15	10	50
21	9	4.5	180	medium	15	4%	5	15	150
22	9	5.5	60	high	5	6%	10	10	50
23	9	5.5	60	high	10	2%	15	15	150
24	9	5.5	60	high	15	4%	5	5	200
25	9	6.5	120	low	5	6%	10	15	150
26	9	6.5	120	low	10	2%	15	5	200
27	9	6.5	120	low	15	4%	5	10	50

Step 7: *Adapting Biological Control Principles*

After the identification of levels of variability, this step applies control principles as learnt from biological processes which handle a lot of variability. Through literature review, it is possible to adopt biological control principles observed in gene transcription and translation into finite capacity scheduling. Biological control principles may be vital in developing autonomous decision-making in finite capacity scheduling and thereby reducing the skilled manual input in planning of tasks. Some of the methods used to model biological processes have been identified in Section 2.7. From the biological control principles, choice of appropriate control factors could be used to develop control logic for a variety of situations. Figure 4.3 (Appendix A) illustrates the principles of biological control using repressor – promoter combination in protein production in a biological cell. It has been found that processes in biological systems are subjected to certain constraints that limit their possible behaviours as a way of providing control (Palsson, 2000):

Figure 4.3 in *Appendix A* provides information on how manufacturing systems could benefit from control principles learnt from biological systems. Three distinct stages for biological control were identified as follows (Scatena, 2007);

- i. The match process finds rules that match against the current condition in the process since there may be several instances where the same rule may match against a process in different ways;
- ii. The conflict-resolution process selects one or more of the rules instantiated in
(a) for application; and

- iii. The act process applies the instantiated actions of the selected rules, thus modifying the contents during the process.

This information is important in understanding the requirements in the development of autonomous finite capacity scheduling control logic. Because a number of rules are tested to determine their applicability to the situation at hand, the system is termed autonomous since there is no control from external.

Steps 8: *Logic Development*

Step 7 provides some control issues and how variability is dealt with in biological systems to attain the same set objectives. Figure 4.4 shows the steps followed in developing the autonomous finite capacity scheduling control logic. This is a generic type logic that can be applied anywhere by modifying it as per the situation because of the operation-based rules.

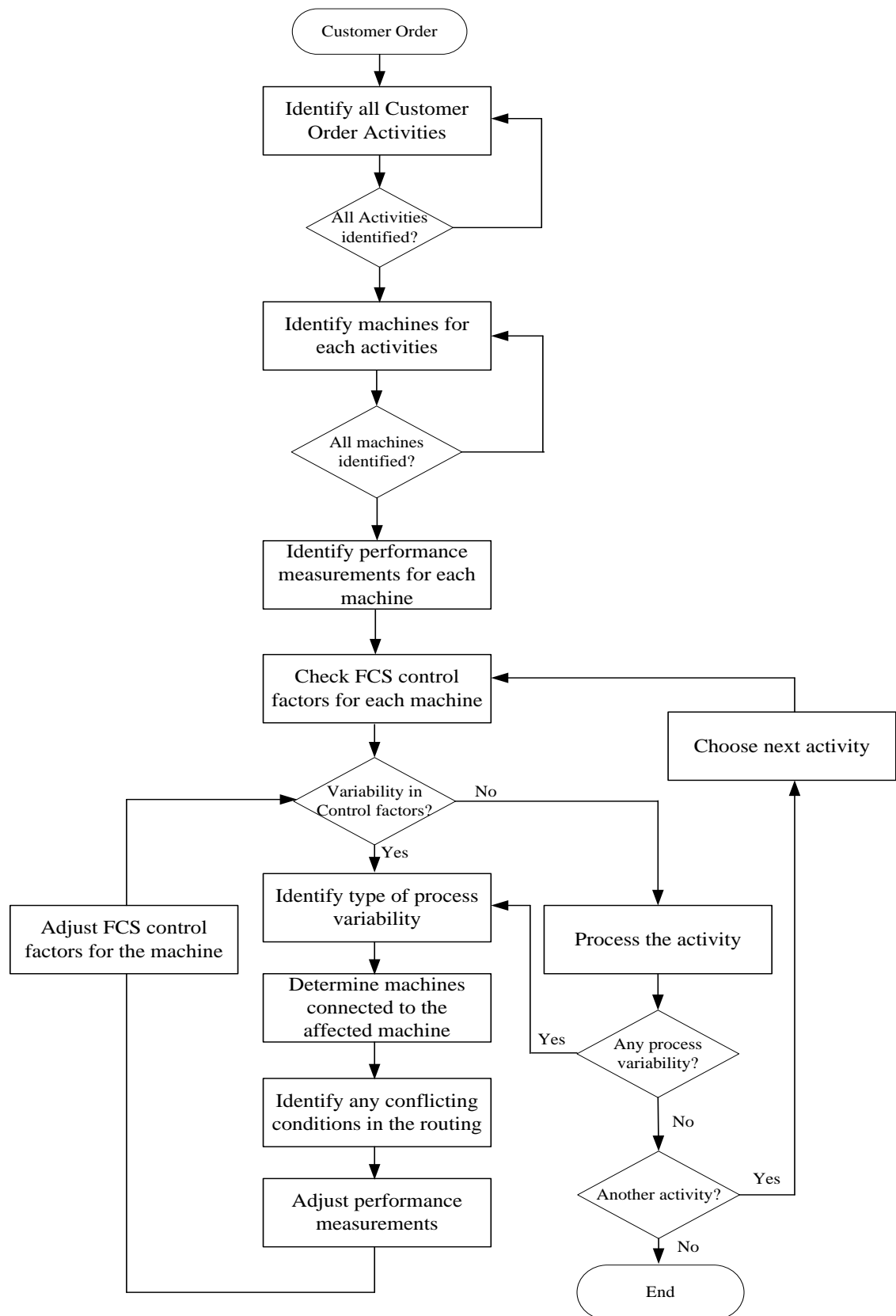


Figure 4.4: Autonomous scheduling procedure

Chapter 5: Results and Analysis

5.1 Introduction

This chapter presents the results obtained from implementing the steps outline in Section 4.3 demonstrating the usefulness and possibilities of adopting biological control principles in autonomous finite capacity scheduling. The results from the experiments showed that there are significant improvements in all the performance measurements identified and because of this, variability in identified factors affects the overall system performance. This effect enables the development of the control logic for the autonomous finite capacity scheduling adopting biological control principles. The experiments showed that scheduling is controlled by variability of different kinds; additionally, variability in factors has different effects on machine variability.

5.2 Results of the Research Experiments

Step 1: *Data collection*

The triangulation research method was used in data collection where both qualitative and quantitative research methods were applied. Methodological triangulation was adopted here by obtaining information from published data used in the simulation model in Step 3.

This research has identified nine factors for modelling purposes that are used as the controllers for finite capacity scheduling as shown in Table 4.4. The matrix shows how the factors affect each other and where each feeds into or utilises the same output information. For example; *Batch size* [1] feeds or affects *Inter arrival time* [3], *Queue*

time [5], *Rework* [6] and *Setup time*[7], while *Short stoppage* is fed by *Cycle time* [2], *Inter arrival time* [3], *Operator skills* [4], *% Rework* [6] and *Setup time* [7].

These relationships flow through the machines as production proceeds and hence relationships between machines also exist such that one machine may have a direct or indirect effect on another machine.

Table 5.1: Relationship between factors

	1	2	3	4	5	6	7	8	9
<i>Batch site</i>	1	1	X		X	X			
<i>Cycle time</i>	2		2	X	X	X	X	X	X
<i>Inter arrival time</i>	3	X	X	3	X			X	X
<i>Operator skills</i>	4			4					
<i>Queue time</i>	5	X	X	X	5	X	X	X	X
<i>% Rework</i>	6	X	X	X	X	6	X	X	X
<i>Setup time</i>	7	X	X	X		X	7		
<i>Short stoppage</i>	8		X	X		X	X	8	
<i>Long stoppage</i>	9		X	X					9

Step 2, 3 and 4: Customer order and Process mapping, Development of simulation model, and Modelling elements and Attributes

The idea represented by Figure 4.2 is implemented as a simulation model. The figure also provided necessary information to determine the manufacturing steps, inputs in terms of raw materials or parts and number of machine in the routine for each part produced to make the final product.

Each activity from the customer order may be accomplished using one or more machines, in conjunction with the production constraints and input factors (identified for each machine) to control the activities of each machine. Table 5.2 shows the input machines, input activities, modelling elements, input factors together with their attributes, and expected outputs.

Table 5.2: Modelling Element and Attributes

Activity	Machine(s) and Materials	Inputs	Attribute (Variability levels)			Output
Base & Front plate fabrication	K1 M1 M2 Operators Raw materials	Batch size (no.)	1	5	9	Base Front plate Quantity
		Cycle time (min)	4.5	5.5	6.5	
		Inter-arrival time (min)	60	120	180	
		Operator skills (level)	1	2	3	
		Queue time (min)	5	10	15	
		Rework (%)	2	4	6	
		Setup time (min)	5	10	15	
		Short stoppage (min)	5	10	15	
		Long stoppage (min)	50	150	200	
Printing	K2 M3 Operators Raw materials	Batch size (no.)	1	5	9	Label stickers Dial Quantity
		Cycle time (min)	4.5	5.5	6.5	
		Inter-arrival time (min)	60	120	180	
		Operator skills (level)	1	2	3	
		Queue time (min)	5	10	15	
		Rework (%)	2	4	6	
		Setup time (min)	5	10	15	
		Short stoppage (min)	5	10	15	
		Long stoppage (min)	50	150	200	
Frame Assembly	K5 A3 Operators Base Front plate Label Sticker	Batch size (no.)	1	5	9	Frame Quantity
		Cycle time (min)	4.5	5.5	6.5	
		Inter-arrival time (min)	60	120	180	
		Operator skills (level)	1	2	3	
		Queue time (min)	5	10	15	
		Rework (%)	2	4	6	
		Setup time (min)	5	10	15	
		Short stoppage (min)	5	10	15	
		Long stoppage (min)	50	150	200	
Movement assembly	K3 A1 Operators Gear set Core Case Transmission Cover	Batch size (no.)	1	5	9	Movement Quantity
		Cycle time (min)	4.5	5.5	6.5	
		Inter-arrival time (min)	60	120	180	
		Operator skills (level)	1	2	3	
		Queue time (min)	5	10	15	
		Rework (%)	2	4	6	
		Setup time (min)	5	10	15	
		Short stoppage (min)	5	10	15	
		Long stoppage (min)	50	150	200	
Paper box preparation	K4 A2 Operators Raw material	Batch size (no.)	1	5	9	Paper box Quantity
		Cycle time (min)	4.5	5.5	6.5	
		Inter-arrival time (min)	60	120	180	
		Operator skills (level)	1	2	3	
		Queue time (min)	5	10	15	
		Rework (%)	2	4	6	
		Setup time (min)	5	10	15	
		Short stoppage (min)	5	10	15	
		Long stoppage (min)	50	150	200	
Clock assembly	K6 A4 Dial Frame Operators Hands set Movement	Batch size (no.)	1	5	9	Desk clock Quantity
		Cycle time (min)	4.5	5.5	6.5	
		Inter-arrival time (min)	60	120	180	
		Operator skills (level)	1	2	3	
		Queue time (min)	5	10	15	
		Rework (%)	2	4	6	
		Setup time (min)	5	10	15	

Packaging & Inspection	Screws	Short stoppage (min)	5	10	15	Souvenir clock Quantity
	Spacers	Long stoppage (min)	50	150	200	
	K7	Batch size (no.)	1	5	9	
	A5	Cycle time (min)	4.5	5.5	6.5	
	Operators	Inter-arrival time (min)	60	120	180	
	Label sticker	Operator skills (level)	1	2	3	
	Desk clock	Queue time (min)	5	10	15	
	Paper box	Rework (%)	2	4	6	
		Setup time (min)	5	10	15	
		Short stoppage (min)	5	10	15	
		Long stoppage (min)	50	150	200	

Step 5: Performance Measurements

To measure the effectiveness of the proposed method, the following eight performance measurements in Table 5.3 were used in testing the logic control for autonomous finite capacity scheduling. The output variability (occurring at machine level) being affected by the variability of finite capacity scheduling factors, has been considered as performance measurements in this research. The output variability is used to determine the overall system performance measurements identified as *throughput*, *throughput rate*, *lead time* and *queue time*. Figure 5.1 shows the objective as relates to each performance measurement.

Table 5.3: Manufacturing performance measurements used in this research

Performance measurement	Representation	} Process variability
Working	percentage	
Waiting	Percentage	
Blocking	Percentage	
Stopped	percentage	} System performance measures
Throughput	finished parts	
Throughput rate	finished units/minutes	
Lead Time (LT)	minutes	
Queue Time	Minutes	

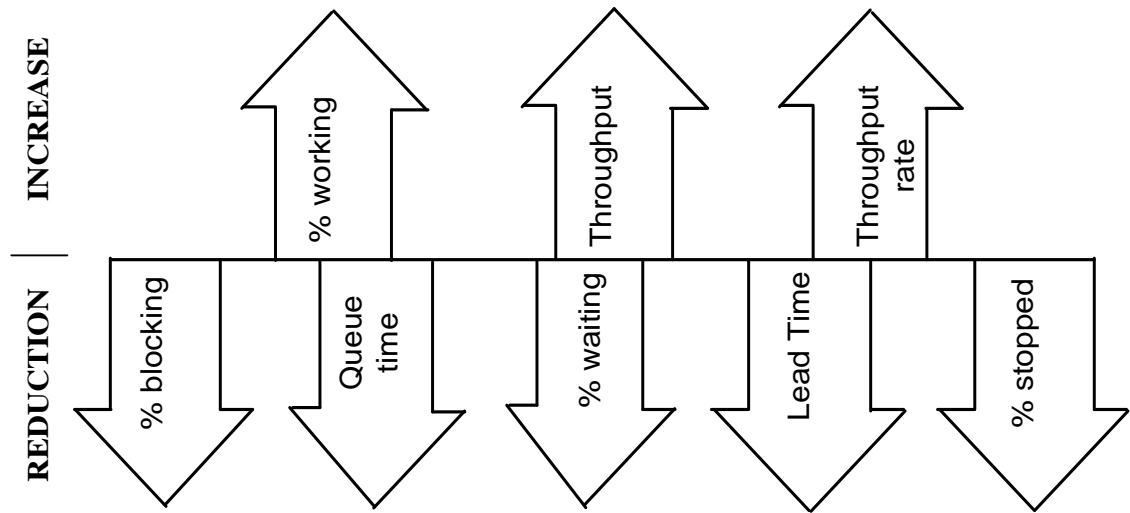


Figure 5.1: Overall objective of the selected performance measurements

The aim of the methodology is to reduce % *blocking*, % *waiting*, % *stoppage*, *queue time* and *lead time*, but to increase the % *working*, *throughput* and *throughput rate*.

Step 6: Applying Taguchi Orthogonal Array

According to the number of factors identified and the levels of depth needed, Taguchi L27 OA was chosen and the values for the set of process parameters for each work centre were identified. The experiments were run for 21000 minutes each and a total of twenty seven (27) experiments were obtained. Triangular distribution was used to represent the variability in machines operation. Table 4.3 shows the factors and levels used and Table 5.2 shows the results obtained after running the experiments before the application of the logic control.

Figure 5.2 show the analysis by running DOE to determine the effect each of the nine factors has on the eight performance measurements identified as shown in Table 5.3.

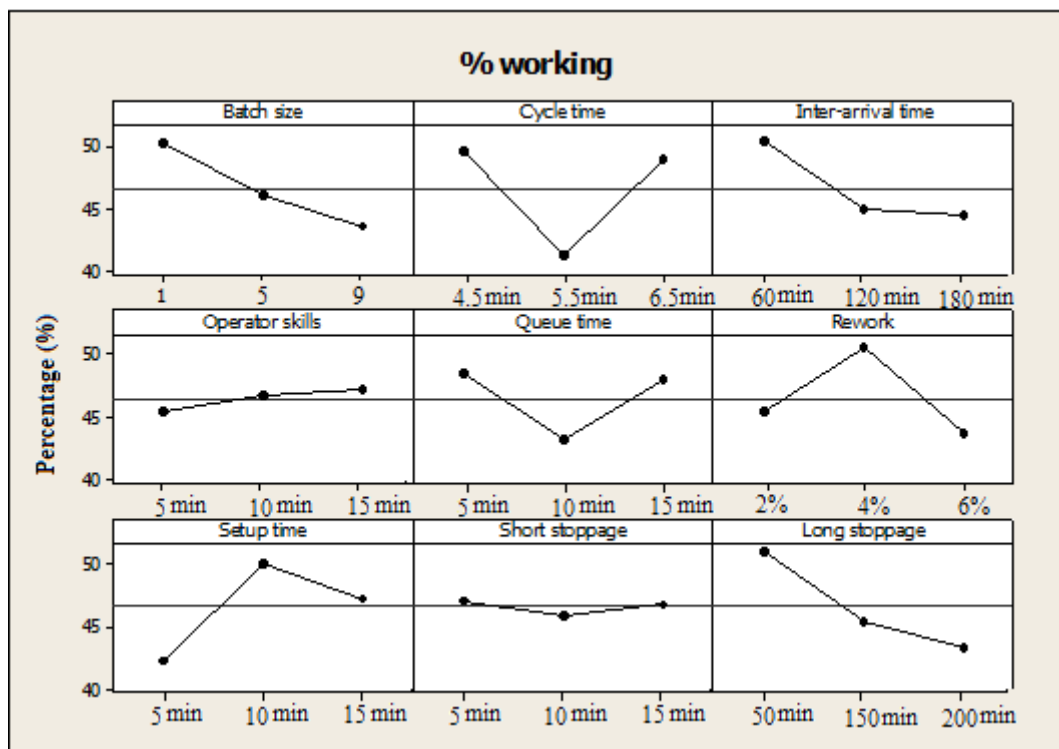


Figure 5.2 analysis of running DOE on % working

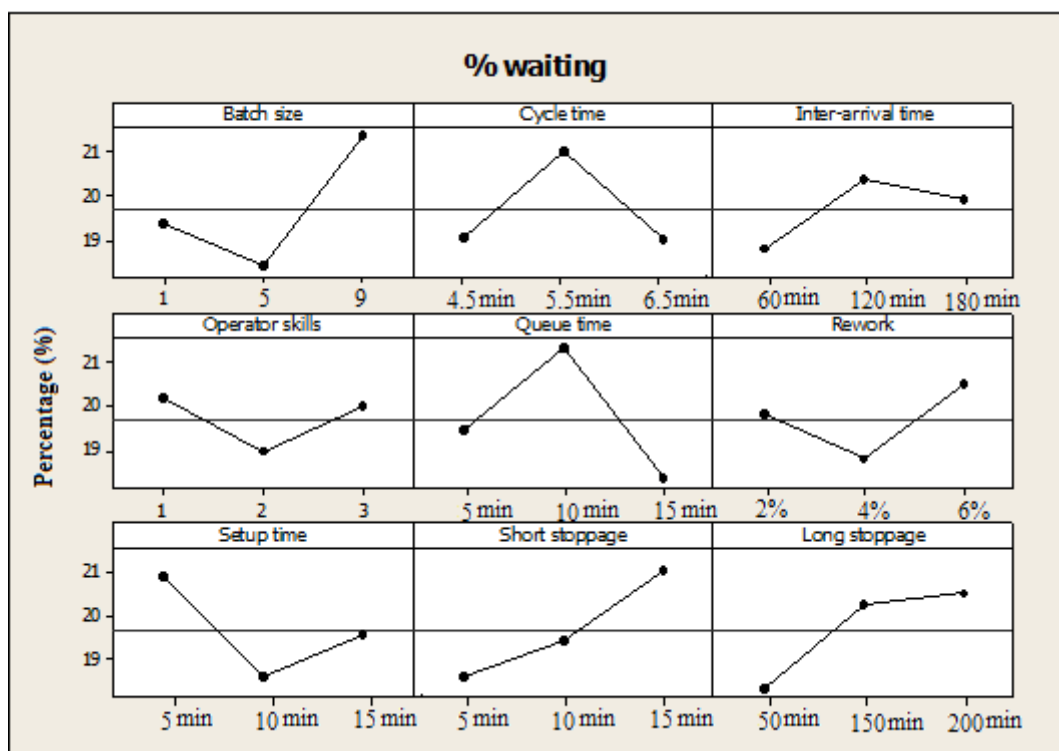


Figure 5.3 analysis of running DOE on % waiting

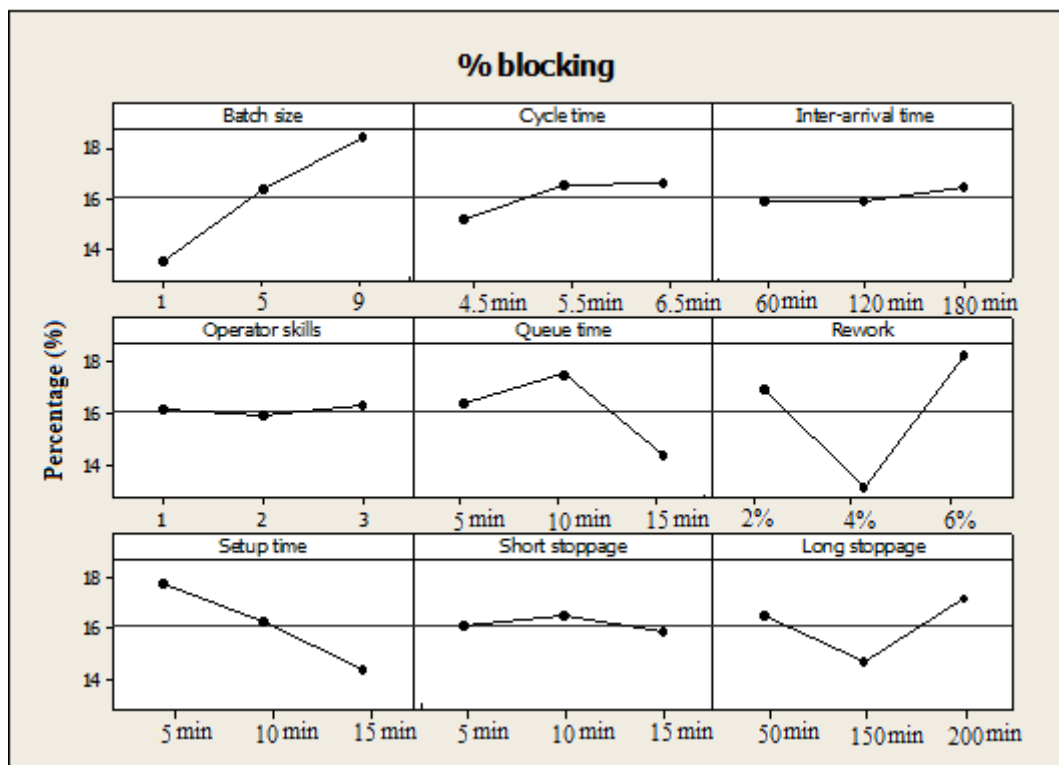


Figure 5.4:analysis of running DOE on% blocking

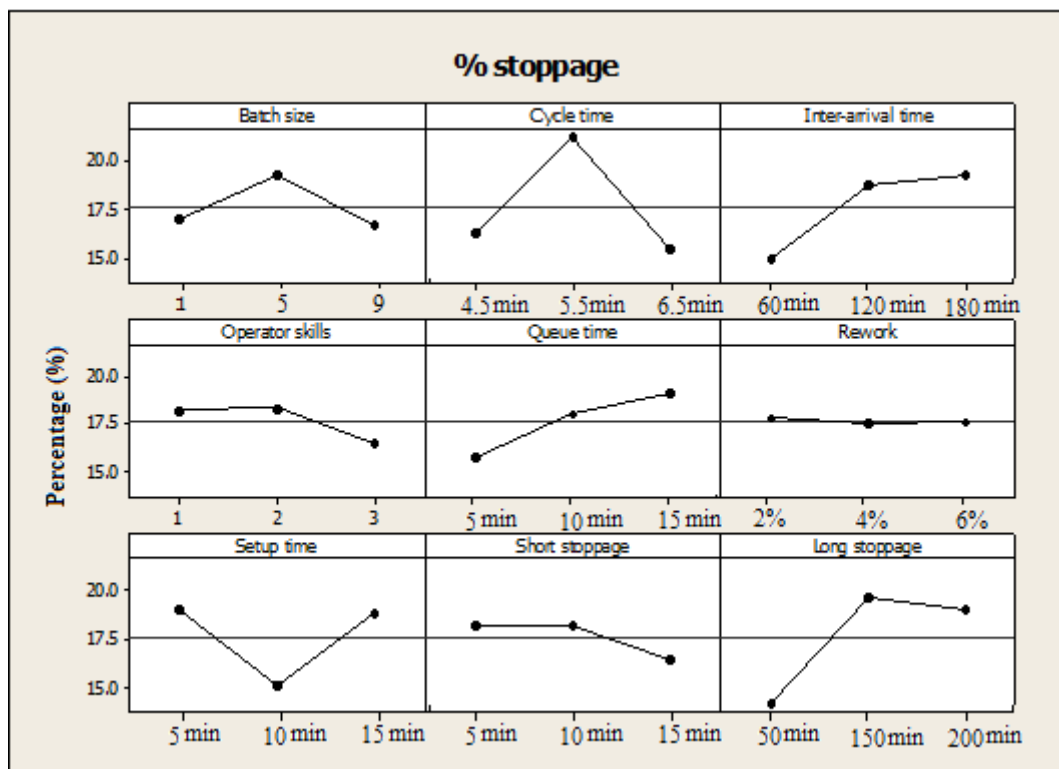


Figure 5.5:analysis of running DOE on % stoppage

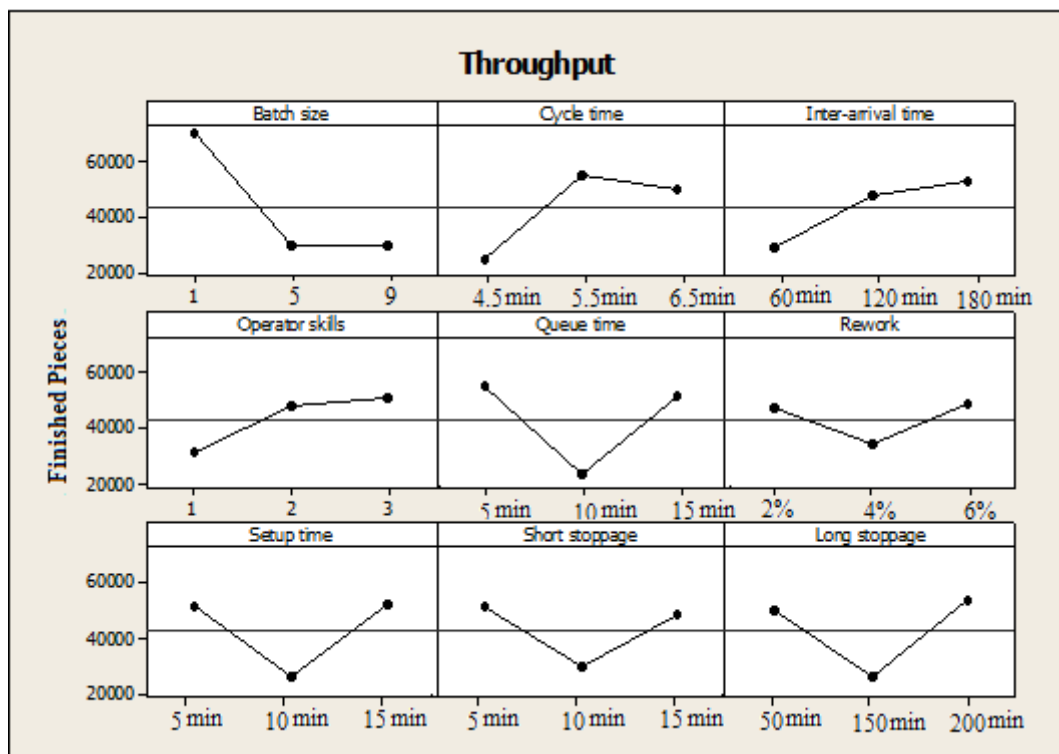


Figure 5.6: analysis of running DOE on throughput

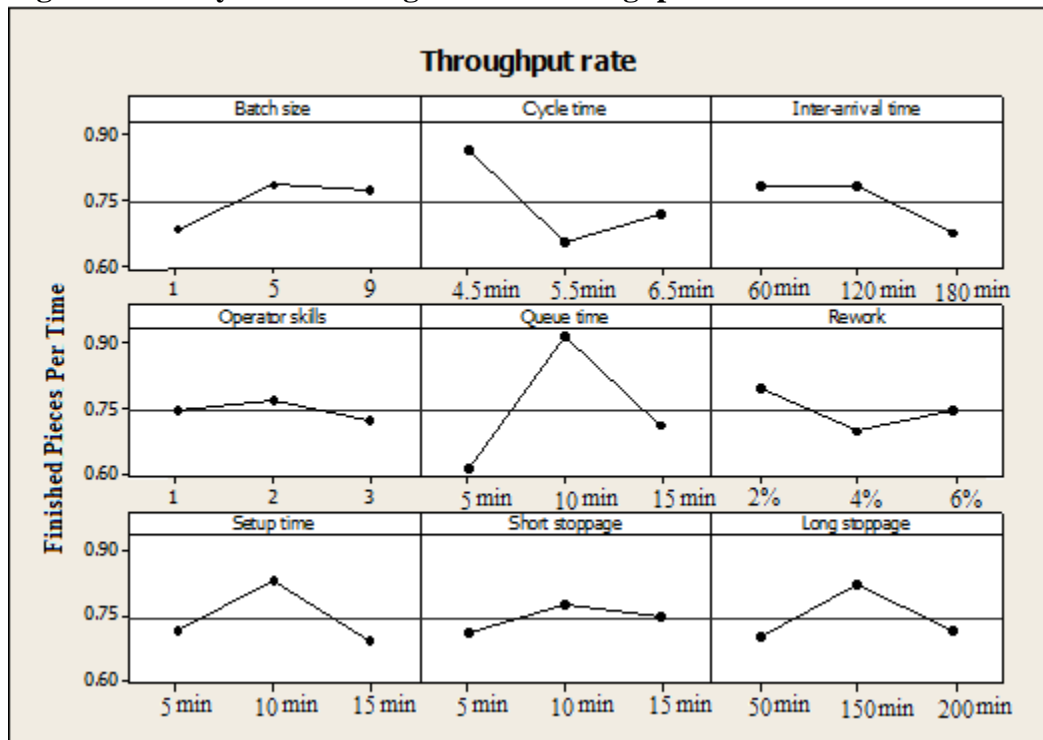


Figure 5.7: analysis of running DOE on throughput rate

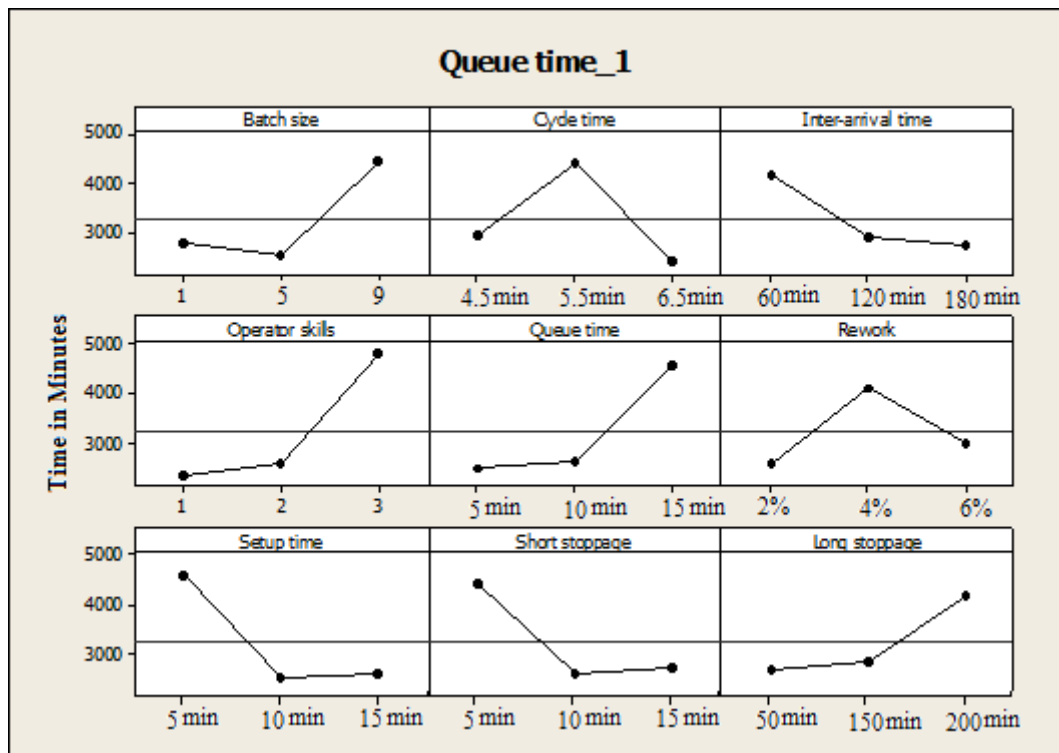


Figure 5.8: analysis of running DOE on queue time

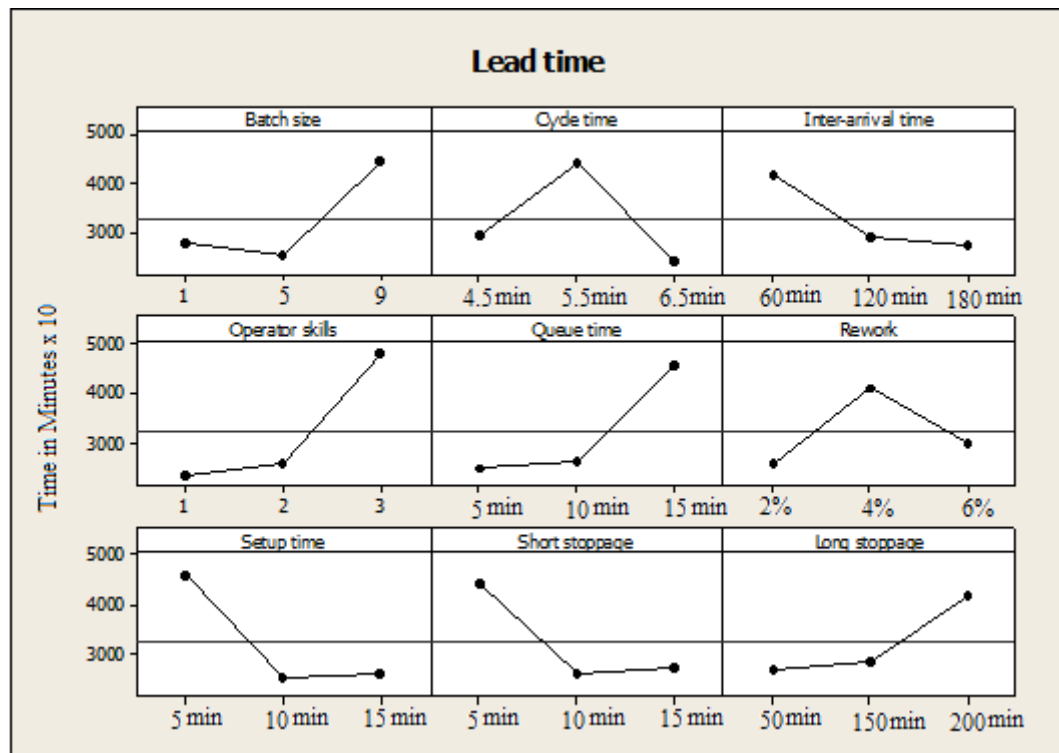


Figure 5.9: analysis of running DOE on lead time

From the analysis of the results, effect of every factor was observed as related to the production performance. Taguchi method helps to identify the gravity of each factor on production, and it becomes easy to know their relationship with the desired performance.

After determination of the variability levels and their related effect on the machines, the experiments were re-run (using the logic developed as explained in Step 8) to note any improvements in the performance. The simulation was again run for the same period of 21,000 minutes, similar to when it was run without the logic to compare the results with previous results. Mean-time-to-Repair and Mean-time-to-Failure were used to determine the machine requirement fulfilment and their availability for finite capacity scheduling. The objective of developing autonomous finite capacity scheduling is to detect the variability in production and remedy the situation early enough without unnecessarily involving manual planning tasks. Table 5.5 and Table 5.8 show both results as obtained from running the simulation.

Step 7 and 8: Adopting Biological Control Principles and Development of Logic Control

Having recognised the effects of each finite capacity scheduling factor through Taguchi techniques, it became important to introduce biological control principles as learnt from the literature. The pattern of regulation of gene expression is consistent with protein making process as an important selective process in response to the changing environmental conditions of the gene, which in manufacturing terms we call variability. This information is quite vital to the development of the control logic for autonomous

finite capacity scheduling. Manufacturing systems can be made to adopt biological control principles by recognising that:

- a. there exists causal relationship of machines in the manufacturing system identified to process a certain product;
- b. there exist partial knowledge of machines (input and output) of direct correlation between observed variability and factors that course them; and
- c. with knowledge reached in (b), application of inductive rule technique can help quickly spot the potential variability in processing when unambiguous diagnosis of the conditions is either complex or impossible.

Biological control induces rules in the form:

If<condition> then <prediction>

where<condition> is a conjunct of existence of factors and <prediction> is the prediction of the variability at machines or it could be a group of variability experienced (if ambiguity is not resolvable) of factors which satisfy the rule's <condition> tests.

Each factor test is of one of the forms:

<variability> = <factor value>

<variability> = <disjunct of factor values>

<variability><comparator><number of factors>

for normal, single and multivalued variability a disjunct of values of factors can be used to determining them. <comparator>is either '>' or '≤'. These rules show that presence

or absence of factors during manufacturing nearly always lead to totally different kind of variability, just as is the case for types of proteins produced with different combinations of amino acids.

Machines are related by the part routing, the machine variability and factors that cause them. The variability on one machine may cause some other variability on another machine upstream and downstream. To create a relationship between machines, inductive rules are applied such that feedback mechanisms are introduced at all hierarchical levels forming inputs to other machines and as control signals to others.

From the literature, it was possible to determine similarities between manufacturing and biological systems as shown in Section 2.4, such that the control mechanisms envisaged in biological systems could be adopted in manufacturing systems to improve on autonomous decision-making functionality, provides high efficiency.

The development of autonomous finite capacity scheduling control logic calls for in-depth understanding of causal relationships of the involved machines from input to output in form of cause and effect, and the factors or conditions that govern them. The logic developed followed the following steps in line with Figure 4.2:

8a.*Determining the relationship between preceding and succeeding machine in a production system flow lines.*

Table 5.4: Connections between preceding and succeeding machines

	A1	A2	A3	A4	A5	K1	K2	K3	K4	K5	K6	K7	M1	M2	M3	Cl	Rm	P1	P2
A1	A1																		
A2		A2																	
A3			A3																
A4				A4															
A5					A5														
K1						K1													
K2							K2												
K3								K3											
K4									K4										
K5										K5									
K6											K6								
K7												K7							
M1													M1						
M2														M2					
M3															M3				
Cl																Cl			
Rm																	Rm		
P1																		P1	
P2																			P2

Table 5.4 shows the connections between preceding and succeeding machines in the routing. For example, K5 is the input of A3 only, but K5 is the output of M1, M2, and M3. Another example is M3 which is the input to K2, and yet it is an output of K5, K6 and K7. In this table, going along columns indicate the input machines and along the rows indicate output machines.

8b. *Determining machine input parameters or finite capacity scheduling factors: for example, unique machine name (buffer1); generic machine type (storage); what controls the machine (shelf life, processing time, etc.); and the preceding and succeeding machines (upstream machines and downstream machines). Figure 5.10 shows three classes of machines and their related types of variability.*

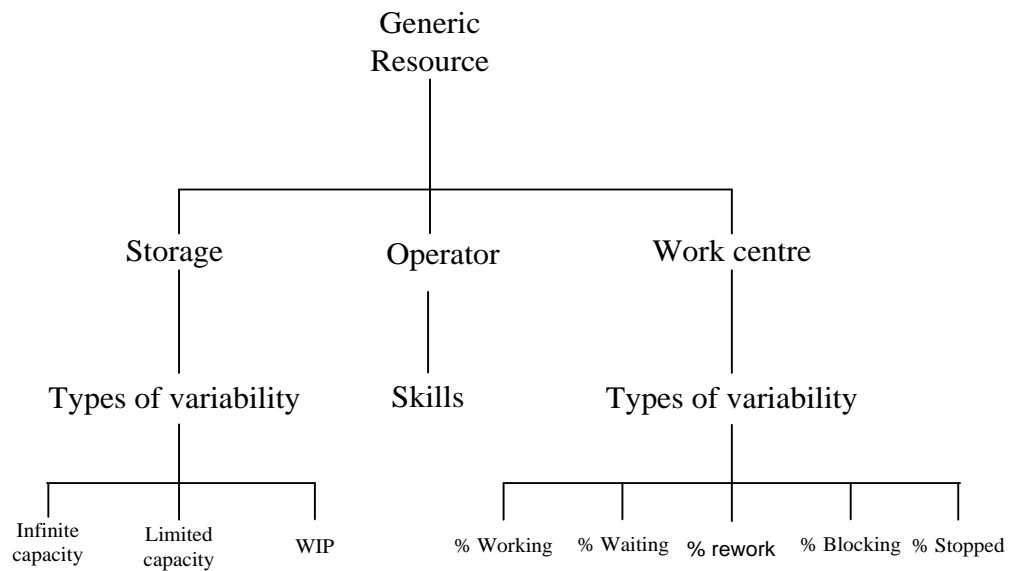


Figure 5.10: Classes of machines and their related variability

- 8c.** *Determining different machine variability and their defining factors or conditions.*
- 8d.** *Identifying performance measurements associated with each machine.*
- 8e.** *Developing the activity rules (as discussed hereunder).*

For example, in Figure 5.11, if Machine 2 fails, it can be seen that a simple conflict occurs where the Buffer 2 contents (with state = finite), is linked upstream to Work

Table 5.5: Results before applying the logic

Batch Size (items)	Cycle Time (min)	Inter-arrival time (min)	Operator Skills (level)	Queue Time (min)	% Rework	Setup Time (min)	Short Stoppage (min)	Long Stoppage (min)	% Stoppages	% Waiting	% Blocking	% Working	Throughput (items)	Throughput Rate	Queue Time (min)	Lead Time (min)
1	4.5	60	1	5	2	5	5	50	9.87	14.75	13.32	62.06	29266	0.72	1817.97	265678
1	4.5	60	1	10	4	10	10	150	13.62	18.5	8.99	58.89	23458	0.90	2639.7	245044
1	4.5	60	1	15	6	15	15	200	16.56	21.51	14.76	47.17	23461	0.90	2825.97	256754
1	5.5	120	2	5	2	5	10	150	23.76	21.47	15.99	38.78	23461	0.90	2930.97	236767
1	5.5	120	2	10	4	10	15	200	19.61	22.65	12.98	44.76	22220	0.95	2363.97	265567
1	5.5	120	2	15	6	15	5	50	23.61	17.74	11.87	46.78	227658	0.09	3479.7	244844
1	6.5	180	3	5	2	5	15	200	16.07	24.95	19.52	39.46	229114	0.09	3485.097	245702
1	6.5	180	3	10	4	10	5	50	10.75	15.63	14.2	59.42	25806	0.81	2009.7	235467
1	6.5	180	3	15	6	15	10	150	18.75	16.87	9.98	54.4	26787	0.78	3479.7	245444
5	4.5	120	3	5	4	15	5	150	22.87	18.96	9.98	48.19	29138	0.72	3150	255444
5	4.5	120	3	10	6	5	10	200	20.63	22.72	19.72	36.93	21682	0.97	2847.6	244944
5	4.5	120	3	15	2	10	15	50	9.54	14.54	16.54	59.38	19876	1.06	4171.65	246651
5	5.5	180	1	5	4	15	10	200	24.76	17.63	16.2	41.41	61354	0.34	1607.34	245044
5	5.5	180	1	10	6	5	15	50	24.48	23.72	20.72	31.08	26249	0.80	2825.76	236455
5	5.5	180	1	15	2	10	5	150	25.65	19.76	14.76	39.83	29371	0.71	2288.307	246112
5	6.5	60	2	5	4	15	15	50	7.13	14.76	9.76	68.35	35745	0.59	1192.758	271376
5	6.5	60	2	10	6	5	5	150	17.85	19.6	24.48	38.07	21116	0.99	3525.69	246212
5	6.5	60	2	15	2	10	10	200	19.85	13.98	15.51	50.66	24442	0.86	1194.27	245104
9	4.5	180	2	5	6	10	5	200	11.78	17.74	19.27	51.21	27187	0.77	2382.135	245244
9	4.5	180	2	10	2	15	10	50	16.51	21.39	19.96	42.14	26260	0.80	2824.5	245144
9	4.5	180	2	15	4	5	15	150	24.39	21.48	13.48	40.65	22221	0.95	3525.69	287644
9	5.5	60	3	5	6	10	10	50	11.87	22.76	24.87	40.5	25566	0.82	3749.907	276243
9	5.5	60	3	10	2	15	15	150	17.13	23.72	15.87	43.28	24337	0.86	2048.9154	244944
9	5.5	60	3	15	4	5	5	200	20.07	19.57	15.87	44.49	54112	0.39	18389.154	245144
9	6.5	120	1	5	6	10	15	150	12.89	21.85	18.85	46.41	37261	0.56	1986.033	245204
9	6.5	120	1	10	2	15	5	200	21.63	23.72	20.72	33.93	18226	1.15	2851.107	246077
9	6.5	120	1	15	4	5	10	50	13.87	19.87	16.74	49.52	33338	0.63	2031.75	266344

centre 1, blocking it from sending out its finished parts. This conflict can be resolved using a general rule such as shown in Table 5.6:

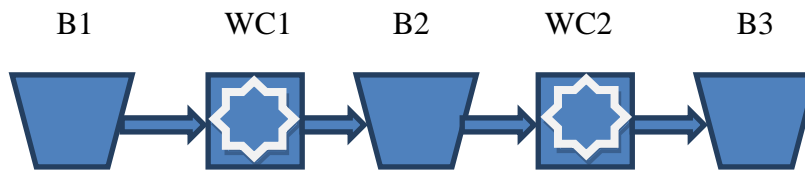


Figure 5.11: Simple production line

Table 5.6: Example of rule

Rule:

IF	machine WC2 of_type_work centre <i>is stopped</i> is linked with machine B2 of_type_storage <i>is finite</i> (capacity of buffer reached)
THEN	machine WC1 of_type_work centre <i>is blocked</i> note_fault in machine WC2 type_work centre
OR	check condition of machine downstream of WC2

As studied from biological systems, the rules governing gene transcription and translation are of the form:

if<condition> then <prediction>

where<condition> is combination of tests on the factors and <prediction> are expectations that satisfy the rules, <condition> tests. These sets of rules indicate correlations between factors (conditions) and the predictions (different variability) for the system. For example, going by Figure 5.4, the control rules are as shown in Table 5.7 based on the variability in the finite capacity scheduling explained discussed in Section 4.3:

Table 5.7: Rules based on simple production line of Figure 5.4

machine 2_of_type work centre = waiting	
if	batch size = 5
and	cycle time ≤ 5.5
and	inter-arrival time ≤ 60
and	long stoppage = 50
and	operator skills > 2
and	queue time = 15
and	rework $< 6\%$
and	short stoppage = 10
and	setup time < 10
then	operators at machine 1 = 2
and	set MTTR = 40

machine 2_of_type work centre = blocked	
if	batch size ≥ 9
and	cycle time ≤ 6.5
and	inter-arrival time ≤ 60
and	long stoppage = 50
and	operator skills ≤ 3
and	queue time ≥ 10
and	rework $\geq 4\%$
and	short stoppage = 10
and	setup time ≥ 5
then	increase operators at machine 2 = 3 operators
and	set MTTR = 70

machine 2_of_type work centre = stopped	
if	batch size ≤ 1
and	cycle time ≥ 5.5
and	inter-arrival time < 120
and	long stoppage > 50
and	operator skills $< 2\%$
and	queue time < 15
and	rework = 4%
and	short stoppage > 10
and	setup time = 15
then	set MTTR = 150

machine 2_of_type work centre = working	

if	batch size = 1
and	cycle time ≤ 4.5
and	inter-arrival time ≤ 60
and	long stoppage ≤ 50
and	operator skills ≤ 2
and	queue time < 15
and	rework = 4%
and	short stoppage ≤ 10
and	setup time ≤ 5
then	set MTTF = 20730

if	Buffer content < 10
then	Stop part entry
if	Buffer content < 3
then	Allow part entry

The rules will inspect a number of different factors before arriving at a conclusion to whether allocate the machine to the activity or otherwise. All this information is valuable for the autonomous finite capacity scheduling control logic. As it stands, a complex manufacturing system may be described and modelled successfully, and a rule set produced.

Since the control logic has only a limited knowledge of the system in the form of activity rules, it can quickly recognise the changing conditions of the machine without having to perform a complex in depth, cause-effect analysis of the system.

The logic aggregates present information occurring at machines' local levels and by so doing, provide control to the manufacturing system as a whole. The decision related to the control function is made according to the available information in form of factors having different attributes (distribution levels) as shown in Table 5.2, and are appropriate for decision-making.

Table 5.8: Results after the applying the logic

Batch Size (items)	Cycle Time (min)	Inter-arrival time (min)	Operator Skills (level)	Queue Time(mi n)	% Rework	Setup Time (min)	Short Stoppage (min)	Long Stoppage (min)	% Stoppages	% Waiting	% Blocking	% Working	Throughput (items)	Throughput Rate	Queue Time (min)	Lead Time (min)
1	4.5	60	1	5	2	5	5	50	8.69	12.685	11.7216	66.91	32778	0.80	1599.8136	233796.64
1	4.5	60	1	10	4	10	10	150	11.99	15.91	7.9112	64.19	26273	1.00	2322.936	210737.84
1	4.5	60	1	15	6	15	15	200	14.57	18.9288	12.6936	53.80	26511	1.00	2486.8536	220808.44
1	5.5	120	2	5	2	5	10	150	20.91	18.8936	13.5915	46.61	26511	1.00	2403.3954	208354.96
1	5.5	120	2	10	4	10	15	200	16.86	19.2525	11.4224	52.46	25109	1.08	1938.4554	223076.28
1	5.5	120	2	15	6	15	5	50	19.60	15.6112	10.4456	54.35	257254	0.11	2853.354	210565.84
1	6.5	180	3	5	2	5	15	200	14.14	21.956	16.7872	47.12	258899	0.10	2857.77954	206389.68
1	6.5	180	3	10	4	10	5	50	9.46	13.7544	12.212	64.57	29160	0.93	1647.954	202501.62
1	6.5	180	3	15	6	15	10	150	16.50	14.6769	8.5828	60.24	30269	0.88	2853.354	211081.84
5	4.5	120	3	5	4	15	5	150	19.67	16.6848	8.5828	55.06	32926	0.81	2772	212018.52
5	4.5	120	3	10	6	5	10	200	18.15	19.9936	16.9592	44.89	24500	1.08	2505.888	213101.28
5	4.5	120	3	15	2	10	15	50	8.20	12.7952	14.5552	64.45	22460	1.18	3545.9025	214586.37
5	5.5	180	1	5	4	15	10	200	21.79	15.1618	13.77	49.28	69330	0.38	1366.239	213188.28
5	5.5	180	1	10	6	5	15	50	21.54	20.8736	18.2336	39.35	30186	0.91	2401.896	208080.4
5	5.5	180	1	15	2	10	5	150	22.57	17.3888	12.9888	47.05	33189	0.82	2013.71016	201811.84
5	6.5	60	2	5	4	15	15	50	6.27	12.9888	8.1008	72.64	40392	0.67	1049.62704	222528.32
5	6.5	60	2	10	6	5	5	150	15.71	17.248	21.0528	45.99	23861	1.11	3067.3503	201893.84
5	6.5	60	2	15	2	10	10	200	17.47	12.0228	12.8733	57.64	27619	0.98	1039.0149	200985.28
9	4.5	180	2	5	6	10	5	200	10.01	15.079	16.3795	58.53	30449	0.87	2072.45745	215814.72
9	4.5	180	2	10	2	15	10	50	14.53	18.6093	16.966	49.90	29411	0.94	2429.07	208372.4
9	4.5	180	2	15	4	5	15	150	21.46	18.258	11.458	48.82	24888	1.12	3032.0934	244497.4
9	5.5	60	3	5	6	10	10	50	10.21	19.5736	21.1395	49.08	30168	0.97	3224.92002	240331.41
9	5.5	60	3	10	2	15	15	150	14.39	20.3992	13.6482	51.56	27744	0.97	1680.110628	213101.28
9	5.5	60	3	15	4	5	5	200	17.66	16.8302	13.4895	52.02	60605	0.43	15079.10628	215726.72
9	6.5	120	1	5	6	10	15	150	11.34	18.5725	16.0225	54.06	42850	0.63	1727.84871	215779.52
9	6.5	120	1	10	2	15	5	200	19.03	20.3992	17.612	42.95	20960	1.29	2480.46309	206704.68
9	6.5	120	1	15	4	5	10	50	12.21	16.8895	14.7312	56.17	37338	0.71	1767.6225	234382.72

The Figures 5.12 – 5.19 present plots that compare the results for each of the identified input variability as well as the performance measurements before and after the application of the autonomous finite capacity scheduling control logic.

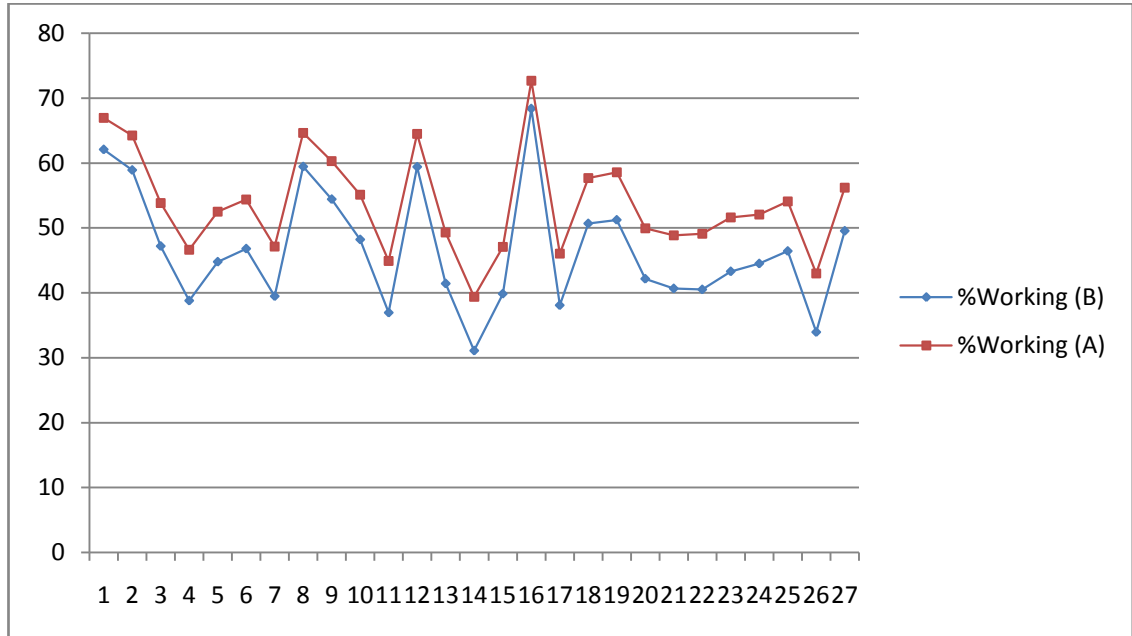


Figure 5.12: % working before and after application of the control logic

% working has been improved after the application of the logic such that more time is spent doing meaningful processing work, for example, in experiment number 14, there is a significant increase of 9% working.

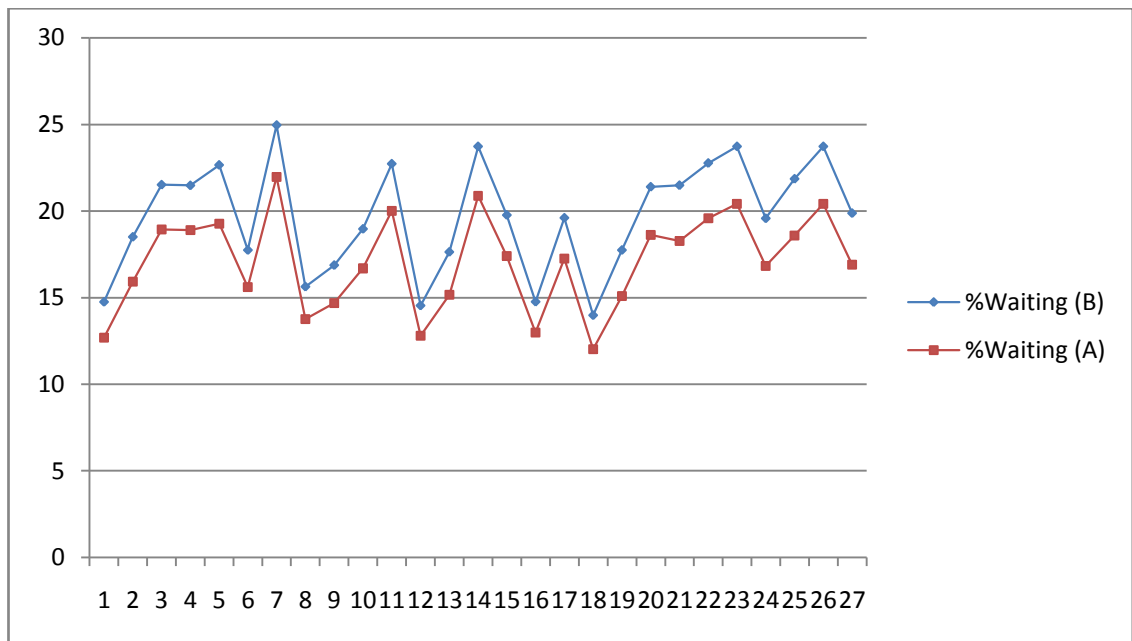


Figure 5.13: % waiting before and after application of the control logic

% waiting has been reduced in every experiment due to an improvement in system synchronisation and consistent and coordinated parts flow in the system.

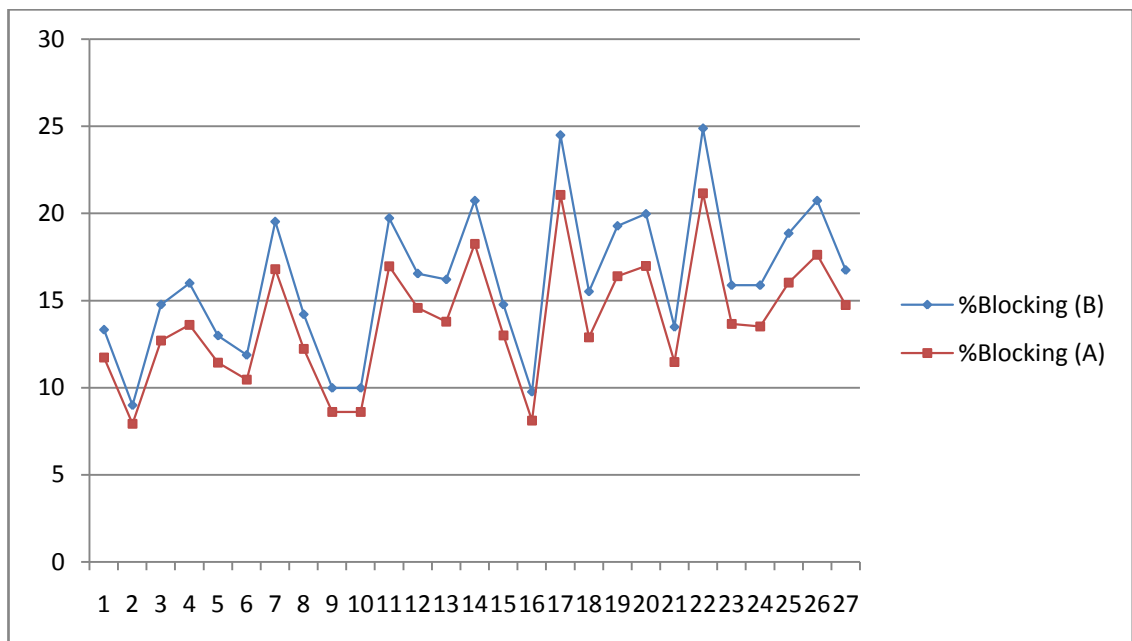


Figure 5.14: % blocking before and after application of the control logic

There is a slight improvement in the % blocking in virtually all the 27 experiments carried. This could be because of the information feedback, which occurs at multiple control points of the manufacturing system. Use of constraints as information signals may have brought about this improvement.

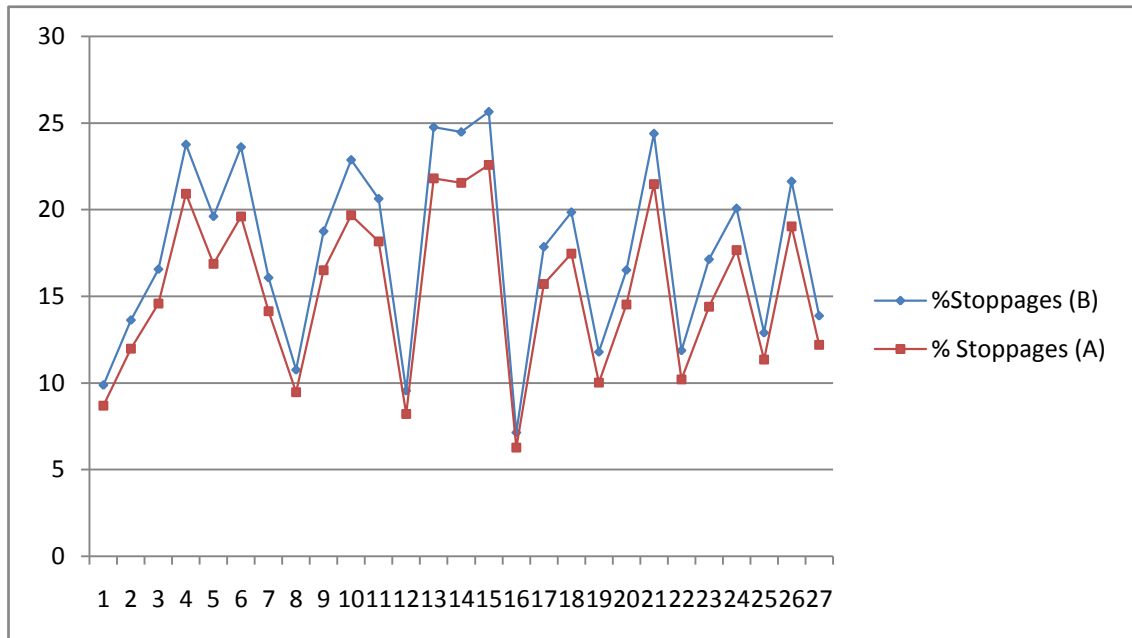


Figure 5.15: % stoppage before and after application of the control logic

There is a marginal reduction in the % stoppage throughout the 27 experiment run. There were fewer machine stoppages because every resource could take appropriate action autonomously and so overall system stoppage to perform maintenance was avoided.

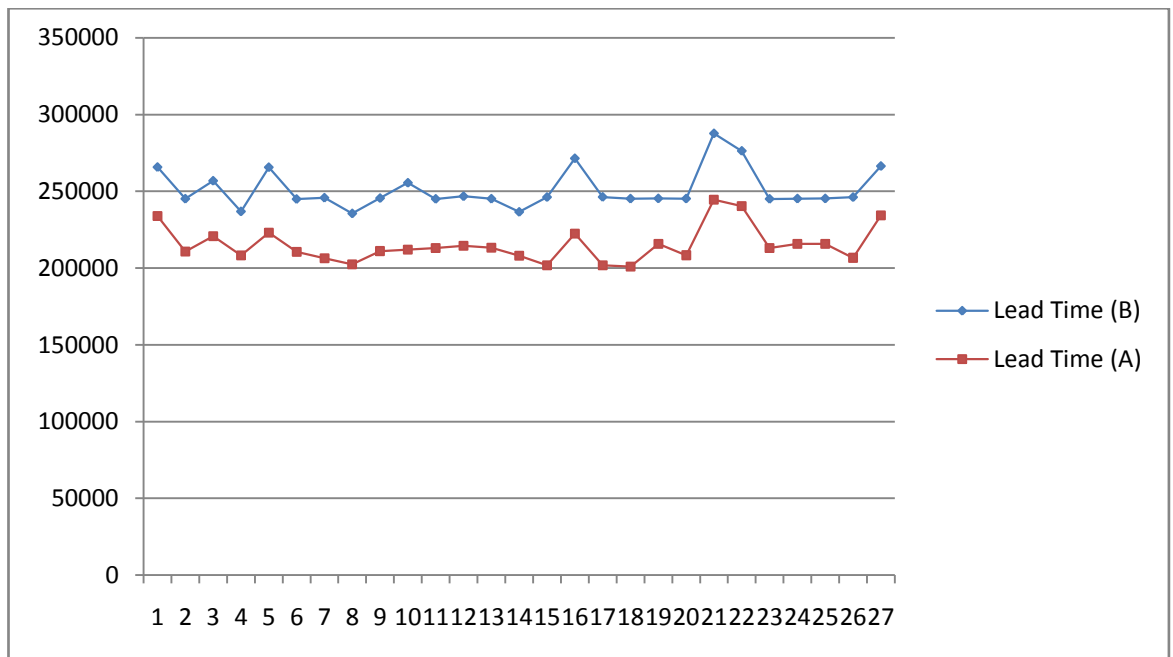


Figure 5.16: Lead Time before and after application of the control logic

Because of the improvements in system performance as witnessed in Figure 5.12 – 5.19, overall manufacturing lead time was reduced, for example, in number 16; the lead time was reduced by about 50,000 minutes.

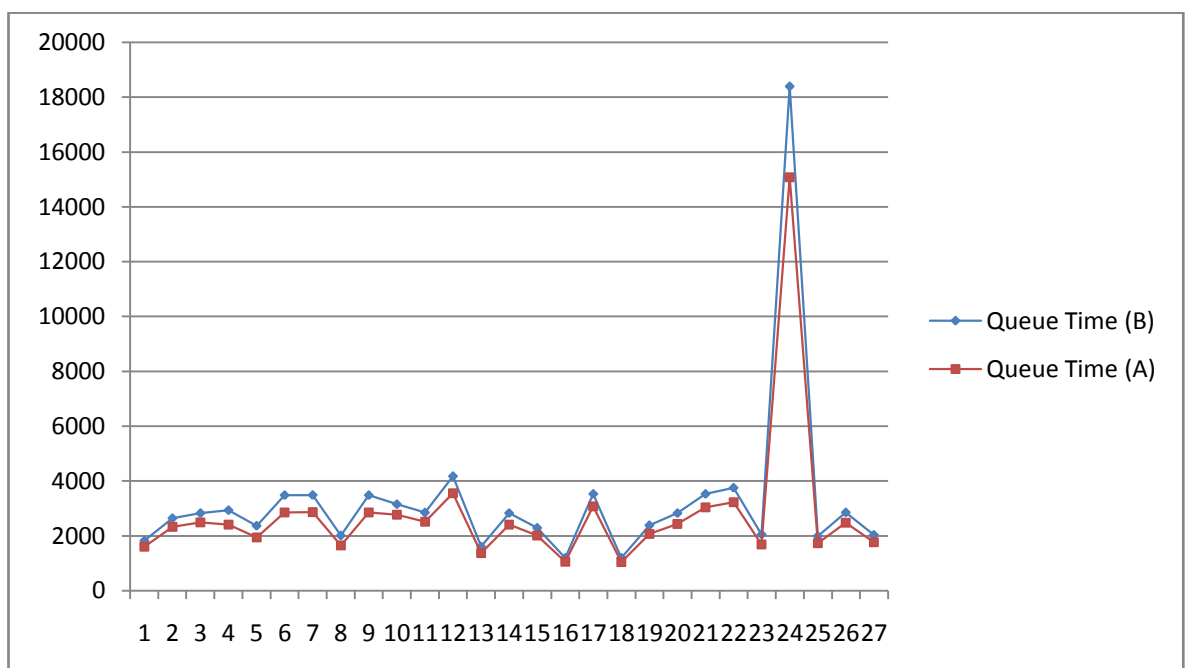


Figure 5.17: Queue Time before and after application of the control logic

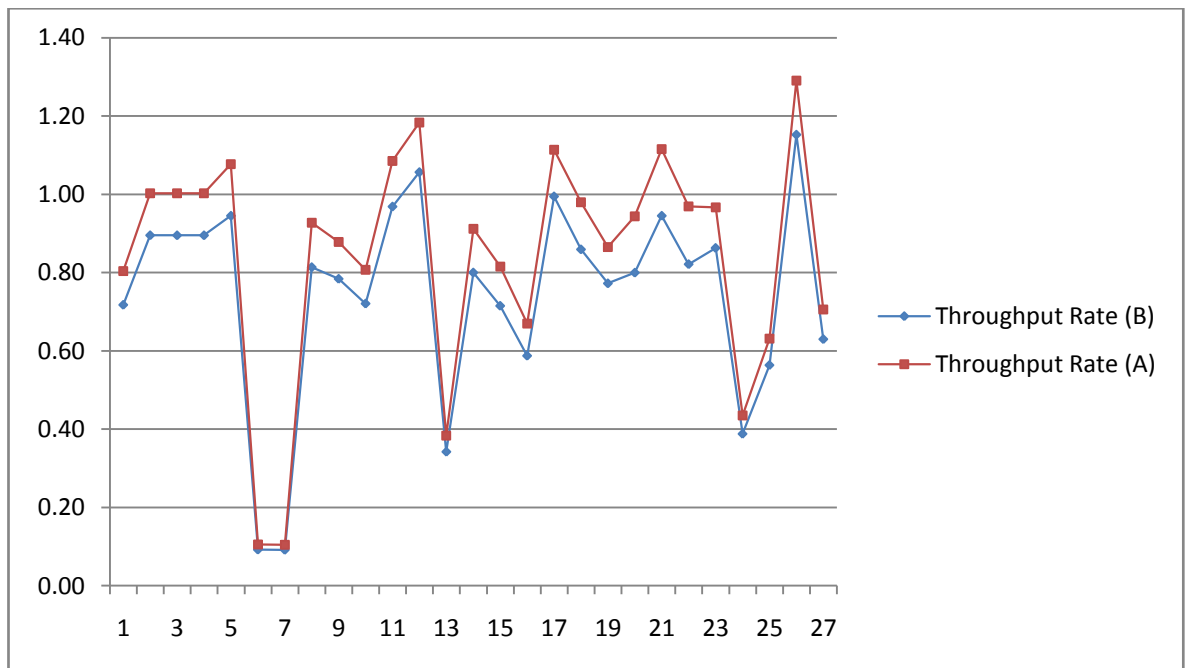


Figure 5.18: Throughput Rate before and after application of the control logic

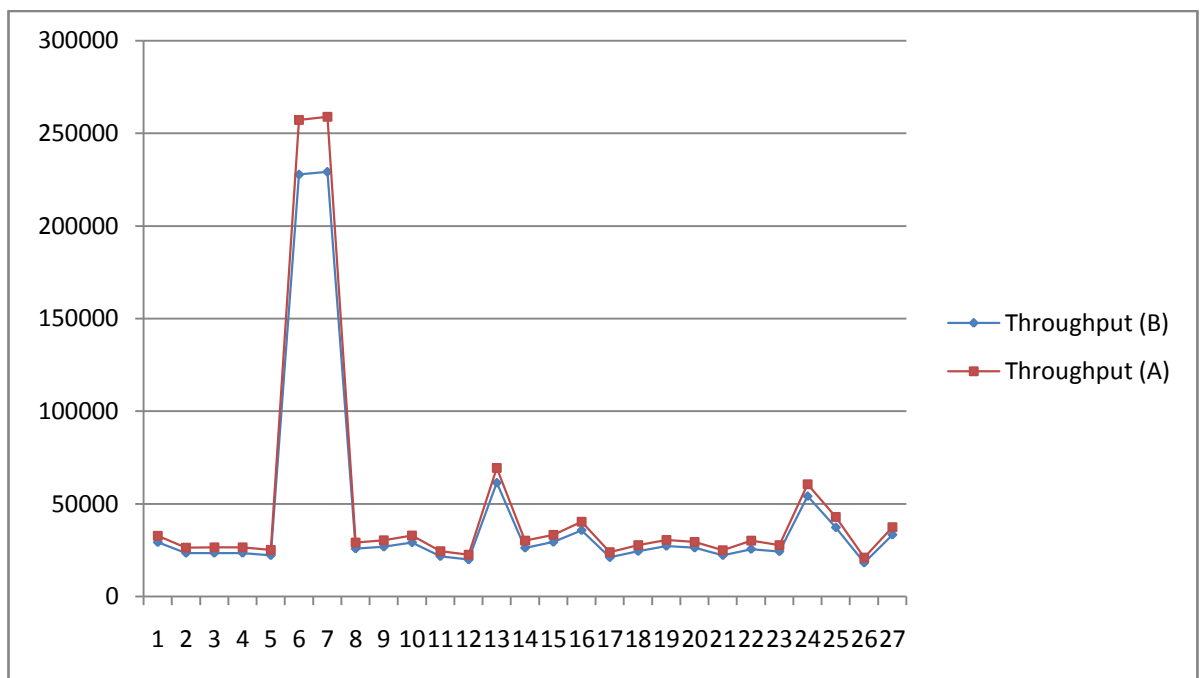


Figure 5.19: Throughput before and after application of the control logic

Table 5.9: Overall percentage improvement after the application of the logic for four performance measurements

% reduction in Lead Time after application of logic	14.3%
% increase in Throughput after application of logic	15.5%
% increase in Throughput Rate with application of logic	13.2%
% reduction in Queue Time after application of logic	15.3%

This research has demonstrated that the correct choice of values of finite capacity scheduling factors has a great impact on the performance measurements. Figures 5.12 – 5.19 show:

- That high throughput rate can be reached with a bigger batch size, lower percentage of rework, and shorter stoppages. Quicker movement of goods through the facility means better utilisation of assets. Better utilisation of assets creates additional capacity resulting from faster throughput improving customer satisfaction through quicker delivery.
- The % waiting, % blocking and % stoppage makes it possible to examine different manufacturing constraints as well as the relationship between non-utilisation and different performance measurements.
- By identifying different scenarios in the running of the experiments and by the help of Taguchi Orthogonal Array gave a good standing of each operational factor that can affect the completion of activities in every step in the transformation process.
- From these results, it can be observed that there was a greater improvement in queue time reduction indicating that with proper coordination, there is the possibility of avoiding or reducing system inefficiencies between successive

steps in the production process. In line with this, to ensure that resources are not starved of raw materials and parts, the methodology implemented ensures that raw materials/parts inter-arrival times are tuned to real time resource availability.

From the results evidenced in Table 5.5 out of the many experiments run with application of Taguchi Orthogonal Array, Table 5.3 shows the performance measurements and the finite capacity scheduling factors affecting them. The simulation was run with 27 experiments according to the L27 Taguchi Orthogonal Array chosen for the nine factors investigated at three (3) levels updated at the end of each run. Results were collected based on the different scenarios in order to determine the effects and influences of the selected performance measurements.

Chapter 6: Discussions

This chapter elucidates the best practices from biological systems and other manufacturing system models and compares the developed solution with existing ones. Results from experiments are also discussed with the findings from the previous chapters.

6.1 Introduction

It is becoming increasingly difficult to disregard the fact that the complexity and the dynamic needs of modern day's customer orders have a major impact on the performance of manufacturing systems. The dynamic nature of manufacturing processes defines the need for new scheduling techniques. In this research, a novel approach for autonomous finite capacity scheduling decision making logic has been proposed based on biological control principles by observing transcription and translation control processes. Based on the results obtained under the decision-making rules, the proposed method offers numerous advantages of simplicity, accuracy and low computational complexity.

The developed autonomous decision-making rules outperform the diagnostic accuracy of the manual input. Biological control principles have been adopted in this research to provide an effective way to perform distributed control where manufacturing activities are controlled independently to enhance autonomous decision making capability. With this capability the manufacturing system provides improved synchronised operations, resulting in:

- i. reductions in work-in-process, and just-in-time manufacturing;

- ii. improving machine utilisation including tools, buffers and operators, and;
- iii. reducing idle times due to tasks synchronisation.

The model adopted in this research captures the tasks undertaken to meet customer order requirements, where autonomous decision rules are developed to regulate the manufacturing activities thereby meeting the identified performance measures as illustrated in Step 8 in Section 5.2.

6.2 Difference between Autonomous Finite Capacity Scheduling and Existing Scheduling Methods

Scheduling work in manufacturing, operations, project or service work environment possess variability of some kind. The proposed method has shown that proper planning of manufacturing activities has benefits to the overall performance. Table 6.1 provides differences between existing and the proposed autonomous finite capacity scheduling.

Table 6.1 Difference between existing and autonomous finite capacity scheduling

Existing Scheduling	Autonomous Finite Capacity Scheduling
<ul style="list-style-type: none"> Assumed constant sources of variability which exist in scheduling tasks 	<ul style="list-style-type: none"> Analyses factors affecting the scheduling process as in Section 4.3 for the nine selected factors.
<ul style="list-style-type: none"> No existing scheduling method is known to integrate scheduling factors and other control factors in real time to control production processes autonomously. 	<ul style="list-style-type: none"> Incorporates a number of control factors to control (including scheduling factors, production constraints and capacity availability) production activities autonomously
<ul style="list-style-type: none"> Schedules production activities offline, thereby failing to cater for uncertainties as they occur from time to time in manufacturing. 	<ul style="list-style-type: none"> Scheduling is always online examining the system as making adjustments due to uncertainties from time to time, and each activity is controlled individually and autonomously.
<ul style="list-style-type: none"> Constraints are considered as precedence relations that have no 	<ul style="list-style-type: none"> Constraints are applied at every point providing control information as feed

control on whole system synchronisation	forward of feedback.
<ul style="list-style-type: none"> Planned according to requirements, weights and priority orders based on their relative importance to customer satisfaction, market trends and forecasts. 	<ul style="list-style-type: none"> Taguchi Orthogonal Arrays have been used to provide analysis of the factor to determine the possible optimal levels that can improve system performance.
<ul style="list-style-type: none"> Considers interrelationships and interdependencies between technical responses only 	<ul style="list-style-type: none"> Uses Taguchi analysis to assess system operation with eight performance measurements all at once.
<ul style="list-style-type: none"> Complex and omniscient processing unit that is tailor made to deal with the problem at hand. 	<ul style="list-style-type: none"> Improved performance brought about by the quick response to variability in the system.
<ul style="list-style-type: none"> The system must gather full data from the whole system and cannot cope with missing data since the solutions are always problem specific. 	<ul style="list-style-type: none"> Flexible in the sense that if there is a change among the manufacturing process and act as quick response to these changes.

6.3 Discussion of Results

This research has presented some important issues in the development of an autonomous finite capacity scheduling control logic adopting the best practices of biological control and existing scheduling methods. This information was introduced in Chapters *Two* and *Three*. The results obtained facilitated the answering of some questions aimed at realising the significance of the designed autonomous finite capacity scheduling control logic.

1. Do the proposed steps identify all the activities to be scheduled and schedule control factors from a customer order?

The proposed steps identify activities to be scheduled from a customer order and the precedence relations for activities identified together with the machine to process those activities. Routing information for the order could also be obtained by

developing the manufacturing flow chart for the customer order following the steps mentioned in Section 4.3, Step 7.

2. Do the proposed steps identify the most effective and influential finite capacity scheduling factors for each activity being scheduled?

The factors have been identified that control or regulate each scheduled activity and were used in the experimental design. Taguchi Orthogonal Array was used to find the effects of variability in the factors and how this variability can cause process variability, machine availability and the overall system performance measures identified. By applying biological control principles, it becomes possible to provide control of processes at various points of the system autonomously thereby improving performance as can be seen from the improvement of the identified performance measurements.

3. Do the proposed steps identify the interrelationships between activities and enhance synchronisation?

The relationships between the control factor's variability levels were identified using Taguchi Orthogonal Arrays determining how they caused process variability and hence machine availability. Table 5.1 shows the relationships between factors, i.e., how they affect each other. In order to simplify the model, the number of variables needed was reduced to nine from the initial seventeen by identifying factors that could easily be measured and eliminating those that could not be measured and which were as well represented by other factors.

4. Do the proposed steps examine and investigate the effects of the variables on the selected performance measures?

Eight performance measurements are identified in this research and were illustrated as response variable from the Taguchi Orthogonal Array – % *working*, % *waiting*, % *blocked*, % *stopped*, *queue time*, *lead time*, *throughput* and *throughput rate*. The research has shown that finite capacity scheduling factors together with control principles adopted from biological systems can improve the performance measures identified. There are remarkable improvements in all the eight performance measurements after the application of control logic as shown in Figures 6.1 – 6.8.

6.4 How the proposed method fits in existing planning and scheduling methods

Common to all scenarios, a customer order requires several independent activities, and as such is completed if and only if all activities are complete. Moreover, jobs compete for the machines performing the activities and the objective is to allocate machines to the activities such that their average completion time is minimised. Autonomous finite capacity scheduling increases the overall system utilisation rate and enables quick response to perceived process variability. An important precondition in this work is the presence of several decision points identified as machines, taking decisions based on identified variability in finite capacity scheduling factors. All these autonomous decision points (machines) are guided by their own local objectives, making it easy to resolve a variety of conditions encountered. Therefore autonomous finite capacity scheduling involves fulfilment of preconditions based on the customer order requirements including machines, tools, variability in scheduling factors, their organisation or their available capacities.

There are several methods that have been applied in controlling production processes and hence the objective of this section is to show how the proposed method can fit into these existing methods. What follows is the explanation of the few selected methods identified:

a) Period batch control

This is where manufacturing planning system is decomposed into a number of stages and each stage is given the same amount of time P to complete the required operations. It operates with fixed cycles or periods during which the parts are produced that are required in a succeeding period or stage by coordinating the various stages of transformation that are required in order to fulfil the demand of customers (Benders and Riezebos 2002).

By applying the proposed method varying values of the stages as well as the period length can greatly influence the performance in periodic batch control. With the proposed method optimal allocation of operations to stages can be determined using Taguchi Orthogonal Array for optimal value selection

b) Assembly line balancing

This method determines the cycle time in which operations at workstations can be finished and the products moved from one workstation to another at the end (Scholl and Becker, 2006). There is no WIP inventory and the transfer batch size is one, however, operators can be assigned to line so that production rate is met within minimised idle time (Riezebos, 2003). Scholl (1999) explains that there

are no assignment restrictions except fixed launching rate and precedence constraints

With the application of autonomous finite capacity scheduling, restrictions are taken into consideration even with the availability of a number of input requirements. By so doing assignment of a job to a resource will consider all the input: the precedence constraints, the operation time, the unused resource time and so on. The objective is to ensure that all the available jobs are assigned to the resources and no operations having precedence or unassigned time constraints are left out.

c) Kanban system

Kanbans are essential visible signals that control the flow of material through a production line. Kanban initiates the flow of material through the shop floor without the need for extensive amounts of paperwork (Kumar and Panneerselvam, 2007). Kanban ensures that materials only move at the time they are required, in the right quantities and parts types are moved to the right resources.

With autonomous finite capacity scheduling, provides control of all the activities of the manufacturing system beyond material flow by considering all other factors that necessary to the production process.

d) Optimised production technology

The objective of optimised production technology is to lower the inventory level in order to increase the throughput of the system, where bottlenecks become

very important in directly determining the output of the manufacturing system (Voss 2005). Processes in the bottleneck are protected with buffers waiting in front of the bottleneck to keep it working and to gain maximum possible production rate.

Unlike starting with determination of the bottleneck resources; determining the buffer sizes; and driving the materials release schedule according to bottleneck and buffers obtained, autonomous finite capacity scheduling adds the issues of performance measurements per resource which eventually improves the cycle time and lead time.

6.5 Useful lessons from Biological method and Contribution of the proposed system

Lessons from biological processes show that they consistently represent the dynamic knowledge about high-level processes in the context of their component part sub-processes and control-flow properties. Some of the requirements desirable for manufacturing systems include:

- i. the static-structural view of the machines and materials involved in the process in the development of a variety of products, their properties and the relationships among them (Leitao, 2008);
- ii. the dynamic view showing how processes are ordered over time (flow-control) and how processes are recursively broken down to component processes and flow lines, supporting the sequential, parallel, conditional and repetitive processes; and

- iii. the functional view showing the machines that perform each process, well specified materials (input) of each function, and products of the process (outputs);
- iv. quick response to variability analysing finite capacity scheduling factors at machine level;
- v. autonomous decision-making functionality enables improvement in machine utilisation of the whole manufacturing system and hence improves efficiency of individual machines through reductions in amounts of raw materials used, work-in-progress and finished goods inventory (Leitao, 2008).

From the objectives of this thesis the contribution made is to improve finite capacity scheduling by incorporating the autonomous response to deal with various manufacturing variability. The proposed method presents the following contributions:

- provides the control of manufacturing activities depending on the variability in the finite capacity scheduling factors enabling almost real time response to process variability;
- providing several points of control in the manufacturing system and hence decoupling points for problem identification and autonomous decision making;
and
- the evaluation of performance measures at each machine thereby improving the machine utilisation to the satisfaction of the customer.

6.6 Applying Autonomous Finite Capacity Scheduling

This method forms framework for activities found in a number environments in manufacturing. As illustrated in Section 6.2, it provides several steps through which its use can be realised as follows:

- i. determine appropriate performance measurements (as presented in Section 4.3) for each machine that processes an identified activity from the customer order;
- ii. determine the factors associated with each activity and required during scheduling;
- iii. analyse the factors using Taguchi Orthogonal Array or any other method to determine their optimal ranges that will produce good performance;
- iv. determine the operational constraints which define the rules in which operations can be scheduled in relation to one another, such that one operation can start prior to the previous operation. Through constraints feedbacks can be provided throughout the system for process synchronisation and reduce *muda*.

All scheduling jobs whether in manufacturing, operations, project work or service work environment possess similar variability such as job duration, job start times, job finish time, and priority rules that manage the scheduling. The proposed method serves well in cases of manufacturing, operations and service work environments and satisfies time window constraints equivalent to start dates and due dates in all these cases. At present the methodology performs synthesis of shallow rules for controlling the machines, rules that are essential for scheduling personnel. Its role as scheduling tool for improving

finite capacity scheduling has been explored in this thesis, and possible application for real-world manufacturing variability explained.

Chapter 7 Conclusions

The contribution of this thesis emerges from the systematic examination of the inherent scheduling problems in manufacturing systems. It provides a novel platform for adoption of biological control principles in developing an autonomous finite capacity scheduling control logic. Literature review was conducted about manufacturing systems and biological systems and the integration of biological control principles to finite capacity scheduling focussed on both the structural and functional similarities of the two systems:

- i. The theoretical development and practical applications of finite capacity scheduling in this research, was defined on the basis of published research primarily as introduced in *chapters two* and *three*.
- ii. Simulation modelling was developed (as explained in *Chapter four*) in order to give a clear and comprehensive description of a manufacturing system, and to test the principles developed for autonomous finite capacity scheduling.
- iii. Finite capacity scheduling factors are considered different types of variability that can be measured in the form of *%working*, *%waiting*, *%blocking*, and *%stopping* as identified in Section 5.2 Step 5. Accordingly, the variability measured determines the overall performance measurements for the production line – they affect *throughput*, *throughput rate*, *queue time* and *lead time*.
- iv. The initial results from the simulation model which covers the scheduling of customer orders were used as the platform on which to identify prior scheduling rules, and control logic was developed adopting biological control

principles while using the finite capacity scheduling factors as controllers to introduce the mechanisms of autonomous decision-making functionality.

- v. Notable successes of this research are shown by the improvements observed in the identified performance measurements.

At present AFCS is still early in development and more work is set to be done to realise the true usefulness of this new approach to scheduling tasks. However, as it stands, complex production systems of any kind may be described and modelled successfully, and a rule set may be produced to describe the events and probable change of machine allocation plan suggested.

Chapter 8: Recommendation and Future Work

This research has proposed steps for the development of autonomous finite capacity scheduling control logic adopting biological control principles that aims at reducing the existing highly skilled manual inputs in planning and scheduling of activities in manufacturing, project and service work environments. The steps of the research were presented in *Section 4.3*. The objectives of the research have been met as indicated by results of the experiments presented in *Section 5.2*. The contribution of this thesis can be considered as a basis for further improvements on the development of decision-making support modelling systems managing different levels of variability in manufacturing operations analysis. Future research and opportunities can be directed, among others, to the following points:

- i. Consideration for application of the logic in re-entrant manufacturing systems (as is the case in semi-conductor manufacturing) with multiple machines and multiple variability is important to test it.
- ii. It is important to investigate how the synchronisation of the processes for different product families could be best accomplished applying this logic unlike has been the case in this research where a single product manufacturing was considered.
- iii. There is need to develop methods that could work together with computational optimisation procedures such as genetic algorithms to provide learning capabilities to improve on the rule set and guide the performance of the whole system.

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Appendix A

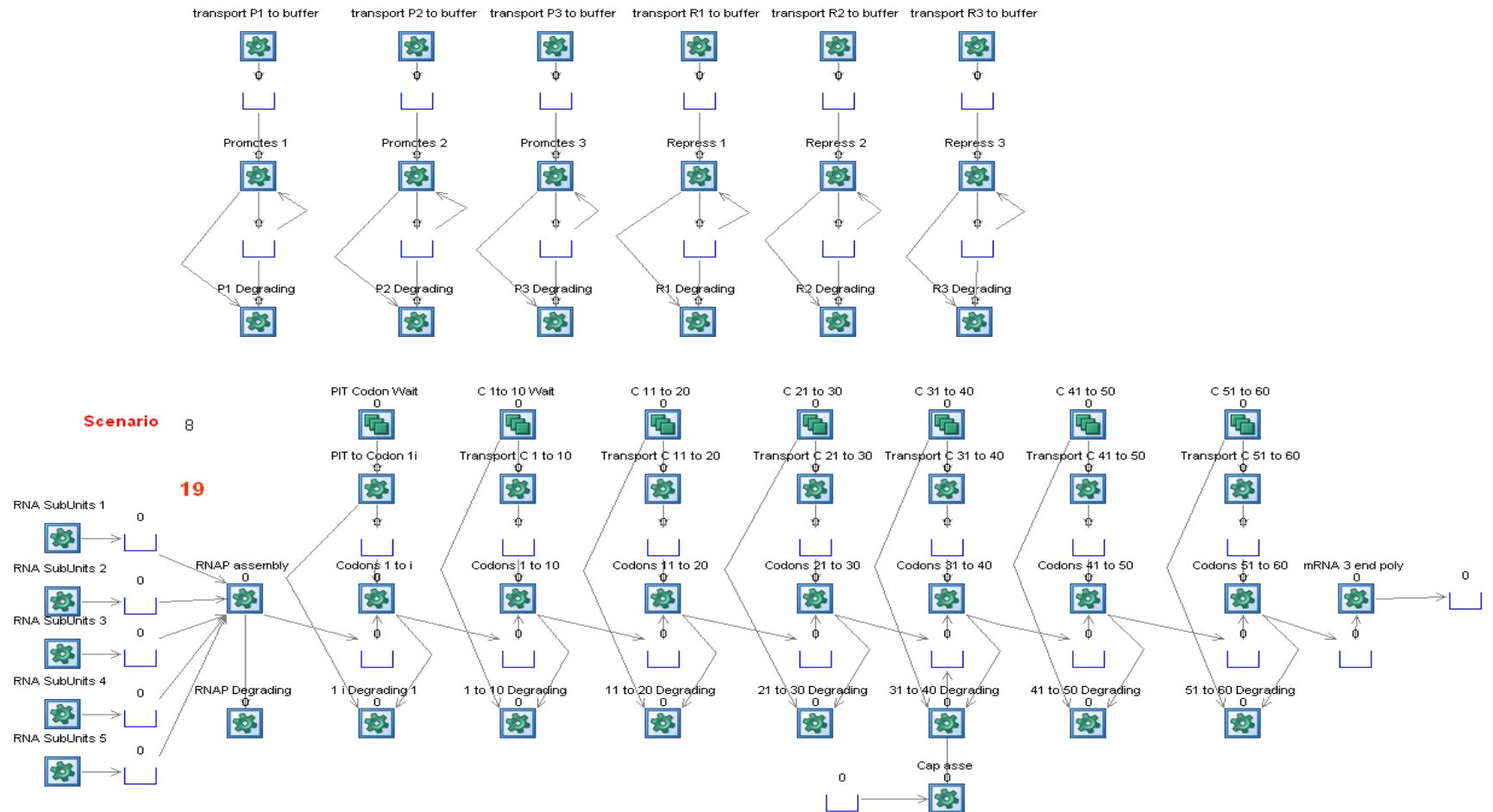


Figure 4.3: Protein production mechanism in a biological cell(Khalil et al., 2009)

