CRANFIELD UNIVERSITY

BOYANG SONG

SIMULATION AND OPTIMISATION OF A SPECIFIC FLEXIBLE MANUFACTURING SYSTEM

SCHOOL OF AEROSPACE, TRANSPORT AND MANUFACTURING

PhD
Academic Year: 2018 – 2019

Supervisor:
Professor Ashutosh Tiwari
February 2019

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Supervisor: Professor Ashutosh Tiwari
Associate Supervisor: Professor Tetsuo Tomiyama
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This thesis is submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

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ABSTRACT

As current market competition evolves, most companies intend to increase their options for product customisation and accelerate their product upgrading. Correspondingly, manufacturers have to face the increasing size of product family, shortened product life cycle or rapid product/process change. Therefore, Flexible Manufacturing Systems (FMS) have been introduced that uses advanced machines and efficient transport systems to produce multiple products at the same time. However, an FMS can be complicated to manage because of the increased variability in products and processes. The research aims to develop manufacturing simulation and optimisation techniques for a FMS. This research will integrate Discrete Event Simulation (DES) and multi-objective optimisation approach to address the complexity and flexibility within an agile manufacturing environment.

Due to the complexity of FMS, most current FMS optimisation research has engaged with FMS production problems separately without considering other inter-related problems in the same system such as dealing with operation sequence problem without considering Level of Flexibility (LoF), thus it is hard for the solution to provide a prospective impact for the whole system. There are very few real-world FMS implementations that are available to literatures, making it difficult to build and verify the models within a complete ecosystem. Consequently, most of the models in the research are oversimplified. Therefore, this research aims to develop a method to optimise FMS production considering the overall system, by having access to an FMS industrial implementation.

This research contributes to knowledge in four main areas, namely, (1) the interactions of FMS production problems have been investigated, (2) a framework has been developed to integrate the simulation and optimisation for FMS to enable optimisation algorithms working with DES models effectively, (3) a comprehensive FMS simulation model has been built and validated on the industrial shop floor and (4) multi-objective optimisation has been applied to the FMS scheduling problem, considering interactions with other problems. Based on the results and limitations of this research, real-time simulation, mock-up FMS and improve computational efficiency are suggested for future work.

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LIST OF PUBLICATIONS

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Song, B., Hutabarat, W., Tiwari, A. and Enticott, S. (2016). Integrating Optimisation with Simulation for Flexible Manufacturing System. In: *14th International Conference on Manufacturing Research (ICMR-2016),* 6-8 September, Loughborough, UK.

Farnsworth, M., Song, B., Hutabarat, W., Tiwari, D. and Tiwari, A. (2018). Dimension Reduction for Flexible Manufacturing Processes. In: *2018 International Conference on Machine Learning (ICML-2018) – Joint Workshop on Deep (or Machine) Learning for Safety – Critical Applications in Engineering (DISE1),* 14-15 July, Stockholm, Sweden.

Submitted:

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ABS	Agent-Based Simulation
ACO	Ant Colony Optimization
AGV	Automatic Guided Vehicle
AI	Artificial Intelligence
ALB	Assembly Line Balance
AMC	Advanced Manufacturing Centre
AMSCI	Advanced Manufacturing Supply Chain Initiative
ASP	Assembly Sequence Problem
BoM	Bill of Material
CAM	Computer-Aided Manufacturing
CMM	Coordinate-Measuring Machine
CNC	Computer Numerical Controlled
COF	Combined Objective Function
CP	Constraint Programming
CR	Critical Ratio
CTS	Central Tool Store
DES	Discrete Event Simulation
DMLs	Dedicated Manufacturing Lines
DoE	Design of Experiment
EDD	Earlier Due Date
EMDD	Earliest Modified Due Date
FAS	Flexible Assembly System
FCFS	First Come First Served
FIFO	First In First Out
FIFS	First In First Service
FJSP	Flexible Job Shop Problem
FMC	Flexible Manufacturing Cell
FMS	Flexible Manufacturing System
GA	Genetic Algorithm
HLO	Highest Level of Operation
IIoT	Industry Internet of Things
JPW	Job Per Week

KPI	Key Performance Indicator
LIFO	Last In First Out
LLO	Lowest Level of Operation
LoF	Level of Flexibility
LPT	Longest Processing Time
LTNO	Least Total Number of Operations
MHS	Material Handling System
MILP	Mixed Integer Linear Programming
MMFMS	Multi-Machine Flexible Manufacturing System
MODPSO	Multi-Objective Discrete Particle Swarm Optimisation
MTNO	Most Total Number of Operations
NP-Hard	Non-Deterministic Polynomial-Time Hardness
OEM	Original Equipment Manufacturer
PN	Petri Net
PPAP	Production Part Approval Process
PSO	Particle Swarm Optimisation
RMSs	Reconfigurable Manufacturing Systems
SA	Simulated Annealing
SPT	Shortest Processing Time
TSP	Traveling Salesman Problem

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1 INTRODUCTION

1.1 Background

Technological advancements, new competitors, global sourcing and industry restructuring result in great challenges for the manufacturing industry. The transition of the manufacturing industry from mass production to mass customisation is based on the need for more customised products to be produced, providing many variants, with the use of fewer resources and materials, in the shortest time possible (Chryssolouris, Papakostas and Mavrikios, 2008). To solve these challenges and to satisfy the growing demands, a Flexible Manufacturing System (FMS) has been proposed to replace many of the traditional mass production lines in an era of a more agile and dynamic market competition environment.

An FMS runs production with different product models and operations in arbitrarily intermixed sequence in a single manufacturing facility. Flexible manufacturing is vital for industry because of the significant cost savings made possible by handling different manufacturing operations for a range of products on the same shop floor. Flexible manufacturing can also absorb significant fluctuations in demand for different product models. This PhD research developed manufacturing simulation and optimisation techniques for FMS. These techniques will reduce planning errors, unnecessary costs in manufacturing and time-to-market for products.

The research has been conducted in collaboration with an industry partner.

1.2 About the AMSCI project

This research is under the umbrella of the UK Government's Advanced Manufacturing and Supply Chain Initiative (AMSCI), this programme is proposed to improve the global competitiveness of UK advanced manufacturing supply chains.

The parent project is called AMSCI Jubilee, which is led by an industry partner -Cosworth. Cosworth originally specialised in motorsport engines; however, it now also supplies into the niche volume performance road car market. To best serve the market demands of the performance automotive market sector, Cosworth’s manufacturing strategy is now centred around latest generation of FMS.

Cranfield University joined this project with two PhD studentships to investigate FMS from the aspects of manufacturing system simulation, optimisation, and supply chain management. The other PhD research was started one year ahead of this research (Rybicka, Tiwari And Enticott, 2016a, 2016b), which focused on the simulation modelling of the FMS, and this research is initially targeting on optimisation of the FMS.

1.3 Problem statement

There are very few commercial practices of FMS applied in industry due to its intrinsic complexity. It has been recognised that more research is required to develop the tools to manage the problems standing in the way of successful implementation. This research’s target is to investigate how to use simulation and optimisation technology to achieve a more profound understanding and better management of FMS.

1.4 Research aim and objectives

The research aims to develop novel manufacturing simulation and optimisation techniques for an FMS. This research will integrate multi-objective optimisation and Discrete Event Simulation (DES) approaches to address the complexity and flexibility within an agile manufacturing environment. This research is intended to support an industrial implementation of FMS, therefore provisioning mass customisation production and transforming many of the traditional production lines.

The main objectives of this research are:

1. Review the state-of-the-art simulation and optimisation technologies for FMS and investigate existing practices of FMSs.

2. Capture the manufacturing problems and compile the requirements for simulation and optimisation for an FMS, by carrying out an industry case study.
3. Develop a simulation and optimisation integration framework for an FMS.
4. Establish a comprehensive simulation model for an FMS, which is able to represent and evaluate multiple manufacturing problems and their dynamic interactions within FMS.
5. Develop a multiple-objective optimisation approach in cooperation with FMS simulation model.

1.5 Research methodology

The research methodology guided through this PhD thesis is shown in Figure 1, the workflow, research objectives and related thesis chapters also are presented in this figure.

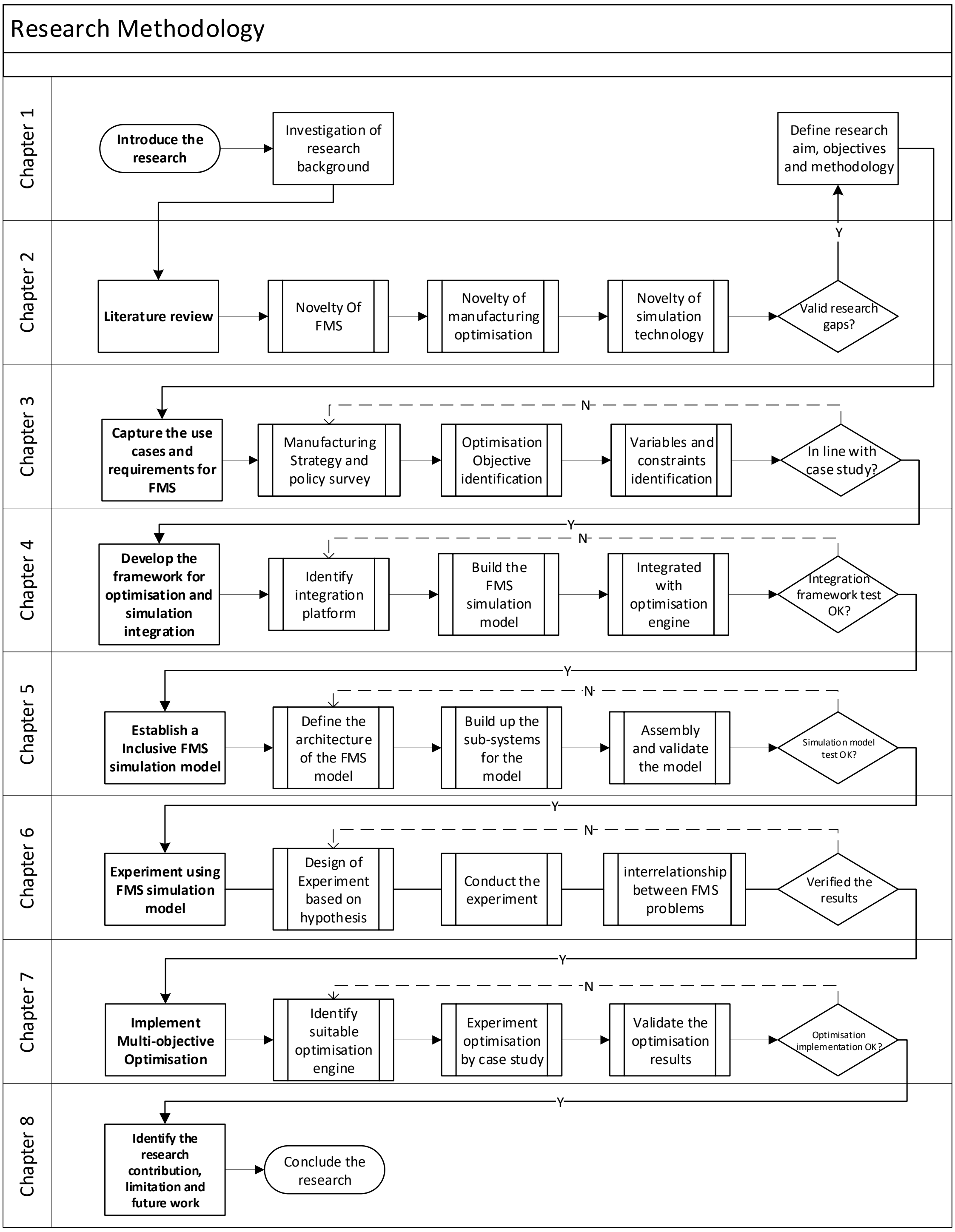


Figure 1 Research methodology and extended thesis structure

1.5.1 Literature review

This chapter presents the methodology of the literature review, described as the collection of literature from different public sources, divided and placed into different categories, then evaluated and selected for detailed analysis. From the benefits of a well-structured methodology, the main research project could increase its focus precision, and achieve a better quality research result based on an understanding of the literature review.

The literature review followed the methodology as shown in Figure 2; in this figure, blue colour states the main focus areas, the grey colour states the related areas but not the main focus for this research, the size of block indicates the level of attention for this research and this literature review. Firstly, this research reviewed the concept of FMS and compared with other manufacturing systems. Then investigated the applied industry sectors for FMS, including their major products and related manufacturing process. From the problem side, the value added of simulation or optimisation work is linked with manufacturing operation functions and their Key Performance Indicators (KPIs). From the solution side, various related simulation and optimisation methods are reviewed.

To search the publications in the relevant research areas, several websites from academic journals, books, and MSc and PhD theses have been investigated:

-Scopus,

-Web of Science (WoS)

-Science Direct

By typing in the keywords and selecting the search fields on these websites, related publications could be found. The titles and abstracts were read first, then highly relevant articles selected, and the full text downloaded for further selection and analysis.

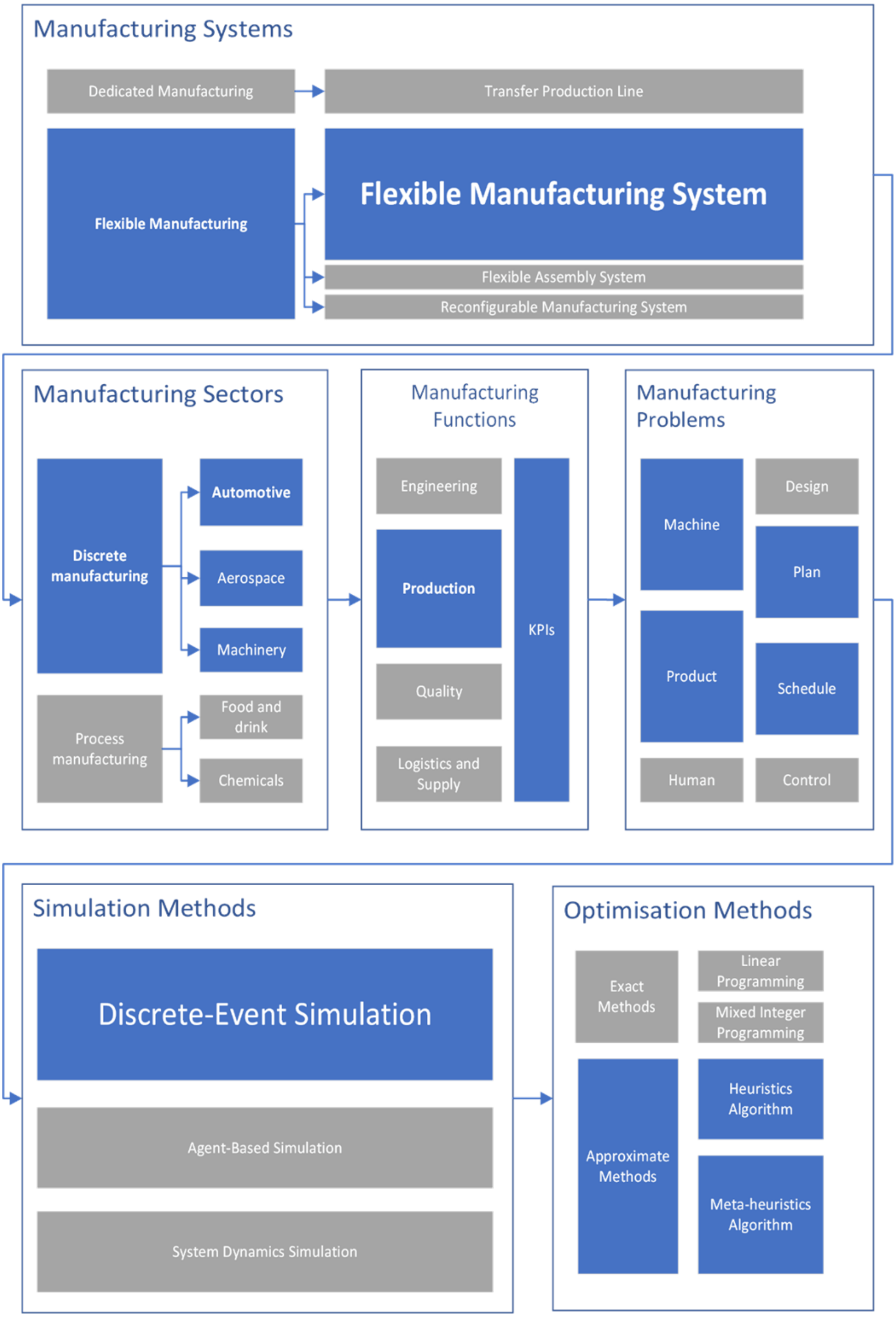


Figure 2 Scope of literature review

1.5.2 Problem definition

This chapter aims to provide an empirical case study of FMS practices and select primary FMS problems for simulation and optimisation. It will provide the knowledge of the problem domain of FMS optimisation method and a clearer direction for designing the simulation and optimisation methods.

By the completion of this chapter, the objectives below will be fulfilled:

- Identify manufacturing problems within the FMS case study
- Prioritise the manufacturing problems of FMS
- Identify relationship of the primary problems with other problems
- Identify simulation and optimisation requirement of the primary problem

The proposed method for the case study is shown in Figure 3. To achieve each objective of the case study, many shop floor visits, industry meetings and workshops were undertaken, and the loop of this procedure was kept running to refine and polish the method for the main research.

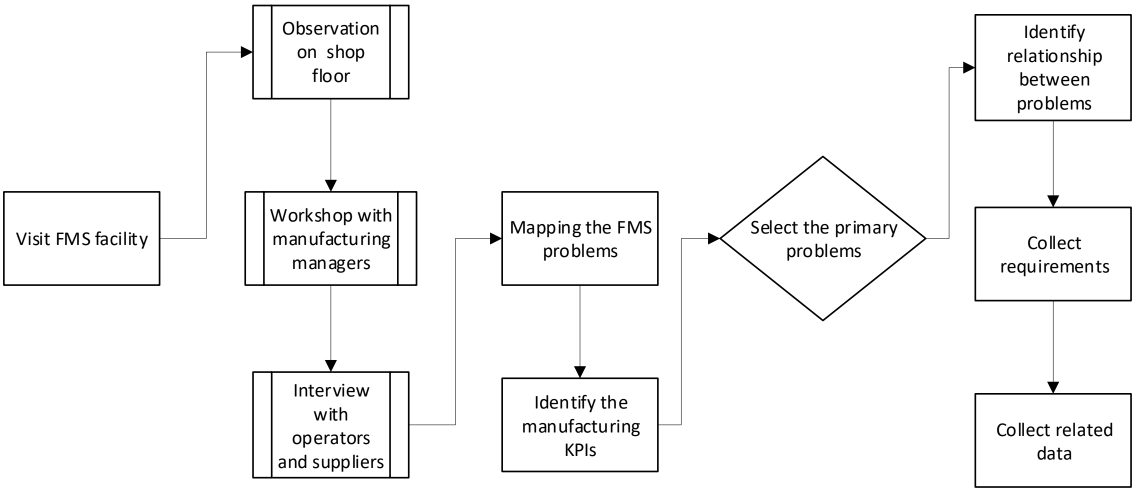


Figure 3 Methodology of an empirical case study

1.5.3 Simulation and optimisation integration framework

This chapter aims to develop a framework enabling the simulation and optimisation work together for FMS problems. Simulation model normally requires better visualisation that can demonstrate the events of manufacturing progress happened during simulation time; however, optimisation prefers better computational effectiveness rather than the visualisation, so that the algorithms can find the optimal results with reasonable short time consumption among large size solution pool. Furthermore, simulation modelling is able to represent complex and dynamic constraints for FMS which is a difficult or heavy cost to complete with mathematical modelling; optimisation algorithms can tremendously improve the efficiency of the analysis progress comparing to the common brutal force researching methods used in simulation experiments. This research would investigate and develop a framework which facilitates simulation model and optimisation algorithm work collectively for FMS problems, as a result, achieve the capability of handling a high level of complexity from problems side, and greater efficiency of optimisation processes.

1.5.4 Simulation modelling

This chapter will develop a simulation model of an FMS using DES method. This simulation model will able to represent multiple FMS manufacturing problems at the same time in order to identify their interrelationship, convenient to tune the required parameters to be using in the experiment work as well. The base of simulation modelling methodology is presented in Figure 4. The base-model of FMS will be validated from shop floor implement. Furthermore, this simulation model will also be considered to be using with optimisation algorithm collectively.

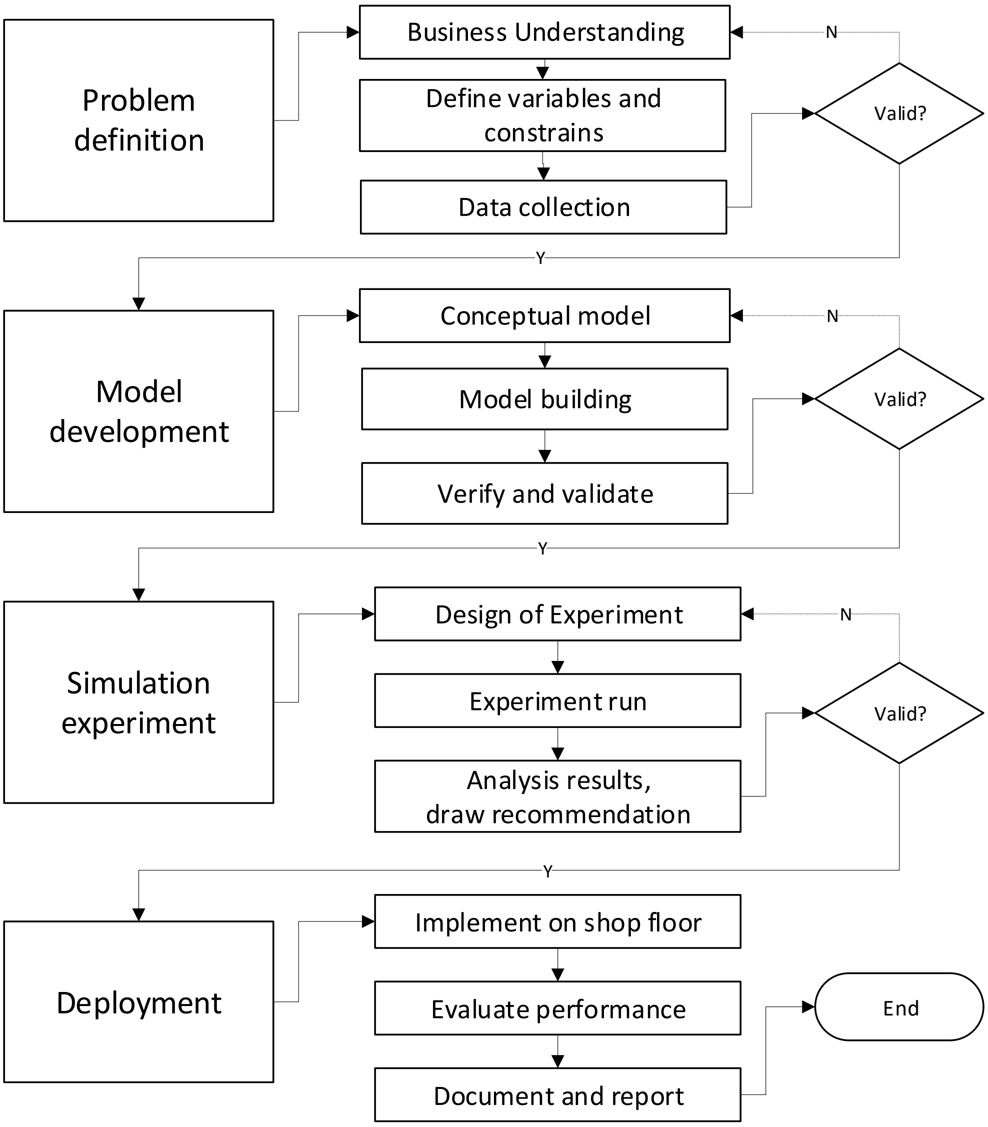


Figure 4 Methodology of simulation modelling

1.5.5 Simulation experiment

According to the methodology of simulation as shown in Figure 4, a series of systemic experiment is required to identify the interrelationship of the FMS problems. Based on the FMS knowledge from literature and practical experience from traditional manufacturing systems, a list of hypotheses is developed. After conducted all experiments using simulation model, the interrelationship of the FMS problem will be identified. Furthermore, by better understand of the interrelationship of FMS problems, the primary parameters for optimisation will also be recognised.

1.5.6 Multi-objective optimisation

Simulation methods is suitable for identifying the FMS system behaviour among a complex constraint, but not good at finding the optimal solution to improve the overall manufacturing performance, hence optimisation work is necessary to carry out. In this chapter, the author proposes a method to apply multi-objective optimisation to solve FMS production scheduling problem, using GA is cooperation with DES. A Pareto Front of optimisation results will be found to improve multiple objectives of FMS manufacturing performance.

1.6 Outline of the thesis

This research is reported in the thesis including the following chapters:

- Chapter 1: Introduce the background, aim and objectives, and the methodology of this research.
- Chapter 2: Provide a review of related fields, indicate the state-of-art research, and identify research gaps.
- Chapter 3: Investigate an industry study case and identify the simulation & optimisation use cases and requirements for FMS.
- Chapter 4: Develop an approach and framework to integrate optimisation and simulation for FMS.
- Chapter 5: Develop an FMS simulation model which consists of the main components of FMS.
- Chapter 6: Experiment the interrelationship of FMS problems using the simulation model.
- Chapter 7: Propose a multi-objective optimisation method adapted to the simulation and optimisation integrated framework.
- Chapter 8: Discussion and conclusion of this research, summarise the contribution to knowledge.

2 LITERATURE REVIEW

2.1 Introduction

The purpose of this literature review is to study the existing related research on manufacturing operation for FMSs and study the potential application of the optimisation and simulation techniques in order to improve the manufacturing performance of FMS.

The aim of the literature review is to review the manufacturing simulation and optimisation techniques related to FMS. This literature review will investigate the simulation and optimisation methods applied to optimise the manufacturing production processes, specifically implemented within FMSs.

With the intention of achieving the above-mentioned aim, the literature review

has been focused on the following objectives:

1. Review the relevant FMSs, primarily consisting of multiple machine centres and including both machining and assembly operations.
2. Review the relevant FMS problems, especially including the problems such as production line balance and operation sequence problems.
3. Review the relevant manufacturing simulation technologies, mainly applied in FMSs.
4. Review the relevant simulation and optimisation methods for FMSs.

The scope of this literature review would not extend 150 articles for brief reading and focus less than 100 articles for detailed analysis. The literature review scope is broader than the scope of the primary research because the cutting-edge technologies have been introduced in the optimisation algorithm development areas but may not have been applied to FMSs. These literatures still have a considerable reference value for the primary research.

After the first round of literature collection, 87 publications were selected by keywords according to the subjects related to the primary research. Later, these references would be evaluated and selected for further analysis.

2.2 Introduction to Flexible Manufacturing Systems

Technological advancements, new competitors, global sourcing and industry restructuring have resulted in significant challenges for the manufacturing industry. The transition of the manufacturing industry from mass production to mass customisation is based on the need for a more customised product to be produced, providing many variants, with the use of fewer resources and materials, in the shortest time possible (Chryssolouris et al., 2008). To solve these new challenges and to satisfy the growing demands, an FMS has been proposed to replace the traditional manufacturing systems.

2.2.1 The different flexibilities in a manufacturing system

Flexibility has an increased importance for manufacturing systems recently, as they need to cope with increasing uncertainty in the market demand. In order to design a new manufacturing system, the method to measure and control the level of flexibility has to be developed, so researchers have identified and classified the flexibility from manufacturing systems.

Browne et al. (1984) defined and described eight types of flexibilities, the classification and definitions maintained in most of the FMS research up to now:

1. **Machine Flexibility**: the ease of making the changes required to produce a given set of part types. For instance, the less set-up time required for the machine to change a cutting tool or fixture when the part is changed, the more machine flexibility would be gained.
2. **Process Flexibility**: the possibility to produce a given set of part types via different process or materials. ‘Process Flexibility’ has also been called ‘job flexibility’ or ‘mixed flexibility’ in other places.
3. **Product Flexibility**: the ease of changeover to produce a new (set of) product(s) very economically and quickly. It is also called ‘action flexibility’ or ‘design-change flexibility’. This flexibility heightens a company's potential responsiveness to competition during market change. Product flexibility can be measured by the time required to switch from one part mix to another, not necessarily of the same part types.

4. **Routing Flexibility**: the ability to replace the fixed routing to face breakdowns and to reduce production stoppage time. This ability exists if either a part type can be processed via several routes, or, equivalently, each operation can be performed on more than one machine.
5. **Volume Flexibility**: the ability to operate an FMS profitably at different production volumes. This ability is essential due to the market demand change or the mismatch between forecasts and real orders.
6. **Expansion Flexibility**: the capability to build a system, and then expanding it as needed, quickly and modularly. Expansion flexibility is hard to realise with most assembly and transfer lines.
7. **Operation Flexibility**: the ability to interchange the order of several operations for producing a specific part. Keeping the routing options open and not predetermining either the 'next' operation or the 'next' machine increases the flexibility to make these decisions in real-time. These decisions should depend on the current system state, for example which machine tools are currently idle, busy, or blocked.
8. **Production Flexibility**: the universe of processing technologies that the FMS can provide. Production flexibility is measured by the level of existing technology. For example, the FMS has different kinds of machines, if one FMS has a plasma machine when others do not, the FMS can produce more part types and has more production flexibility than others.

The relationship between different kinds of flexibilities of manufacturing systems is shown in Figure 5. This classification of flexibilities can help categorise different types of FMS.

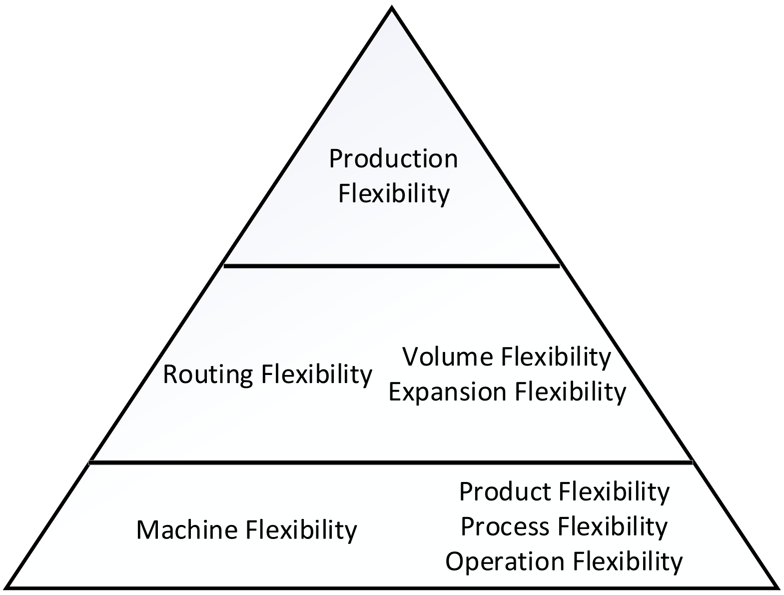


Figure 5 Relationship among types of Flexibility

2.2.2 The initiative of the FMS

With the development of automated manufacturing, especially for automated small-batch production, the initial concept of the FMS started to be mentioned in the literature and industry reports in the late 1980s.

O'Grady and Menon (1986) indicated that the early technological initiative for FMSs was promoted by the British National Engineering Laboratory. This initiative was followed by significant government funding to encourage large-scale investment in FMSs by British companies, such as Anderson Strathclyde plc., Gardner & Sons, Normalair-Garett Ltd. and SCAMP/600 Group plc. There were also some FMS installations in contemporary American companies.

It should be noticed that the initial FMS concepts in the late 1980s are similar to current ones, but the machines and technologies integrated inside of this automated manufacturing system have changed significantly. On the other hand, the complexity of FMSs has been increased by technological advancements.

2.2.3 Definition of FMSs

FMSs have been defined in a number of ways, but there is not a standard acknowledged definition for the general term of FMS. Most of the definitions are based on the hardware used in the system. Chan et al. (2002) listed and summarised the popular definitions:

Donald et al. (1988) stated that:

“A flexible manufacturing system (FMS) is a manufacturing system in which groups of numerically controlled machines (machine centres) and a material handling system work together under computer control.”

O’Keefe and Kasirajan (1992) defined an FMS as:

“A group of workstations connected together by a material handling system (MHS) producing or assembling a number of different part types under the central control of a computer.”

Other definitions are based on the capability or performance of the system. For example, Jones and McLean (1986) stated that:

“Flexible manufacturing systems (FMS) are highly automated production systems, able to produce a great variety of different parts by using the same equipment and the same control system.”

Draper (1984) stated that:

“FMS is designed to combine the efficiency of a high-production line and the flexibility of a job shop to best suit the batch production of mid-volume, and mid-variety of products.”

More definitions can be found in the literature (e.g. Bruno et al.,1986; Fox and Smith, 1984) Despite the range of definitions, it is accepted that an FMS consists of three primary subsystems:

- A machine/workstation subsystem that at least can provide machine flexibility.
- A material handling and storage system that at least can provide routing flexibility.

- A computer control system which can dynamically manage all subsystems.

2.2.4 Related manufacturing systems

As the FMS has a comprehensive definition, the FMS discipline could also be applied to broader manufacturing environments, and then be integrated into other manufacturing systems, such as Flexible Assembly Systems (FASs) and Reconfigurable Manufacturing Systems (RMSs).

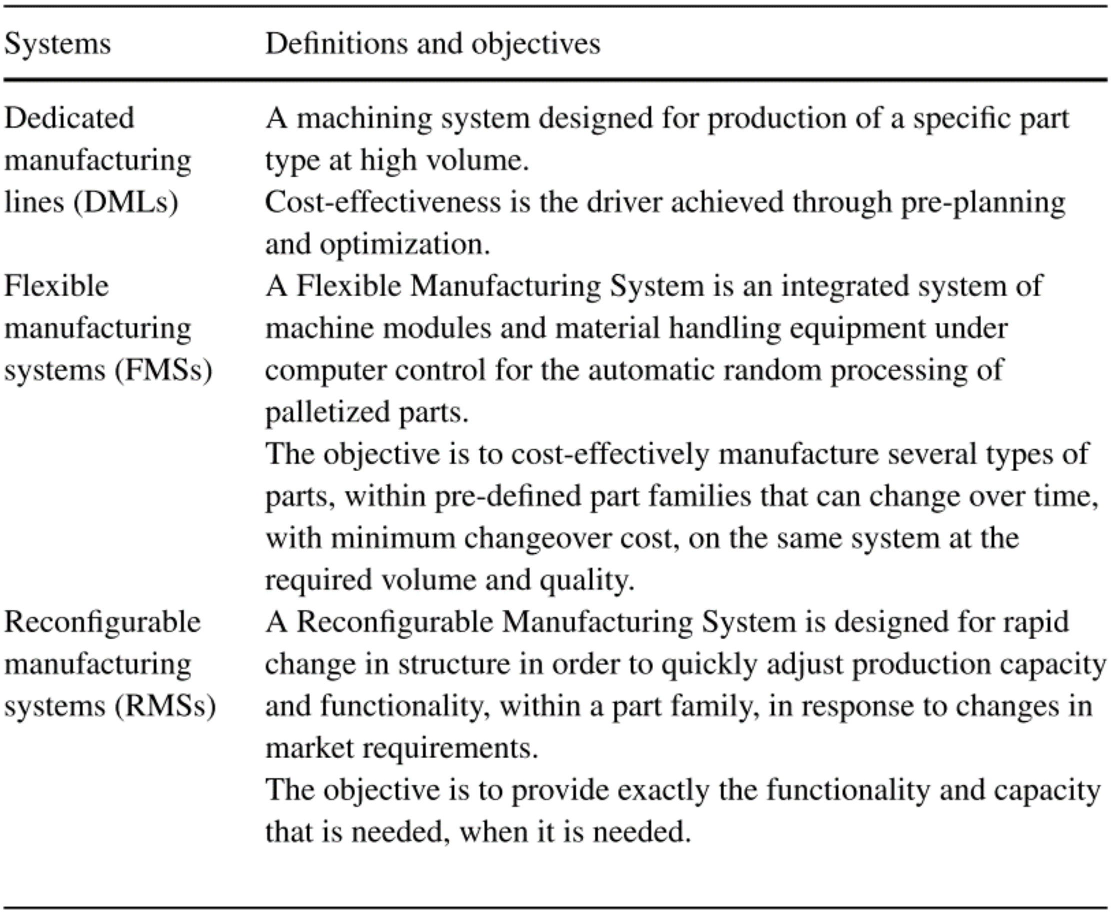
An FMS is initially developed for automated manufacturing, which mainly consists of machining processes. Flexible manufacturing discipline has been used for assembly operations as well; De and Lee (1993) referred to such systems as Flexible Assembly Systems (FASs). Assembly systems are used to convert raw materials and components into products of a known and desired functional quality. Common assembly operations include screw insertion, mating of parts, and electric board assembly. Unlike the machining system with precise performance parameters, the assembly operation rate is less predictable. In FASs, parts requiring assembly are not independent of each other. For example, the parts are related by an assembly precedence structure; hence, if a circuit board assembly machine breaks down, then the affected parts include not only the parts waiting to be assembled on the circuit board but also those parts waiting for the assembled circuit board. These added dimensions of complexity make the assembly environment more difficult to model.

The RMS is a new proposed manufacturing systems paradigm that aims at achieving cost-effective and rapid system changes by incorporating principles of modularity, integrability, flexibility, scalability, convertibility, and diagnosability (ElMaraghy, 2005). The RMS promises customised flexibility on demand in a short time, while the FMS provides generalised flexibility designed for the anticipated variations. Compared with the FMS, the RMS has introduced more about the importance of having harmonised human-machine manufacturing systems.

The traditional production lines which are called Dedicated Manufacturing Lines (DMLs), FMSs, RMSs are compared in Table 1.

In summary, FASs, RMS are developed by the inspiration of FMSs and the specific requirement from industry. Put simply, all of these three systems are pursuing more manufacturing flexibility than a traditional production line; FASs and RMSs involved more human elements than FMSs; RMSs are faced with a more rapid change of hardware than others. These proposed advanced manufacturing systems exist overlap functions. There is no absolute answer regarding which system is the best; this would depend on the industry manufacturing strategy. However, all of these systems are much more complex than the dedicated manufacturing systems. For this research, the FMS is the main focus.

Table 1 Comparison of three types of manufacturing systems (ElMaraghy, 2005)



Systems	Definitions and objectives
Dedicated manufacturing lines (DMLs)	A machining system designed for production of a specific part type at high volume. Cost-effectiveness is the driver achieved through pre-planning and optimization.
Flexible manufacturing systems (FMSs)	A Flexible Manufacturing System is an integrated system of machine modules and material handling equipment under computer control for the automatic random processing of palletized parts. The objective is to cost-effectively manufacture several types of parts, within pre-defined part families that can change over time, with minimum changeover cost, on the same system at the required volume and quality.
Reconfigurable manufacturing systems (RMSs)	A Reconfigurable Manufacturing System is designed for rapid change in structure in order to quickly adjust production capacity and functionality, within a part family, in response to changes in market requirements. The objective is to provide exactly the functionality and capacity that is needed, when it is needed.

2.2.5 Type of FMS

Different authors classify different types of FMS (Chan et al., 2002).

Browne et al. (1984) classified FMSs into four types: flexible machining cell; flexible machining system; flexible transfer line; and flexible transfer multi-line. This classification was based on process attributes and captures the principal attitudes of system design and operation such as the equipment selection, layout, capacity decisions, and other issues.

Stecke (1984) extended the classification scheme to include the type of material handling system as a further descriptor. Her classification scheme was based on the flow pattern of parts through the system and emphasises routing flexibility.

MacCarthy and Liu (1993) classified FMSs into four types: a single flexible machine, a Flexible Manufacturing Cell (FMC), a Multi-Machine FMS (MMFMS), and a Multi-Cell FMS (MCFMS). Then they discussed the relationships and boundaries between these four types of FMS. The approach considered the number of characteristics of the material handling devices as well as the configuration of the processing elements.

2.2.6 Main subsystems of an FMS

The basic subsystems of an FMS are:

- workstations,
- material handling and storage systems,
- computer control system,
- operators and supervisors

Here are the descriptions of the workstations, computer control systems and humans in FMS.

1) **FMS Workstations**: FMSs have various workstations which are designed for different tasks, but in general they can be classified into five types according to their functions: load/unload, machining, assembly, supporting and others.

- **Load/Unload:** physical interface between the FMS and the rest of the factory; it is where new parts enter the system, and temporarily or completely exit the system after the operation is finished. Loading and unloading can be performed manually or handled by a material handling system, which should be designed to permit the safe movement of parts and may be supported by various mechanical devices (e.g. cranes, forklifts). The station includes a data entry unit and monitors as the communication interface between the operator and computer system, regarding parts both to enter and exit the system. In some FMSs, various pallets or fixtures may have to be put in place at nearby load/unload stations.
- **Machining:** the most common FMS application uses machining centres. These are usually Computer Numerical Controlled (CNC) machine centres with appropriate automatic tool changing and tool storage features, to facilitate quick changeover as necessary. The machine centre may able to automatically change pallets or fixtures, and normally would normally be integrated with the material handling system.
- **Assembly:** the assembly operation usually consists of a number of workstations with industrial robots that sequentially attach components to the base part. They can be programmed to perform tasks with variations in sequence and motion pattern to accommodate the different product styles assembled in the system. Usually, there would also be some assembly operations conducted manually, and not connected to the material handling system. Whether the manual assembly is inside of the FMS depends on how the border of the FMS is defined. One definition of the border of the FMS is when the whole shop floor is within same facility, the other definition of the border of the FMS is when only includes the automated subsystems, which separate the manually assembly and manually inspection processes outside of the FMS.
- **Supporting:** supporting subsystems may include various quality inspection stations. Co-ordinated measuring machines, special inspection

probes, and machine vision may be used here. Other supporting stations may include pallet and part washing stations for particularly dirty or oily situations, and can be temporary storage stations for both parts and pallets. Supporting subsystems have the same issues as the assembly subsystem; the automated machine inspection workstation such as a Coordinate-Measuring Machine (CMM) would generally be considered as inside of the FMS border, and the manual inspection workstation may be considered as out of FMS in some cases.

- **Other:** Other possible stations may be found in specific industries, such as—for example—sheet metal fabrication, which has stations for press-working operations, such as punching, shearing, and certain bending and forming processes. Forging is another labour-intensive operation which may be broken into specific station categories, such as a heating furnace, forging press, and trimming station.

2) **FMS computer control systems:** Due to the high complexity levels of FMSs, the system controlling tasks are critical, so any fault in the controlling system may lead to production stoppage or product damage. As this research also aims to better manage and control the FMS, it is necessary to have a solid understanding about FMS computer control systems.

   The FMS computer control systems have been defined into the following sub-categories: workstation control, distribution of control instructions to workstations, production control, traffic control, workpiece monitoring, tool control, performance monitoring and reporting, and diagnostics. The detail is described as below:

   - **Workstation control**: fully automated FMSs use some form of workstation control at each station, often in the form of CNC control.
   - **Distribution of control instructions to workstations**: a central computer is required to handle the processing occurring at disparate workstations; this involves the dissemination of part programmes to individual workstations, based upon an overall schedule held by the central computer.

- **Production control**: management of the mix and rate at which various parts are launched into the system is essential; alongside data input of a number of essential metrics, such as daily desired production rates, number of raw workparts available, work-in-progress, etc.
- **Traffic control:** management of the material handling system is essential so that parts arrive at the right location at the right time and in the right condition.
- **Workpiece monitoring:** the computer must monitor the status of each part or pallet in the primary and secondary material handling systems, to ensure that the manager know the location of every element in the system.
- **Tool control:** this is concerned with managing tool location (keeping track of the different tools used at different workstations, which can be a determinant of where a part can be processed), and tool life (keeping track on how much usage the tool has gone through, so as to determine when it should be replaced).
- **Performance monitoring and reporting:** the computer must collect data on the various operations ongoing in the FMS and present performance findings based on these data.
- **Diagnostics**: the computer must be able to diagnose, to a high degree of accuracy, where a problem may be occurring in the FMS.

3) **Humans in FMS:** Human personnel manage the overall operations of the system. Humans may be also be required within the FMS to perform a variety of manual operations and supporting operations. These manual operations include: assembling the parts before or after the machining operations; loading raw materials into the system; unloading finished parts or assemblies from the system; changing and setting tools; performing equipment maintenance and repair; performing CNC part programming; programming and operating the computer system; and managing the overall system operation.

2.2.7 Potential benefits of a successful FMS implementation

While Lean and Six Sigma are well known and widely adapted, FMS has rarely fully understood and implemented in the current manufacturing industry. This concept is, however, more attractive for the companies operating in niche volume production and want to expand their business to service more customers or to produce more kinds of product.

In most cases, productivity and the flexibility are usually in conflict and should be a good trade-off or balanced according to the business strategy. The FMS is a way to set productivity and flexibility harmony, and thereby optimise other objectives including product quality.

Today’s unpredictable market environment demands low-cost solutions that provide:

- high quality of product;
- quick product turnaround;
- adaptability and responsiveness to changes in demand;
- capability to easily resurrect discontinued designs.

In many instances, an FMS does provide both hardware and software solution to this fourfold management challenge. Chen and Adam (1991) stated potential FMS benefits on measurable productivity and quality criteria, as shown in Table 2.

It should be noted that the potential benefits of an FMS can only be achieved by its successful implementation; however, before reaching these benefits, there is a long-term planning and set-up period. Due to the high investment in FMS, after the FMS implementation, it is inevitable that there will be a long period before there is any return on the investment. After the FMS goes alive, the company should reconfigure its business strategy to ensure the FMS fits with their suppliers and customers.

Table 2 Summary of FMS potential benefits (Chen and Adam, 1991)

	Criterion	Potential Operational Benefits	Potential Strategic Benefits
Productivity	1) Systems	Overall lower costs than transfer lines per type of product	Plant modernisation for future competitiveness
	2) Equipment	Reduced in number due to increased spindle utilisation. Expand machinery capability	Less plant space required
	3) Direct labour	Reduced in number for less cost	Higher skilled labour
	4) Work-in-process	Less inventory cost	Less storage spaces. Simpler plant layout
	5) Equipment utilisation	Reduced idle time and downtime	Better return of equipment investment
	6) Production lead time	Shorten lead time and higher throughout	Capable to meet urgent market demand
	7) Production maintainability	Enhanced for continued output	Able to cope with extreme cases
	8) Operational flexibility	Reduced setup time between product or process change	Agile respond to market change. Flexible in accommodating future products and projected production volumes.
	9) Phased technology introduction	Better control of capital	Reduced risk of investment
Quality	1) Prevention measures	Reduced workload for integrated processes	Less maintenance downtime required
	2) Appraisal measures	Reduced for inspection cost	Shorten production lead time
	3) Internal failure	Reduced costs on scrap and rework	Achieved smooth and consistent production process flows
	4) External failure	Reduced costs on warranty, recalls and liability	More customer satisfaction for a fast-changing market

2.3 Problems in developing Flexible Manufacturing Systems

Starting from the design of an FMS to the FMS going alive, there are several stages. Each stage has specific problems and the decisions made in the early stages may have a consequential impact on following the stages. In terms of optimisation, the problems and selected solutions in the early stages could become the constraints of the following optimisation tasks. Consequently, it is hard to deliver realistic optimisation results unless having full understanding for the problems of FMSs in all stages.

In general, when a company plans to build an FMS, it should be targeted as a design and should implement an advanced manufacturing system to handle the market challenge and maximise productivity. These targets are difficult to achieve unless all of the following stages have been conducted successfully:

- System Designing;
- Production planning;
- Scheduling;
- Controlling.

The problems of the FMS in each phase are summarised in Figure 6, and explained in the following sections:

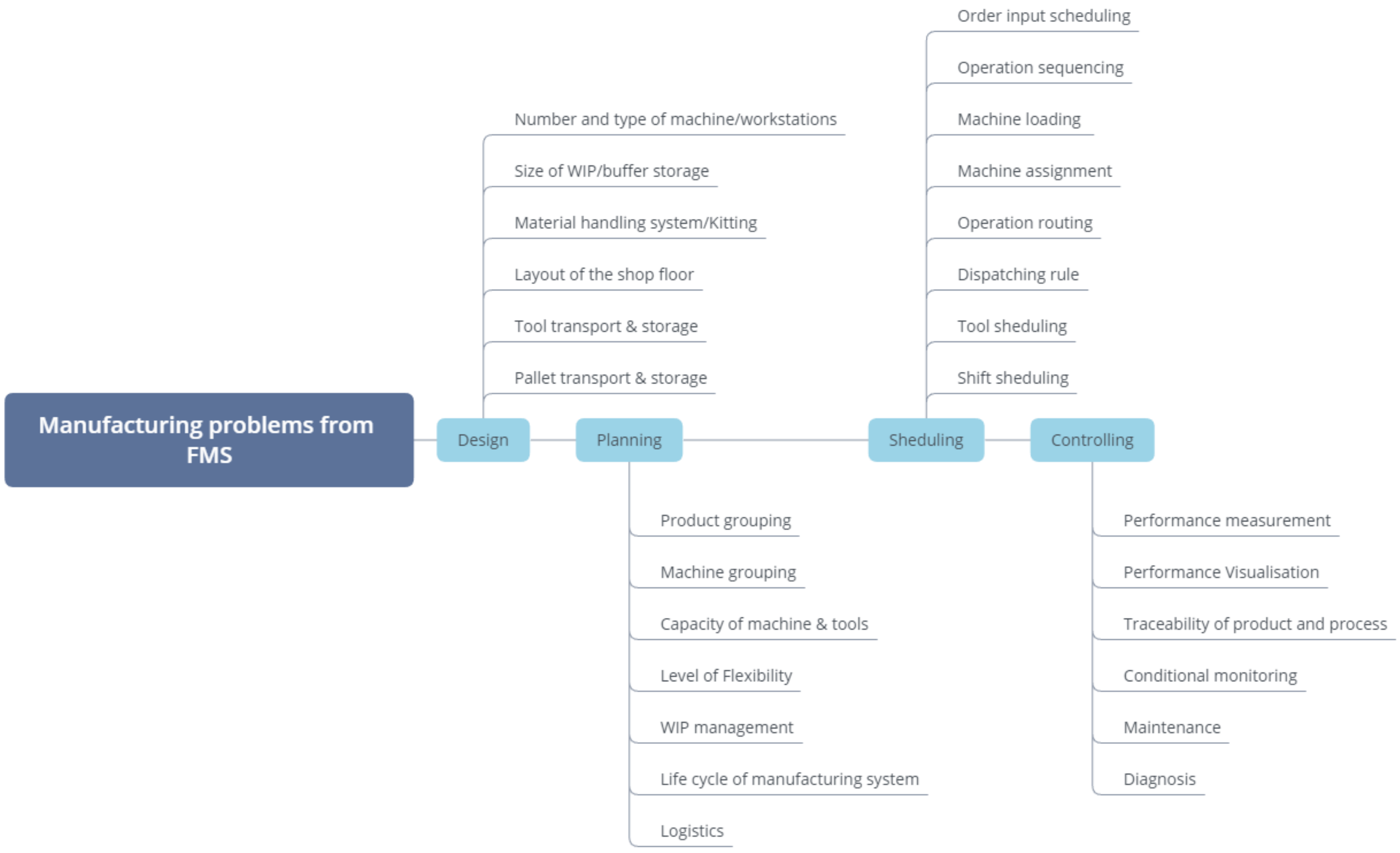


Figure 6 Summary of manufacturing problems of FMS in four stages

2.3.1 Design problems

Designing FMS is similar to a series of checklists. It starts more like to selecting the best business strategy to fit current market and future markets, rather than to selecting the best manufacturing engineering solutions. Once the high-level management board has a good understanding of its market and has defined a certain business strategy, the operations manager and manufacturing department should start the initial assessment to check whether an FMS would appropriately suit that business strategy. For example, if the market demand is stable, requests high volume and a product family, the dedicated manufacturing systems, such as the transfer production line applied Lean Manufacturing principle, would be a better choice than an FMS.

A set of questions relevant to manufacturing engineering should be considered during the FMS designing stages:

- **Types of workstation:** Workstation choices have to be made depending on manufacturing processing requirements. The shop floor layout and utilisation of transportation should also be considered.
- **Variations in process routings and FMS layout**: If part processing variations are minimal, the manager may decide to use more linear links in the process flow; if part processing variations are high, it may operate more like the job shop which maximises the routing flexibility.
- **Material handling system**: The manager must select an appropriate primary and secondary material handling system to suit the layout chosen.
- **Work-In-Process (WIP) and storage capacity:** Determining an appropriate level of WIP is important, as it affects the level of utilisation and efficiency of the FMS. It is necessary to define enough physical space on the shop floor to store these WIPs.
- **Tooling:** The number and type of tools required at each workstation must be determined. Enough number of spare tools should be prepared by considering enabling routing flexibility in the system, or to couple with unplanned breakdowns.

- **Pallet fixtures:** Selection of the type and number of pallet fixtures is important. Factors that influence the decision include levels of WIP chosen and differences in part style and size.

A design approach for FMS, as shown in Figure 7, is also drawn with the respecting of the data acquisition and constraint definitions such as manufacturing strategy, production requirements (Fallis et al., 2009). This approach also shows a lack of analysis and evaluation tools which could be used in the designing stage.

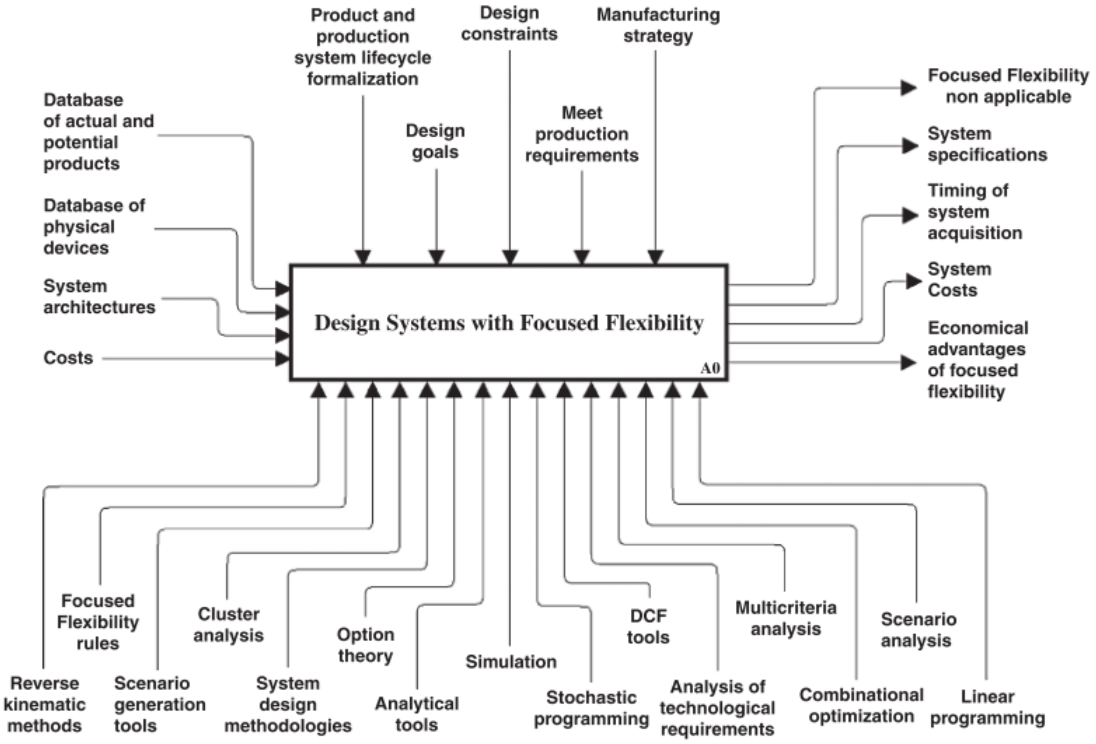


Figure 7 A design approach for FMS (Fallis et al., 2009)

2.3.2 Planning problems

After the designing stage has chosen the right system configuration and the design objectives to be in line with the company’s manufacturing strategy, the planning stage will then plan the right manufacturing capacity and production resource to fulfil the given requirements.

Stecke (1985), Nayak and Acharya (1998), Liang and Dutta (1993) identified several planning problems for FMSs:

- **Part type selection:** from a set of part types that have production requirements, determine a subset for immediate and simultaneous processing.
- **Part family considerations:** a choice has to be made regarding group technology and the part family to be produced on the FMS, with all possible physical attributes of the parts that may be processed in the FMS.
- **Processing requirements:** once the entire range of possible parts to be processed is known, this information would help choose associated processing requirements for each part, furthermore, decide the type of equipment that is associated with the process.
- **Machine grouping**: the decision on how to group the machine associated with the process group or the product groups. In dedicated manufacturing systems, machine grouping is normally associated with the product group; in FMSs, it is more desired to associate with the progress group.
- **Production rate**: determine the relative production rate for each product. Production rate would also determine the inter-arrive time of the material feeding and the strategy of the supply chain.
- **Resource allocation:** confirm the limits and constraints of the manufacturing capacity, allocate the number of pallets and fixtures among the selected part types.
- **Loading problem:** define the collection of rules about how to consume the material and utilise the machine, subjected to the technological and capacity constraints of the FMS.

2.3.3 Scheduling problems

While planning problems focus on the decisions should be made before the launch of production, scheduling problems mainly focus on the rules applied during the product period. Thus, the FMS could coordinate the all subsystems in a flexible and dynamic way.

The main scheduling problems occurring in an FMS are the following (Donath, Graves and Carlson, 1989; Solot, 1990; Stecke, 1983):

- **Input sequencing problem:** the sequence of each product order entry into the system. For example, it can input a small batch of one certain type of product and switch to small batch of another product later, or it can input all products simultaneously. It can be difficult to fix the decision of this problem at the beginning of the implementation of an FMS, because this decision would impact on almost all subsequent problems.
- **Operation sequencing problem:** this problem can be very easily confused with the dispatching sequencing problem in an FMS. Most of the literature has not separated the definition of operation sequencing from dispatching sequencing with a crystal-clear description.

  Operation sequencing normally refers to the sequence of conducting all operations required to produce one specific product. It is only focused on a single product. Dispatching sequencing, or dispatching rule refers to the sequence of selecting one WIP to enter the system in the next moment with the consideration of all WIP currently in the queue. Besides, each WIP has its own states of what is the last operation completed and what is the next operation that should be carried on according to the operation sequence.

  Operation sequencing and dispatching sequencing can be one thing in a transfer line, such as working with a linear work flow, because the dispatching sequence just repeats the operation sequence again and again. However, in an FMS, it is able to input multiple WIP into the system simultaneously, thus, the dispatch sequencing works in a different manner from operation sequencing.

  With regard to the operation sequence alone, it can be fixed for in the whole production period, or flexible so it can change during the production period. The common assumption of an entirely fixed precedence of operation sequencing is an unfortunate renouncement to releasing the flexibility of an FMS.

- **Workstation selection problem:** when an operation can be performed on several work stations, the one to actually use has to be determined.
- **Part dispatching sequencing problem:** the part, namely, WIP that must be processed first on a workstation has to be selected from the waiting queue or buffer. This problem is also generally called the dispatching rule problem.
- **Material handling carrier selection problem:** in case automatic guided vehicles or multiple transport tools are used in the FMS, one vehicle needs to be selected from among the others to carry a specific part.
- **Traffic control problem:** in case several routes can be followed by a vehicle to reach its destination, one of them must be chosen.
- **Operator selection problem:** if an operation is not totally automatic, an operator must be assigned to it.

2.3.4 Controlling problems

Controlling problems are relevant regarding with how to keep the FMS running at its expected performance. The computer control system would take the main tasks to continuously monitoring the system. Controlling problems also include setting up the right quality management system to record and track the valuable information for each product and process. It should be noted that the controlling problem is actually closely connected to the scheduling problems. Without a stable and functional controlling system, there is no way to solve the scheduling problems in the real-world operation of an FMS.

The main controlling problems within an FMS are listed below:

- **Machine and tools breakdown:** these are common problems in most of manufacturing systems. There should be a plan to repair the machine, change to a backup machine, or switch to alterative operation routings as soon as possible; by solving this problem, the production would remain in or return to the normal state.

- **Maintenance:** the maintenance should be scheduled, whether within in the working hours or occurring in the off shift regularly, so that the productivity of the FMS could be remained sustainable.
- **Inspection:** the way to control the quality of product and the performance of the process. It also needs to record the selected information of the product or process.
- **Monitor and report:** monitor and measure the performance of the system, such as tool life, machine condition and inventory level. The controlling system should warn the manager if error or failure has occurred. The diagnostic function should also support the manager to find the source of the failure.

2.4 Optimisation of Flexible Manufacturing Systems

This section reviews the FMS optimisation research in literature, with regard to the optimisation problems and the optimisation models. In order to analyse the behaviour of FMSs and to develop a method for manufacturing optimisation, this section aims to support the researcher in identifying suitable optimisation problems in FMS and build the right model for the chosen optimisation problems.

The optimisation algorithms have also been reviewed, by focusing on how to apply the optimisation algorithms, not on how to build the algorithm internal programming or coding, because the key logics of optimisation algorithms have already been developed by computer science researches. This research is targeted to apply these advanced computer science tools to solve the problem in manufacturing systems.

The optimisation models have been reviewed under the following five key elements:

- Type of FMS
- Categories of optimisation problem

- Objective functions
- Variation and constraints (summarised in the discussion)
- Selected optimisation algorithm

There are few optimisation researches allocated to the problems classified in the designing stage, so the designing optimisation has not been listed here. On the other hand, the rest of the optimisation problems still help the industry to better define, modify, and implement the FMS.

The reviewed FMS models have been listed in Table 3

Table 3 List of Reviewed FMS literature

Ref. ID	Ref.	Year	Systems	Problems	Methods
FMS01	(Jerald et al., 2005)	2005	MCFMSs	Scheduling	GA,PSO
FMS02	(Yücel, 2005)	2005	SFMSs	Simulation	DES (ARENA®)
FMS03	(Gertosio, Mebarki and Dussauchoy, 2000)	2000	MMFMSs	Simulation	DES
FMS04	(Rifai et al., 2016)	2015	MMFMSs	Scheduling, Loading, layout	GA
FMS05	(Joseph and Sridharan, 2011)	2011	MMFMSs	Evaluate routing flexibility, sequencing flexibility and part sequencing rules	DES
FMS06	(Solot, 1990)	1990	MMFMSs	Scheduling; Planning	Simulation
FMS07	(Zeballos, 2010)	2010	MMFMSs	Scheduling	Constraint programming
FMS08	(Seok Shin, Park and Keun Kim, 2011)	2011	MMFMSs	Planning	GA
FMS09	(Chan and Swarnkar, 2006)	2006	MMFMSs	Planning	ACO

FMS10	(Abou-Ali and Shouman, 2004)	2004	MMFMSs	Simulation	DES (SIMFACTORY II.5)
FMS11	(Inaba, 1982)	1982	MCFMSs		
FMS12	(Caumond et al., 2009)	2009	MMFMSs	Scheduling	Mixed integer linear program (MILP)
FMS13	(Zambrano Rey et al., 2014)	2014	MCFMSs	Controlling	semi-heterarchical architecture simulation-optimisation
FMS14	(Prakash, Chan and Deshmukh, 2011)	2011		Scheduling	GA
FMS15	(Ullah, 2011)	2011	MMFMSs		Petri Net, Queuing Network
FMS16	(Suresh Kumar and Sridharan, 2009)	2009	MMFMSs	Scheduling	DES
FMS17	(Başak and Albayrak, 2015)	2015	MMFMSs	Scheduling	Petri Net
FMS18	(Novas and Henning, 2014)	2014	MMFMSs	Scheduling	Constraint programming
FMS19	(Ma and Matsui, 2002)	2002	MMFMSs	Preference Evaluation	closed network theory
FMS20	(Csokmai et al., 2014)	2015	SFMSs	simulation	
FMS21	(Saygin, Chen and Singh, 2001)	2001	MMFMSs	Simulation	Simulation (C++)
FAL01	(De and Lee, 1993)	1993	FALs	Scheduling	

The optimisation objectives have been recorded in Appendix Table A-1.

2.4.1 Planning optimisation

Solot (1990) modelled an existing FMS called TUGEFA - Turbolader Gehiiuse Fabrik, which belongs to Asea Brown Boveri, Baden, Switzerland who manufactures medium to large turbocharger casings. As shown in Figure 8, this is a Multiple Machines Flexible Manufacturing System (MMFMS), used to investigate on planning and scheduling problems. This research built a framework and proposed to apply them with optimisation and simulation tools.

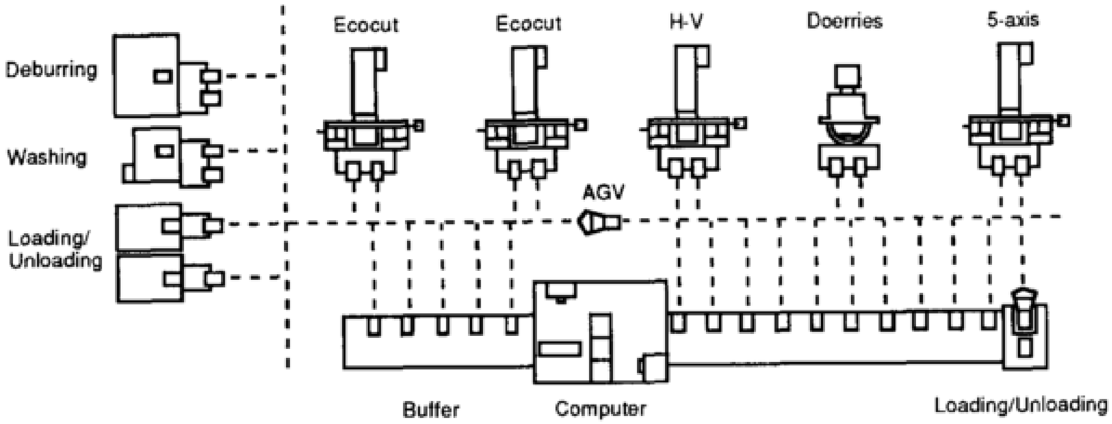


Figure 8 Multiple Machines FMS for planning and scheduling problems (Solot, 1990)

A comparison between Petri Net (PN) and Queuing Network has been conducted for FMS optimisation (Ullah, 2011). The optimisation model is based on an MMFMS which manufactures the automotive engine. This study involved planning and scheduling problems. The objectives are minimum WIP, maximum throughput, and reduced lead time. This model also involved costing issue.

Fuzzy goal programming integrated Ant Colony Optimization (ACO) is used to solve FMS planning problems (Chan and Swarnkar, 2006). The objectives are minimising the machine cost, set-up cost, Material Handling System (MHS) cost regarding to machine tool selection and operation allocation problems.

A FMS built by Fujitsu Fanuc Ltd. has also been recorded (Inaba, 1982). This FMS is a MCFMS including manufacturing robots, and wire-cutting machines. This is one of the few materials which reported the benefits of the successful implementation of an FMS.

2.4.2 Scheduling optimisation

An optimisation procedure has been developed to solve the scheduling problem in FMS via different Artificial Intelligence (AI) approaches (Jerald et al., 2005). The manufacturing environment is an MCFMS, as shown in Figure 9. One combined objective function (COF) of minimising the machine idle time and minimising the total penalty cost is considered. The variables include part index, process sequence, process time, due date, batch size, penalty cost. This study tested different complexity scenarios and found Particle Swarm Optimisation (PSO) gave the best optimisation results during the comparison between Genetic Algorithm (GA), Simulated annealing (SA), Memetic Algorithm (MA), and Particle Swarm Optimisation (PSO).

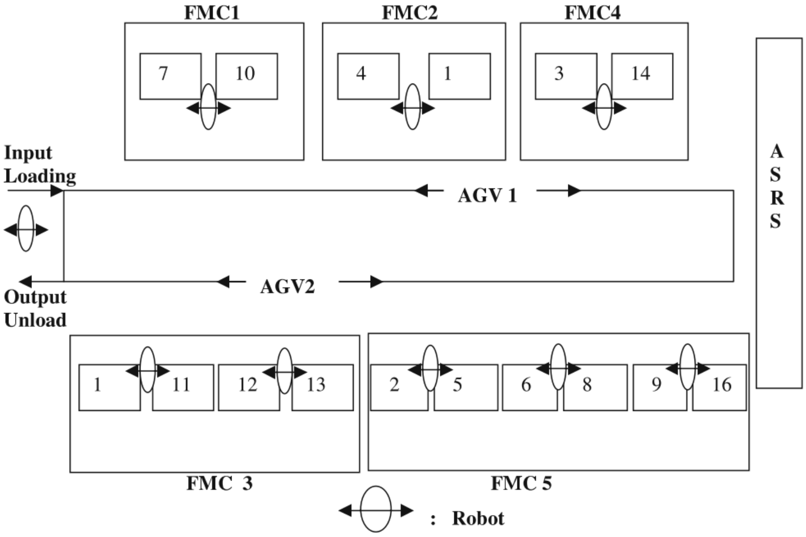


Figure 9 Optimisation model for Multiple Cells FMS (Jerald et al., 2005)

An evolutional algorithm which called multi-objective symbiotic evolutionary algorithm (MOSEA) has been developed and applied to solve FMS scheduling problem (Seok Shin, Park and Keun Kim, 2011). The objective functions include balancing the machine workload, minimising part movements, and minimising tool changes. This study also evaluated the computational capabilities of proposed method by comparing with other algorithms.

A hybrid evaluation optimisation approach has been developed to solve FMS scheduling problems (Prakash, Chan and Deshmukh, 2011). The generic algorithm has been integrated with Knowledge Base, which includes classic scheduling rules. Throughput and mean flow time are the main objective functions. From the expertise gained in the Knowledge Base, the efficacy and accuracy of the optimisation has also been improved.

The scheduling problems in Re-entrant FMS have been investigated by GA optimisation algorithm (Rifai et al., 2016), shown in Figure 10. The model enables the machining workstations on the FMS to be interrupted by other unautomated operations such as manual assembly or manual washing process. The objective function is targeted to minimise make span, mean flow time, and total tardiness. This study compared the performance of the manufacturing system following different scheduling rules and compared the classic scheduling rules such as Shortest Processing Time (SPT), Longest Processing Time (LPT), Earlier Due Date (EDD), and the rules optimised by GA and SA. This would help to identify the benefit of applying optimisation scheduling instead of classic scheduling rules. The optimised part dispatching sequences have been evaluated in Discrete Event Simulation (DES) via FlexSim software.

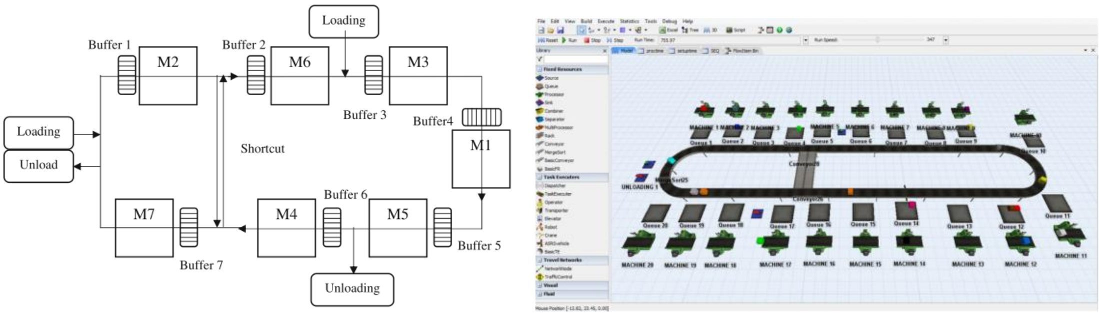


Figure 10 Re-entrant FMS optimisation and simulation (Rifai et al., 2016)

A semi-heterarchical approach was proposed to control the FMC based on simulation–optimisation (Zambrano Rey et al., 2014) as shown in Figure 11. This study is located at the AIP PRIMECA centre at the University of Valenciennes. The novelty of this study is using simulation to calculate global performances of the manufacturing system and to evaluate the solutions proposed by the optimisation mechanisms. It used GA and ‘Arrival-Time Control’ as the optimisation mechanisms; Agent-Based Simulations (ABS) as the simulation method. The main objectives are optimising the release sequence and machine routings.

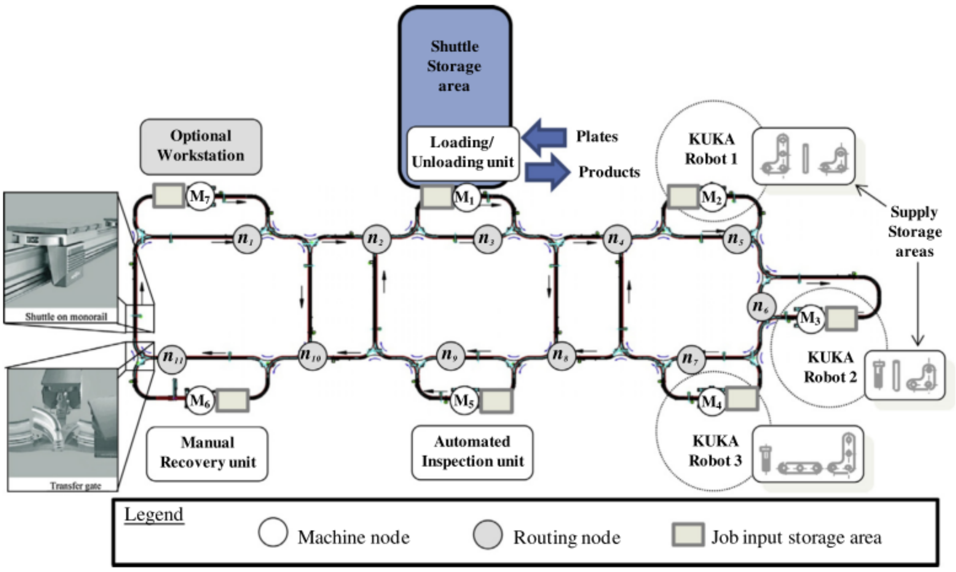


Figure 11 Flexible Manufacturing Cell simulation-optimisation model (Zambrano Rey et al., 2014)

A DES model is built for an existing FMC (Yücel, 2005). The system is shown in Figure 12 and include CNC machines, load/unload robot, MHS, CMM and the computer controlling system. It used DES on ARENA software. The main objectives include reducing both the lateness and the lead time by optimising the production schedule- input sequence problem.

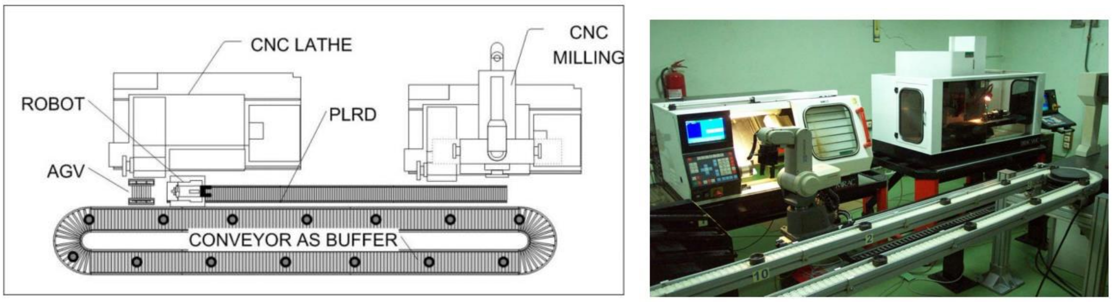


Figure 12 A Flexible Manufacturing Cell in simulation for scheduling (Yücel, 2005)

An optimisation study is applied for lab experiment FMS with object-oriented Petri nets approach (Başak and Albayrak, 2015). This optimisation model is built for real-time scheduling problems. The optimisation objectives include: to minimise the total time required and the set-up costs, meet the due date, and maximise the machine utilisation.

The model is developed to identify the best, part movement policy for a MMFMS (Suresh Kumar and Sridharan, 2009). This optimisation problem is within the scheduling problem, regarding how to manage the movement of the parts after releasing the part into the manufacturing system, and how to minimise the mean flow time, mean tardiness, and mean waiting time. Other models normally only considering the First In First Out (FIFO) Rule; however, this study has evaluated wider classic scheduling rules, which give the production manager a comprehensive understanding about how the scheduling rules would impact on the performance of the FMS:

- First Come First Served (FCFS) also known as FIFO
- Shortest Processing Time (SPT)
- Earliest Due Date (EDD)
- Earliest Modified Due Date (EMDD)
- Critical Ratio of the part (CR)
- arrival time minus remaining processing time
- ratio of processing time and time in system

- slack time for a part is equal to due date minus current time minus remaining processing time
- processing time of imminent operation + slack
- combination of critical ratio and processing time of imminent operation
- combination of slack per remaining processing time and processing time of imminent operation
- combination of due date and processing time

If only selecting one of above scheduling rules for the manufacturing system, this would then be a static dispatching strategy. A study has also looked into the dynamic dispatching strategy which means the scheduling rule may change regarding the state at the different time frames during the production (Abou-Ali and Shouman, 2004). SIMFACTORY II.5 has been used as the simulation platform. This research saw that the dynamic dispatching strategy would improve overall performance.

An FMS study of the interaction among part sequencing, sequencing flexibility, and routing flexibility has been done by DES (Joseph and Sridharan, 2011). Shown in Figure 13, the study tested the system performance in different levels of sequencing flexibility, and routing flexibility, and found the classic part sequencing rules such as earliest due date and earliest operation due date provide better performance for all the measures at higher flexibility levels.

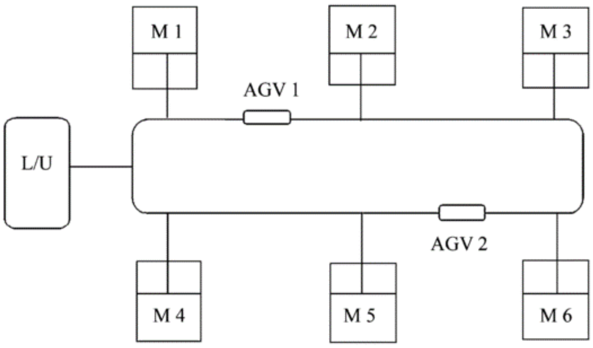


Figure 13 Simple MMFMS models for testing part sequencing (Joseph and Sridharan, 2011)

A knowledge-based scheduling system has been developed for an existing FAS, which covers machining and manual operations (De and Lee, 1993). The proposed two-level hierarchical scheduling approach is on an out of date software platform, but the model is highly relevant to the FMS which is currently being worked with and will be modelled. It is also a British automotive company - Austin Rover's Longbridge (ARG) plant in the United Kingdom - which produces the car engine; the model of the FMS is shown in Figure 14. The products and process raw data are similar to the FMS which this research is going to model.

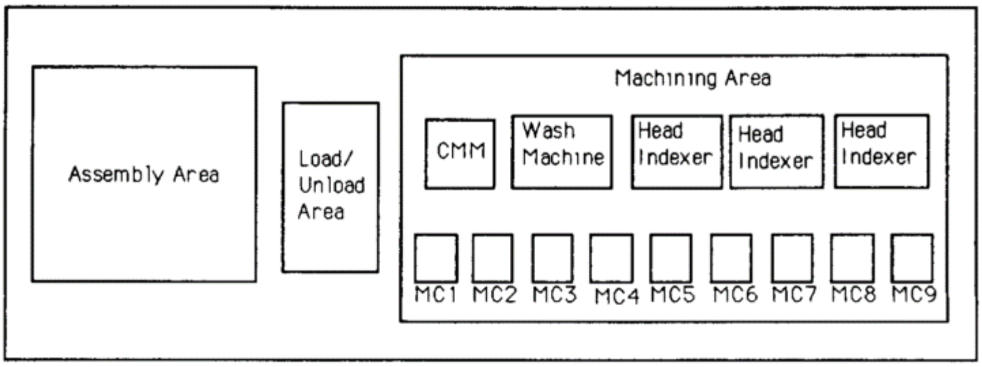


Figure 14 Existing FAS in the Austin Rover plant (De and Lee, 1993)

Constraint Programming (CP) methodology is also used to solve FMS scheduling problems (Zeballos, 2010), and more specifically in tool management problems. This study used the test data from a single FMC, as shown in Figure 15.

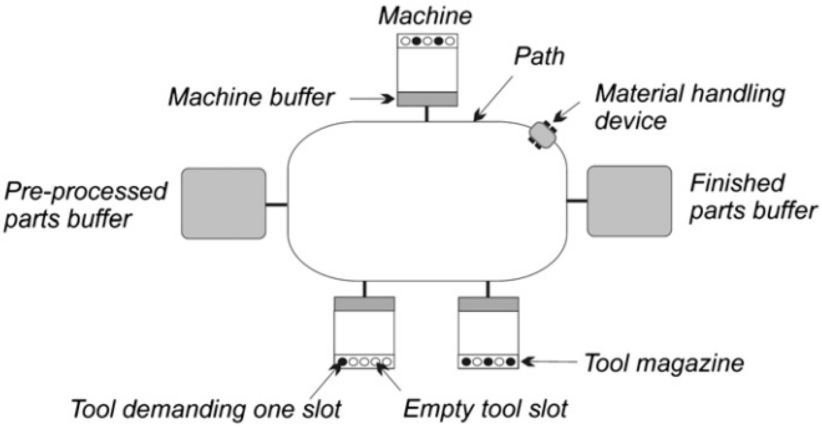


Figure 15 Simple Flexible Manufacturing Cell model for tool management problem (Zeballos, 2010)

A CP formulation approach has been developed to cover multiple scheduling problem (Novas and Henning, 2014). These optimisation problems include machine loading, operation sequencing, part routing, machine buffer scheduling, tool planning and allocation, and MHS scheduling. This is a complex model covering massive variables and objective functions. The interrelationship between different manufacturing capacities has been well considered within this model, at the same time the work stress of this model has also been increased. The FMS structure is shown in Figure 16.

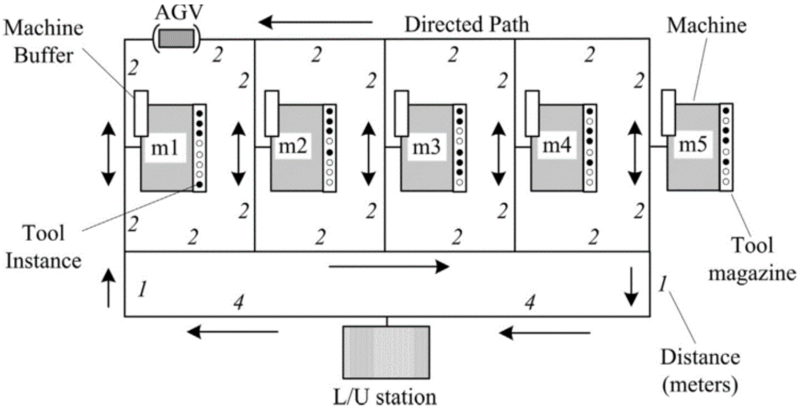


Figure 16 FMS model for CP approach (Novas and Henning, 2014)

A Mixed Integer Linear Programming (MILP) approach has been applied to the FMS scheduling problems. As shown in Figure 17, the main objectives include reducing empty transportation and minimising the total WIP in the system (Caumond et al., 2009).

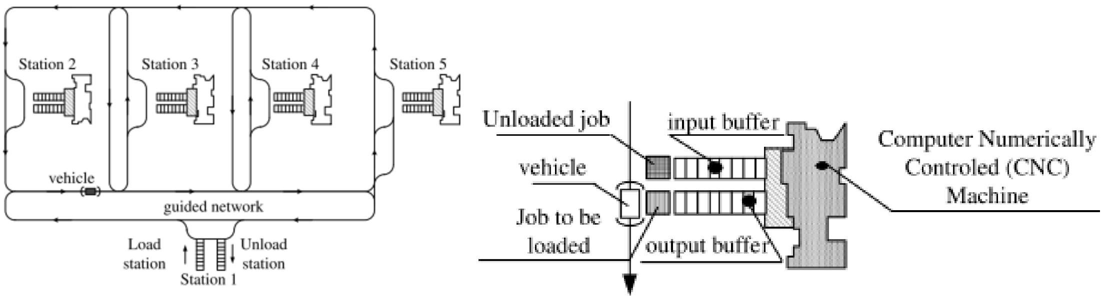


Figure 17 FMS model with buffer management and transport control (Caumond et al., 2009)

2.4.3 Controlling optimisation

A simulation model has been built for an MMFMS (Gertosio, Mebarki and Dussauchoy, 2000). This system, shown in Figure 18, contains two parts: one is the automated capacity which includes CNC, wash machine, and CMM; the other part is a manual workshop with human operators. There is an intermediary buffer between these two parts. This model is used to test different FMS controlling problems with regard to the physical constraints and the production objectives.

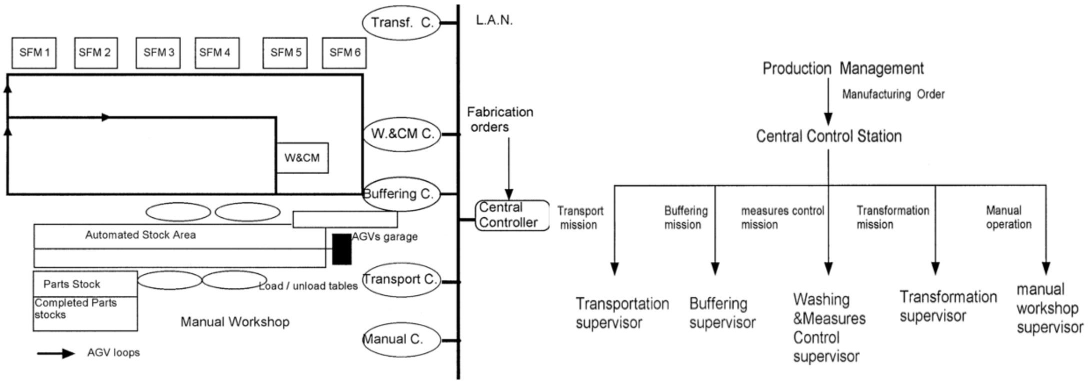


Figure 18 Multi-machine FMS simulation model for controlling problems (Gertosio, Mebarki and Dussauchoy, 2000)

A study of the controlling problems - diagnosis or troubleshooting – has been developed based the software framework (Csokmai et al., 2014). This would also be a part of an FMS decision support system.

2.5 Research trend

The research trend is investigated based on the data from Scopus, by searching specific topic in title, keywords, and abstract.

With the development of automated manufacturing, the FMS was been introduced in the literatures in the 1980s, so it already has more than 30 years' history. The trend (Figure 19) is generally growing positively in the long-term, with three peaks in 1986, 1996, 2010, and two troughs in 1992 and 2001.

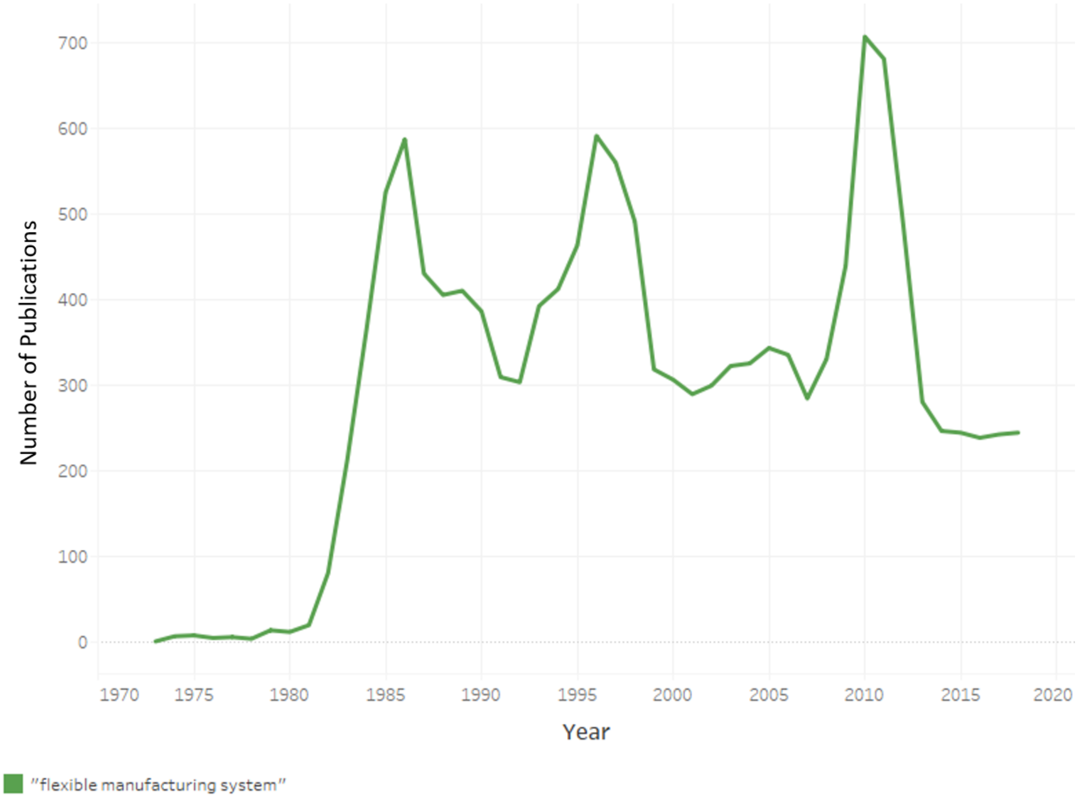


Figure 19 Research trend of ‘Flexible Manufacturing System’ Source: Scopus

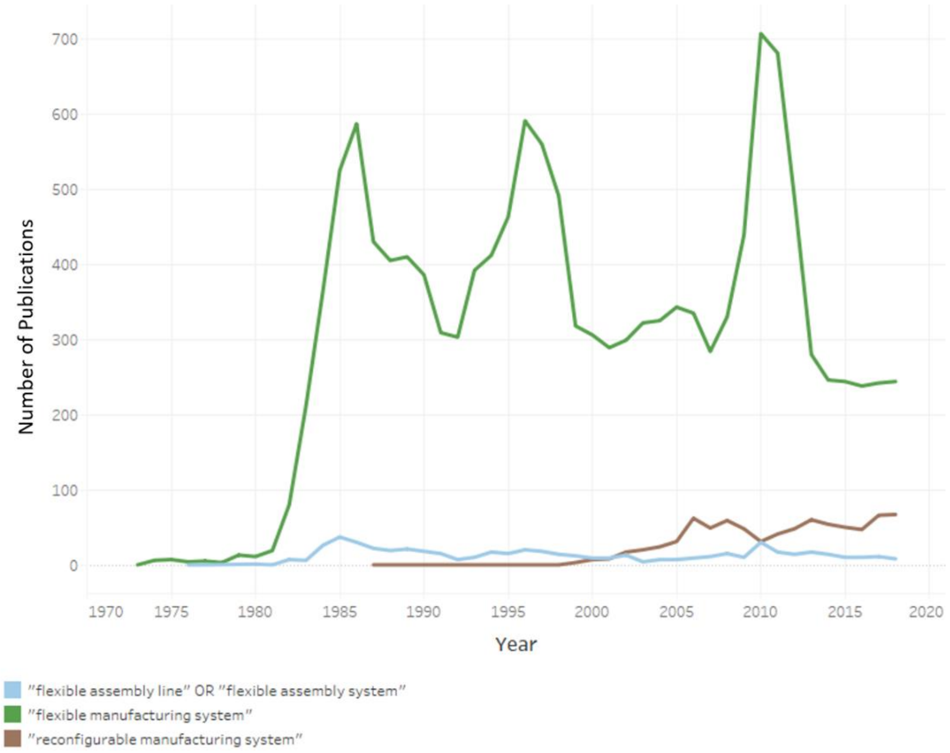


Figure 20 Research trend of related manufacturing systems Source: Scopus

Compared to other manufacturing systems which share the principle of flexible manufacturing, FMS still is the main trend which is beyond the ‘flexible assembly system’/’flexible assembly line’, and the ‘reconfigurable manufacturing system’, shown in Figure 20. In another view, the assembly process is still at a low level of flexible manufacturing implementation.

After analysis of trend of optimisation and simulation in the FMS (Figure 21), they still are still within the low portion of the general FMS research. From the author’s understanding, most research still experiments with and studies the nature of the FMS, understands the behaviour of FMS, and identifies the interrelationship between different problems occurring in FMS. Only by having this prior knowledge, can the right optimisation techniques be applied to the right problem at the right time.

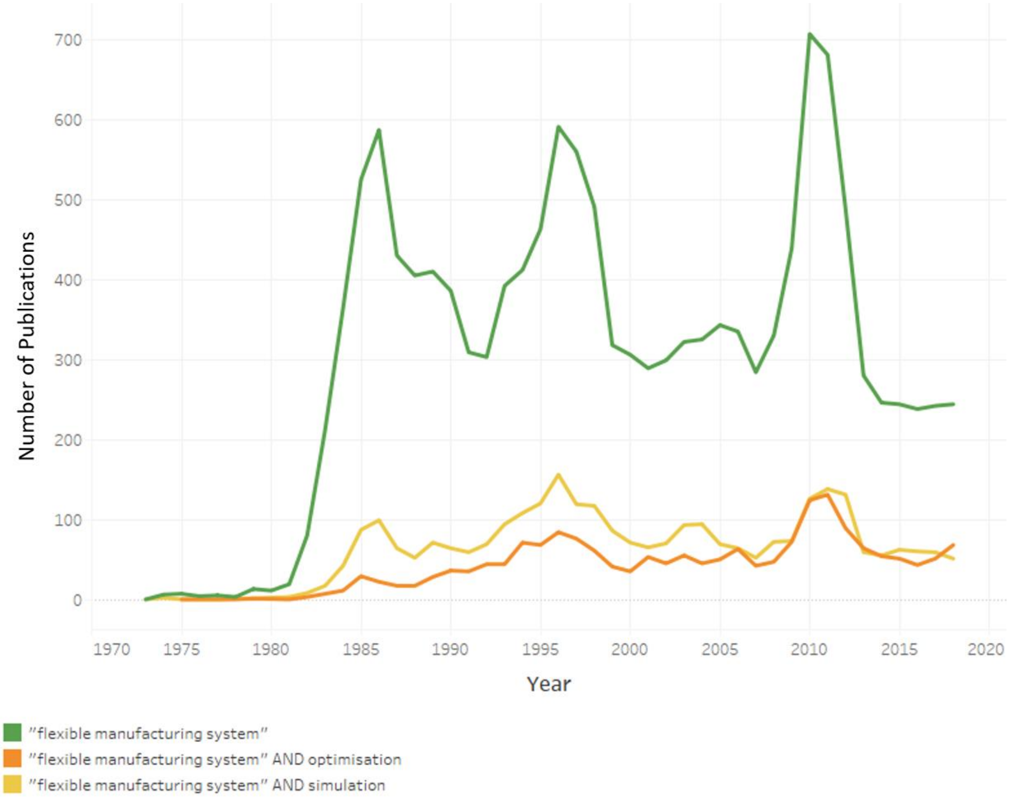


Figure 21 Research trend of optimisation and simulation Source: Scopus

The optimisation research on FMSs has the same history as the FMS general research, but became more active after 2008, and reached its peak in 2011

(Figure 22). The optimisation research on FMS has become more popular through the development of computer science, optimisation algorithms.

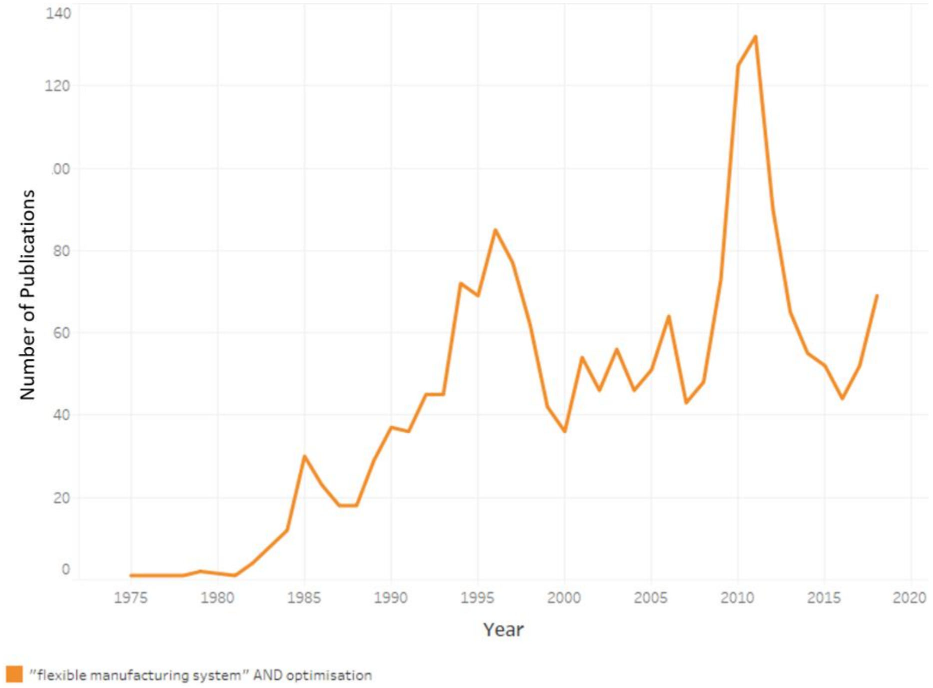


Figure 22 Research trend of FMS optimisation Source: Scopus

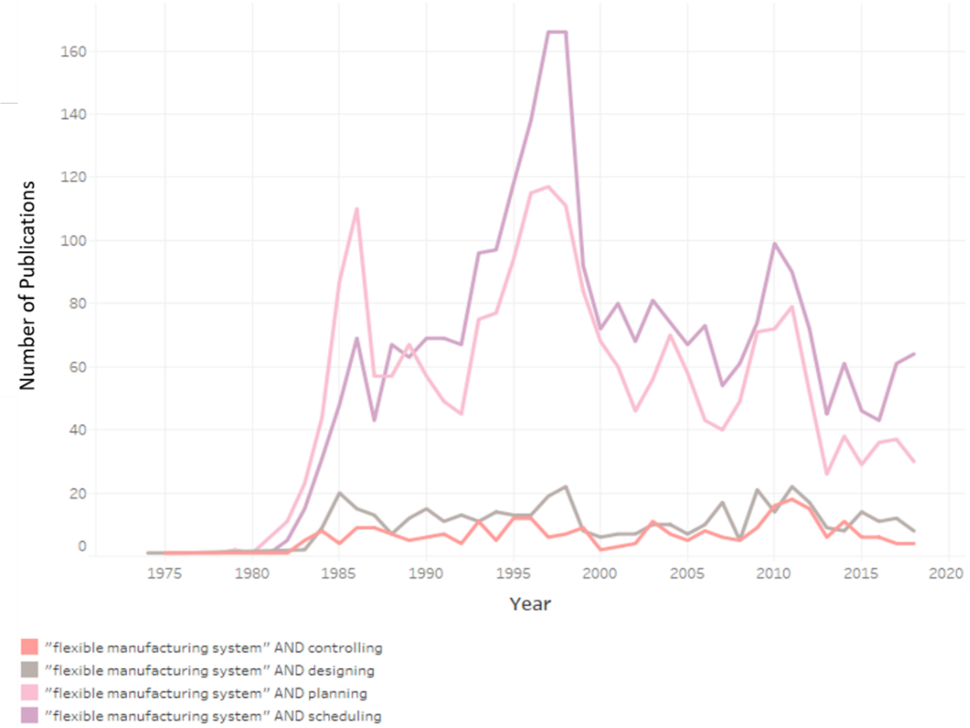


Figure 23 Research trend of FMS stages Source: Scopus

For the problems in FMSs of the different stages, ‘planning’ and ‘scheduling’ are much more attractive for the researchers than ‘designing’ and ‘controlling’, as shown in Figure 23.

In terms of the specific manufacturing problems within FMS, the trend is shown in Figure 24. ‘Dispatching/dispatch rule’ is the most popular manufacturing problem, followed in the order of ‘machine loading’, ‘operation sequence’, ‘level of flexibility’ and ‘machine assignment’ in the last.

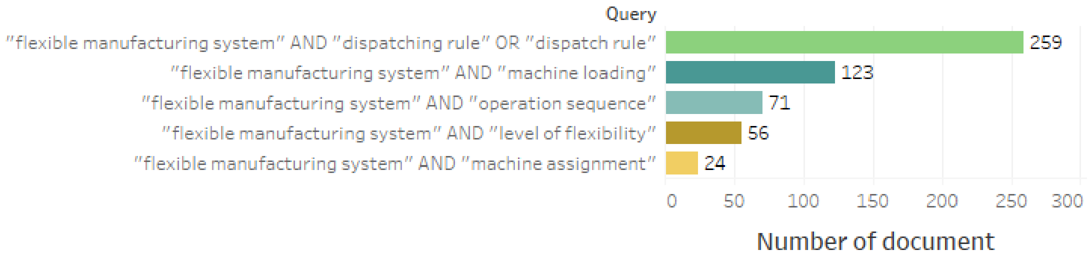


Figure 24 Research trend of FMS problems Source: Scopus

2.6 Research Gaps

2.6.1 Understanding of FMS behaviours

Most of the FMS optimisation models are built from synthetic data, using the models from other researchers’ publications, or by collecting the data from small size FMS test labs. By doing this, the model and the optimised results may be different from the FMS behaviours happened in the real world.

This research is a cooperative effort with the industry partner, Cosworth, which has already built a factory furnished with an FMS system. This has enabled the researcher to observe the behaviour of an FMS in real time, collect the real-world data, and build an optimisation model to accurately reflect the real-world paradigm. The model itself has considerable intrinsic value in its ability to represent a living FMS, and this can be adapted for use by other researchers.

2.6.2 FMS integrated manual operations

The case study factory is relatively unique from the general description in the literature, in which the FMS normally consists of the machining process, or the machining process and manual process are conducted separately. In this factory, the machining process and manual process intersect each other. If the company is not building a totally new factory but wants to upgrade the current facilities to an FMS, during the upgrading to this highly automated manufacturing system, some processes always have to remain unautomated. This situation is likely to happen particularly for SMEs who want to cut the cost by using existing capacities. But the optimisation for this kind of realistic issue has rarely been studied in the literature.

The research on how to manage and optimise the automated process that is integrated with many manual processes could contribute considerable value both for academia and industry.

2.6.3 Optimisation for scheduling problems in FMS

Multi-Objective Particle Swarm Optimisation (MODPSO) method has already been developed for mixed-model assembly, based on the Particle Swarm Optimisation (PSO) approach (Rashid, 2013). It has been recognised that MODPSO has similar objective functions and a suitable search strategy which can also be used for scheduling problems in FMSs. There are multiple problems for scheduling in the FMSs. MODPSO has already been validated for operation sequence problems and line balance problems, and it is also possible to apply it to the dispatching scheduling and part routing problems. So, the other novelty of the research can be gained by applying multi-objective optimisation algorithm to optimise FMS scheduling problems.

2.6.4 Evaluate optimisation results using simulation

In literature, some studies have already used simulation to validate the proposed solution generated by optimisation (Rifai et al., 2016; Zambrano Rey et al., 2014). The limitation of these researches is that they only tested this method by using a simple artificial FMS model. In this research, the simulation model is more comprehensive than the model in the literature and would be validate by industry. So, if the optimisation solution would be simulated with more variable and constraints, the impact or benefit of the optimisation would be easier to observe and evaluate.

2.7 Summary

In general, an FMS is an advanced manufacturing system which is most suitable for the agile business strategy. This kind of manufacturing system has absorbed the most technological advancements of the hardware, i.e. digital machining centre, and the software i.e. computer controlling system. By successfully implementation of an FMS, remarkable benefits can be achieved for the company, such as enabling it to produce multiple products on the same production line, a higher utilisation of the manufacturing capacity, quick product turnover, and the ability to respond in an agile way to the changes in the market.

Due to the greater complexity from multiple products and from the FMS itself, it is hard to achieve all of the benefits of this manufacturing system unless the firm manages all of the problems in the designing, planning, scheduling and controlling stages. Both the nature of an FMS and its problems in FMS are relatively new to most of the companies, as they have become used to the more traditional production systems. Though the FMS has been introduced and studied in academia for about 30 years, its successful implementation in commercial industry is still seldom undertaken globally. The issues in the FMS covers vast research fields in terms of manufacturing system, manufacturing process, logistics and supply chain, computer science, enterprise system, and so on. To fully handle this manufacturing system, companies also need enough talent human resource talent, and have the awareness to accept a consistent journey to research and development about FMS.

Manufacturing optimisation technology has been enhanced significantly by the development of computer science and the ever increasing hardware computing power. There are several optimisation methods which include the traditional methods such as linear programming, CN, PN, and the more untraditional methods, in terms of evolutionary algorithms, such as GA, artificial life algorithms such as Particle Swarm Optimisation (PSO), and AI such as Artificial Neural Network (ANN). In the academic field, many researchers are investigating how to apply these mathematical optimisation methods to solve the FMS problems, and identify which method is most suitable for a specific problem. The validation of these researches mainly focuses on measuring the arithmetic capability, such as computing time, and optimisation result quality, rarely measuring the improvement in the real-world when the industry implements its optimisation results.

Most of the optimisation models are built for specific optimisation problems, and only represent a small part of the problems in the manufacturing system. If one firm wants to solve all of the manufacturing problems for a real-world FMS, it may require building multiple models for different problems.

Recently the simulation has also been widely applied into FMS studies, and possibly in order to cooperate with optimisation by evaluating the proposed optimisation solutions using simulation.

3 PRIMARY MANUFACTURING PROBLEMS IN FMS

3.1 Introduction

As a key observation from literature, there is a lack of knowledge about the links and interactions among various problems in FMS, and there is no clear answer about the priority and sequence to solve these problems. It is neither feasible nor efficient to engage with all these problems at the same time. Therefore, the author needed to identify the most valuable and challenging problems to deal with and pair appropriate simulation and optimisation method. While narrowing down the research scope, it is necessary to figure out the interrelationships or constraints of the selected manufacturing problems within the eco-system of the FMS. This chapter presented the details about how and why to select the primary manufacturing problems of FMS using a practical case study.

3.1.1 Lack of implementation

Concept of FMS has been first general introduced and reviewed since 1980s (O'Grady and Menon, 1986). After more than half a century's development, there are many types of research carried out to form the concepts and strategies of FMSs, which are now clear for academia and practitioners to follow and adopt. However, there is an odd fact - it is hard to find the implementation case studies. Only a very few case studies come from the industrial practice or are validated from the shop floor; most of the case studies from the literature use the conceptual mathematical model even referenced from the 1990s publications. It is well acknowledged that it is challenging to implement a fully functional FMS due to the intrinsic complexity; a feasible and efficient tool is still needed to handle every dimension of the complexity. Because of the inadequacy of the implementation practice, academia would face the difficulty in having a tangible vision and depth of understanding of an FMS eco-system and the subsystems within it. Most of the researchers should construct the knowledge of the FMS only from the fragments in the literature. As a result, it is common to find different interpretations and explanations of a similar problem, which sometimes can be confusing and misleading. Furthermore, it is easy to miss consideration of the interrelationship and the interaction between the subsystems by reading the fragmented reports. Hence, it is beneficial to acquire an empirical case study to gain a comprehensive and lively vision of the whole FMS system.

3.1.2 Interdisciplinary field of knowledge

The problems of FMSs have attracted many researchers from different areas, such as manufacturing, operational research, computer science, etc. At the same time, most of the researchers may come from a single original field, which may mean they are short of the experience of FMS problems or solution approaches. For example, the researcher with only manufacturing background may face the challenges of adopting and applying a diverse range of optimisation algorithms; vice versa, the researcher with only computer background may find it difficult to understand the workflow of an FMS. As a result, researchers tend to focus on narrowed down and simplified problems, proposing a method that only works for the limited and specific scenarios, and therefore the method always become infeasible to implement when taking into the global environment. Covering each and every problem in depth is difficult. Understanding the challenges associated with the successful implementation of an FMS requires a closer look at each and every problem more specifically and in greater depth. (Kaighobadi and Venkatesh, 1993). Only after gaining the expertise in both the problem and solution domains, can the researcher propose a feasible and efficient method to solve FMS problems. Along these lines, an empirical case study would help researcher gain access to the interdisciplinary experience from the experts in the various fields, i.e. both from industry companies and academic research institutions.

3.1.3 Short of validation testbed

Similarly, to the shortage of empirical case studies, it has also been found that most of the proposed methods in FMS research were short of a sufficient validation phase. For instance, the FMS optimisation research may take a case study from the literature, targeted on a simplified problem; without an adjustable and responsible testbed, the validation can only compare the computing performance, without the ability to measure the improvement in manufacturing performance on the shop floor. In practice, the flexibility decisions are complex, but the existing frameworks in the literature seem to be too simple to explain the whole actual decision making process (Ngamsirijit, 2008). An empirical case study would provide the feedback that is closer to reality, and would make it possible to conduct a trial and error loop, which may then validate and refine the method.

In summary, it is necessary to investigate the FMS problems from practice. It would benefit this research to gain a comprehensive understanding of the whole FMS system and provide a validation testbed for the proposed method. The report of the empirical case study would also be quite valuable for future interested researchers.

3.2 Selected case study

This PhD is under a collaboration research project called ‘jubilee’, which is in cooperation with Cosworth, Flexeye, and Cranfield University. The ‘Jubilee’ project aims to develop and implement a state-of-the-art Advanced Manufacturing Centre (AMC) which will apply the principle of flexible manufacturing, as shown in Figure 25. It will be the very first new generation FMS in the UK. The project has raised the investment of over £22m through the company shareholders, the Department for Business, Innovation and Skills (BIS), and the local government of Northampton Borough Council. The aim of this PhD research is to investigate the simulation and optimisation technology needed to better manage the FMS . The research is sponsored by AMSCI (Grant number 36017-233554), which sources from the UK government. This research is based around this live case study, and it is the only real-world FMS facility that the author can access during this research. The author has been granted unfettered visitation privileges to this manufacturing facility and afforded frequent communication with the industrial managers and the engineers who are working on this project. The author has kept track of the journey the way through the development and implementation of the FMS. This has enabled a solid understanding of the of untraditional manufacturing system, the FMS.

Figure 25 FMS Shop floor (left) and engine part installed on pallet (right) from selected case study (from Cosworth)

3.2.1 Representing the general FMS

There is a crucial challenge faced by this research; it has been extremely hard to find another practical case study in the current time and within the UK. The author tried to find multiple case studies from industry, but apparently no other facility is reported as targeting implementation of a full set of FMS in the UK. There are laboratory experiments from research institutions or commercial companies; however, there are a few companies successful or even completed FMS implementation reported from the industry practice. There are a few companies in Europe and the U.S. that have announced that they started to implement an FMS, but the author was unable to make contact with them, or the detailed information about their FMS implementations could not publish, so the author could not identify how they handled any problems within their FMSs.

In the case of having only gained one case study from practice, it is necessary to identify whether the selected case study is able to represent the general FMS concept, and how the selected case study matches the various features of the FMS in detail. This section will discuss how the chosen case study represents the general FMS and would therefore be useful for future researchers to investigate the FMS practice.

There is no standard definition of an FMS, but it is usually identified by the physical components and the flexibility represented.

As shown in Figure 26, a shared understanding is acknowledged in this research, that an FMS consists of three key elements (Chan et al., 2002; Donald et al., 1988; O’Keefe and Kasirajan, 1992); the representative of the selected case study is also described:

3.2.1.1 Three key elements of FMS

- **Flexible machine**

Concept: the digital controlled machines or workstations that can process various operations and products.

In selected case study: the selected case has 12 sets of advanced CNC machine centres within the FMS, which can carry out different kinds of operation by changing the Computer-Aided Manufacturing (CAM) programs, tools, and pallets.

- **Material handling system**

Concept: it can connect and transport the materials or tools for all of the machines or workstations

In selected case study: the selected case has a stacker crane on the rail tracks to grab and transport the pallets and the parts on them; the average transportation time for each operation is about four minutes, the actual time can be varying depends on the specific job.

- **Intelligent control system**

Concept: it can function as an auto or semi-auto plan and commands the operations inside one production line.

In selected case study: the selected case is controlled by the central computer; a control software is operating with the FMS, designed and supplied from the hardware vendor.

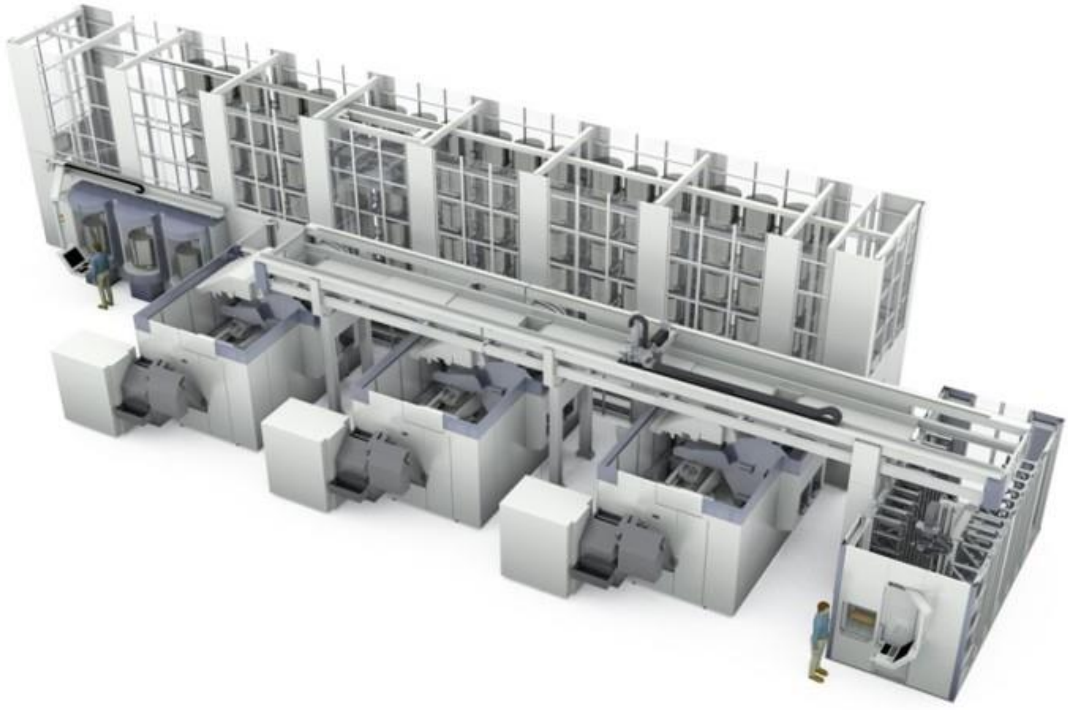


Figure 26 Illustration of the FMS (source: fastems.com)

3.2.1.2 The taxonomy of flexibility

- **Machine flexibility**

Concept: the ease of making the changes necessary to manufacture a specific set of part/product types.

In selected case study: the machine centre can conduct the change of operation easily and quickly by change the program, the pallet and the tools.

- **Process flexibility**

Concept: the capacity to manufacture a given set of part/product types in a variety of ways, each possibly using different materials.

In selected case study: The machine centres considered in this case study have segmented into five-axis machine and four-axis machine. The five-axis machine can take all kinds of machining operation; the CAM programme can be changed easily. Four-axis machine can carry out normal machine operations, but some unique or complex operation can only be load to five-axis machine centre.

- **Product flexibility**

Concept: the systematically unique ability to change over to produce a new set of parts or products economically and quickly.

In selected case study: it can produce multiple products at the same time, currently 2-3 kinds of product family; the FMS is designed to minimise the impact of changeover one product on other products in the same manufacturing system.

- **Routing flexibility**

Concept: the capability to cope with breakdowns and continue manufacturing a given set of part/product types using alternative routes.

In selected case study: it is currently only available for a very limit range of operations for many reasons, but the selected case study proposed to investigate and release the routing flexibility with the assistance of this research.

- **Volume flexibility**

Concept: the ability to operate profitably across a range of different production volumes.

In selected case study: each product is under a different production volume, and the production volume is possible to change in some scenarios such as production rate ramp up, or accident from the market respond.

- **Expansion flexibility**

Concept: the potential to expand in a modular fashion incrementally.

In selected case study: the FMS of the selected case is a kind of plug-in system, which reserves plenty of slots to connect various kinds of machine when needed.

- **Production flexibility**

Concept: the volume of the set of part/product types that a system can produce.

In selected case study: there is no limitation to how many kinds of product could be launched into FMS. The primary limitation is the total capacity of all machine centres, subordinate limitations include capacity of pallets, tools, and transportation etc..

The selected case study from the Cosworth AMC facility comprises all necessary components for FMS implementation and able to release all key flexibilities. Accordingly, the selected case study provides a comprehensive representation of general FMSs. The experience captured, and the method developed from this case study could apply to other FMS installations.

3.2.2 Operation of the FMS

The FMS considered in this case study is a multiple machine FMS. There is no standard workflow of FMS, but the workflow of the FMS considered here is shown in Figure 27. The workflow explains the procedure for producing a product step by step, from a one order entry to FMS to the competition of all operations and exiting the system. The key decision making points are also noted in the chart.

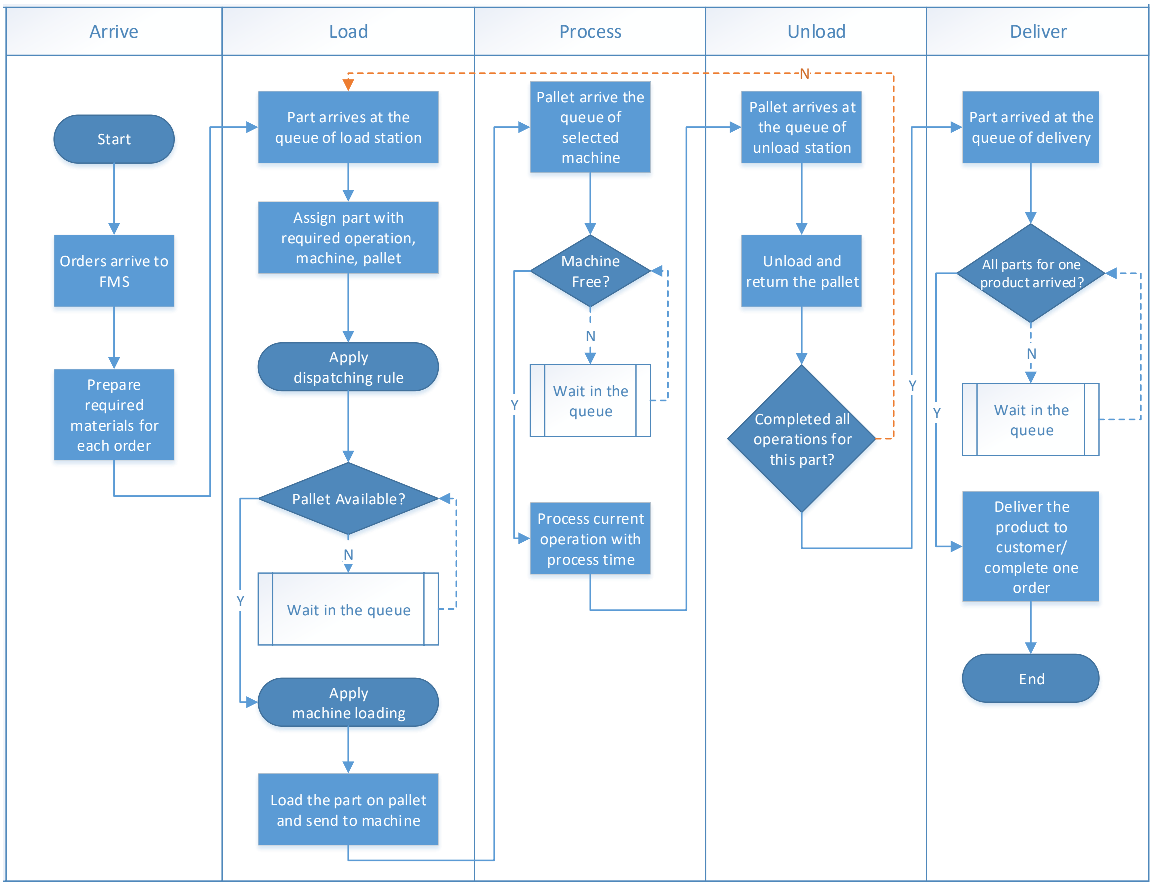


Figure 27 The workflow of the selected FMS

3.3 Identify the primary optimisation problem

Due to the confidential policy of this project, all details of the meetings and interviews are not presented in this thesis, but the results and findings from the proposed method (Figure 3) are presented in the following sections.

3.3.1 Mapping the FMS problems in practice

As summarised in the literature review, a successful implementation of FMS should go through all the problems in four critical phases—design, plan, schedule, controlling. This research investigated and then compared these problems mentioned in the literature with what happened in practice from the case study respectively.

- **Design phase**: The problems in the design phase mainly consist of the decision making of the functionality of the FMS, such as what kind of product and process would be involved, and pairing appropriate configurations of hardware such as the machine type, MHS type, tools type and so on. The option would be provided and advised by the hardware vendors.

  In the design phase optimisation technology would not engage directly.
- **Plan phase:** There are many traditional manufacturing problems existing in this phase, such as the shop floor layout planning, inventory management, and transport management. Products and processes would immigrate from transfer line to the FMS or directly launch to the FMS. In the selected case study, the FMS was initially separated into disconnected machine groups according to a different product, and each machine group was operated as a transfer line. At this moment, the dimensions of flexibility are not entirely released. However, current period provides a manufacturing environment which is familiar to most of the engineers, as it is easy to go through the standard production launch procedure such as Production Part Approval Process (PPAP), which is the common standard applied in the automotive industry.

  The plan phase is the stage of installing the equipment and validating the equipment, material, and operations. It could be the preparation for releasing the core flexibilities of the FMS.

  In the plan phase, researchers engaged in capacity planning, which mainly applied simulation techniques. The optimisation of the transportation system and layout design also participates in the plan phase in the literature (Rekiek et al., 2002), if the FMS has applied Automatic Guided Vehicles (AGV) as the main transportation system. However, the optimisation problem would continue to the next phase because the change of schedule may impact on the transportation strategy.

  At a practical level, the planning problems are commonly guided by the standards and best practice for traditional production lines and conducted by internal engineers and external consultants, such as applying lean manufacturing to shop floor management.

- **Schedule phase:** After each individual product, process, and machine is validated, the production will face with the problem of how to locate and utilise all resources in the optimal way—the scheduling problem. At this stage, the manufacturing objective would be to apply the flexible manufacturing. In the planning stage, the FMS facility may be separated by multiple transfer lines working in the same factory. Ideally all the machine groups should be connected as an integrated FMS. The different products and various subcomponents would be produced on the same production line; thus, the complexity has occurred. The first problem is how to assign operations to machines - the loading problem. While releasing the routing flexibility, one operation would have multiple machines to located; to select which machine is dependent on the current state of the available machines and the dispatching rule. Because of the flexibility provided by the FMS and the complexity generated from multiple products, and respecting the numbers of operations, there would be a massive number of variables and an astronomical quantity of possible solutions. The optimisation job is no longer what can be handed by the traditional ways; the advanced optimisation algorithm should therefore be applied here.

  In the selected case study, the engineers faced the difficulty of decision making regarding the scheduling problem. It was an ongoing problem to solve. The given software provided from the hardware supplier would manage each machine well, but could not manage the whole system sufficiently, especially for making and changing the production schedule.

  The subproblems of scheduling from this case study are identified by the author as follows:

  - **Operation sequencing** is simulated and optimised by the DES technique. The optimised result has already been implemented on the shop floor.

  - **Dispatching rule** would manage the queue at the load station; it should be able to act agilely, for example, releasing the operation which requires the minimum process time in the queue first. This is a common FMS optimisation problem investigated by the academic researchers. In the case study, the FMS is not able to execute a complex dispatching rule, because of the insufficient function of the controlling software. Currently, the dispatching at the loading station is manually controlled or semi-automated.
  - **Loading problem** is acknowledged as the most critical scheduling subproblem for the FMS. Because of the massive number of variables and being connected/interacted with other subproblems, the loading problem is tough to model completely and represent in a mathematical format, such as the traditional format of problem representation scheme for optimisation programming. Most of the researchers have used very simplified data from the literature to investigate this problem and isolated the interaction with other subproblems. Until now there has not been a sufficient optimisation method that can fully handle the loading problem and be able to apply to the industry.
- **Control phase**

  The problem for control phase is mainly about how to react according to any change in performance (such as throughput, utilisation, quality indicators), unexpected internal downtime (such as machine or tool breakdown), and external changes (such as shortage of material supply, urgent order, product change). The key is how to measure or predict these changes and react in time. The feedback from the measurement system normally would be given to the scheduling system so that these problems would be considered as an extension of a scheduling problem; the requirement of time is then changed to rapid response or real-time response.

> Although control problems or maintenance problems are common in general manufacturing systems, One has not been found that is specific to the FMS. This seems to be due to the few implementations of FMSs, and currently, the main progress of FMS implementations is still limited by solving the scheduling problem efficiently.

3.3.2 Sequence of releasing flexibility

There are multiple dimensions of flexibility, a part of them are formed by the hardware and others depend on how to operate the manufacturing system. There is also a sequence to release and validate these flexibilities, from the flexibility defined by the hardware to the flexibility defined by the operational management.

Machine flexibility is given by the function of the machine centre, and product flexibility is defined by the similarity and distinctive attributes of a range of products and their processes; these two flexibilities should be considered firstly, and they are also the easiest ones to configure.

The process flexibility is next to be considered. It existed but rarely appeared in the selected case study, because this FMS mainly consists of machining operations, for which the material and process are predetermined and would not change after launching the operation online. The process flexibility would appear more frequently in an FMS which mainly focuses on the assembly operations.

The volume flexibility should be considered before committing to a contract for a new product. Because the total production capacity is limited and fixed, while all the products are sharing the same production line, the rise in production volume for one product would occupy more manufacturing capacity, which may lead to a decrease in the utilisation and production volume for other products. The volumes of products are usually conflicting with each other unless the products share some common parts and operations. The extreme example is locating a mass production level product to the FMS; the mass production product occupies most of the manufacturing capacity, while the other niche volume products would face a shortage in capacity. It is not wise to put a mass production level product on the FMS in the long-term; it could work more efficiently and cost savings on the traditional transfer line.

The last and hardest part is releasing the routing flexibility. The routing flexibility highly depends on the operation management and must be constrained by the quality control plan. The routing flexibility was under investigation but has not been actioned yet in the selected case study due to the complexity of this problem. A better release of the routing flexibility would optimise the performance of the FMS, but at the same time, massive variables are required to be controlled. The routing flexibility can be released from low level to high level, depending on how many optional machines there are for each operation and the range of operation is allowed to have routing flexibility. In the selected case, there are over 10^{25} possible solutions to deal with; it is certainly impossible to carry out analysis and calculation by human or traditional analysis methods. So, the author is looking for advanced computation tools or algorithms to optimise the management of the routing flexibility.

In conclusion, the scheduling problem of FMS, especially the loading problem should be the primary problem to be considered in this research.

3.4 Requirements for the selected problems

3.4.1 Problem representation

Due to the complexity of the FMS problem, the problem representation should not only include the selected problem - loading problem but should also account for the relationship with other subproblems of scheduling. For instance, it needs to represent the optimisation sequence and dispatching rule; these can be a constant value in the model. Furthermore, the representation scheme should be able to represent the underlying workflow of the FMS. It would be difficult to encode the complex requirements of an FMS in a standard mathematical format; however, it is appropriate to use DES to build the model of the FMS problem.

3.4.2 Relevant data

The data and information related to the selected problem - loading problem are separated into three categories:

- **Manufacturing system:** the information which would configure the FMS as a whole system including:
    - the type of machine, tools, and pallets, and the quantities for each
    - the configuration of the MHS, transportation speed
    - available working time for the whole system and each machine
    - dispatching rules and maximum buffer size for WIP
    - level of flexibility for routing
- **Product and process:** the information about different products would be produced in the FMS and the related operations, including:
    - Type of product
    - The components of each product, which usually described as Bill of Material as the industry standard document
    - The required operation for each component and product including process time and required machine and pallets. This information usually exists in the operating instructions as the industry standard document
    - The requirement for an operation sequence. Normally the requirement for an operation sequence only exists for each product and components; there normally no operation sequence requirements for all products as a whole.
- **Customer requirement and manufacturing objective:** Normally the manufacturing objective is to satisfy customer requirements, however, in an FMS, there is a manufacturing objective to improve the overall system:
    - Product order: the volume and time need to be met for each product. In a stable situation, the product order could transfer to the inter-arrive time of each product, for example, the order if product A is arriving in every eight hours.

- Manufacturing objective: the basic manufacturing objective is meeting the due date of each product. Additionally there may be the requirement for targeting throughput or the utilisation rate of the whole FMS. Related to the customers’ requirements, there may also be quality objectives such as targeting a scrap rate or rework rate for each component.

The decision variables for the loading problem would be the level of flexibility, required machine and pallet types for each operation, total number of each type of machines and pallets. All other data would construct the environment or the constraints of the problem.

The data are possible to be generated in a random way in order to develop the optimisation method. However, it is better to collect these data from the case study and use them for optimisation, so that it would be possible to compare and validate the optimisation results with real-world practice.

3.4.3 Optimisation algorithm

The basic requirement of the optimisation algorithm is enabled to deal with non-linear relationships of massive numbers of decision variables, and enable to dealing with multiple objective optimisation, Non-Deterministic Polynomial-Time Hardness (NP-hard) level problem. Enabling processing a mixed-integer would be an optional requirement, but it would be more complex than a real value problem. There is no strict computation cost requirement for a selected optimisation problem. However, ideally the computation should enable finding the global optimal solution within 24 hours; this is relevant to the experience of the reaction period of product volume change, machine breakdown repair period, and adoptable throughput variation threshold. The requirement of computation cost would be varied regarding a specific product and industry; generally, the less computation cost, the more likely to achieve real-time scheduling management. Comparing the currently available optimisation algorithm, GA would fit these requirements and easier to apply. It would be likely to apply GA firstly and after gaining better control of the problem representation scheme and the whole optimisation programme, to then switch to more accurate optimisation algorithms.

3.5 Summary

In this chapter, the author investigated the links and relationships of manufacturing problems within FMS, matched and compared these problems from the literature to the practical case study. By conducting the investigation, this chapter identified the most challenging and critical problem in the FMS – the loading problem of FMS scheduling. This problem is also suitable to be handled by the optimisation method and it will be taken as the primary optimisation problem for the main research. The requirements for designing the simulation and optimisation method identified. The relevant data and constraints have also been identified and will be collected from the case study. In the following chapters, the author will develop the optimisation method focused on the selected optimisation problem within FMS.

4 SIMULATION AND OPTIMISATION INTEGRATION FRAMEWORK

Previously, the need for developing a simulation and optimisation integrated framework has been identified. Due to the intrinsic complexity of the FMS, it is a challenge to programme the representation scheme that covers multiple target problems and constraints in a mathematical format.

Thus, this section aims to apply an integrated and interactive approach using both DES and GA optimisation techniques to understand and address the optimisation problems in FMS. The chosen platform is SimEvents, selected because of the relative ease with which the complex logic in the FMS can be simulated, as well as its ability to connect to powerful MATLAB optimisation tools. An MMFMS case study is modelled in this section. The result demonstrated that the integration of an optimisation and simulation approach to understand and address the problems in such a complex system as an FMS.

4.1 Proposed framework

This section aims to develop a simulation-based optimisation approach to deal with typical FMS problems, as shown in Figure 28. The problem is selected from an empirical case study and defined within a small scope with fewer constraints. The problem is simulated in the MATLAB SimEvents toolbox, and the solution is generated in the MATLAB global optimisation toolbox; the version of MATLAB is 2016a.

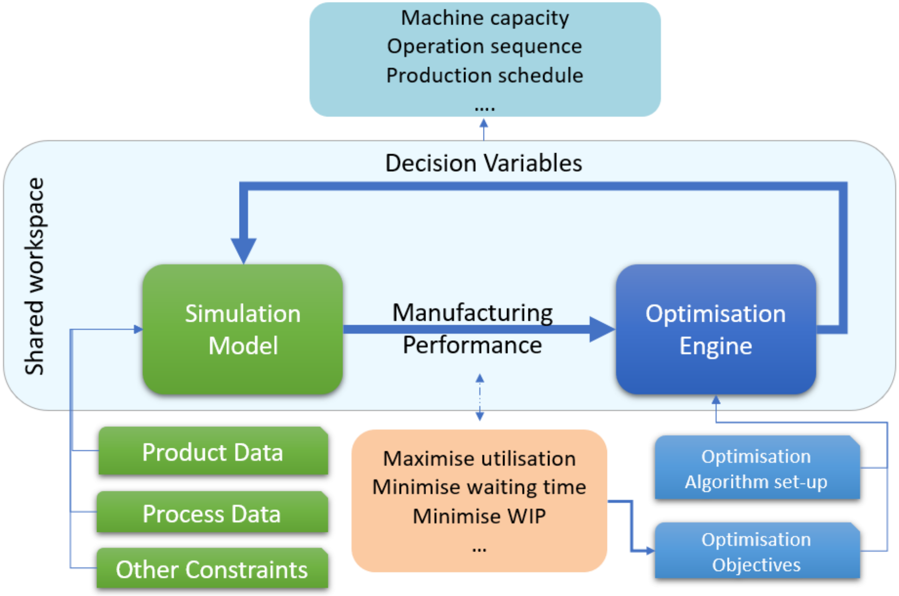


Figure 28 Simulation and optimisation integration

4.2 Simulate the FMS problems

The FMS model is original from a real-world FMS in an automotive industry case study (Rybicka, Tiwari and Enticott, 2016b). In this case, the FMS is a typical MMFMS which consists of four types of machines, load and unload stations and a Material Handling System (MHS). Two types of products would be produced within this manufacturing system with the following assumptions:

- The system consists of different types of machines, each type of which can perform a variety of operations, and each machine can process one operation at a time.
- A workpiece cannot change machines until the current operation is completed.
- After each operation, the part will go to the unload station.
- Each part type requires multiple operation.
- Buffer and the MHS are considered as always available and with infinite capacity.
- The part moving time is considered to be zero.
- Machine set-ups and breakdowns are not considered.
- Tools and fixtures are ignored.

The problem is modelled into four sections as shown in Figure 29: production order section, machine loading/unloading section, operation process section and performance measurement section.

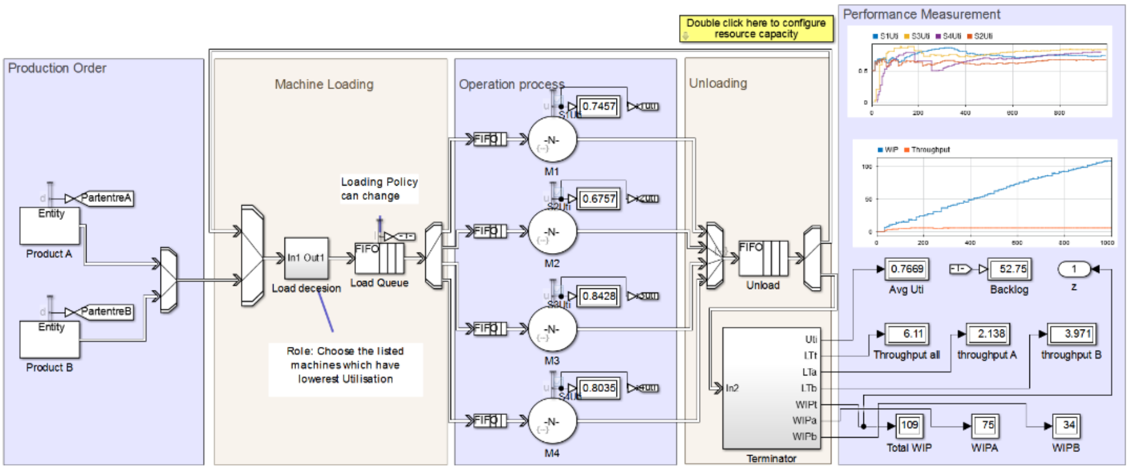


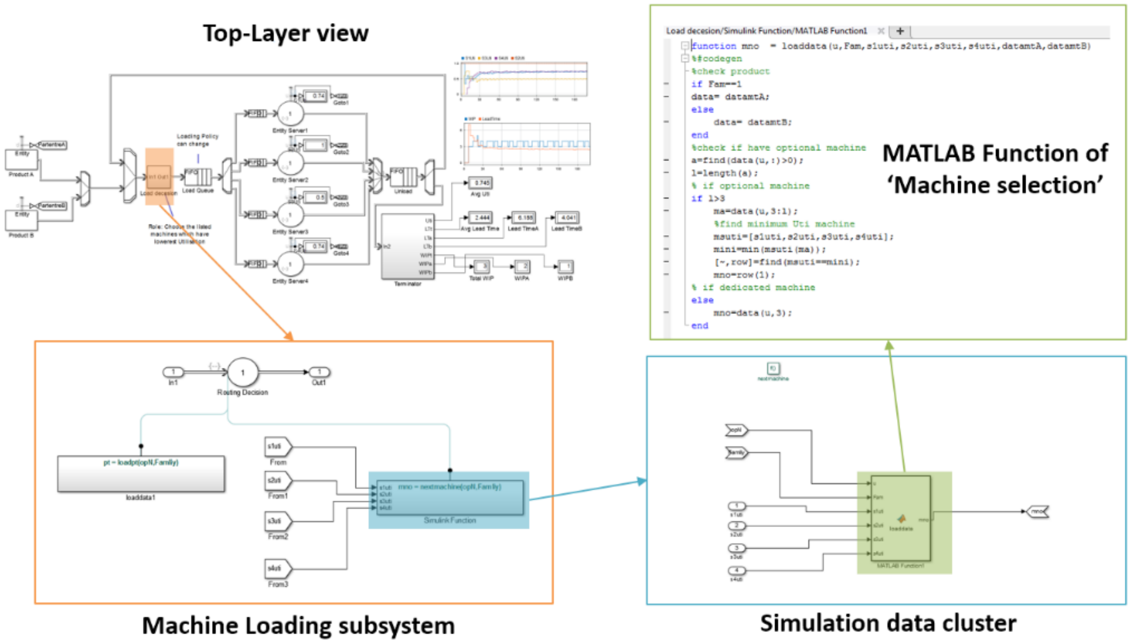
Figure 29 Top layer of the FMS simulation model

Only two kinds of product are considered, as shown in Table 4, each product has a certain operation sequence corresponding to the process time. The operations can be dedicated to only one or multiple types of machine.

Table 4 Product and process data

Product data	Operation sequence	Process time	Machine option 1	Machine option 2
Product A	1	13	1	
	2	4	2	4
	3	27	3	
	4	6	1	3
	5	10	4	
Product B	1	14	2	
	2	20	4	1

In this case, while one operation can be allocated with multiple options of machine type, the decision will select the machine type with the smallest total utilisation (Joseph and Sridharan, 2011). The decision function is modelled as a hierarchical architecture within SimEvents, as shown in Figure 30. The top layer represents the high level of manufacturing operation logic. Under the top layer there are some subsystems designed for specific functionality. At the low level of this architecture can use MATLAB functions which able to scrip programming instead of using build-in SimEvents or Simulink blocks.



```
function mno  = loaddata(u,Fam,s1uti,s2uti,s3uti,s4uti,datamtA,datamtB)
%#codegen
%check product
if Fam==1
data= datamtA;
else
    data= datamtB;
end
%check if have optional machine
a=find(data(u,:)>0);
l=length(a);
% if optional machine
if l>3
    ma=data(u,3:l);
    %find minimum Uti machine
    msuti=[s1uti,s2uti,s3uti,s4uti];
    mini=min(msuti(ma));
    [~,row]=find(msuti==mini);
    mno=row(1);
% if dedicated machine
else
    mno=data(u,3);
end
```

Figure 30 Subsystems and MATLAB function for machine loading decision

4.3 Integrate optimisation with simulation

This work applied GA from the MATLAB global optimisation toolbox. The toolbox enables conducting the optimisation and simulation in the same platform and can use the MATLAB workspace as the interface to exchange the data between them.

This section operated the optimisation for the objective: Minimise the cost of each type of machine investment while reducing the total number of WIPs. The objective function is the sum of the total cost of machine investment and WIP costing. From the 1st to the 4th type of machine the cost is 400, 300, 200, 100 each. Every WIP would also be treated as a penalty costing of 1000. The machine investment has an upper bounder {10, 10, 10, 20} and lower bounder {1, 1, 1, 1}.

GA would minimise the customised objective functions in MATLAB and output the optimal decision variables, such as the number of different types of machine to be simulated. Then the simulation would be run based on these decision variables and deliver the performance measurement back to the optimisation side. The process becomes a loop and can continue for massive generations or iterations until finding the best or optimal solutions within the relevant scope.

4.4 Results

For objective1 (Figure 31) show that the GA found the optimal solution for 362 seconds to run the simulation 400 times (20 populations x 20 iterations) despite there being 20,000 possible configurations for this model.

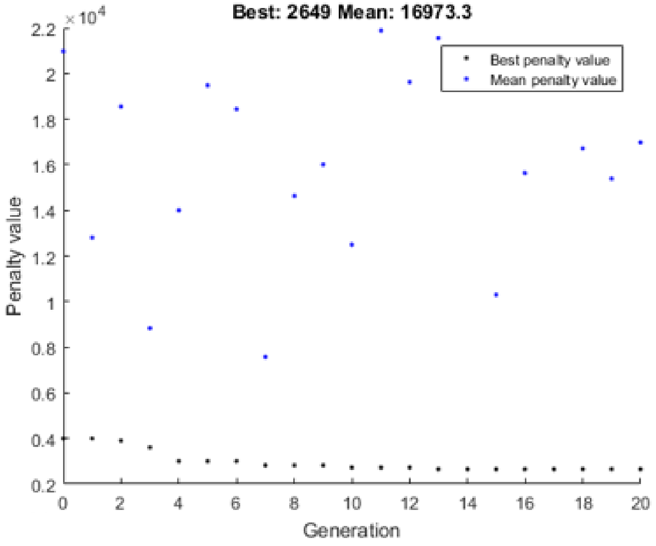


Figure 31 Right: The GA optimisation record

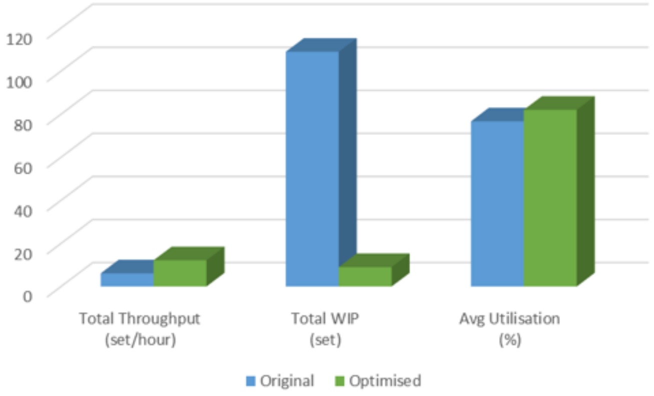


Figure 32 Comparison between original and optimised situation

The comparison (Figure 32) is between an original set of four types of machine {2, 2, 2, 2} and the optimised set {2, 2, 4, 4}. The result shows significantly improvement for the machine costing and WIP; the other performance also had a positive impact, such as throughput and average machine utilisation.

4.5 Summary

The chapter has proposed and demonstrated the optimisation - simulation integration approach applied to solving FMS problems. MATLAB was used as the shared platform for both the optimisation mathematical programming and DES modelling. This approach has been identified as a powerful tool to understand and address the problems for highly complicated systems such as the FMS

In the next step, a more detailed data will be used to build a comprehensive FMS model; then the results are more suitable for validation. In the future, Multi-objective optimisation algorithms will also be employed in this approach.

5 SIMULATION MODELLING OF FMS

5.1 Introduction

The nature of FMS has not been fully explored. Literature proposes various simplified models of FMS, but there is shortage of real-world cases to test and validate these FMS models. In this chapter, the author proposes to develop and validate an FMS model from the real-world case by using DES. This model represented a global view of multiple FMS problems and their interactions. This work has been verified with industrial practice, and the model is tuneable to be used as a test bed for further research.

5.2 Motivation and Scope

To keep competitiveness, manufacturers are required to be more agile and flexible. Thus, increasing the flexibility of manufacturing systems has become a critical issue for survival in the 21st century (Saygin, Chen and Singh, 2001).

5.2.1 Divided paths of FMS research

The FMS research can be divided into two directions and has attracted researchers from different fields. The original research direction is to discover the unique behaviour of FMSs, design and build a new generation of the manufacturing system. This research path is closer to the problem side and has been practised by researchers mainly from the manufacturing and engineering fields. As the initial researchers realised the ultra-levels of complexity of the FMS, the concept of the FMS has become another classical problem for operational research. Researchers from the mathematics or computer science fields have used the complexity from FMS problems to develop better solvers, such as optimisation algorithms. This path is close to the solution side, and the FMS can always be simplified into a mathematical model.

In some cases, the FMS can work in the same way as the Traveling Salesman Problem (TSP), which stands for an NP-Hard problem; this path has a significant contribution to algorithm development but with less consideration of implementation. The researchers from these two paths would share some of the standard material from FMSs; they may have different proposals to investigate FMSs and different destinations beyond. The research into FMSs has to be a long and continuous journey, and only if the researchers from the two paths work together, can the FMS fully release its value to the real world.

This work intends to follow the original proposal of FMS research, which investigates and explores the nature of FMS, to know better how the FMS works. Thus, this research will model a complete FMS based on a real case study. At the same time, the author also intends to build the model not only for representing FMS problems, but also to prepare the model to be used for simulation-based optimisation.

5.2.2 Conventional expectation from traditional manufacturing systems

Since Ford introduced the production line and the Toyota production system became the benchmark of the modern manufacturing system, a series of management techniques have been developed and introduced as the standard guidelines for manufacturing operations, such as ‘lean manufacturing’, and ‘Six-Sigma’. In the last decades, the majority of the manufacturing systems around the world have been built to enable mass production, designed as a dedicated manufacturing system, and they are controlled with flow shop scheduling discipline. However, the management techniques developed for flow shop and mass production do not always work well for other scheduling problems, e.g. job shop scheduling problem, especially for FMSs. From the successful experience of implementing the management techniques such as lean and Six-Sigma, some experts and scholars also attempt to apply the same techniques and tools directly to FMSs, or they believe that using these powerful tools can also solve the problems in FMSs, but there are rarely proven successful cases. An FMS can be a combination of flow shop and job shop scheduling. The mixture is far more complex than only flow shop or only job shop, so researchers and engineers need to work to test the understanding of FMS rather than directly carry over the hypothesis and assumption models from the imagination of FMS. However, because of the complex nature of FMS, there are very few reports of full implementation of FMSs in the real world.

5.2.3 Analytical approach vs simulation approach

The analytical approach has been widely applied in the field of operational research, and mathematical modelling has with a natural fit with optimisation algorithms. However, many researchers have pointed out that the analytical approach and mathematical model would be further complicated and less practical to use for a dynamic and sophisticated environment such as the FMS (Al-kahtani et al., 2014).

On the other hand, the simulation approach is much easier to handle than the complex manufacturing system, since it can model the stochastic variables at a dynamic pace without major simplification.

5.2.4 Lack of a comprehensive model of FMS

Most FMS models in the literature are a simplified mathematical model. The most famous reference is the random-type FMS (also known as non-dedicated FMS) (Rachamadugu and Stecke, 1994).

The motivation and scope of this chapter are to contribute to the above-mentioned shortage of FMS research, and are summarised as follows:

- The author proposes to gain an understanding of FMSs, prepare appropriate modelling methods, such as DES, which can collaborate with optimisation methods, such as evolutionary algorithms.
- The author proposes to experiment and identify the difference of behaviours between the FMS and the transfer production line commonly used for batch or mass production.
- The author proposes to build a comprehensive FMS simulation model which will represent major manufacturing problems and their interactions, validate and generalise this model for further FMS studies.

5.3 A case study of modern FMS implementation

5.3.1 Background of the case study

The case company is located in central England and specialises in designing and manufacturing a number of high-performance automotive engine components, including machined parts, electronic assemblies and software. The company has branched out from its beginnings as a design consultancy and short-run manufacturing business supplying into Original Equipment Manufacturers (OEMs) for race series; it now also supplies goods and services for a number of high-performance road car manufacturers. The products in this market share some similar key characteristics:

- niche volume manufacturing requirements (performance car volumes are generally significantly lower than more ‘everyday’ road cars);
- relatively short product life cycles;
- diverse product family (each product family may have many configurations);
- ongoing engine development/frequent engineering changes (requiring implementation of new technology and expedited engineering and production validation).

The company accommodates multiple customers and products from the target market, which was the driver for the manufacturing capacity augmentation. The business already retained short order manufacturing facilities; however, the existing facilities were not sufficient to serve the increased production demands and customer base - hence the advent of the new FMS facility. This facility not only provides an increase in capacity but through its dynamic product/process scheduling ability allows a seamless changeover to realise the optimal use of the increased capacity.

The author was not involved with the design phase of the FMS, and only joined the project after the hardware selection and installation. The installed machining centres are all furnished with factory fitted advanced digital technology, which enables the facilitation of the designed system flexibility. This means that the machining centres can handle different materials (different types or different dimensions and shapes), conduct different machining operations with defined tools, pallets (fixtures) and machining programmes. In other words, the advanced machining centres have enabled the system to be flexible in nature. The Material Handling System (MHS), also a key component in the FMS, is an advanced rail track and multi-functional crane vehicle. The rail track on which the crane travels connects every machining centre and can transfer the pallet and the material efficiently. When compared with the Automated Guided Vehicle (AGV) system which is a standard option within FMS design, the rail track based MHS is a much simpler solution. Furthermore, because the moving speed on the rail track is much faster than a normal AGV, the workload that would require multiple AGVs can be completed by a single crane vehicle.

In contrast to much of the advanced hardware placed on the shop floor, the control system still has abundant space to be developed. The hardware came with some support software; however, it can be hard to schedule the production for different products and processes in an effective way. Therefore, there is a need to research for FMS scheduling. The system comes with seamlessly integrated scheduling software, capable of scheduling a number of batches of parts with multiple operational levels. The scheduling engine can prioritise operations and/or parts based on their required completion date and provide a number of reports and visual aids to understand prior performance and communicate forthcoming machine, pallet, tooling and load station activity. One key aspect of the scheduling system, however, is that it schedules based on batch requirements. When orders are released into the system, one of the pieces of information required is a due date. The system considers other work to be completed and schedules the newly released order with appropriate prioritisation, to realise all required work within the associated need dates. If the entered demand cannot be achieved, the system shows this. If a part requires a number of operations to complete it, the system will schedule the initial lowest level operations and develop them into upper level operations. Once the upper level operations are complete, the remaining parts in progress are completed and the scheduling engine considers the order to be delivered. Should a following order or batch of the same part be required, the system’s behaviour remains the same. This means that the parts assigned to the current batch (regardless of whether or not a following batch of the same part has been released) will be completed without migrating parts from one batch to the next. To combat this a number of batches can be released to the machine simultaneously with staggered start and finish dates to balance the number of concurrent lower and upper level operations; however, it is difficult in a production environment to know which batches the parts belong to without large dynamically labelled WIP storage facilities. This causes inefficiency in series production.

Through contact with the engineering and manufacturing personnel employed in the flexible manufacturing facility, it is evident that many are familiar with more traditional dedicated manufacturing systems, such as transfer lines, but have limited experience with FMSs. Before narrowing down the research focus for FMS manufacturing problems, it is necessary to discover and explore the nature of the FMS, identifying the differences between an FMS and conventional dedicated manufacturing systems. Due to its more intrinsically complex nature, simulation of the FMS has been recognised as an excellent method to better understand the FMS. Through the testing of different scenarios, advance knowledge can be gained prior to implementation in the manufacturing environment.

5.3.2 Representation of FMS in case study

5.3.2.1 Entities of FMS

The selected case study is an MMFMS. The shop floor layout is shown in Figure 33, the entities of the FMS include multiple machine centres, MHS, tool store, pallet and material temporary material store.

- **Machining centres**, of which there are two primary types, though they all have FANUC controls and horizontal spindles, they are different in their capabilities in that some are 5-axis machines and others are 4-axis. Each run a FANUC programming system.

- **Material Handling System (MHS)** consists of a crane vehicle and a crane track. The crane vehicle carries only one pallet at a time and can travel the track collecting and depositing pallets into load stations, material storage areas and machining centres. This crane and track system is more efficient than the AGV system as picking up the pallet from one bay and releasing it to the other bay would cost around 2 minutes. This research is not focused on transportation problems, so the MHS would keep as simplified as possible in the simulation model.
- **Load / unload station** loads/unloads parts to / from pallets from the line-side WIP areas. The loading / unloading is prioritised based on production demands.
- **Material** refers to the two product families that are machined in the FMS; both of which have different subcomponents and production demands.
- **Pallet** interfaces with the machining centre and holds the fixtures and materials for transportation by the MHS. The fixture is installed on the pallet as an assembly onto which the material is loaded and machined. Pallets may be suitable for one or more machining operations, with some machining operations having more than one pallet. The loading/unloading of the material are carried out manually at load/unload stations.
- **Tool store** the Central Tool Store (CTS) holds a large number of tools ready to be called up by the machines in accordance with the demand of the machine running for a given material. The tools are transported to the machining centres by gantry mounted robots which travel each side of the line from the CTS to each of the machines. They can supply the cutting tools to the machining centres’ built-in magazine in preparation for use when called up by the program. As this study does not aim to understand the system’s tool management, this part is ignored in the simulation model.
- **Temporary store** can be directly accessed by the MHS and can hold limited numbers of pallets and materials. The temporary store is designed to maintain FMS operations during lights out / without loading operators.

As this research does not aim to study shift change, this part will not be considered within the scope of the simulation model.

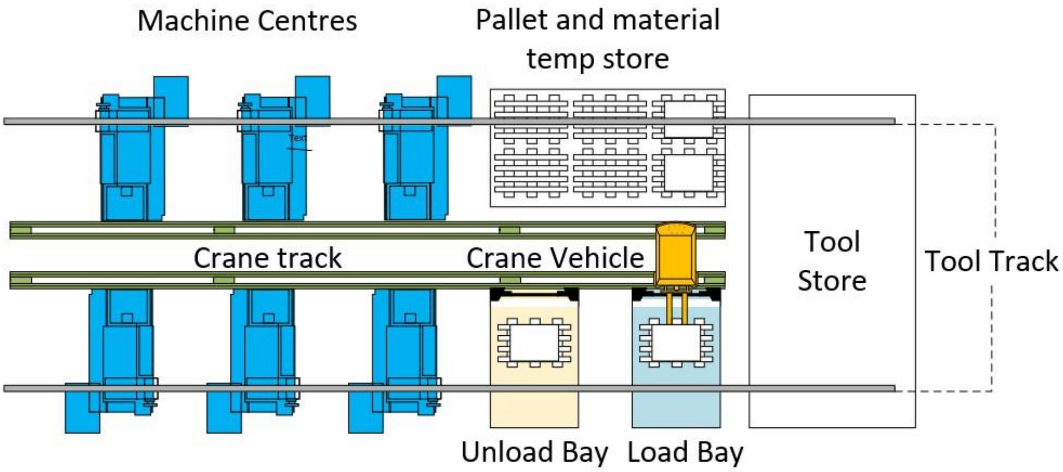


Figure 33 Shop floor layout of FMS from a case study

5.3.2.2 Events of an FMS

The operation of an FMS can be described as a series of events, as shown in Figure 34.

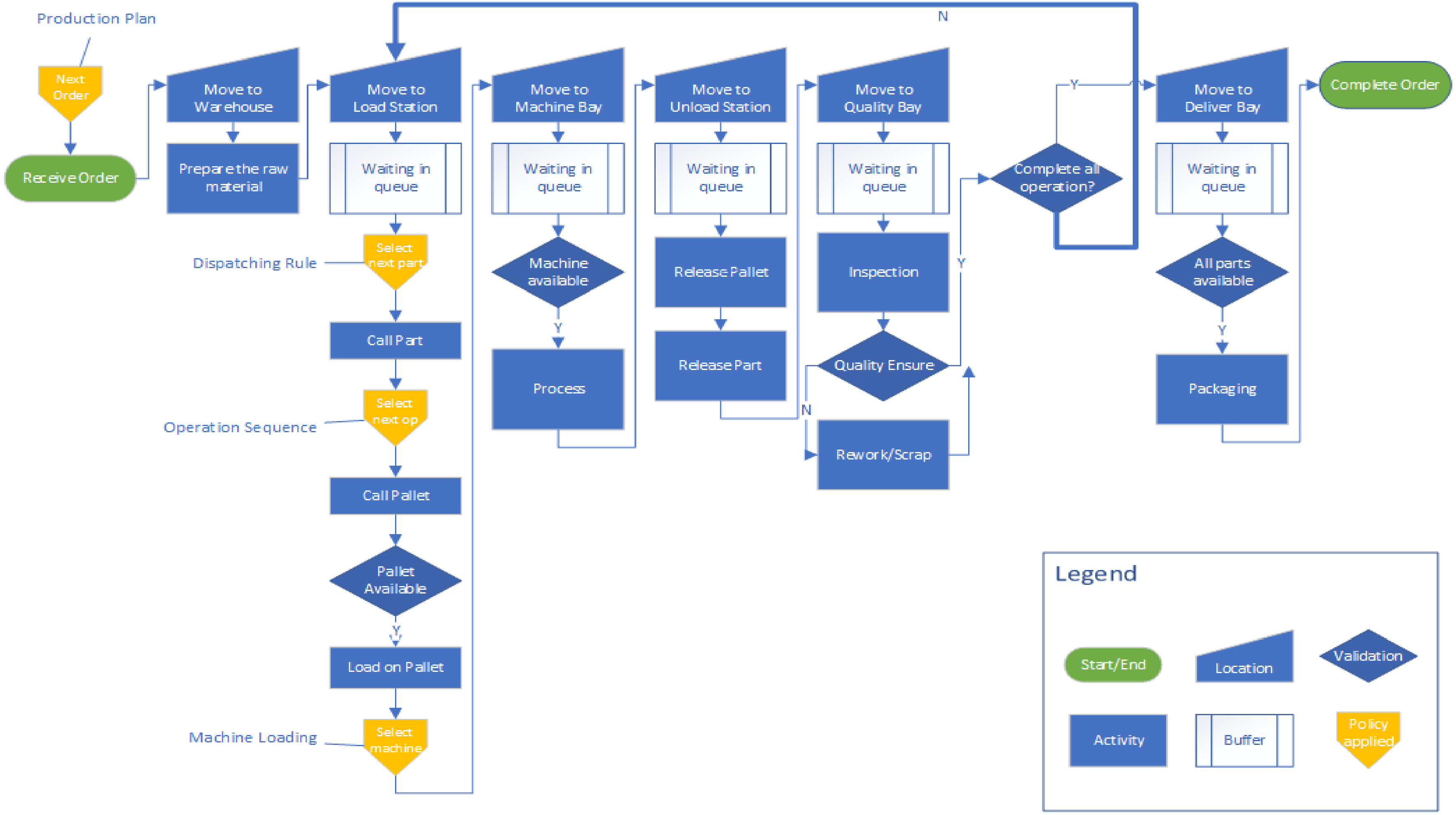


Figure 34 Main events of FM

1) After the customers give their orders to manufacturers, the production planning team may organise these orders and schedule a production plan. The decision making of this production plan often refers to the ‘offline scheduling problem’. After having created the production plan, the order will arrive at the manufacturing system in a specific time and frequency. The FMS is able to welcome the orders for multiple types of product at the same time, but the arrival time and arrival frequency of the different types of product may not be the same. The question of ‘which order to feed the FMS with next’ is decided in this phase; it is normally a business decision rather than a manufacturing operation decision.

2) After the order arrives, the warehouse prepares the raw material for that order. The question of ‘what parts are inside of this order’ would be defined. The order for a single finished product may require multiple parts or subcomponents. The list of subcomponents is also called a ‘Bill of Material’ (BoM). Each part or component would require its manufacturing process.

3) WIP enters the manufacturing capacities from the load station. At the load station, three key questions for the FMS would be decided: ‘which part to process next’, ’what is the next operation for this part’ and ‘which machine to use next’.

From the raw material entering the manufacturing system until it leaves, it would be defined as ‘Working In Process’ (WIP). The WIP would firstly waits in the queue or buffer. The load station decides which WIP in the queue is to be picked up for the next step, according to the dispatching rules. The most common dispatching rule is ‘First In First Out’ (FIFO). The dispatching rule could also depend on other attributes, for example, how many operations are lefts for the WIP, the priority of the type of product, and so forth. The dispatching rule can be a very simple or extremely complex policy. There are many dispatch rules to study for FMSs.

The question of ‘what is the next operation for this part?’ is generally assigned at the load station. The operation sequence is typically fixed, but it is possible to assign partial flexibility to the operation sequence, which allows some steps to be switchable. This phase makes an FMS different for a purely linear workflow; the nature of an FMS would not qualify as being the same as the transfer production line. From the point of view of the material, it may experience several loops of entry and exit of same machine. The behaviour of an FMS is closer to the job shop scheduling problem, or the combination of job shop and flow shop problems. The complex nature makes the scheduling of the FMS reach the NP-hard level.

After deciding which WIP to dispatch, according to what is the next operation, the pallet would be called. If the pallet is available, the WIP would be fixed on the pallet, and next question for the FMS appears - which machine should the WIP send to. This question is called the ‘machine loading problem’, because in an FMS, one operation may have multiple optional machines to go to, so it now has to decide which one to approach.

4) After the machine has been selected, the pallet with the WIP is transported by MHS to the selected machine. The matched CAM program is then loaded to that machine, and the correct tool would be collected. The WIP spends time in the machining process. These times are the major value-added time for an FMS.

5) After the machining process has finished, the pallet and WIP is transported by MHS to the unload station. The part is released from the pallet; if required, it would be sent to quality check or other manual operations. The pallet would be free for next use. The most likely decision that needs to be made at here is ‘has the part finished all operations’.

6) If the WIP requires a quality inspection, it is sent to a quality zone which may have equipment such as CMMs, or pressure test machines. The quality inspection process can be simple or complex, and the WIP may fail to meet the quality requirement. If a quality defect is found, the WIP might have to repair or scrap. If the WIP has to scrap, all processes that happened with that WIP would then be wasted, and one new raw material would be sent to be processed from the initial step. The quality aspect is essential for any manufacturing business, but most FMS research publications have not covered the quality inspections, because the quality control methods can be diverse for different products or processes and can be too complicated for an initial FMS study.

7) Before the WIP has completed all required operations, it returns to the load station for the next operation.

8) After the WIP has completed all required operations, it is transported to the delivery bay. To deliver one order, all subcomponents within the order would then be packaged together and shipped out of the manufacturing system, to the customers.

The above-mentioned are the main events of the FMS. The FMS may have many orders experiencing these events at the same time, so the interrelationship of all events happening within the FMS make it extremely complicated to understand or control. Therefore, a simulation study of an FMS is helpful to investigate the understanding of an FMS and it would be more effective and cost-saving to validate the control strategy on a simulation model before the real shop floor production validation.

5.3.3 Representing FMS problems

The complexity of an FMS makes it like an iceberg, with substantial parts hidden. From the current progress of academic research and industry practice (Gupta and Goyal, 1989; Seok Shin et al., 2011; Yücel, 2005), the significant problems of FMSs have been discovered, but there is rarely reporting of their interactions and coefficients which definitely will appear when implementing an FMS in the real world. In the literature, most of the simulation models focus on one specific problem and a ignore the coefficients from other problems. These studies have not been fully validated from a complete FMS environment in which multiple problems exist. Researchers (Chan et al., 2002; Priore et al., 2001) have already identified that these myopic studies have been identified as incorrect or not accurate enough. Reading the single problem-focused studies, sometimes makes it misleading for these who want to implement the FMS. It is necessary to investigate the interaction and coefficient, and this kind of study can provide a guide for the researcher to consider the predetermined coefficient when they focus on the single problem. To address this issue, this research decided to cover all of the discovered major problems of FMS and simulate them in one model.

The discovered FMS manufacturing problems for production operation include the problems that also appeared in a conventional manufacturing system and other problems that uniquely only exists within the FMS.

- The manufacturing operation management problems that appeared in the FMS and other conventional manufacturing systems:
  - **Capacity planning**
    the volume and due time of the specific product are given, and the quantity (and type) of various manufacturing entities (e.g. machine, pallet, workstation, labour) has decided accordingly.
  - **Operation Sequence**
    the sequence to complete all operation should be carried out for one product (or one part). Usually the operation sequence is in a fixed order, for example, the operation A, B, C should be carried out in alphabetical order. The operation sequence can also be flexible, which allows the operation to be processed in the order of ABC or ACB. The flexible operation sequence is like the Assembly Sequence Problem (ASP).
- The manufacturing operation management problems in FMSs and behaviour are significantly different from another conventional manufacturing systems. They are segmented here into the type of flexibility:
  - **Machine flexibility**
    The digitalised advanced machine centres bring the machine flexibility to FMSs, which is lacking in conventional manufacturing systems. Machine flexibility defines the **Level of Flexibility (LoF),** e.g. LoF 1 means a particular operation can be handled by one alternative machine, which totals two options. When the LoF has a positive value, the **machine assignment problem** and **machine loading problem** appear. The machine assignment problem is determined before the FMS is running; it is the assignment of one specific operation to any optional machine (specific ones). The

machine assignment is partly like the traditional line balancing assignment; the objective of the machine assignment is to maximise the utilisation of all machines and reduce the workload variations. The machine loading problem is the policy to select one machine from multiple optional machines for a specific operation in a specific situation; this policy is usually conducted as a real-time decision when the FMS is running.

- **Volume flexibility**

  The FMS can produce different products at the same time, but the difference and change in the production volume could create an imbalance for the whole system. The change of production volume for a single product may impact on all other products sharing the same FMS facility. The volume flexibility is rarely studied at a quantitative level; for example, there is no study that defines the maximum gap of production volume for different products. Most FMS studies have neglected the impact of volume flexibility on the whole system performance.

- **Routing flexibility**

  Routing flexibility is generated by machine flexibility when the LoF is more than one; one specific operation would face multiple optional machines from which to choose. To make one part from raw material to the finished product, many operations should be conducted in a given sequence, and multiple decisions have to be made from start to end. All the decisions and selections become the routing of the part. The routing can be dynamic and is often related to dispatch rules. In the literature, usually the **dispatch rules** refer to the queuing policy when material enters the system for the first time. The routing rules also include the queuing policy when the material has been partially processed and re-enters the system, which is often referred to as the **machine loading problem**. Both dispatching rules and machine loading problems are generally referred to as a subset of **FMS scheduling problems**.

There may be some mixed and confused parts between FMS research and general manufacturing system research. Many researchers have attempted to apply the knowledge of general manufacturing problems and methods from conventional manufacturing system to FMS, and developed their own concept and methods on the assumption that the experience from a conventional manufacturing system can work in an FMS. For example, the problem definition of a mixed-model assembly is similar to that for an FMS that produces multiple products at the same time, but the methods of mixed-model assembly are only applied to a flow shop scheduling system, and are not applicable to an FMS which is not a flow shop scheduling system. Further confusion may exist between, Assembly Sequence Problem (ASP) vs FMS dispatching rules problem, Assembly Line Balance (ALB) problem vs. FMS machine loading problem.

5.3.4 Performance measurement

If the FMS is treated as a black box, its output is similar to another manufacturing system—produce the finished product and deliver it at a particular time. So, the general performance indicators can also be applied to measure the FMS. As FMS studies has involved many disciplines, e.g. manufacturing engineering, operational research, thus, the appeared terminology is not uniformly defined. Therefore, it is necessary to clarify the performance indicators used in this research, the meanings, and their alternative names that are referred to in other places.

Key performance measures of an FMS:

- **Throughput** (**1)**: the number of the product can be produced (Fin_i) in certain time periods. Also called the production rate. In an FMS, there is overall throughput for the whole system, and the throughput for individual products which share the same FMS facilities.

$$Out_i = \frac{Fin_i}{Time\ unit} \tag{1}$$

- **Utilisation (2)**: The usage of the manufacturing entity or equipment, e.g. machines, workstations. In theory, the manufacturing entity should be 100% utilisation to make the best return on investment, but in reality, idle time and breakdown time have to be deducted. In most of the cases, in order to maintain the system operating functionally in the long-term, planned downtime for the manufacturing entities is necessary, so the manufacturing manager would never expect 100% utilisation in the long-term. The calculation of utilisation is typically the rate of value-added time (process time) divided by available time of the entity.

$$Uti_i = \frac{Value\ added\ time\ of\ entity_i}{Total\ avaliable\ time\ of\ entity_i} \tag{2}$$

- **Workload variation (3)**: the variation of workload among multiple manufacturing entities under the same system. It is subjected to ‘bottleneck’ analysis. ‘Workload variation’ is an index figure and indicates the level of balance/imbalance in the manufacturing system. Normally it is calculated as the sum of the gap between the utilisation of individual manufacturing entity and the mean utilisation of the whole system. The better the workload variation (less indexed value), the less the impact of the ‘bottleneck’ phenomenon on the whole system, and it then closer to a balanced set-up of the manufacturing system.

$$WorkVaris = \frac{\sum_{i=1}^{n} |Uti_i - Uti_{mean}|}{n} \tag{3}$$

- **Level of WIP (4)**: The average number of WIPs in a manufacturing system. The number of WIPs is directly linked to the buffer space and inventory cost and indirectly linked to ‘time in the system’ and throughput. According to Little’s Law, there is a minimal level of WIP required to warm up and maintain favourable throughput for the whole system. However, if the WIP level is too high, it would result in more blockage and waiting time in the system and gain higher cost for inventory. Maximising the throughput and minimising the level of WIP are two conflicting optimisation objectives. Usually a manufacturing manager desires to find a ‘sweet point’ which benefits from both objectives. If the single cost of the product is very high, the manager would like to keep the level of WIP to a minimum. If the lead time to market is more important, the manager would fulfil enough WIPs to reach maximum throughput.

$$Lwip = \frac{\sum_{t=0}^{n} number\ of\ WIP}{n} \qquad (4)$$

- **Flow time** (**5)**: The amount of time a single unit of product spends between entering the manufacturing system and leaving it. It is related to ‘time-in-system’ analysis. The difference between flow time and ‘lead time’ is that latter only calculates the total value-added process time, but the former would also include the non-value-added time that happens in a manufacturing system, such as the waiting time, blocking time, downtime, and so on. The mean flow time would give the manufacturing manager a more realistic indication of the smoothness of the manufacturing system’s operation. The gap between mean flow time and lead time can help the manufacturing manager determine how much the non-value-added time is. Ideally, the minimum flow time would be close to lead time. The maximum flow time would also help to identify any potential risk in the manufacturing system. In the academic literature, ‘makespan’ is also appears frequently. ‘Makespan’ is the amount of the time that the whole batch of product spends from the first item entering the manufacturing system to the last finished product leaving the manufacturing system. Makespan divided by the number of the product would be the mean flow time. Makespan is used more often to evaluate the efficiency of mid- or long-term scheduling policy, and flow time is more useful to measure short-term or real-time performance.

$$FlowTime_{mean} = \frac{\sum_{i=1}^{n}(Texit_i - Tentre_i)}{n} \qquad (5)$$

Although there are other specific indicators, ‘throughput’, ‘utilisation’, ‘workload variation’, ‘Level of WIP’ and ‘flow time’ are the most acknowledged performance indicators to evaluate the overall performance of general manufacturing system and work well for an FMS. These five indicators are selected to measure the performance of FMS simulation models (Hoffman and Tadelis, 2018).

5.4 Modelling FMS

5.4.1 Design of simulation experiments

Different kinds of simulation technologies share a general proposal for research study—representing the problems in the abstract environment rather than the serious real-world case; the central added value of a simulation study is helping people to understand and solve the problem in less time, at less cost with more possibility of being able to do the same things in the real world.

The selection of a simulation modelling method and technique is dependent on the level of detail from the problems and the result expected to be found after the experiment. For the time sequence of project development, the proposed simulation has been segmented into phases (Barton, 2010):

1. Early: identify the problems existing in the system,
2. Early: screen the variables, identify the primary dependent variables,
3. Middle: sensitivity analysis, identify the primary independent variables,
4. Middle: predictive model,
5. Late: selecting best configuration,
6. Late: optimisation, robust design, additional optimisation method may be applied.

For this research, the problems of the FMS have been discovered, the independent variables for each problem have been identified, and the dependent variables are shared in the same system. The coefficients of the independent variables from the different problems have not been fully understood, and the impact to on intermediate variable has not been fully understood. So, the experiment only involving the independent variables from the single problem may be misleading.

According to the previous study on an FMS, a series of hypotheses have been developed. There is a need to develop a base-model which can represent the problems, and this base-model needs to be validated before the experiment is run. After the base-model has been validated, the experiments should be carried out to examine the hypotheses.

1. Identify the problems of the FMS
2. Develop the hypotheses on the effect of problems, propose the independent and dependent variables
3. Build a base-model to represent the problems in a simulation model
4. Validate the base-model with a real-world scenarios test
5. Experiment to test the hypotheses
6. Summarise the simulation results and suggest the optimisation

The experiment is designed to test the hypothesis as shown in Table 5:

Table 5 Experiment design for FMS simulation

Item	Problem	Sub-Problem	Hypothesis	Independent Variables
1	Capacity planning	Throughout and WIP	Increase of order arrival frequency would lead to increase in performance	Order input rate 1
2	Capacity planning	Pallet quantity	Increasing the number of pallets would increase the performance	Number of pallets
3	Operation Sequence	Random or fixed	Sequence of operation would have a substantial impact on performance	Operation sequence fixed or random
4	Machine flexibility	LoF	Higher LoF gives higher performance	Level of Flexibility
5	Machine flexibility	Machine Assignment	Better machine assignment can increase performance	Assign machines to operations
6	Routing flexibility	Dispatching Rule	Dispatching rule would impact on performance	Dispatching rule at the load station
7	Routing flexibility	Machine Loading	Machine load rule would impact on performance	Machine loading rule

5.4.2 Modelling method

Because the FMS is a discrete manufacturing system rather than a continuous process manufacturing system, this work is carried out through the method of DESs, based on the SimEvent of MATLAB (Clune et al, 2006). SimEvent is embedded in Simulink which is a traditional time-driven simulator, so that it is equipped with a functionality that enables an effective co-existence of time-driven and event-driven components in complex hybrid systems. As it share the same workspace inside of MATLAB, it also has the advantage of transmitting the data, and a call out programming function between the simulation model and optimisation programming.

The simulation model is also designed to work with the optimisation method. The primary requirement from optimisation is computing efficiency. The requirement includes the following aspects:

- The simulation model should have the capability to transmit the data with an optimisation tool with a low latency. The data transmission means inputting the decision variables from the optimisation tool and outputting the production performance results to optimisation tools. If the data have to walk across too many intermediary workspaces or interfaces, this would create excess latency and reduce the efficiency for the core part of the optimisation process.
- The simulation model could run efficiently with less consumption of time and computing power. Ideally, the simulation model should be able to run without any visualisation, because the visualisation function would occupy the computing power heavily, and it does not usually add any value during the optimisation process.

These two points are especially important if the simulation model is to cooperate with the optimisation process.

To fulfil these requirements, multiple manufacturing simulation methods have been compared (Mourtzis, Doukas and Bernidaki, 2014) . SimEvent is selected because, 1. it can work with the optimisation tools within the same workspace in

MATLAB, there is no other interface to transmit the data; and 2. it can run the model without loading any visualisation function, which saves considerable computing power, making the time to run a simulation scenario much shorter.

5.4.3 Model structure

The final model is called FMS comprehensive model. The most challenging part of building the FMS model is that these existing of enormous components inside and they cooperate in a very interactive logic. Facing this challenge, this FMS inclusive model is built with hierarchical architecture, as shown in Figure 35. The main modules are the essential function of any FMS. These main modules are built robustly for working with each other as the top-level system but contain less detail, which would be specified in submodules. The advantage of a hierarchical architecture is that the individual module can be built and tested respectively. After completing any sub-system module, it can be easily plugged into the top-level system, and it is also easy to pass by the sub-system model in specific scenarios. The proposed hierarchical architecture of building a complex simulation model has also been inspired by the method of coding a comprehensive program – the object-oriented programming method.

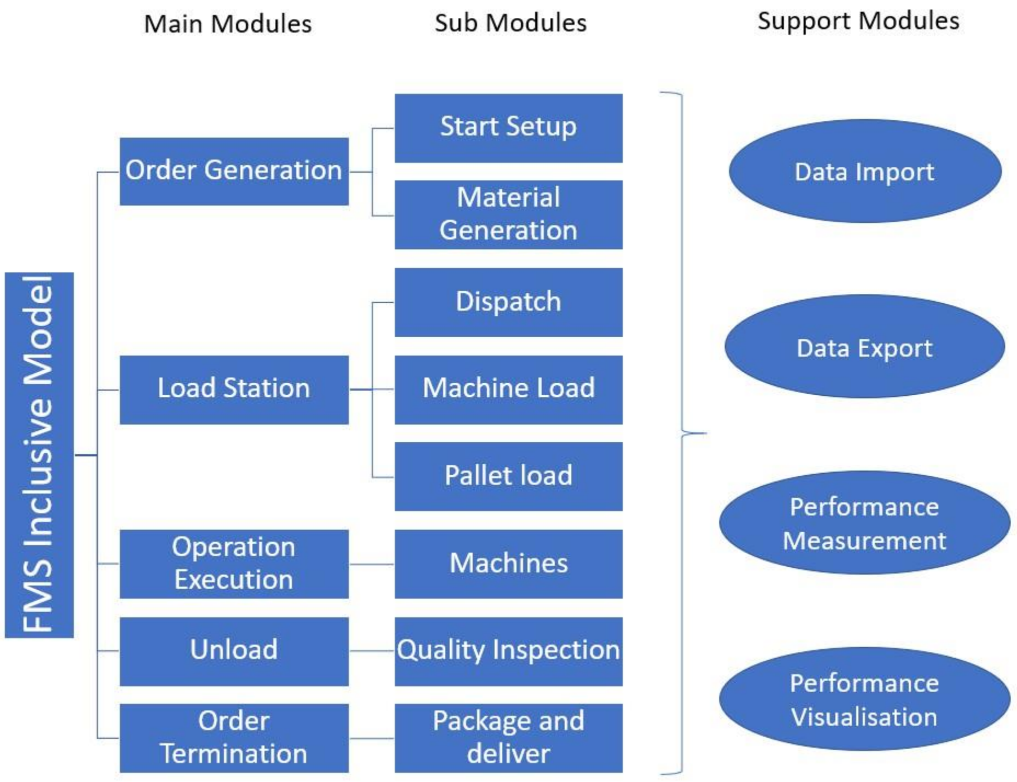


Figure 35 Structure of the comprehensive FMS model

5.4.4 Model development

5.4.4.1 Top level

As shown in Figure 36, the top level of the inclusive FMS model is developed from the sample FMS model used while developing the simulation and optimisation integrated framework. The essential functions presented in the top level include order input (order generation), load station, operation execution (machines process), unload station and the delivery (order termination). The support modules of ‘performance measurement’ and ‘performance display’ also shown on the top level.

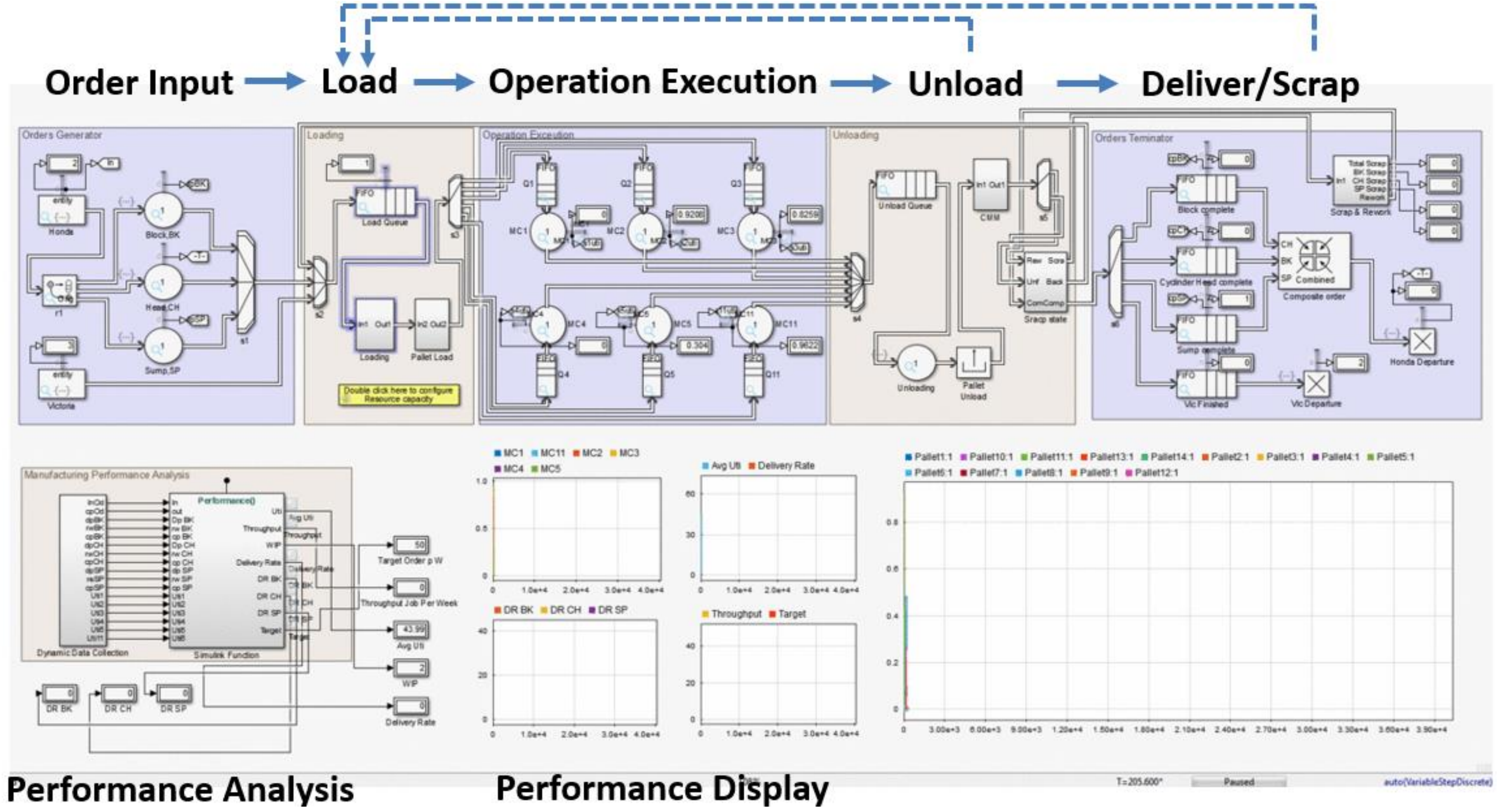
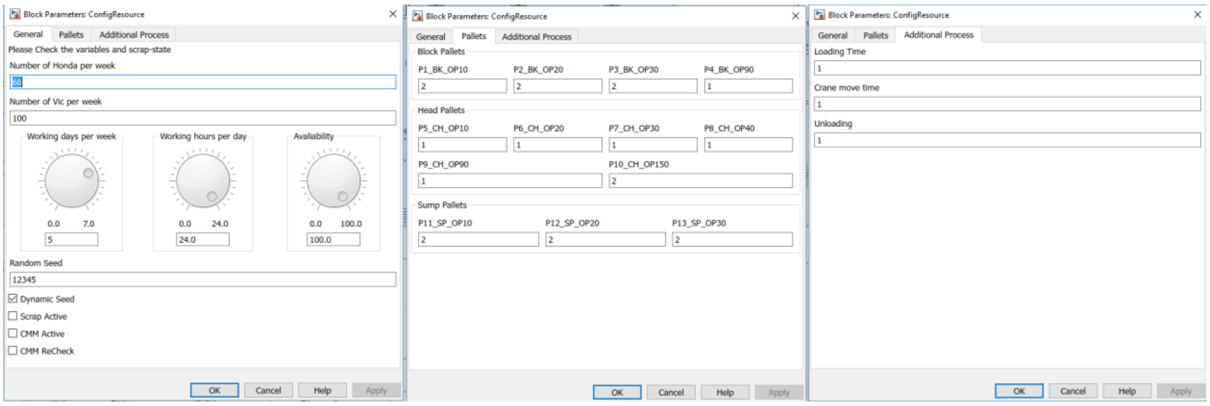


Figure 36 Top level of the inclusive FMS model

5.4.4.2 Start Set-up interface

The model start set-up interface, shown in Figure 37, is designed to ease the set-up or change in the variables of the simulation model with a user-friendly interface. The variables include the order input frequency, the available working hours, the planned downtime, ideal overall utilisation, number of the pallet, and the transportation times. It also can switch the sub-systems on or off and control the random seed for the simulation experiment.



Please Check the variables and scrap-state

Number of Honda per week: 66
Number of Vic per week: 100
Working days per week (0.0 – 7.0): 5
Working hours per day (0.0 – 24.0): 24.0
Avaliability (0.0 – 100.0): 100.0
Random Seed: 12345
☑ Dynamic Seed
☐ Scrap Active
☐ CMM Active
☐ CMM ReCheck

Block Pallets
P1_BK_OP10: 2
P2_BK_OP20: 2
P3_BK_OP30: 2
P4_BK_OP90: 1

Head Pallets
P5_CH_OP10: 1
P6_CH_OP20: 1
P7_CH_OP30: 1
P8_CH_OP40: 1
P9_CH_OP90: 1
P10_CH_OP150: 2

Sump Pallets
P11_SP_OP10: 2
P12_SP_OP20: 2
P13_SP_OP30: 2

Loading Time: 1
Crane move time: 1
Unloading: 1

Figure 37 Start set-up interface

5.4.4.3 Order generation

The order generation module will generate the order according to customer requirements, with a specified frequency. When the order is put into the FMS, it will create materials or generate multiple parts according to the BoM of a specific product from the generated order, as shown in Figure 38.

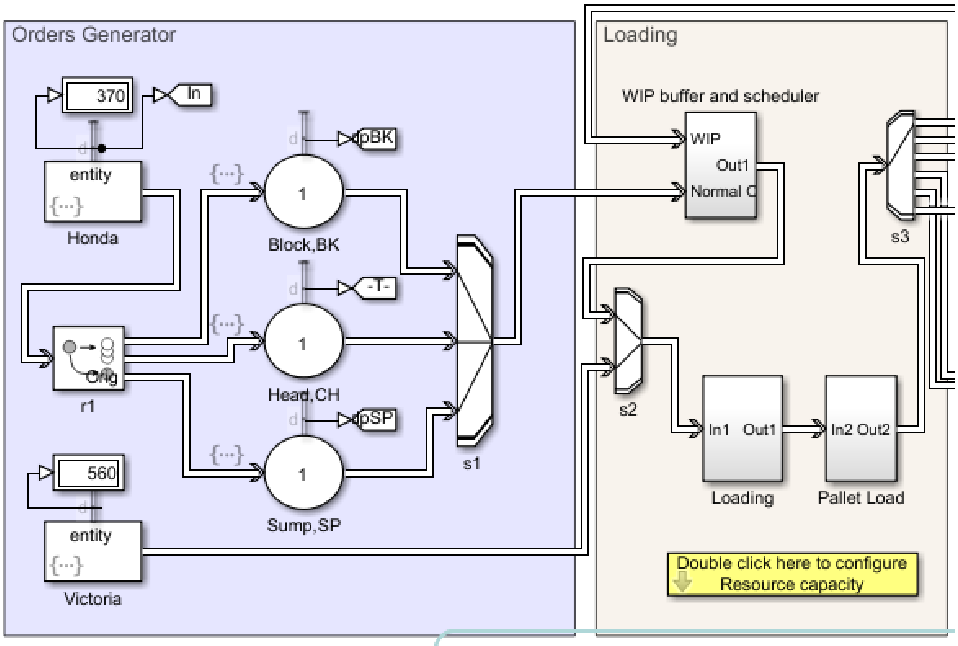


Figure 38 Order generation module (left) the load station module (right)

5.4.4.4 Load station

The load station is the most intelligent and complex place of the FMS. As shown in the left part of Figure 38, the load station receives different products including raw material and WIP. The loading system identifies the current state of a part, select the right pallet for the part and identify the right machine to send. Within the scheduling sequence, sub-system, it can also load the parts in a given sequence.

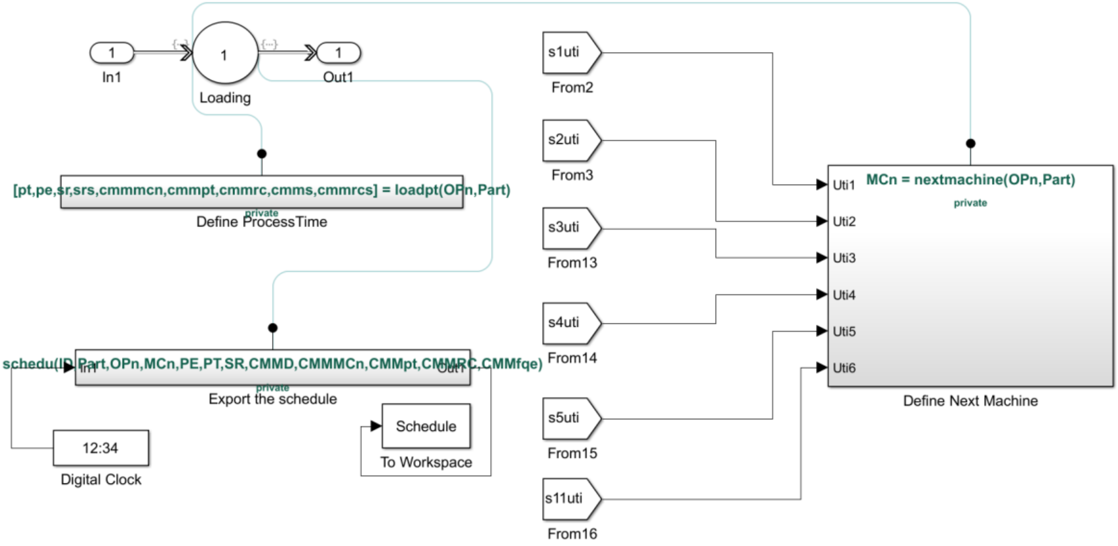
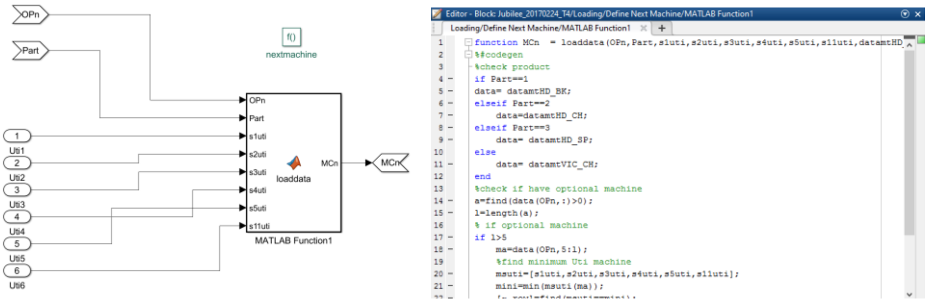


Figure 39 Loading system

As shown in Figure 39, when the part comes to the loading system:

- It would first read the part ID, and operation ID uses these indices to search the data matrix and identify which machine can process the current operation for this part, and which pallet should pick up for this operation.
- With the advancement of the FMS, some specific operations can be carried out on the different machines. If one operation has multiple options of the machine to be sent, the decision would be made based on the most available machine chosen in order to improve the utilisation of the whole system and reduce the workload variations. To realise this function, the MATLAB function for coding is also applied, as shown in Figure 40



```
function MCn  = loaddata(OPn,Part,s1uti,s2uti,s3uti,s4uti,s5uti,s11uti,datamtHD_
%#codegen
%check product
if Part==1
data= datamtHD_BK;
elseif Part==2
    data=datamtHD_CH;
elseif Part==3
    data= datamtHD_SP;
else
    data= datamtVIC_CH;
end
%check if have optional machine
a=find(data(OPn,:)>0);
l=length(a);
% if optional machine
if l>5
    ma=data(OPn,5:l);
    %find minimum Uti machine
    msuti=[s1uti,s2uti,s3uti,s4uti,s5uti,s11uti];
    mini=min(msuti(ma));
```

Figure 40 MATLAB function for machine selection

- To track and record the complex operation of the loading system, it also records every decision made by the loading system and related information such as timestamps, and product serial number.

5.4.4.5 Schedule and operation sequence

The scheduling problem of the FMS can be classified into multiple levels. In low-level control of the FMS, the scheduling is in the form of the dispatching rule. The most common dispatching rule followed is FIFS. A high-level control is expected as that the control system can pull together all of the required information in real-time, and make and update the schedule continuously. The middle-level control is to operate and repeat one simplified optimised the sequence of operation, this level of control is more accessible to implement on the shop floor and easier to manage. Figure 41 shows the schedule sub-system which realises the middle-level control, loads the operation under a simplified sequence. It can switch between low-level control and middle-level control.

To maintain the defined schedule sequence regularly, it also needs a WIP buffer to cover the fluctuation inside of the system. The WIP buffer is therefore built into this sub-system.

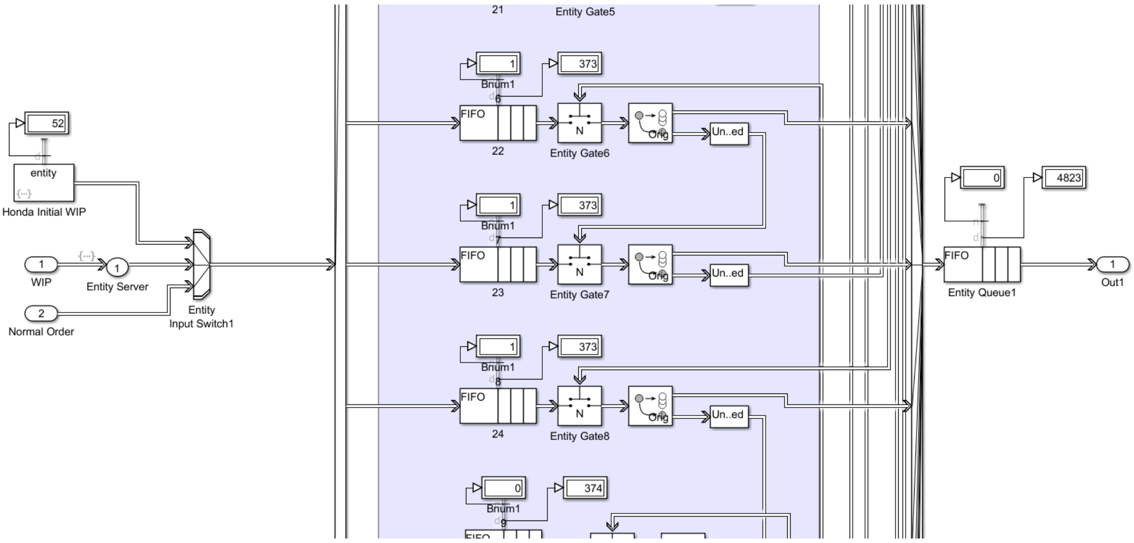


Figure 41 A part of the scheduling sequence system

5.4.4.6 Operation execution

There is a predetermined capacity of machines or workstation to undertake the different operations for a different product, as shown in Figure 42. The loading system has already arranged the work for each machine; the machine only needs to process the arrived task in the required time and send the part off having completed the operation. All of the performances of these machines have been monitored; for example, the figure showed beside the machine is the utilisation in real-time during simulation runs.

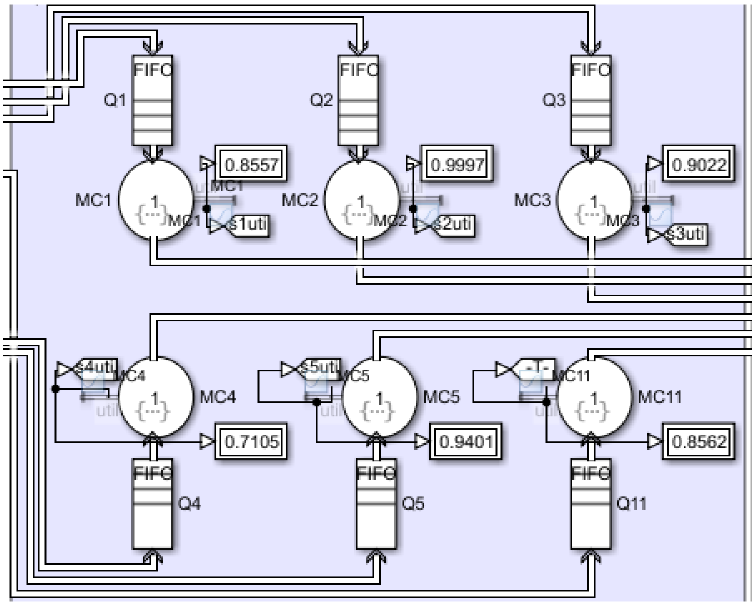


Figure 42 Operation execution

5.4.4.7 Unloading module

As the reverse function of the loading system, the unloading module is responsible for splitting the part with the pallet, as shown in Figure 43. Depending on the state of the part, the unloading module would send the part to the loading system again if there is still an operation waiting to be done for the part, or send it to the CMM and Scrape/rework sub-system towards the terminal of the FMS.

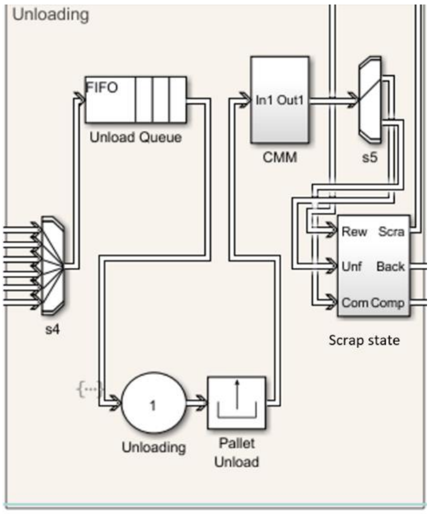


Figure 43 Unloading module

5.4.4.8 Order delivery

This is the end of production as shown in Figure 44; different products would be delivered to customers respectively, or, leave the manufacturing system. If the product needs to ship an assembly part, it would be assembled before leaving this module.

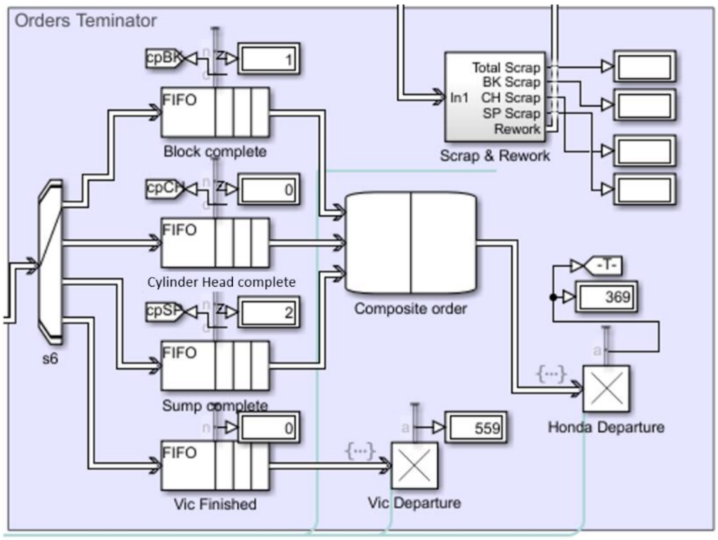


Figure 44 Order delivery

5.4.4.9 Scrap and rework

This is one optional sub-system module. If a quality check is required, there would be a ratio of scrap or rework, and this module would simulate this behaviour, as shown in Figure 45. For scrapping, the part would be directly thrown into the bin and add in another set of raw material added into replace the scrapped part, and the whole operation would re-start from zero. For rework, the part would be sent to a rework area and time spent on its to repair, always being cautious that there is the possibility, the part can fail during reworking and become a scrap part.

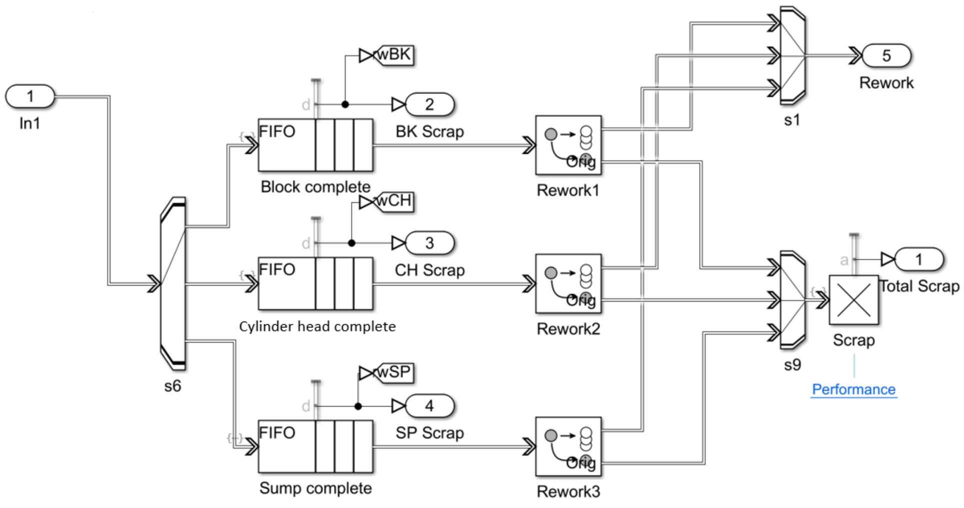


Figure 45 Scrap and rework

5.4.4.10 CMM quality inspection

The CMM quality check sub-system would checks the WIP in each stage of operations as shown in Figure 46; some operations need a full inspection, some need a random inspection with a given frequency. If the CMM initially finds a the quality failure, there would be the possibility of a check repeat by CMM quality inspection again. There is also the possibility that adds a step of manual inspection will be added after the CMM found the quality defect. If a part failed to pass the quality inspection, it is sent to scrap or rework.

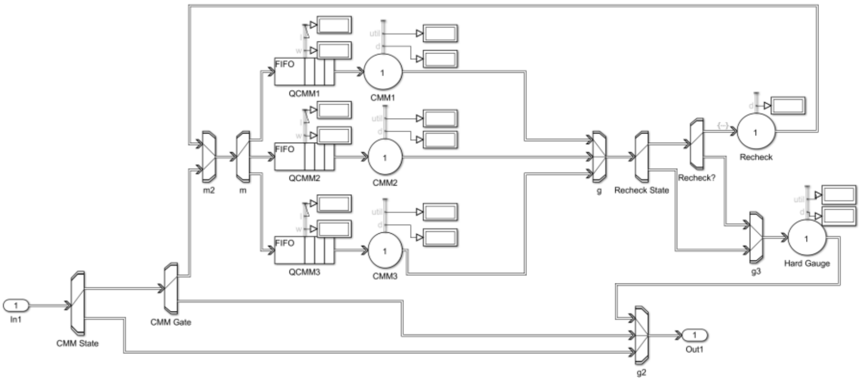


Figure 46 CMM quality inspection

5.4.4.11 Performance Dashboard

To realise the function of the performance dashboard, as shown in Figure 48, it will use a performance monitor to collect the performance figures at every checkpoint, such as the utilisation of the machines, or the stock of WIP.

The performance dashboard also indicates a historical record of utilisation of machines, utilisation of pallets, throughout, delivery rate, WIP stock, and so on.

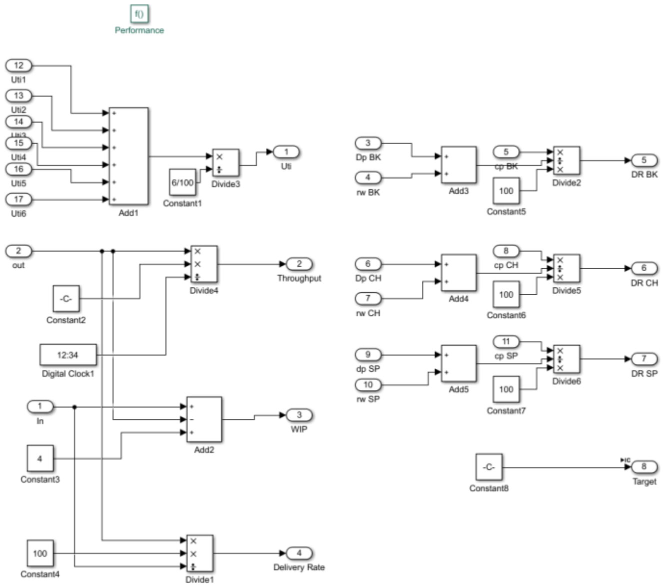


Figure 47 Performance monitor

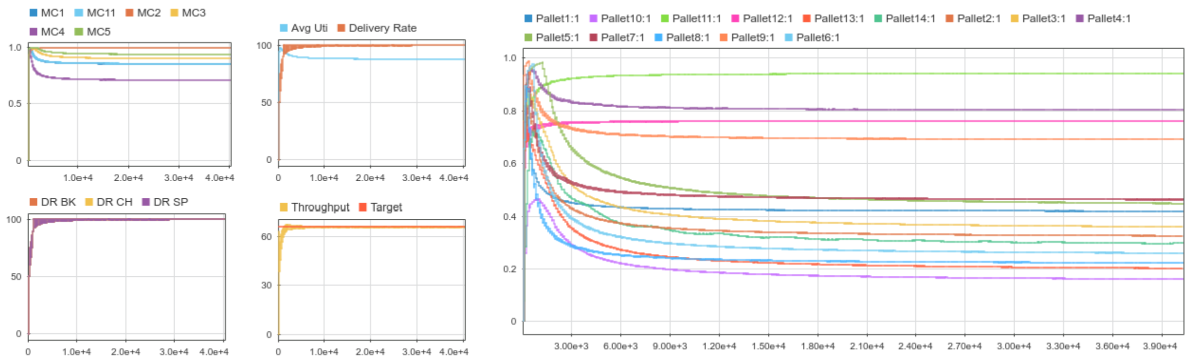


Figure 48 Performance Dashboard (from left to right: machine utilisation, overall utilisation, throughput, pallet utilisation)

6 SIMULATION EXPERIMENT OF FMS

6.1 Setting up a base-model for the FMS

The base-model for the FMS is the baseline for FMS simulation experiment. For the design of the simulation experiment, in the performance measurement or comparison aspect, firstly, the researcher should define a zero point or origin of coordinates from which to start. The base-model works as the baseline or origin of coordinates. Then, the simulation experiment will modify the base-model, after changing any independent variable, and the simulation result can be compared with the performance of the base-model. The base-model is also applied to calibrate performance measurement in a further experiment. More closely the base-model can represent the real case, so a better accuracy and precision of performance measurement can be achieved by the further experiment.

Because of the lack of implementation of the FMS, most of the researchers have found the base-model from the literature. Moreover, because of the limited space of each piece of literature, e.g. the pages of one journal paper, the reported information also limited to the reproduction of the details of the base-model. Even most of the original FMS base-models from the literature are built from theoretical concepts or mathematical hypotheses models. As a result, most of the FMS simulation models in the literature are too abstractive and too focused on the single problem with a myopic interest, and the simulation experiment results can therefore be misleading as the model cannot represent a complete or comprehensive FMS ecosystem.

Therefore, in this research, the first step of the simulation experiment is to build a base-model that can represent a complete FMS ecosystem, which covers all the major problems which would occur during the FMS operation and impact on the manufacturing performance. This base-model would also be validated with a real-world shop floor, afterwards, and the quality of further simulation experiments based on this base-model would then be ensured.

6.2 Initialisation data for FMS base-model

To initialise a simulation, the information below should be prepared:

6.2.1 Data source

The original data are collected from the case study. The simulation model has been firstly built and experimented by the original data then reported in the thesis by nominated data. By removing the sensitive information regarding the company's business concerns, the data set has already been nominated for this research, however, the simulation model is still representing the same behaviours as using original data.

6.2.2 Simulation set-up initialisation parameters

As shown in Table 6, to capture the warmup and stabilisation progress of FMS, the simulation period is set at 40,320 minutes, which is four weeks' time. The simulation period is considered as representing a stable manufacturing system performance (all simulation experiments have been stabilised within four weeks' simulation time) and trying to save on computation cost (system performance would not change significantly after four weeks' simulation time, any additional simulation time beyond this point would be considered as no value-added). The longer the simulation period can avoid the simulation stopped during the manufacturing system warm-up period the longer it can reduce the impact of system errors or random noise. However, the longer simulation period would also lead to more computation cost. The random seed is related to the random number generating mechanism. To reproduce the simulation result, the initial random seed is recorded. As the principle design of the experiment, allowing the random seed to dynamically change in each simulation run would help to reduce system errors for performance measurement.

Table 6 Simulation initialisation parameters

Item	Value	Unit
Simulation period	40320	Minute
Initial Random seed	12345	
Dynamic change random seed	Y	Logical

6.2.3 FMS system initialisation parameters

The overall setting of FMS system initialisation parameters is shown in Table **7**. In this FMS model, 11 machine centres are separated into two types, the 4-axis and 5-axis machine centre. Some operations can only be carried out on 5-axis machine centres. 5-axis machine centres can take whatever 4-axis machine can do, but 4-axis cannot replace 5-axis machine centres for some specific jobs.. There are two types of products produced in this FMS at the same time. The inter-arrive times (the time between each order arriving in the system) for each product are 28 per week and 103 per week. The loading time (time for assembling the part to the pallet), and unloading time are both one minute for each operation. The transportation time for carrying one pallet between the load/unload station and machine centres is one minute. The buffer capacity limitation is not considered at this stage, so it has been settled as infinite. At the buffer of the load station, the dispatch rule is initially defined as FIFO. After choosing which part to process, the selection of the optional machine centre depends on the machine loading rule, which in real-time compares the optional machines, then loads the part to the machine with the lowest utilisation.

Table 7 FMS system initialisation parameters

Item	Value	Unit
Total number of machining centres	11	set
Machine type	2	type
Product in system	2	type
Production volume (product 1)	28	set per week
Production volume (product 2)	103	set per week
Loading time	1	minute
Transport time	1	minute
Unloading time	1	minute
Buff capacity	Inf	
Initial dispatching rule	FIFO	policy
Machine loading rule	Shortest Queue	policy

6.2.4 Product and process data set

As shown in Table 8, there is an index and value for each product and process parameters. For each kind of product, multiple parts are required, and each part may require multiple machining operations. Each operation would require a unique type of pallet which can hold the specific part and fix them on the pallet for a specific operation. For each type of pallet, there may have one or more replicas of instance. For each operation, the required machine type is defined. As mentioned before, the operation assigned to machine type 1 (5 axis machine centre) can only be conducted on type 1 machines, the operation assigned to machine type 2 (4 axis machine centre) can be also be carried out on type 1 machine. In the two machine assignment columns, it shows the operational machines are available for this operation. If there are two operational machines, e.g. at the first row, machine #11 and machine #1 both would both be available for this operation; at the second row, machine #3 is the only option for this operation. The final choice between multiple optional machines would be made at the load station, depending on the machine loading policy.

Table 8 Product and process data set for base-model

Product	Part	Operation	Pallets	No of Pallets	Process Time(mm)	Machine type	Machine assignment	
1	1	1	1	2	65.4	2	11	1
1	1	2	2	2	64.22	2	3	0
1	1	3	3	2	35.47	2	5	0
1	1	4	4	1	50.88	1	1	0
1	2	1	5	1	63.13	2	3	10
1	2	2	6	1	52.45	2	11	0
1	2	3	7	1	93.27	1	1	0
1	2	4	8	1	47.25	2	6	0
1	2	5	9	1	101.37	2	4	1
1	2	6	10	2	27.58	2	5	0
1	3	1	11	2	40.08	1	2	11
1	3	2	12	2	43.48	1	2	0
1	3	3	13	2	32.83	2	5	0
1	4	1	14	1	45	2	4	2
1	4	2	15	1	20	2	4	0
1	5	1	16	1	6	2	6	0
1	5	2	17	1	20	2	6	0
1	5	3	18	1	22	1	1	0
2	1	1	19	1	54.92	2	9	0
2	1	2	20	1	58.25	2	7	0
2	2	1	21	1	31.45	2	8	0
2	2	2	22	1	27.63	2	8	0
2	3	1	23	1	40.67	2	6	0
2	3	2	24	1	8.58	2	5	0
2	3	3	25	1	58.7	2	10	0

6.2.5 Simulation results of base-model

After inputting these data set to the model and running the simulation, and the results can be found in Figure 49, and the critical performance is shown in Table 9.

Table 9 Performance of FMS base-model

KPI	Value	Unit
Thoughput_1	27.73	order per week
Thoughput_2	102.5	order per week
Flowtime_1	462.69	minute
Flowtime_2	160.55	minute
WIP_1	2	set of order
WIP_2	3	set of order
Mean Utilisation	67.42	%
Workload Variation	23.21	%

There are two particular performance that are worth considering, namely, the utilisation of each machine in Figure 50 and the utilisation of each pallet in Figure 51.

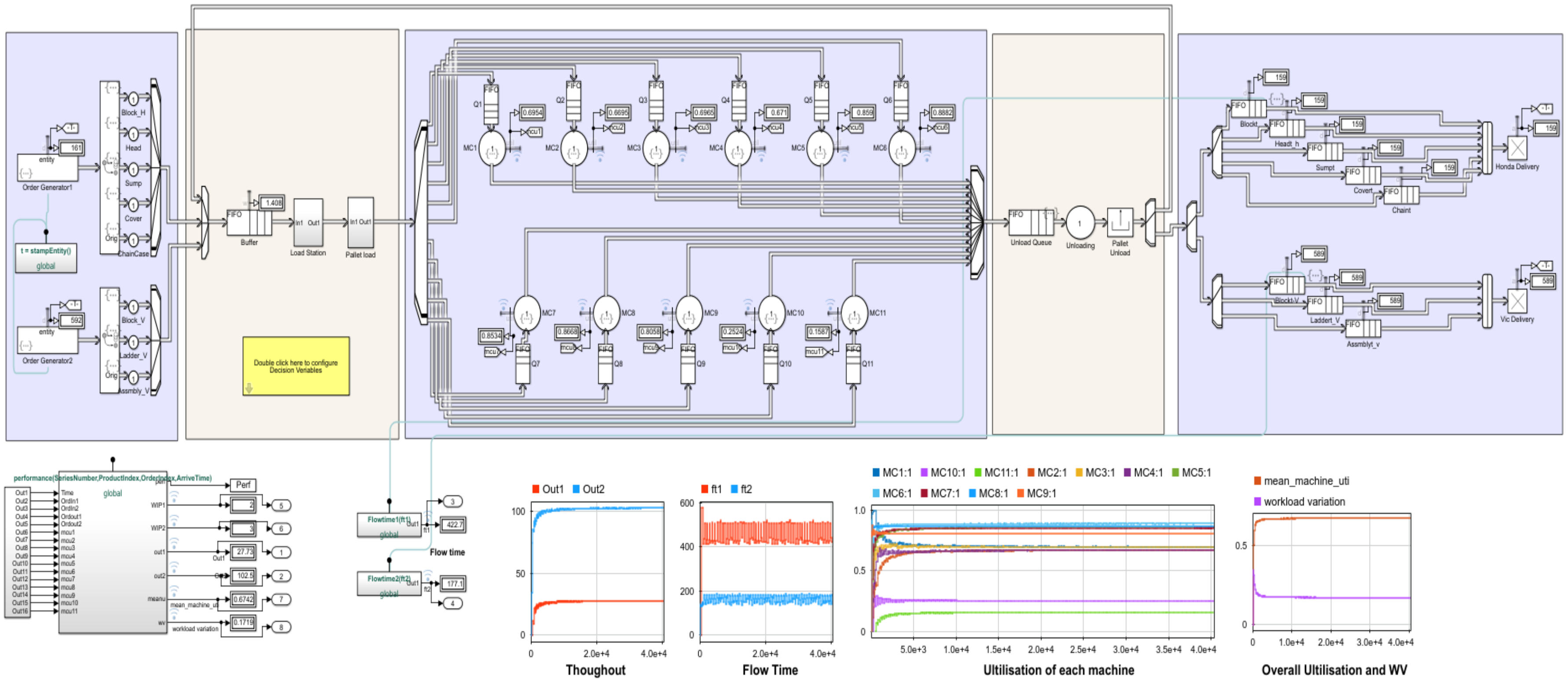


Figure 49 Performance of FMS base-model

The performance of the FMS base-model can give the following insights to the manufacturing manager:

Throughput: for product 1, FMS receive 28 sets of order per week and delivers 27.73 sets of order per week. This means the FMS can adequately handle these orders and achieve satisfactory throughput. The gap between 28 and 27.73 is caused by the WIP still staying in the system. For product 2, the FMS receives 103 and delivers 102.5 set of orders per week; its throughput is also satisfactory.

Machine utilisation: the overall machine utilisation is 67.42%. Based on the author’s experience, this figure is similar to a suitable utilisation rate but still can be optimised to 80% - 90%. Detailed utilisation is shown in Figure 50.

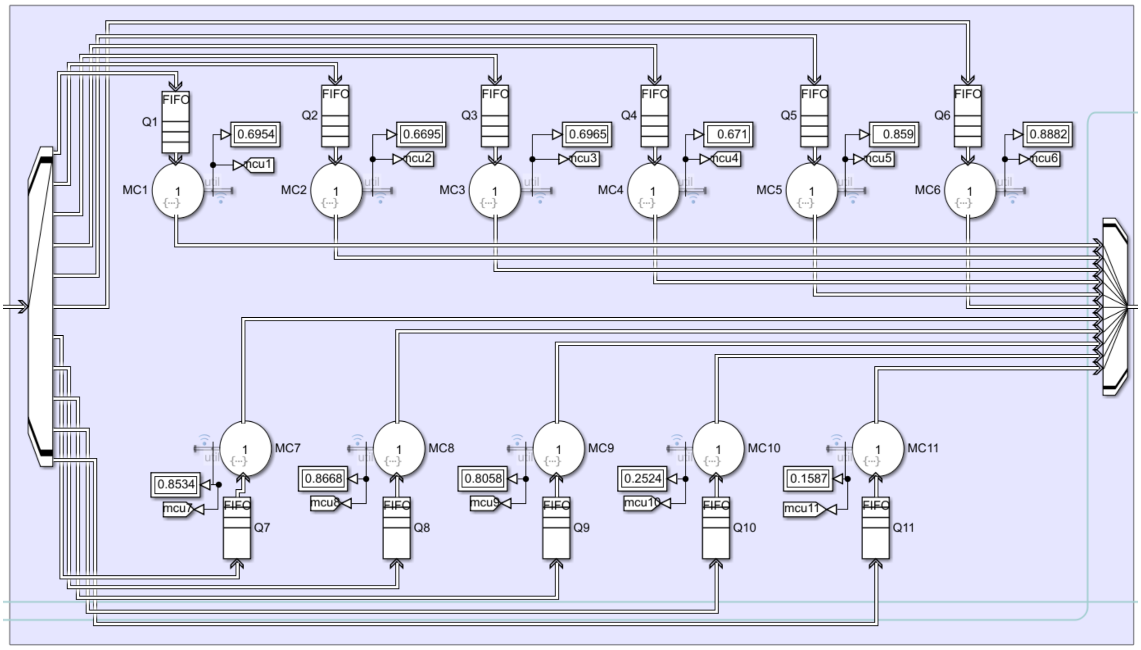


Figure 50 FMS base-model: machine utilisation

Pallet utilisation: the product 1’s overall pallet utilisation is lower than product 2, namely in range 7 %-50 % and 43%-88%, shown in Figure 51. In the other word, product 2’s pallets are more likely to become bottleneck because some pallets reached 88% utilisation.

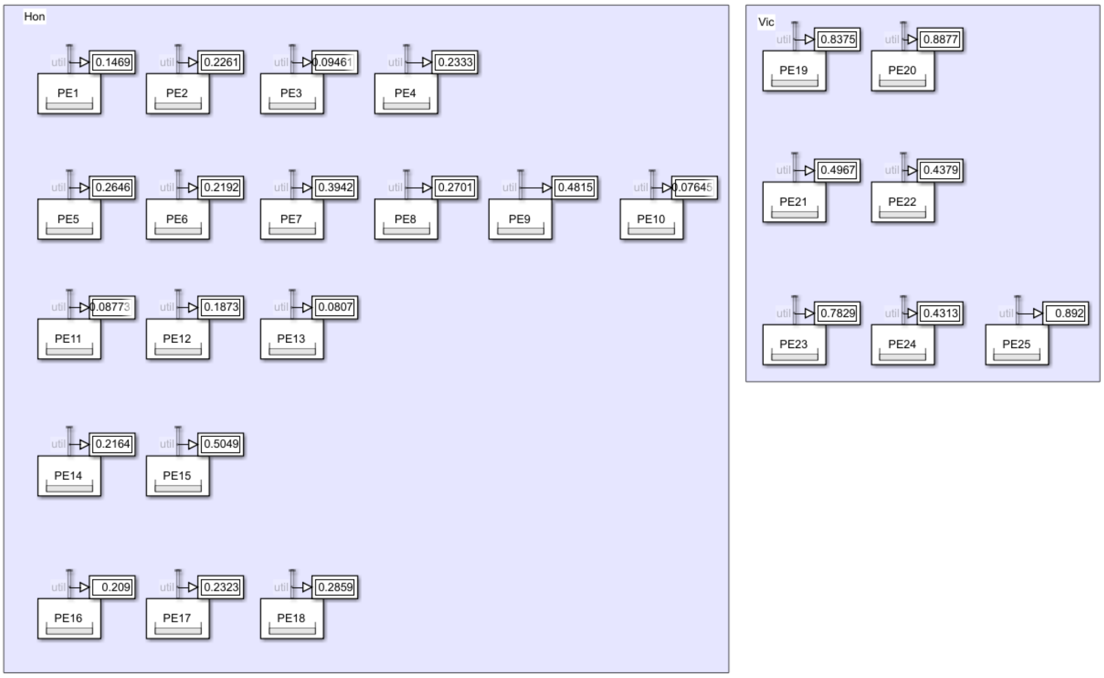


Figure 51 FMS base-model: pallet utilisation

Workload variation: the 17.19% workload variation is an exceptional situation; the work balance of these machines is not satisfactory. It is necessary to investigate the root cause of such a high workload variation, and big potential to improve the workload variations.

Level of WIP: the levels of for both products are remaining at a low level which means the WIP inventory cost is reasonably low and controlled well.

Flow time: having the mean flow time is already a valuable insight for the manufacturing manager; it is the actual manufacturing lead time for delivering one order. Without known the market lead time, or the due time required from the customer, it is hard to judge whether the current performance is sufficient or not.

In summary, the performance of the FMS base-model indicates the current FMS has warmed up and started to carry the average level of operation. There is considerable space to optimise the FMS's operation and achieve maximum productivity.

6.3 Validation of the FMS base-model

The FMS base-model is validated from the industry partner's real-world FMS shop floor. As the base-model is built as hierarchical architecture, the complete model is assembled by each sub-model. For every step of building the base-model, the author has visited and investigated the FMS shop floor. To understand the function and logic of each sub-model, the author has been consulting with the manufacturing engineers, the equipment suppliers, and the operators on the shop floor. After finishing the modelling of each sub-model, the sub-model has been reviewed with manufacturing engineers.

After completing the modelling, the FMS base-model has been firstly compared with another simulation model, which shares the same input data but built using another method and different software, as developed by other researchers (Rybicka, Tiwari and Enticott, 2016b) who worked together in this project. Most of the bugs in the model have been discovered and fixed by this peer review process.

After completing the peer review of two models, the next step is a review with the manufacturing engineer and feeding the operational data from the shop floor to the model, then comparing the simulation result with the real FMS's performance. The FMS base-model has carried out many real-world data validations during the development and implementation of FMS, so base-model has already been well tested and proved to work robustly. Due to the sensitivity of the business information, the detailed data of real-world industry shop floor validations will not be reported in this thesis. The FMS base-model model and simulated results based on real-world data have been compared with real operation performance from the shop floor. Though the original data and results contained business information cannot be presented in the thesis, the industrial partner has kindly provided a feedback as a ground of validation, which attached in Appendix C. Furthermore, the tracking log of the development and validation of the FMS base-model can be found in Appendix Table B-1. In the development log, some sub models and scenarios experiments have not been introduced and reported in this thesis, because they have been developed specifically for the industry case and may not be easy to apply to a general FMS study, or they involved with other professional felids in which the author has less confidence to interpret them to thesis readers, for example, the quality measurement and quality control sub models.

In summary, the FMS base-model has been fully validated with real-world FMS shop floor comparisons. The base-model has been used to predict the manufacturing performance by giving an industrial level data set, and the predicted performances have been proved in line with industry practices. Therefore, this FMS base-model provides a solid foundation for further simulation experiments.

6.4 Experiment 1: Order Input

For the first experiment based on the validated FMS base-model, the objective is to investigate the order input rate's (also called 'inter-arrive time' from the simulation terminology) impact on the system performance. It was expected that the increase of order input rate would lead to an increase of throughput until reaching the maximum manufacturing capacity. In a simplified conceptual manufacturing system, the order input rate would have a linear relationship to the throughput. Realistically, the order input could only keep a linear relationship with the throughput at the low or middle stage; if the order input reached a considerably high level, the manufacturing performance would become unstable, and the throughput would be limited by other factors such as not enough buffer storage.

In the view of manufacturing manager or the business leadership, the maximum throughput is always the first question they want to be answered. Because the maximum throughput would decide how many products can be produced in the specified period, and this would determine how fast the investment can be returned. Usually the first experiment to verify the maximum throughput is to give a 'saturation attack' to the manufacturing system—gradually increasing the order input rate until the manufacturing system being overloaded and blocked.

In this order input experiment, the only changing independent variable is the input rate of product 1; all other variables would keep fixed.

Simulation experiment set-up: this experiment had 50 runs, each run would change the value of the selected independent variable—the order input rate for product 1. The experiment simulation had an order input rate from 0 (no order) to 80 orders per week.

The simulation experiment code is given in 8.5B.2.

The total simulation computing time was 153.957 seconds, and for each run was 3.07913 seconds. This experiment was undertaken on an Intel Core i7-7700HQ CPU @ 2.80GHz laptop. Parallel Computing toolbox has not been applied in this experiment, so it only used CPU single core's computing power. If needed, the computing performance can be improved by another method such as parallel computing which uses multiprocessing or multithreads .

Experiment Result: The detail of the simulation experiment is shown in 8.5B.3.

Overall, the simulated system has not successfully reached the targeting input value—80 orders per week for product 1 while the input rate remain the same for product 2 . The system would be overloaded if the orders input rate of product 1 become higher than 37 orders per week. If give order input rate higher than 37, the manufacturing system would be blocked internally, which means there may be too many WIPs arriving to be able to finish all operations on time.

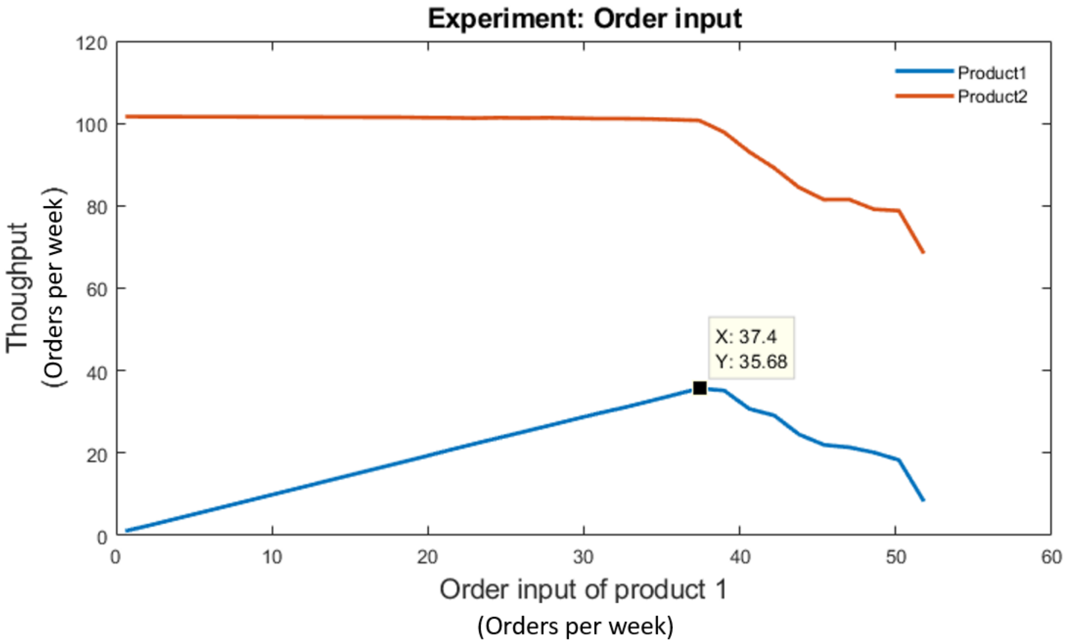


Figure 52 Experiment result: Order input vs Throughput

As shown in Figure 52, the order input rate of product 1 increases as the linear relationship with throughput until reaching the maximum throughput that the current system set-up can achieve, 35.68 orders per week, while the input rate is 37.4 orders per week. Beyond that point, the FMS becomes overloaded, and block appears, thus decreasing the throughput. The overload and blockage would also impact on other products sharing the same FMS facilities, and then decrease the throughput. For example, if the machine is blocked by product 1's WIP, the machine can use neither service for product 2.

For maximising the throughput, the ideal input rate of product 1 would be 37.4 orders per week.

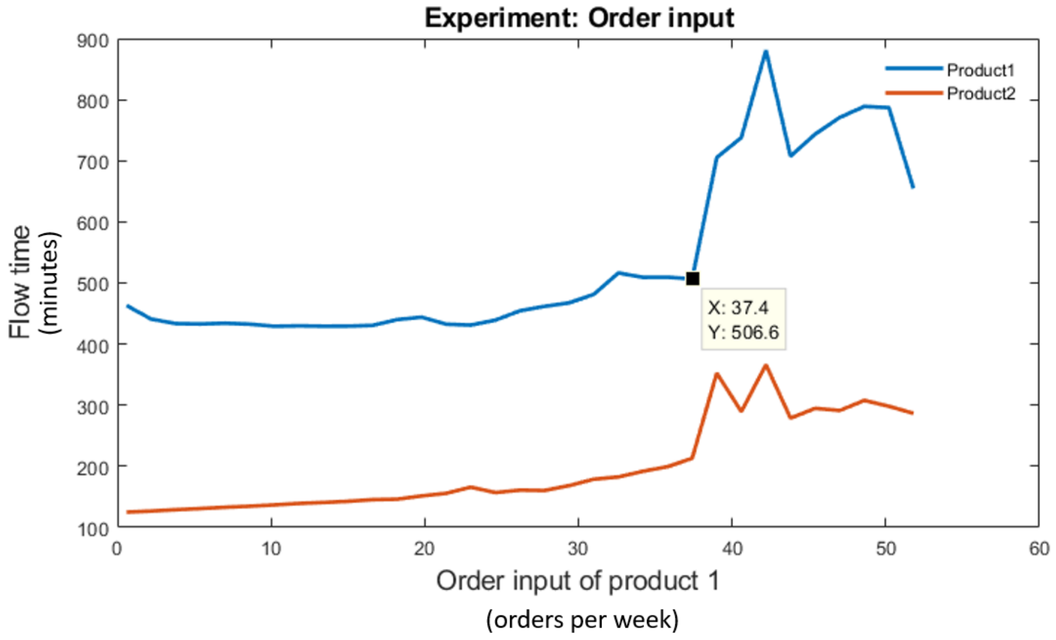


Figure 53 Experiment result: Order input vs Flow time

The flowtime remained at a stable level before the FMS start to overload, as shown in Figure 53. There is a significant increase of flow time after the order input rate reached 37.4 orders per week. The flow time of product 2 also impacted at the same level, even though it started significantly increasing, the order input rate of product 2 never changed.

For minimising the flow time, the ideal input rate of product 1 would be any point below 37.4 orders per week.

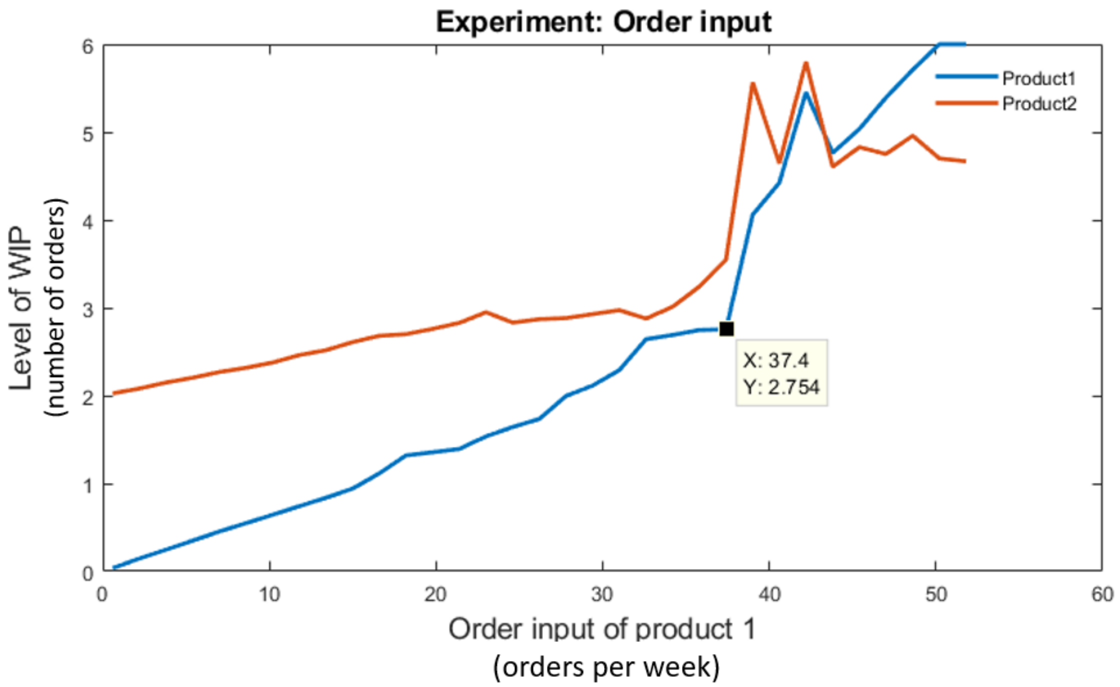


Figure 54 Experiment result: Order input vs level of WIP

As shown in Figure 54, from the level of WIP aspect, the state also changed obviously at the same threshold while product 1 reached 37.4 orders per week. The FMS has limited space to store the WIP, so if the buffer reached the limitation, the WIP would block the flow of material movement, and the overall manufacturing performance would be impacted. The level of WIP product 2 has also been impacted.

For minimising the level of WIP, the ideal input rate of product 1 would be any point below 37.4 order per week.

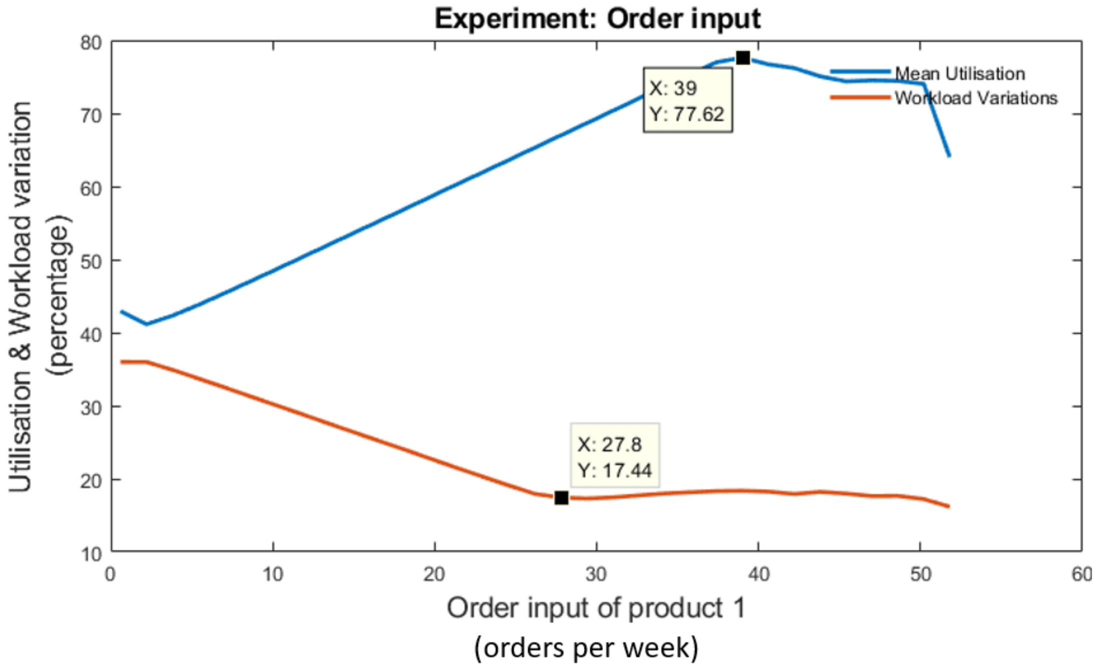


Figure 55 Experiment result: Order input vs Utilisation & Workload variation

As shown in Figure 55, the mean utilisation has been driven by the increase in the order input rate of product 1 until reaching the threshold when the input rate is 39. The maximum mean utilisation is 77.62%. The workload variation has been decreased by increasing the order input until reaching the threshold when the input rate is 27.8; after the threshold, the workload variation could not decrease significantly.

For maximising the overall utilisation and minimising the workload variation, the ideal input rate of product 1 would between 27.8 and 39 orders per week.

The summary of the simulation experiment for input rate: the relationship between the input rate and manufacturing performance has been identified; the threshold when the system state changes significantly has been discovered. The ideal set of input rate which can optimise each individual performance has to be found. The ideal set of input rate to optimise the overall performance has been narrowed down to a certain range.

The hypothesis of 'the increase in order arrival frequency would lead to an increase of throughput' is validated; however, this hypothesis is partly correct. It should be changed to ‘the increase in order input rate would lead to an increase of throughput in a certain range until meeting the thresholds caused by other factors, then the throughput would not increase with the order input rate’.

6.5 Experiment 2: Pallet Capacity

After conducting the simulation experiment for input rate, the thresholds of the system performance have been discovered. However, the root causes of these thresholds have not been fully understood. It is still not entirely clear which factors made the thresholds, or how the factors limited the thresholds at certain levels. Input rate can be one factor, and there may be other factors which have interaction. Therefore, the simulation experiment would test other elements, and verify each mentioned hypothesis. Two questions always have to be repeated during the experiments:

1. Would this element be the factor to impact or limit the manufacturing performance?
2. If yes, how would the factor effect on manufacturing performance? (e.g. is that a linear relationship, is there any threshold)

This experiment is now focused on another element that is rarely considered but is necessary to check, the pallet capacity. Pallet capacity depends on number of replica instance of certain type of pallet.

The author did not cover the pallet capacity in the initial simulation model, and the engineers from the case study also did not require to simulate it at the beginning. While having tried to change every independent variable included in the initial simulation model but still could not improve any manufacturing performance, the author recognised that some critical independent variable might be missing in the initial model, and one of the hidden independent variables is pallet capacity.

In most of the FMS models reported in the literature, the pallet capacity always is ignored or assumed as infinite. However, it has been observed from industry practice, that the pallet used in the FMS is expensive and should be considered.

This is because usually the pallet is designed primarily for a specific machining operation or can only handle specific parts. Therefore, the company usually only purchase the least possible number of pallets, and that would be the ‘bottleneck’ to limit manufacturing performance.

As shown in Figure 51, in the FMS base-model, the maximum utilised pallet is ‘PE23’ with 78.29%, and the minimum utilised pallet is ‘PE13’ with 8.07%. The significant workload variation of pallets has been recognised.

To validate the pallet capacity to check whether it is one of the ‘bottlenecks’, the simulation experiment is set up. The simulation starts at a system overloaded point, where the increase of input rate would not improve any manufacturing performance such as throughput. Then simulate a different number of instance of each type of pallet is simulated.

Aware that the FMS base-model has 25 types of the pallet, if each type has four replica instances, that would be totally 100 pallets that it is not affordable for the company. At this moment, the simulation experiment is targeted to verify the relationship between the factor and result, it not to find an optimal set-up.

In a more realistic case, the manufacturing manager may require finding an optimal set-up; this would need further research. If each type of pallet has at least one, up to four replica instances, for 25 types of pallet there would be 4^{25} , equally to 1,125,899,906,842,624 sets of possible solutions. This would require another method to find optimal set up rather simulate all the possible solutions.

Simulation experiment set-up: this experiment had ten runs, each run changed the value of the selected independent variable—the number of replicas for every type of pallet. The experiment simulated the number of replicas from 1 (no to 10 replicas for every type of pallet).

The order of input for product 1 has been changed from the base-model and fixed at 40 orders per week. The FMS has already overloaded at the start of this experiment.

The total simulation computing time was 50.08 seconds, i.e. for each run was 5.00 seconds. The computing power is as the same as introduced in the previous experiment.

Experiment Result: The detail of the simulation experiment is shown in Appendix Table B-3.

The experiment showed the increase in pallet capacity would increase the throughput (improvement), increase the flow time (deterioration as first insight), increase the level of WIP (deterioration as first insight) and no dominant influence about the mean utilisation and workload variations of the machine centres.

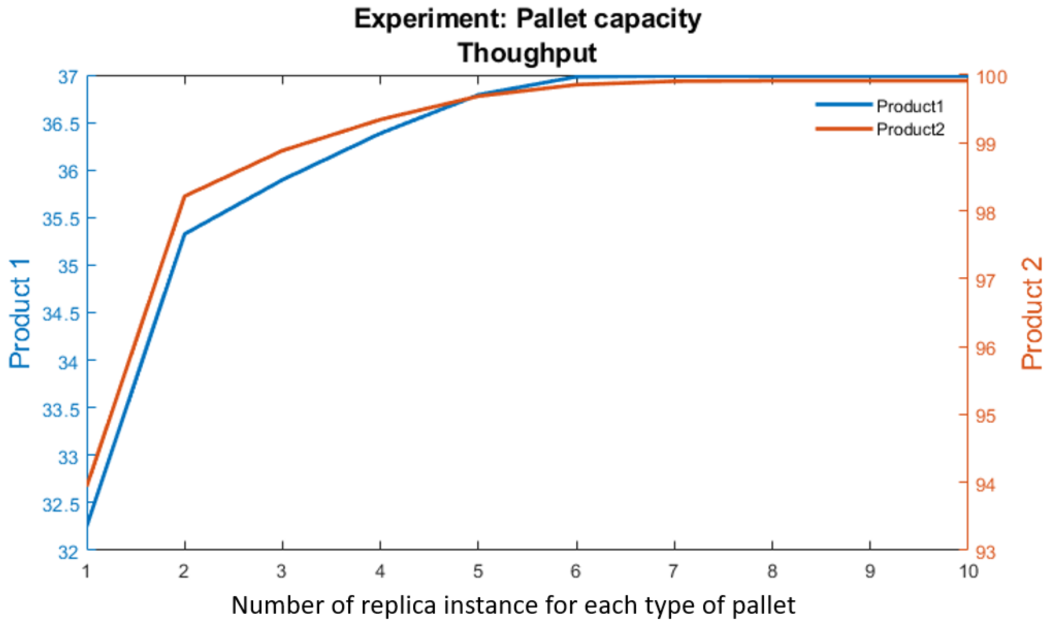


Figure 56 Experiment result: Pallet capacity vs Throughput

As shown in Figure 56, providing additional replica s of the pallet can help the throughput to archive higher levels, especially in the range of one to three replicas. The threshold can be found at six replicas, so giving any more than six replicas would not improve the throughput anymore.

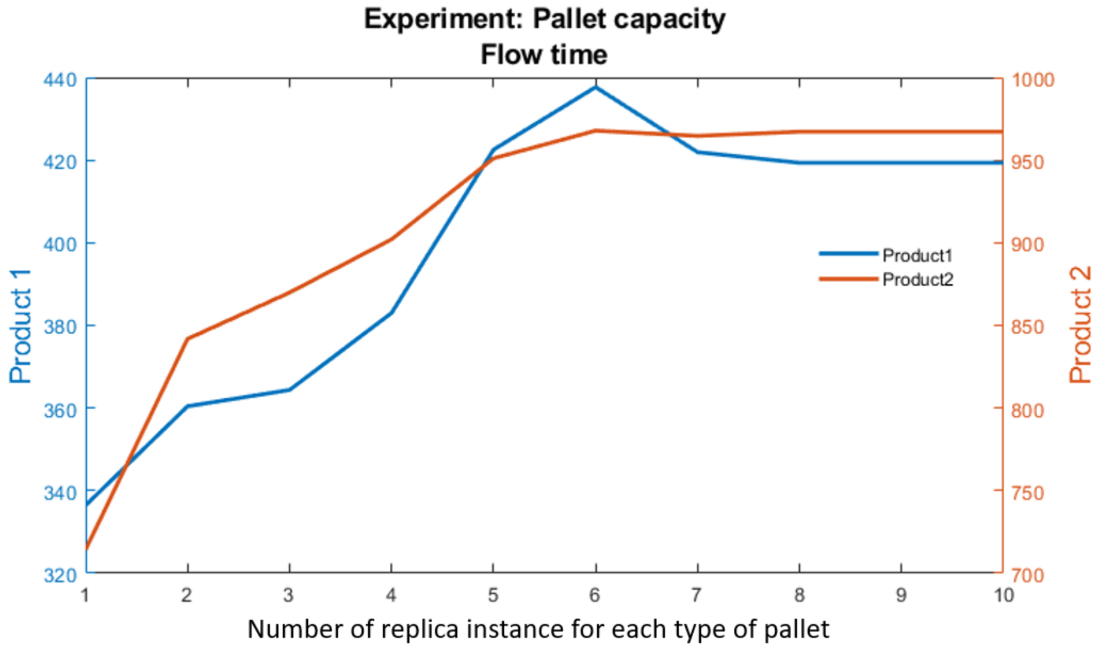


Figure 57 Experiment result: Pallet capacity vs Flow time

As shown in Figure 57, giving more replicas of pallet would increase the flow time. The threshold is at six replicas. It made flow time have a worse performance. But after comparing with the result from the experiment on input rate, the average flow time for product 1 is close to 500 minutes, where here the peak flow time of product 1 is about 440 minutes, still below the average. Though there appeared to be an increasing trend, the actual values of flow time indicated an above average performance. Furthermore, be aware that in the initial set-up of this experiment the FMS started as an overloaded state, so the increase of flow time is in line with the release of more throughput.

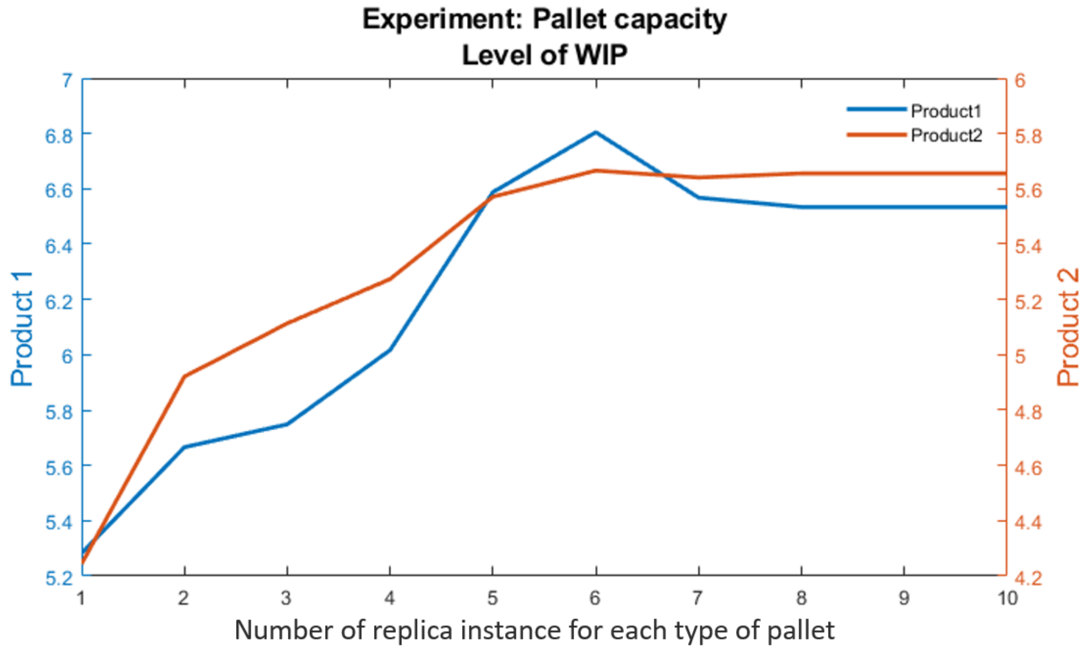


Figure 58 Experiment result: Pallet capacity vs Level of WIP

As shown in Figure 58, the increase of replicas of pallet led to an increase in the WIP level until it reached the threshold at six replicas. Referring to the experiment on input rate, the ideal level of WIP for product 1 is about three orders of materials. In this experiment, all results are above the ideal level. While increasing the replicas of pallets makes a positive impact on throughput and flow time, it appears to have a negative impact on the level of WIP.

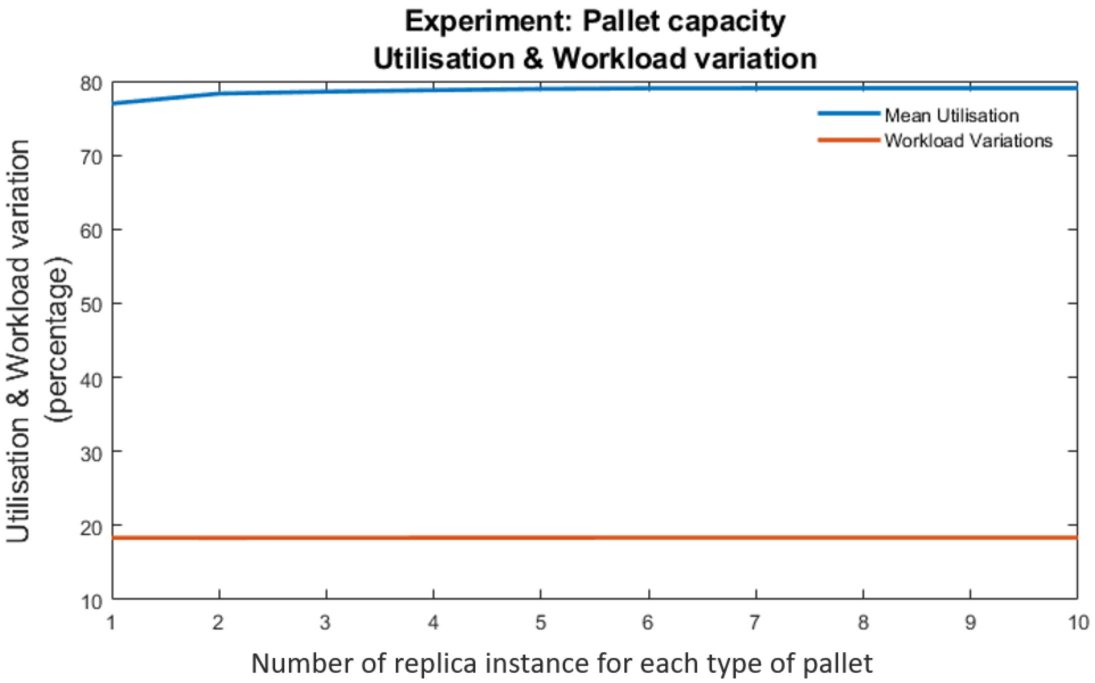


Figure 59 Experiment result: Pallet capacity vs Utilisation & Workload variations

As shown in Figure 59, at the initial set-up of the experiment the FMS starts with an overload state, so it is obvious that while the capacity of the machine centres already reached its limitation, the increasing number of replicas of pallets would not lead to any significant improvement for utilisation and workload variations of the machine centres. This experiment cannot prove all situations when the machines of the FMS are underutilised. Because of the above-mentioned size of the possible solution pool, a full investigation cannot be undertaken only with the simulation method alone, it will have to join with another method such as optimisation algorithms.

Summary of the simulation experiment for pallet capacity: this simulation experiment has proven the hypothesis of ‘Increasing the number of pallets replicas would increase the throughput’ and also identified one side-effect. Pallet capacity has a positive correlation with throughput and flow time, negative correlation with the level of WIP, and no dominant influence for the machine utilisation and workload variations. Moreover, out of these performance indicators used in the simulation experiment, the cost of the pallet itself would make increasing the number of pallets a difficult monetary decision.

Because of the tremendous number of possible solutions to set up the pallet capacity, the simulation method has limited power to process and find an optimal solution. In the current experiment the simulation method conducted the ‘AS-IF’ analysis; in further research, ‘TO-BE’ analysis has to cooperate with other optimisation methods.

6.6 Experiment 3: Operation Sequence

The Assembly Sequence Problem (ASP) is a classic manufacturing operation optimisation study for a traditional manufacturing system, especially with the flow shop scheduling system. If multiple operations are required to produce a finished product, the sequence of carrying out these operations would be limited by individual circumstances, e.g. the physical limitation—the bolt must be put into the hole before fastening the nut, the operation sequence cannot be reversed otherwise the bolt with nut cannot go through the hole any more. It is possible that there are still some operations left, in which the operation sequence can be switched more freely than others, and there would be many possible operation sequences. There are various methods to identify which operation sequence is the optimal solution against the manufacturing performance. The precedence matrix for the operation sequence has always been applied in the assessments.

Linked to the FMS, there are multiple operations to produce one finished product; the initial operation sequence has been introduced in

Table **8**, for instance, for product #1's part #1, there are four operations that have to be undertaken, and they should follow the sequence of operation, i.e. OP 1, OP2, OP3 and OP4. If the operation sequence is available to modify, it would be interesting to investigate whether the ASP from the traditional manufacturing system is also appeared in the FMS. If the operation sequence is sensitive to the FMS, it may be necessary to develop a method to find the optimal operation sequence for the FMS.

The operation sequence problem can be linked to further scheduling problems, especially for online scheduling—determining what operation should be processed next. Dispatching rules would be affected by operation sequence, but only if the operation sequence problem does matter. So, it is such important to investigate whether the operation sequence problem has the same power as it has in traditional manufacturing systems. The operation sequence problem of the FMS should be verified before the approach to the dispatching rule.

As the FMS base-model has 25 operations, if we assume the operations for their own part can be arranged in free sequence, there would another tremendous size of possible solution pools which the simulation method would not be appropriate to find the optimal solution. However, the simulation experiment is good at qualitative analysis. To simplify, this experiment randomly switches the operation sequence, but if the manufacturing performance has not changed with the changing of the operation sequence, then the operation sequence problem would not work for the FMS.

Simulation experiment set-up: The simulation is based on the FMS base-model. This experiment had 30 runs; each run would change the value of the selected independent variable—the operation sequence.

The original operation sequence is in the third column of Table 10. Then for each simulation run, the operation sequence is randomly switched. The generated random sequences are partly shown in Table 10; the original operation sequence column is also listed in the table for comparison. The full list is shown in Appendix Table B-4.

Table 10 Independent variables – example of set of operation sequences

	Original Base-model	Simulation iteration				
		1	2	```	29	30
Operation sequence column	1	1	4	```	4	4
	2	2	3	```	2	2
	3	4	2	```	1	3
	4	3	1	```	3	1
	1	6	3	```	2	4
	2	2	5	```	6	6
	3	4	1	```	1	2
	4	5	2	```	5	5
	5	3	4	```	4	3
	6	1	6	```	3	1
	1	2	2	```	2	1
	2	1	3	```	3	3
	3	3	1	```	1	2
	1	2	2	```	1	1
	2	1	1	```	2	2
	1	2	1	```	2	1
	2	1	3	```	3	2
	3	3	2	```	1	3
	1	2	2	```	2	1
	2	1	1	```	1	2
	1	1	2	```	2	1
	2	2	1	```	1	2
	1	3	2	```	2	2
	2	1	1	```	3	3
	3	2	3	```	1	1

The total simulation computing time was 155.908 seconds, for each run was 5.19693 seconds. The computing power is the same as introduced in the previous experiment.

Experiment Result: The detail of the simulation experiment is shown in Appendix Table B-5. In overview, the experiment results are the opposite of the experience of a dedicated manufacturing system. In the dedicated manufacturing system, each operation is assigned to a single machine and moves in a linear workflow. In a dedicated manufacturing system such as transfer production line, the operation sequence would have an important impact on manufacturing system performance, However, as shown in the experiment result, that operation sequence has a minimal impact on the overall performance.

Figure 60 Experiment result: Operation Sequence vs Throughput

As shown in Figure 60, a change of operation sequence has almost a zero impact on throughput, which the most important Key Performance Indicator (KPI) of a manufacturing facility in many cases. This is one of the most significant differences between the FMS and the traditional dedicated manufacturing system.

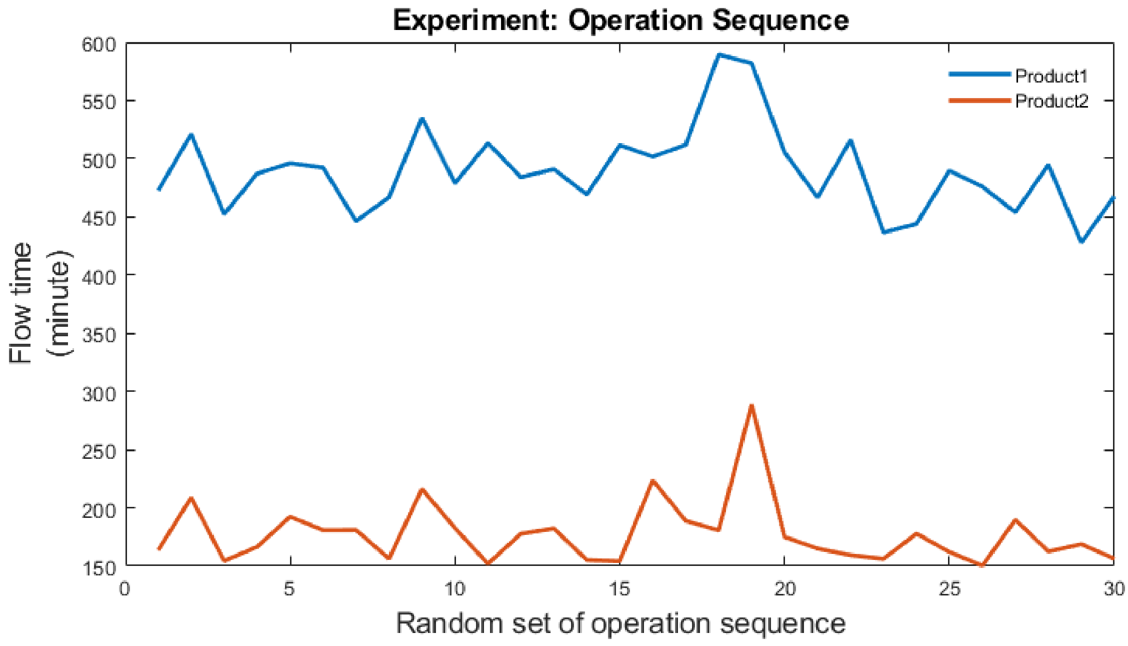


Figure 61 Experiment result: Operation Sequence vs Flow Time

As shown in Figure 61, the change of operation sequence would slightly impact on the flow time, varying from 450 to 600 minutes for product 1, and varies from 150 to 300 for product 2. The variation means optimisation of the operation sequence would still benefit for reducing the flow time.

Figure 62 Experiment result: Operation Sequence vs Level of WIP

As shown in Figure 62, the change of operation sequence has a limited impact on the level of WIP, the variation kept in the range of 1.5 sets of WIP for product 2 and had less than one set of WIP for product 1. Reducing one set of WIP would not be a significant improvement for the product which has a low unit value such as small electronic item but would be a massive saving for a product such as an aeroplane engine. Therefore, the judgement of adding the value of optimising operation sequence is more depends more on the product itself rather than the value from the manufacturing process.

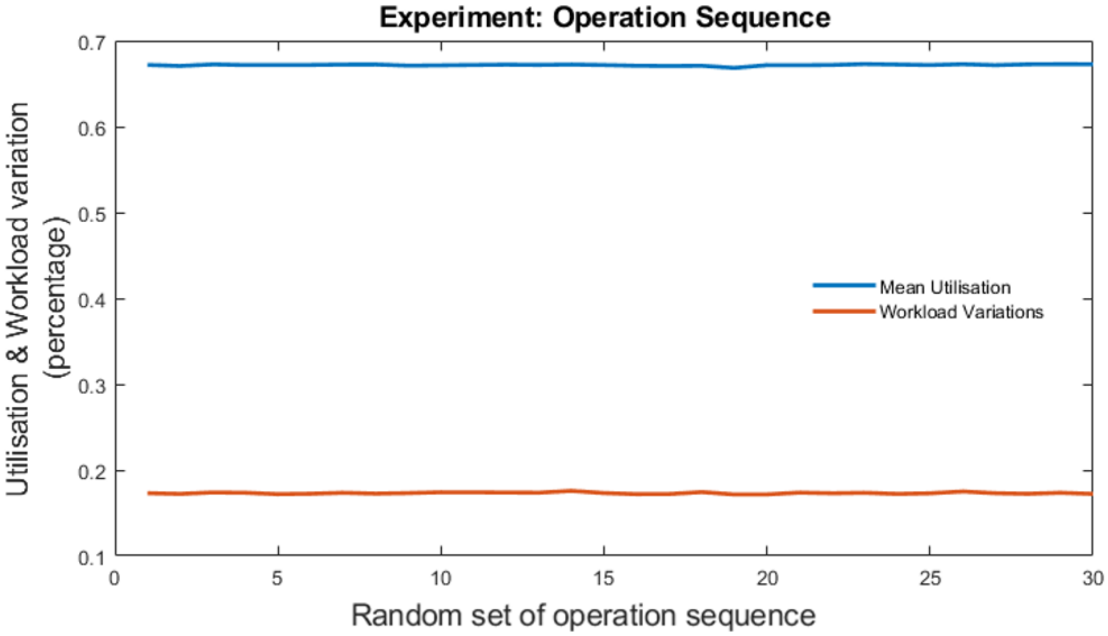


Figure 63 Experiment result: Operation Sequence vs Utilisation & Workload variation

As shown in Figure 63, the change of operation sequence has almost a zero impact on for the overall utilisation and the workload variation of machines. The utilisation of the machine is another KPI of the manufacturing system that would define the return on investment of the machine. As shown, optimising the operation sequence would not bring any benefit from machine utilisation.

From the experiment of the operation sequence, the significant differences between the FMS and a traditional dedicated manufacturing system have been discovered, and the findings are summarised as follows:

- The change of operation sequence would not impact the throughput of the FMS
- The change of operation sequence would slightly impact the flow time
- The change of operation sequence would have a limited impact on the level of WIP
- The change of operation sequence would not impact the utilisation and workload variation of the machines

6.7 Experiment 4: Level of Flexibility

The FMS is designed to release the flexibility of the manufacturing system, thus enhancing the ability to respond to the market change. The general flexibility of the manufacturing system has been defined and segmented into different dimensions, e.g. machine flexibility, product flexibility, and so forth. However, there is no satisfactory standard to quantitatively measure all the dimensions of the flexibility. While the ‘level of Flexibility (LoF)’ has appeared in the research (Yücel, 2005), this phrase is most likely only applied to measure machine flexibility. LoF is the number of alternative machines that can be selected for a specific operation, e.g., for operation 1, there is only one machine available, but no alternative machine, so the LoF for operation 1 is 0; for operation 2, there are machines a, b, c available to carry out this operation, so there are 2 alternative machines. Thus, the LoF is 2.

Machine flexibility is the most important and the root flexibility of the FMS. Without releasing the machine flexibility, it unlikely to sufficiently release extra flexibility, such as routing flexibility. One cost of releasing more flexibility is that it would create more complexity, which challenges the workload of the controlling system. This experiment aims to investigate if increasing the LoF leads to increased manufacturing performance, and whether the higher LoF would benefit that performance.

Simulation experiment set-up: The simulation is based on the FMS base-model. The LoF is the independent variable; the manufacturing performance is the dependent variable; all the rest of the variables are control variables. Because the LoF problem relates to the machine assignment problem, thus, to reduce the influence of machine loading problem, each LoF would have 20 samples of random machine assignment. Five LoFs are covered in this experiment, namely LoF-0, LoF-1, Lof-2, LoF-3, LoF-4.

Except for the influence from the machine assignment problem, the other limitation of this experiment is a shortage of consideration of the mixed LoF. It is unnecessary to unify all operations as having the same LoF. Typically, the basic operations would have a higher LoF, and the high-cost operation would have a lower LoF. This is considering the cost of set-up, and the cost of quality control. However, this experiment is sufficient to identify the overall impact of LoF to the manufacturing system.

To improve the performance, this experiment has changed the customer order of product 1 from 28 (value in the base-model) to 48; the unit is the ‘Job Per Week (JPW)’. It is a hard challenge to ramp up to 48 JPW without releasing the machine flexibility. The design of this experiment is assuming that a higher LoF would achieve higher manufacturing performance such as throughput, so now the setting is going to push this FMS into high pressure. The customer requirement for product 2 remains the same as a control variable. Thus, the passive impacts on product 2 can be observed. Besides, product 2 can be treated as the baseline which is linked to the base-model, and the performance of product 2 is comparable between the current experiment and the base-model.

Based on the above amusements, 100 samples of inputs for the experiment have been generated. For each LoF (0-4), 20 samples of machine assignment have been randomly generated as uniform distribution. Parts of these samples are shown: a sample for LoF-0 is shown in Table 11, a sample for LoF-2 is shown in Table 12, a sample for LoF-5 is shown in Table 13.

Table 11 Sample of LoF experiment input, #4, LoF = 0

Control Variables					Independent Variables				
product index	part index	operation index	pallet index	process time	machine alt1	machine alt2	machine alt3	machine alt4	machine alt5
1	1	1	1	65.4	3	0	0	0	0
1	1	2	2	64.22	3	0	0	0	0
1	1	3	3	35.47	3	0	0	0	0
1	1	4	4	50.88	8	0	0	0	0
1	2	1	5	63.13	5	0	0	0	0
1	2	2	6	52.45	6	0	0	0	0
1	2	3	7	93.27	8	0	0	0	0
1	2	4	8	47.25	1	0	0	0	0
1	2	5	9	101.37	5	0	0	0	0
1	2	6	10	27.58	7	0	0	0	0
1	3	1	11	40.08	4	0	0	0	0
1	3	2	12	43.48	3	0	0	0	0
1	3	3	13	32.83	2	0	0	0	0
1	4	1	14	45	4	0	0	0	0
1	4	2	15	20	2	0	0	0	0
1	5	1	16	6	5	0	0	0	0
1	5	2	17	20	4	0	0	0	0
1	5	3	18	22	2	0	0	0	0
2	1	1	19	54.92	8	0	0	0	0
2	1	2	20	58.25	9	0	0	0	0
2	2	1	21	31.45	9	0	0	0	0
2	2	2	22	27.63	6	0	0	0	0
2	3	1	23	40.67	9	0	0	0	0
2	3	2	24	8.58	7	0	0	0	0
2	3	3	25	58.7	7	0	0	0	0

Table 12 Sample of LoF experiment input, #48, LoF = 2

Control Variables					Independent Variables				
product index	part index	operation index	pallet index	process time	machine alt1	machine alt2	machine alt3	machine alt4	machine alt5
1	1	1	1	65.4	1	6	8	0	0
1	1	2	2	64.22	7	3	7	0	0
1	1	3	3	35.47	4	8	9	0	0
1	1	4	4	50.88	2	5	1	0	0
1	2	1	5	63.13	4	3	8	0	0
1	2	2	6	52.45	1	9	1	0	0
1	2	3	7	93.27	9	5	5	0	0
1	2	4	8	47.25	2	8	2	0	0
1	2	5	9	101.37	3	4	6	0	0
1	2	6	10	27.58	3	6	3	0	0
1	3	1	11	40.08	9	1	1	0	0
1	3	2	12	43.48	5	8	5	0	0
1	3	3	13	32.83	4	2	6	0	0
1	4	1	14	45	8	3	9	0	0
1	4	2	15	20	1	9	1	0	0
1	5	1	16	6	9	1	7	0	0
1	5	2	17	20	7	9	3	0	0
1	5	3	18	22	7	7	3	0	0
2	1	1	19	54.92	5	5	2	0	0
2	1	2	20	58.25	6	9	5	0	0
2	2	1	21	31.45	1	4	9	0	0
2	2	2	22	27.63	4	5	8	0	0
2	3	1	23	40.67	4	1	2	0	0
2	3	2	24	8.58	6	9	6	0	0
2	3	3	25	58.7	8	2	3	0	0

Table 13 Sample of LoF experiment input, #96, LoF = 4

Control Variables					Independent Variables				
product index	part index	operation index	pallet index	process time	machine alt1	machine alt2	machine alt3	machine alt4	machine alt5
1	1	1	1	65.4	5	6	5	7	3
1	1	2	2	64.22	7	2	4	1	5
1	1	3	3	35.47	4	3	6	4	2
1	1	4	4	50.88	8	8	3	6	5
1	2	1	5	63.13	1	7	3	3	4
1	2	2	6	52.45	3	8	5	2	3
1	2	3	7	93.27	9	8	3	6	8
1	2	4	8	47.25	6	7	2	2	2
1	2	5	9	101.37	9	5	5	2	5
1	2	6	10	27.58	8	7	5	4	6
1	3	1	11	40.08	6	4	1	8	2
1	3	2	12	43.48	1	2	8	3	3
1	3	3	13	32.83	3	3	4	1	9
1	4	1	14	45	5	3	3	7	8
1	4	2	15	20	7	2	5	7	1
1	5	1	16	6	6	2	6	7	6
1	5	2	17	20	8	2	6	4	8
1	5	3	18	22	2	7	4	4	1
2	1	1	19	54.92	9	2	7	6	1
2	1	2	20	58.25	9	1	9	4	7
2	2	1	21	31.45	5	8	1	3	9
2	2	2	22	27.63	3	2	2	5	8
2	3	1	23	40.67	7	9	4	7	6
2	3	2	24	8.58	6	4	3	5	4
2	3	3	25	58.7	6	6	9	6	3

Experiment results: All experiment results have been shown in two styles of the chart:

a. Each data point comes from one sample, giving a total of 100 samples. Every LoF would have 20 samples and the same number of data points for the experiment result. It is more convenient to observe the deviation.
b. Each data point comes from the mean value of experiment results within the same LoF, e.g. the first data point stands for the mean value of the experiment result from 20 samples of LoF 0.

As shown in Figure 64, it was challenging to accomplish with the 48 JPW for product 1 with LoF 0; only a few random machine assignments survived below 20 JPW. That demonstrated that in LoF 0, machine assignment is a vital problem to consider. The machine assignment problem is similar to the line balance problem in the dedicated manufacturing system and has a similar level of importance. However, after releasing the machine flexibility to LoF 1, the FMS is able to reach that high production rate, which is almost impossible in LoF 0. As shown in Figure 65, with the further release of flexibility, there is no noticeable improvement beyond the throughput performance at LoF 1; the curve is more flattened from LoF 1 to 4 than LoF 0 to 1. This is because in LoF 2-4, all machines have already been fully utilised, as shown in Figure 70. It can be observed that the deviation of random samples is decreasing while the LoF is increasing and demonstrates that the machine assignment is less than or not relevant in higher LoF. The same trends appeared for both product 1 and product 2. The performance influence of increasing LoF from 2 to 4 is not as effective as from 0 to 2.

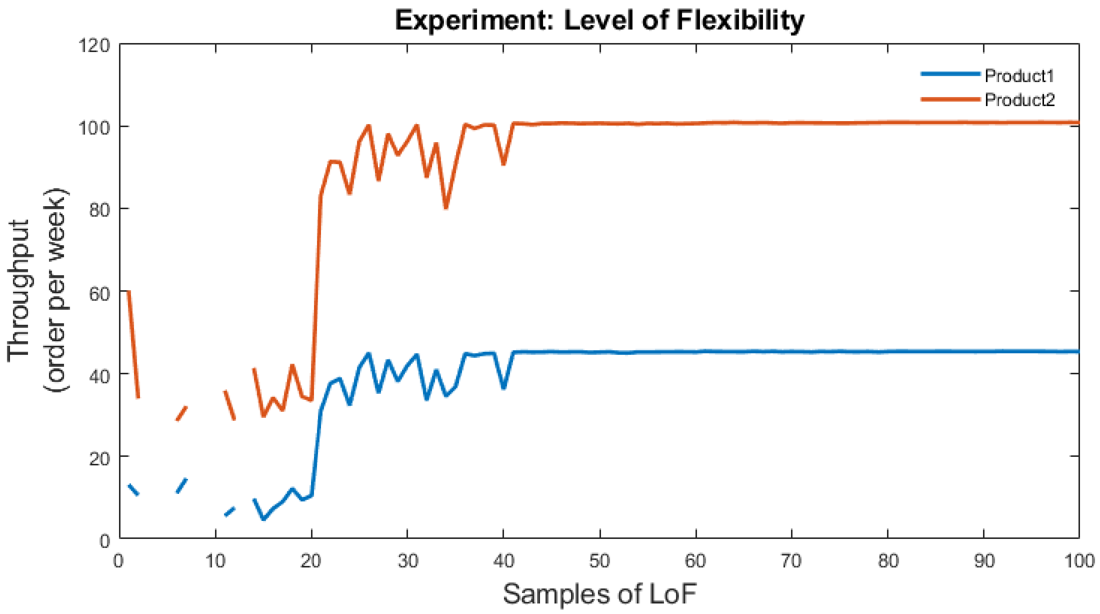


Figure 64 Experiment result: Level of Flexibility vs Throughput, 100 samples

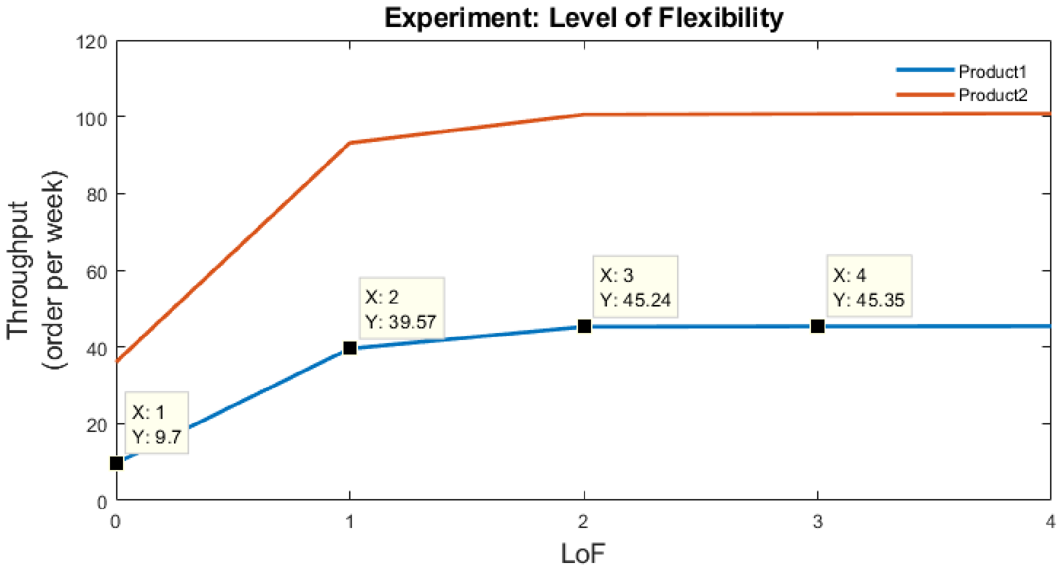


Figure 65 Experiment result: Level of Flexibility vs Throughput, mean values of LoFs

As shown in Figure 66 and Figure 67, the flow time is decreasing with the increasing of LoF. This trend of flow time is not in line with the trend of throughput. It shows that an increase in LoF would significantly reduce the flow time. The deviation is sharply reduced after the LoF raised from 2 to 4. The flow time did not continually reduce while the LoF realised from 2 to 4, because the system has already reached the upper boundary regarding utilisation, as shown in Figure 70. The same trends appeared for both product 1 and product 2; product 2 has more evident and positive impacts than product 1. The performance influence of increasing the LoF from 2 to 4 is not as effective as from 0 to 2.

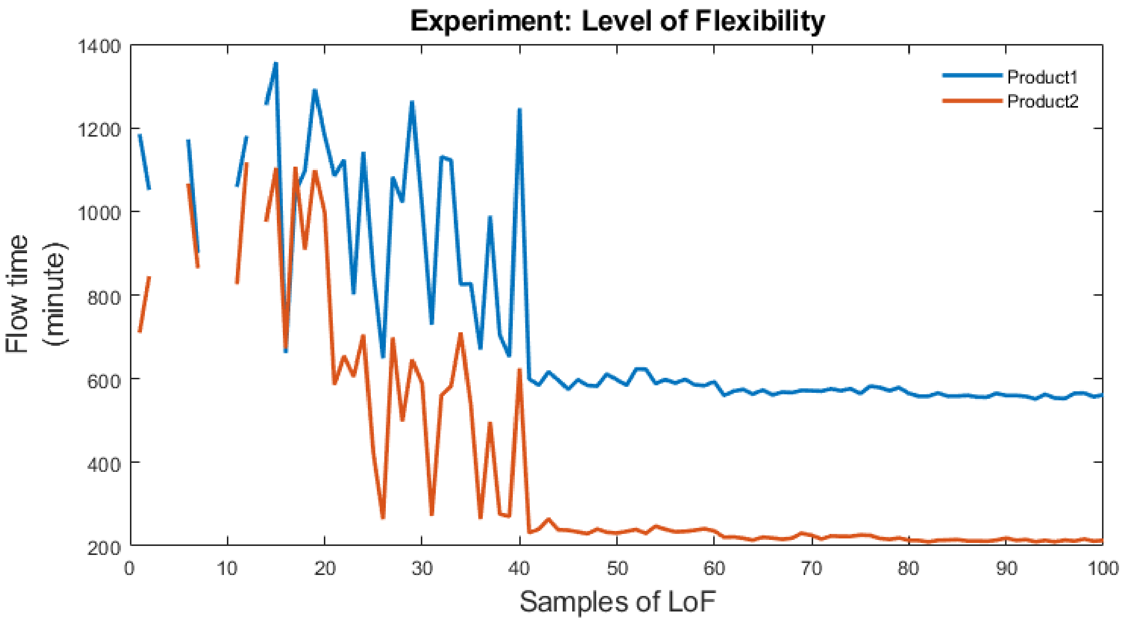


Figure 66 Experiment result: Level of Flexibility vs Flow Time, 100 samples

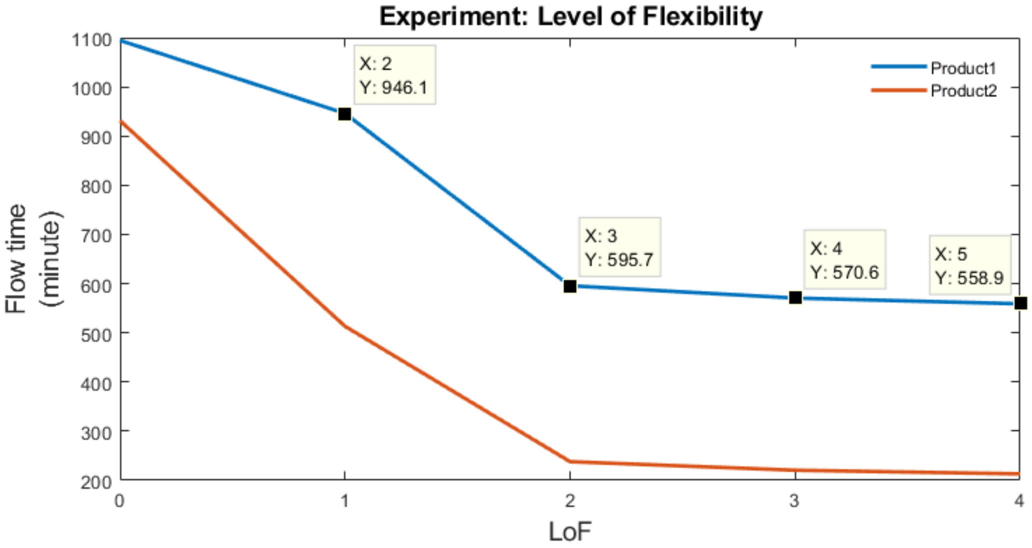


Figure 67 Experiment result: Level of Flexibility vs Flow Time, mean values of LoFs

As shown in Figure 68 and Figure 69, the releasing and increasing of the LoF resulted in a decreasing level of WIP - a positive impact of the manufacturing performance. The deviation of the results also sharply reduced by increasing the LoF. After increased to LoF 2, the deviation is hardly visible compared to the results in LoF 0 and LoF 1. The performance influence of increasing LoF from 2 to 4 is not as effective as from 0 to 2.

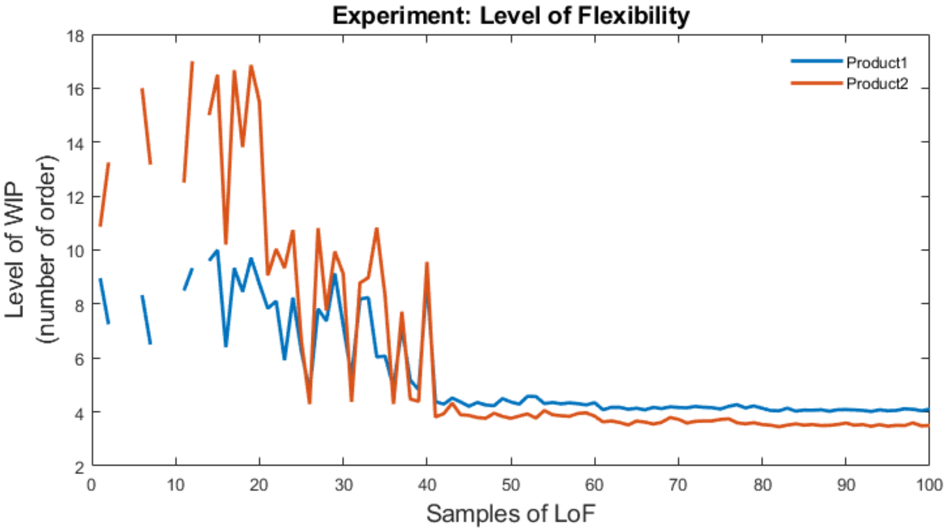


Figure 68 Experiment result: Level of Flexibility vs Level of WIP, 100 samples

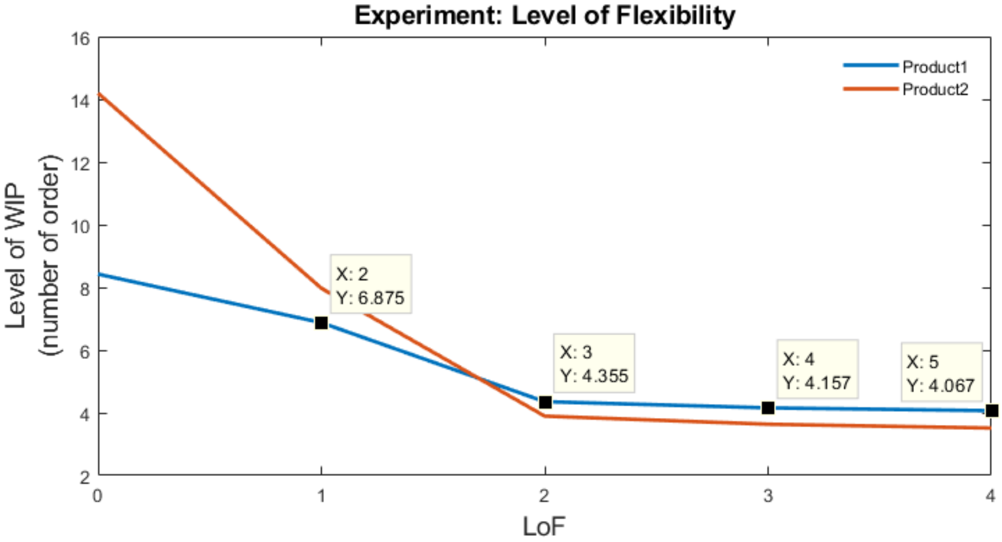


Figure 69 Experiment result: Level of Flexibility vs Level of WIP, mean values of LoFs

As shown in Figure 70 and Figure 71, the experiment results indicated that increasing the LoF leads to an increase of the utilisation of machines and a decrease of the workload variation - both positive impacts. The performance influence of increasing LoF from 2 to 4 is not as effective as from 0 to 2.

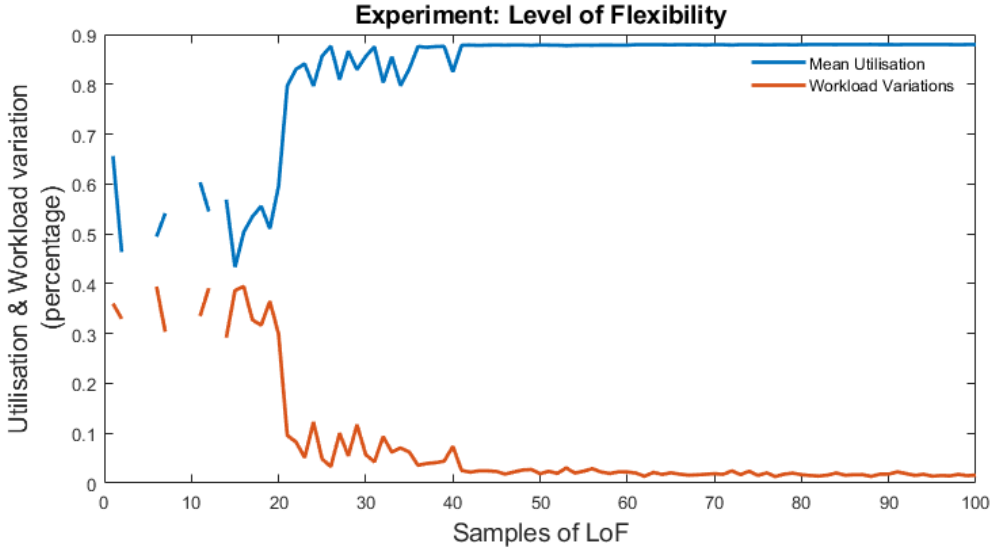


Figure 70 Experiment result: Level of Flexibility vs Utilisation & Workload Variation, 100 samples

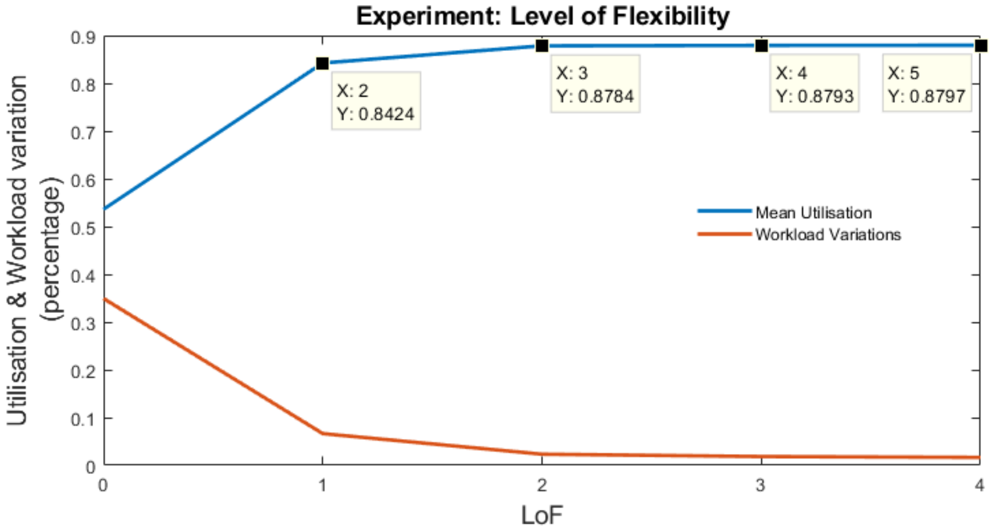


Figure 71 Experiment result: Level of Flexibility vs Utilisation & Workload Variation, mean values of LoFs

The summary of the results and indications from this experiment is as follows:

1. Releasing the flexibility would have a significant positive impact of improving the throughput;
2. Releasing the flexibility would decrease the flow time within an upper boundary, positive impact;
3. Releasing the flexibility would decrease the level of WIP within an upper boundary, positive impact;
4. Releasing the flexibility would significantly improve the utilisation of machines, and reduce the workload variation, positive impact;
5. The deviation of manufacturing performance is highly interconnected with machine assignment in a zero LoF or low LoF. In a high LoF, the impact of machine assignment is much less or not relevant, positive impact;
6. Most benefits can be achieved by releasing the LoF 1 or LoF 2. The performance influence of increasing LoF from 2 to 4 is not as effective as from 0 to 2. The performance improvement of increasing LoF from 2 to 4 is not as useful as from 0 to 2.

6.8 Experiment 5: Machine Assignment

The experiment of the LoF has already demonstrated that the machine assignment would significantly impact on the performance in LoF 0 (dedicated manufacturing) and LoF 1. Furthermore, the machine assignment becomes less relevant or even irrelevant to the manufacturing performance in LoF 3 or higher.

Returning to the machine assignment itself, it is the job of assigning specific operation to a certain machine, or multiple machines. In other manufacturing terms, machine assignment is similar to the line balancing problem, which assigns a specific operation to a particular workstation, thus, reducing bottleneck and workload variation, to achieve optimal lead time and maximum throughput.

Using simulation experiment can validate the manufacturing performance from different machine assignment set-ups, but this is not efficient enough to identify the optimal machine assignment from the complex scenarios that are commonly in the FMS. Simulation experiments can cope with brutal-force search methods, but ideally, the machine assignment should be undertaken by optimisation methods. Simulation lacks a searching ability but can be the bridge for the AI or multiple objective optimisation methods (Chan, Chan and Lau, 2002). In the next chapter, the author will apply an optimisation method to solve the machine assignment in a no, or low Level of Flexibility.

6.9 Experiment 6: Dispatching Rule

The dispatching rule is the most popular topic for all FMS research and this trend has continued for decades. The dispatching rule is directly linked with the scheduling problems of FMS, which is also a famous NP-hard problem that has attracted many researchers from operational research field. There are many studies that have been carried out for dispatching rules (e.g. Mirshekarian and Šormaz, 2016; Negahban and Smith, 2014; Priore et al., 2014).

The general definition of a dispatching rule is one part of a manufacturing policy that defines the time and sequence of the jobs to be launched into the manufacturing system. The dispatching rule can be static which is consistent for the whole production period or can be dynamic, changing based on the current situation. In theory, in each place with a queue, it can apply a dispatching rule as the rules are also linked with queueing theory. To ease the management of the queues or buffers in a production system, the default dispatching rule is Frist-In-First-Out (FIFO). There are several places that are essential to control the dispatching rule:

1. The order entrance: the FMS usually produce multiple types of product at the same time, but the due time or the inter-arrive time of the order from the different product may differ. So, it is possible to set a dispatching rule to release order into the FMS, especially when the manufacturing works under a pull principle with a Kanban system. Normally, the manufacturing system would be a push system.
2. WIP supermarket: After one product order has entered the manufacturing system, logistics would prepare the raw material for each part of the product. Once the raw material has been fed into the system, it would be called WIP during the manufacturing period until it was packaged and

delivered out of the system as an end product. The buffer to hold and manage these WIPs is also called a supermarket. The WIP would be sent to the machines from the supermarket and returned to the supermarket if it has yet to finish all operations. If all operations for this WIP have been completed, it would move to the shipping and packing zone. The WIP supermarket is the most critical place to implement dispatching rules because the WIP would be travelling here most frequently and most of the waiting time would happen here.

3. Quality inspection, repair and rework zone: the quality aspect is an even more complicated topic for FMS than the dispatching rule itself. There can be various set-ups for inspection frequency, or random inspection, the policy of quarantine, rework, repair, scrap and replenish of the parts and material. The re-entrance of a repaired WIP or the replenished raw material can possibly to change or disrupt the concurrent production schedule, thus impact on the overall performance of the manufacturing system. Considering the shortage of available data from a quality aspect, the complex and dynamic nature, and the timeframe of the current study, the author has decided to put the dispatching rule for quality in the future research. As a reminder, the challenge of the dispatching rule for quality should be solved before the full implementation of FMS.

Most of the studies only take account of the dispatching rule problem based on the oversimplified FMS model, without considering the interconnection with other problems of FMS, e.g. LoF. These studies have mainly investigated the dispatching rule at the WIP supermarket. Very few researchers have considered the FMS to be running with a pull principle, which is also linked with Kanban methods.

In this experiment, the author also mainly focuses on the dispatching rules for the WIP supermarket, as it is the most active place for dispatching. The following static dispatching rules have been explored in this experiment:

1. **FIFO** - Frist In Frist Out: the first item arriving at the queue would come out of the queue first;

2. **LIFO -** Last In First Out: the last item arriving at the queue would come out of the queue first;
3. **SPT -** Shortest Process Time: the item with the shortest process time for the next operation would come out first;
4. **LPT -** Longest Process Time: the item with the longest process time for the next operation would come out first;
5. **EDD -** Earlier Due Date: this experiment did not use the term 'due date', but, as EDD is one of the most common dispatching rules, so this rule is still named the EDD. In this experiment, the same function of EDD can be executed, that lets the item which has the longest time staying in the system leave of the queue first; this takes account of the time between the timestamp of this item arriving at the system and the current time;
6. **HLO** - Highest Level of Operation: this is an untraditional dispatching rule, which lets the item which has had the highest level of operation come out of the queue first, e.g. if a part has to take four operations to complete, the part which is going to have operation 3 would come out of the queue before the other part which is just waiting for operation 1. This rule is designed based on the real-life experience from the FMS shop floor, i.e. that the part undergoing a higher level of operation would stand at a higher cost. The manufacturing manager needs to ensure these parts come out of the system more quickly; the longer them stay in the system, the higher the inventory cost and higher risk of damage to them. The manufacturing manager does not wish these 'bombs' to stay in the system any longer than they have to.
7. **LLO -** Lowest Level of Operation: this is opposite rule as HLO, and just considers whether processing the items at the low level of operation would reduce the blocking of the system, thus, to let a higher level of operation exit the queue quicker.
8. **MTNO -** Most Total Number of Operations: This rule would give the priority to the part which has the most complex process would be processed first.

9. **LTNO -** Least Total Number of Operations: As the opposite of MTNO, the part which means the simplest part would be given priority.

Experiment set-up: The simulation is based on the FMS base-model. There are three levels of nested independent variables:

LoF, in this experiment, only considers the base-model which is primarily with a few low-level operations in LoF-1, and the relatively high LoF-2, from the set-up in Table 12;

1. Orders Per Week of product 1, from 23 to 38. It is worth observing the impact of different dispatching rules and related system behaviour under low and high production rate pressure.
2. Dispatching rule: the nine dispatching rules are applied as mentioned above.

There were 108 iteration runs of simulation experiment (2 sets of LoF * 6 sets of Orders Per Week * 9 sets of dispatching rules).

The manufacturing performance is the dependent variable, all the rest of the variables are control variables. The manufacturing performance includes throughputs, flow times, levels of WIP, overall utilisation of machines, and workload variation. The pallet capacity problem is not considered in this experiment, so each type of pallet would have nine replicas, which means the pallet would not be the limitation of the performance.

Experiment Result: the complete experiment results are attached in Appendix Table B-6. Table 14 gives the result from LoF 1 when given 38 orders per week for product 1, while

Table 15 shows the results from LoF 2. To simplify the comparation between these scenarios, the results from Table 16 and Table 17 have been nominated into ranking score of each dispatching rules' performance, while the higher score means the better performance.

Table 14 Experiment Result: Dispatching Rules, LoF=1, JPW=38

Dispatching Rules	FIFO	LIFO	SPT	LPT	EDD	HLO	LLO	MTNO	LTNO
Throughput1	35.26	35.34	35.28	35.24	35.24	35.24	35.26	35.27	35.23
Throughput2	100.26	100.54	100.30	100.27	100.27	100.27	100.21	100.41	100.40
Flowtime1	596.95	579.58	585.28	581.06	581.06	581.06	598.60	587.92	603.29
Flowtime2	286.34	258.06	276.22	277.44	277.44	277.44	286.76	274.56	272.20
WIP1	3.26	3.14	3.17	3.14	3.14	3.14	3.23	3.19	3.29
WIP2	4.59	4.19	4.45	4.50	4.50	4.50	4.61	4.40	4.36
Utilisation	76%	76%	76%	76%	76%	76%	76%	76%	76%
Workload variation	21%	21%	21%	21%	21%	21%	21%	21%	21%

Table 15 Experiment Result: Dispatching Rules, LoF=2, JPW=38

Dispatching Rules	FIFO	LIFO	SPT	LPT	EDD	HLO	LLO	MTNO	LTNO
Throughput1	35.42	35.39	35.37	35.42	35.42	35.42	35.38	35.38	35.32
Throughput2	101.22	101.24	101.16	101.21	101.21	101.21	101.20	101.21	101.22
Flowtime1	520.58	528.17	536.52	524.92	524.92	524.92	532.41	530.81	541.00
Flowtime2	189.07	189.11	191.88	193.50	193.50	193.50	194.20	191.30	190.22
WIP1	2.91	2.94	2.98	2.91	2.91	2.91	2.95	2.91	3.00
WIP2	3.13	3.13	3.18	3.20	3.20	3.20	3.18	3.17	3.15
Utilisation	77%	77%	77%	77%	77%	77%	77%	77%	77%
Workload variation	2%	2%	3%	2%	2%	2%	2%	2%	2%

Table 16 Experiment Result: Dispatching Rules, LoF =1 JPW =38, Ranking Score

Dispatching Rules	FIFO	LIFO	SPT	LPT	EDD	HLO	LLO	MTNO	LTNO
Throughput1	3	9	5	6	6	6	2	4	1
Throughput2	2	9	6	3	3	3	1	7	8
Flow time1	6	9	8	2	3	4	5	7	1
Flow time2	2	9	6	3	3	3	1	8	7
WIP1	6	9	7	1	1	1	4	8	5
WIP2	7	1	9	3	3	3	2	6	8
Utilisation	2	9	5	6	6	6	3	4	1
Workload variation	2	9	6	3	3	3	1	7	8
Total Score	30	64	52	27	28	29	19	51	39

Table 17 Experiment Result: Dispatching Rules, LoF =2 JPW =38, Ranking Score

Dispatching Rules	FIFO	LIFO	SPT	LPT	EDD	HLO	LLO	MTNO	LTNO
Throughput1	9	5	2	6	6	6	3	4	1
Throughput2	9	8	5	2	2	2	1	6	7
Flow time1	6	5	2	7	8	9	3	4	1
Flow time2	8	9	1	3	3	3	2	6	7
WIP1	9	2	3	6	6	6	5	4	1
WIP2	9	8	1	2	2	2	5	6	7
Utilisation	9	4	2	6	6	6	3	5	1
Workload variation	8	9	4	1	1	1	5	6	7
Total Score	67	50	20	33	34	35	27	41	32

The overview of these results is as follows:

- In general, the impacts from different dispatching rules are not significant for the overall performance of the FMS. From the literature, the popular trend of the FMS research is focused on the dispatching rule topic, in which many researches assumed the dispatching rule would make a meaningful impact on the overall manufacturing performance. This experiment showed the selection of the dispatching rule is not the critical decision for the manufacturing manager of the FMS - not as critical as the LoF.

The dispatching rules have hardly any noticeable difference regarding the impact of manufacturing performance under low production pressure which means a low given number of Orders per Week. As shown in Table **14**, the significant difference is about the flow time.

- The best overall performance is the Frist In First Out dispatching rule, and the worst is the Shortest Process Time dispatching rule.

6.10 Experiment 7: Machine Loading

In this research, the machine loading rule is the policy to select one machine from many optional machines for one operation to undertake.

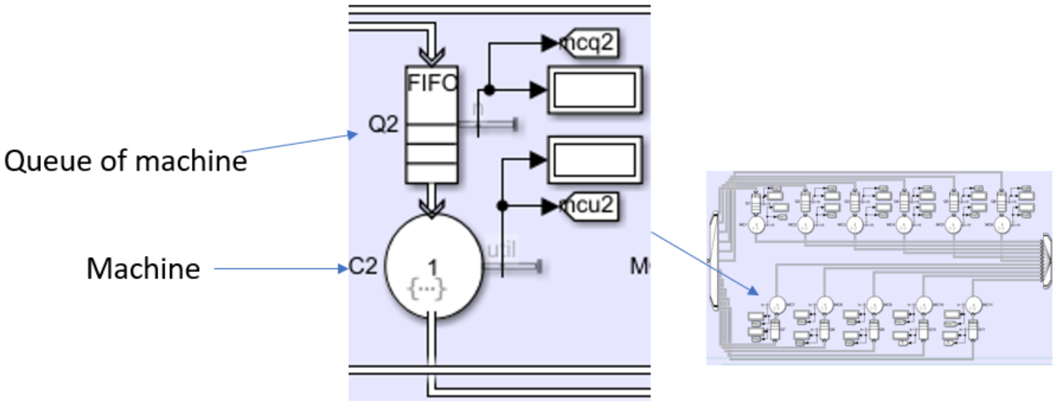
The machine loading rule is one topic that is not well defined in the literature, and has always been either ignored or merged with the dispatching rule problem. The machine loading rule is one of queuing problems or scheduling problems, similarly to the dispatching rule, but the difference between the two is their objects. Dispatching rule's object is the product or material, which support the decision of selecting the next product to process based on the attributes of products. However, the machine loading rule's object is the machine, which supports the decision of selecting the next machine to use based on the concurrent attributes of multiple machines can be selected in FMS. Machine loading rule does not exist in dedicated manufacturing system or transfer line, because the product would move in a linear pipeline, and there is no need to select one machine between many. In FMS, both dispatching rule and machine loading rule can be proactively decided before production and be static during the production period. Dispatching rule is likely to be dynamic that may change during the production period depending on occurred events. Machine loading rule is not likely to be dynamic.

The machine loading rule has fewer listed policies than the dispatching rule, therefore the following machine loading rules are considered in this research and will be carried forward into an experiment:

1. **LU** - Least Utilisation: Select the optional machine which has the least utilisation at the decision making moment. For example, on 17 Sep 2018

11:25:00, the FMS needed to select one machine to process operation A; there are three machines that can process operation A: machine 1 is at 60%, machine 2 at 70%, machine 3 at 30% utilisation; by the least utilisation rule, machine 3 would be selected for the operation A. Be aware, that utilisation is one aggregated data based on the historical logs. The change of utilisation may be slower than what happened in the previous seconds.

2. **SQ -** Shortest Queue: The machine can process one part at a time or can process a batch of parts at one shot. As shown in Figure 72, usually there is one buffer or temporary storage for each machine; the size would greater than or equal to the batch size of the machine but would be smaller than the WIP supermarket, which is more appropriate to store and manage the WIP. This rule would compare the number of parts in the queue for each machine and select the one with the least. If there are multiple machines (as a collection) with the same number in the queue, and these machines have shorter queues than the rest, it would apply a random selection among the collection.



One machine

All machines

Figure 72 Example of machine and queue of machine

3. **LAPT -** Least Average Process Time: Sum of the process times for parts departing the machine divided by their total number. Process time is the

duration between the machine entry and exit of a part. Average wait time would be impacted by the variety of the operation conducted on the machine. It is also an aggregated data.

4. **RAND -** Random: Randomly select one machine between the optional machines for the coming operation.
5. **RRBN -** Round robin: Select the machine between the optional machines literally according to the order of the machine index.

Set up of the experiment: The simulation model is based on the FMS base-model. There is no machine loading problem in LoF 0, as the experiment used the set-up for LoF 2 from Table 12. To observe the ability to handle the pressure, the order per week of product 1 has increased from 28 to 38; product 2 remain the same. The pallet capacity problem is not considered in this experiment, so each type of pallet would have nine replicas, which means the pallet would not be the limitation of the performance. The independent variable is the machine loading rules, and the dependent variables are the manufacturing performance including the throughputs, flow times, level of WIP for two products, and the overall utilisation, workload variation for the machines.

Experiment Result: As shown in Table 18, the differences between these machine loading rules are significant.

Table 18 Experiment Result: Machine loading rules

	Least Utilisation (LU)	**Shortest Queue (SQ)**	**Least Average Process Time (LAPT)**	**Random (RAND)**	**Round robin (RRBN)**
Throughput1	3.79	36.58	3.96	16.47	20.43
Throughput2	53.10	102.60	55.40	65.86	72.65
Flow time1	658.71	511.85	1,310.69	1,231.17	1,061.95
Flow time2	897.72	198.43	1,640.10	413.34	232.77
WIP1	9	3	3	8	8
WIP2	14	3	25	16	16
Utilisation	na	77%	na	na	na
Workload variation	na	1%	na	na	na

The summary of the experiment result for machine loading rules are as follows:

- Only the ‘Shortest Queue (SQ)’ survived from the whole simulation period - 1 month simulated production time. All rest rules made the FMS break down before the end of the target period, as it overloaded to a particular machine, and blocked the whole system.
- ‘Least utilisation (LU)’ and ‘Least Average Process Time (LAPT)’ would usually be the first rules from the production manager to try, but both of them failed in delivering the required performance. After reviewing the timeframe of the simulation run, it showed the selected machine (either LU or LAPT) had been assigned too many operations in the queue before the completion of its current operation. The aggregate attribute would only change after the operation was completed, and the time taken can be too long enough to make a decision in time. This experiment has proven that aggregate values are not suitable for the real-time decision making.
- Both the ‘Random’ and ‘Round Robin’ rules failed because of a shortage of consideration of current machine states. They can randomly give one machine too many jobs to do which results in overload and blockage. These two rules cannot optimise the utilisation of machine capacity.

- ‘Shortest Queue (SQ) is the only machine loading rule considering the real-time machine states and trying to optimise the utilisation of all machines. It is a highly recommended policy, but to support this rule, it would need real-time data from the machines, which would be a requirement of the manufacturing information system to achieve.

6.11 Summary

This chapter introduced the modelling of FMS using a case study, which contains multiple manufacturing problems in the same model. By testing multiple problems using one model, the interactions between problems and the impact of each problem on overall performance have been discovered. The FMS simulation model has been validated on the real-world shop floor.

The author has proposed hypotheses based on FMS manufacturing problems and designed a series of simulation scenarios to investigate the impact on FMS overall performance. The experiment results have found the distinguish characteristics between the FMS and dedicated manufacturing systems.

The experiment has explored and validated the hypotheses proposed in Table 5, the results are summarised corresponding to each hypothesis:

1. **Increasing the order input rate would lead to an increase of performance: Partly True.** The experiment result has indicated that the increase of order input rate would increase the throughput until it reaches the threshold value. If the order input rate is higher than the threshold value - the more the order input, the worse the performance. The threshold value would depend on many other factors such as the order input rate of other products, machine capacity, pallets capacity, level of flexibility and so on; this needs further validation beyond simulation models, such as shop floor implementation or physical mock-up model.
2. **Increasing the number of pallets would increase the performance: Partly True.** The experiment has indicated that increasing the number of pallets would benefit performance. Not enough pallets can become the bottleneck of the whole system. The minimum number (lower boundary)

of pallets is an essential factor to release the productivity. In this experiment, all operations have been set with an equal number of pallets in order to simplify the experiment scenarios. In a practical implementation, the minimum number of pallets for each operation to maximise the productivity should be found to minimise the cost of the pallet at the same time.

3. **Operation sequence would lead to substantial impact on performance: False.** From the experiment, change of operation sequence has nearly no impact on key performance indicators such as throughput, utilisation and workload variation. Operation sequence has slight impact on the flow time and level of WIP. Optimising the operation sequence is still valuable for the manufacturer that needs to restrict the flow time and level of WIP on the shop floor.
4. **Higher LoF gives higher performance: Partly True.** As observed from the experiment, releasing LoF brings a crucial improvement to all dimensions of manufacturing performance, and presents the benefits of an FMS. Even so, after a threshold value, a higher LoF would not bring greater performance improvement but would incur more cost. The threshold value found in this research is LoF 3. At LoF 3, the system can access all benefits from releasing the flexibility. The threshold may differ for another FMS with a different set-up.
5. **Better machine assignment can increase performance: False.** Assigning the machine to each operation is a critical task for a dedicated manufacturing system. However, after reaching a higher LoF, for example LoF 3 in this research, machine assignment is irrelevant for performance improvement; however, machine assignment is still critical for a low LoF. A functional FMS should be able to realise flexibility and machine assignment would not impact on the overall performance on high LoF.
6. **Dispatching rule would impact on performance: False.** The dispatching rule has a minimal influence on the manufacturing performance and only slightly impacts on the flow time. This result is

against the popular trend, i.e. many optimisation researches are trying to improve dispatching rule. The unexpected result is caused by: 1, the dispatching rule can be applied to many places in the FMS - in some literature, there is no clear definition of the dispatching rule, and it may be confused with machine loading rule; 2, if a research uses an oversimplified model which only represents an individual problem without considering the interaction among all elements in FMS, the results may not be accurate. This cannot be fully validated by only using simulation and needs further validation beyond simulation.

7. **Machine load rule would impact on the performance, True.** This research has broken down the scheduling problems and differentiated between the dispatching rule and machine loading rule; the former addresses ‘select which part next’ and the latter solves ‘select which machine next’. The machine loading rules based on real-time data are better than rules based on aggregated or historical data. Collecting real-time data and reacting based on real-time data require further development of the control system for the FMS.

7 MULTI-OBJECTIVE OPTIMISATION TO FMS

In this section, the author introduces a method to apply multi-objective optimisation to solve FMS production scheduling problems, using Genetic Algorithm (GA) working with Discrete-Event Simulation (DES).

7.1 Introduction

MacCarthy and Liu (1993) state that a FMS is a production system in which groups of numerically controlled or computer numerically controlled machine tools and an automated material handling system (MHS) work together under computer control. Stecke (1985) identifies four hierarchical levels in which decision problems in an FMS are partitioned: design, planning, scheduling and control problems. Scheduling decision problems of FMSs continue to attract the interest of both the academic and industrial sectors (Joseph and Sridharan, 2011).

In this thesis the author focuses on the scheduling problem of FMS and selected the key components to be considered with high priority and high complexity.

7.1.1 Scheduling problem in FMS

Production scheduling has been one of the most popular research topics in operations research, management science, and artificial intelligence. The goal of production scheduling is to effectively utilise the available resources to achieve some organisational objectives such as minimising the average time that jobs have to spend in the system and minimise penalties caused by late deliveries (Nguyen, Mei and Zhang, 2017).

In the complex and dynamic environment of FMSs, the solving the production scheduling problem is more crucial to managing well the whole system and delivery expecting performance well, at the same time, it is also an NP-hard problem that is difficult to handle it straight forward.

Production scheduling problem is a combination of various rules and decision-making points, which here is more closed to the Flexible Job Shop Problem

(FJSP). The FJSP focuses on the assignment of the operations to machines, and determine the sequence of the operations on all machine, in order to achieve the optimisation criteria (Xia and Wu, 2005).

Key components of the FMS scheduling problem:

- **Machine loading** deal with the assignment of various resources (machines, tools, fixtures, pallets, etc.) to the operations of different part types that are already planned for production in a given planning horizon. (Tiwari and Vidyarthi, 2000).
- **Dispatching rule or priority rule** is used for sequencing tasks in a buffer queuing problem. At the moment when a sequencing decision needs to be made, dispatching rules will prioritise the jobs in the queue of a considered machine. Then, the task with the highest priority is processed next.
- **Operation sequencing and routing problem** determine the successive order to process a group of operations. It can be static or dynamic and can be switched or optimised, which depends on the precedence relations defined by nature of the product. The decision on machine loading assignment and operation sequence impact on routing rules, which are usually investigated when dealing with flexible job shop scheduling problems. Routing problems appear when routing flexibility is allowed (Priore et al., 2014).

The most common optimisation objectives of FMS scheduling problem are:

- Maximising system throughput
- Maximising system/machine utilisation
- Minimising workload variation of machines
- Minimising mean flow time
- Minimising work in progress (WIP) inventories
- Minimising tardiness
- Minimising costing of manufacturing capacities (machine, tools, pallet, fixture, AGV, etc.)

7.1.2 Challenge for optimisation

Though there are decades since the concept of FMS has been introduced, there are still very few of commercial practices that have appeared in the industry due to the intrinsically complexity of the FMS. It has been recognised that it is impossible to manage the complex nature of FMS efficiently by the traditional analytics methods. The academic research has introduced a number of the traditional and untraditional optimisation methods such as non-linear programming, heuristics algorithms, and knowledge-based methods such as machine learning. The research field kept to the advancement of the optimisation method design space, but it is a pity that most of these works are weak on the problem domain, which developed based on the conceptual and quite simplified literature case studies focused on local and unilateral optimisation objectives, difficult to apply to FMS implementation directly. A common acknowledgement by the researchers, is that the design of the optimisation for FMS highly relies on the understanding of the problem domain, and how to represent the problem for an optimisation programme. It is hard for a mathematical formulation of the problem representation scheme to handle the complex interrelationship of the sub-problems and the dynamics of the flexibilities of FMS.

The main challenges of the optimisation research of FMS are summarised as follows:

- Acquiring the experience and knowledge from a practical case study which can provide a comprehensive understanding of the whole FMS eco-system problem domain;
- Missing consideration of the impact of the interaction between sub-problems during the optimisation design that may lead the optimisation result to become meaningless to the overall performance improvement of FMS;
- Handling the massive amount of decision variables and their constraints in problem representation scheme, keeping a good balance between the accuracy of the fitness evaluation and the efficiency of the computation.

7.2 Proposed method

In this section, the author proposes a method to apply multi-objective optimisation to solve FMS production scheduling problem, using GA is cooperation with DES.

This work will split the mechanisms of the problem representation scheme and the optimisation solver and operate the optimisation procedure on a shared platform and workspace. The separation

- Makes it ease to handle the massive and complex decision variables and their constraints of the FMS
- accurately presents the discrete behaviours and dynamic performance of the FMS
- efficiently operates the optimisation solver with lower computational cost
- enables changing or modify the optimisation solver or problem representation scheme with minor reset work

The structure and the main workflow of the proposed optimisation method is shown in Figure 73:

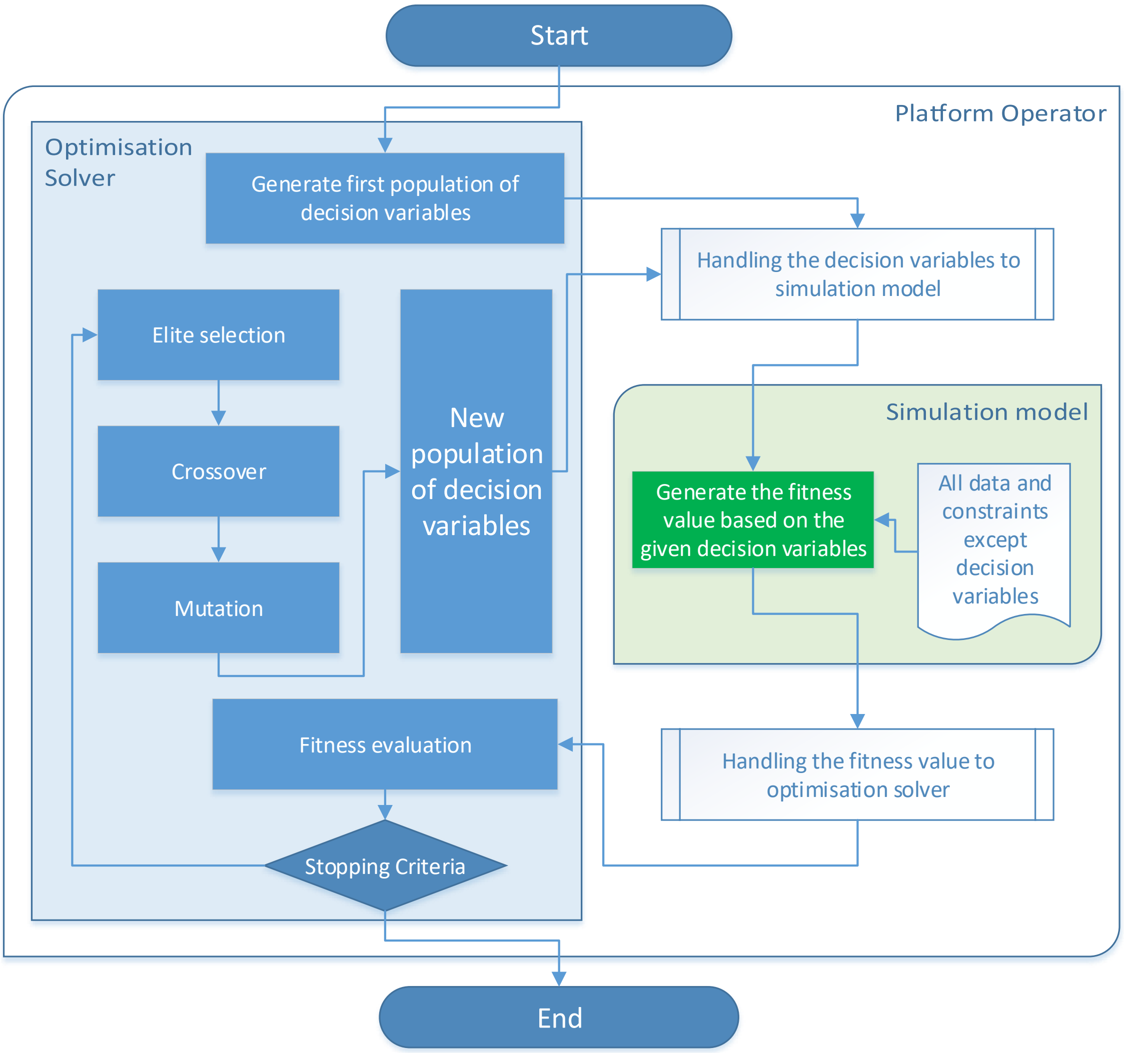


Figure 73 Structure and workflow of the proposed optimisation method

Overall platform operator: the program manages the optimisation solver and simulation model, transfers the data between different workspace, control the overall optimisation process, call out and connect all internal and external functions, such as data import and optimisation result output and report generation. In this work, the operator is encoded in MATLAB programming, in version of 9.1.0.441655 (R2016b).

Optimisation solver: take the main work of optimisation operation. The NSGA II (Deb et al., 2002) approach is applied in this work; it can be changed to another optimisation solver easily. In this work, the author selected standard and mature optimisation toolbox from MATLAB:

- Global Optimization Toolbox Version 3.4.1 (R2016b) (DeLand, 2017),
- Optimization Toolbox Version 7.5 (R2016b) (MathWorks, 2017a).

To assist the computation efficiency of the optimisation, Parallel Computing Toolbox Version 6.9 (R2016b) (Various, 2011) also applied in this work.

Simulation model: instead of the traditional mathematic formulation of the problem representation scheme, this work used DES to represent the problem. It is separated from the optimisation solver but can be call out as the ‘function’ of the programming, returning the fitness value by given decision variables. In this work, SimEvent Toolbox Version 5.1 (R2016b) (Mathworks, 2017b) is used to build the FMS model. The detail of how to create the model is introduced in Chapter 5 of the thesis.

7.3 Problem definition

There are various problems to be solved for the successful development and implementation of FMS. This work focuses on the scheduling problem of FMS, more specifically, its loading problem of the FMS. The loading problem would determine how to assign the given set of manufacturing capacities (machines, pallets) to each required operation, and the decision would result in the key manufacturing performance of the FMS. This section will introduce the overall eco-system of FMS, relevant variables and the optimisation objectives considered.

7.3.1 Strategies and policies for FMS

7.3.1.1 Key flexibilities to manage

In this work, the model will target and represent the following flexibilities of FMS:

- **Product Flexibility**: enables the production of multiple products and different parts sharing the same production line
- **Machine Flexibility**: the same kind of machine centre can carry out multiple kinds of operation
- **Routing Flexibility**: the capability to cope with breakdowns and continue manufacturing a given set of part/product types using alternative routes

7.3.1.2 FMS workflow

The FMS considered in this research is a multiple machine FMS from an industry case study. There is no standard workflow of the FMS; the workflow of the FMS is also considered here, as shown in Figure 27. The workflow explains the procedure for producing a product step by step, from a one order entry into the FMS to the completion of all operations and exit the system. The key decision making points are also noted in that chart.

7.3.2 General assumptions

7.3.2.1 System:

- the FMS consists of a certain number of machines, each of which can perform a variety of operations if proper pallets are provided. These machines are the key entities and capacity of the FMS, and the challenge is how to utilise them well as a whole system. The number of machines and pallets of each type that are available during a planning period are known.
- each machine can only perform at most one operation at a time.
- each machine has the same the maximum working hours.
- all pallets can be loaded to any of the machines.

7.3.2.2 Product:

- a set of products (volume) to be produced is given during a planning period, for instance, five set of product A should be delivered in one week. This is transferred to the inter-arrive time of the order and due time of the product. The inter-arrive time is the rate of feeding the order to the manufacturing system; it would not always match with the due time or the production volume which achieved.

- the inter-arrive time of each product order can be different.
- the number of each type of part to convert to one product may differ, for example, one product consists of one piece of part a and two pieces of part b.
- each part can also have one or multiple operations to be processed followed by a certain sequence.

7.3.2.3 Operation:

- from the previous investigation of the operation sequence problem in the FMS, it has been found that the impact of the operation sequence on the overall production performance became weakened when the flexibility level of the machine assignment increased. Thus, it is not the priority component to be considered in this research. Here the operation sequence is treated as a fixed and given variable.
- the assignment of an operation to a machine is constrained by the machine type; for example, some operations can only be done on five-axis machines, others can be done both on five-axis or four-axis machines.
- pre-emption and splitting of operations are not permitted. Thus, machine change is not allowed until an operation is completed.
- the processing time of each operation is the same on the different machine.
- all the processing time is deterministic and pre-selected.
- all parts should arrive at the loading station to be assigned to required machine/s and loaded with the required pallet to do the ongoing operation.
- each operation requires a pallet of a particular type to be processed in the machine.
- after each operation the part must go through the Unload Station to unload the pallet then return to the queue at the loading station or terminal of the production line depending on whether all operations of that part are completed.

7.3.2.4 Dispatching Rule:

The study of the dispatching rule is a common field in FMS research. In this research, the dispatching rule is predetermined, applied at the queue in front of the load station and defined with two level of priorities:

- The first priority is FIFO for the order entry timestamp. For example, if an WIP belongs to order A which entered into the FMS at 8:00 AM and another WIP belongs to order B which entered at 8:30 AM, the system will load the WIP belonging to order A and release it for its next operation.
- The second priority is FIFO depending on the sequence of WIP entering the queue of load station. If all operations waiting in the queue of load station, besides all of they belong to the same order, the system will serve the earliest arrived operation first.

7.4 Definition of variables

7.4.1 Notations

There are huge numbers of variables used to represent the targeting FMS scheduling problem, and these are classified into three categories, as shown in Table 19:

Input Arguments: these variables are the static or constant variables that are predetermined before the optimisation process. These variables are stored in the simulation model and would not be handled by the optimisation solver. They define overall eco-system of the FMS, including the constraints of the policy and environment.

Decision Variables: the decision to set up these variables would impact on the performance of the FMS and make the results of targeting the FMS scheduling problems significant. The decision variables have a default value and would be manipulated by the optimisation solver. The combination of a series of decision variable values would result in one single solution, and there would be a huge number of different combinations which then the possible solution pool.

Table 19 Definition of variables

Category	Notation	Description
Input Arguments	R_{dsp}	dispatching rules
	L_{of}	level of flexibility
	T_{pro}	production period
	i	types of product
	p	index of part
	op	index of operation
	pt	process time of the operation
	t_{in}	release time of order
	t_{out}	completion time of order
	pe	type of pallet
	mc	index of machine
	mc_t	type of machine
	Op_{se}	sequence of operation
Decision Variables	Amc	assignment of machine to operation
	pe_{qty}	number of pallets
	T_{ia}	inter-arrive time
Output Arguments	Out	throughput
	Uti	average machine utilisation
	WV	machine workload variation
	FT	mean flow time

Output Arguments: After having given input arguments and decision variables to the simulation model, the performance can be simulated by running the model. The output arguments are the KPIs of the FMS and the targeted optimisation objectives. The value of these KPIs would send to the optimisation solver for a fitness evaluation.

Ignored variables:

- The movement of materials in which AGVs are not utilised, are taken as negligible
- Buffer restriction and operation of material handling resources are not considered.
- There is no delay in the availability of raw material
- The tool and fixture are ignored because they are correlated with the pallet, so combined with pallet parameters (type and number), in mind of reducing dimensions

7.4.2 Constraints on Decision variables

To make the solution feasible for implement, this research applied the upper and lower boundary constraints for the decision variables

7.4.2.1 Assignment of machine:

If an operation required type 1 machine (five-axis); only one type of machine can be chosen.

If an operation required type 2 machine (four-axis), can choose all the machines which include type 1 and type 2.

7.4.2.2 Quantity of pallets:

The amount of each type of pallet cannot be more than three sets. In the real world, the machine centre is a quite standard product, but most of the pallets are customised. Therefore, the cost of the pallet can be prohibitive; some of their unit prices are higher than a second-hand machine centre.

7.4.2.3 Inter-arrive time of product:

Inter-arrive time is determined by the targeted production rate of each product. Each product occupies a certain amount of manufacturing capacity. While different products are sharing the same manufacturing capacity in the FMS, the rising production rate of one product would conflict with other products. How to balance the production rate of all products in the FMS and achieve maximum throughput of the whole FMS are also the challenges for the manufacturing manager. Here in the simulation, the inter-arrive time is limited by the experience and expectation from industry practice.

7.4.3 Data matrix of FMS

To introduce the proposed FMS, the data matrix defined the numerical shape and boundary of the system.

Except for the data matrix, the FMS model also used other data such as the number of working days per week, available working hours, planned downtime etc.; the environment variables are set in the simulation model.

Table 20 shows an example of the data matrix used for the FMS.

Except for the data matrix, the FMS model also used other data such as the number of working days per week, available working hours, planned downtime etc.; the environment variables are set in the simulation model.

Table 20 Data matrix of FMS

Product	Part	Operation	Pallets	Num of Pallet	Process Time(mm)	Machine type	Machine assignment	
i	*p*	*op*	*pe*	pe_{qty}	*pt*	mc_t	*Amc_1*	*Amc_2**
1	1	1	1	2	65.4	2	11	0
1	1	2	2	2	64.22	2	3	0
1	1	3	3	2	35.47	2	5	0
1	1	4	4	1	50.88	1	1	0
1	2	1	5	1	63.13	2	3	0
1	2	2	6	1	52.45	2	11	0
1	2	3	7	1	93.27	1	1	0
1	2	4	8	1	47.25	2	6	0
1	2	5	9	1	101.37	2	4	0
1	2	6	10	2	27.58	2	5	0
1	3	1	11	2	40.08	1	2	0
1	3	2	12	2	43.48	1	2	0
1	3	3	13	2	32.83	2	5	0
1	4	1	14	1	45	2	4	0
1	4	2	15	1	20	2	4	0
1	5	1	16	1	6	2	6	0
1	5	2	16	1	20	2	6	0
1	5	3	18	1	22	1	1	0
2	1	1	19	1	54.92	2	9	0
2	1	2	20	1	58.25	2	7	0
2	2	1	21	1	31.45	2	8	0
2	2	2	22	1	27.63	2	8	0
2	3	1	23	1	40.67	2	6	0
2	3	2	24	1	8.58	2	5	0
2	3	3	25	1	58.7	2	10	0

*: If the value of Amc_2 is zero, it means that the operation only has one choice of machine to be processed. If Amc_2 is not zero, there would be two alternative options for this operation. It would choose the less utilises rate machine at that moment.

7.4.4 Optimisation objectives

There are four outstanding performances of FMS targeted in this research:

Out **Throughput**: throughput of each product achieved in a determined production period (default as four weeks). The higher throughput can be attained, the easier to satisfy the required order from customers.

$$Out_i = number\ of\ product\ i\ delivered\ in\ T_{pro} \qquad \textbf{(6)}$$

Uti **Average utilisation of the machines:** the better utilisation of the machine would return better investment of these manufacturing capacities.

$$Uti_{mean} = \frac{\sum Uti_{mc}}{total\ number\ of\ machine} \qquad \textbf{(7)}$$

WV **Average workload variation of the machines**: the workload variation would represent the balancing of the machines. The balancing problem of FMS is an open shop scheduling problem, it unique than the flow shop scheduling problem.

$$WV_{mean} = \frac{\sum\ |Uti_{mc} - Uti_{mean}|}{total\ number\ of\ machine} \qquad \textbf{(8)}$$

FT **Mean flow time of the products:** the flow time is the period between the moment of product entry into the manufacturing system to the completion of all operation and leafing the system. The lower flow time would stand for lower WIP level and fewer blocking of the operations within the system.

$$FT_{mean,i} = \frac{\sum t_{out,i} - t_{in,i}}{Out_i} \qquad \textbf{(9)}$$

7.4.5 Simulation model of FMS

The simulation model is built within SimEvents from MATLAB, which combined event-based simulation engine with the time-based simulation engine in Simulink.

The modelling approach to building the considered FMS in introduced in the previous section.

The top level of the simulation model (Figure 36) demonstrated the layout of the considered FMS, which corresponds to Figure 27 The workflow of the selected FMS, including the order, arrive section, load section, process section, delivery section and performance analysis section.

7.5 Optimisation set-up

7.5.1 Set-up the optimisation algorithm

The optimisation algorithm applies the multi-objective optimisation from Global Optimisation Toolbox of MATLAB (DeLand, 2017), more precisely, it applies NSGA II as the optimisation solver (Deb et al., 2002). GA is taking advantage to solve non-explicit or black box objective function, which is enabled to cooperate with the DES objective function.

The GA setting are shown in Table 21. Except for the default setting, the parameters of 'max generations', 'population size', 'max stall generations' and 'Pareto Fraction' are manually controlled.

The using of the optimisation algorithm is quite straightforward procedure: setting up optimisation options; deploy the (multi-core) parallel computing function and load the simulation model to each parallel workspace; obtain the optimisation algorithm; call out the output from simulation; get optimisation results after running the optimisation algorithm iteratively. The script that is used for optimisation is shown in Appendix D.1, and the MATLAB optimisation function setup is shown in Appendix Figure D-1.

By test running the optimisation programme, it has been found that increasing the rate of mutation and decreasing the rate of crossover (from 0.8 to 0.6) would obtain better results. This is due to the discrete relationship between the machine assignment variables.

Table 21 Set-up of the GA multi-objective optimisation solver

Parameter	Value	Parameter	Value
Display	'iter'	CrossoverFraction	0.6
MaxGenerations	30|100|400	HybridFcn	[]
OutputFcn	@fig2mov	InitialPopulationMatrix	[]
PlotFcn	{@gaplotpareto, @gaplotrankhist, @gaplotspread, @gaplotdistance}	InitialPopulationRange	[]
PopulationSize	400|1000	InitialScoresMatrix	[]
UseParallel	1	MaxStallGenerations	100
MigrationInterval	5	MaxTime	Inf
ConstraintTolerance	1.00E-03	MutationFcn	@mutationadaptfeasible
CreationFcn	@gacreationuniform	ParetoFraction	0.35
CrossoverFcn	@crossoverintermediate	PopulationType	'doubleVector'
DistanceMeasureFcn	{@distancecrowding 'phenotype'}	SelectionFcn	{@selectiontournament [2]}
FunctionTolerance	1.00E-04	UseVectorized	0

The schematic operation of the optimisation process is introduced in Chapter 4. A similar concept of structuring the optimisation with separation of the problem space and solution space (Al-Zuheri, Luong and Xing, 2013).

7.5.2 Formulate fitness function

The fitness function is a black box for the GA. This work forms the objective function by running the DES simulation, connecting the decision variables received from the optimisation algorithm. The scores of objectives are taken by the output function block of the simulation model, as shown in Figure 74.

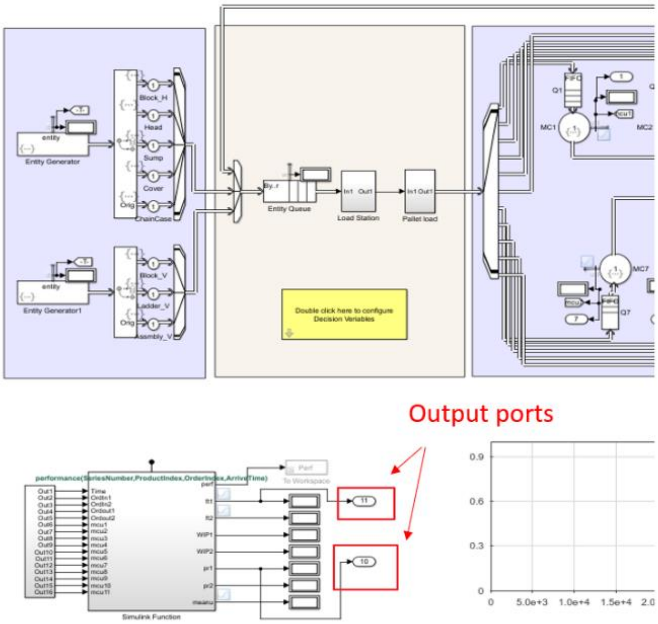


Figure 74 Simulation results are exported from simulation model output ports

The objective function is encoded in the platform operator to call out the simulation model, shown as the below structure, in Appendix Figure D-2.

The objective function would have modified based on the same structure, in different scenarios.

7.6 Design of experiment

There are multiple components involved in the targeted production scheduling problem of the FMS, and it is easier to engage with these elements gradually, in the order from a simple to complex order, from less to more. It is also a good way to investigate the interrelationship of different kind of variables and objectives. Thurs, a series of scenarios were built to hit every component, in the end, to handle the targeted production scheduling problem and its massive decision variables. The scenarios represent the scope of the optimisation in this chapter, as shown in Table 22.

Table 22 Optimisation objectives and decision variables for optimisation scenarios

	Optimisation Objectives					**Decision Variables**				**Summary**		
Scenarios	Throughput	Mean flow time	Average utilisation	Workload variation	Pallet quantity	Machine assignment	Alternative Machine assignment	Inter-arrival time of product	Pallet quantity	Optimisation objectives	Decision variables	Solution pool
	y1	y2	y3	y4	y5	x1	x2	x3	x4	Ys	Xs	Size**
	Maximum or minimum optimisation					Number of variables for each category*				Total number		
	Max	Min	Max	Min	Min	25	25	2	25			
#1	√					√		√		1	27	9E+21
#2	√	√				√		√		2	27	9E+21
#3	√		√	√		√		√		3	27	9E+21
#4	√	√		√		√	√	√		3	52	3E+44
#5	√	√		√	√	√	√	√	√	4	77	3E+56
#6	√		√	√	√	√	√	√	√	4	77	3E+56

* for each variable, its value constrained by a range of the upper and lower bounds

** the size of the solution pool is the total number of different possible combination of the decision variables

7.7 Results and decision making

7.7.1 Optimisation results

The experiments were carried out using Amazon Web Service, EC2 Elastic Compute Cloud (Varia and Mathew, 2017). The selected type of instance is c4.8xlarge, the latest generation of compute-optimised instances, which applied

36 cores Intel Xeon E5-2666 v3 (Haswell) processors and 60 GB memory. The summary of the optimisation results is shown in Table 23:

Table 23 Summary of optimisation results

Scenario	**Objective Value**					**Optimisation Performance**					
	Throughput	Mean flow time	Average utilisation	Workload variation	Pallet quantity	Population size	Generations	Number of points on the Pareto front	Average distance measure of the solutions on the Pareto front	Average computing time for each fitness evaluation (seconds)	Computation time (minutes)
	y1	y2	y3	y4	y5						
	Maximum or minimum optimisation										
	Max	Min	Max	Min	Min						
#1	112					200	50	1		0.181	30
#2	135	411				200	100	53	0.064	0.204	68
#3	181		91	21		500	200	140	0.138	0.555	925
#4	181	364		6		500	200	140	0.065	0.688	1146
#5	181	416		5	28	1000	300	140	0.037	0.862	4308
#6	181		91	1	25	1000	300	140	0.023	0.836	4181

The optimisation results have been improved by a better set-up of the optimisation objectives, and the relationship between the objectives is represented in the matrix of the Pareto frontier charts.

The computational efficiency of this optimisation method is significantly advanced: for example in scenario #6, size of the solution pool is 3.00E+56, if using a brute force search, it would take 7.95E+48 years (3.00E+56*0.836/60/60/24/365), but in this method, it has been found that the non-dominated optimal solutions only used 4181 minutes. This demonstrates the ability and superb efficiency in handling the complexity of the FMS problem.

7.7.1.1 Scenario #1: Single objective optimisation - throughput

The experiment achieved one optimal solution as below:

[2,7,1,2,6,3,1,6,6,2,6,4,1,6,4,9,7,2,5,9,7,1,3,8,8,20.35,104.09] the last two variables are the inter-arrive time of two products, and the rest are the assignment of the machine (only one machine option). This solution would achieve the throughput objective value as 112 sets per month.

The simulation of this solution is shown in Figure 75; this is the state of machine utilisation.

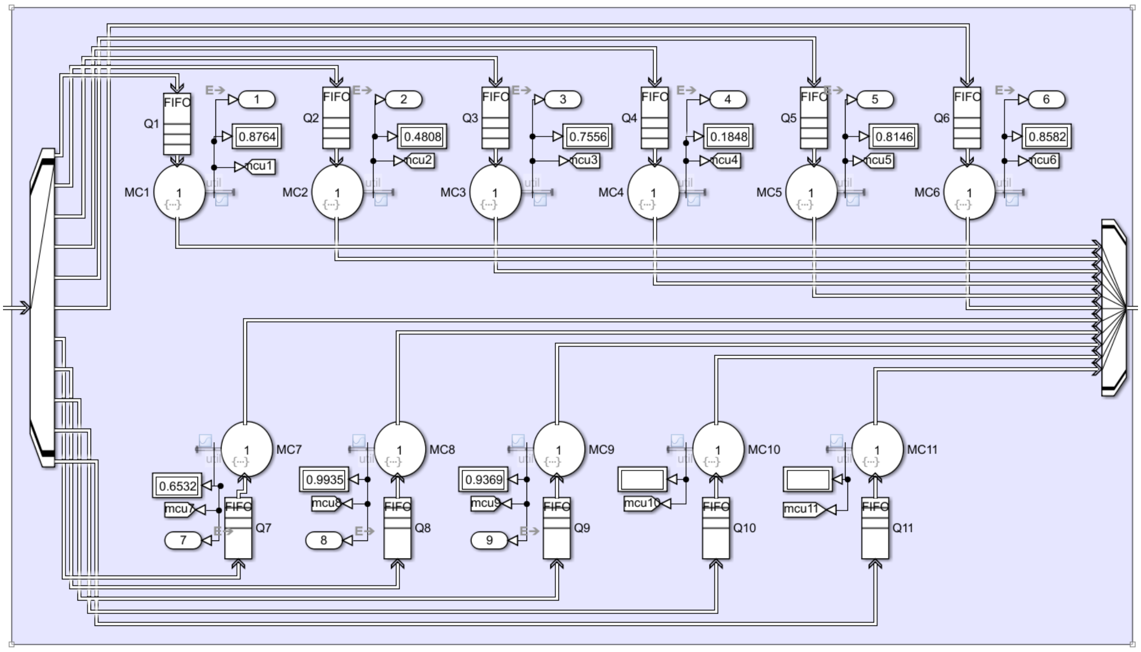


Figure 75 Simulation of scenario 1# optimisation result

7.7.1.2 Scenario #2: Multi-objective optimisation – throughput, flow time

There is multi-objective optimisation in all scenarios from #2 to #6. An optimisation result for scenario 2 is presented here: The number of points on the Pareto front was 53; the average distance measure of the solutions on the Pareto front was: 0.064; the computing time was: 68 minutes; and average computing time for each fitness evaluation was: 0.204 seconds.

The result provides 53 non-dominate Pareto front solutions, as shown in Figure 76. This solution would provide the performance of 135 throughputs per month and 411 minutes of mean flow time respectively.

In Figure 76, from left to right, top to bottom:

- **Pareto front** plots the Pareto front for the two objective functions. Objective 1 is the throughout, it has a negative value because the default optimisation direction is looking for minimum value, but objective 1 requires maximum, which is the opposite direction compared to the default direction. Objective 2 is the mean flow time. It indicates that objectives 1 and 2 are conflicting with each other. Some Pareto frontiers are overlapping.
- **Rank histogram** plots a histogram of the ranks of the individuals. Individuals of rank 1 are on the Pareto frontier. Individuals of rank 2 are lower than at least one rank 1 individual but are not lower than any individuals from other ranks, etc.
- **Average Pareto spread** plots the average Pareto frontier spread as a function of the iteration number.
- **Distance** plots the average distance between individuals at each generation.

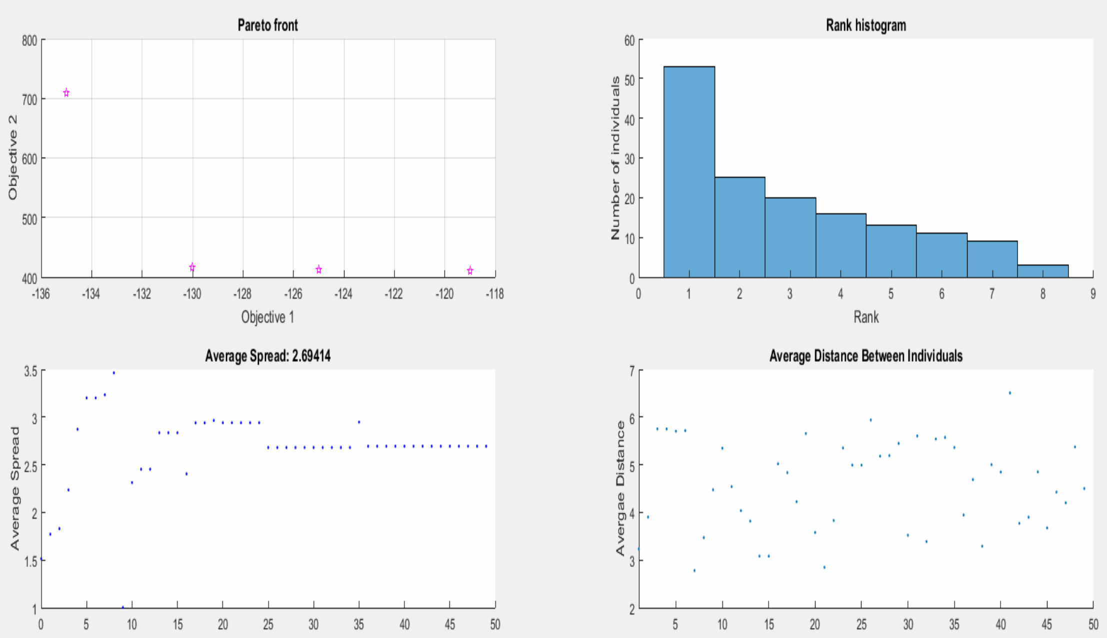


Figure 76 Optimisation result of scenario #2

7.7.1.3 Scenario #3: Multi-objective optimisation – throughput, utilisation, workload variation

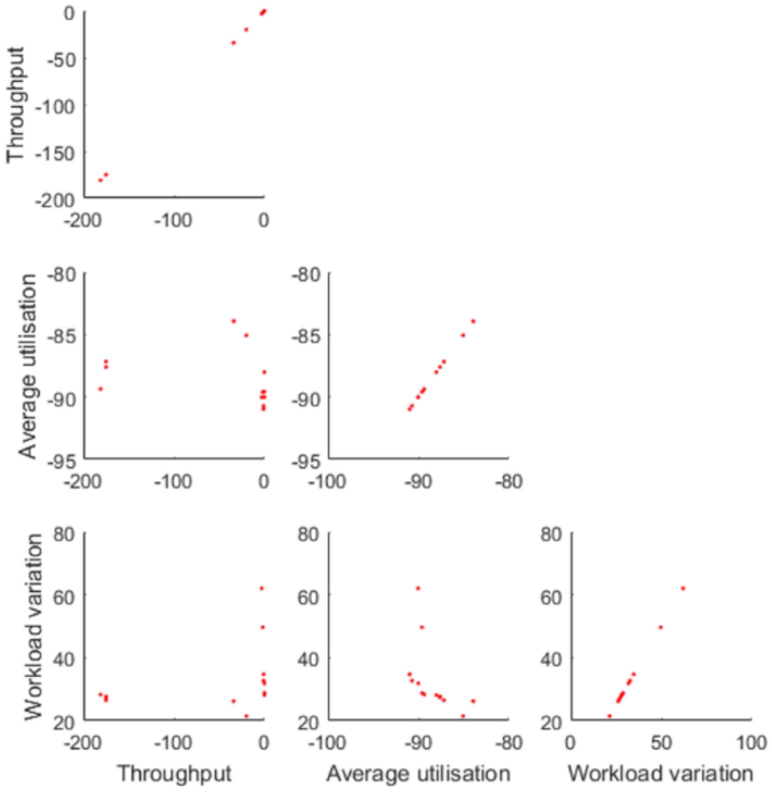


Figure 77 Pareto Fronts of scenario #3

Figure 77 shows the optimisation results of scenario #3. The decision variables are the same as for scenario #2, but with three objectives for optimisation. It can be observed that the average utilisation and workload variation are the conflict objectives.

7.7.1.4 Scenario #4: Multi-objective optimisation – throughput, flow time, workload variation

Starting from scenario #4, the FMS release the key flexibility for routing flexibility. Each operation could locate to one of two optional machines. By releasing the routing flexibility, the complexity also increased sharply. The size of the solution pool increased from 9E+21 to 3E+44. It almost impossible to use traditional analysis methods to solve this problem, but the author proposes that the optimisation method proves its capability for handling this complexity. In the definition of the LoF, if the operation has one alternative option (totally two choices in total), it is called the LoF 1. This research is targeting the LoF 1, but it is still possible to investigate the higher LoF, with the exponential increase in complexity.

Figure 78 shows the optimisation results of scenario #4. It handled three optimisation objectives and decision variables. It can be observed that ‘mean flow time’ and ‘workload variation’ conflict with each other, while ‘throughput’ and ‘workload variation’ conflict slightly.

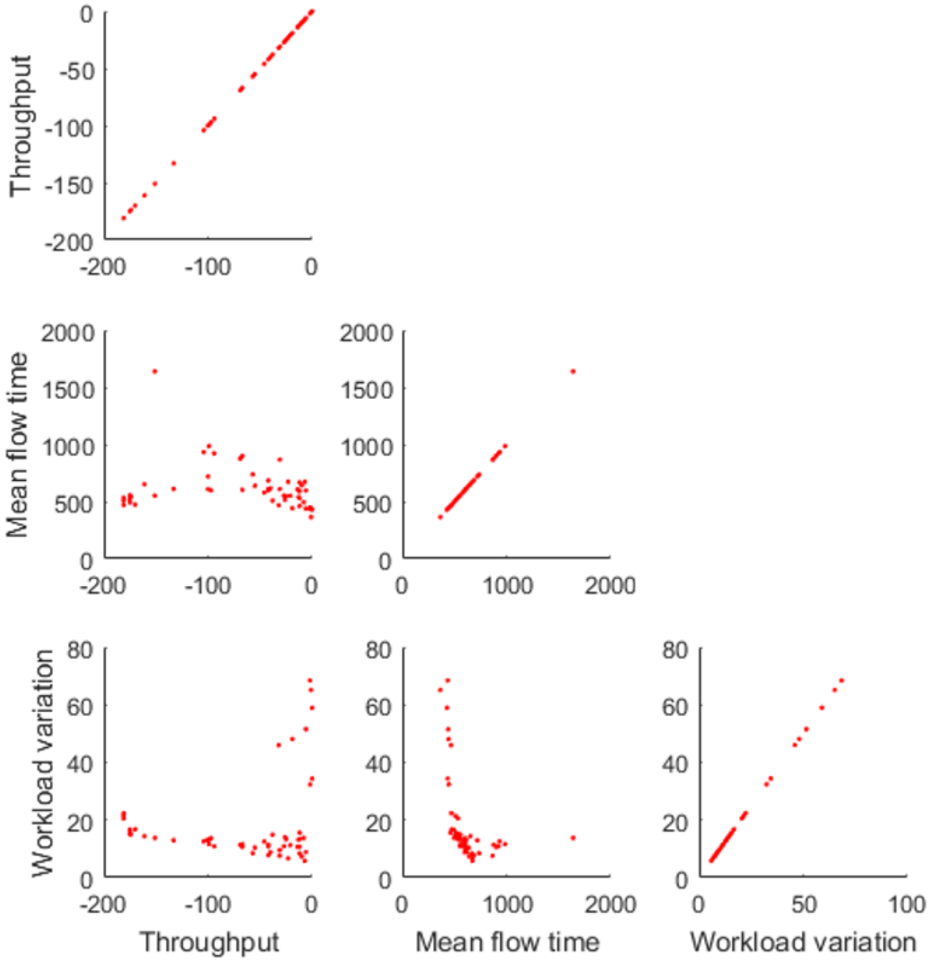


Figure 78 Pareto Fronts of scenario #4

7.7.1.5 Scenario #5: Multi-objective optimisation – throughput, flow time, workload variation, pallet quantity

From scenarios #5 and #6, the optimisation is involved with the quantity of pallets. This problem is rarely reported in the academic papers but has a significant impact in the practice. In the FMS, as an open job shop flow schedule, the operation A from the previously released order may load onto the system with the same operation A from the new order at the same time. In level one of routing flexibility, one operation would have 2 options of a machine to go to, but they can do this only if there are enough machines available and furthermore, enough pallets available. Otherwise, one of the operations has to wait until the pallet is released, and that would block of the flow, increase flow time and WIP level, and even limit the throughput. As mentioned before, the pallets are expensive, because most of them are customised. Thurs the manufacturing manager also expects to minimise the quantity of pallets required without harming the manufacturing performance.

Figure 79 shows the Pareto frontiers of scenario #5; as the number of objectives increase, the Pareto frontiers are located more dispersedly. It can be observed that ‘mean flow time’ and ‘workload variation’ are still in conflict with each other, and ‘throughput’ and ‘workload variation’ are also conflicting. Furthermore, the ‘quantity of pallet’ is in conflict with the ‘workload variation’.

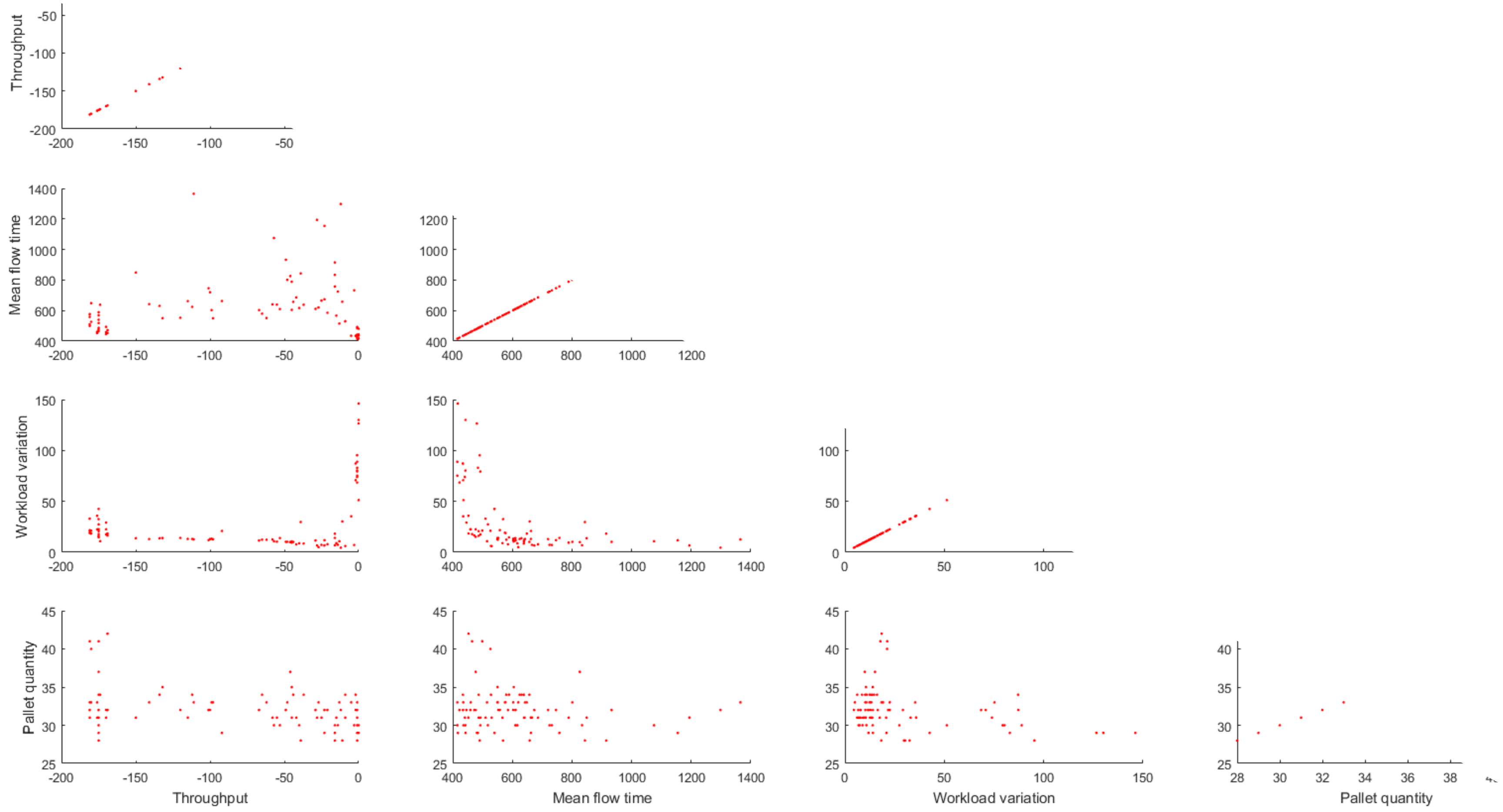


Figure 79 Pareto Fronts of scenario #5

7.7.1.6 Scenario #6: Multi-objective optimisation – throughput, ultilisation, workload variation, pallet quantity

The only difference from #5 to #6 is that the #6 takes the ‘average machine utilisation’ instead of ‘mean flow time’ as one optimisation objective. It can be observed clearly in Figure 80, that ‘average machine utilisation’ and ‘throughput’ are conflicting with ‘quantity of pallet’. This means that if the FMS wants to increase the ‘throughput’ and the ‘utilisation’, it has to increase the investment in pallets and tools or other manufacturing entities correlated to the pallets.

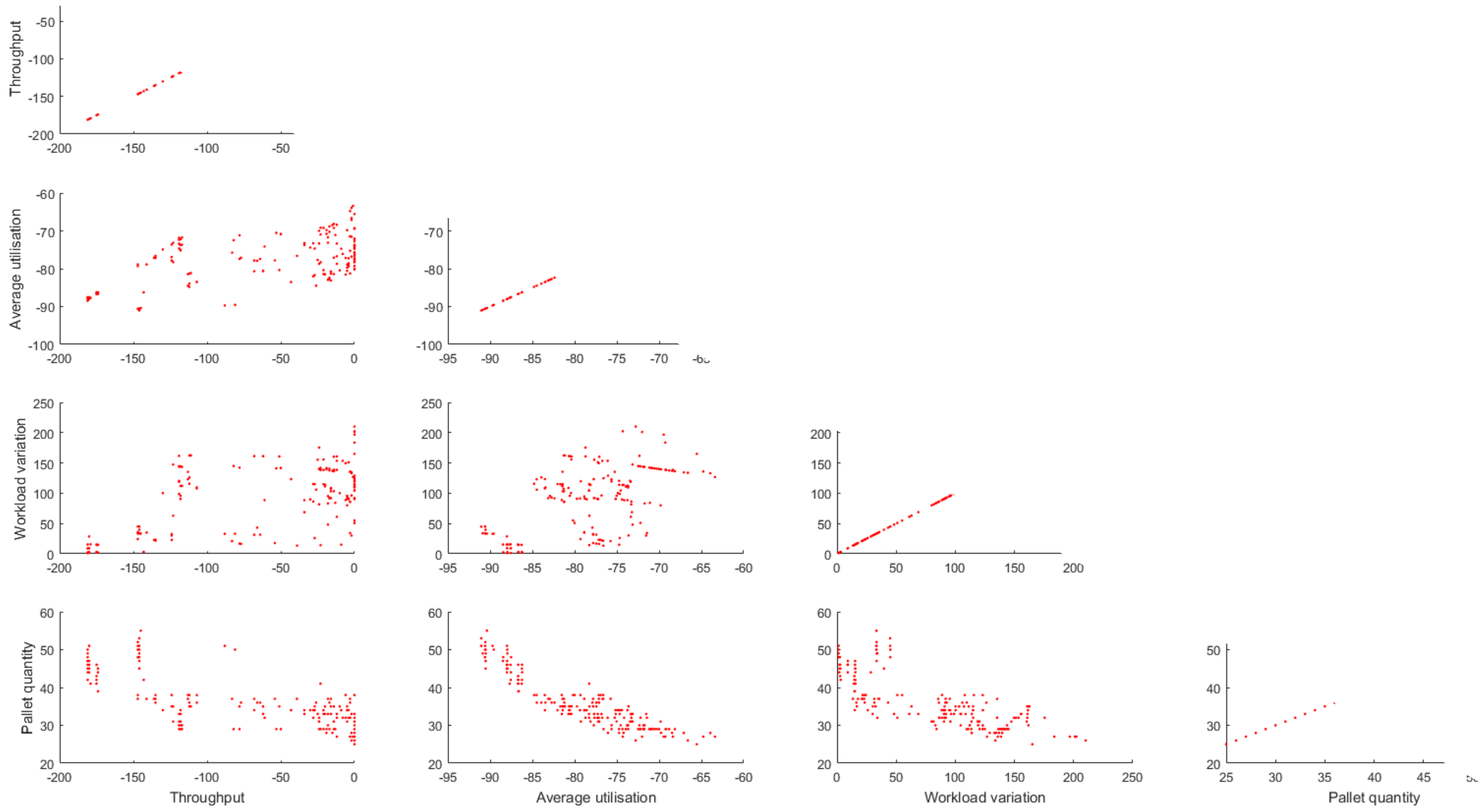


Figure 80 Pareto Frontiers of scenario #6

7.7.2 Decision making

In Figure 81, it shows the optimisation result of two conflicting objectives, including all populations in the last generations. After finishing the optimisation, it is only halfway done to towards making the final decision. The solution on the Pareto Front would provide a series of options for the production managers, who would value each objective from their practical experience and choose one of these options considering other circumstance inside or outside the manufacturing system. For instance, if they have a rapidly increasing demand, the solution providing more throughput could be better; if they have to act on the costing saving, they may consider more about a solution with less flow time, so that they can reduce the WIP during production.

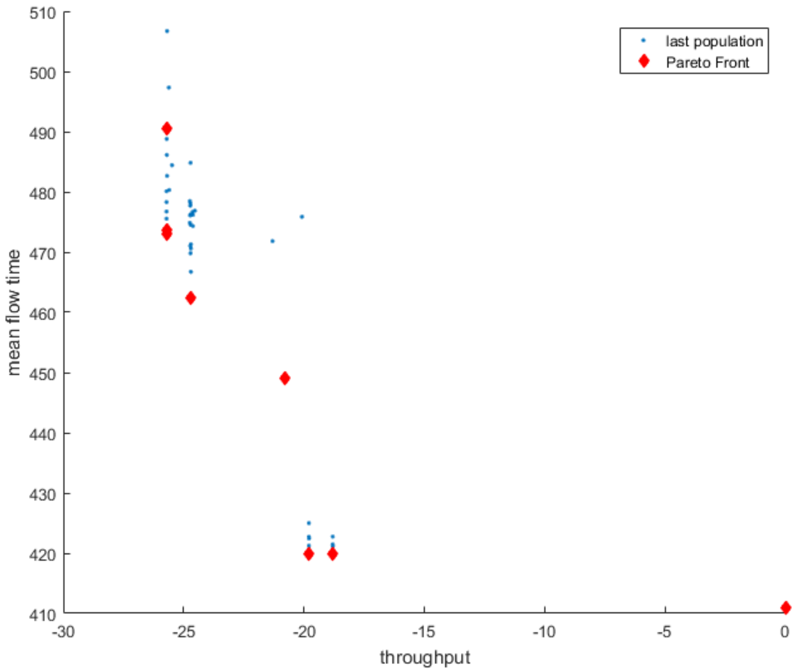


Figure 81 Objective function of the last population

7.8 Summary

In this chapter, the aim was to develop a multi-objective optimisation method, which works with the proposed DES optimisation integration framework, and then apply the proposed optimisation approach on FMS.

The work presented here demonstrates the integrated framework of optimisation and problem represented by simulation model. The separation enables fast design space exploration by experimentation with different variables and parameters for FMS scheduling. This study has presented a framework that can connect DES models with multi-objective engines such as NSGA II. Comparing previous optimisation research on FMS production scheduling, this approach provides a novelty for improvement in modelling complex system and optimisation computational efficiency. It enables the application of heuristic optimisation methods to engage with the complex environment and dynamic policies within the FMS to deliver optimisation results to production managers of FMS.

The results of this study provide a way to conduct global optimisation based on massive variables in FMS; this is difficult to carry out by using manual or traditional analysis methods due to complex interactions among FMS problems.

8 DISCUSSION AND CONCLUSIONS

This research is set-up with the aim of developing simulation and optimisation methods to solve the manufacturing problems of FMS. This chapter summarises the main observations found in this research. Introspections and reflections regarding the research aim and objectives are addressed. The research contribution is outlined, which corresponds to the research gap. The limitations found in this research are clarified, and the recommendations for the future work are proposed. Finally, the general conclusions of this research are drawn.

8.1 Findings and discussion

Research findings are summarised corresponding to the research objectives, and in line with the chapters of the thesis.

8.1.1 State-of-the-art of optimisation and simulation for FMS

Chapter 2 LITERATURE REVIEW has addressed research objective 1:

‘Review the state-of-the-art simulation and optimisation technologies for FMS and investigate existing practices of FMS’

In this chapter, first the concepts and definitions of FMS and related manufacturing systems have been explored, and the principal manufacturing problems associated with FMS have been collected from the literature. Subsequently, the state-of-the-art of optimisation and simulation technologies related to FMS have been identified. Through the literature review, the differences and understandings of FMS problems, shortage of validated FMS simulation models, and the lack of effective optimisation methods in the context of the overall system have been recognised. The research trends and research gaps have been analysed and guided the following work within this research.

8.1.2 Discover FMS problems from a case study

Chapter 2 PRIMARY MANUFACTURING PROBLEMS IN FMS has addressed research objective 2:

‘*Capture the manufacturing problems and collect the requirements of optimisation for a FMS, by carrying out an industry case study.’*

In this chapter, the author investigated relationships and the interactions of the manufacturing problems within the FMS, and matched and compared these problems from the literature with the practical case study. By conducting the investigation, this section identified the most challenging and critical problem in the FMS – the loading problem of FMS scheduling. This problem is also suitable to be handled by the optimisation method and is taken as the primary optimisation problem for the main research. The requirement for the design and solution space of the loading problem is identified. The relevant data and constraints have also been identified and collected from the case study.

8.1.3 A framework to integrate optimisation and simulation for FMS

Chapter 4 SIMULATION AND OPTIMISATION INTEGRATION FRAMEWORK has addressed the research objective 3:

‘Develop a simulation and optimisation integration framework for an FMS.’

The chapter has proposed and demonstrated the optimisation-simulation integration framework applied to solve the FMS problems. The efficiency improvements were observed both from solution providers’ and problem representatives’ perspectives. The MATLAB was used as the shared platform for both the mathematical optimisation programming and DES modelling. This approach has been identified as a powerful tool to understand and address the problems for a highly complicated system such as the FMS.

8.1.4 Modelling a comprehensive FMS simulation model

Chapter 5 SIMULATION MODELLING OF FMS and Chapter 6 SIMULATION EXPERIMENT OF FMS have addressed the research objective 4:

‘Establish a comprehensive simulation model for an FMS, which is able to represent and evaluate multiple manufacturing problems and their dynamic interactions within FMS.’

This chapter 5 introduces the modelling of the FMS from the case study, which contains multiple manufacturing problems in the same model. By testing multiple problems in the same model, the interactions between the problems and the impact of each problem on the overall performance has been discovered. The basic version of an FMS simulation model has been validated on the real-world shop floor.

In chapter 6 The author has proposed the hypotheses based on the discovered FMS manufacturing problems and designed a series of simulation scenarios to investigate the impact of FMS performance. The experiment results have found distinguish characteristics between the FMS and dedicated manufacturing systems. The limitations of the simulation experiment have been discussed, and an FMS physical scaled experiment has been recommended for future work.

By conduction the experiment, this research has investigated the depth of FMS as follows:

- This research has simulated the major components of the FMS and represented the interactions of the known manufacturing problems using one model.
- The simulation experiment has investigated the multi-dimension of the manufacturing performance and the impacts of multiple factors. The LoF experiment is the most valuable part of the research, which has proven the performance improvement by revealing the manufacturing flexibility.
- The experiment results have given an insight into FMS system behaviours; some discoveries are contradictory to previous literature.
- Operation sequence is one major manufacturing problem for a transfer production line, but it has a limited impact of the overall performance in a high LoF.
- Dispatching rule is one of the most popular topics of operational research or optimisation research applied to FMS. However, by experimenting with a full-scale FMS simulation model, the results have indicated that the dispatching rule would only lead to a limited and partial impact on the FMS performance.

8.1.5 Apply Multiple Objective Optimisation for FMS scheduling problem

Chapter 7 MULTI-OBJECTIVE OPTIMISATION TO FMS has addressed the research objective 5:

‘Apply a multiple-objective optimisation approach in cooperation with the FMS simulation model’

In this chapter, the multi-objective optimisation method is developed by cooperating within the proposed DES optimisation integration framework and applying the proposed optimisation approach to the considered FMS with a high level of complexity.

The work presented here demonstrated a detachable framework of optimisation functionality and problem representation functionality. The separation enables fast design space exploration by experimentation with different variables and parameters for FMS scheduling problem. This study has shown that the framework can connect complex DES models and the powerful multi-objective engine such as NSGA II. Comparing previous optimisation research on FMS production scheduling problem, this approach provides a significant improvement in modelling efficiency and computational efficiency. It enabled the application of a heuristic optimisation method to engage with the complex environment and dynamic policies within the FMS and also enable heuristic optimisation delivery of practical optimisation results to the production managers of FMSs.

The results of this study indicate a way to conduct a global optimisation based on overall variables in the FMS, which is almost impossible to carry out using manual or traditional analysis methods by the obstruction of extensive data, complex interaction, dynamic change environment.

There are limitations and possible extensions beyond this research:

- **Mixed integer multi-objective optimisation**: Currently using real value in optimisation by the restriction of Global Optimisation Toolbox. It would save computing cost if the optimisation engine could process using integer or discrete variables. It may need to modify the cross-over and mutation function.
- **Level of Flexibility**: Control and optimise the LoF for each individual product or each individual operation; for example, the operations would have a different LoF from none to the maximum.
- **Unexpected events**: Urgent order (engineering test), unplanned downtime of machines (breakdown), unplanned product change or operation requirement change. All of these situations would appear in a real FMS factory, and any of

these unexpected events would affect the current production schedule. It is expected that some solutions would be more robust for the same level of the unexpected event. In addition, it would useful to investigate a certain threshold boundary of the FMS in order to adopt the deviations from unexpected events.

- **Real-time data input and simulation**: To obtain higher flexibility, the schedule may need to update in an agile way. Before the optimisation, it is necessary to simulate real-time change from the market or customer and predict and measure the near future performance.
- **Dynamic scheduling approach**: To realise dynamic scheduling, it is the challenge to the optimisation program running frequently and obtain the result instantly. It would encounter some performance of evolutionary optimisation. Machine learning, and reinforcement learning would be an alternative add-in.
- **Local optima vs. global optima:** GA as heuristic optimisation accepts inferior candidate solution “occasionally” to escape from local optima. The choice of representation of a GA is fundamental to achieving success. The coding scheme and the fitness function are the most important aspects of any GA because they are problem dependent. The specification of an appropriate fitness function is crucial for the correct operation of a GA.
- **Fitness function vs. objective function**: To use Global Optimisation Toolbox functions, first write a file (or an anonymous function) that computes the function you want to optimise. This is called an objective function for most solvers, or fitness function for ‘GA’. The function should accept a vector, whose length is the number of independent variables, and return a scalar. For ‘gamultiobj’, the function should return a row vector of objective function values. For vectorised solvers, the function should accept a matrix, where each row represents one input vector, and return a vector of objective function values (Geletu, 2007).
- **Parallel computing**: In several cases, the application of GAs to actual problems in business, engineering, and science requires a long processing time (hours, days). Most of this period is usually spent on thousands of fitness function evaluations that may involve long calculations. Fortunately, these assessments can be performed quite independently of each other, which makes GAs particularly adequate for parallel processing.

8.2 Research Contributions

With the aim of developing manufacturing simulation and optimisation techniques for an FMS, this research first conducted a literature review to investigate the state-of-the-art of FMS simulation and optimisation methods. The main research gap has been identified: the lack of understanding of the relationships and interactions of individual manufacturing problems raised in FMSs, and a shortage of an effective method to represent multiple manufacturing problems in one integrated model, and the failure to optimise the performance in the context of the overall system. Corresponding to the research aim and research gap, the main contribution to knowleadge from this research is summarised below.

8.2.1 Framework of simulation-optimisation integration

Current optimisation approaches have typically required a problem representation scheme in a mathematical model. However, it can be difficult to code and verify a mathematical formulation to represent the discrete and dynamic behaviours from multiple subsystems such as the case of an FMS. This research proposed a framework that integrates DES and an optimisation program. The DES model can excellently represent the interactions of multiple subsystems of FMSs, and is able to connect with the optimisation program, efficiently running the simulation model during the optimisation iteration. By using this framework, the optimisation is able to work on multiple optimisation objectives in the context of overall system performance. This framework also provides the flexibility to switch the optimisation engine conveniently.

8.2.2 Method of simulation modelling for complex manufacturing system

The common DES methods and manufacturing simulation software usually lead to building all components of a manufacturing system in the same layer. Therefore, it would be hard to debug or verify all subsystems and provide a high confidence simulation result. This research developed a novel approach to simulate a complex manufacturing system such as the FMS. The hierarchal architecture and object-oriented approaches enable developing, debugging and validating each subsystem respectively, and are able to connect or disconnect with the general model conveniently. Besides, it also provides the interface with a scripting programming language such as python or MATLAB programming that enables the simulation and customisation of the specific manufacturing entities or logistics which are generally not within existing manufacturing simulation software. Furthermore, the framework also improved the connectivity with the optimisation programme or optimisation toolbox, which enabled improving the computation effectiveness during the optimisation process.

8.2.3 A comprehensive simulation model of an FMS

The comprehensive simulation model of an FMS presented the manufacturing problems during the implementing of a modern FMS from a real-world case study. By using the proposed simulation modelling method, the simulation model includes all primary components of FMS, and is able to represent multiple manufacturing problems and the interactions between different FMS subsystems in the same model. The comprehensive FMS model first simulated the concurrent situations from the case study, and iteratively validated them by testing the scenarios on the real-world shop floor. Subsequently, by using the validated model, this research connected the experiments that combine the simulation of future scenarios with hypothetical solutions. Several behaviours of FMS that are distinct from the behaviours of dedicated manufacturing systems were discovered. Most importantly, the experiment has demonstrated the benefits of significant productivity improvement by releasing flexibility. After steps of development and validation, this comprehensive FMS simulation model also provides confidence that the model can be used as an ideal test-bed for further research.

8.2.4 Multi-Objective optimisation for FMS scheduling problem

This research developed a multi-objective optimisation method applied NSGA II in coupled with the proposed simulation-optimisation integration framework. A case study was carried out which focused on the scheduling, especially for the loading problems of the FMS. It has successfully demonstrated how the proposed model can effectively optimise the manufacturing problems of the FMS within the context of the interaction of all primary subsystems and the impact on overall system performance. It also demonstrated the computational efficiency of this optimisation approach provided by the interface between the simulation model and optimisation engine and speeded up by using cloud computing technology. Cloud computing technology and related distributed computing method also provide another benefit of accessibility to apply the advanced optimisation approach by the regular manufacturers, which generally would not sustain high-performance computing power.

8.3 Research Limitations

8.3.1 Generalisation of research findings

8.3.1.1 From one case study to general FMS

The selected case study for this research is relatively difficult to compare with other FMS implementations because very few industrial FMS implementations have been reported in the literature. However, this case study has covered most of the manufacturing problems of FMS that appeared in the literature, and thus discovered the relationship between these manufacturing problems and their interactions. Therefore, the findings of this study are suitable to carry over to general multiple machine FMSs.

In this research, the following FMS problems have not been investigated:

- The ASP: Even the involved FMS case study consisted of both a machining process and a manual process; the machining processes have covered 90% of the work hours. Thus, priority has been assigned to the machining process. Furthermore, the controlling methods of advanced machine centres and the relevant, less digitalised, manual workstations are different, as the machines are considered as an online system and can be directly controlled by the computer system, but the manual workstations are generally considered to be an offline system.
- The AGV or transport vehicle and transport routing problem: in the selected case study, this FMS has implemented an advanced rail track and robot-crane system instead of an AGV system. Thus the AGV and relevant problems are not considered in this research.
- The operator related problem: this study's main focus is on how to utilise the advanced machine centres better, because they are the most expensive

manufacturing entity on the shop floor, and the stakeholder in the FMS is keen to ascertain the return on investment of this heavy capital outlay, rather than the operator and related manual process.

8.3.1.2 From FMS to general complex manufacturing system

The proposed simulation-optimisation integrated framework and the simulation approach developed within this study are suitable to apply to another complex manufacturing system, especially the manufacturing systems consisting of multiple subsystems, and with a complex, non-linear or discrete scheduling logic.

8.3.2 Validation of simulation results

The simulation work can predict the FMS behaviours in realistic or unlimited scenarios, but the simulation work is hard to validate by itself. Only shop floor implementation or scaled physical experiment can validate the simulation models. In this research, only the FMS base-model has been validated on the shop floor; the high LoF has not been validated on the shop floor for many reasons; for example, a lack of a suitable quality control plan for the FMS, and lack of confidence from external customers.

Due to the current development progress from the case study, it has yet to release the flexibility fully, due to many realistic reasons: no established quality control plan to cope with high flexibility; still developing the software to control the system in a flexible and real-time reactive way; lack of confidence of releasing the flexibility from client sides; lack of guidance to smoothly arrange the engineering validation and production validation in the same facility. Thus, the high LoF sensors have not been implemented and validated on the shop floor yet.

8.3.3 Computational expenses in simulation optimisation

The optimisation approach developed in this research would use about 4000 minutes, equal to 2.7 days, for one completed optimisation job. It is more efficient to reduce the computing time from 7.95E+48 year using brutal force search. The computation time can be reduced further by recruiting more computer servers or using more powerful hardware, but neither of these approaches is suitable for a regular manufacturing department which generally has limited IT capacity.

8.4 Recommendations for Future Research

8.4.1 Physical Twin

It is difficult to directly use real production shop floor to validation of the simulation model and simulation result, mainly due to the cost of real manufacturing facility, furthermore, the cost of failure in real world may not be affordable. Therefore, it is necessary to find a method that can validate the simulation model in an effective and cost saving way.

The author recommends developing a simulation method involve physical simulation modelling, as shown in Figure 82; instead of directly test the simulation result in real world, the simulation result should be tested with a physical simulation model. As simulation model can be one part of the digital twin of the manufacturing system, the physical simulation model can be defined as the physical twin of a manufacturing system.

The physical twin should be built with low cost solutions, such as Lego Mindstorms (Savarino et al., 2018) and Fischertechnik model (Zheng et al., 2018). The physical twin should be easy to reconfiguration, so that able to match with various simulation scenarios. The benefits of building a physical twin are expected as following:

- able to validate the simulation model with more physical constrains, or factory physics (Hopp and Spearman, 2011) which is not easy to be included in the digital simulation model
- increase the confidence of the suggestions produced by the experiment using simulation model
- reduce the cost and risk of production validation for new manufacturing strategy
- physical twin is able to place in a lab, and easy to demonstrate the manufacturing system and the problems in a tangible way
- able to become an education kit for the training of manufacturing system

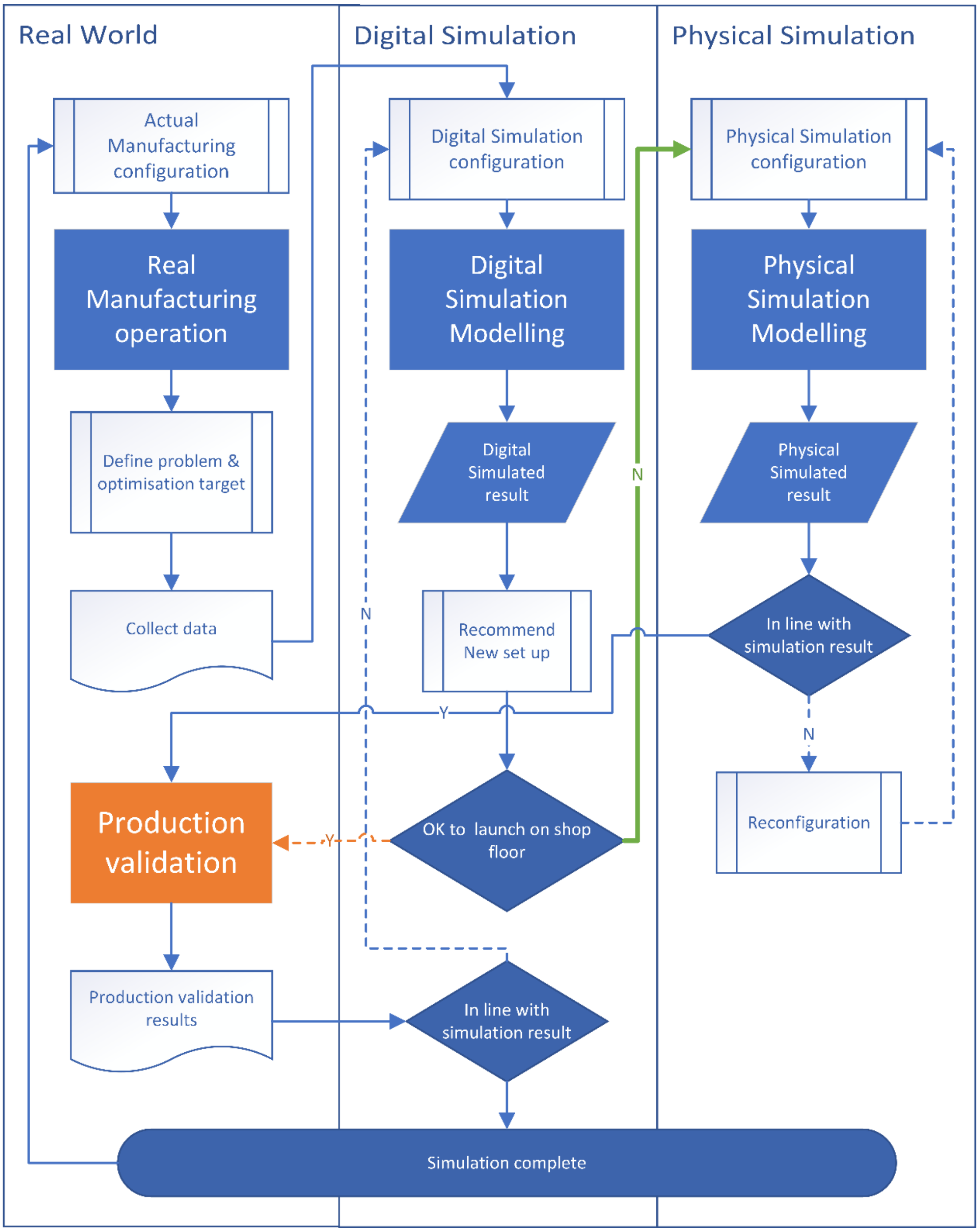


Figure 82 Methodology of physical simulation modelling

8.4.2 Real-time simulation enabled by IIoT

Through the advancement of the digitalised machine and the development of the industry internet, the data from the machine and other digitalised equipment are much easier to collect. If it is possible to update the simulation model with real-time or near real-time data, it would be able to both measure and predict the system performance more accurately, and diagnose the problems within the system in time or give the alarm of a possible failure with enough response time.

However, the real-time data collection and communication with a simulation model would require additional study in the field of smart sensors, data collection, data analysis, communication systems which are suitable for shop floor applications, in general, and related to the Industry Internet of Things (IIoT).

8.4.3 Improve computational efficiency

In this research, NSGA II and the MATLAB 'global optimisation toolbox' have been applied in the case study. In the advancement of operational research, it is worth trying other optimisation algorithms to better fit with the non-linear and NP-hard problem. Because the proposed simulation-optimisation integrated framework provides a convenient interface to handle the data exchange, so it is also possible to couple with a machine learning method, in terms of using a simulation model to train a machine learning model to support the decision making process for FMS.

8.5 Conclusions

Flexible manufacturing is an essential capability for manufacturers to survive in the current intensive and dynamic market competition; however, with the intrinsic complexity of the FMS, there is a lack of practical tools for the manufacturing manager to realise and control the flexibility of the FMS fully. Therefore, this research was undertaken to advance the understanding of the manufacturing problems within the FMS, and to develop simulation and optimisation technologies to support its management. The state-of-the-art in simulation and optimisation methods related to FMS have been identified. An empirical case study was carried out to observe and identify the interactions and behaviours of the primary manufacturing problems in FMS. A simulation-optimisation integration framework is proposed to address the dynamic, discrete and non-linear relationship of the events for FMS, and thus be able to represent and optimise the multiple manufacturing problems simultaneously. A novel simulation method is developed to capture and represent primary subsystems and their interactions with FMS. Iterative experiments using the comprehensive simulation model have been carried out, that combine the simulation of future scenarios (Tan et al., 2019). Based on the proposed framework and the developed FMS simulation model, a multi-objective optimisation approach has been carried out to solve the identified FMS scheduling problems within the context of the overall system. The simulation and optimisation methods developed from this research has been validated and applied to the real-world FMS, benefited the decision-making process of manufacturing operation strategy for the industry partner (Appendix C).

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APPENDICES

Appendix A Optimisation objectives from literature review

Table A-1 List of optimisation objectives

List of Objectives	
Minimise the machine idle time	IT
Minimise the total penalty cost	PC
Minimise the WIP	WIP
Minimise the lead time	LT
Minimise the Makespan	MS
Minimise the Flowtime	FT
Minimise the tardiness	TD
Minimise the load of MHS	MHS
Minimise the machine cost	MC
Minimise the separation of the machines	MSM
Minimise the tool changes at each machine	TC
Minimise the movement	MM
Maximise the throughput	TP
Maximise the production rate	PR
Maximise the machine utilisation	MU
Balance the machine workload	BW
Machine tool selection	MT
Operation allocation	OA

Appendix B Simulation experiment subsidiary details

B.1 Develop and validate log for FMS base-model

Table B-1 Develop and validate log for FMS base-model

Version	Date	Description	Type
1	09/03/2016	Basic Manufacturing Operation	Basic
2	13/03/2016	Multiple Machine and pallet functions	Add Function
3	23/03/2016	Loading, Buffer functions	Add Function
4	28/03/2016	Data input file, add machine selection, analysis functions	Add Function
5	05/04/2016	System set-up interface, create shared workspace for optimisation	Add Function
6	18/06/2016	Input industry data, single model, mixed product	Add Function
7	28/06/2016	Pallet sub-system, Initial industry scale	Add Function
8	01/07/2016	Input real variation data, introduce scrap	Add Function
9	04/07/2016	Add Manual assembly operation, rework	Add Function
10	05/07/2016	Add Vic operation	Release Flexibility
11	19/07/2016	Add CMM function	Add Function
12	27/07/2016	Flexible releasing (One OP, multiple machines)	Release Flexibility
13	09/08/2016	PT ramp up, add output schedule	Add Function
14	15/08/2016	Flexible releasing (One OP, multiple machines) update	Release Flexibility
15	01/09/2016	PT ramp up, Scrap rate update	Data update
16	13/09/2016	PT ramp up, Move Head OP40	Process Change
17	22/09/2016	M3 CT reduction, Move Head OP40	Process Change
18	06/10/2016	PT ramp up, loading schedule update	Data update
19	17/10/2016	Missing components (head or block)	Product Change
20	21/10/2016	Missing components, Rebalancing, new schedules	Product Change
21	09/11/2016	split O90 MC 4 and MC 6, but machining only one head at a time	Release Flexibility
22	22/11/2016	PT update, and Pattern verify	Data update

23	05/12/2016	CH40onMC6CH90onMC4	Process Change
24	11/01/2017	Validate the defined patterns	Add Function
25	27/02/2017	implement the pattern as Kanban, updated	Add Function

B.2 Simulation Experiment: Order input programming scripts

```
%created: 20180127 Last updated: 20180327 Author: Boyang SONG
clear
clc
tic
load_system('FMS_Sim');
load('dataMEGA');


%% Set-up 1
%var_0=[250.714285714286,68.1553398058253,2,2,12345,7020];  %  inter-arrive time_1, inter-arrive time_2,Loading, Unloading, Seed, Available Time
    var=[250.714285714286,68.1553398058253,2,2,12345,7020];
    %var(1)=var(6)/32; %initiate inter-arrive time for product 1


%% Simulation parameters
totalrun=10; %step of experiment
startpoint=0;
range=50;
step=range/totalrun;


X=[];
Y=[];


for i=1:totalrun
    X(i)=i*step-1+startpoint;


    var(1)=var(6)/X(i);
    assignin('base','DecisionVariables',var);
```

```
    sim('FMS_Sim');

    yout=unique(yout,'rows');

    Y(i,:)=mean(yout(10:end,:));

end

close_system('FMS_Sim')

totalctime=toc;


fprintf('The total computing time was: %g seconds\n', totalctime);

fprintf('The   computing   time   for   each   run   was:   %g   seconds\n',
totalctime/totalrun);

%% Plot

f=figure('units','normalized','Color',[1 1 1],'outerposition',[0 0 1 1]);

ax1 = subplot(2,2,1);

plot(ax1,X,Y(:,1),X,Y(:,2),'LineWidth',2);

title(ax1,'Experiment: Order input','FontSize',14)

xlabel(ax1,{'Order input of product 1', '(order per week)'},'FontSize',14)

ylabel(ax1,{'Thoughput','(order per week)'},'FontSize',14)

legend(ax1,'Product1','Product2')

legend('boxoff')


ax2=subplot(2,2,2);

plot(ax2,X,Y(:,3),X,Y(:,4),'LineWidth',2);

title(ax2,'Experiment: Order input','FontSize',14)

xlabel(ax2,{'Order input of product 1', '(order per week)'},'FontSize',14)

ylabel(ax2,{'Flow time','(minute)'},'FontSize',14)

legend(ax2,'Product1','Product2')

legend('boxoff')


ax3=subplot(2,2,3);

plot(ax3,X,Y(:,5),X,Y(:,6),'LineWidth',2);

title(ax3,'Experiment: Order input','FontSize',14)

xlabel(ax3,{'Order input of product 1', '(order per week)'},'FontSize',14)

ylabel(ax3,{'Level of WIP','(num of order)'},'FontSize',14)
```

```
legend(ax3,'Product1','Product2')
legend('boxoff')

ax4=subplot(2,2,4);
plot(ax4,X,Y(:,7)*100,X,Y(:,8)*100,'LineWidth',2);
title(ax4,'Experiment: Order input','FontSize',14)
xlabel(ax4,{'Order input of product 1', '(order per week)'},'FontSize',14)
ylabel(ax4,{'Utilisation & Workload variation','(percentage)'},'FontSize',14)
legend(ax4,'Mean Utilisation','Workload Variations')
legend('boxoff')
```

B.3 Simulation experiment: results

Table B-2 Simulation Experiment: Order input, results

	Independent Variables	Dependent Variables							
Run	Order input rate of product 1	Throughput 1	Throughput 2	FlowTime 1	FlowTime 2	WIP1	WIP2	Mean Utilisation	Workload variation
iteration	(order per week)	(order)		(Minute)		(order)		(Percentage)	
1	0.6	1.08	101.63	463.10	124.95	0.04	2.03	43%	36%
2	2.2	2.52	101.62	440.93	126.78	0.15	2.08	41%	36%
3	3.8	4.02	101.61	433.54	128.95	0.25	2.15	42%	35%
4	5.4	5.53	101.60	432.94	130.84	0.35	2.20	44%	34%
5	7	7.04	101.59	434.11	132.99	0.45	2.27	45%	33%
6	8.6	8.55	101.57	432.64	134.64	0.55	2.32	47%	31%
7	10.2	10.08	101.55	429.16	136.81	0.64	2.38	49%	30%
8	11.8	11.59	101.54	429.84	139.23	0.74	2.46	50%	29%
9	13.4	13.12	101.52	429.29	140.79	0.84	2.52	52%	28%
10	15	14.63	101.51	429.40	142.72	0.94	2.61	54%	26%
11	16.6	16.15	101.48	430.53	145.39	1.12	2.68	55%	25%
12	18.2	17.65	101.48	440.02	146.14	1.32	2.70	57%	24%
13	19.8	19.18	101.39	444.05	151.53	1.36	2.76	59%	23%
14	21.4	20.74	101.35	432.52	155.80	1.39	2.83	60%	21%
15	23	22.27	101.26	431.10	165.81	1.54	2.95	62%	20%
16	24.6	23.74	101.37	439.21	157.02	1.64	2.83	64%	19%
17	26.2	25.23	101.30	454.55	161.04	1.73	2.87	65%	18%
18	27.8	26.71	101.36	461.78	160.36	2.00	2.88	67%	17%

19	29.4	28.22	101.25	467.47	168.42	2.11	2.93	69%	17%
20	31	29.70	101.14	481.38	178.87	2.29	2.97	70%	17%
21	32.6	31.07	101.13	516.40	182.61	2.64	2.88	72%	18%
22	34.2	32.59	101.06	509.21	191.87	2.69	3.01	74%	18%
23	35.8	34.13	100.89	509.44	199.41	2.75	3.24	75%	18%
24	37.4	35.68	100.70	506.63	213.05	2.75	3.55	77%	18%
25	39	35.17	97.81	705.27	352.46	4.06	5.56	78%	18%
26	40.6	30.74	93.08	738.01	289.47	4.42	4.64	77%	18%
27	42.2	29.13	89.19	880.89	366.29	5.45	5.80	76%	18%
28	43.8	24.52	84.42	707.43	278.79	4.76	4.61	75%	18%
29	45.4	21.97	81.50	743.53	294.82	5.03	4.83	74%	18%
30	47	21.40	81.53	770.90	291.32	5.39	4.75	75%	18%
31	48.6	20.14	79.15	788.90	307.79	5.71	4.96	74%	18%
32	50.2	18.31	78.80	786.91	298.28	6.00	4.70	74%	17%
33	51.8	8.30	68.41	654.67	286.64	6.00	4.67	64%	16%
34	53.4	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
35	55	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
36	56.6	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
37	58.2	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
38	59.8	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
39	61.4	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
40	63	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
41	64.6	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
42	66.2	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
43	67.8	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
44	69.4	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
45	71	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
46	72.6	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
47	74.2	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
48	75.8	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
49	77.4	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
50	79	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN

Table B-3 Simulation Experiment: Pallet Capacity, results

Run	Independent Variables	Dependent Variables							
	Order input rate of product 1	Throughput 1	Throughput 2	FlowTime 1	FlowTime 2	WIP1	WIP2	Mean Utilisation	Workload variation
iteration	(order per week)	(order)		iteration		(order per week)		(order)	
1	1	32.25	93.94	714.24	336.42	4.24	5.28	76.97%	18.35%
2	2	35.33	98.21	841.80	360.42	4.92	5.67	78.31%	18.33%
3	3	35.90	98.89	869.86	364.36	5.11	5.75	78.58%	18.34%
4	4	36.39	99.34	902.07	382.99	5.27	6.02	78.78%	18.35%
5	5	36.79	99.69	951.09	422.54	5.57	6.59	78.94%	18.35%
6	6	36.98	99.86	967.82	437.68	5.67	6.80	79.03%	18.36%
7	7	36.99	99.91	964.65	421.92	5.64	6.57	79.04%	18.36%
8	8	36.99	99.91	967.21	419.34	5.66	6.53	79.04%	18.36%
9	9	36.99	99.91	967.21	419.34	5.66	6.53	79.04%	18.36%
10	10	36.99	99.91	967.21	419.34	5.66	6.53	79.04%	18.36%

Table B-4 Simulation Experiment: Operation sequence, independent variables

30 Simulation iterations of operation sequence (each column)																													
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	4	2	4	2	2	2	3	3	4	1	4	4	1	4	4	1	1	2	2	2	4	1	2	4	3	2	2	4	4
2	3	4	3	3	1	1	1	2	3	3	2	3	3	1	2	4	4	3	3	3	2	2	4	1	1	4	1	2	2
4	2	3	1	1	3	3	2	1	1	2	1	2	4	3	1	2	2	1	1	1	1	4	3	2	2	1	4	1	3
3	1	1	2	4	4	4	4	4	2	4	3	1	2	2	3	3	3	4	4	4	3	3	1	3	4	3	3	3	1
6	3	5	6	5	4	2	4	3	3	2	5	6	6	5	1	4	6	6	5	5	2	5	5	3	6	1	1	2	4
2	5	6	4	6	5	6	2	2	4	1	3	1	5	4	4	1	1	2	1	2	5	3	6	5	2	6	5	6	6

	4 1 3 2 3 2 3 5 1 5 4 1 5 3 3 2 5 5 5 3 6 4 6 3 2 4 2 3 1 2
	5 2 1 5 1 6 1 6 6 2 5 2 4 1 6 5 6 4 3 6 1 3 4 2 6 1 4 6 5 5
	3 4 2 3 2 1 4 1 5 1 6 4 2 2 1 3 2 2 4 2 4 6 1 4 1 3 5 2 4 3
	1 6 4 1 4 3 5 3 4 6 3 6 3 4 2 6 3 3 1 4 3 1 2 1 4 5 3 4 3 1
	2 2 2 3 1 1 2 2 2 2 1 2 3 1 1 2 3 3 2 1 3 2 3 1 2 3 3 1 2 1
	1 3 1 1 3 2 3 3 3 1 3 1 2 3 2 3 1 2 3 2 2 1 2 2 1 2 2 3 3 3
	3 1 3 2 2 3 1 1 1 3 2 3 1 2 3 1 2 1 1 3 1 3 1 3 3 1 1 2 1 2
	2 2 2 2 2 2 2 2 1 1 1 1 2 1 1 1 2 1 1 1 2 2 1 1 1 2 2 2 1 1
	1 1 1 1 1 1 1 1 2 2 2 2 1 2 2 2 1 2 2 2 1 1 2 2 2 1 1 1 2 2
	2 1 3 2 1 3 1 3 1 2 2 1 3 1 1 1 2 2 2 1 1 3 1 3 2 3 1 3 2 1
	1 3 2 3 2 2 3 2 3 1 1 2 2 3 3 2 3 3 3 3 2 2 3 2 3 2 3 1 3 2
	3 2 1 1 3 1 2 1 2 3 3 3 1 2 2 3 1 1 1 2 3 1 2 1 1 1 2 2 1 3
	2 2 2 1 2 2 1 1 2 1 1 2 1 2 1 2 1 1 1 2 1 2 1 1 2 1 1 1 2 1
	1 1 1 2 1 1 2 2 1 2 2 1 2 1 2 1 2 2 2 1 2 1 2 2 1 2 2 2 1 2
	1 2 1 2 1 2 2 1 2 1 1 2 2 1 1 1 1 1 1 2 1 1 2 2 1 1 1 1 2 1
	2 1 2 1 2 1 1 2 1 2 2 1 1 2 2 2 2 2 2 1 2 2 1 1 2 2 2 2 1 2
	3 2 3 1 1 2 1 1 3 3 2 3 1 2 3 3 2 2 2 3 2 2 2 3 3 2 1 1 2 2
	1 1 2 2 2 1 2 2 2 1 3 2 2 3 1 1 1 3 1 1 1 3 3 1 1 3 2 3 3 3
	2 3 1 3 3 3 3 3 1 2 1 1 3 1 2 2 3 1 3 2 3 1 1 2 2 1 3 2 1 1

Table B-5 Simulation Experiment: Operation Sequence, results

Run	Dependent Variables							
	Throughput 1	Throughput 2	Flow Time 1	Flow Time 2	WIP1	WIP2	Mean Utilisation	Workload variation
iteration	(order)		(Minute)		(order)		(Percentage)	
Root	26.91	101.36	459.72	161.17	2.00	2.88	67.21%	17.39%
1	26.90	101.32	472.52	163.70	1.90	2.84	67.18%	17.30%
2	26.74	100.87	521.25	208.94	2.19	3.48	67.07%	17.22%
3	26.98	101.34	452.26	154.52	1.84	2.78	67.25%	17.38%
4	26.86	101.21	487.19	166.61	1.99	2.88	67.17%	17.35%
5	26.87	100.96	496.06	192.44	1.99	3.09	67.18%	17.19%
6	26.82	101.14	492.37	180.94	1.99	2.95	67.18%	17.23%
7	26.95	101.16	446.36	181.08	1.84	3.03	67.23%	17.34%
8	26.88	101.36	466.80	156.41	1.89	2.80	67.24%	17.25%
9	26.64	100.76	535.04	216.24	2.41	3.66	67.10%	17.31%
10	26.90	101.11	478.80	182.71	2.01	3.09	67.14%	17.41%
11	26.72	101.43	513.45	152.00	2.21	2.64	67.18%	17.40%
12	26.88	101.17	484.07	177.87	2.11	3.01	67.22%	17.38%
13	26.86	101.13	490.98	182.35	2.01	3.05	67.19%	17.36%
14	26.83	101.42	469.17	155.28	1.96	2.63	67.23%	17.57%
15	26.77	101.36	511.63	154.34	2.17	2.76	67.17%	17.31%
16	26.88	100.64	501.73	223.71	2.09	3.81	67.09%	17.19%
17	26.78	101.02	511.84	188.90	2.18	3.17	67.06%	17.20%
18	26.59	101.14	589.42	180.80	2.38	3.07	67.09%	17.43%
19	26.62	100.18	581.95	288.71	2.48	4.66	66.83%	17.15%

20	26.83	101.15	505.38	175.06	2.15	3.03	67.16%	17.15%
21	26.89	101.24	466.71	165.13	1.93	2.89	67.15%	17.36%
22	26.77	101.32	516.16	159.43	2.28	2.79	67.18%	17.29%
23	26.89	101.40	436.62	156.28	1.85	2.53	67.29%	17.34%
24	27.02	101.17	444.02	177.97	1.79	3.00	67.23%	17.22%
25	26.86	101.29	489.71	162.09	1.99	2.91	67.17%	17.28%
26	26.83	101.45	475.85	150.46	1.91	2.55	67.27%	17.50%
27	26.95	100.97	453.90	189.86	1.91	3.16	67.16%	17.29%
28	26.79	101.31	494.85	162.63	2.05	2.85	67.26%	17.23%
29	27.00	101.23	427.96	168.88	1.70	2.88	67.28%	17.35%
30	26.86	101.37	467.57	156.42	1.88	2.73	67.27%	17.21%

Table B-6 Simulation Experiment: Dispatching Rules, results

ITER	LOF	TICKER	ORDER PER WEEK	THROUGHPUT1	THROUGHPUT2	FLOWTIME1	FLOWTIME2	WIP1	WIP2	UTILISATION	W.V.
1	1	FIFO	23	21.67	101.10	478.28	198.23	1.60	3.34	61.29%	27.09%
2	1	LIFO	23	21.69	101.12	478.90	193.77	1.59	3.28	61.30%	26.26%
3	1	SPT	23	21.66	101.09	480.37	200.39	1.61	3.38	61.29%	27.08%
4	1	LPT	23	21.71	100.99	473.88	207.74	1.58	3.48	61.30%	27.00%
5	1	EDD	23	21.71	100.99	473.88	207.74	1.58	3.48	61.30%	27.00%
6	1	HLO	23	21.71	100.99	473.88	207.74	1.58	3.48	61.30%	27.00%
7	1	LLO	23	21.66	101.08	481.14	201.09	1.61	3.39	61.29%	27.07%
8	1	MTNO	23	21.72	101.03	471.89	199.63	1.57	3.36	61.28%	26.92%
9	1	LTNO	23	21.66	101.16	497.42	196.24	1.66	3.30	61.29%	26.19%
10	1	FIFO	26	24.47	100.90	496.30	216.43	1.85	3.60	64.35%	25.64%
11	1	LIFO	26	24.45	101.04	494.96	203.28	1.85	3.41	64.34%	24.74%
12	1	SPT	26	24.46	100.89	499.46	215.33	1.87	3.60	64.35%	25.75%
13	1	LPT	26	24.45	100.86	490.48	219.38	1.84	3.63	64.32%	25.77%
14	1	EDD	26	24.45	100.86	490.48	219.38	1.84	3.63	64.32%	25.77%
15	1	HLO	26	24.45	100.86	490.48	219.38	1.84	3.63	64.32%	25.77%

16	1	LLO	26	24.46	100.90	497.36	213.49	1.86	3.57	64.35%	25.65%
17	1	MTNO	26	24.48	100.99	490.22	209.25	1.84	3.49	64.35%	25.71%
18	1	LTNO	26	24.43	101.02	510.66	208.02	1.91	3.44	64.33%	25.82%
19	1	FIFO	29	27.20	100.70	506.42	241.81	2.11	3.99	67.37%	24.74%
20	1	LIFO	29	27.21	100.93	508.99	224.08	2.13	3.68	67.39%	24.38%
21	1	SPT	29	27.20	100.64	503.17	235.31	2.08	3.89	67.38%	24.46%
22	1	LPT	29	27.21	100.66	501.75	232.17	2.10	3.84	67.35%	24.73%
23	1	EDD	29	27.21	100.66	501.75	232.17	2.10	3.84	67.35%	24.73%
24	1	HLO	29	27.21	100.66	501.75	232.17	2.10	3.84	67.35%	24.73%
25	1	LLO	29	27.19	100.67	510.08	247.45	2.10	4.10	67.37%	24.84%
26	1	MTNO	29	27.21	100.75	496.39	229.66	2.07	3.78	67.37%	25.03%
27	1	LTNO	29	27.17	100.93	517.04	220.83	2.17	3.64	67.38%	24.49%
28	1	FIFO	32	29.88	100.52	534.73	255.22	2.45	4.18	70.39%	23.63%
29	1	LIFO	32	29.94	100.72	519.78	237.13	2.39	3.88	70.40%	23.15%
30	1	SPT	32	29.88	100.51	531.94	253.23	2.42	4.16	70.39%	23.37%
31	1	LPT	32	29.94	100.54	523.03	255.49	2.39	4.17	70.39%	23.67%
32	1	EDD	32	29.94	100.54	523.03	255.49	2.39	4.17	70.39%	23.67%
33	1	HLO	32	29.94	100.54	523.03	255.49	2.39	4.17	70.39%	23.67%
34	1	LLO	32	29.88	100.49	535.45	258.22	2.41	4.24	70.38%	23.42%
35	1	MTNO	32	29.96	100.62	510.91	241.34	2.34	3.95	70.41%	23.93%
36	1	LTNO	32	29.89	100.66	541.77	243.93	2.48	4.00	70.39%	23.95%
37	1	FIFO	35	32.65	100.43	553.08	269.40	2.76	4.37	73.43%	22.26%
38	1	LIFO	35	32.63	100.58	551.18	250.20	2.75	4.08	73.42%	22.58%
39	1	SPT	35	32.60	100.43	538.71	257.37	2.70	4.20	73.42%	22.23%
40	1	LPT	35	32.63	100.50	540.12	260.37	2.70	4.24	73.43%	22.49%
41	1	EDD	35	32.63	100.50	540.12	260.37	2.70	4.24	73.43%	22.49%
42	1	HLO	35	32.63	100.50	540.12	260.37	2.70	4.24	73.43%	22.49%
43	1	LLO	35	32.59	100.35	550.46	272.90	2.76	4.42	73.40%	22.22%
44	1	MTNO	35	32.66	100.36	542.31	263.58	2.70	4.27	73.39%	22.71%
45	1	LTNO	35	32.62	100.49	556.27	252.13	2.81	4.12	73.41%	22.28%
46	1	FIFO	38	35.26	100.26	596.95	286.34	3.26	4.59	76.40%	20.95%
47	1	LIFO	38	35.34	100.54	579.58	258.06	3.14	4.19	76.44%	21.16%
48	1	SPT	38	35.28	100.30	585.28	276.22	3.17	4.45	76.41%	20.78%
49	1	LPT	38	35.24	100.27	581.06	277.44	3.14	4.50	76.38%	21.09%
50	1	EDD	38	35.24	100.27	581.06	277.44	3.14	4.50	76.38%	21.09%
51	1	HLO	38	35.24	100.27	581.06	277.44	3.14	4.50	76.38%	21.09%

52	1	LLO	38	35.26	100.21	598.60	286.76	3.23	4.61	76.39%	21.10%
53	1	MTNO	38	35.27	100.41	587.92	274.56	3.19	4.40	76.42%	21.06%
54	1	LTNO	38	35.23	100.40	603.29	272.20	3.29	4.36	76.40%	20.94%
55	2	FIFO	23	21.69	101.37	496.30	171.07	1.63	2.92	61.34%	2.56%
56	2	LIFO	23	21.68	101.42	488.58	170.22	1.60	2.88	61.33%	2.76%
57	2	SPT	23	21.67	101.38	488.40	171.92	1.60	2.91	61.33%	2.75%
58	2	LPT	23	21.65	101.35	490.92	172.16	1.62	2.92	61.32%	2.12%
59	2	EDD	23	21.65	101.35	490.92	172.16	1.62	2.92	61.32%	2.12%
60	2	HLO	23	21.65	101.35	490.92	172.16	1.62	2.92	61.32%	2.12%
61	2	LLO	23	21.68	101.37	490.41	171.38	1.61	2.94	61.34%	2.27%
62	2	MTNO	23	21.68	101.42	484.64	169.10	1.57	2.83	61.34%	2.33%
63	2	LTNO	23	21.65	101.38	511.52	171.02	1.68	2.90	61.32%	2.47%
64	2	FIFO	26	24.46	101.38	500.11	172.42	1.86	2.94	64.40%	2.13%
65	2	LIFO	26	24.43	101.41	501.93	171.98	1.85	2.89	64.39%	2.29%
66	2	SPT	26	24.45	101.37	499.15	170.89	1.87	2.93	64.39%	2.06%
67	2	LPT	26	24.42	101.39	502.34	172.01	1.87	2.91	64.39%	2.08%
68	2	EDD	26	24.42	101.39	502.34	172.01	1.87	2.91	64.39%	2.08%
69	2	HLO	26	24.42	101.39	502.34	172.01	1.87	2.91	64.39%	2.08%
70	2	LLO	26	24.42	101.39	498.70	172.67	1.87	2.94	64.40%	2.25%
71	2	MTNO	26	24.49	101.36	489.53	171.44	1.81	2.88	64.41%	2.65%
72	2	LTNO	26	24.40	101.34	505.34	175.08	1.87	2.94	64.38%	2.18%
73	2	FIFO	29	27.19	101.26	510.90	181.15	2.15	3.03	67.45%	2.17%
74	2	LIFO	29	27.18	101.31	505.63	178.44	2.12	2.99	67.43%	2.65%
75	2	SPT	29	27.18	101.34	504.53	180.32	2.14	3.00	67.46%	2.46%
76	2	LPT	29	27.24	101.31	499.85	176.45	2.10	2.97	67.45%	2.42%
77	2	EDD	29	27.24	101.31	499.85	176.45	2.10	2.97	67.45%	2.42%
78	2	HLO	29	27.24	101.31	499.85	176.45	2.10	2.97	67.45%	2.42%
79	2	LLO	29	27.20	101.29	509.22	181.20	2.16	3.01	67.46%	2.37%
80	2	MTNO	29	27.23	101.33	502.55	175.28	2.10	2.95	67.46%	2.61%
81	2	LTNO	29	27.14	101.32	517.49	177.76	2.18	2.99	67.43%	2.07%
82	2	FIFO	32	29.95	101.28	512.94	182.71	2.39	3.02	70.51%	2.52%
83	2	LIFO	32	29.94	101.29	517.28	181.01	2.41	3.01	70.49%	2.38%
84	2	SPT	32	29.95	101.27	514.39	182.27	2.40	3.04	70.50%	2.13%
85	2	LPT	32	29.93	101.31	514.50	181.67	2.38	3.04	70.50%	2.56%
86	2	EDD	32	29.93	101.31	514.50	181.67	2.38	3.04	70.50%	2.56%
87	2	HLO	32	29.93	101.31	514.50	181.67	2.38	3.04	70.50%	2.56%

88	2	LLO	32	29.91	101.29	515.81	184.87	2.39	3.07	70.52%	2.08%
89	2	MTNO	32	29.95	101.29	508.45	180.47	2.36	3.01	70.52%	2.10%
90	2	LTNO	32	29.93	101.31	526.61	181.09	2.44	3.04	70.50%	1.88%
91	2	FIFO	35	32.70	101.22	519.77	185.74	2.62	3.09	73.57%	2.55%
92	2	LIFO	35	32.69	101.24	523.83	186.89	2.63	3.08	73.54%	2.85%
93	2	SPT	35	32.67	101.22	516.79	185.86	2.67	3.07	73.57%	2.20%
94	2	LPT	35	32.66	101.21	524.51	185.98	2.66	3.09	73.55%	1.97%
95	2	EDD	35	32.66	101.21	524.51	185.98	2.66	3.09	73.55%	1.97%
96	2	HLO	35	32.66	101.21	524.51	185.98	2.66	3.09	73.55%	1.97%
97	2	LLO	35	32.65	101.23	518.32	186.08	2.66	3.10	73.57%	2.17%
98	2	MTNO	35	32.70	101.30	514.24	184.08	2.61	3.04	73.58%	2.19%
99	2	LTNO	35	32.64	101.23	536.73	191.13	2.71	3.16	73.54%	2.34%
100	2	FIFO	38	35.42	101.22	520.58	189.07	2.91	3.13	76.61%	1.75%
101	2	LIFO	38	35.39	101.24	528.17	189.11	2.94	3.13	76.59%	1.78%
102	2	SPT	38	35.37	101.16	536.52	191.88	2.98	3.18	76.60%	2.54%
103	2	LPT	38	35.42	101.21	524.92	193.50	2.91	3.20	76.61%	2.47%
104	2	EDD	38	35.42	101.21	524.92	193.50	2.91	3.20	76.61%	2.47%
105	2	HLO	38	35.42	101.21	524.92	193.50	2.91	3.20	76.61%	2.47%
106	2	LLO	38	35.38	101.20	532.41	194.20	2.95	3.18	76.61%	2.39%
107	2	MTNO	38	35.38	101.21	530.81	191.30	2.91	3.17	76.60%	2.32%
108	2	LTNO	38	35.32	101.22	541.00	190.22	3.00	3.15	76.58%	2.03%

Appendix C Quote from industry partner

At the end of this PhD research project, the author has received the feedback from the industry partner.

From: Enticott, Shane

Sent: 18 October 2016 13:57

To: Song, Boyang

Cc: Tiwari, Ashutosh

Subject: RE: New presentation and quote

Hello Boyang,

The collaborative efforts jointly expended by Cosworth and Cranfield University over the life of the programme thus far, have yielded great benefits for both parties. The novel simulation and optimisation research carried out to date, has provided both effective and adaptable tools, frequently used in the intricate decision-making processes intrinsic to our Flexible Manufacturing System.

– Shane Enticott, Program manager, Cosworth

Appendix D Optimisation subsidiary details

D.1 Optimisation programming script

```
%% H1 Intro
close_system('FMS_new')
clear
clc
dianame=['myTextLog' datestr(now,'yyyymmddHHMMSS')] ;
diary([dianame '.txt']);

%% H2 Setting up
%Optimisation
FitnessFunction = @fms_multiobjective; % Function handle to the fitness function %TBD
numberOfVariables = 27; % Number of decision variables
lb =[ 1    1    1    1    1  1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1    1
1    1    1 18 100]; % Lower bound
ub = [9    9    2    2    9    9    2    9    9    2    9    9    2    9    9    9    9    2    9    9    9
9    9    9    9 35 110]; % Upper bound
A = []; % No linear inequality constraints
b = []; % No linear inequality constraints
Aeq = []; % No linear equality constraints
beq = []; % No linear equality constraints

MaxGen=1000;

%Overhead
%rng default % for reproducibility

%IntCon = [1 2]; % Integer constraints
%ga handles options for integer constraints differently; this notation does not apply to gamultiobj.
options = optimoptions(@gamultiobj,'Display','iter',...
'PlotFcn',{@gaplotpareto,@gaplotrankhist,@gaplotspread,...
@gaplotdistance,@gaplotscorediversity,@gaplotselection},...
'OutputFcn',@fig2mov,...
'MaxGenerations',MaxGen,...
'UseParallel',true)

%'MaxGenerations',MaxGen,...
%'ParetoFraction',0.5,...
%'PopulationSize',500,...'MaxStallGenerations',50,...
%'MaxGenerations',MaxGen,...
%% H3 Optimisation Function
tic
pool = parpool; % Open a parallel pool
tt1=toc;

tic
pctRunOnAll('load_system("FMS_new")');% Loading the model to run on all parallel workers
tt2=toc;

tic
[x,fval,exitflag,output,population,scores] = ...
gamultiobj(FitnessFunction,numberOfVariables,A,b,Aeq,beq,lb,ub,options);
tt3=toc;

tic
```

D.2 Optimisation set-up

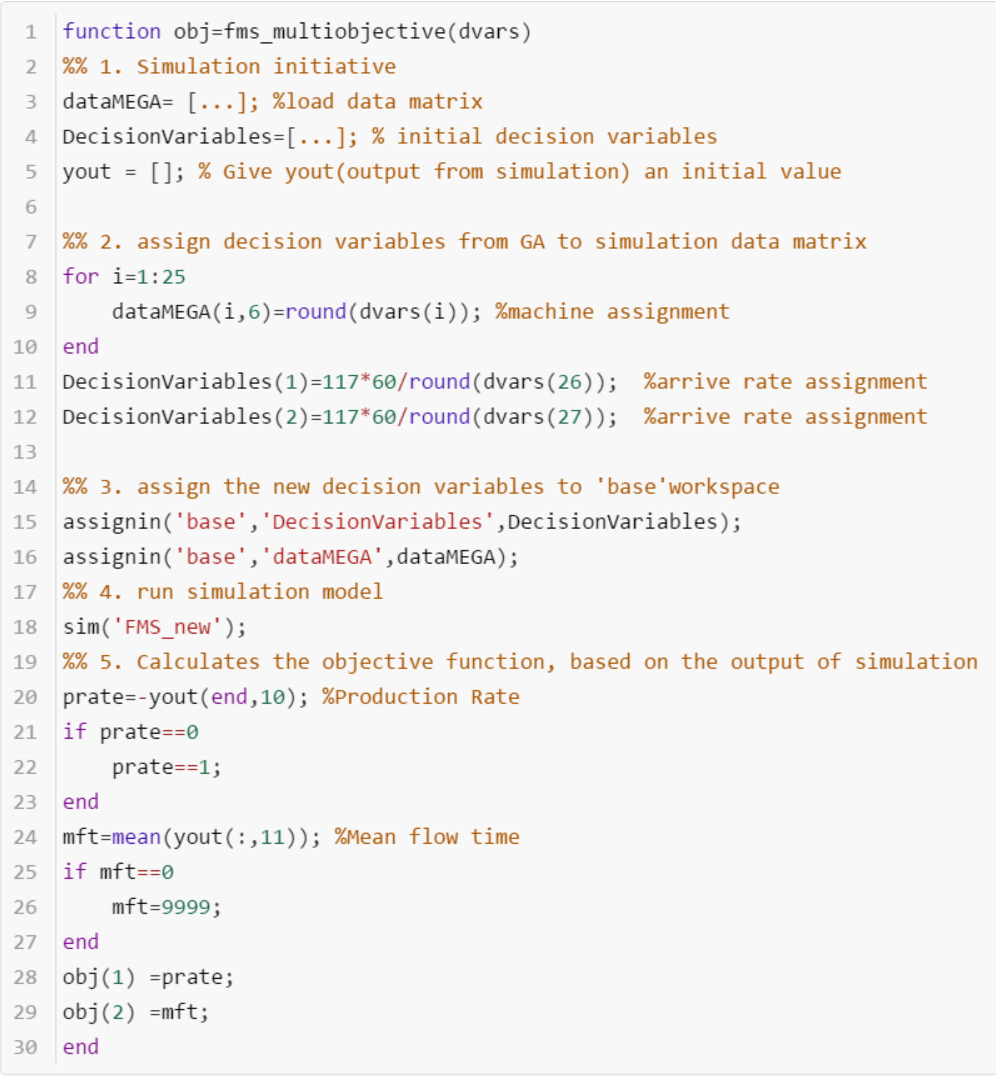
```
gamultiobj options:

  Set properties:
                   Display: 'iter'
            MaxGenerations: 100
                 OutputFcn: @fig2mov
                   PlotFcn: {1×6 cell}
               UseParallel: 1

  Default properties:
       ConstraintTolerance: 1.0000e-03
               CreationFcn: @gacreationuniform
              CrossoverFcn: @crossoverintermediate
         CrossoverFraction: 0.8000
        DistanceMeasureFcn: {@distancecrowding  'phenotype'}
         FunctionTolerance: 1.0000e-04
                 HybridFcn: []
   InitialPopulationMatrix: []
    InitialPopulationRange: []
       InitialScoresMatrix: []
       MaxStallGenerations: 100
                   MaxTime: Inf
               MutationFcn: @mutationadaptfeasible
            ParetoFraction: 0.3500
            PopulationSize: '50 when numberOfVariables <= 5, else 200'
            PopulationType: 'doubleVector'
              SelectionFcn: {@selectiontournament  [2]}
             UseVectorized: 0
```

Figure D-1 Set-up of @gamultiobj--Global Optimisation Toolbox

D.3 Objective fitness function



```
function obj=fms_multiobjective(dvars)
%% 1. Simulation initiative
dataMEGA= [...]; %load data matrix
DecisionVariables=[...]; % initial decision variables
yout = []; % Give yout(output from simulation) an initial value

%% 2. assign decision variables from GA to simulation data matrix
for i=1:25
    dataMEGA(i,6)=round(dvars(i)); %machine assignment
end
DecisionVariables(1)=117*60/round(dvars(26));  %arrive rate assignment
DecisionVariables(2)=117*60/round(dvars(27));  %arrive rate assignment

%% 3. assign the new decision variables to 'base'workspace
assignin('base','DecisionVariables',DecisionVariables);
assignin('base','dataMEGA',dataMEGA);
%% 4. run simulation model
sim('FMS_new');
%% 5. Calculates the objective function, based on the output of simulation
prate=-yout(end,10); %Production Rate
if prate==0
    prate==1;
end
mft=mean(yout(:,11)); %Mean flow time
if mft==0
    mft=9999;
end
obj(1) =prate;
obj(2) =mft;
end
```

Figure D-2 Example of objective fitness function