CRANFIELD UNIVERSITY

Justyna Rybicka

Modelling Flexible Manufacturing Systems through Discrete Event Simulation

School of Aerospace, Transport and Manufacturing
PhD in Manufacturing

PhD
Academic Year: 2014 - 2017

Supervisor: Professor Ashutosh Tiwari
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This thesis is submitted in partial fulfilment of the requirements for the degree of PhD

ABSTRACT

As customisation and product diversification are becoming standard, industry is looking for strategies to become more adaptable in responding to customer's needs. Flexible manufacturing systems (FMS) provide a unique capability where there is a need to provide efficiency through production flexibility. Full potential of FMS development is difficult to achieve due to the variability of components within this complex manufacturing system. It has been recognised that there is a requirement for decision support tools to address different aspects of FMS development. Discrete event simulation (DES) is the most common tool used in manufacturing sector for solving complex problems. Through systematic literature review, the need for a conceptual framework for decision support in FMS using DES has been identified.

Within this thesis, the conceptual framework (CF) for decision support for FMS using DES has been proposed. The CF is designed based on decision-making areas identified for FMS development in literature and through industry stakeholder feedback: set-up, flexibility and schedule configuration. The CF has been validated through four industrial simulation case studies developed as a part of implementation of a new FMS plant in automotive sector. The research focuses on:

(1) a method for primary data collection for simulation validated through a case study of material handling robot behaviour in FMS;

(2) an approach for evaluation of optimal production set-up for industrial FMS with DES;

(3) a DES based approach for testing FMS flexibility levels;

(4) an approach for testing scheduling in FMS with the use of DES.

The study has supported the development of systematic approach for decision making in FMS development using DES. The approach provided tools for evidence based decision making in FMS.

Keywords: Flexible manufacturing systems, decision support, simulation

LIST OF PUBLICATIONS

Published

Rybicka, J., Tiwari, A., Enticott, S., (2015) *Testing a Flexible Manufacturing System Facility Production Capacity through Discrete Event Simulation: Automotive Case Study, World Academy of Science*, Engineering and Technology, International Science Index, Industrial and Manufacturing Engineering, Vol.2 (4),pp. 924 -930.

Rybicka, J., Tiwari, A., Enticott, S., (2016) *Improving data accuracy in simulation of flexible manufacturing systems*, International Conference of Manufacturing Research 2016, Advances in Manufacturing Technology XXX: Proceedings of the 14th International Conference on Manufacturing Research, Incorporating the 31st National Conference on Manufacturing Research, September 6–8, 2016, Loughborough University, UK.

Submitted

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LIST OF ABBREVIATIONS

ABS	Agent Based Simulation
CF	Conceptual Framework
CM	Conceptual Model / Modelling
CNC	Computer Numerical Control
DES	Discrete Event Simulation
DMS	Dedicated Manufacturing
IT	Information Technology
KPI	Key Performance Indicator
MHR	Material Handling Robot
MHS	Material Handling System
PLC	Programmable Logic Control
RMS	Reconfigurable Manufacturing System
SLR	Systematic Literature Review

1 Introduction

This chapter introduces the research background, highlights the motivation for this PhD, as well as provides the PhD thesis structure.

1.1 Background

With the computation advancements supporting manufacturing, new production solutions have been explored in research and industrial settings. Although technological advances provide the capability to gain greater value with fewer resources, sometimes utilisation of the manufacturing capabilities available to organisation are difficult to achieve. Flexible Manufacturing Systems (FMS) are an example of a production system that utilises power of computation to create a flexible and robust production environment. FMS can provide unique capability to manufacturing where there is a need for product range diversification providing line efficiency and production flexibility. This is very valuable in demand driven production set-ups or niche volume production requirements.

Although a flexible manufacturing system provides a flexible and efficient facility, its optimal set-up is key to achieve production performance. As many variables are interlinked, due to the flexibility capabilities provided by the FMS, analytical calculations are not always sufficient to predict the FMS performance. This PhD focuses on the provision of support in decision-making for FMS development, with the use of tools to handle complex problems.

Simulation modelling is capable of capturing complexity and constraints associated with an FMS. Discrete Event Simulation (DES) involves the modelling of a system, as it evolves over time, by representing the changes as separate events. It has been found to be a commonly used tool in the manufacturing sector, solving complex problems and investigating complex configurations. There are numerous applications that make use of discrete event simulation, particularly in manufacturing systems; however, what has not been explored is how DES can support FMS development in a systematic transparent way.

Provision of support in decision-making for FMSs with the use of DES has not been studied holistically before and makes this research a valid contribution to understanding and guiding FMS development with use of DES.

1.2 Research Focus

This PhD research will focus on how DES can support decision-making in FMS development. This research will model and analyse a number of scenarios to support decision-making related to FMS development at sensitive decision points. The focus of the research will be on: (i) identification of FMS complexities and decision-making areas where DES could support its development; (ii) development of a framework for FMS development using DES; (iii) demonstration through case studies of DES potential to support decision-making.

1.3 Motivation

This research has been funded as part of an Advanced Manufacturing Supply Chain Initiative (AMSCI), designed to improve competitiveness of advanced manufacturing supply chains in the UK. The motivation for the study is to support the development of productive capacity in the automotive industry through support in the development of novel production solutions. Flexible Manufacturing Systems (FMS) are one of the promising but complex production environments that have been developed currently by a tier 1 automotive supplier to improve competitiveness and offer niche production capabilities. The development of a new FMS manufacturing line is challenging for industry, as high quality control and standards need to be maintained where multiple production configurations are possible. This PhD project goal is to address the FMS complexity and support the development of an FMS system in an applied context.

1.4 Problem statement

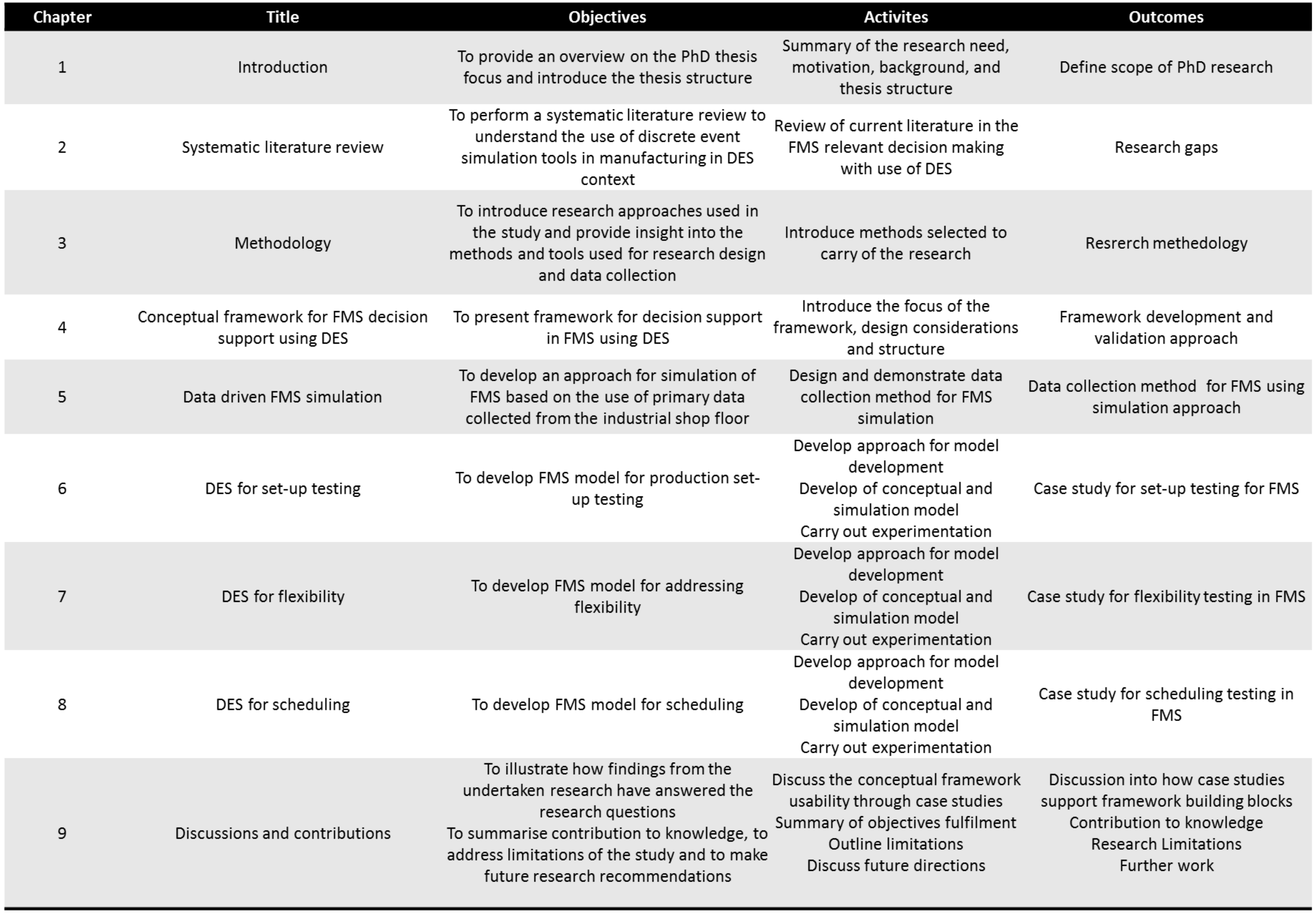
The challenge of this research is to support FMS development designed for niche production manufacturing in the automotive industry context. Cosworth, performance engineering and manufacturing supplier has invested in a state-of-art FMS for development of the next generation of automotive combustion engines.

Due to the novelty of the production process, as well as the complex nature of a FMS, it is difficult to make operational decisions. Discrete event simulation is a tool widely used to model and test complex environments. Exploration of how DES can support FMS development in this context is the key to understanding the FMS development process and support operational decision-making in this novel operational context.

1.5 Thesis structure

Figure 1 presents the thesis structure for this PhD research.

Chapter 1 provides an overview on the PhD research focus, motivation and problem statement, and introduces the thesis structure. Chapter 2 provides a systematic literature review of discrete event simulation and flexible manufacturing systems in the context of decision-making support, identifying the research gap that is addressed in this PhD research. Further, Chapter 3 outlines the aims and objective of this study and specifies the selected methodology. Chapter 4 provides the outline of the conceptual framework for DES decision support in FMS. Chapters 5 to 8 provide case studies developed to validate the conceptual framework focusing on data collection (5), set-ups (6), flexibility (7) and scheduling (8). Finally, Chapter 9 provides discussions and conclusions of the PhD research including limitations and future work.



Chapter	Title	Objectives	Activites	Outcomes
1	Introduction	To provide an overview on the PhD thesis focus and introduce the thesis structure	Summary of the research need, motivation, background, and thesis structure	Define scope of PhD research
2	Systematic literature review	To perform a systematic literature review to understand the use of discrete event simulation tools in manufacturing in DES context	Review of current literature in the FMS relevant decision making with use of DES	Research gaps
3	Methodology	To introduce research approaches used in the study and provide insight into the methods and tools used for research design and data collection	Introduce methods selected to carry of the research	Resrerch methedology
4	Conceptual framework for FMS decision support using DES	To present framework for decision support in FMS using DES	Introduce the focus of the framework, design considerations and structure	Framework development and validation approach
5	Data driven FMS simulation	To develop an approach for simulation of FMS based on the use of primary data collected from the industrial shop floor	Design and demonstrate data collection method for FMS simulation	Data collection method for FMS using simulation approach
6	DES for set-up testing	To develop FMS model for production set-up testing	Develop approach for model development Develop of conceptual and simulation model Carry out experimentation	Case study for set-up testing for FMS
7	DES for flexibility	To develop FMS model for addressing flexibility	Develop approach for model development Develop of conceptual and simulation model Carry out experimentation	Case study for flexibility testing in FMS
8	DES for scheduling	To develop FMS model for scheduling	Develop approach for model development Develop of conceptual and simulation model Carry out experimentation	Case study for scheduling testing in FMS
9	Discussions and contributions	To illustrate how findings from the undertaken research have answered the research questions To summarise contribution to knowledge, to address limitations of the study and to make future research recommendations	Discuss the conceptual framework usability through case studies Summary of objectives fulfilment Outline limitations Discuss future directions	Discussion into how case studies support framework building blocks Contribution to knowledge Research Limitations Further work

Figure 1 Thesis structure

2 Literature Review

This chapter covers the current and relevant literature in flexible manufacturing systems, discrete event simulation and decision-making. Further, gaps in existing knowledge are identified.

2.1 Flexible Manufacturing Systems

This section outlines the definition of flexible manufacturing system (FMS) and its characteristics. A flexible manufacturing system (FMS) is a system regulated by computer numerical control that brings together material handling system, machines and industrial robots (Abd, Abhary and Marian, 2014) creating highly-automated production facility (Ali and Wadhwa, 2011). Caprihan, Wadhwa and Kumar (2005) defines a FMS as a state of-the-art system that is able to process multiple part types through the synergy of flexibility, integration and automation. The basic FMS outline is demonstrated in Figure 2.

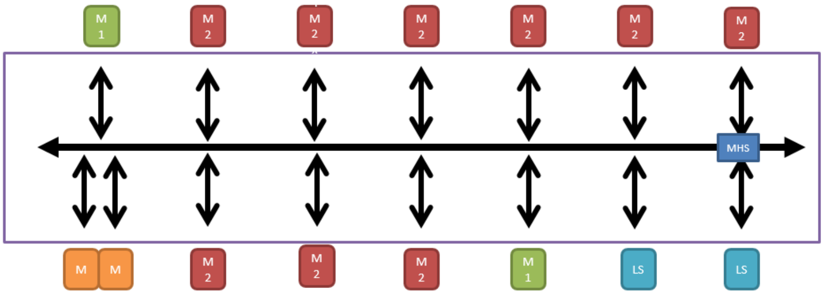


Figure 2 Outline of basic FMS

A typical FMS system consists of:

- Group of machines (M)
- Loading/Unloading station(s) (LS)
- Material handling robot (MHS)
- PLC system

FMS characterise a high automation level, minimising manual intervention with the system to the loading and unloading. In addition, nowadays most common practice is to let algorithms in the PLC lead schedule generation, automating the majority of the production process. The work of Kostal and

Velisek, (2011) has focused on characterising the features of a FMS system in detail.

In order to build understanding of FMS within the manufacturing systems paradigm Table 1 summarises the types of manufacturing systems recognised today.

Table 1 Types of common manufacturing systems

Type of system	Purpose	Benefits
Job shop (process)	Production system consisting of set of machines that can deliver a variety of jobs relying on routing (Hillion and Proth, 1989)	Production targeting low and irregular volume demand but high product variety (Jing-Wen, 2005)
Cellular manufacturing system	Production system following the group technology philosophy where a group of workstations are arranged into smooth flow (Djassemi, 2005)	Production of variety of products while minimising waste (Djassemi, 2005) – time and resources
Dedicated manufacturing system	Machining system designed for a specific part at high volume (ElMaraghy, 2006)	Cost-effectiveness due to pre-planning and optimisation (ElMaraghy, 2006) provision of low variety but high volume
Flexible manufacturing system	System that is able to process multiple part types in variable volume through the synergy of flexibility, integration and automation (Caprihan, Wadhwa and Kumar, 2005)	Cost-efficient manufacture to target volumes of part families with reduced time at changeover (ElMaraghy, 2006)
Reconfigurable manufacturing system	Designed for rapid change in structure in order to quickly adjust production capacity and functionality (ElMaraghy, 2006)	Provision of capacity and functionality on demand (ElMaraghy, 2006)

Within the typology of manufacturing systems FMS has a unique position as it allows achievement of volume and variety of products, maximising the flexibility capability to achieve productivity. Figure 3 demonstrates the fit within other types of systems.

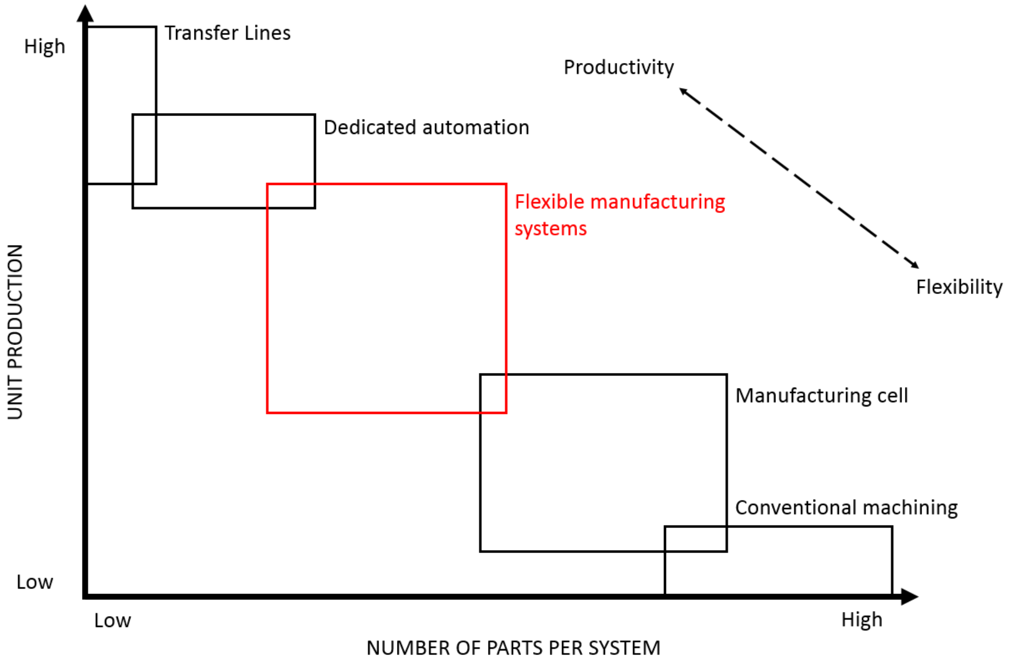


Figure 3 Classification of FMS in manufacturing systems typology, adapted from Upton (1994)

Also, with the development of flexibility concepts in manufacturing, ElMaraghy (2006) has recognised flexible manufacturing systems paradigm, demonstrating FMS positioning within that space between reconfigurable manufacturing systems (RMS) as well as dedicated manufacturing systems (DMS) (Figure 4).

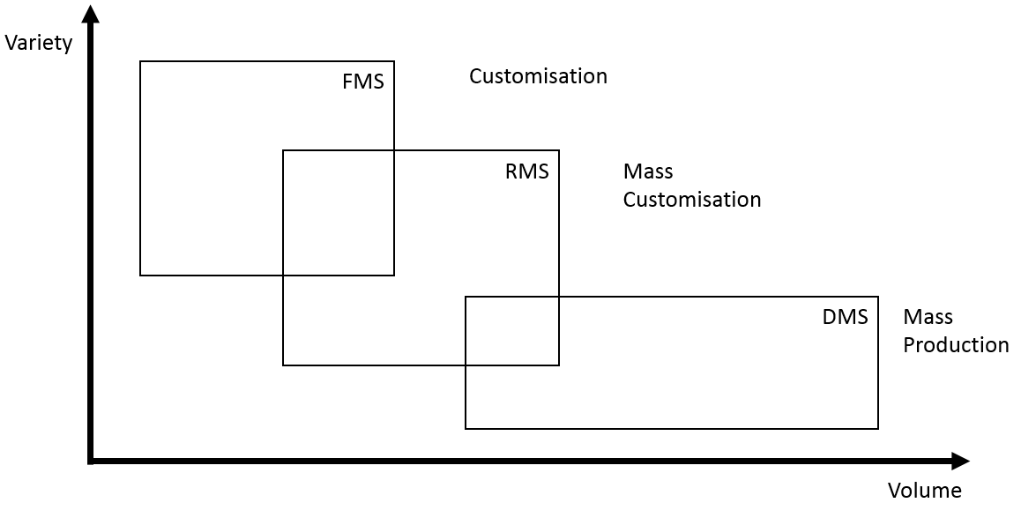


Figure 4 Manufacturing paradigms, adapted from ElMaraghy (2006)

From the two graphs presented above it can be drawn that FMS is able to adapt to produce variety of products in an economically viable volume as well as allowing for adaptation for product customisation beyond mass customisation (like in case of RMS) where personalisation in production can become affordable.

A FMS relies on its ability to adapt which supports tackling several production challenges in the current increasingly demanding markets: increasing machine utilisation, reducing manufacturing lead-time and in-process inventory, and providing flexibility (El-Sayed,1989) in mid-volume, mid-variety set-ups (ElMaraghy, 2006). It has elements of adaptability that traditional models are not capable of, but it can be clearly defined in its flexibility, which allows for further exploration in industrial applications.

2.1.1 Types of flexibility in FMS

Flexibility of FMS is a major argument for its benefits to industry. Joseph and Sridharan (2011b) defines flexibility as the ability of a system to respond effectively to changes. However, to achieve optimal flexibility level in FMS can mean variety of different things.

First, the idea of responsiveness to change provides the idea of what the system should do, but does not imply how this is achieved. Production related flexibility can be managed at different levels, as well as in different ways. Each of these can be a source of competitive advantage. One of the first attempts in classification of flexibility in manufacturing was by Browne et.al. (1984) who distinguished flexibility based on the elements of the system where it is applied: machine flexibility, routing flexibility, process flexibility, operation flexibility, product flexibility, volume flexibility and expansion flexibility. More recently, Vokurka and O'Leary-Kelly (2000) describe four additional flexibility dimensions, such as automation flexibility, labour flexibility, new design flexibility, and delivery flexibility. Table 2 defines the types of flexibility recognised as relevant to manufacturing.

Table 2 Types of flexibility relevant to manufacturing, adapted from Vokurka and O'Leary-Kelly (2000)

Type	Definitions of flexibility dimensions in manufacturing
Machine	range of operations that a piece of equipment can perform without incurring a major setup
Material handling	capabilities of a material handling process to move different parts throughout the manufacturing system
Operations	number of alternative processes or ways in which a part can be produced within the system
Automation	extent to which flexibility is housed in the automation computerization of manufacturing technologies
Labour	range of tasks that an operator can perform within the manufacturing system
Process	number of different parts that can be produced without incurring a major setup
Routing	number of alternative paths a part can take through the system in order to be completed
Product	time it takes to add or substitute new parts into the system
New design	speed at which products can be designed and introduced into the system
Delivery	ability of the system to respond to changes in delivery requests
Volume	range of output levels that a firm can economically produce products
Expansion	ease at which capacity may be added to the system
Program	length of time the system can operate unattended
Production	range of products the system can produce without adding new equipment
Market	ability of the manufacturing system to adapt to changes in the market environment

Flexibility capabilities have impact on what type of performance could be achieved from different types of changes. Recognition of the effect of the type of flexibility on system performance could build understanding limitations and opportunities in FMS development.

Additionally, Basnet (2009) recognises that in the FMS configuration there can be multiple factors which set a requirement for a high level of complexity. Some of the FMS operating elements that scope flexibility are: pallet availability, part routing alternatives, availability of material handling devices, availability of tools, machines capacity, jobs arrivals (Basnet, 2009). On the other hand, Joseph and Sridharan (2011b) divide the elements at the higher degree of granularity into: components, capabilities, interconnections, model of operation and control.

Wiendhal et.al. (2007) has contributed in recognition of where flexibility falls in the landscape of production (Figure 5). He combines five structuring product levels and production levels of details to demonstrate five classes of changeability. Figure 4 presents classes of factory changeability, where FMS is positioned as tactical ability for the system to adjust the whole production system to fit the new requirements by addressing processes, material flows and logistics.

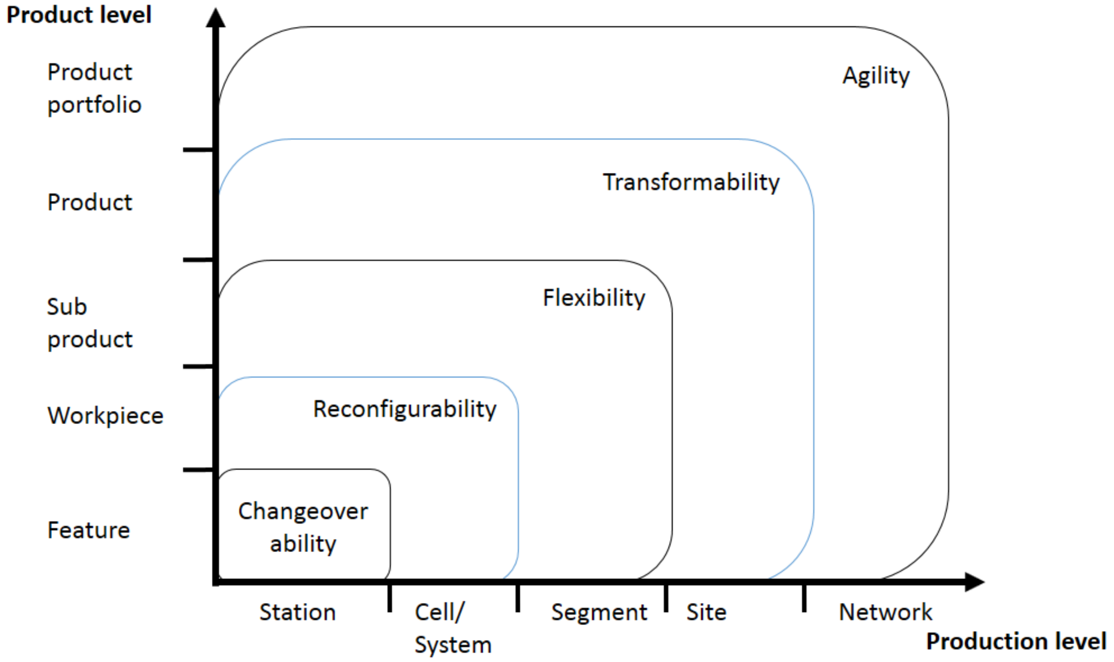


Figure 5 Classes of factory changeability, adapted from Wiendhal (2007)

It has been recognised that there is a requirement for decision support tools to address flexibility levels in FMS and with the advancement of computation in manufacturing it becomes vastly explored with the support of simulation.

2.2 Discrete Event Simulation

This section looks into discrete event simulation as a support in decision making. Firstly, simulation definition and approaches are presented, and then simulation in manufacturing context is explored.

2.2.1 **Context of simulation**

Simulation is one of the ways of studding a system (Law and Kelton, 2000). To put simulation in system research perspective Law and Kelton’s (2000) classification introduce ways to study a system (Figure 6). Simulation is defined as an “experimentation with a simplified imitation (on a computer) of an operations system as it progresses through time, for the purpose of better understanding and/or improving that system.” (Robinson, 2004).

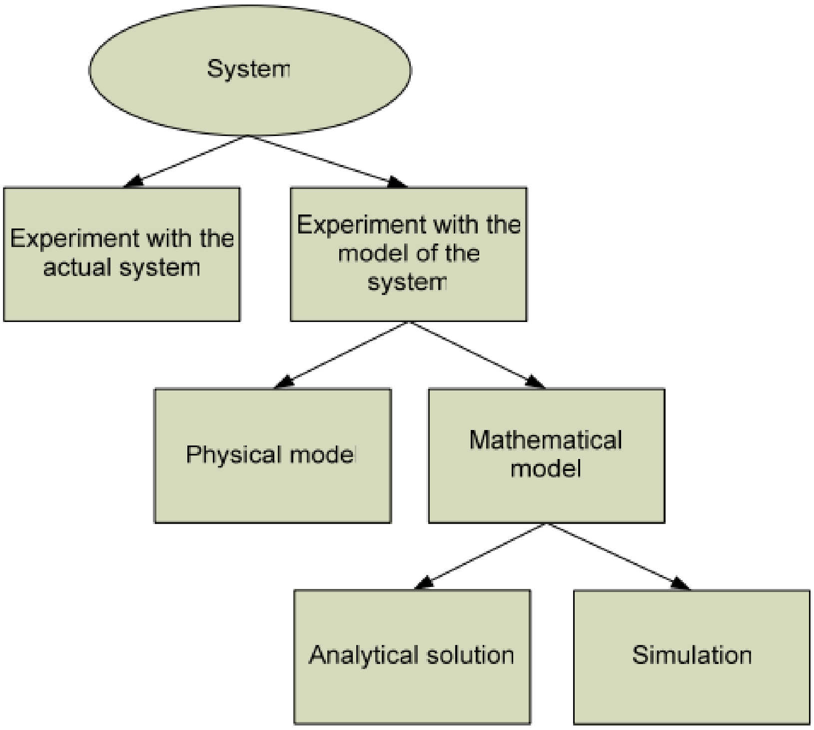


Figure 6 Way to study a subsystem, adapted from Law and Kelton (2000)

Simulation is used when it is important to capture the complexity of the studied system to deliver realistic results. It is apparent that increasing complexity of system problems increases the need for simulation (Diaz-Madronero, Mula and Peodro (2014); Liu et.al., (2012); Li, et.al. (2014); Jahangirian et.al. (2010)). Also, the important reason for using simulation for many is that it reduces the time and cost associated with other types of testing and development in complex systems.

2.2.2 **Simulation modelling**

Although there is variety of methodologies in simulation, simulation research work adapts four stages of development: conceptual modelling, simulation development, experimentation and analysis (as illustrated in Figure 7). The process focus around understanding of the problem area, data collection and selection of simulation approach. This forms basis of conceptual model. Further, simulation model can be build, verified and validated. Next, experimentation is carried out which is basis on the problem analysis. The key stages of simulation are further discussed in methodology.

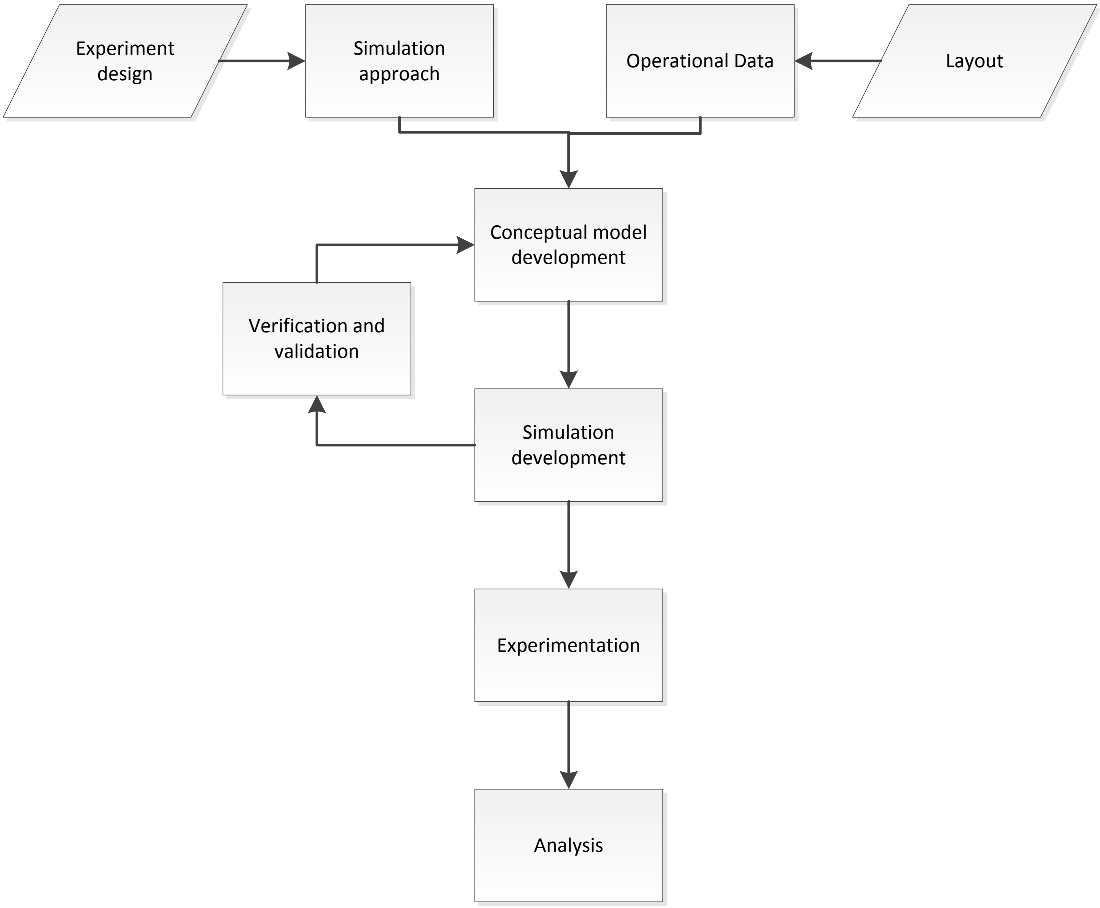


Figure 7 Simulation project activities

Different approaches in simulation development need to be recognised to select appropriate technique for modelling FMS. The definition of the three main simulation approaches are summarised in Table 3.

Table 3 Main approaches in simulation modelling

Approach to simulation	Definition	Modelling characteristics	Changes of the system in relation to time characteristics
System dynamics (SD)	A system is defined as a collection of elements that	A system of stocks and flows where continuous-state	Continuously at small segments of time (Dt)

	continually interact over time to form a unified whole. Dynamics refers to change over time (Jamalania and Feli, 2013)	changes occur over time (Jamalania and Feli, 2013)	
Discrete event simulation (DES)	A system or real-world process over time (Zolfaghari and Lopez, 2005)	A network of queues and activities, where state changes occur at discrete points of time (Jamalania and Feli, 2013) but the objects are individually represented and can be tracked through the system	Discrete points in time
Agent-based simulation (ABS)	A system is represented by independent agents interacting witch each other over time	Association of control agents, as autonomous control units, where control approaches not centralised and managed in dynamic and open architecture (Renna, 2010)	Prescribed by agents characteristic tasks to complete over time

The selection of appropriate approach is important as its delivery varies depending on the context of the modelled system. Borshchev and Filippov (2012) have provided review of simulation approaches classified by the level of abstraction (Figure 8). The authors highlight that although ABS is capable of delivering models at high level of abstraction (like ecosystems) as well as low level of abstraction (i.e. production processes), SD in its nature is more suited for strategic level problems whereas DES is suited for tactical and operational level problems.

The presented approaches have been proved useful for different applications. For example, Banks et.al. (2005) has listed the following possible applications: manufacturing systems; public systems: health care, military, natural resources; transportation systems; construction systems; restaurant and entertainment systems; business process reengineering/management; food processing; computer system performance. In all cases the focus was on studying the system at decided level of detail and using simulation is proving to deliver many benefits to variety of industries.

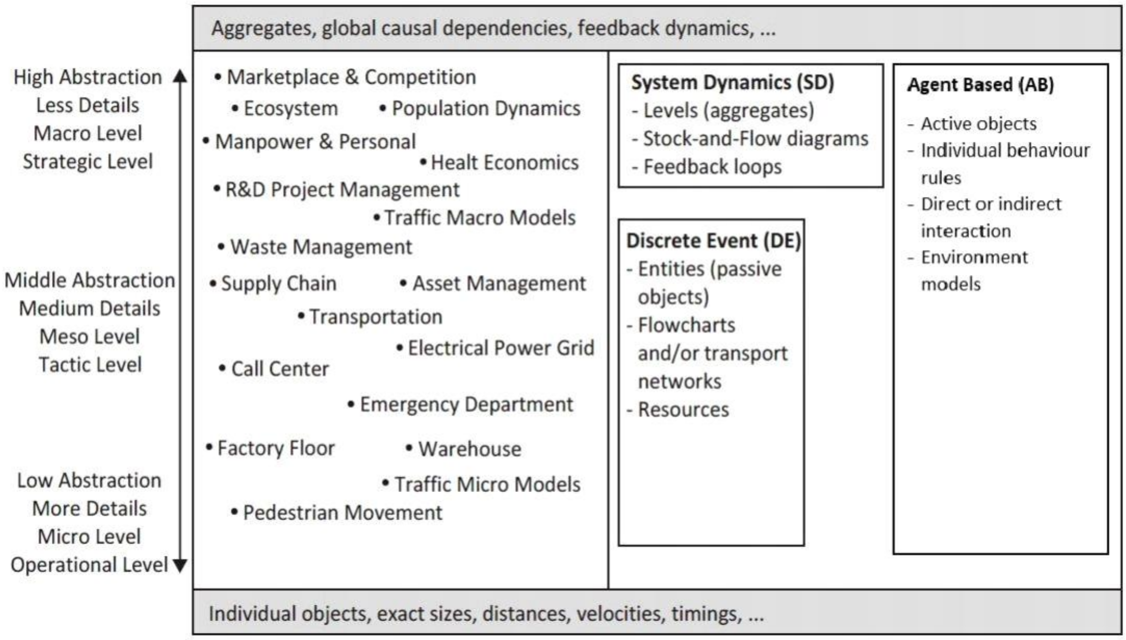


Figure 8 Classification of the simulation approaches and issue according to its typical level of abstraction, adapted from Borshchev and Filippov (2012)

Figure 9 introduces review of approaches used in simulation from manufacturing and business (Jahangirian et.al., 2010) and discrete event simulation dominated the landscape of tools, followed by system dynamics, hybrid models and agent based simulation. Hybrid simulation models in work of is defined as a simulation where continuous and discrete aspects of system analysis are used (Jamalania and Feli, 2013). In this light, simulation modelling with DES seems to be an appropriate choice for manufacturing focused research. The next section provides more detailed insight into DES approach.

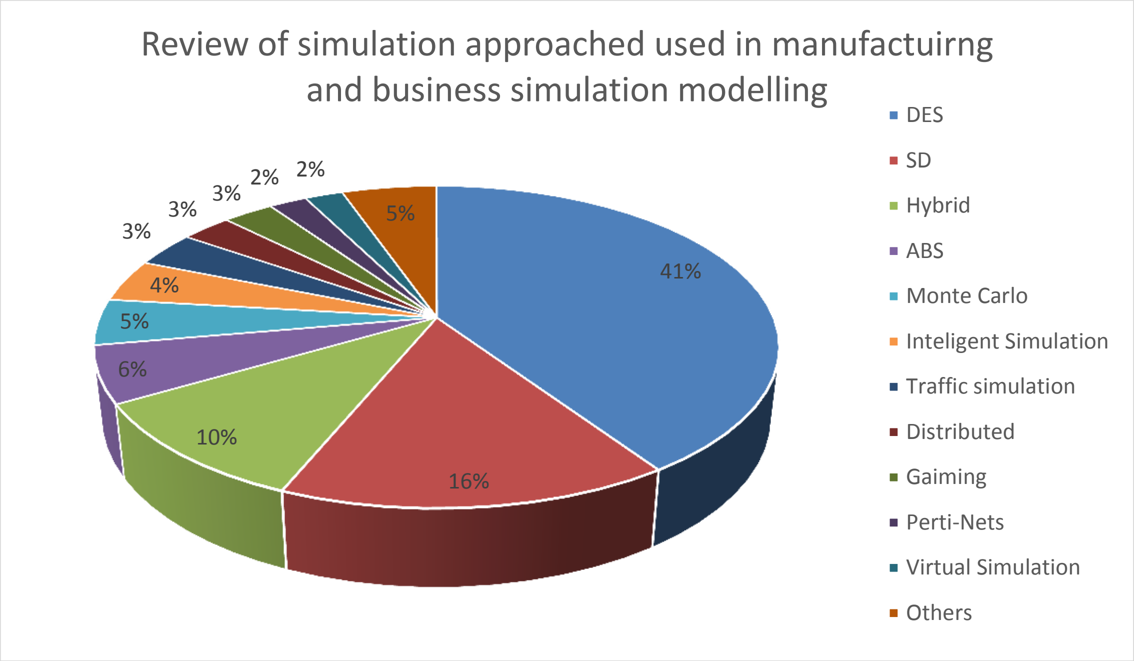


Figure 9 Review of simulation approached used in manufacturing and business simulation modelling, adapted from Jahangirian (2010)

2.2.3 **DES definition**

Discrete event simulation (DES) is an object-oriented simulation method defined as imitation of operation of the real-world processes or system over time (Banks et al., 2005). According to Banks et.al. (2005) it main features are:

- DES generates artificial system/process history
- DES uses set of assumptions to define system behaviour
- DES enables observation of the artificial history to draw conclusions about system behaviour implications

Bodon et.al. (2011) states that DES can be a useful tool for long term strategic decision making as well as short term planning and operational decisions depending on a DES scope. DES can address in many aspects of studying a system: design of new systems, understanding of complex systems and studying the effect on system performance through variables (Ali and Wadhwa, 2010). The objectives definition shape the responses that are achievable through the use simulation. In a system context it could suit range of purposes:

- Understanding large scale systems (Bradley and Goentzel ,2012)

- System design and problem solving (Kunnathur, Sundararaghavan and Sampath 2004)
- Planning, design and control of complex systems (Kunnathur, Sundararaghavan and Sampath, 2004)
- Gain understanding of dynamics and efficiency of processes (in production –planning context) Diaz-Madronero, Mula and Peodro (2014)
- Identification of real impact of improvements to the system taking into account real environment (Talibi, El Haouzi and Thomas, 2013; Reeb et.al., 2012)
- Evaluation of investment into increase of capacity (Mousavi, Broomhead and Devagiri, 2008)

With such range of applications, DES provides capability to cover range of scopes for FMSs modelling. Due to the complexity of FMS, it might require modelling where simulation objectives are redefined at different stages of FMS development.

Within the simulation domain, DES is one of the areas that can capture dynamic changes in the system taking into account discrete events over time. Additional characteristic of such system is that it can be stochastic or deterministic. Stochastic models use probabilistic elements, which means that it allows replication of simulation experiments to deliver variation in results. Deterministic models characterise with no randomness, which implies that the system will be always replacing the same results in scenario. Both are useful ways of modelling in different applications depending on context.

2.3 DES in manufacturing and FMS for decision making

This section introduces the review of literature related to the investigation on how DES simulation can support the FMS development. Firstly, methods used to conduct systematic literature review has been outlined. Next, related research and findings from review of 67 papers has been presented.

2.3.1 **Systematic Literature Review**

This section explains the approach undertaken to develop the literature review-adapted systematic literature review. Jesson, Matheson and Lacey (2011) provide a methodology for carrying out a SLR. Figure 10 presents the SLR methodology approach. The top headings introduce the phases: defining a research question, constructing research strategy, assessment of publications (2 phases – screening and full text read), literature analysis, synthesis and reporting.

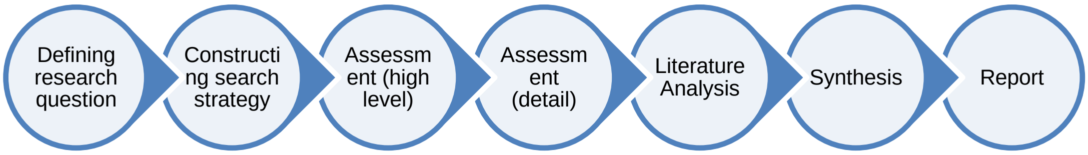


Figure 10 Systematic literature review approach, adapted from Jesson (2011)

Tools used in SLR approach execution are detailed in Table 4. The table provides steps used to fulfil each stage of SLR with defined aim of the tool or method in delivering of SLR approach.

Table 4 Systematic literature review execution process, developed by author

SLR Stage	Steps
Defining a research question	• Scoping Study
Constructing a research strategy	• Define research concepts boundary (include/exclude) • Define keywords • Define search strings

	• Define journal search criteria (timescales, databases, types of document)
Assessment (Screening)	• Define data organisation structure • Define selection criteria (1st screening – Abstract read) • Develop data collection templates (key themes to which the data are clustered)
Assessment (Full text)	• Develop journal analysis template • Define selection criteria (Full text screening)
Literature Analysis	• Data structuring into relevant themes
Synthesis	• Research gap definition
Report	• Literature review write-up

Defining a research question

In this section unstructured literature review search is carried out. The purpose of this activity is to understand issues in the research area and support formulation of the research question as well as inform research strategy definition. The research question for the scoping study in this work is as follows:

How discrete event simulation (DES) can support development of flexible manufacturing systems (FMS)?

The research question formulation define the search areas: flexible manufacturing system (FMS), and discrete event simulation (DES). This research question formulation is consciously defining DES as a simulation modelling approach that is chosen for this research. It also defines FMS as application area for the research exploration. Finally, it implies decision making as main capability to be explored.

Constructing a research strategy

This section aims to define, as accurately as possible, the research scope. It was done systematically by taking the key findings from the scoping study search and organising them to develop the research structure. First, the key concepts boundaries were defined. The key concepts boundaries definition represents the areas of knowledge included in the literature search. The concept boundary for this work is demonstrated in Figure 11. The reason why the search has been so broad was due to the fact decision making in FMS with DES research has been very limited and only 16 papers has been identified within that scope. Therefore, it was important to look at DES decision-making in the broader manufacturing context. Taking manufacturing and FMS into account allowed broadening the understanding around how FMS decision support could potentially be supported by DES.

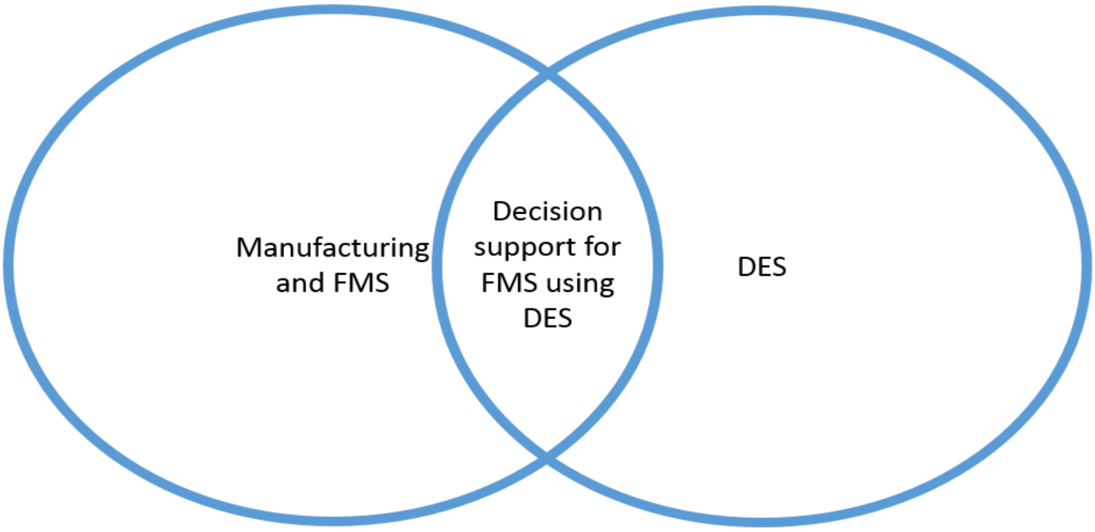


Figure 11 Concept boundaries developed from scoping study, developed by author

The next step was key search terms definition and creation of search strings. Table 5 defines the key words extracted from the scoping study. The key words represent alternative worlds for key search terms.

Table 5 Key search terms in the knowledge research areas defined from scoping study, developed by author

Index	A	1	2
Theme	**DES**	**FMS**	**Decision making**
Search terms	Discreet Event Simulation	Flexible Manufacturing System	Decision support system
	DES	FMS	DSS
		Automated Guided Vehicle	Performance
		AGV	Production planning
		Cellular Manufacturing System	
		Job shop Manufacturing	
		Flowshop Manufacturing	

Once the key search terms were identified the search strings has been created. This has been done by allocation an index number or letter to the research area and combining them with each other. The search took into account the alternative key searches. Table 6 demonstrates that FMS (“1”) provides four options. Option “1.2” corresponds to FMS and option “1.4” corresponds to the fourth search term on the list, which is “AGV” and so on.

Table 6 Search strings definition for SLR

Search Strings	Search engine configuration
A1	“A” AND “1.1” OR “1.2” OR “1.3” OR “1.4”
A2	“A” AND “2.1” OR “2.2”
A12	“A” AND “1.1” OR “1.2” OR “1.3” OR “1.4” AND “2.1” OR “2.2”

The choice of databases for this search had to cover not only science but applied research spectrum of research. Also, as the areas of searches have been falling into Manufacturing /Engineering and Management it has been required to look into variety of databases. Scopus, ABI, Business Source Complete, IEE Explore and Web of Science have been selected as appropriate. The coverage of the databases is outlined in Table 7.

Table 7 Research databases coverage summary

Database	Database coverage
Science Direct (Scopus)	Scopus- A huge database covering all areas of science, technology and medicine. It has several functions that allow searchers to personalise it to their own interests
ABI	Full-text access to approximately 2,500 international business periodicals contained within the ABI Inform Global, Trade and Industry and Dateline databases. Coverage: 1971
BSC	Full-text access to more than 2,800 scholarly business publications including over 900 peer-reviewed journals. Also includes book content, conference proceedings, country, industry and market reports. Coverage: variable, 1922 – current.
IEE Explore	Full text access to IET and IEEE journals, transactions and conference proceedings from 1988 onwards, and select content from 1872. Also includes all current IEEE standards.
Web of Science (WoS)	Previously known as Web of Knowledge, WoS includes the Conference Proceedings, Journal Citation Reports (JCR) and Medline databases. It covers a very broad range of subjects relating to science, technology, social sciences and medicine.

The journal search criteria scoped the publication time and type of publications. For this review the following have been defined:

- Journal Articles (academic peer-reviewed literature)
- Conference articles (last 2 years)
- Time scale: 2004 – 2014 (brief searches evidence no publication in three research areas before 2004)

Search organisation

The important element of the search in SLR is data structuring. Many authors (Gough, Thomas and Olivier, 2012; Jesson, Matheson and Lacey, 2011; Deyner and Tranfield, 2009) emphasises its importance due to transparency and rigour as well as for caring out synthesis. The data structuring needs to be able to provide a track record of where the publication came from (database). Therefore, the structured data allocation linking Refworks, Mandaley and Excel has been developed.

All searches from the databases have been carried out and its results have been saved in Refworks. Search strings have been saved separately in the database relevant folders. Next, all searches have been copied to the one folder providing total number of searches. This folder is further exported to Mendaley database where the publications are de-duplicated. Following that the de-duplicated publication list was exported to excel and serves as a base database for the assessment phase. This process is visualised in Figure 12.

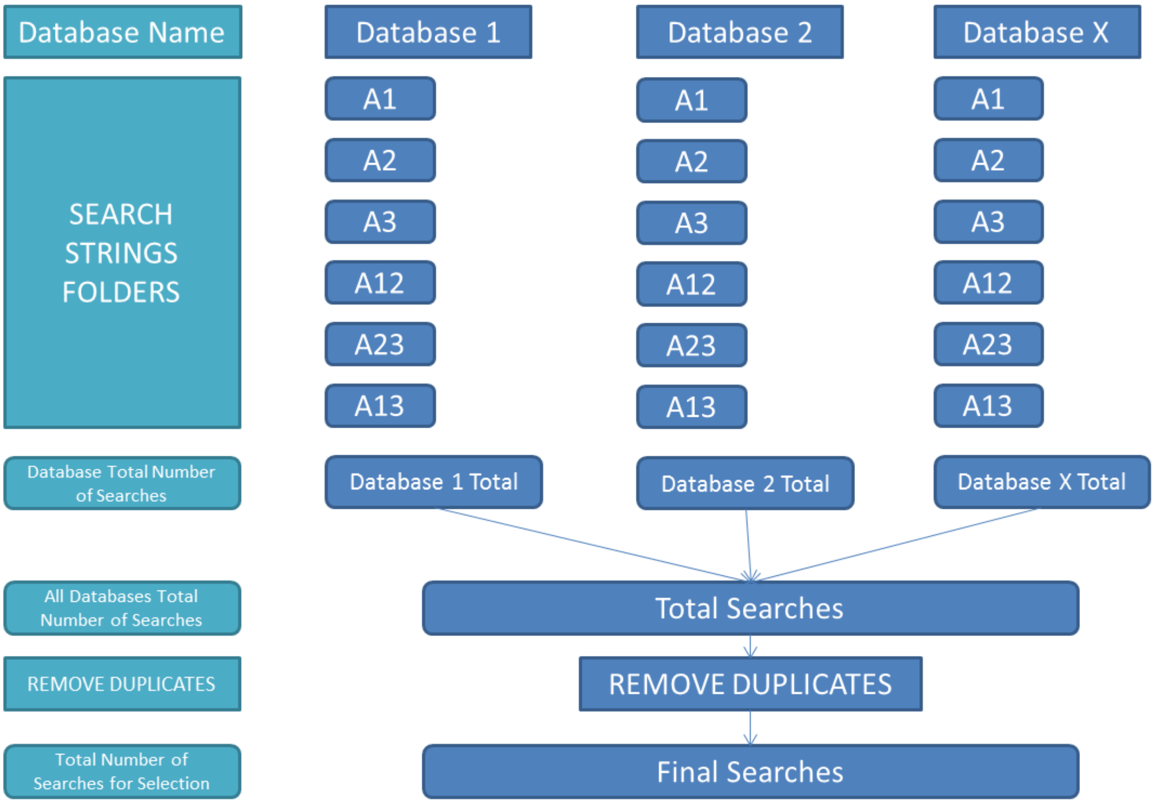


Figure 12 Search results data allocation

The data structuring demonstrated ability to come back to the roots of the paper generation origin; however, it does not allow following standard paper classification in the later stages of the publication data organisation. This means that although it is possible to see how many papers have been searched in different search strings, it is not possible to continue allocation of papers in the further assessment stages.

Table 8 provides the string search publication numbers organised in defined data structuring.

Table 8 Paper search publications in numbers structured in database allocation, developed by the author

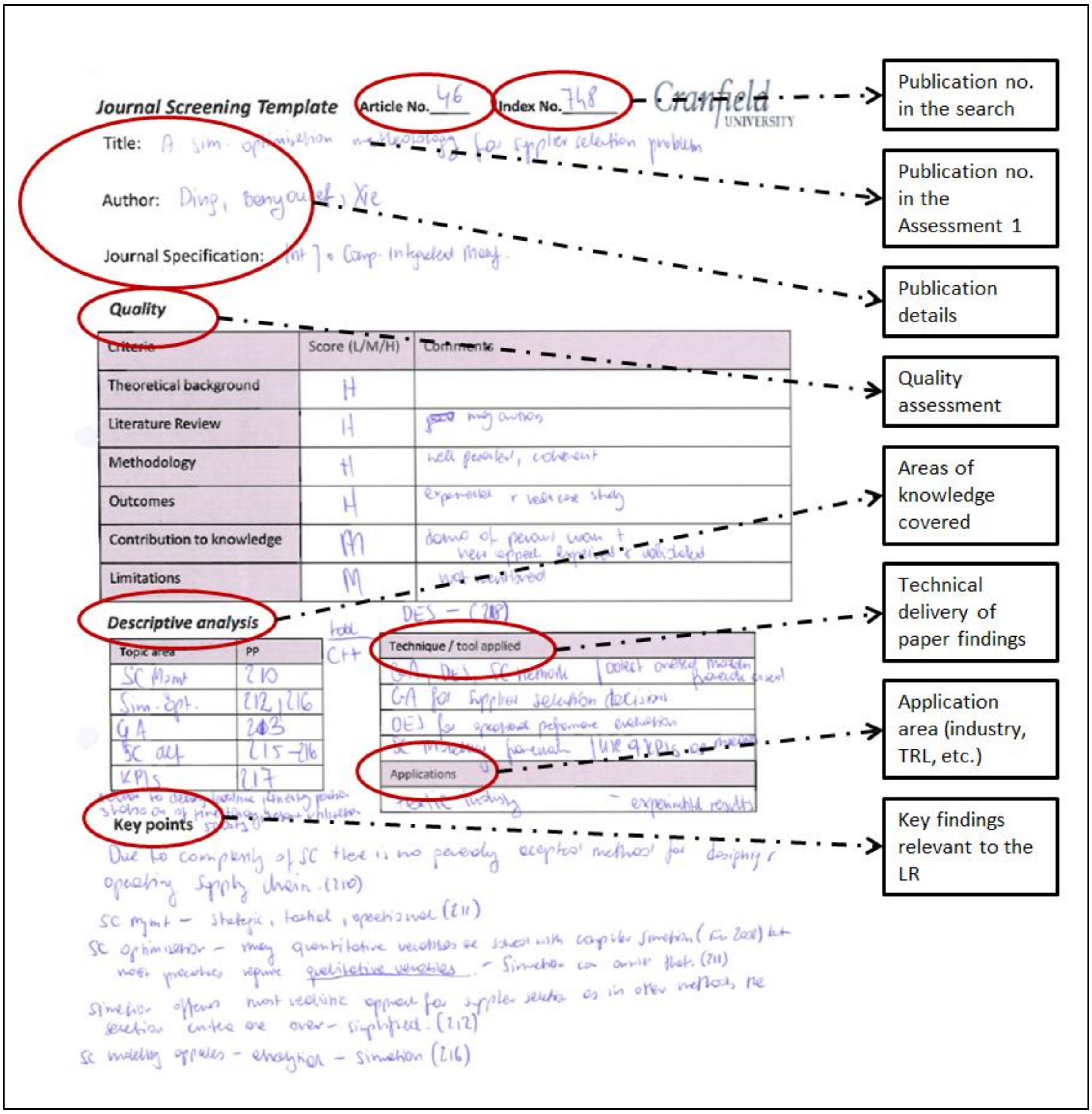
SEARCH STRING	NUMBER OF PAPERS
SCOPUS	
A1	130
A2	52
A12	0
Total	182
ABI	
A1	227
A2	218
A12	444
Total	889
BSC	
A1	633
A2	251
A12	882
Total	1766
IEE Explore	
A1	395
A2	195
A12	131
Total	721
Web of Science	
A1	867
A2	675
A12	21
Total	1563
TOTAL	
A1	2252
A2	1391
A12	1478
All Documents Total	5121
De-duplication	3662

After the database with journal article results was composed, it was important to define selection criteria for the paper assessment. First assessment was based on title and abstract read; and selection assessment level focused on reading full article to assess its relevance to the areas of knowledge and the criteria. Selection criteria for search, assessment (abstract) and assessment (full text reading) are illustrated in Table 9.

Table 9 Selection criteria for systematic literature review, developed by author

Literature review search	Assessment 1 (Abstract)	Assessment 2 (Full text)
Technical		
Journal Articles (academic peer-reviewed literature) Conference articles (last 2 years) Time scale: 2004 – 2014 (brief searches evidence no publication in three research areas before 2004)	All criteria applied in Literature review search Re-check of publication type and date of publishing - wrongly clarified papers	All criteria applied in Assessment 1
Research		
Use DES as a simulation tool Fall into a DES and one or two of the other research areas	All criteria applied in Literature review search Take into account exclusion areas: semiconductors, analytical methods	All criteria applied in Assessment 1 Relevancy to FMS decision making Application of DES as a tool assessment (does it address the flexibility issues?)

Once criteria has been defined, a temple for information gathering has been developed to be able to assess the quality of a paper as well as capture the relevant knowledge contributing to the literature review. The example of temple can be found in Figure 13. The quality criteria matrix is demonstrated in Figure 14.



Journal Screening Template **Article No.** 46 **Index No.** 748

Cranfield UNIVERSITY

Title: A sim. optimisation methodology for supplier selection problem

Author: Ding, Benyoucef, Xie

Journal Specification: Int J. Comp. Integrated Manuf.

Quality

Criteria	Score (L/M/H)	Comments
Theoretical background	H	
Literature Review	H	~~[illegible]~~ many authors
Methodology	H	well presented, coherent
Outcomes	H	experiments & real case study
Contribution to knowledge	M	demo of previous work & new approach, explained & validated
Limitations	M	not mentioned

Descriptive analysis

DES – (208)

tool C++

Topic area	PP
SC Mgmt	210
Sim. Opt.	212, 216
GA	203
SC def	215–216
KPIs	217

Technique / tool applied
GA, DES, SC network | object oriented model based used
GA for supplier selection decisions
DES for operational performance evaluation
SC modelling formal | the 4 KPIs are measured
Applications
textile industry – experimental results

used to decide baseline inventory position [illegible] of [illegible] between [illegible] strategy

Key points

Due to complexity of SC there is no generally accepted method for designing & operating supply chain. (210)

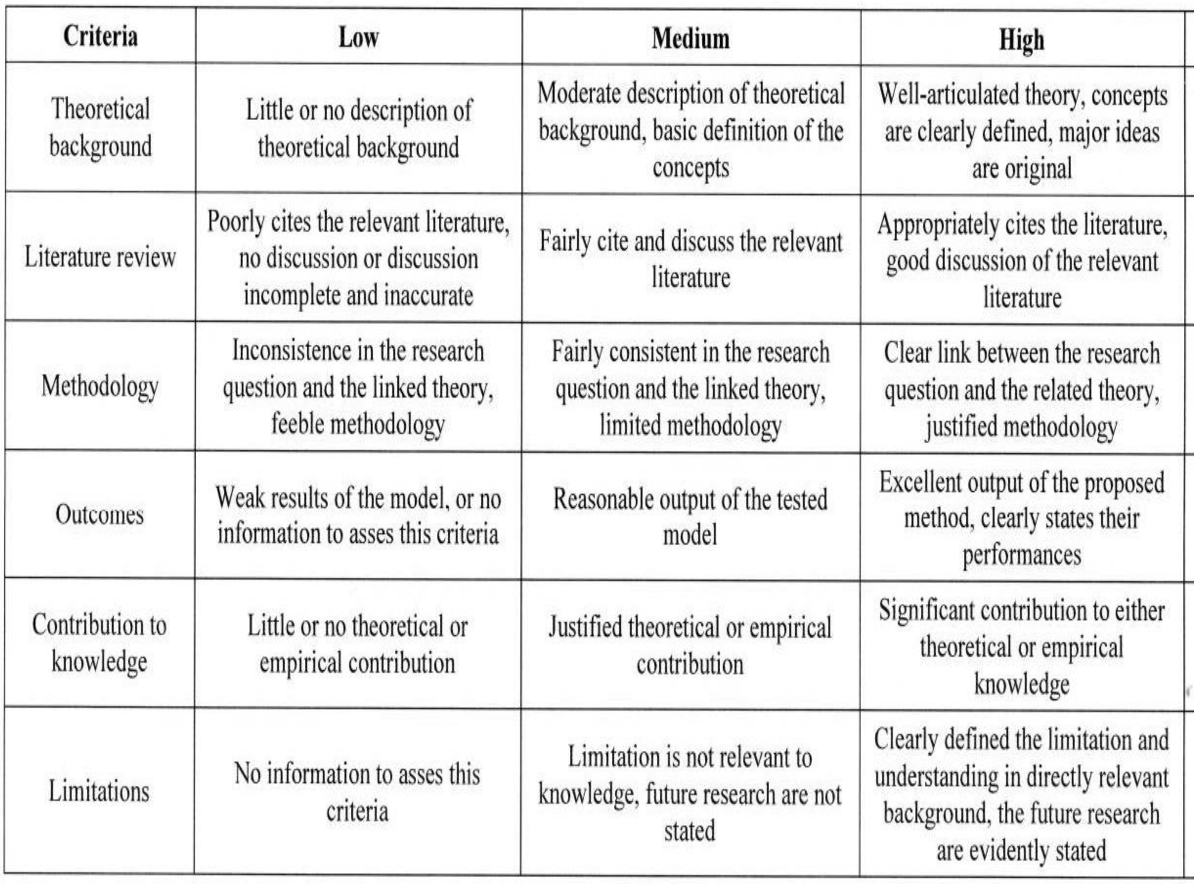
SC mgmt – strategic, tactical, operational (211)

SC optimisation – many quantitative variables are solved with complex simulation (Fu 2002) but most practices require qualitative variables. – Simulation can avoid that. (211)

Simulation offers most realistic approach for supplier selection as in other methods, the selection criteria are over-simplified. (212)

SC modelling approaches – analytical – simulation (216)

Figure 13 Example of a journal analysis temple



Criteria	Low	Medium	High
Theoretical background	Little or no description of theoretical background	Moderate description of theoretical background, basic definition of the concepts	Well-articulated theory, concepts are clearly defined, major ideas are original
Literature review	Poorly cites the relevant literature, no discussion or discussion incomplete and inaccurate	Fairly cite and discuss the relevant literature	Appropriately cites the literature, good discussion of the relevant literature
Methodology	Inconsistence in the research question and the linked theory, feeble methodology	Fairly consistent in the research question and the linked theory, limited methodology	Clear link between the research question and the related theory, justified methodology
Outcomes	Weak results of the model, or no information to asses this criteria	Reasonable output of the tested model	Excellent output of the proposed method, clearly states their performances
Contribution to knowledge	Little or no theoretical or empirical contribution	Justified theoretical or empirical contribution	Significant contribution to either theoretical or empirical knowledge
Limitations	No information to asses this criteria	Limitation is not relevant to knowledge, future research are not stated	Clearly defined the limitation and understanding in directly relevant background, the future research are evidently stated

Figure 14 Quality assessment criteria for publications in Assessment 1 screening, source: Cranfield Library, Systematic literature review notes (2014)

The assessment process allowed rigorous and transparent selection of papers that contribute to the adapted SLR. Table 10 demonstrates how number of publication has changed through the assessment stages.

Table 10 Papers evaluation in the systematic review approach

Literature review search	**Assessment 1 (Abstract)**	**Assessment 2 (Full text)**
5121 (3662)	170	**(67)**

Once papers have been read, the information from templates has been organised in themes in excel spreadsheet and explored in terms of descriptive characteristics and themes emerging. The themes has then be organised into a literature review structure. In total, 67 papers has been identified as relevant within this focus of this search. Next section outlines relevant reviews.

2.3.2 **Related studies**

DES has been claimed a most common tool used in manufacturing sector solving complex problems or investigating complex configurations (Nagahban and Smith, 2014). Nagahban and Smith (2014) class research in manufacturing related discrete event simulation focus in three general areas: manufacturing system design, manufacturing system operation, simulation language development. Chan (2004) report that simulation is the most widely used tool for modelling FMS. Jahangirin et.al. (2010) in a review of simulation techniques demonstrates that discrete event simulation is most widely used technique in business and manufacturing accounting for 40% of total number of papers reviewed. He also points out that DES is appropriate for tactical and operational decision-making levels.

Further, Semini, Fauske and Strandhagen (2006) focus on how DES as approach supports real-life manufacturing logistics decision-making where production systems design, production policies, short term planning, scheduling and inventory policies have been identified most prominently developed research. Jeon and Kim (2016), on the other hand, focused on simulation modelling for production planning identifying range of simulation applications: facility resource planning, capacity planning, job planning, process planning, scheduling, inventory management, production and process design, purchase and supply management.

Currently there is no FMS focused review considering decision support for different stages of FMS planning. However, Table 11 summarises the current review research that considerers the simulation at different levels of decision making in manufacturing. Mahdavi and Shirazi (2010) have reviewed control mechanisms for intelligent decision support systems for FMS scheduling. Moreover, Chan and Chan (2004) have looked into FMS scheduling with mathematical simulation approaches but not DES simulation. Although not FMS focused, Gagliardi, Renaud and Ruiz (2012) have reviewed methods for automated storage and retrieval systems (AS/RS), which share similar principles to requirements of the material handling systems for FMS, concluding that simulation models dominate recent literature in dynamic modelling. Also, Diaz-Madronero, Mula and Peodro (2014) have looked into optimisation for tactical production planning where simulation is used among other methods. This review aims to focus on the DES approaches used as a part of support of decision making in FMS development. It considers FMS as well as manufacturing system modelling relevant to FMS decision making themes.

Table 11 Summary of existing review papers covering simulation in FMS

Author	Application	Objective	Decision supported areas
Nagahban and Smith (2014) (comparisons with Smith (2003) results	Manufacturing system design and operation	Classification of manufacturing relater simulation research	Recognition of contributions in system design, system operation and simulation methods development
Jahangirian, et.al (2010)	Simulation on manufacturing and business	Coverage of simulation techniques applied across sectors	Research focus on: scheduling, process engineering manufacturing and supply chain management.
Semini, Fauske and Strandhagen (2006)	Review of discrete-event simulation in real-world manufacturing logistics decision-making	Identification how DES is actually used to support decision-making in industry	Production systems design, production policies, short term planning and scheduling, inventory policies
Jeon and Kim (2016)	Simulation modelling techniques in production planning and control	Systematic identification of suitability of simulation technique approach for PPC problems	PPC issues: facility resource planning, capacity planning, job planning, process planning, scheduling, inventory management, production and process design, purchase and supply management
Mahdavi and Shirazi (2010)	Simulation based intelligent DSS for FMS	Review of architecture of simulation-based intelligent decision support systems for	Presentation of simulation-based IDSS as a valuable tool for FMS scheduling

		FMS real time control.	
Diaz-Madronero, Mula and Peodro (2014)	Simulation and optimisation of tactical production planning	A review of discrete-time optimization models for tactical production planning	Material Requirement Planning and Manufacturing, Resources Planning (MRP), Aggregate Production Planning, Hierarchical Production Planning, Master Production Schedule (MPS)
Gagliardi, Renaud and Ruiz (2012)	Models for automated storage and retrieval systems	Review of methods for modelling AS/RS systems	Analytical paradigms, Simulation paradigms, Sequencing, Storage assignment

2.3.3 **Overview of existing research**

Systematic literature review has been conducted to carry out review of DES for supporting decision making in FMS development. The benefits of undertaking SLR approach is that is provides a structure to the review that is rigorous, transparent and reputable and therefore it allows verification and validation of the review. Through the SLR process 67 papers have been selected for the review and each paper has been analysed based on: type of application, level of application, decision support area, methods used.

All papers considered in the review cover years 2004- 2014. During scoping it has been discovered that pervious research is limited in combination of DES, FMS and decision support. Figure 15 shows increasing trend in the publications. Nine out of 67 papers have been from conferences and remaining papers sourced from journal publication.

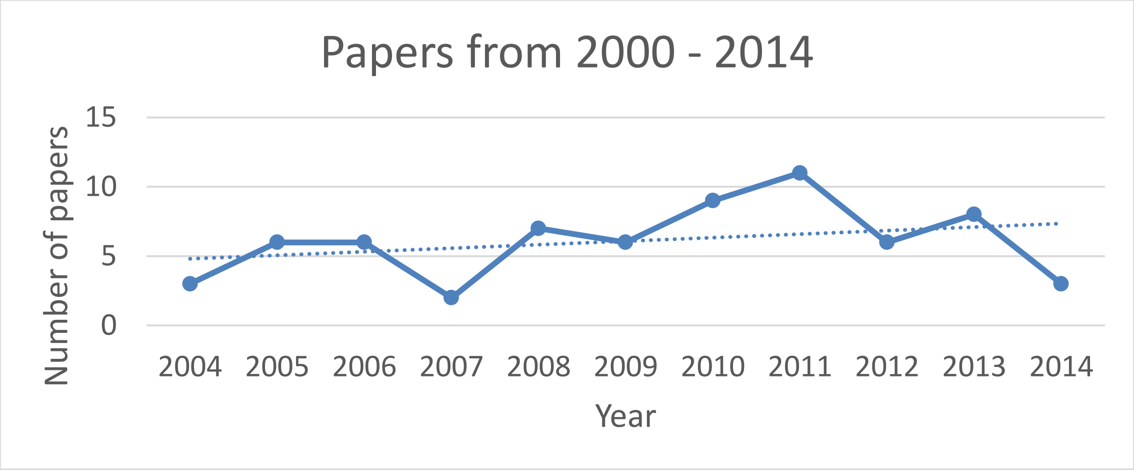


Figure 15 Number of papers by year (2000 – 2014), {67 papers}

The case studies in the performed SLR has been identified as majorly academic case studies (40), however 23 papers have been identified as industrial cases which is encouraging prediction that simulation, in a context of decision making in manufacturing, has been adapted as decision support tool to solve real life problems. In 4 cases it was not possible to identify the case study nature.

In terms of type of publications, 37 journal publications titles has been identified. Figure 16 provides top five publication sources from which is apparent that International Journal of Production Research is dominating the publication topic. Additionally, the papers impact factors suggest that the research have average importance in the field of manufacturing and management.

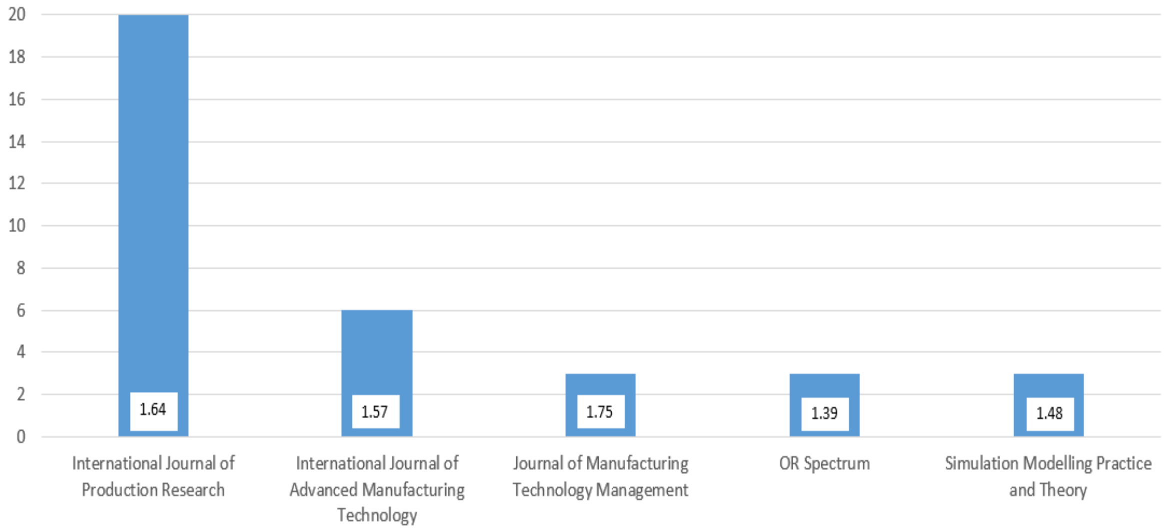


Figure 16 Top publication sources with the impact factor score for 2015

In terms of simulation development tools, most common simulation software used in the projects is AREANA and programming language was C+. However, from Figure 17 summary of top tools used in simulation it can be generalised that software programs are more popular in use than building models with programming languages.

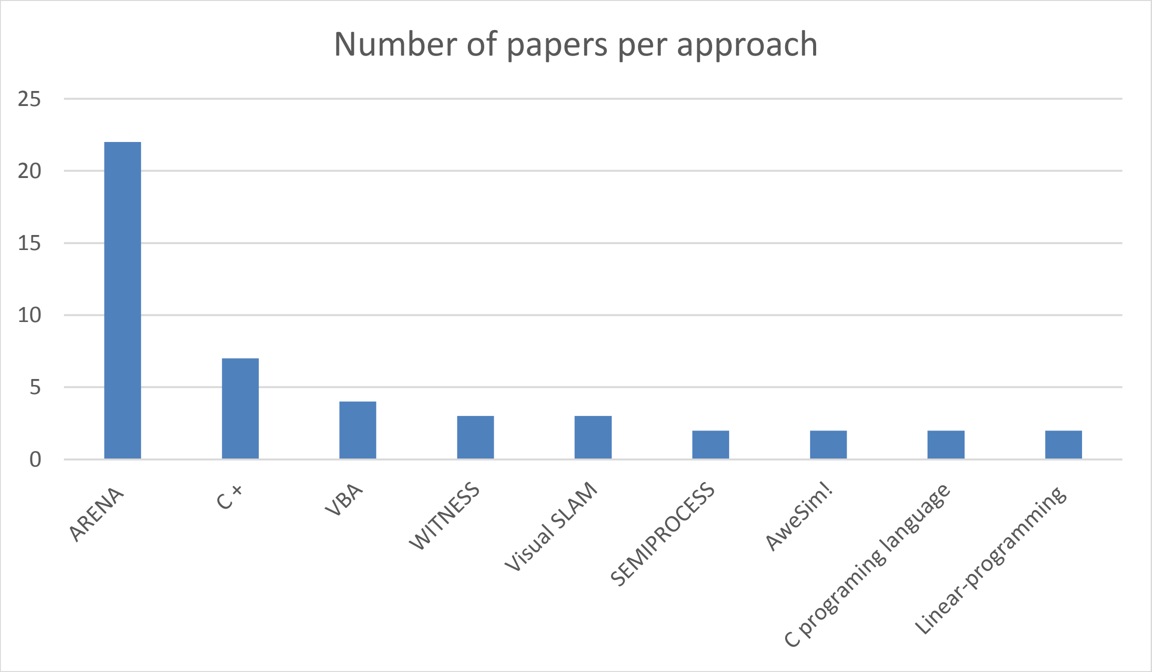


Figure 17 Top programming and software tools used in simulation development

ANOVA and sensitivity analysis are most common technique when randomness and high level of variability are present in the simulation (Figure 18). Other simulation project focused on comparing scenarios in a manner of what-if analysis but there was not a formal analysis tools introduced in the research methodologies.

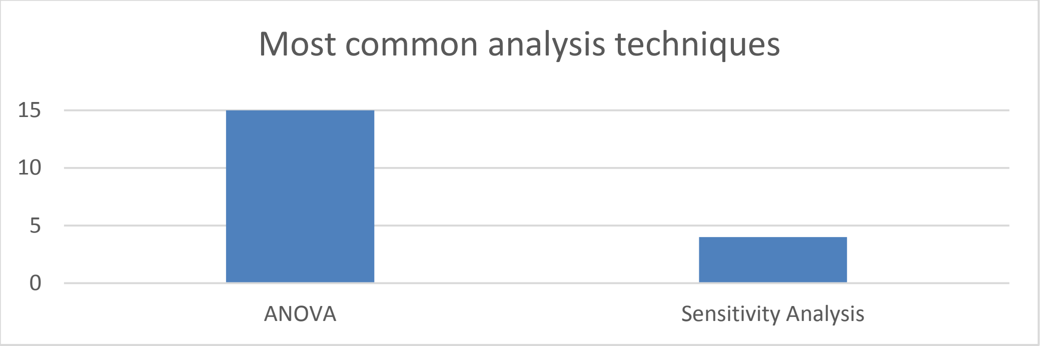


Figure 18 Types of analysis in simulation projects in decision making for manufacturing simulation projects

Additionally, it has been observed that DES has been used alongside other modelling approaches at 21 instances (summary in Figure 19). The models took advantage of mixing approaches to be able to archive better results. For example, which the use of system dynamic approach and DES the modellers were able to take into account continuous and discrete types of events in the simulation when looking a supply and manufacturing processes (Jamalania and Feli, 2013).

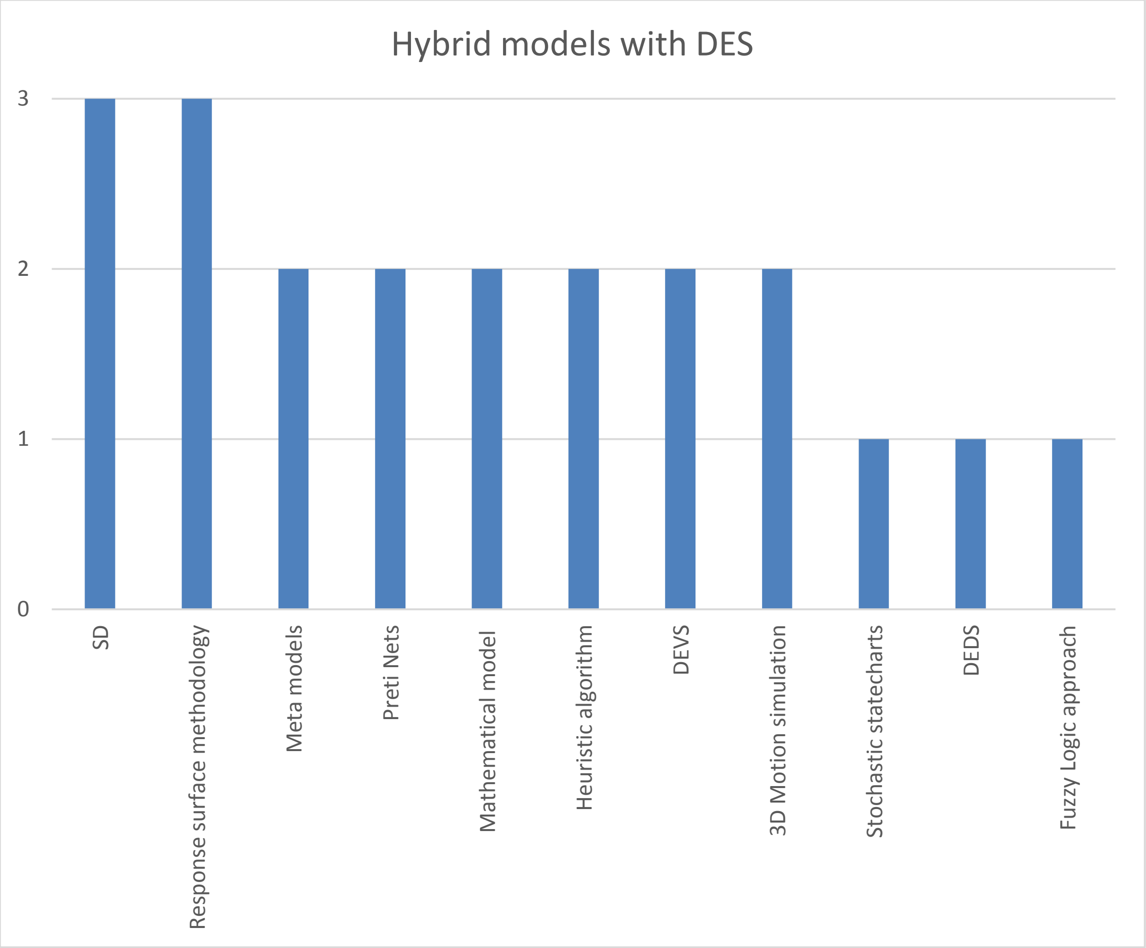


Figure 19 Use of additional modelling approaches with discrete event simulation in decision making for manufacturing simulation projects

Further, in the paper the emerging themes in decision making are discussed to grasp the interest of DES community in different operations areas. The focus of the analysis was on the type of manufacturing production modelled as well as the decision support area addressed.

2.3.4 **Emerging decision support areas**

The decision support areas emerging form the literature focus on two themes: decision support area, type of system studied. Table 12 demonstrates the emerging areas in the two themes. FMS, as a type of system, has been recognised by 16 papers in this review; however other types of production systems has also been considered as they are relevant to FMS characteristics. Therefore, this literature will later split into two sections: FMS specific and general manufacturing systems. By doing this comparisons between the FMS specific and general manufacturing it is possible to evaluate if the decision-making in FMS correlates to the general manufacturing systems breadth of research.

Table 12 SLR emerging themes and areas

DECISION SUPPORT AREA	
Set-up	30
Flexibility	10
Scheduling	22
PLC (controls)	5
Strategy	10
Method	11
Layout	11

TYPE OF SYSTEM	
Cellular manufacturing	6
FMS	16
Job shop	6
AGV	7

Type of systems investigated that recognise specification relevant to the system characteristics are:

- Flexible manufacturing systems research area not only cover FMS as a specific layout, but different aspects of flexibility in manufacturing is explored (Abd, Abhary and Marian, 2014; Ali and Saifi, 2010; Basnet, 2009, Caprihan, Wadhwa and Kumar, 2005; Dhib, Elleuch and Frikha, 2013; Joseph and Sridharan, 2011a; Joseph and Sridharan, 2011b; Kia, Davoudpour and

Zandieh, 2010; Ko et al., 2013; Kumar and Sridharan, 2010; Kumar and Nottestad,, 2009; Li et al, 2014; Mahdavi and Shirazi, 2010; Savsar, 2006; Sharma, Garg and Sharma, 2011; Suresh Kumar and Sridharan, 2009). This theme is further elaborated on in section 2.3.4.

- Automatic guided vehicles (AGV) are relevant to material handling system problems in FMS and they have been widely covered by simulation (Berman, Schechtman and Edan, 2009; Bocewicz and Pawlewski, 2013; Dhib, Elleuch and Frikha, 2013; Grunow, Günther and Lehmann, 2006; Hafidz Fazli bin Md Fauadi, Murata and Prabuwono, 2012; Kessan and Baykoc, 2007; Singh, Sarngadharan and Pal, 2011). The focus is spread around scheduling and testing for different the AGV movement in different applications (FMS, job shop environment, etc.).

- Cellural manufacturing focus on layout comparisons with other systems (Elleuch, Bacha and Masmoudi, 2008; Ferreira and Reaes, 2013; Renna, 20011a; Renna, 2011b; Zolfaghari and Lopez, 2006). This type of research focus on comparing and testing production scenarios in different conditions, which is also relevant to FMS environment.

- Job shop scenarios address layout comparisons (Ferreira and Reaes, 2013; Li, 2010; Li, 2005) or focus on performance evaluation of different aspects of flexibility (Mahdavi and Shirazi, 2010; Monch and Zimmermann, 2011) which can contribute knowledge base on practices in approaching flexibility.

2.3.5 **Classification of decision making areas**

Further, in the clustering, it has been found that decision support through simulation is used at different levels of manufacturing process decision making. Seven areas have been uncovered: set-ups, flexibility, scheduling, PLC controls, strategy, layout and methods for simulation. These were the key words used by the authors in describing the simulation objectives. The summary of emerging areas is introduced and analysed in the view of how DES supported the decision-making and is provided in Table 13. It should be noted that none of the papers cover more than three of the seven decision support areas. Moreover, there is no single work that covers the application of simulation to all decision support areas. In general research is on very specific applications. This could suggest that decision making is narrow and misses out opportunities for wider optimisation.

Table 13 Matrix of decision-making areas in simulation of manufacturing systems, developed by author

Author	Flexibility	Scheduling	Method	Set-up	Layout	Strategy	PLC (controls)
Djassemi, 2005	1						
Joseph and Sridharan, 2011a	1						
Joseph and Sridharan, 2011b	1						
Kumar and Nottestad, 2009	1						
Baykasoğlu and Göçken, 2011	1	1					
Bokhorst and Nomden, 2008	1	1					
Sharma, Garg and Sharma, 2011	1	1				1	
Ferreira and Reaes, 2013	1			1	1		
Elleuch, Bacha and Masmoudi, 2008	1			1			
Shuiabi, Thomson and Bhuiyan, 2005	1			1			
Ali and Saifi, 2011	1	1		1			
Dhib, Elleuch and Frikha, 2013		1		1			
Bin Md Fauadi, Murata and Prabuwono, 2012		1		1			
Siemiatkowski and Przybylski, 2006		1		1			
Abd, Abhary and Marian, 2014		1					
Ekren and Ornek, 2008		1			1		
Kumar and Sridharan, 2009		1					1
Berman, Schechtman and Edan, 2009		1					
Basnet, 2009		1					
Bocewicz and Pawlewski, 2013		1					
Bzymek, Nunez and Powers, 2008		1					
Monch and Zimmermann , 2011		1					
Kumar and Sridharan, 2010		1					
Kia, Davoudpour and Zandieh, 2010		1					
Singh, Sarngadharan and Pal, 2011		1					
Caprihan, Wadhwa and Kumar, 2005		1					
Venkateswaran and Son, 2005		1	1				
Bergero and Kofman, 2011			1				
Xia and Sun, 2013			1				
Wy et al., 2011			1				
Mic et al., 2014			1				1
Dotoli and Fanti, 2012			1		1		
Ciufudean and Satco, 2009			1	1			
Ertay and Satoğlu, 2012			1	1			
Haouzi, Thomas and Petin, 2008			1	1			
Yang, Choi and Ha, 2004			1	1			
Kernan et al., 2011			1	1			
Bigand, Korbaa and Bourey, 2004		1	1	1			
Ko et al., 2013				1			1
Mahdavi and Shirazi, 2010				1			1
Caggiano and Teti, 2012				1			
Caggiano and Teti 2013				1			
Cardin, Castagna and Meghelli, 2012				1			
Gharbi, Kenné and Hajji, 2006				1			
Grunow, Günther and Lehmann, 2006				1			
Kessan and Baykoc, 2007				1			
Li et al., 2014				1			
Reeb et al., 2010				1			
Subulan and Cakmakci, 2012				1			
Talibi, El Haouzi and Thomas, 2013				1			
Renna, 2011a				1	1		
Renna, 2011b				1	1		
Jing-Wen, 2005				1	1		
Zolfaghari and Lopez, 2006		1		1	1		
Mayer, Irani and Adra, 2008					1		
Li, 2010					1		1
Süer, Huang and Maddisetty, 2010					1		
Liu, Jula and Vukadinovic, 2004					1		
Savsar, 2006				1		1	
Bhattacharya and Bandyopadhyay, 2010				1		1	
Berthaut and Gharbi, 2011						1	
Briskorn et al., 2006						1	
Cerekci and Banerjee, 2010						1	
Dotoli and Fanti, 2007						1	
Jamalnia and Feli, 2013						1	
J-W, 2005						1	
Mousavi, Broomhead and Devagiri, 2008						1	

2.3.5.1 DES for FMS

DES for decision support in FMS have been identified in sixteen paers. Some projects have covered multiple themes and so 24 entries for decision-making in FMS has been captured (Figure 20).

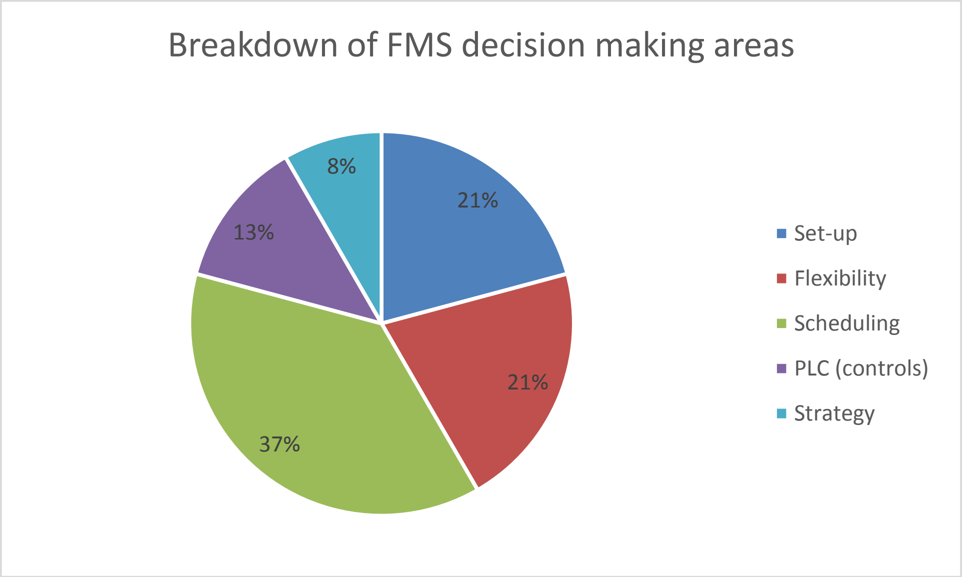


Figure 20 Breakdown of decision-making areas in DES for FMS research

Scheduling has been considered most researched area in FMS with use of DES. Three general case studies has been identified: Abd, Abhary and Marian (2014) looked into scheduling in robotic flexible assembly, Suresh Kumar and Sridharan (2009) have explored part and flow controls decisions in FMS preference and Dhib, Elleuch and Frikha (2013) have looked into scheduling of AGV system in FMS. Also, scheduling and dispatching rules have been a centre of attention in Basnet et.al.,(2009) who looked at dispatching rules selection; Kia, Davoudpour and Zandieh (2010) who have explored dispatching for sequence dependent set-up times, and Kumar and Sridharan (2010) looked at decision making for FMS in tool-sharing set-up. Caprihan, Wadhwa and Kumar (2005) have looked at impact of information delays on scheduling in FMS and Sharma, Garg and Sharma (2011) explored impact on delays in FMS performance.

The next decision making area identified is linked to the flexibility of FMS systems. Ali and Wadhwa (2010) and Joseph and Sridharan (2011b) explored routing flexibility in FMS. Sharma, Garg and Sharma (2011) used elements of routing flexibility in exploration of the impact of delays on FMS performance. Other projects involving flexibility have been considered too: Joseph and Sridharan (2011a) looked at dynamic due-date assignment in FMS and Kumar and Nottestad, (2009) looked at overall system flexibility in terms of capacity of the system and look into how this might affect capital investment under range of configurations.

Set-ups also have been a researched for FMS decision-making. Ali and Saif (2011) in study of FMS performance have combined set-up, scheduling and flexibility elements. Also, Dhib, Elleuch and Frikha (2013) in study of AGV impact on FMS have used set-up related parameters (i.e. number of AGVs). Further, Li, et al., (2014) have dedicated their work to evaluation of FMS performance with DES and Mahdavi and Shirazi (2010) developed a decision support model for flexible job shop manufacturing with focus on PLC. Ko et al., (2013) has presented modelling formalism for PLC in FMS with use of DES. Some elements of set-up has been considered but focus has been on provision of guidelines for FMS PLC development and implementation.

Savsar (2006) and Sharma, Garg and Sharma (2011) evaluated strategy impact on FMS performance. Sharma, Garg and Sharma (2011) looked at impact of delays in scheduling for FMS demonstrating the knock on effect on system performance and Savsar (2006) looked at effect of maintenance policies on FMS demonstrating variance of different strategies affection system performance.

Exploration of DES for FMS covered wide range of decision-making areas but what is lacking is a systematic approach for FMS development decision support. This means that there is no research the of FMS system that takes into account all aspects of development in a repeatable steps. As other manufacturing systems consist of elements that could benefit FMS, the exploration of DES for wider manufacturing systems also has been reviewed in the next section.

2.3.5.2 Exploration of decision making areas for relevant manufacturing systems with DES

This section focuses on further exploration of the decision making themes that has emerged from the SLR that include broader manufacturing systems that are relevant to FMS characteristics.

Scheduling

Within scheduling, the research focus has been around dispatching rules and scheduling rules as well as its combinations.

Dispatching rules refer to the way the parts are released to the system. Kia, Davoudpour and Zandieh (2010) listed most common rules as: first in first out, shortest processing time, shortest setup and processing time, least work remaining, earliest modified due date, critical ratio. Through simulation they tested whether heuristic algorithms in dispatching rules can improve flexible flow line production system. Bokhorst and Nomden (2008) has looked into impact of family-based dispatching (FBD) on batch manufacturing system performance taking into account jobs routing, flexibility of machine routing and location of FBD.

Scheduling rules represent the way parts are scheduled in production as input to the system. Those are based on specific routes and are affected by route flexibility. For instance, Basent (2009) has tested a range of dispatching rules to test different scheduling scenarios (single-pass, multi-pass, transient-based and utilisation based). Whereas Singh, Sarngadharan and Pal (2011) looked into the effects of dispatching rules and flow related factors (number of vehicles, number of Kanban and arrival rate demand) on performance measures. Abd, Abhary and Marian (2014) have considered sequencing rules, dispatching rules, cell utilisation and due date tightness for evaluation of robotic flexible assembly cells. Suresh Kumar and Sridharan (2010) looked at part and tool flow in FMS analysing impact of scheduling rules on performance.

AGV (automatically guided vehicles) has also been approached in simulation as a variable part of the system affecting performance. AGV play vital role in FMS systems as they include two key FMS elements: material handling and loading and unloading stations. They ensure the right flow of parts through the system, and therefore have significant impact on the FMS performance. Dhib, Elleuch and Frikha (2013) have focused on the impact of the transfer system parameters on AGV performance. Whereas Grunow, Günther and Lehmann (2006) looked into dispatching strategies for AGV in container terminals looking at single- and dual- carrier modes. Hafidz Fazli bin Md Fauadi, Murata and Prabuwono (2012) focused on evaluation of the AGV quantity requirements from manufacturing. The focus on AGV decision support is aimed at part flow improvement in production. It has been also confirmed by Kessan and Baykoc (2007) that the number of vehicles has a significant effect on performance which suggest that set-up of production is also sensitive area for exploration that can be approached through simulation in DES. Additionally, Subulan and Cakmakci (2012) took set-up based approach in AGV performance evaluation with use of DES and Tagchuchi methods for material handling system design for automation technologies. In this case focus was on part flow capacity. On the other hand, Briskorn et al., (2006) has investigated AGVs performance in the container terminals context under inventory-based versus due date based control policy.

Flexibility

In this section flexibility related simulation research is discussed in terms of focus of the research common issues studied.

Types of flexibility has been mentioned in introduction to FMS (Section 2.1.1) however, measurement of flexibility in FMS is relative to the type of flexibility studied. Shuiabi, Thomson and Bhuiyan (2004) have looked into entropy as suitable measure of flexibility as an ability to respond to changes in product mix and demand. They have highlighted limitations of ability to handle product variation and extra capacity. Alternatively, Joseph and Sridharan (2011b) defined flexibility through the following measures: routing efficiency, routing versatility, routing variety, routing flexibility of the system.

Although different levels of flexibility have been recognised in the literature in FMS application most common types evaluated is routing flexibility. Joseph and Sridharan (2011b) regard routing flexibility as the main contributor to the flexibility of an FMS. In their research simulation and analysis have been used to evaluate how five levels of routing flexibility affect the production system performance. A DES model has been developed to describe the operation of the FMS under different flexibility levels. Two cases have been considered with respect to the processing times of operations on alternative machines.

In many cases the routing flexibility is lined with scheduling rules. Baykasoğlu and Göçken,(2011) have approached this by analysing job release under variable workload, different order release mechanism, degree of flexibility on shop floor and dispatching rules. They have concluded that key sensitive factors affecting performance are order realise mechanism and degree of flexibility. Also, Joseph and Sridharan (2011a) combined routing flexibility, sequencing flexibility levels and part sequencing rules to investigate FMS performance through build understanding of the significant interactions of the three factors.

Flexible capacity has been considered valuable capability where long term investment or variable environment is concerned. It is a study around systems that can change their capacity according to dynamic requirements (i.e. demand). Kumar and Nottestad (2009) have proposed a DES simulation model for industrial FMS where there is requirement for flexible material flow requirements adaptation. This concept is close to achieving system setup reconfigurability capability through addressing number of machines and shifts.

Form considering the eleven papers on flexibility it can be summarised that types of flexibility considered in the research focus on mainly on two types of flexibility: routing and machine. Additionally, workforce flexibility in cell manufacturing has been also explored as well as sequencing and capacity flexibility has been investigated for FMS related type of simulation research (summary in Table 14).

Table 14 Summary of types of flexibility considered in the DES simulation research

Type of flexibility	Sequencing	Labour	Route	Machine	Capacity
Number of papers	1	2	6	3	1

PLC control

Investigation into programmable logic control (PLC) has also been considered important FMS feature as, currently, its development is time and resource consuming and error prone (Ko,2013). Simulation has been used to design better method for implementation of PLC in FMS. Ko et al., (2013) has used discrete event simulation formalism (DEVS) allowing to make programming process shorter and easier to spot mistakes through ability of visualisation. Also, Mahdavi and Shirazi (2010) have investigated set-up and PLC related decision making based on multi-objective simulation optimisation focusing on achievement of best cell utilisation.

Further, performance of different control strategies has been investigated in production of serial-batch processor systems has also been tested with use of benchmarking and simulation (Cerekci and Banerjee, 2010).

Layout

Layout comparisons has also been delivered through use of DES as this method allows visual and data comparisons of the as-is and to-be type of analysis.

Ferreira and Reaes (2013) have compared virtual cell and job shop configurations. This work focus on set-up-related experimental factors and two sequencing rules as scope of analysis. Renna (2011a) and Renna (2011b) have focused on different cell manufacturing layouts comparison (virtual manufacturing cells, fractal cells and remainder cells) for production volume and product variety. Although this is not FMS type layout, it addresses similar type of production requirements. Li et al., (2014) has also used simulation for layout comparisons in job shop environment with aim to move into constant work-in-process production control (CONWIP). The experimental factors used correspond with Jing-Wen’s (2004) approach who used layout change (from functional to cellular) for quality improvement and set-up time reduction.

Dotoli et al., (2012) has used a case study of forklift trucks manufacturing to demonstrate layout change in correspondence with lean strategies. Also, AGV as automotive solution to container layout has been compared for performance improvement by Liu, Jula and Vukadinovic (2004).

Jing-Wen (2004) has compared functional and cellular manufacturing layout in the pull system production control with the aim to investigate improvement through use of JIT practices: cellular manufacturing, operations overlapping, reduction of set-up/processing time variability (variability reduction) and set-up time reduction. The study has explored performance improvement in coordination of cellular manufacturing and set-up reduction.

Zolfaghari and Lopez (2006) have compared cellular manufacturing system versus hybrid production systems in multi-factor comparisons identifying that scheduling rules have a significant impact on the performance of all types of systems. Ekren and Ornek (2008) have looked into evaluation of different layout use in manufacturing (functional vs. cellular layout) however scheduling rules, breakdowns, batch sizing and transport has also been included as key parameters. The authors argue that use of range of parameters considerably affects the simulation performance. Also, Mayer, Irani and Adra (2008) have compared process layout and virtual cell solution through use of simulation. Correspondingly, cell utilisation improvement has been investigated through simulation by Caggiano and Teti (2012) where layout and material handling system was simulation in pursuit to improve cells utilisation for batch production.

Set-up

Set-up refers to the way the production system is configured physically. It has been studied in in variety of manufacturing systems as the optimal configuration affects the ability to achieve best system capacity. In set-up related simulation projects variety of production aspects are considered depending on the objectives nature.

Süer, Huang and Maddisetty (2010) has demonstrated a case study for testing alternative manufacturing cell designs among dedicated and cultural designs focused on minimising WIP, maximising throughput. Caggiano and Teti (2013) has looked at how simulation can support analysis and improvement of mass and small batch manufacturing. Digital factory was used to model manufacturing call, analyse bottlenecks and test improvement with what-if scenarios. Further, Reeb et al., (2010) applied simulation for selection of part families in cell manufacturing with aim of lead time and WIP reduction. Monch and Zimmermann (2011) have used simulation for shifting bottlenecks in multi-product complex job shop operations in semiconductor manufacturing. Focus of this work is on increasing on time delivery performance, optimising throughput and cycle times.

The set-up simulation also allowed investigation with other decision making areas. Savsar (2006), for example, has investigated effects of maintenance policies on FMS productivity, testing six set-up options. Overall, FMS has achieved best production rate with the opportunity-triggered maintenance policy where preventative operations are triggered by failure mechanism. Berthaut and Gharbi (2011) have focused on determining optimal maintenance policy and production and inventory control for manufacturing cell. Whereas, Siemianowski and Przybylski (2006) have looked at inspection planning strategies and job sequencing effects on performance of multi-station machining cell in FMS set-up aiming for WIP reduction.

In set-ups, the important role of real life variability is addressed by researchers. For instance, impact of delays has been studied by Sharma, Garg and Sharma (2011) where the effect of delays been compared in various layout alternatives. This model has taken into account scheduling and dispatching rules as well as routing and machine flexibility. From the operational perspective, Bhattacharya and Bandyopadhyay (2010) has focused on impact of deadlock recovery strategies of AGV systems performance using makespan as key performance indicator. Also, Dotoli and Fanti (2007) have looked into simulation of deadlock resolution strategies for automated storage and retrieval systems testing the effect of control polices on throughput and utilisation. Elleuch, Bacha and Masmoudi (2008) looked into breakdown impact reduction in cell manufacturing by applying group technology set-up. The important factors apart from breakdowns and repair time have been degree of machine flexibility. The flexibility has been proven to impact on utilisation rate of machines. On the other hand, Gharbi, Kenné and Hajji (2006) has proposed a hybrid approach for production rate control in unreliable manufacturing system. The production rates and sequence of setups has been main influencers to minimise set ups and surplus cost.

Set-up related DES supports range of system element variables as well as it can make it realistic picture by exploring the impact of real life system constraining events.

Strategy

In strategic context, simulation has been supporting measuring impact of application of different production related concepts on to the manufacturing systems. For instance, impact of different operation strategies has been investigated through simulation in a context of AGV. Kumar and Sridharan (2010) have looked into effects of JIT on AGV system experimenting with dispatching rules, number of vehicles, number of Kanban and arrival rate demand. Following the same approach Kessan and Baykoc (2007) have investigated impact of using just-in-time strategy in AGV in the job shop environment.

Further, different strategies in manufacturing system management has been considered. Li (2005) has evaluated impact of push versus pull system in cell-based job shop environment concluding that push systems are more effective. Whereas, Jamalania and Feli (2013) have looked into decision making in aggregate production planning taking into account supply and manufacturing system. Hybrid system dynamics and DES model have been used to test profitability of different strategy application scenarios. Also, Talibi, El Haouzi and Thomas (2013) have demonstrated adaptive Kanban versus traditional Kanban impact on cost of production using data-driven simulation proving that the first method application leads to savings and improved performance.

Model development

Another area of interest lays in building understanding and provision of methods for building simulation models. His section demonstrates tools and methods used for building decision-making models with DES.

Bigand, Korbaa and Bourey (2004) have demonstrated FMS performance evaluation using information system design where specification, design, simulation, and implementation is built from product viewpoint. The meta-modelling covers performance and scheduling focus. Also, Mousavi, Broomhead and Devagiri (2008) have introduced a design and implementation of framework for real time data collection from shop floor combined with DES as a predictive behaviour tool feeding to enterprise resource planning system. Further, Bergero and Kofman (2011) have focused on introduction of PowerDEVS tool that links hybrid simulation modelling. Also, Ertay and Satoğlu (2012) have developed and demonstrated methodology for new product introduction supporting decision making in parameter selection using axiomatic design and simulation.

Some modelling works focused on purpose of simulation modelling. It attempted to introduce a method for specific problem area. Cardin et al., (2012) has developed a method for performance evaluation for storage and retrieval plc system defined by algorithm and tested by simulation. Whereas Ciufudean and Satco (2009) have focused on demonstrating a method for performance evaluation of DES using Henstock-Kurzweil integral to account for resource loss. Yang, Choi and Ha (2004) presented a procedure governing transport vehicles to automated lifting vehicles with evaluation of number of AGVs required in given scenario.

Simulation models are in great majority produced as bespoke models used for particular objectives and use. Standardisation of simulation for in a conceptual level has been attempted by Haouzi, Thomas and Petin (2008) who have focused on delivery of modular and reusable simulation models for manufacturing applications, demonstrated the demand flow technology focused manufacturing system. Standardisation, specifically for FMS, has been attempted by Mic et al., (2014) where the attempt to define formal product specification for wood industry has been carried out. The paper introduces formalisms for: product specifications, FMS capabilities, product manufacturing and concurrent control to achieve the desired products. Also, Dotoli and Fanti (2012) have proposed a method for lean manufacturing strategy testing in manufacturing setup using value stream mapping, unified modelling language and DES. Whereas, Xia and Sun (2013) have demonstrated how DES can enhance value stream mapping by demonstrating As-Is and To-Be scenarios.

Other methodologies presented, address solving valid problem is real life manufacturing. For instance, Kernan et al., (2011) has developed a method for measuring impact of resource constraints on machine utilisation in manufacturing systems. This work focus on identification of key resources to improve manufacturing systems to reduce overall system constraints. Venkateswaran and Son (2005) presented a method for hierarchical production planning introducing the multilevel simulation. Wy et al., (2011), on the other hand, presents method for building data-driven generic simulation model for logistics-embedded assembly and demonstrates it in cellular and manufacturing layout example.

Although the papers in this section has focused on introduction of model development methodologies, they are connected to valid manufacturing problems and provide demonstrative case studies. The effectiveness of this presentation lays in its usability and transparency to other users.

Crossover

It was clear that simulation projects cover more than one decision-making area in manufacturing. Table1 5 presents the overlap matrix for crossover themes in decision making in manufacturing system simulation. As method refers to the practice of simulation and layout refers to trading one type of system over another, it can be claimed that set-up flexibility and scheduling are most connected decision-making areas for FMS development.

	Set-up	**Flexibility**	**Scheduling**	**PLC control**	**Strategy**	**Method**	**Layout**
Set-up	**x**						
Flexibility	**3**	**x**					
Scheduling	**5**	**4**	**x**				
PLC control	**2**	**0**	**1**	**x**			
Strategy	**1**	**1**	**1**	**0**	**x**		
Method	**6**	**0**	**2**	**1**	**0**	**x**	
Layout	**5**	**1**	**2**	**1**	**0**	**1**	**x**

Table 15. Crossover themes in decision making in manufacturing system simulation

Further, from the pool of decision support it was identified that PLC has been assigned with at least one other area in all cases whereas strategy has the least crossover with other decision support areas (see Table 16). It might be case that strategy acts as an overarching “layer” of the production system and represents a higher level lens on the system as a whole.

Whist set-up has high crossover with other decision support areas, it was not associated with 40% of cases. This suggests that within set-up a high level of variability in DES development is possible.

	Set-up	**Flexibility**	**Scheduling**	**PLC control**	**Strategy**	**Method**	**Layout**
Single DM area	**12**	**4**	**12**	**0**	**9**	**5**	**3**

Percentage of one DM area papers	**40%**	**36%**	**55%**	**0%**	**90%**	**42%**	**27%**
Total	**30**	**11**	**22**	**5**	**10**	**12**	**11**

Table 16. Breakdown of non-associated papers

Examination quantitative data of the tables supports earlier assertions made in the paper, namely:

- Within strategy decision support area, general manufacturing case studies are widely explored but it is absent for FMS specific cases. Study into different strategies has not been explored.
- PLC/Control research is low and always associated with at least another decision support
- There is a gap on exploring how PLC control changes can impact on FMS flexibility levels
- Whilst methods are well explored, there are gaps in exploring how decision support can link to flexibility and strategy. Additionally, links to control and layout are poorly addressed.
- FMS has not been compared with other manufacturing systems. There is an opportunity to compare FMS based solutions with non-FMS types of layouts.
- Surprisingly there are few papers crossing over between flexibility and layout even though layout would seem to be a significant factor affecting flexibility levels.
- Up to three decision making areas have been covered by case studies. No papers cover the breadth of the decision support areas identified with the literature.

2.4 Discussion

The systematic literature review of decision support through DES related to FMS context has been studied in this chapter. The review has focused DES as a decision-making support tool as it was considered most used simulation approach in manufacturing. Additionally other manufacturing systems DES studies has been included as they have covered relevant to FMS characteristics. Although the focus in the research was on FMS, it has been recognised that FMS scope itself is limited and broadening scope of exploration in manufacturing systems encourages mixing approaches to achieve understanding and results of complexity in FMS. This review explored wide range of databases, and identified 67 papers relevant to this field of study. Focusing on decision-making enabled through simulation allowed to build understanding on types of decision making the DES can support. This work fits in with similar review papers developed in the manufacturing and operations management focus.

The limitation of this study is the focus on DES as a main simulation approach, excluding, for example, mathematical approaches. Therefore, it does not cover the full scope of decision-making relevant to FMS. Rather, it provides the understanding on how DES is able to support development of FMS decision making across the decision-making spectrum. On the other hand, although the focus of this study was on FMS, consideration of other types of systems was valuable as it allowed to digest the relevant to FMS concepts, for instance, on material handling scheduling has been widely explored in AGV research.

Another element that has been noticed during the process is the variability of data that is used for simulation studies. It has been difficult to evaluate the data accuracy in modelling of the simulation project as little information about the data set and data collection for simulation is provided in the research papers.

From the data-set findings, it has been clear that DES has consistently been of interest in decision making in range of areas: strategy application, layout testing, set-up configuration, scheduling, PLC control and methods in building simulation models. The model development cluster does not refer to decision making in FMS directly, nonetheless it has provided most useful introduction of methodologies for replication of simulation experimentation for different system proving a valuable study area especially in set-ups scenarios.

Analysis of the FMS and DES literature obtained allowed identification of avenues for research which were extended by considering wider manufacturing literature that shared the same features as FMS. Opportunities for decision support were clustered into: set-up configuration, flexibility, scheduling, PLC, layout, strategy and method of building simulation models.

The decision-making area of methods of building simulation models offers potential for significant development within FMS. Methods are well developed for general manufacturing systems but not explicitly for FMS. How to refine methods for FMS could promote model standardisation and in turn speed up model development and enable reuse. For the six other decision support areas discussed next, there is value in developing a framework for FMS decision support through DES. The decision support areas span levels from strategic through to detailed technical PLC. Through better decision support across the breadth of FMS challenges there is potential to avoid sub-optimal solutions.

Layout research is common for general manufacturing systems but rarely addressed for FMS; comparison of alternative layout types to FMS is absent in the literature. This surprising finding suggests there is an opportunity to use DES to investigate alternative layout types to FMS to verify decision robustness as well as seek opportunities for layout refinement. DES has the capability to model diverse layout types and extending this to automated layouts should not present technical modelling challenges in uncovering new knowledge on differences in performance.

Flexibility is an obvious area for FMS and DES research but surprisingly few papers cross-over with layouts even though layout could be a significant factor affecting flexibility levels. Simulation of flexibility has potential for broad assessment of FMSs, however, research narrowly focuses on routing flexibility. Whilst general manufacturing systems research also covers capacity flexibility, workforce flexibility and machine flexibility this is not the case in FMS even though changes in technical and human resource levels could be a factor in the overall FMS operating performance.

Strategy as a decision support area is absent in FMS. It was explored in general manufacturing case studies but not for FMS. Therefore, room exists to explore strategic decisions and their impact on operational performance. One aspect would be to consider whether flexibility restrictions or opportunities arise because of strategy decisions. Referring to the earlier tables, strategy is considered in isolation and not linked to any other area. Understanding how other decision making areas affect and are affected by strategy could lead to new decision support approaches or better manufacturing system solutions.

PLC and general control research was low. This was unexpected given the automation with FMS and the abilities of DES to incorporate detailed decision logic. That said, PLC research was always considered as part of another decision-making area and not alone. This cross-over of decision making is interesting and there is potential to take learning here and apply with other decision making. Again, relating back to flexibility, there is little research on the impact of PLC logic on flexibility and hence research could investigate how detailed hardware configurations impact on over system level flexibility.

The most popular decision support areas are set-ups and scheduling. Additionally, these areas are commonly combined with other areas, with scheduling having clearer definition of objectives for modelling. Complex problems where often addressed, especially when combined with assessing flexibility. The two areas of set-ups and scheduling cover short-term operational decision making and so consideration could be given to how real-time decision making could be improved given the pace of developments in Industry 4.0. Further, AGV research is widely explored but surprisingly not in FMS context. Therefore, material handling scheduling as part of a systems view of FMS could be investigated. Unlike other areas covered above, set-ups and scheduling are well explored and no further recommendations are made here for exploration.

2.5 Research gap

The main research gap identified over the course of this review is that:

1. There is lack of DES decision support for FMS development. Although there are decision support DES models in specific decision-making areas, like in scheduling, there has been no systematised approach for FMS development covering all aspects of FMS design.

Due to the fact that a range of aspects of DES as decision-making support of FMS development have been explored further sub-gap areas have been identified:

2. Methods for ensuring modelling data accuracy in DES models development
3. DES for set-up testing in FMS development
4. DES for flexibility examination in FMS development
5. Method for scheduling for FMS with DES

This PhD aims to address the research gaps by development of conceptual framework for decision support in FMS development using DES and validate it through use of case studies developed for every sub-objective identified.

2.6 SLR findings summary

This research explored a common space between discrete event simulation and flexible manufacturing systems for decision-making support.

This research has focused on exploration of decision making support provided by DES in FMS development. The study has focused on identification and classification of the decision support areas. DES is able to support variety of FMS issues stared to set-up (machines), scheduling (loading/unloading), PLC control and flexibility, especially routing and material handling (highlighted by AGV projects). This work builds foundation for building an understanding into a range of decision making support and is a stepping stone towards building a framework for FMS decision support through use of DES. Decision support though DES has been explored as tool across the division making level spectrum in pursuit of support for decision making in FMS. Systematic literature review carried out in this paper have identified the following findings:

- There is lack of view on how DES cold support the development of different aspects of FMS in systematic approach
- There is variable amount of data available for studying different aspects of FMS
- Main decision making clusters are: strategy application, layout testing, set-up configuration, scheduling, PLC control and methods in building simulation models.
- Set-up, flexibility and scheduling has been identified as the most connected themes in decision making covered by DES.

The research gap uncovered through the research will be addressed by development of conceptual framework for decision support in FMS development using DES.

3 Aim, objectives and methodology

3.1 Aim and Objectives

From identifying the gaps in the literature, the aim of this research is to develop a decision support framework for flexible manufacturing systems using discrete event simulation.

Therefore, the objectives of this study are specified as follows:

1. To develop conceptual framework for development of decision support in FMS using DES
2. To develop an approach for simulation of FMS based on the use of primary data collected from the industrial shop floor
3. To develop a DES-based approach for evaluation of production set-ups in FMS
4. To develop DES-based approach for addressing different levels of flexibility in FMS
5. To develop DES-based approach for testing schedules in FMS
6. To validate the conceptual framework and the proposed approaches through case studies on FMS

3.2 Methodology

Methodology provides means of validating the research quality and ensures that systematic, sceptical and ethical standards are considered (Robson, 2002). This chapter introduces relevant research philosophy, approaches and methodology applied in this PhD. Additionally, it provides in depth explanation of chosen research methods.

3.2.1 **Research philosophy and approaches**

Creswell (2009) recognises four philosophical worldviews in research postpositivism, constructivism, advocacy and pragmatism (defined in table 16). Those views form the set of beliefs that drive the research activities as well as guide method selection based on the definition of research focus/problem.

Table 15 Research Worldviews, adapted from Creswell (2009)

Postpositivism	**Constructivism**
• Deterministic philosophy • Reductionism • Empirical observation and measurement shape knowledge • Theory verification • Assumed objectivism	• Building understanding • Multiple participant meanings • Social and historical construction • Theory generation • Subjective view
Advocacy	**Pragmatism**
• Political • Issue-orientated • Collaborative • Change-orientated	• Consequences of actions • Problem-centred • Pluralistic • Real-world practice oriented

Research philosophy within this study focus on pragmatism (aka realist) philosophies that look into provision of model of scientific explanation where research is grounded in the real world context (Robson, 2002). It focused on observation of context, mechanisms and outcomes in pursuit to find patterns (as illustrated in Figure 21).

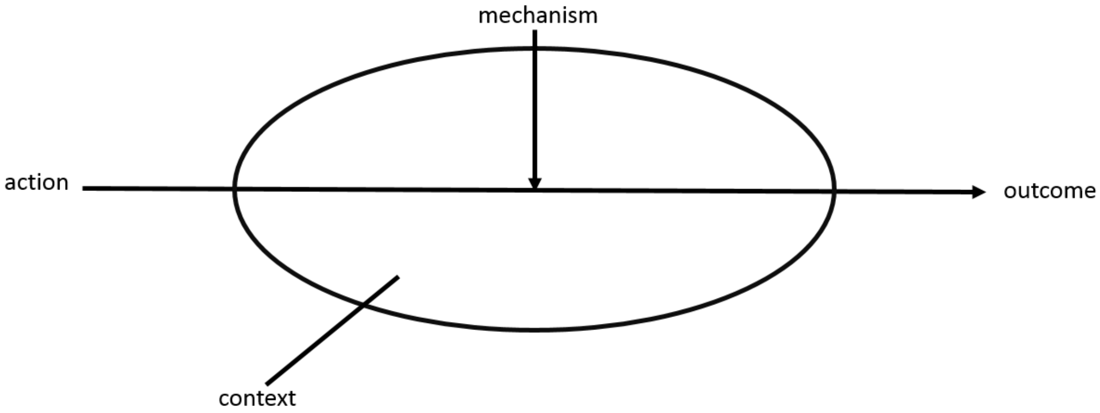


Figure 21 Representation of realist philosophy, adapted from Robson (2002)

The research covered by this work focused in the area of applied research. This means that the solutions provided in this work shall be practical and address immediate problems that society or organisations are facing (Kothari, 2008). According to Robson (2002) it is an approach that presents limited consistency from one topic to the next and applies multiple methods as it is targeting problem solving, rather than gaining knowledge. Therefore, it is fitting that applied research characterise with use of mix method research approach.

In order to be able to consider mixed method approaches one's need to understand types of approaches available. Table 17 summarises the approaches characteristics. Mixed-methods can remove the bias in using only one method. Additionally, one method can provide data to feed in in another method.

Table 16 Characteristics of research method approaches, adapted from Creswell (2009)

Approach / Characteristic	Qualitative	Quantitative	Mixed Method
Design	Pre-determined	Emerging	Predetermined and emerging
Question design	Instrument based	Open-ended	Instrument based and open-ended
Types of data	Performance based, measurable, observational	Interview observation data, audio-visual data	Multiple types of data
Analysis	Statistical analysis	Text analysis	Statistical and text analysis
Interpretation	Statistical interpretation	Themes, patterns interpretation	Across databases interpretation
Philosophical assumptions	Constructivism/ Advocacy	Postpositivism	Pragmatism
Strategies of enquiry	Phenomenology, grounded theory, ethnography, case study, narrative	Surveys and experiments	Sequential, concurrent, transformable
Methods	Open-ended questions, emerging approaches, text or image data	Closed-ended questions, predetermined approaches, numeric data	Pre-determined and emerging approaches, both qualitative and quantitative data and analysis

3.2.2 **Methodology structure**

Taking into account all methodological and contextual considerations the methodology build for the purpose of this PhD is outlined Figure 22. The process of methodology development has been kept broad. The order of the case studies has been emergent and this is because the research has been carried out in a real world context. The case studies emergence has dictated the methodology structure. Additionally, at every case study verification and validation had to be carried out to ensure to the the research are meeting defined objectives.

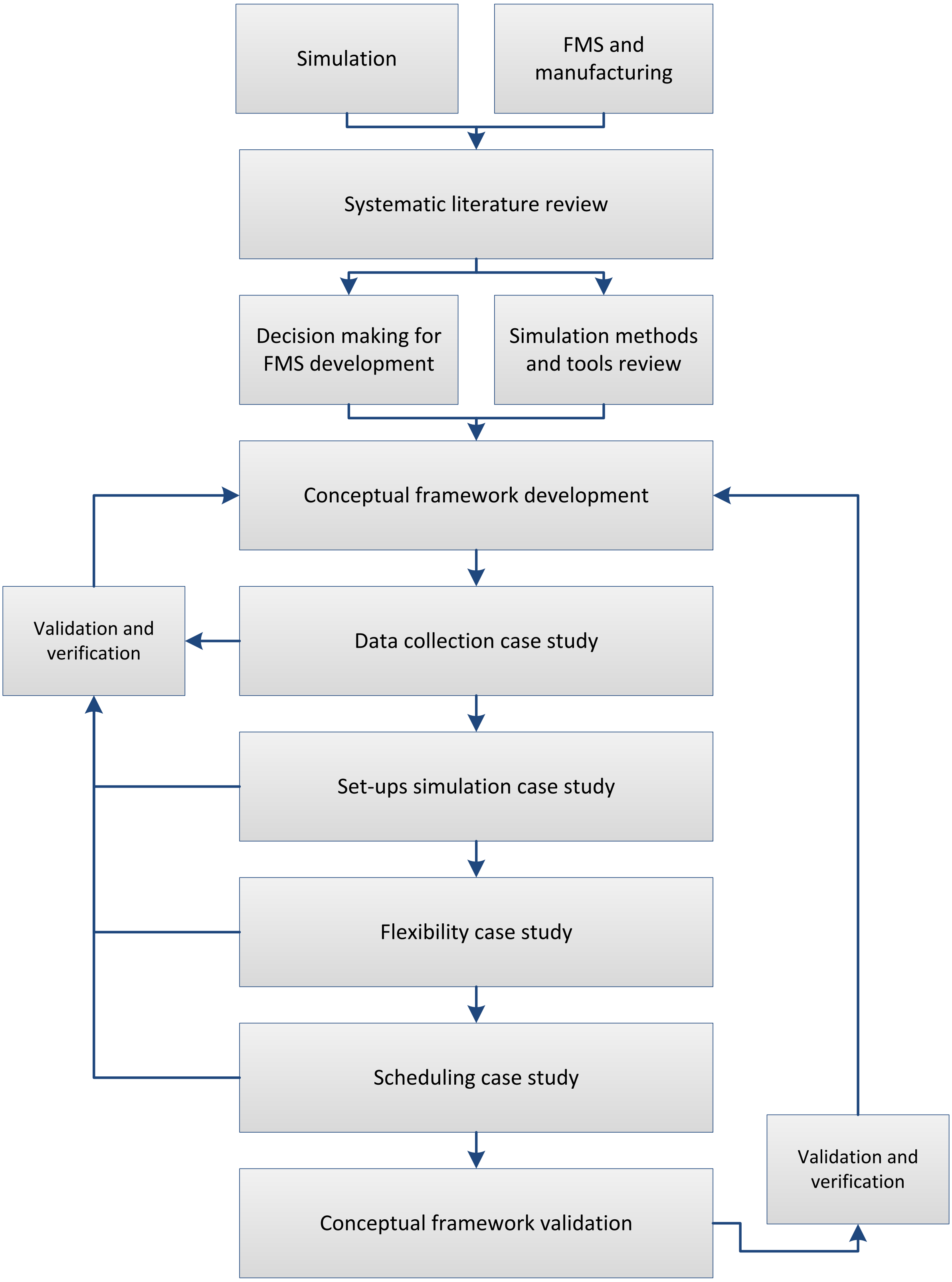


Figure 22 Methodology structure

The research methodology for this PhD focus on case study development for conceptual framework elements. The Systematic literature review was performed in order to understand the use of discrete event simulation (DES) tools in manufacturing to support FMS development.

Following that, data collection from the organisation involved in the study-Cosworth- was executed to define conceptual model for the simulations for defined case studies: set-up, flexibility and scheduling. Once the conceptual framework was developed, the simulation studies has been developed with industry. Data collection method for primary data in simulation was constructed (Chapter 5). Factory level simulation (manufacturing process) case studies for set-up (Chapter 6), flexibility (Chapter 7) and scheduling (Chapter 8) were developed in the WITNESS simulation software. The models were verified and validated. Verification stage was based on the modeller experimenting with the conceptual model assumptions until the model matures reach the level where modeller and the industry partner will be in agreement of meeting the requirements with the model simulation. Validation was carried out in a form of a systematic optimisation, for example through use of design of experiments. This is further covered in section 3.2.3.5 as well as in individual case studies.

The conceptual framework was validated though case studies development, demonstrating systematic approach to decision making levels of FMS development and demonstrating DES capability in this field. Further sections discuss methods applied in the PhD.

3.2.2.1 Research influence

As mentioned before the research carried out in this PhD has been embedded in the context of automotive industry facing challenges of development of FMS for the medium size production high value goods. This means that the research has been influenced by this context and by challenges that industry have faced in FMS development. Therefore, the conceptualisation of FMS has been driven by existing system as well as data collected were relevant to the specific production system. Although the methodologies to develop case studies were structurally driven from academic context, the development of case studies scope was emergent process. It has been focusing on the complex problems were simulation was essential tool to support decision making.

Although this is in depth study of one FMS system, it is representative of FMS in automotive industry targeting smaller size production throughput with capability to be adaptable to change.

3.2.2.2 Tools in this research

As the understanding of the methodology structure has been established, it is important to define specific tools that had been selected in case studies of this PhD. The summary of the methods used are presented in Table 18.

Table 17 Tools used in different stages of research

	Data collection	Data analysis	Validation
SLR (Ch2)	Review of current journal and conference literature	Statistical	N/A
Decision support Framework(Ch7)	SLR	Mapping from Literature and industrial inputs	Case Studies
Data collection for FMS (Ch3)	Videoing	Behavioural coding Statistical analysis	Real life data comparisons
Set-up (Ch4)	Conceptual model	Simulation Design of experiments	Alternative model comparisons (loading capacity)
Flexibility (Ch5)	Conceptual model	Simulation What-if analysis	Alternative model comparisons (loading capacity)
Scheduling (Ch6)	Conceptual model	Simulation Scenario experimentation	Alternative model comparisons (loading capacity) Real life data comparisons

The research tools are discussed further in more detail in the next sections of this chapter.

3.2.3 **Research methods**

Taking into account the philosophical considerations of this PhD as well as research context, mixed method data collection techniques will be utilised as presented in Table 19.

Table 18 Data collection methods, sources and purpose

Data collection method	**Source of data**	**Purpose**
Systematic literature review search	Journals, conference papers	To explore literature gaps and identify case studies focus
Conceptual Framework	Conceptual model – SLR; Validation – Case studies	To build conceptual framework for decision making for FMS with DES
Case Study	Project meetings requirements development, simulation	To provide evidence based decision support in selected case studies
Conceptual modelling	Project meetings, part flows, Cosworth FMS plant, CAD drawings	To build conceptual models for case studies with real world requirements
Simulation	Conceptual model, operation data	To build test environment for case studies
Experimentation	Simulation	To validate the case studies validity in applied manufacturing context

3.2.3.1 Systematic literature review

In order to ensure valuable input and high quality of the literature review chapter a systematic literature review (SLR) approach had been adapted. Detail into use of SLR in this research is outlined in section 2.3.1.

3.2.3.2 Conceptual framework

Conceptual framework (CF) is a means of theory introduction in a diagrammatic form (Robson, 2002). CF can explain the system of concepts, assumption and expectations that guide and support research (Maxwell, 1996). Robson (2002) finds CF useful in real life research when CF is used to conceptualise the behaviour of the system in particular context. CF through use of mix-methods at the data collection and analysis allows to verify whether the system will behave the prescribed way to support or not support research theories.

Based on the SLR findings and guidance from industry, CF was found to be appropriate method for visualising the decision support for FMS with DES.

3.2.3.3 Case study

A case study focus on answering “how” and “why” type research questions with grounding into context (Yin, 1994). Case study as a method focus on unravelling a decision (or set of decisions) with the context of why, how and with what result have they been applied. This method has been described as empirical inquiry that investigates phenomenon in depth and within its context when the boundaries between the phenomenon and context are not clearly visible (Yin,1994). Voss, Tsikriktsis and Frohlich (2002) champion a case study as suitable for new theory and testing tool, although Diamond (1996) criticises it for lack of application of scientific methods, which may lead towards verification bias. Case study as a method has been criticised as unclear due to subjectivity, validity and verification. However, Yin (1994) has addressed concerns for lack of rigour and lack of basis for scientific generalisation by providing case study components: question, propositions, unit of analysis, logic linking data to propositions and criteria for interpretation the findings.

For this PhD work, the basis to form a case study will be conceptual modelling and simulation as main structure for its development. Simulation can be viewed as a research strategy or means of case study implementation. It has been considered as data collection method where an attempt is made to develop controlled environment to illustrate and test real world phenomenon (Robson, 2002). Therefore, this research methodology will apply simulation case studies as cases of investigation to answer and understand the identified research gaps and explore the research areas for decision-making support in FMS as well as to systematise the decision making process.

Within remit of case study, it is possible to conceptualise the CF use: automotive company who is investing into novel FMS requiring decision making support. As this is a new process within the production environment, the expertise and historical data available are limited and requirement of expectation (assumption about the system) need to be verified with observation of the real system. Simulation enables visualisation of the system behaviour and studying the effect of different types of decision on system performance. Simulation and conceptual modelling has been broadly covered in the literature review section of this PhD.

The main limitations for case study development are:

1) limited time that can be spend on development of cases;

2) limited data access for each case study (sometimes estimated data rather than real data sets are available);

3) access to one application of FMS in automotive industry which will provide in depth insight into development of FMS, but provides recommendations fitted towards automotive applications and the automotive company.

Further, conceptual modelling and simulation are discussed as selected research methods.

3.2.3.4 Conceptual modelling

Conceptual model (CM) is a representation of the problem in such a form that it can inform the developers of the simulation about the simulation development direction . CM is a helping tool and its aim should be focused on improvement of problem solution and build understanding around the problem solutions (Robinson,2004). Robinson (2004) outlines five key activities that CM is fulfilling:

1. Understanding the problem situation
2. Determining the modelling and general project objectives
3. Identifying the model outputs (responses)
4. Identifying model inputs and experimental factors
5. Determining the model content (scope and level of detail), identifying assumptions and simplifications

Figure 23 provides the conceptual model abstract representation.

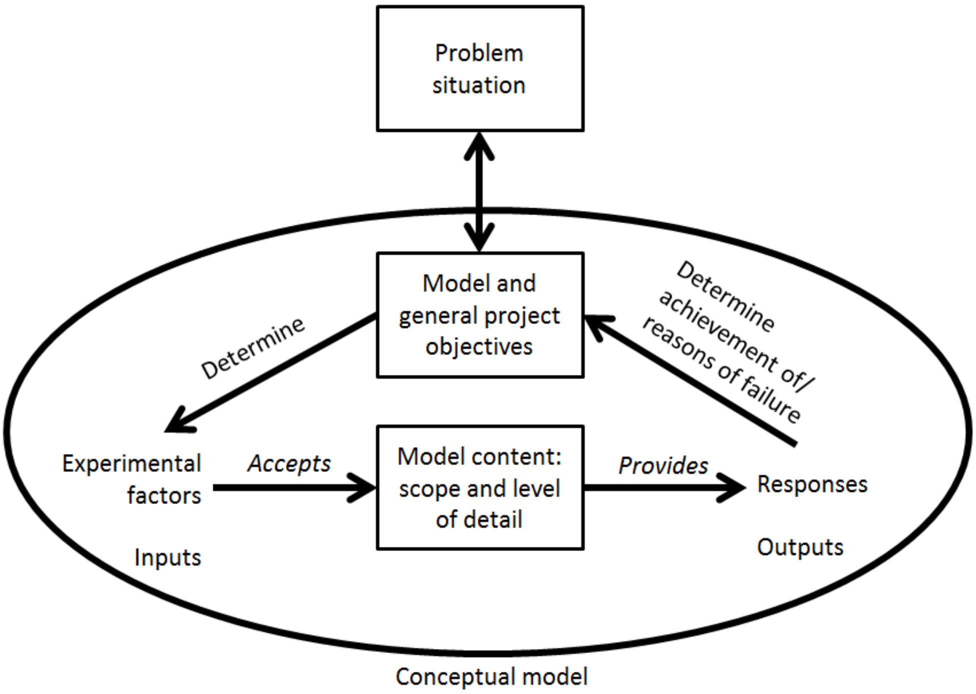


Figure 23 Conceptual model framework, adapted from Robinson (2004)

Additional elements that are key for the simulation is assumptions and simplifications that the model is going to be build. Table 20 provides the breakdown of the key activities contribution to understand the scope of modelling.

Table 19 Conceptual modelling elements explained

CM activity	Purpose
Understanding the problem situation	Developing a sheared understanding of the problem simulation (Robinson et al., 2001; Baldwin, Eldabi and Paul, 2004)
Determining the modelling and general project objectives	Modelling obj. – describe the purpose of the model General project obj. – timescales, nature of the model and its use (requirements)
Identifying the model outputs (responses)	Report results from run simulation model
Identifying model inputs (experimental factors)	Elements of the model that can be alerted
Determining the model content	Components that represent the model and their interconnections Scope – model boundary/ breath of the real system Level of detail - the detail to be included for each component in the model scope
Assumptions	Made where there are uncertainties or beliefs about the real system in the model
Simplifications	Incorporated in the model to enable rapid model development and use Allows to reduce data requirements Improve transparency (understanding)

For a purpose of capturing right data, it might be concluded that CM should include all relevant elements and their relationships, the model boundary, assumptions and limitations. Therefore, data collection for this activity needs to be able to capture not only range of information, but variable types and formats of data.

CM data collection

CM data collection aims to support the development of the abstract of reality, which will support capturing valuable information to fulfil project objectives in a business context. Although there is no standard way of building conceptual models (Moody, 2005), there is a range of tools available for building different building blocks of the CM. As the CM is a communication tool between the modeller and other stakeholders who invest into simulation, it is important to capture data in clear and transparent way. The stakeholders may have different interest in the simulation and therefore variety of communication tools is necessary to gain common understanding between all parties. In order to gain insight and understanding of the processes to be simulated the required information needs to be collected through looking into real life data. Data collection involves preliminary data collection for building a CM scope, this may overlap with data for model realisation in simulation, and however the purpose of its use is different. Table 21 provides summary of the tools available and its use in building the communication through conceptual model. Some elements are discussed in detail further.

Table 20 Tools and its use in building of the CM

Data Required	Tool	Justification for use	Format of data	Type of information gathered / Questions
"Problem" definition	Soft Systems methodology (Checkland 1981) Cognitive Mapping (Eden and Ackermann 2001) Casual loop diagrams (Sterman, 2000)	Allows to connect issues related to the problem and explore areas of focus as well as potential goals	Visual mapping	Set of issues / challenges /goals
Objectives definition	Prompt questions / Objectives template from Robinson (2004)	Definition of CM direction and how to measure success	Table	Define the aim of the organisation in the project/ How will CM contribute to the simulation? /Set of tangible objectives that can be measured
Expected benefits	Discussion	Definition of CM purpose	List of benefits	How the results will aid the organisational goal?
CM representation	Process Mapping / Visual flow map	CM boundaries definition	Process model/ VSM/ Table	Process model/ Equipment specification/ Resources input/ Expected outputs
Inputs	Process Mapping /discussion/ secondary sources	Allows to discuss required level of detail for CM development / Input capture	Table	Dynamic components
Outputs	Discussion/ production KPIs	Client opinion on measurements for assessing simulation success	List/ Table	How the modelling objectives achievement is demonstrated? / What is the measures matrix?
Assumptions and limitations	Discussion	Definition of intangible boundaries and scope verification	List Inclusion/Exclusion table	Limitations: the simulation boundary
Simplifications	Discussion Identification of non-value adding elements	Definition of trades for gaining transparency and improvement of development speed	List	List of possible simplifications and elements
Scenarios definition	Brainstorming	Allows to explore multiple scenario and down select to key importance use cases	Use case	Scenario/s

CM representation is one of the key deliverables as it represents the snapshot of the scope of the simulation. Therefore, visual tools are appropriate for scoping CM and Figure 24 outlines simple scoping example of a simple manufacturing facility. All the elements covered contribute to development of scope and level of detail specification. In simple terms, graphically introduction of CM allows to capture the elements, their relationships with one another as well as the boundary of the simulation model.

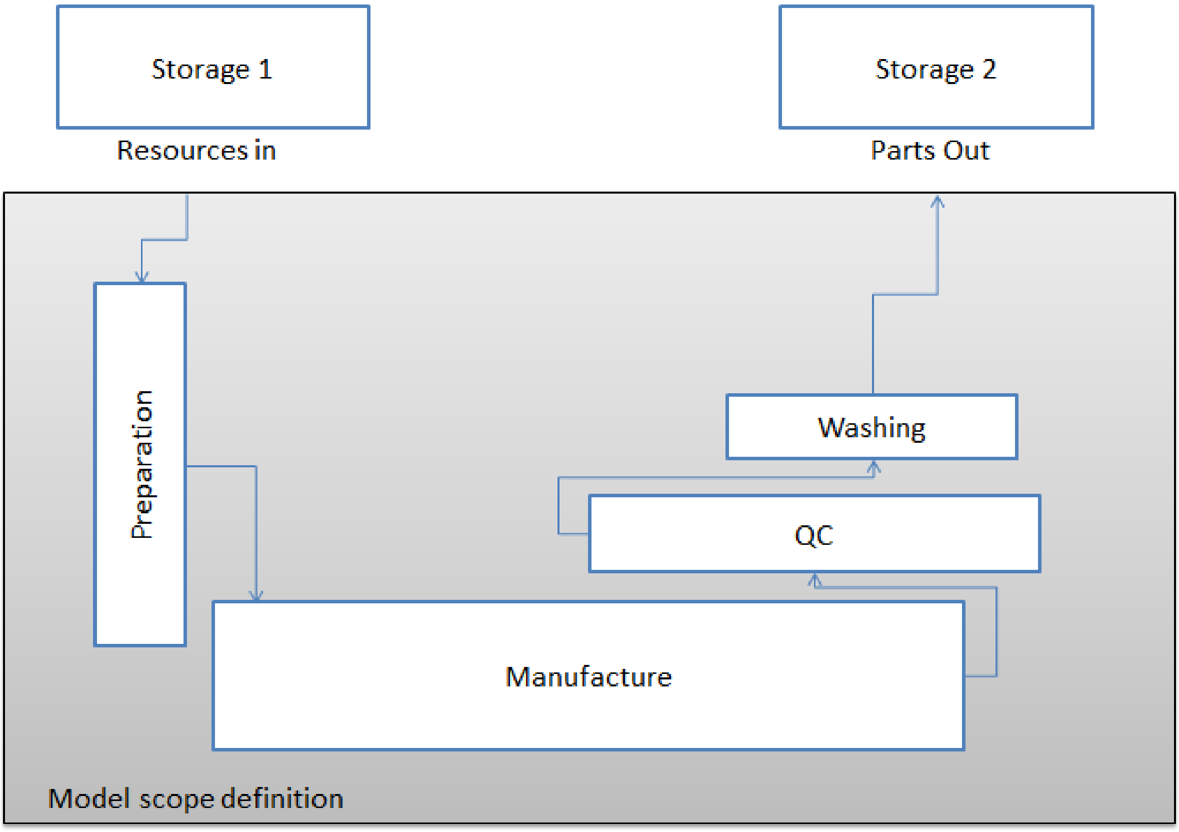
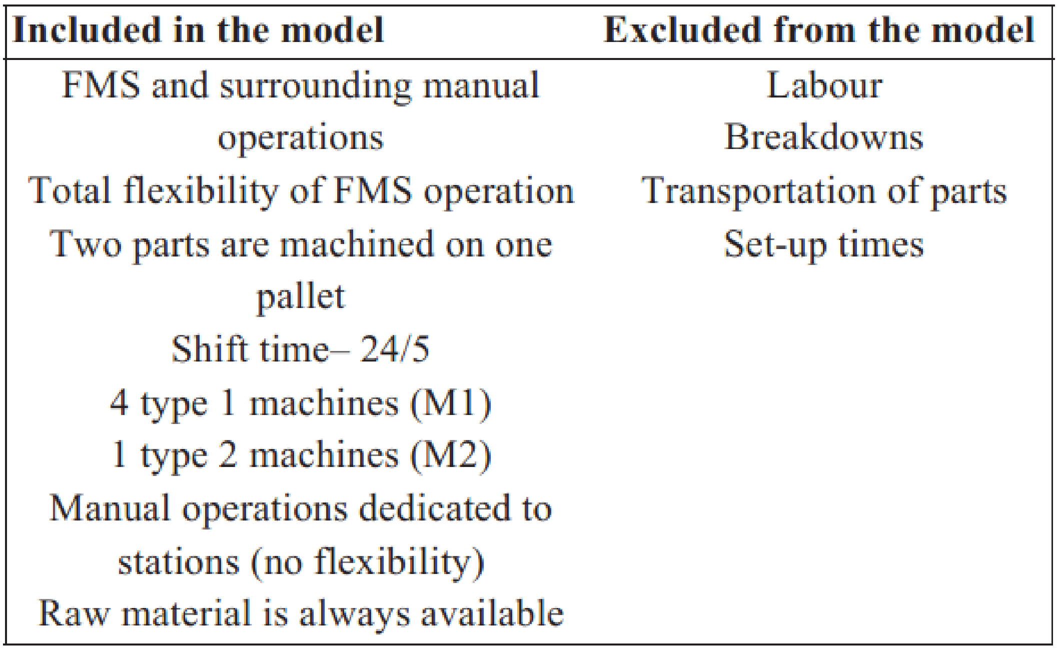


Figure 24 Example of simple conceptual model

For CM data collection Robinson (2004) proposes building scope and level of detail through division of the details into inclusion and exclusion criteria (as demonstrated in Figure 25). Level of detail refers to the level of data used in the simulation. Pidd (2004) recognises four types of components where level of detail needs to be established: entities, active states, dead states and resources.



Included in the model	Excluded from the model
FMS and surrounding manual operations Total flexibility of FMS operation Two parts are machined on one pallet Shift time– 24/5 4 type 1 machines (M1) 1 type 2 machines (M2) Manual operations dedicated to stations (no flexibility) Raw material is always available	Labour Breakdowns Transportation of parts Set-up times

Figure 25 Model level of detail

Definition of level of details is useful due to the precise definition of scope as well as partial ability to provide limitations and assumptions that will be applied to CM. The combination of those two tools is capable of provision of the required simulation environment. Additional detail focuses on data feeding the simulation and this is usually established in the phase of modelling. However, what is worth establishing at the CM stage is the format of data and its structure.

The verification of CM is been considered a very subjective area. The idea of verifying something that is a concept provides little field for rigorous and structured verification (Moody, 2005) In most cases it is based on what the modeller and the customer (i.e. user expressing interest in model results) agree is appropriate. The verification (re-scoping) is then a discussion that uses CM tools to communicate and capture the agreed simulation requirements.

3.2.3.5 Simulation modelling

In technical perspective simulation is described as an imitation of the system (on a computer) that passes through time for the purpose of better understanding or improving that system (Robinson, 2004). Robinson (2004) provides on overview on key stages in simulation modelling highlighting that at the core of any simulation is understanding of the real world problem that is a subject of exploration. The conceptual model is then constructed to outline the scope of the simulation. Once the simulation scope is defined the computer model is developed and experimentation is carried out. Figure 26 presents this modelling philosophy.

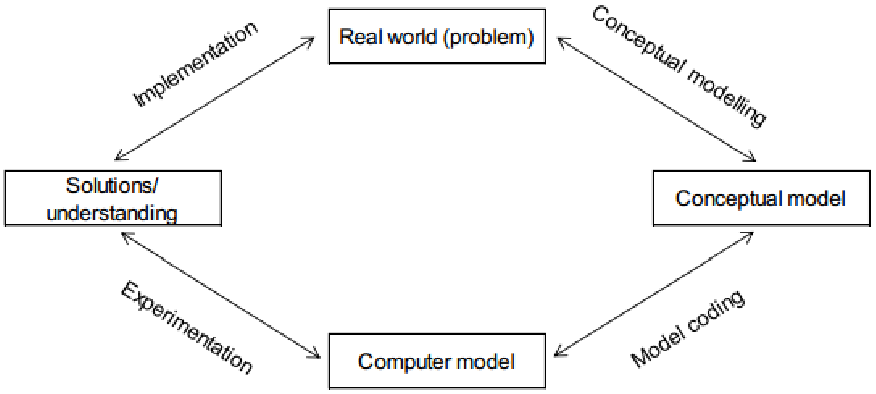


Figure 26 Key stages in simulation modelling, adapted from Robinson (2004)

Simulation modelling tools have been generalised into three types of tools: spreadsheet based, simulation software and programming languages (Robinson, 2004). Table 22 introduces the features of such approaches.

Table 21 Comparisons of modelling tools for simulation, adapted from Robinson (2004)

Feature	Spreadsheet	Software	Programming language
Skills development	Short	Medium	Long
Ease of use	Medium	High	Low
Flexibility of modelling	Low	Medium	High
Duration of model build	Medium	Short	Long
Run time	Low	Medium	High
Range of application	Low	Medium	High
Price	low	High	Low

The decision for tools selection is based on the modelling objectives, modeller's skills and project limitations (cost and time). For this PhD software as a main tool has been selected as it accessible to the researcher and provides functionality requirements that are general enough to be able to cover different aspects of FMS development and the usability, although requires training, is appropriate in the PhD timeframe.

Data collection for simulation

For simulation related data collection the focus is on data that will support the realisation of the CM objectives. For example, in case of manufacturing related research interview, technical workshops and production line demonstration would be appropriate means of collecting data. The summary of possible data required and its use can be found in Table 23.

Table 22 Linking data collection wits conceptual model elements

Data Source	Data Use
Operation Matrix	Part flow – operations/machines
Factory layout	Visual reflection of the system and part flow understanding
Operating Equipment Efficiency data	Scenario development – targets for scenario
Factory CAD drawing workshop	General understanding of factory layout Stages of model development Basic assumptions
Production line visit	Operation times Verification of original assumptions

The key element of successful decision making through simulation lays in accurate data collection and interpretation (Banks, 2005). The quality of data fed in to the simulation affects the quality of outputs which in consequence translates to the trust that the simulation is reliable source of analysis. Data cleaning and transformation is usually required to be usable for simulation purposes as it comes in variety of formats and different levels of granularity (Davé et al., 2014). Another challenge in data collection is that, often, there is no data available and primary data is required. Observation through physical presence or videoing allows generating pool of required data. Videoing for data collection is a tool widely explored across research where real life data and behaviour understanding is required, for instance, in medicine (Caldwell and Atwal (2005); Parnian, Martin and Conrad (2003)). Noldus et.al. (2000) introduces software for collection and analysis of observational data demonstrated in medical application.

Modelling process

As simulation is an iterative process it is vital to understand the process of building simulation and set achievable goals for the modeller to accomplish through the development process. The example of simulation model process is outlined in Figure 27. First stage focus on getting basic assumptions, basic logic and understand the modelling logic that is going to be used throughout, Next stage is about development of depth in the simulation and thinking about model communication to stakeholders and lastly full scope and interactivity is delivered in the final version of the model.

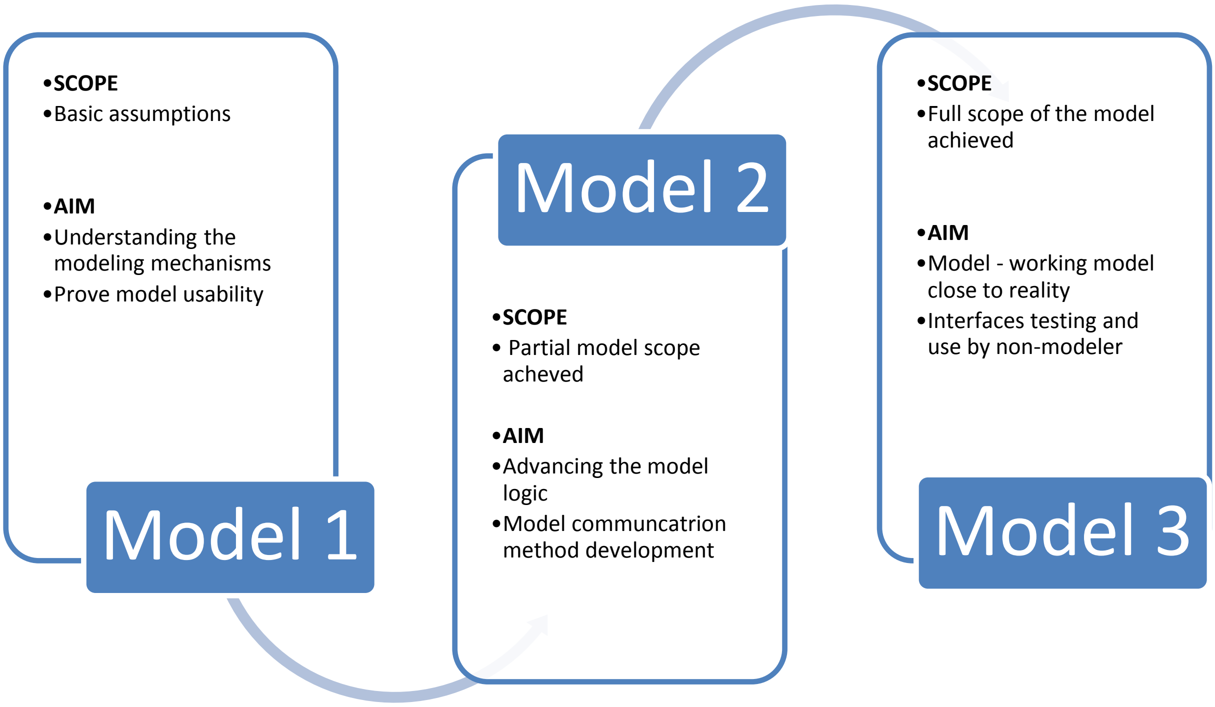


Figure 27 Example of simulation model development progression

The iterations of model development lead naturally to validation and verification, which is introduced in the next section.

Verification and validation

There are two types of model checks: verification that focuses on evaluation of the model working with the intent assumed and that consistent with its specification (U.S. Department of Defense, 2003); and validation, which evaluates model behaviour to the given accuracy (assumer or real life data) and alignment to represent to the modelled system. Although, those are essential in the research world, those techniques cannot qualify if the model is valid or invalid, but allows understanding the degree of accuracy with real life. On the other hand, Robinson (2004) points out the difficulties with validation and verification:

- No general validity (model serves a purpose and therefore is valid for that purpose, but not any other objective)
- Lack of real system to compare to (if model is proposed)
- Multiple views of real world can make comparisons difficult
- Inaccuracy or lack of real world data
- Time constraint on validation and verification

It might be drawn that validation and verification are mechanisms to build confidence in model validity rather than confirm its 100% accuracy.

Here range of verification and validation tools has been overviewed. Some verification mechanisms relay on adapting common sense approach (face validity) based on judgement and observation. Usually prompt questions like “does this seem all right?” or “does this process is well represented?”. This is done through observing simulation run. Next, verification method focus on isolating one parameter that will be modified (variable parameter) and observing if the model results are as excepted. For example, if number of parts arriving in the simulation increase, the utilisation of machines increases. Another level of this technique is sensitivity analyses which aim to identify any mistakes in modelling logic as well as test the simulation effectiveness. Another technique is building a logic for a triggering event that allows assessment if the activity is valid or not. For instance: stopping the model if specific part is ejected or follows unintended route.

Robinson (2004) has defined validation types as: black-box validation (with real system and with alternative model), experimental validation, solution validation and turning test. Those are defined in Table 24.

Table 23 Validation methods in simulation, adapted from Robinson (2004)

Validation method	Definition
Black-box	Testing of overall model behaviour based on comparisons to the real system performance or alternative model and measuring accuracy of results
Experimental	Assurance of simulation experiment accuracy through verification of set-up parameters and sensitivity analysis
Solution	Comparisons between the model the final model solution and the implemented solution to explore validity of final solution
Turning test	Assessment of simulation results and real world data comparisons (or other elements) by independent experts

As Kleijnen and Gaury (2003) points out the outlined processed require documentation as evidence of model accuracy and demonstrating understanding of model meeting CM objectives as well as displaying expected behaviour. In this PhD different validation and verification tools has been selected per case study and they are outlined in the respective chapters.

3.2.3.6 Experimentation

Experimentation with the simulation environment enables testing of the hypothetic production environment. Once the model has been verified and validated the experimentation can be performed. Experimentation relays on selection of experimental factors (variable) and measure them through selected responses (outputs). Figure 28 outlines the experimentation process. Similarly, to validation, experimentation can be an iterative process. Once the results have been obtained, it can lead to the readjustment of the experimental factors or simulation model logic and so on.

Figure 28 The experimentation process

The experiment set-up is important element of simulation as it “sets the scene” and defines the parameters used for the simulation. The further determination of the parameters is summarised in Robinson (2004) but main features are presented in Table 25.

Table 24 Parameters defining simulation set-up

Setting parameters	Definition
Run time	Length of the simulated period (1 year, 1 week etc.)
Warm-up period	The time after which the simulation achieves steady state (it needs to be noted that steady state might not exist in some cases and it that case the cut time needs to be determined)
Number of replications	The number of replication of the same scenario (using random number seeds for variable results)

The types of analysis enabled by simulation are dependent on the simulation objectives and can take various forms. The types of analysis in manufacturing applications are summarised in Table 26.

Table 25 Summary of experimentation methods, adapted from Robinson (2004)

Type	Definition
Interactive	Observation of the effect of changing parameters and seeing the effect
Batch	Setting the experimental factors and running the model for pre-defined length and defined number of replications
Comparing alternatives	Comparisons of predefined scenarios
Search experimentation	Setting a target level for KPI and vary experimental factors until the result is achieved
Design of experiments	Definition of levels of experimental factors and setting up matrix of scenarios to carry out and comparisons of results
Metamodeling	Generalising simulation results and plotting it to a response surface that include factor/level combinations from which mathematical model can be constructed
Optimization	Searching “best” solution for predefined objective function with use of experimental factor ranges
What-if analysis	Measures how set of independent variables impact set of dependent variables (responses) with reference to simulation model (Kellern, 1999)
Sensitivity analysis	Assessment of consequences of varied experimental factor on the measured response

More detailed explanation for the experimentation is explained within the case studies.

3.2.4 **Validity, reliability and generalisation**

As mentioned in section 3.2.2 case studies has been criticised for unscientific approach and difficulty to assess the quality of the research work. Therefore, to ensure the quality consistency the considerations for this PhD, validity, reliability and generalisation of outputs has been outlined in Table 27.

Table 26 Tactics for research quality, criteria defined by Leedy and Ormrod (2001)

	Criteria for research quality	**Suggested tactics**	**Considerations within this study**
Validity	Ensuring that the correct measures are applied and providing targeted outcomes	Using multiple sources of evidence	Triangulation of multiple data sources: literature, documentation and project meetings
Reliability	Demonstration that the research can be repeated with the same results	Documentation of research methods Consistency of used tools Reliability check	Definition and documentation of research methods used in each case study
Generalisation	Establishing a domain where the findings can be generalised	Cross-referencing case study findings against the literature review findings in a broader perspective	Use of emergent themes as a generalisation for decision making in FMS

3.2.5 **Summary**

This chapter focused on explanation of philosophical approaches used in the PhD research to fulfil research aim and objectives. The decision to use pragmatism worldview and mixed-method methodology has been discussed and justified.

Conceptual framework has been selected as a mechanism to introduce the theoretical grounds for the decision making tool for FMS using DES. Case study format has been selected as appropriate means of validation for CF. Tools used in the case studies has been selected to be conceptual modelling and simulation due to its grounding in the real world research and ability to utilise qualitative and quantitative data collection techniques as well as ability to provide quality transforming mechanisms and validate results.

Chapter 4 introduces the conceptual framework that has been developed to for decision support system for FMS and chapters 5, 6, 7 and 8 introduce case studies that inform and validate the framework.

4 Conceptual framework for FMS decision support using DES

This chapter focuses on systematising the knowledge and decision making required to support FMS development with use of DES. The presented conceptual framework is addressing decision making support for FMS using DES. This chapter proposes the concept of “FMS decision support framework” development.

4.1 Conceptual framework design considerations

The efficient FMS can be achieved through configuration of range of elements at different production levels. A systematic approach to develop FMS is a valuable tool as it ensures that key areas of development have been considered and the trade-offs of the decisions made at each stage of development are understood.

As literature has pointed out, at the moment, there is no holistic view on FMS development and due to its complexity it is often too difficult to achieve in one model. It has been identified that FMS can be viewed at different level of abstraction that have different objectives and types of decision to be considered (Section 2.3.5). At strategic level key elements focus on system design and strategies for operations, at operational level identification of configuration for production requirements flexibility trade-offs needs to be considered and for tactical appropriate scheduling and PLC control has been identified. At the same time, it has been clear that those levels of abstraction cross-over at many simulation modelling examples and can address different objectives depending on the problem situation. It is also apparent that decisions on higher levels will affect the range of decisions possible to make at lower levels.

4.2 Conceptual framework development

The conceptual framework development process drew out from the research gap identified in the SLR as well as from the needs of the industrial collaborators. The conceptual framework development has been an emergent process due to the fact that the research has been evolving along the build and launch of new FMS production line. Therefore, the framework development emergent process based on iterating ideas on what FMS requires as well as how industry is driving FMS development. This approach allowed a knowledge based baseline idea to be evolved to realistic picture of FMS development in the industry context.

The methods used for the development of the conceptual framework are illustrated in Figure 29. The three stage process has been adapted: scoping, definition and validation.

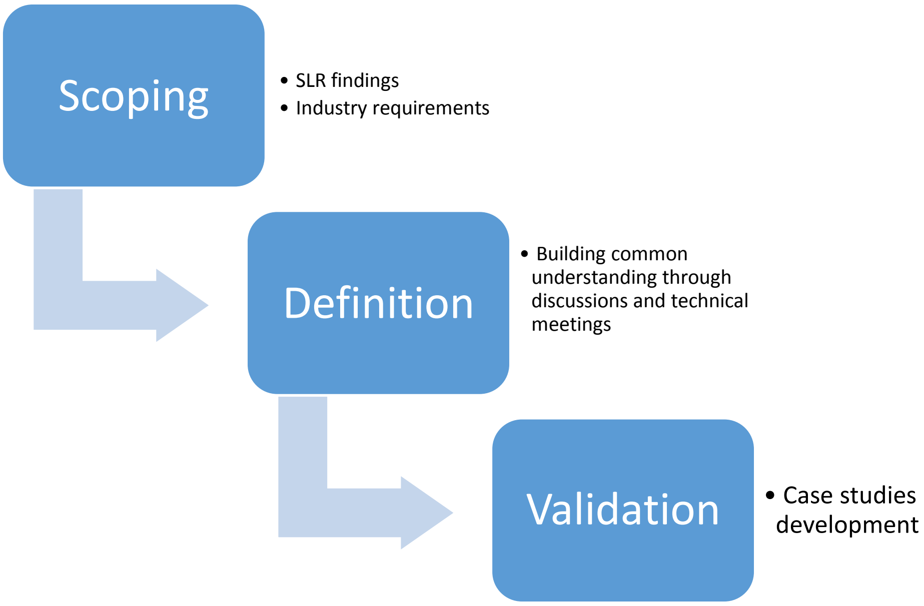


Figure 29 Conceptual framework development methods

The research gap allowed identification of potential decision making areas for FMS development. Strong emphasis was on understanding the FMS development process step-by-step to guide the applied side of the research. The conversation with industry had strong influence on what stages of FMS development should be tackled first. This has been done by very close collaboration with industry through workshops on FMS system development, their current processes identification and providing data available about their FMS set-up and planned operations. Further, during the course of the project, especially during the individual case study development, most of the time has been spend at manufacturing facility. This allows to build understanding of industry practices and strategies related to FMS development and operations.

In addition, the availability of data had to be considered due to the fact that at the beginning of the research project only estimated data has been available. As the project progressed more accurate estimations and production data has been populated and used in this PhD research project. The reason for this is that, the industrial FMS has been developed alongside the PhD timeline.

In definition of the conceptual framework for decision making for FMS development, it has been important to establish the scope for the framework as it would not be possible to consider all elements. The decision for scoping has been based on three factors:

1. Layout modelling is usually based on comparisons of alternative production systems and this is not the interest of this PhD thesis, therefore it will be excluded for the framework scope.
2. The proposed framework focused on most crossover themes within the study as it has been assumed that there are requirements to consider set-up, flexibility and schedule as key areas of FMS development.
3. The research took into account emerging focus areas for FMS development from industrial point of view. This has been done through holding discussions with the company taking part in this study and observing the FMS development process in practice.

The validation process has been achieved through development of case studies. Due to high level of complexity it is not possible to take into account all required decisions in one model as high level of variables would disable the usefulness of simulation modelling as visualisation and analysis tool. In order to validate the framework, four case studies has been developed (in the latter chapters) where different aspects of FMS development are considered: data consideration for building simulation models, set-up, flexibility and scheduling.

4.3 Conceptual framework

By taking view that FMS design requires systematic approach, this framework presents a method for decision support in FMS development at stages of set-up configuration, flexibility and scheduling. However, the key decision making stages that has been highland from both industry and literature are:

1. Requirements definition – what is the required demands, types of parts, physical limitations of the factory, layout options, data requirements
2. Set-up - number of machines / material handling robot; what is the best configuration to achieve the objectives (mainly focused on achieving demand)
3. Flexibility – decision on which elements are going to enable flexibility ad to what extend/ how resilient will be the solution to changes?
4. Schedule – how to maximise the capacity through scheduling/ what is appropriate WIP levels?

The conceptual framework is presented in Figure 30. The case studies for the framework validation are presented in the following chapters: Chapter 5 – data consideration for building simulation models; Chapter 6 – set-ups; Chapter 7- flexibility; and Chapter 8 – scheduling.

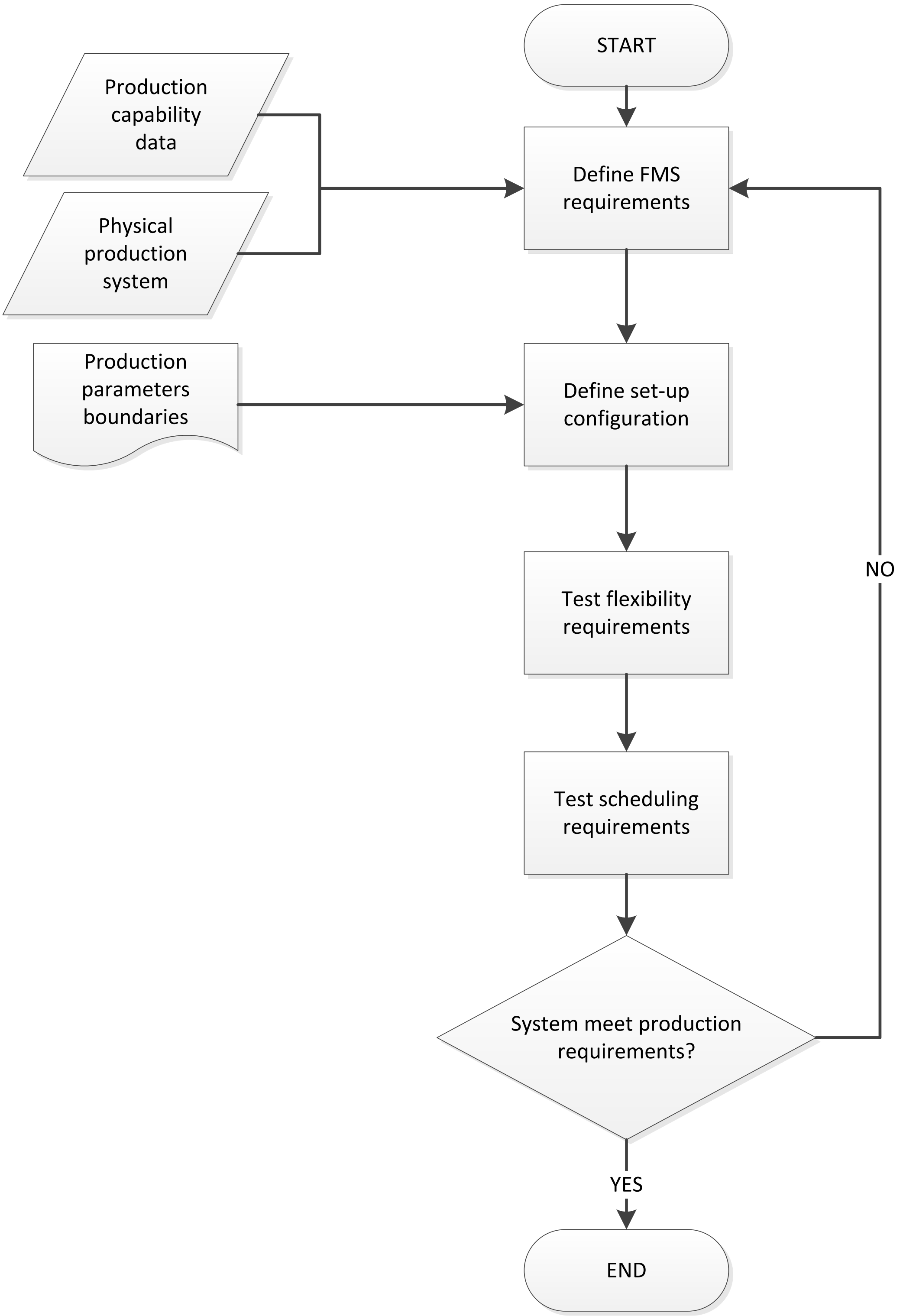


Figure 30 Framework for decision support in FMS development

4.4 Summary

This chapter has focused on introduction of conceptual framework for FMS development with the use of DES. Key design considerations has been outlined and framework development process has been presented and justified. Further, the conceptual framework has been introduced and allocation of relevant case studies for conceptual framework validation has been provided.

5 Data driven FMS simulation

This chapter aims to provide an overview on data collection methods for FMS simulation and address ambiguity in modelling machine behaviour through introduction of a methodology to extract data from the production shop floor.

5.1 Data collection for FMS simulation

The key element of successful decision-making through simulation lays in accurate data collection and interpretation (Banks et al., 2005). The quality of data fed in to the simulation affects the quality of outputs, which in consequence translate to the trust that the simulation is a reliable source of analysis. Data collection methods have been discussed in the methodology section. This work focuses on cases where data is not available. Within the FMS system, collection of data can be explicit (i.e. through visiting site or looking at layout) or implicit (requires in depth understanding to build behaviour profile). Table 28 introduces the data collection for FMS elements.

Table 27 Data consideration for FMS elements

FMS element	Data purpose	Data source
Group of machines (M)	Mapping FMS elements	Layout
Loading/Unloading station(s) (LS)	Understanding loading / unloading behaviour	Historical data / observation
Material handling robot (MHS)	Utilisation	Operational data
PLC system	Logic controlling the schedule and machine allocation	PLC logic commands / Observation

The element based data collection allows to build to simulate elements and understand the internal system mechanisms. However, data availability can be ambiguous, especially in cases where FMS is delivered by external companies and some elements are IP protected. The example of this is internal decision-making, where FMS systems rely on internal algorithms optimising the production schedule and work of the machines in the system, most of which is unknown to the equipment operators. There is limited understanding of the machine behaviour and therefore its inaccurate modelling can affect the results of the simulation.

This chapter aims to address ambiguity in modelling machine behaviour through introduction of a methodology to extract data from the production shop floor.

5.2 Primary data collection method

When data collection cannot be achieved through secondary data collection (historical or estimates), primary data collection is the only way forward. Videoing has been selected as a data capture method because it provides capability to capture empirical evidence (Jewitt, 2012). As the purpose of the videoing the manufacturing process is to look at patterns in machine behaviour, it is easy to overcome criticism of videoing as limited by decisions in the field and partial capture of phenomena (Jewitt, 2012). The intention of videoing in this case is to observe selected manufacturing processes, identified as limited in existing data availability. The example of this practice can be found in Engström and Medbo (1997) who has used videoing to collect real life data from shop floor for assembly operations.

Videoing for data collection is a tool widely explored across research, where real life data and behaviour understanding is required; for instance, in medicine (Caldwell and Atwal, 2005; Parnian, Martin and Conrad, 2003). Alongside the videoing, behavioural data coding has been used to develop assessment method for data conversion. Building data through the use of such methodology could aid more accurate simulation development; however, it has been criticised as lengthy process (Jewitt,2012). Noldus et al., (2000) introduce software for collection and analysis of observational data demonstrated in medical application. The application of the Observer Video Pro software, (also introduced in detail by Noldus et.al (2000), has helped to record the behaviour of patients to asses them for repetitive strain injury. However, it has been identified that with regard to the manufacturing process the number of observations does need to be as extensive as in social science research as the scope of observation is small and repetitive. Therefore, the idea of behavioural data coding from observation can be also valid for the manufacturing shop floor study. Behavioural coding relays on continuously watching the recorded material and recording of all behaviours related to the research question; those behaviours are distinctive actions that can be converted into measurable data outputs.

Videoing has been a tool used in the variety of research as a data collection tool; however, limited knowledge is shared into how to design a structured data collection for behaviour of ambiguous elements in simulation. This research focuses on demonstrating a methodology for converting data from recording machine behaviour into simulation useful data-sets using videoing as a tool, and adapted behavioural coding as a data classification method.

When limited data is available, an approach to collect data from the shop floor could make the simulation model more accurate. The approach adapted to gather data on FMS, focuses on the collection of data directly from the shop floor, systematising it and converting for simulation input (Figure 31).

Figure 31 Systematic approach to collecting data from the production shop floor

The methodology focuses on systematic analysis of the machine behaviour. It aims to identify, classify and quantify data recorded through videoing. The steps are as follows:

1. Record observable behaviour – record the machine or process that is critical to the simulation results that is either a “black box” or data poor
2. Identify distinctive actions – recognise the distinctive, repeatable and measurable behaviour classification of actions performed

3. Collect data related to distinctive actions – observe and record data regarding the classes of behaviour

4. Convert relevant data into useful data-set – identify the appropriate data conversion format and analyse data according to the simulation parameters.

5. Validate data-set – validate the data-set produced from the analysis comparing the recorded behaviour with the datasets available or technical expertise.

This methodology represents technical delivery of simulation–ready data from data material to the valuable data input. The case study of an automotive FMS system is introduced in the section below.

5.3 FMS case study for data driven DES model

A case study of obtaining data from the production shop floor to create accurate FMS model is presented. This case study focuses on the work of a material handling robot (MHR) and the PLC system in the FMS. The MHR is a robot that is put on a bi-directional rail with set of forks attached to it. Its function in the FMS is to transport the pallets between loading stations, CNC machines and storage system around the FMS. The parts are loaded manually to the loading and unloading stations on a pallet and the MHR is the only material handling mechanism inside the FMS. The robot PLC system is driven by the utilisation and due date objectives and it requires resource availability data alongside volumes and production order dates to generate the task list that will drive the FMS work. The summary of PLC logic is illustrated in Figure 32.

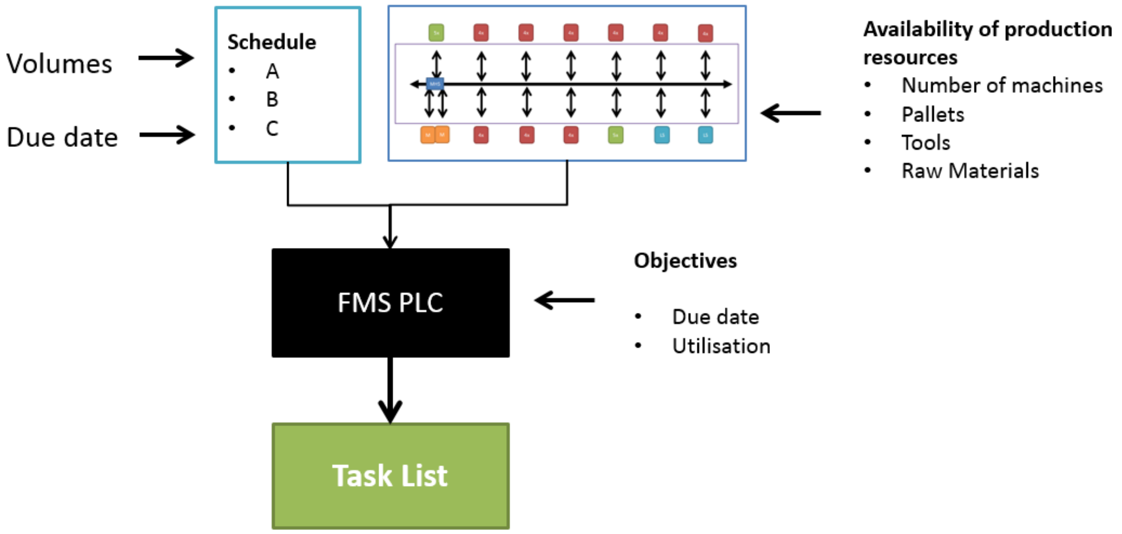


Figure 32 The PLC data requirements

The PLC is updated every time there is a change to either the available resources, the schedule or every 15 minutes. The PLC system is IP protected and it is not possible to investigate the algorithm driving decision-making. The robot behaviour has been a “black box”. The process flow illustrated in Figure 33 provides the logic of the system operations.

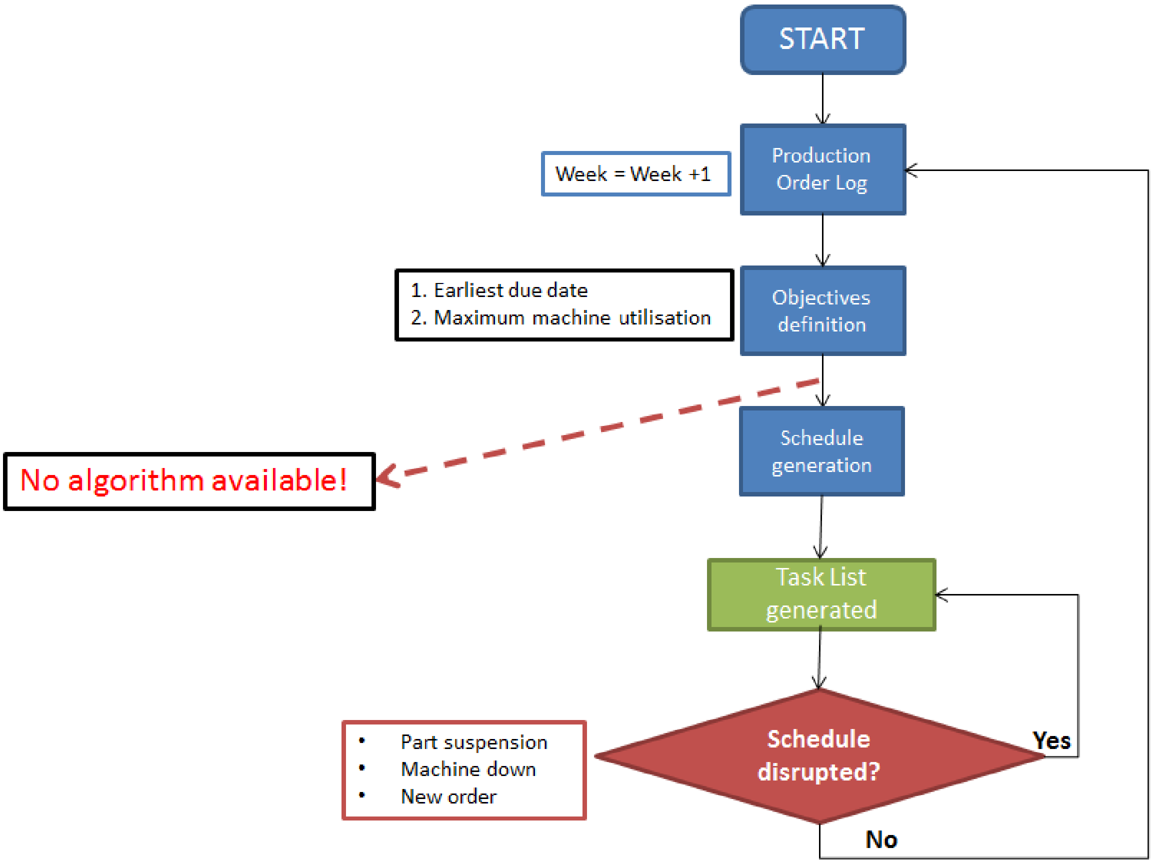


Figure 33 The PLC Logic process flow

Although there is general understanding on how PLC operates the system provides data on machine loading capacity, there is no understanding on the loading of the MHR that is responsible for distributing parts inside the FMS system. Also, limited data on MHR cycle time in the FMS were available due to the nature of scheduling. The process of scheduling has focused on distributions to machines where MHR is a tool to deliver the work. Therefore, there is no pre-set operational cycle time or expected behaviour. By building understanding of MHR behaviour and timescales it would be possible to predict the utilisation (check if the MHR can cope with production demand) and forecast for new production scenarios (i.e. change of demand/ part mix). Therefore, the objective of this study was to investigate whether the MHS model could cope with the FMS demand.

5.3.1 **Observe the behaviour**

The video recording of the MHR has been conducted to observe the MHR behaviour. It allows capturing the machine actions and collecting data on time it takes for the robot to travel and perform task. This has been identified as the most appropriate means of data collection as the standard data accusation from the PLC was not possible due to the IP of the producer. Validation of this is also possible through verification of collected information with multiple people and experts. Five separate recordings have been taken during various shift times to ensure coverage of the full machining time to understand machine working as a whole, rather than as an activity related to the process flow. The MHR has been recorded for the total time of 5 hours. The MHR moves in horizontally and vertically alongside a rail and it has a fork attached to load and unload the parts from the system. Figure 34 illustrates the stacker crane video snapshot, whereas Figure 35 provides a conceptual model of the machine.

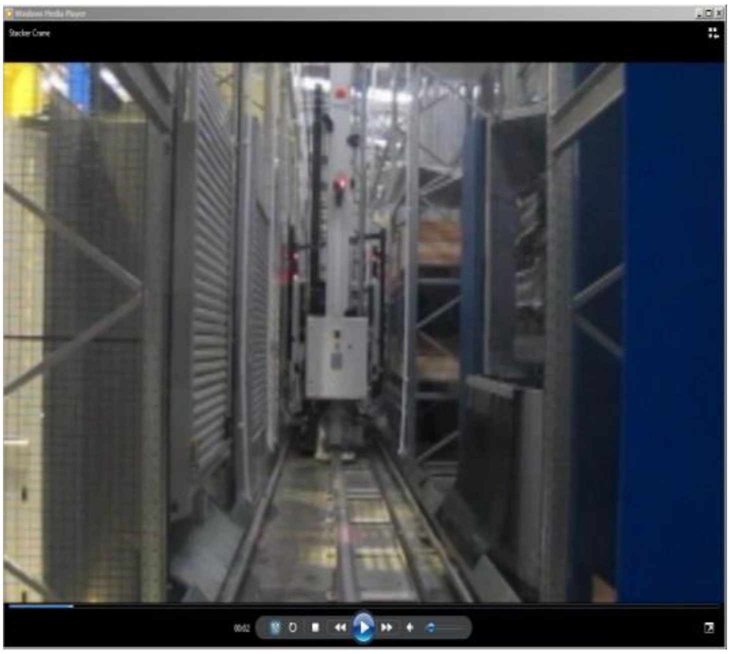


Figure 34 Snapshot of stacker crane video

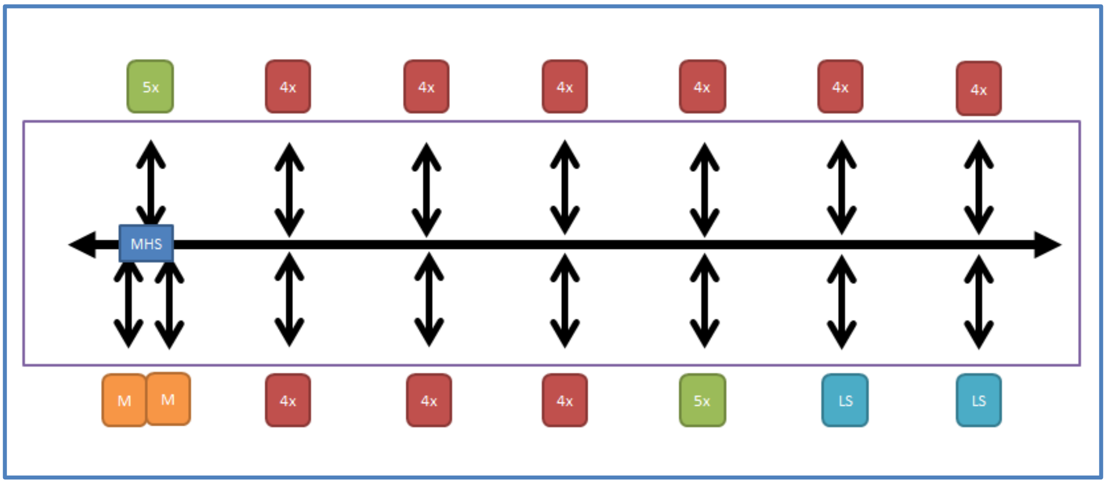


Figure 35 FMS conceptual model

5.3.2 **Identify distinctive actions**

The MHR behaviour has been represented by in a graphical way in Figure 36. Three types of movements have been identified as distinctive actions to the machine: “move”, “load” and “wait”. Action “move” refers to the stacker crane movement on the rails, whereas “load” refers to the action of moving the forks to load or unload a part from the stacker crane. Action “wait” refers to the machine at idle.

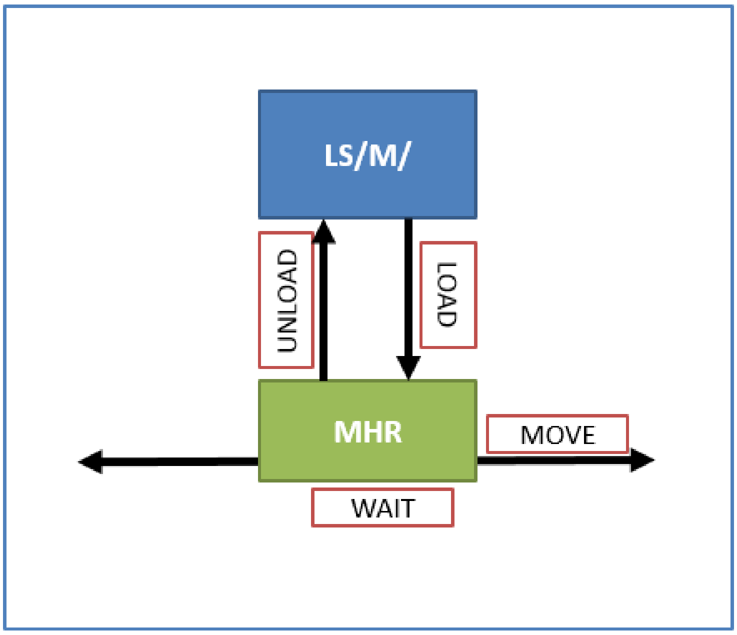


Figure 36 MHR distinctive actions

5.3.3 **Collect data related to distinctive actions**

Table 29 provides a sample of data collection of distinctive actions. In this case, the interest was in capturing the cycle times of the actions as well as investigation, whether there is a difference in loading and unloading of the forks in MHR.

Table 28 Sample of the distinctive action data systematisation

Date	22/01/2016					
Time	11.30-12.20					
Production	All Customer 2					
CLIP	MVI_2954_JR					
		Loading detail		**Cycle Time**		
Movement No.	Action	Position	Loading	Recording Time	Time in seconds	Cycle time (s)
1	Start		OUT		0	
2	Move	MC7		0.18	18	13
3	Load		IN	0.31	31	30
4	Move	Rack		1.01	61	13
5	Load		IN	1.14	74	13
6	Move	Rack		1.27	87	26
7	Load	Rack	OUT	1.53	113	10
8	Move	MC2		2.03	123	3
9	Load	MC2	IN	2.06	126	25
10	Wait			2.31	151	84
11	Move	L1		3.55	235	7

12	Load	L1	IN	4.02	242	29
13	Move			4.31	271	13
14	Load	Racks	OUT	4.44	284	15
15	Move			4.59	299	10
16	Load	Racks	IN?	5.09	309	17
17	Move	L1		5.26	326	10
18	Load	L1	OUT	5.36	336	29
19	Move	MC3/4		6.05	365	13
20	Load		IN	6.18	378	18
21	Move			6.36	396	13
22	Load	L2	OUT	6.49	409	30
23	Wait			7.19	439	64
24	Move			8.23	503	22
25	Load		IN	8.45	525	25

Once cycle time data was collected and systematised into action-relevant detail, the cycle time data were grouped into the action categories. From the observation it was discovered that “wait” action is related to the staff not feeding the FMS and therefore the impact on stacker crane capacity loading was not relevant to the study. Also, it has been found that there is no difference between loading and unloading aspects of the “load” action.

5.3.4 **Convert relevant data into useful data-set**

With that simplification in mind, frequency distributions for “move” and “load” actions have been developed based on data sample. This was based on sample of cycle time for actions identified across all video recordings. Those are illustrated in Figures 37, 38.

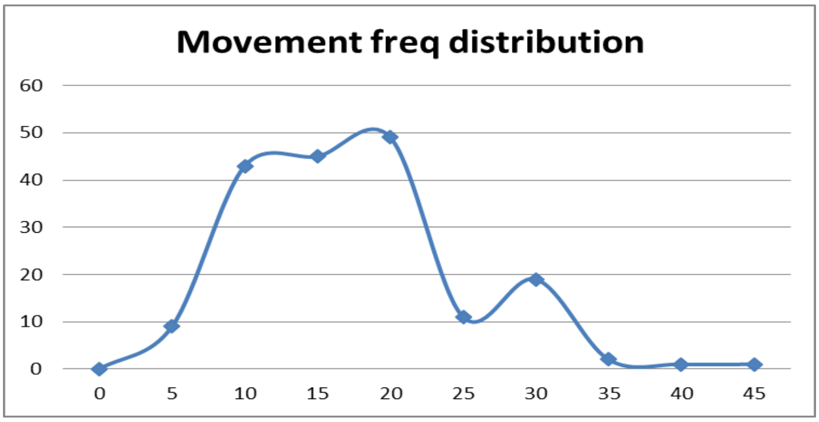


Figure 37 Movement frequency distribution (seconds)

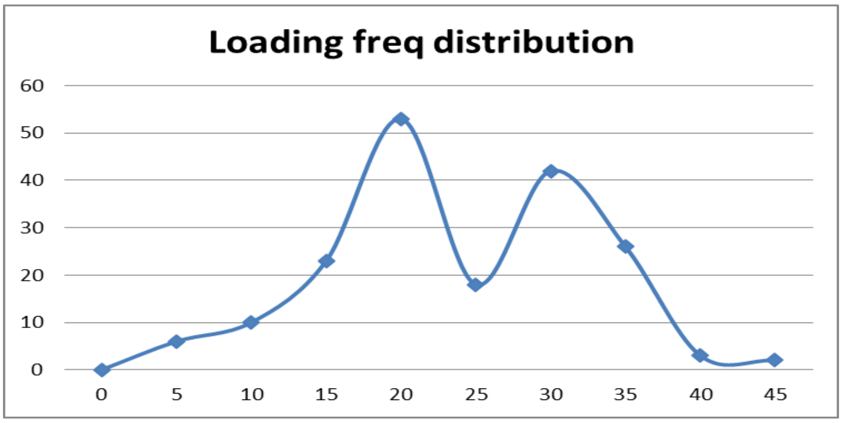


Figure 38 Loading fequency distribution (seconds)

The frequency distributions become an input to the simulation in the further experimentation. Although the MHR data were not possible to obtain for the standard data sources, through this approach it was possible to build an understanding of the machine behaviour. Additionally, it was possible to capture useful data and convert as simulation inputs. This process allows to gain confidence in data used in the simulation by the modeller, as well as stakeholders, especially industry collaborators.

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5.3.5 **Validate data-set**

To be able to validate the MHR capacity loading in the simulation, the design of experiment type analysis has been made to determine, at rate, the required loading on the stacker crane. The investigation below demonstrates the proposed benchmarking.

The data for input calculations were as follows:

- Loading / unloading time distributions (-1 sigma, mean, +1 sigma and -3 sigma, mean, +3 sigma)
- Stacker crane movement and delivery time distributions (-1 sigma, mean, +1 sigma and -3 sigma, mean, +3 sigma,)
- Number of machining operations to be completed per part per operation (related to the part profiles)
- Number of pallet movements per operation (2 or 3) – this refers to number of actions “move” that need to be performed in the system
- Average week production demand

The outputs measured the utilisation percentage of the stacker crane under given input conditions. The summary of results is provided in Table 30 and a full calculation is available in Appendix A. The conclusion for the provided dataset was that when the stacker crane performs an average of two “move” actions per operation the range of capacity loading will range from 68% to 95%, However, when there is an average of three “move” actions the stacker crane capacity is exceeded, suggesting it would not be able to cope with the load.

Table 29 Summary of the DOE on stacker crane capacity using distribution frequencies

Utilisation			
	Mean	+1sigma	+3sigma
2 “move” action	0.5	68%	95%
3 “move” action	0.75	101%	142%

This calculation provided insight into limitations of the MHR behaviour with regard to performance requirements. Excessive storing of parts in the FMS storage system would mean that the MHR is likely to become overloaded and not be able to cope with production requirements. To translate this to the operational level, decision-minimisation of using storage should be adapted in order to ensure MHR availability to key value adding operations. With all that in mind, a case study has been carried out to validate if the machine behaviour is reflected.

There are several possible ways that the obtained configuration can be validated for the simulation purposes. The option, which was used to validate results from this case study, is a comparison of the results with other outputs from simulated in WITNESS production line as real data were not available at the time. The line has been set up mimicking existing production system with no constrains. . The process for case study evaluation is explained in Figure 39.

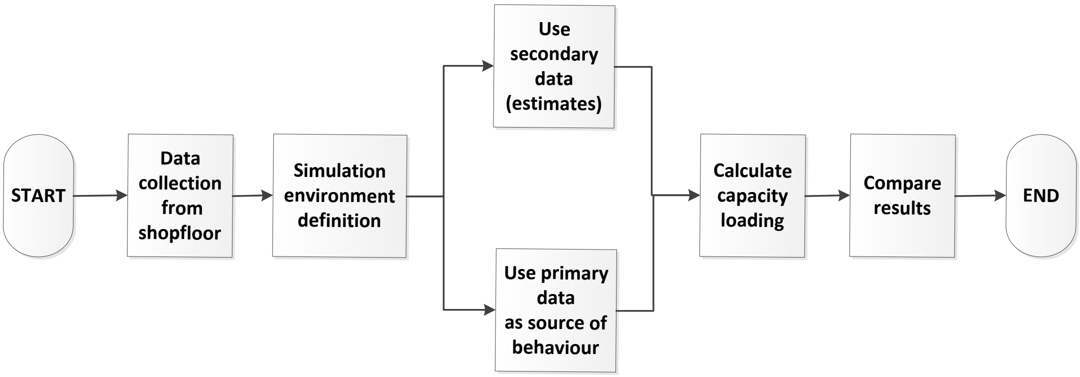


Figure 39 Case study evaluation structure

The case study, visualised in Figure 40, is a FMS system consisting of one MHR serving 5 exactly the same machines, aiming where the cycle time per operation of 38 minutes per part and 2 types of parts are in production (each having 5 operations). It is assumed that every machine can perform any operation (free flow). In addition, the shift was assumed to be 24 hours over 5 days.

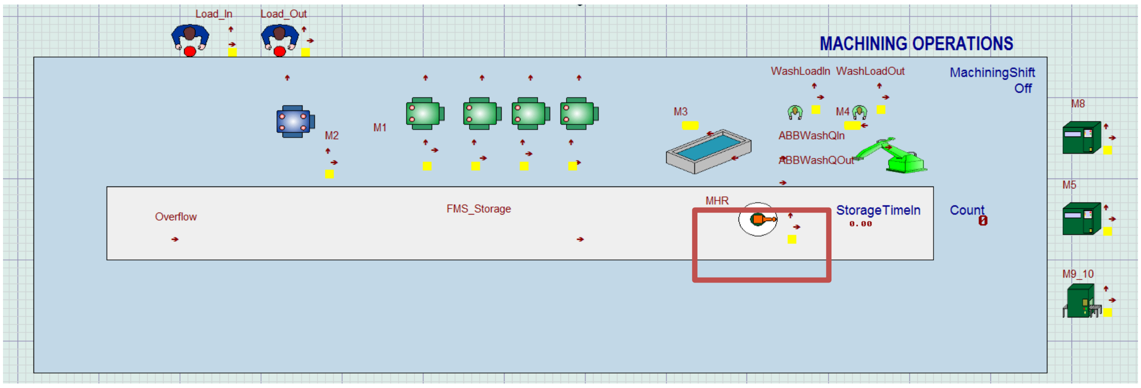


Figure 40 Snapshot of simulation environment

The simulation runs were set up to run for 1 year, assuming 1 week of warm-up period. For the fixed CT scenarios 1 simulation has been run as the model is deterministic (no variables are present), whereas frequency distribution scenario has been replicated 5 times with the use of different random numbers and the results were then averaged out. The results are provided in Table 31.

Table 30 Results of simulation runs

Experimental design		Utilisation	Available time	Utilised time	Number of parts	Average MHR time per part	
Scanario	Details	%	m	m		m	s
Fixed	CT = 1.75	0.80	7200	5774.4	333	17.341	0.289
DIST 1	Dist (Load, Move, Load)	0.72	7200	5184	343	15.11	0.252
DIST 2		0.72	7200	5185.44	344	15.07	0.251
DIST 3		0.72	7200	5192.64	343	15.14	0.252
DIST 4		0.71	7200	5133.6	343	14.97	0.249
DIST 5		0.73	7200	5247.36	342	15.34	0.256
	Avg. Utilsation	0.72				Avg. MHR CT	0.252

The loading calculation for machines (available in the appendix B) has been used as a validation benchmark. Two simulation runs – first using fixed cycle time 1.75 minutes; and second that use the frequency distributions. The fixed cycle time corresponded to the mean cycle time calculated for "move-load-move" action.

Loading capacity is a useful calculation where straightforward load calculation is required. It is useful as a benchmark for simulation when only a little variability is introduced. Loading capacity calculation relies on understanding the availability of time to utilise in production period and compare it against the calculated time required for the production of the targeted number of parts.

To calculate the machine available time the following calculation needs to be performed:

Number of machines * number of days * number of hours * number of minutes

Equation 1 Machine available time

For example for 24/5 production with 1 machine available the available time will be 1*5*24*60 = 7200 Minutes

To calculate the expected loading time the following need to be calculated:

Volume * cycle time

Equation 2 Machine load

If we assume the volume of 300 parts and cycle time of 38 minutes, the expected production time will be 300*38 = 11400

Therefore, the loading capacity is:

Total available time / expected production time

Equation 3 Loading capacity

For instance for : 10080/11400 = 0.88 (88%)

Hence, the expected utilisation for the machine is 88% (assuming no breakdowns, set-ups or scrap).

Figure 41 presents the utilisation results of both simulation runs compared with the loading capacity calculation estimates. The simulation that used frequency distribution (Scenario 2) results in closer results to the loading capacity calculation (-0.14%), whereas the simulation that used fixed cycle time (Scenario 1) resulted in a (+9.99%) much higher result than expected. It can be concluded that use of frequency distributions reflects a much closer fit to the predicted results in comparison to using the average cycle time.

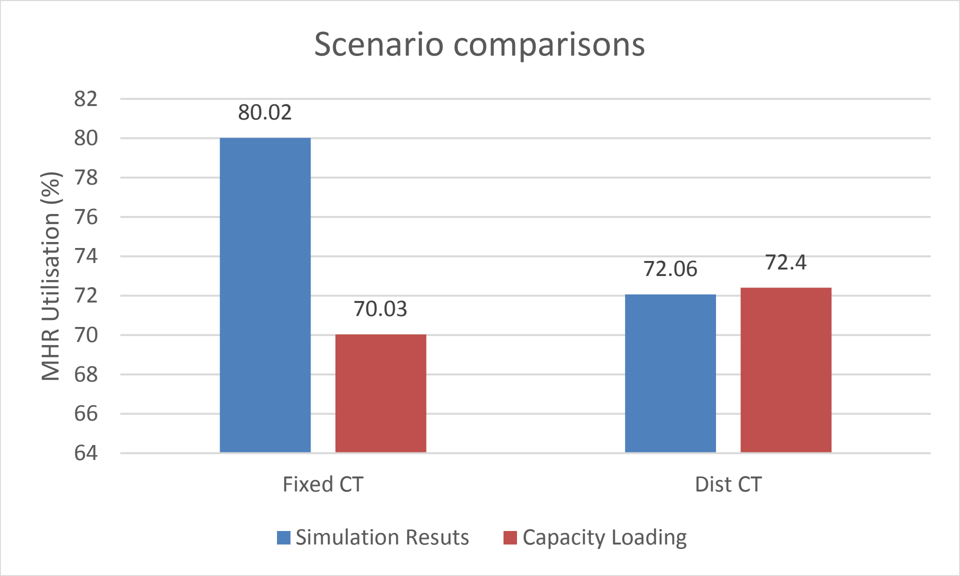


Figure 41 Results of the simulation experiment

This method of data collection can also tackle the issue of trusting simulation model results. As the experimentation is based on the real data-set and the simulation model was able to capture the hidden dependencies in MHR and machines interactions, it was possible to achieve a more realistic picture of MHR performance. Once more variability is introduced, relying on loading capacity is not sufficient to be able to validate the accuracy of results; however, it works for testing data profiles accuracy.

5.4 Discussion

The concern with accurate data for simulation is a valid challenge in a simulation for FMS. In instances where historical or current data are not available, it is necessary to develop an approach that will enable data collection from the shop floor in a systematic and transparent way. Furthermore, data transformation for simulation needs to be clear and captured at the appropriate level of detail. This chapter introduced the primary data collection approach for simulation using videoing and behavioural coding as the main tools for data capture and as a systematic approach for data transformation. Videoing and behavioural coding have been used in other applications, like healthcare, but not in FMS observations. This approach has been validated through the case study of MHR in FMS use of the aforementioned tools as means of capturing and systematising machine behaviour data. As machine behaviour is prescribed and repetitive, identification of distinctive actions was consistent and measurable. By identifying a set of distinctive actions for MHR, it was possible to systematise data required for modelling the MHR behaviour in simulation. As each distinctive action has been measurable in time, it was possible to transform data sets into distributions that have been the used to model MHR in a simulation case study. Distributions allows to capture the variability in the MHR behaviour and provide more realistic data as simulation inputs. The simulation study for two scenarios – with distribution cycle times and with estimated average cycle time were considered and the results were compared with loading capacity. Loading capacity was useful as a benchmark for required machine utilisation as it calculates machine load based on processed volume of parts. The simulation results confirmed that using distribution provides a better fit to the expected results. From the case study of MHR behaviour modelling, the approach for data collection for simulation in FMS has been validated.

5.5 Summary

This research work focused on addressing data in modelling MHR behaviour. This was achieved by development of videoing based data collection method supported by systematic data analysis approach and simulation testing. This approach provided a mechanism to record, systematise and test machine behaviour for simulation applications. The novelty of this approach lies in integration of data analysis to validate the required datasets, as well as using them to improve simulation results. Additionally, through maintaining the transparency of the data and its verification methods, it is possible to build trust into the simulation validity for industrial applications.

6 DES for FMS set-up

This chapter focuses on decision making for the set-up of FMS and how simulation can aid it. It demonstrates how DES can address complexity in an FMS and aid in the optimisation of the production line performance within the automotive industry. The section covers introduction, approach outline and validation through case study.

6.1 Importance of set-up in FMS

Flexible manufacturing systems (FMS) provide a unique capability to manufacturing organisations where there is a need for product range diversification by providing line efficiency through production flexibility. This is immensely valuable in trend driven production set-ups or niche volume production requirements. As customisation and product diversification is becoming standard, industry is looking for strategies to allow for greater adaptability in responding to customers' needs. Exploration of flexible manufacturing system set-up is one of the explored avenues.

Benjafaar and Sheikhzadeh (2000) highlight the need for more flexible, reconfigurable and modular factories to address the dynamic changes of the market demands, supply and legislation. Although FMS can provide a flexible and efficient facility, its optimal set-up is key to achieve maximum production performance. As many variables are interlinked, due to the flexibility provided by the FMS, analytical calculations are not always sufficient to predict the FMS' performance.

Although the idea of FMS has been studied for decades, utilisation of its full potential can be explored in significantly greater detail through the use of simulation. Simulation modelling is more intrinsically capable of capturing complexity and constraints associated with FMS. Chan and Chan (2004) has reported that simulation is the most widely used tool for modelling FMS. Also, Jahangirian et.al. (2010) in a review of simulation techniques demonstrates that discrete event simulation is the most widely used technique in business and manufacturing, accounting for 40% of the total number of research documents reviewed.

6.2 Set-up objectives and parameters

Set-up in manufacturing usually focuses on configuration of production elements to meet set requirements. The most common set-up objectives focus on achieving throughput or particular machine utilisation. From the review of literature, 14 papers have defined throughput as the main key performance indicator (KPI), and 9 have defined cell utilisation as the main KPI. These two parameters drive the set-up related simulation studies.

The definition of these KPIs can be interpreted differently depending on the variables included in the simulation, however the basic definitions are:

Machine utilisation can be defined as idle machine time deducted from total available machining time. The equation is as follows:

Total available time – Idle time = Machine utilisation rate

Equation 4 Machine utilisation

Average throughput is measured by the total number of parts divided by the number of weeks. This can be illustrated as follows:

Parts produced/ Number of weeks = Average throughput

Equation 5 Average throughput

The experimental factors are defined based on the main simulation objectives (i.e. maximising throughput / or maximising machines utilisation), as well as the level of depth, and identification of performance-impacting manufacturing processes and system constraints.

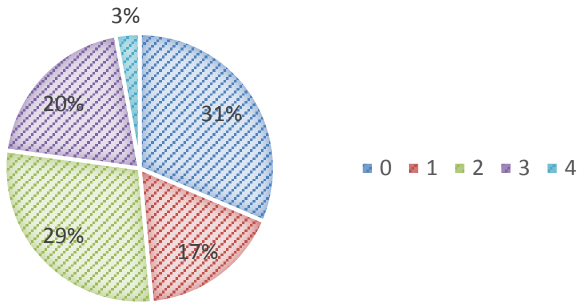


Figure 42 Number of experimental factors in set-up related papers for manufacturing and FMS decision-making, based on SLR

This is demonstrated in the analysis of the combinations of experiment factors within different simulation case studies (Figure 42). In 31% of papers, it was not possible to identify experimental factors individually, rather, it was based on comparing two layouts that had a range of parameters configured and comparing KPIs. However, for the majority of projects one or up to four experimental factors have been defined and considered.

There are a range of experimental factors related to set-up found in the current literature. From the SLR search the most frequent are WIP and number of machines, followed by job arrivals, storage, set-up time and sequencing rules (as illustrated in Figure 43). It is assumed that this is not an exhaustive list as the level performance-driving elements will differ in each case.

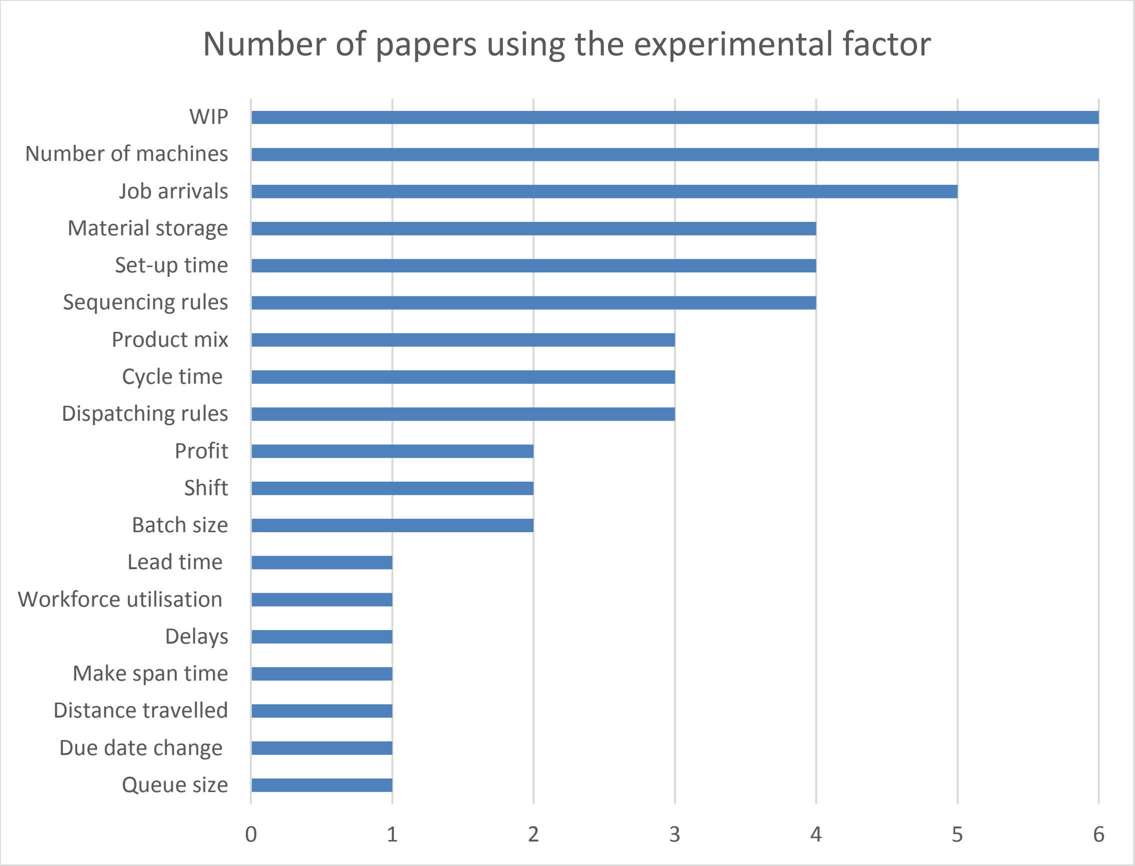


Figure 43 Experimental factors across DES decision support for manufacturing, based on SLR

Table 32 provides an overview of the experimental factors definitions and their use in terms of improvement areas for production. It is clear that the experimental factors are a range of selected (value adding) production elements that can affect the achievement of key KPIs.

Table 31 Experimental factors definitions and use

Experimental factor	Definition	Use
Queue size	Number of parts allowed to queue in front of machines	Control of WIP
Due date change	Time up to which the production need to be completed	Throughput maximisation Cost minimisation
Distance travelled	Distance parts need to travel to be processed to finish good stage	Optimisation of layout Cost minimisation
Make span time	total length of the schedule	Optimisation of throughput Minimisation of lead time
Delays	Period of time by which something is late or postponed	Throughput maximisation
Workforce utilisation	Number of workers assisting the manufacturing process	Test of multiskilling or dedicated workstations of performance
Lead time	Time between part starting and finishing production of a part	Minimisation of time in production
Batch size	Number of items that will be produced after a machine has been setup	Balancing operations
Shift	Time frames for workers attending the manufacturing process	Improvement of performance through shift optimisation
Profit	Monetary value of produced goods	Assessment of performance based on cost
Dispatching rules	Algorithms for which the decision about which job to run next is made based on the jobs	Increasing throughput
Cycle time	Time between part starting and finishing operation	Line balancing
Product mix	The volume of different parts to be produced	Production optimisation - throughput
Sequencing rules	Rules for sequencing parts into production system	Line balancing Throughput maximisation
Set-up time	Time to change from the last item of the previous order to the first good item of the next order	Machine utilisation maximisation
Material storage	Number of spaces for storing parts across the system	Impact of inventory management of production
Job arrivals	Number of parts to be realised / processed in a set period of time	System capacity
Number of machines	Number of machines used to perform dedicated operations	Production capacity Bottlenecks identification
WIP	Average number of parts in the production system	System capacity System efficiency

6.3 DES approach for set-up decision making

This section introduces the approach for FMS set-up DES to measure the system performance.

The focus of the approach is on selection and testing the set-up within defined FMS physical boundaries and their relationships with one another. The idea of capturing set-up requirements in this way allows the boundaries of physical layout to be tested and experimentation with relevant experimental parameters that will affect the performance. Once experimentation has taken place, informed decisions on the best configuration can be made. The approach is guided by the following steps:

1. Select production requirements – establish the FMS performance objective and define the production system key performance indicators (KPIs)
2. Define FMS boundary – define the system elements and its relationships, as well as assumptions about the system and limitations
3. Select set-up parameters – select the experimental elements of the model; build design of experiment
4. Test set-up performance – carry out experiments in DES simulation
5. Decide set-up configuration – select the best configuration based on KPIs

The approach structure is presented in Figure 44.

Figure 44 Approach for set-up testing with DES

As there are multiple factors to consider for FMS, simulation is able to cope with different levels of complexity at that level. This is why simulation is the appropriate method for the defined approach. The simulation approach takes into account: definition of objectives, building a conceptual model, building simulation and validation, experimentation, results validation (Robinson, 2011). The evaluation of this approach is presented through the FMS case study.

6.4 FMS set-up case study

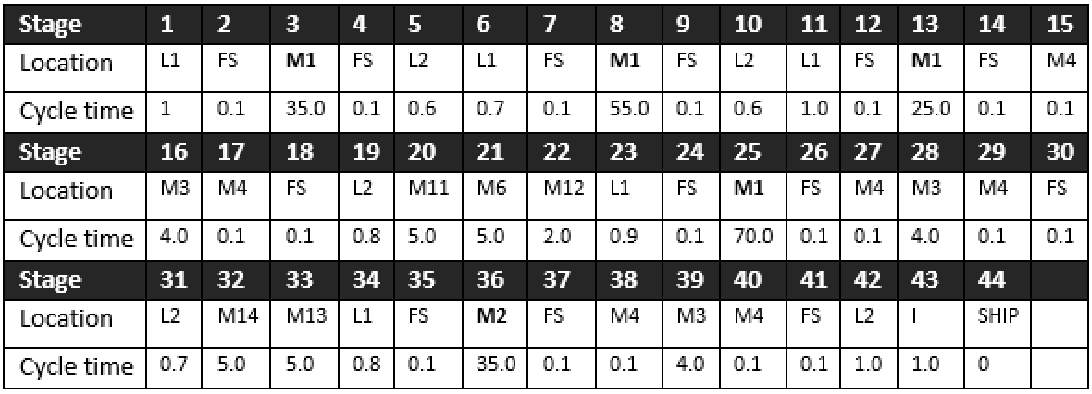
The case study of automotive FMS has been carried out to demonstrate the use of the approach for FMS set-up selection. The company is a high value automotive parts provider that is implementing a new FMS production line.

6.4.1 **Select production requirements**

The production requirements focus around the availability of resources against what is achievable by the system. Production requirements have been defined to explore set-up in the context of capacity in FMS. The aim was to evaluate the best production configuration for maximum capacity.

6.4.2 **Define FMS boundary**

The building of a conceptual model for the automotive FMS is introduced in the section as a means to develop a FMS boundary. The studied FMS consists of a system supervised by the PLC where two types of CNC machining stations process two part variants (M1 and M2). The parts are mounted on dedicated pallets and transported within the FMS by a MHR. The system has 68 internal storage spaces. The part routes used in the simulation are displayed in Figure 45. Stage and location represent the sequence, and cycle times represent the time spent in locations. Within the sequence, five operations occur in CNC machines (highlighted bold in Table 45). The remaining operations are either automatic operations in FMS or assembly operations that occur in dedicated assembly stations outside the FMS.



Stage	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Location	L1	FS	**M1**	FS	L2	L1	FS	**M1**	FS	L2	L1	FS	**M1**	FS	M4
Cycle time	1	0.1	35.0	0.1	0.6	0.7	0.1	55.0	0.1	0.6	1.0	0.1	25.0	0.1	0.1
Stage	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
Location	M3	M4	FS	L2	M11	M6	M12	L1	FS	**M1**	FS	M4	M3	M4	FS
Cycle time	4.0	0.1	0.1	0.8	5.0	5.0	2.0	0.9	0.1	70.0	0.1	0.1	4.0	0.1	0.1
Stage	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**	**41**	**42**	**43**	**44**	
Location	L2	M14	M13	L1	FS	**M2**	FS	M4	M3	M4	FS	L2	I	SHIP	
Cycle time	0.7	5.0	5.0	0.8	0.1	35.0	0.1	0.1	4.0	0.1	0.1	1.0	1.0	0	

Figure 45 Part A profile (M1, M2 – CNC machining centres, M3- Robot, M4- Wash Cell)

The model assumes full labour availability and no transportation time outside the FMS as this has been identified as insignificant for the FMS performance. A detailed model boundary is outlined in Table 33 and the model layout is represented in Figure 46.

Table 32 Boundary of FMS facility defined in conceptual model

Included in the model	**Excluded from the model**
FMS and surrounding manual operations	Labour
Total flexibility of FMS operation	Breakdowns
Two parts are machined on one pallet	Transportation of parts
Shift time– 24h/5d	Set-up times
4 type 1 machines (M1)	
1 type 2 machines (M2)	
Manual operations dedicated to stations (no flexibility)	
Raw material is always available	

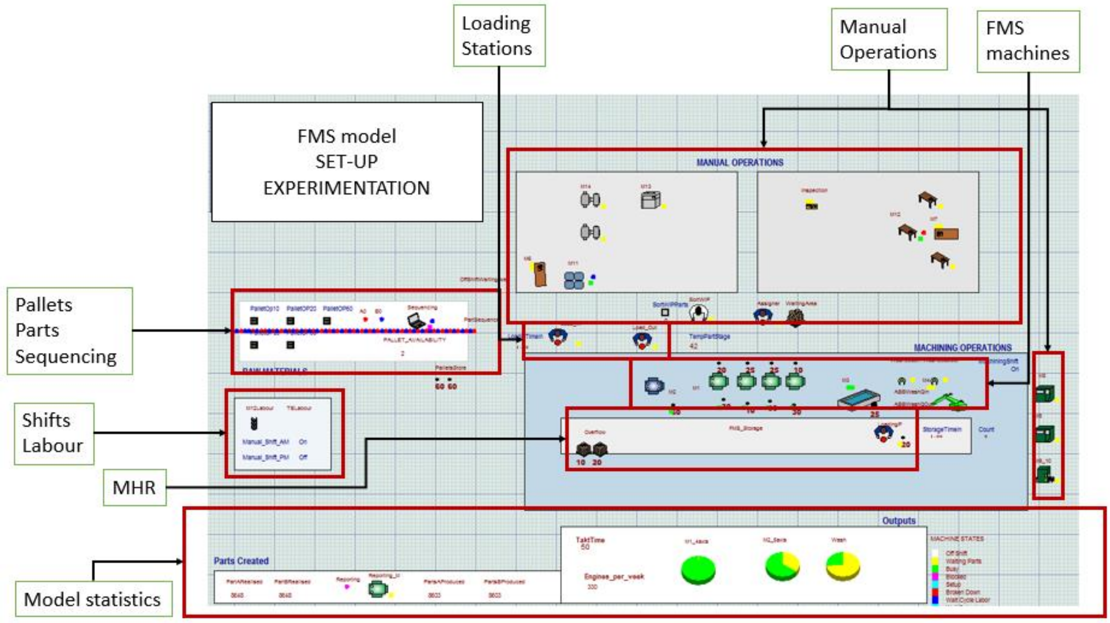


Figure 46 Simulation model layout of the facility

6.4.3 **Set-up parameters selection**

The selection of experimental parameters for this study has been based on industrial input from the automotive company. The capacity has been a main concern of the simulation, and consequently throughput and utilisation were defined as main key performance indicators (KPIs). The three experimental parameters selected to test possible system capacity were sequence (S), number of machines (A) and number of pallets (N). The summary of experimental parameters and responses is contained in Table 34. The sequence parameter (S1,S2) refers to the change in the scheduling. The sequence S2 has an additional 3 processes and the cycle time for manual operations is 75 minutes longer than S1. The aim is to investigate whether a change in part sequence cycle time will influence the system performance in terms of capacity. The number of pallet (N2,N3,N4) parameters refers to constraining the production system while maintaining the machine capacity. It is between 2 to 4 pallets per operation. The number of machine (A3,A4) parameters refers to limiting available capacity. M4 refers to four available machines and M3 to three machines available.

Table 33 Summary of the model experimental factors and responses

Experimental Factors	Range	Responses
Sequence of parts (S1, S2)	Sequence1 , Sequence2	Throughput
Number of pallets (N2,N3,N4)	2, 3, 4	Machine Utilisation
Number of machines (A3,A4)	3, 4	(m1, m2)

As the model has no variability at this stage, it is considered as deterministic. This also meant that only one run of each scenario is necessary. The experiment set-up is based on a design of experiment approach. A total of 12 experiments have been performed (summarised in Table 35).

Table 34 The design of experiments set-up

Scenario	**Parameters**		
No.	Sequence (S)	Number of pallets (N)	Number of machines (A)
Base Case	1	3	4
1	2	3	4
2	1	2	4
3	2	2	4
4	1	4	4
5	2	4	4
6	1	3	3
7	2	3	3
8	1	2	3
9	2	2	3
10	1	4	3
11	2	4	3

For the simulation, the warm-up period has been established from time-series inspection of throughput (Robinson, 2007). It has been identified that after week 10 the throughput is stable and reaches the steady-state. The run time of the model is 52 weeks, which was sufficient to provide consistent data. The validation of results has been carried out by using the loading capacity analysis and comparisons of variance in responses. The full calculations are available in appendix C.

6.4.4 **Test set-up performance**

This section covers the results of the experiment to investigate FMS performance. The three parameters are discussed separately and further, the overall view on combined parameters performance is overviewed to demonstrate decision making for set-up.

Sequence related parameters (S) indicate that extension of the manual operation processes has influenced the performance of the FMS. S1 scenarios have performed better in terms of average throughput (Figure 47) and utilisation for M1 and M2 (Figure 48). The reason for S2 scenarios not performing as well is that the manual processes set-up has created bottlenecks in the system, which caused machine starvation.

Figure 47 Average throughput in scenarios for S-parameter

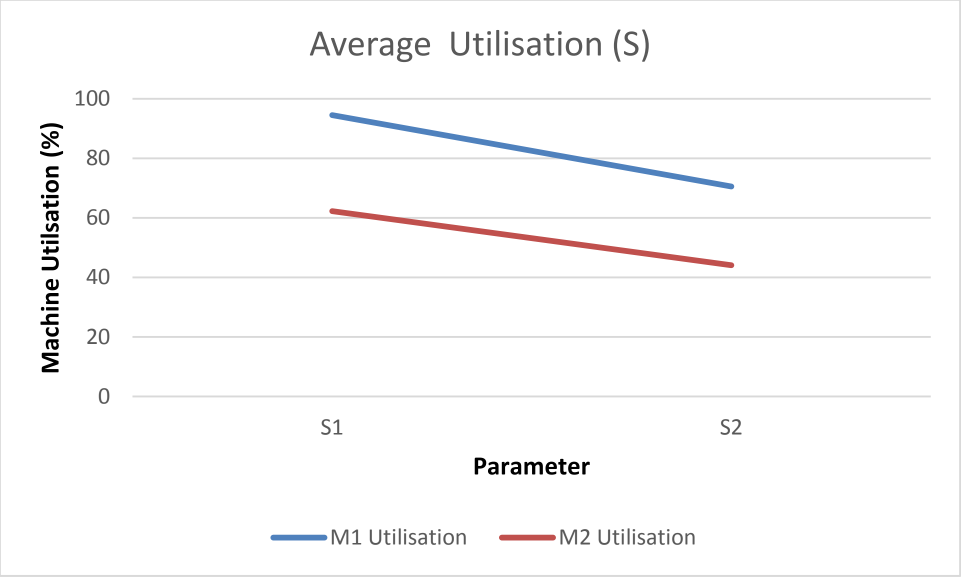


Figure 48 Average utilisation in scenarios for S-parameter

The results for the number of part parameters (N) imply that the optimal number of pallets for the system is three. Both throughput (Figure 49) and utilisation (Figure 50) show that two pallet scenarios underperform. This suggests that two pallets are not sufficient to utilise the full capacity of the machines and therefore lead to maximum throughput. On the other hand, four pallets create more WIP in the FMS, which contribute to bottlenecks in production. That is why the average throughput for N4 parameter has not increased when machine utilisation has slightly increased.

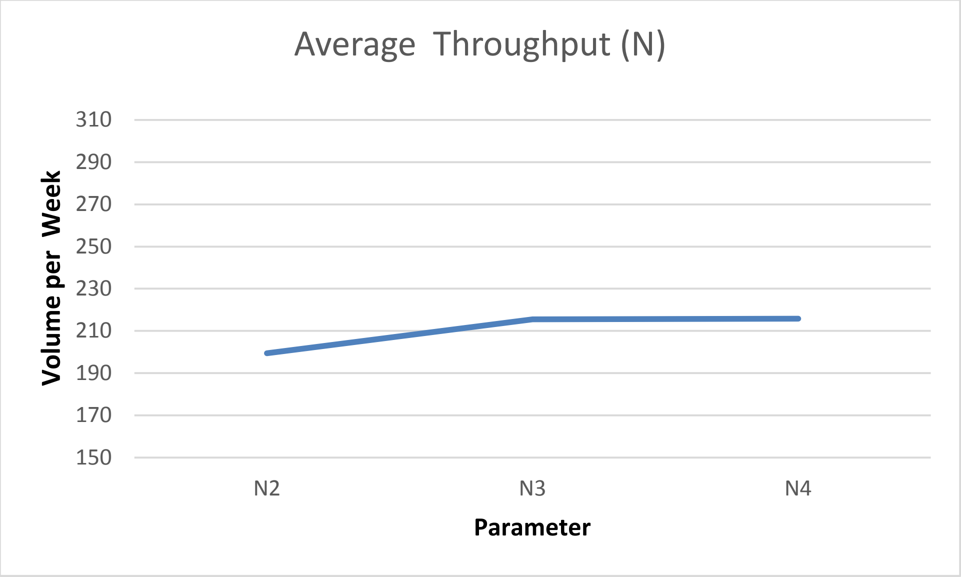


Figure 49 Average throughput in scenarios for N-parameter

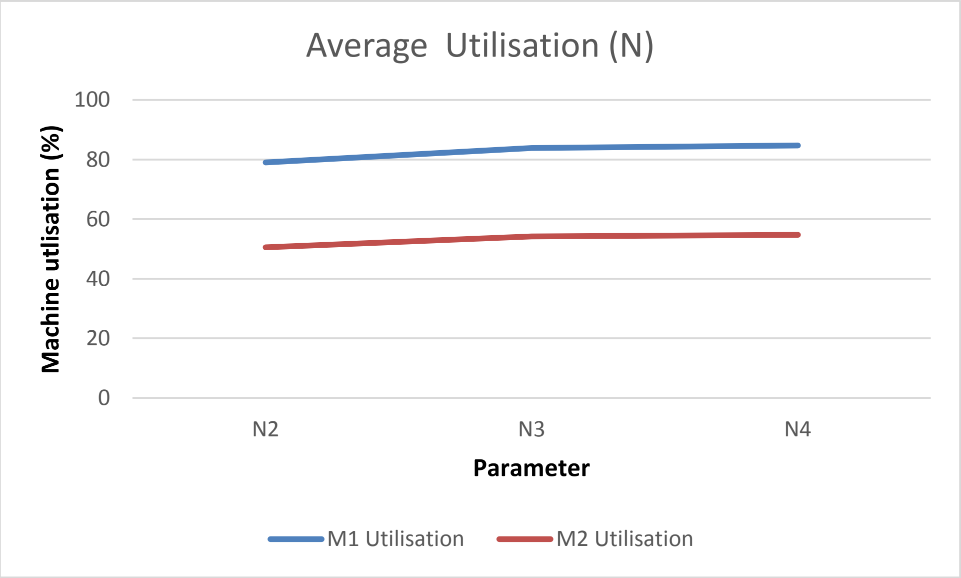


Figure 50 Average utilisation N-parameter

The related results for the number of machines (A) show that limiting the number of machines limits the possible throughput, which is an expected result (Figure 51).

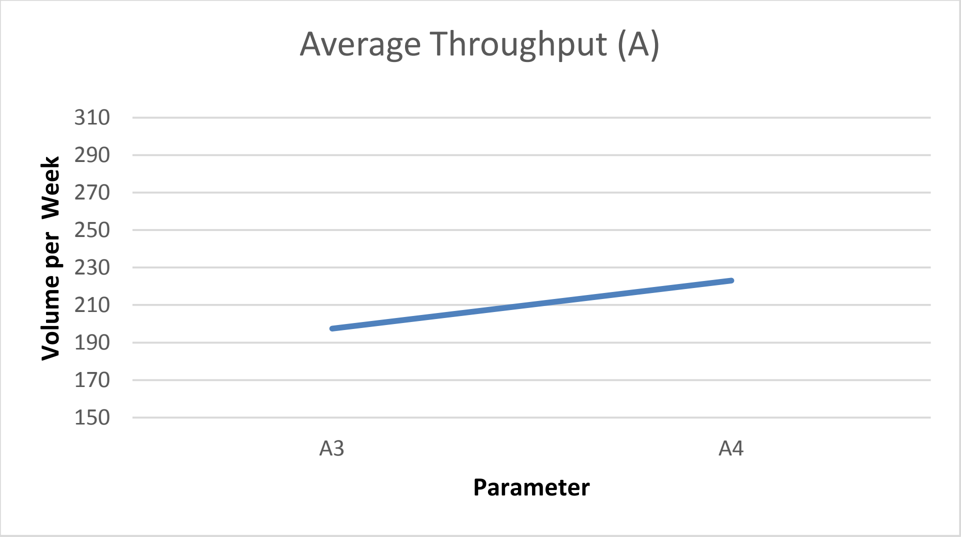


Figure 51 Average throughput in A-parameter

Utilisation results provide insight into relationships between machines (Figure 52). When four machines were available, the overall loading on M1 type machines has decreased due to the fact that the machines were able to cope with parts processed. M2 type machines had to process a higher volume of parts when in A4 parameter scenarios and consequently the utilisation of the machine has increased.

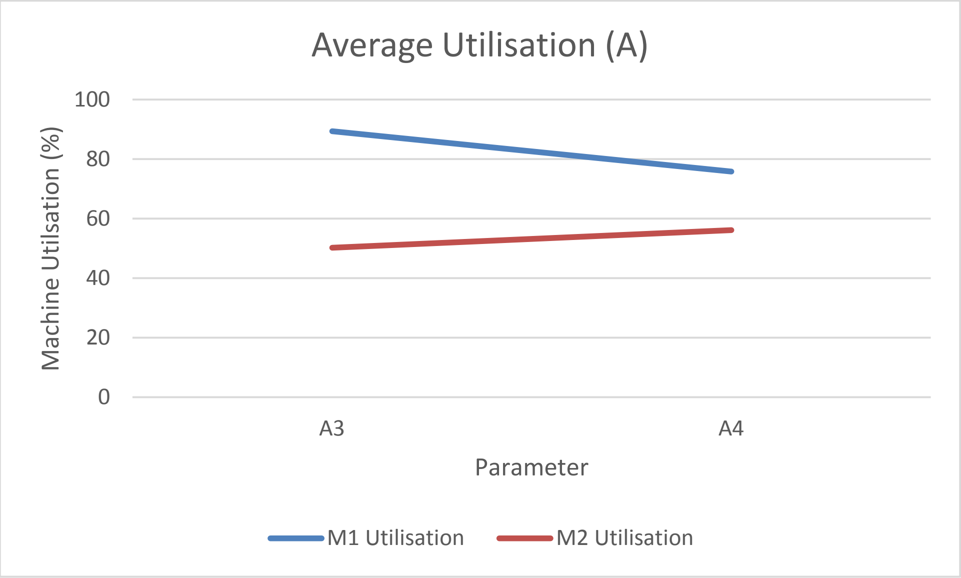


Figure 52 Average utilisation M-parameter

Knowing the parameters' behaviour was a useful insight into the importance for FMS set-up configuration. The next step is to decide what configuration is best.

6.4.5 **Decide set-up configuration**

The results from all scenarios have been plotted on one graph. When combined, the results matrix suggests that the best machine utilisation for the flexible manufacturing set-up in the experiment is S1, N3, A4 or S1, N4, A4, both in maximising machine utilisation and throughput. It is worth noting the sequence has high impact on possible throughput and utilisation as all results for parameter S1 compared better than S2. Figure 53 provides a summary of the results.

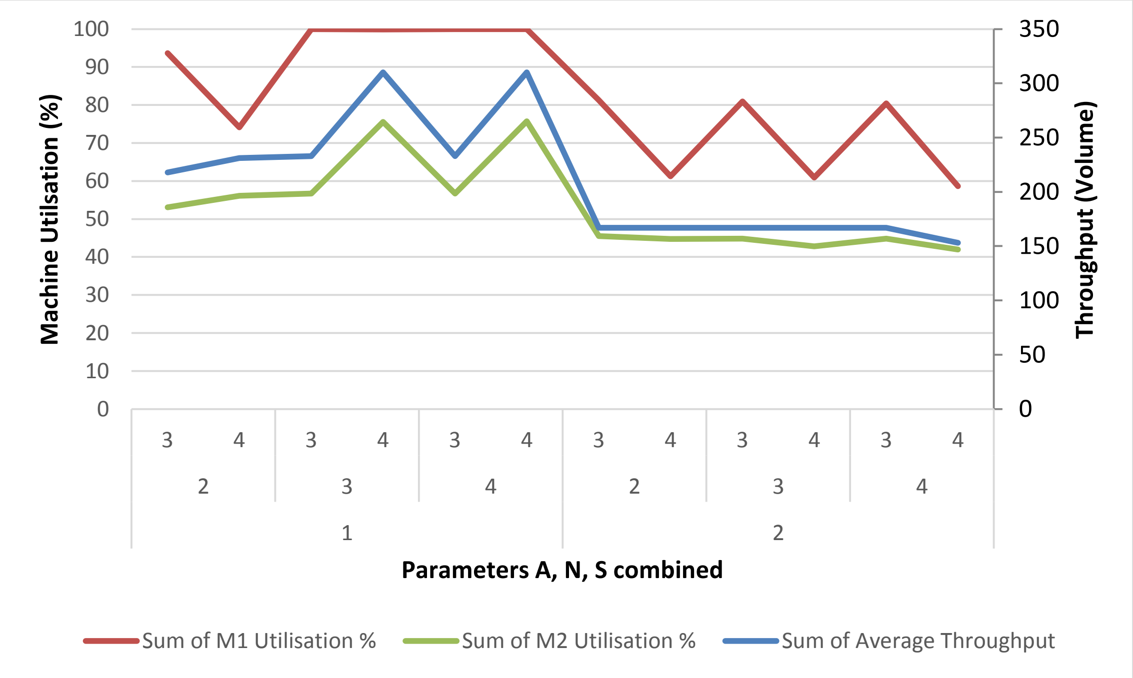


Figure 53 Combined scenarios fo S,N,M parameters

6.5 Discussion

Set-up is important for FMS development as it is a source of FMS competitive advantage with the capability to reconfigure and adapt. Planning set-up could prove difficult due to the high variability and complexity of the FMS system. In this chapter an approach for FMS set-up modelling with DES has been proposed.

The proposed approach focuses on defining FMS development requirements first. The framework is designed based on the modelling of FMS with DES approach. The framework has been validated though a FMS automotive case study. Within the case study set-up, impact on capacity has been major focus. The next step focused on outlining the FMS boundary; defining physical system elements and the dependencies between them, as well as part flow. Simplifications have been necessary due to data availability issues as, well as identification of value adding elements of FMS. For example, as the research focuses on maximising capacity, it was assumed that no breakdowns have been present. This was done to enable validation of the results, as well as to understand the maximum capacity of the system for the given configuration. Further research could take into account the impact of breakdowns on the system performance.

Once the FMS environment has been outlined, the experimentation parameters can be defined. KPIs for the system have been throughput and utilisation. The experimental factors were the number of machines, number of pallets and sequence. The design of experiments was used in the next step to perform the scenario experimentation ensuring that all possible combination of set-up are used. Lastly, the results comparison allowed for building understanding of parameter impact on performance and defining the optimal set-up parameters for the FMS scenarios.

The presented approach allowed for establishing what is possible for FMS to achieve in the given conditions, as well as building understanding around the impact of set-up change on the FMS performance.

6.6 Summary

The aim of this chapter was to demonstrate how discrete event simulation software is able to support set-up in a FMS. Firstly, the importance of set-up in FMS has been outlined. The set-up parameters and objective commonly used in DES have been illustrated. Further, an approach for FMS set-up modelling using DES. Lastly, the automotive case study has been presented to validate the approach applicability.

7 DES for FMS flexibility

Flexibility in FMS is explored in this section. This chapter focuses on exploration of how FMS flexibility is addressed by DES and how decision-making on flexibility affects FMS performance. A further approach for modelling flexibility with DES is introduced and validated through an automotive case study.

7.1 Flexibility in FMS

The flexibility of FMS can yield significant benefits to industry due to its adaptation capabilities. However, achieving an optimal flexibility level can mean a variety of different things in FMS as it has been characterised at many levels (this is discussed in depth in section 2.1.1).

Form the current literature, it is clear that the definition of flexibility levels is not consistent in production processes and it is interpreted on a case-by-case basis. Baykasoğlu and Göçken (2011) looked at how performance of a job shop production set-up is affected by different degrees of flexibility. He concluded that the degree of flexibility has a different effect on various performance indicators, and there is a strong relationship with WIP levels, which supports the reduction of mean absolute performance errors in workload delivery. Djassemi (2007) found that providing flexibility in operations by a skilled workforce in cellular manufacturing system improves overall system performance. Renna (2010) proposed applying simulation to capacity reconfiguration problems in the reconfigurable manufacturing system. Sharma, Garg and Sharma (2011) uses simulation to test the effect of period delays on FMS with different routing flexibility levels. Suresh Kumar and Sridharan (2010) investigates the impact of scheduling rules and tool request decisions in an FMS environment when tool sharing is applied. Tool sharing has been found to minimise the total number of tools in the system while maximising the tool utilisation, but insignificant effect on performance has been reported. Use of different scheduling rules at the launch of the production have revealed to have a significant impact on performance. Ali and Wadhwa (2010) uses simulation to compare how different levels of routing flexibility affect the performance of manufacturing systems. It was concluded that the optimal level of flexibility is to provide one alternative machine to improve system performance.

Simulation research has considered different types of flexibility depending on the type of production and production system constraints. Routing flexibility has been identified by Joseph and Sridharan (2011b) and Joseph and Sridharan (2011a) as a main contributor to the flexibility of FMS and is described as availability of machines for part processing (Djassemi, 2007).

Although there are many cases of measuring routing flexibility and its effect on performance, there has been limited insight into systems that assume total flexibility in FMS. The usual strategy is to define the system constraints and set-up flexibility levels to test performance. In most cases, the higher the number of pallets, the better the results, simply because increasing the number of parts in the system can absorb the idle time of the machines (Ali and Wadhwa, 2010).

7.2 Flexibility parameters

From the SLR of flexibility-focused simulation, 5 major objectives have been identified: utilisation, throughput, flow time, tardy jobs and tardiness (illustrated in Figure 54).

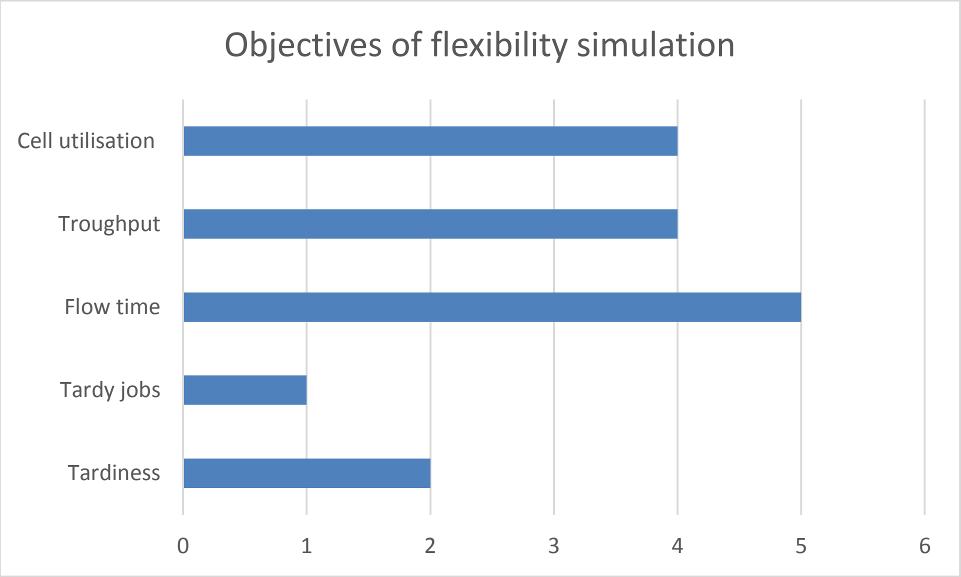


Figure 54 Objectives for flexibility focused simulation projects, based on SLR

Throughput and cell utilisation have been mentioned in the previous case study (section 6.2). Flow time, also called lead-time, refers to the total time of part production from start to finish. Tardiness refers to delays in job processing and tardy jobs can be defined as jobs that has been delayed in the system. Tardiness is calculated as average value of time, whereas the number of tardy jobs are counted in a form of number of occurrences; but they both refer to the same event. Flexibility objectives are parameters that exploit the best use of available time in production. The levels of flexibility allow to minimise or maximise the before-mentioned objectives.

In terms of experimental factors, the following have been noted from literature: queue size, sequencing rules, dispatching rules, job arrivals, batch size, WIP, cycle time, set-up time, material storage size, shift, OEE and make span time (as illustrated in Figure 55).

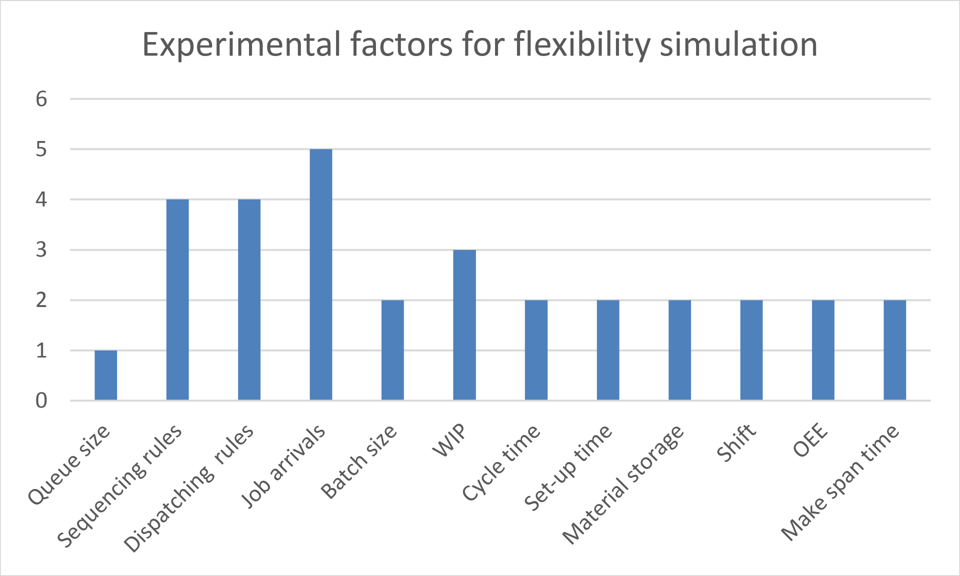


Figure 55 Experimental factors for flexibility simulation, based on SLR

Job arrivals, sequencing and dispatching rules are three most common experimental factors. All these are connected to the way parts flow through the system. The distinctive areas for FMS in this context are: scheduling (sequencing and dispatching rules); and how machines and routes are managed in the system (queue size, job arrivals batch size, size of storage etc). Machines are also an area of interest, but rather than the number of machines, the concern is in machine set-up (cycle time, set up time, OEE,). In addition some system parameters have been recognised (shift, make span time).

The range of flexibility-related experimental factors reflect the versatility of flexibility in manufacturing applications. As flexibility is a diverse concept for FMS, it is difficult to generalise decision support requirements in this area. What is possible is the exploration of flexibility parameters used in simulation decision support systems, as well as demonstrating a general approach for addressing flexibility. This approach for simulation of FMS flexibility has been outlined in the next section.

7.3 Approach for simulation of FMS flexibility

This section presents the approach for simulation of FMS flexibility. It is illustrated in Figure 56. The approach adapts methods for simulation development to create structured approach for addressing flexibility levels. The flexibility modelling requires understanding the system studied and identification of parameters for simulation. The approach takes into account data inputs and industrial context expectations using the available data as well as industrial expertise.

The approach for FMS flexibility simulation has been structured as follows:

1. Selection of flexibility type studied – identification and definition of what type of flexibility (as defined in section 2.1.1) is at the heart of concern for FMS context
2. Selection of the flexibility objectives – definition of the study objective and KPIs
3. Definition of FMS context – identify the model scope, assumptions and limitations based on industrial input
4. Decide type of experimentation – evaluate and select best approach for carrying out experimentation, select the variables that will be used in experimentation
5. Carry out experiments – perform the experimentation

6. Validate results – evaluate if the results provided grounds for decision-making. If decision has not been reached – re-evaluate.

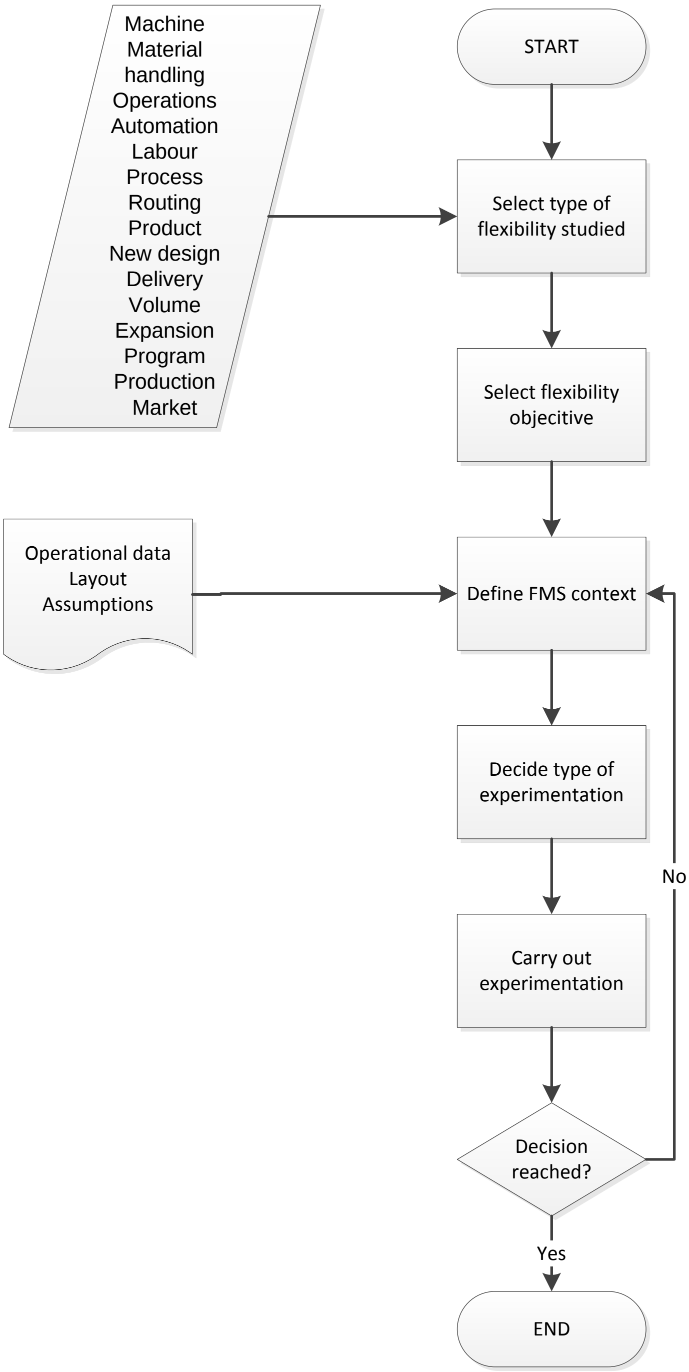


Figure 56 Approach for simulation of FMS flexibility

The introduced approach focuses on selection of the type of flexibility studied and allows to explore the concept of flexibility at different angles. Within this approach decision-making might not be reached at the first time of experimentation. Once findings from experiments are known, there may be a need for further experimentation, to reach decision. This approach is evaluated through mix-model FMS case study evaluating routing flexibility. It is presented in section 7.4.

7.4 Mix-model FMS case study

The case study regarding flexibility of mix-model FMS is studied in an automotive industry context. A discrete event simulation model for mix-model production in FMS set-up has been developed to investigate the effects of routing flexibility on performance of FMS. The first three steps in the approach are the same for all cases, as the initial phases focus on case study scoping. Further steps are defined separately for each experiment.

7.4.1 **Selection of flexibility type studied**

The selection of the type of FMS studied will influence how the FMS will be explored for improved performance. A flexible manufacturing system (FMS) provides many opportunities for better line configuration as it can maximise opportunities for producing by providing routing flexibility (multiple production routes) (Joseph and Sridharan, 2011a), operation flexibility and production flexibility (responsiveness to the changing demand in mix model production set up over time).

The focus of this case study is on flexible routing in FMS as it has been claimed to have most effect on performance. Routing flexibility can be defined as the number of alternative paths a part can take through the system in order to be completed.

7.4.2 **Selection of the objectives**

The objectives of this study were derived from the automotive case study of mix-model FMS. The question formed around discussions with industry on whether full flexibility of a FMS provides better performance than dedicated production line.

The KPIs has been agreed to be throughput and machine utilisation. Throughput directly shows how many parts can be produced in the system, whereas utilisation can show unused capacity or imbalance in production.

7.4.3 **Define FMS context**

The level of complexity for FMS modelling in this case study has been defined based on the automotive FMS processing multiple customer orders. For enabling capturing of production scope and limitations the simulation model needs to cover:

- mix model production in flexible manufacturing system set-up
- complex constrain within the FMS – pallet system
- the behaviour of a flexible manufacturing system and the manual operations associated with production of desired mix of products

The detailed model about the studied FMS is provided below.

7.4.3.1 Pallet system in FMS

Newman, Warren and Denzler (1991) pointed out in his study of pallet impact on flexibility in FMS that when uncertainty of demand in systems increases, the importance of general purpose pallets also increase. His suggestion implies to reduce as many constraints related to pallets as possible to enable greater flexibility of the overall system. Currently in high quality goods production and high-speed production systems, specialised fit for purpose pallets are indispensable to achieve competitiveness. This is because it can provide opportunity to perform specific operations at multiple machines which can increase system capability to produce products. Therefore, understanding the limitations that pallet configuration can bring to FMS as well as the impact of pallet configuration on production could be critical for the FMS performance.

Newman, Warren and Denzler (1991) has also concluded in his research that limiting the number of pallets available to FMS can reduce its performance. More recently, Ali and Wadhwa (2010) has used the number of pallets as a parameter influencing the FMS flexibility. Although the number of pallets is a parameter that is treated as an important factor in the FMS performance (Ali and Wadhwa, 2010) it has not been studied in detail. Ali's (2009) assumption is that the number of pallets parameter controls the work-in-progress inventory inside the system and sets the levels of available pallets (12, 24, 36, or 48).

This case study in this research considers a more complex pallet set-up and its influence on the facility capacity and machine utilisation. The number of available pallets, pallet/part configuration and pallet/operation configuration need to be studied in order to understand pallet system impact on the fulfilment of demand, as well as machine utilisation.

7.4.3.2 Pallet system in case study

In this case study, pallets are specified per operation that need to be performed. This means the number of pallets per part type increases depending on the number of machine operations performed. The pallet allocation per operation is summarised in Table 36.

Table 35 Pallet allocation per customer

CUSTOMER	**Customer 1**				
Fixture Description	A0 OP10	A0 OP20	A0 OP25	A0 OP30	A0 OP60

CUSTOMER	**Customer 2**									
Fixture Description	BH OP10	BH OP20	BH OP30	BH OP40	BH OP50	BH OP60	BH OP70	EH OP10	BH1 OP10	BH1 OP20
Fixture Description	DH1 OP10	DH1 OP20	DH1 OP30	CH OP10	CH OP20	DH OP10	DH OP20	DH OP30	DH OP40	

CUSTOMER	**Customer 3**									
Fixture Description	FV OP 20	FV OP30	FV OP60	FV OP70	KV1 OP10	KV1 OP20	KV OP10	KV OP20	KV OP30	KV OP100

This mix model addresses not only multiple independent parts in the FMS but also demonstrates the complex pallet-part allocation system where depending on the type of part a different type of pallet is required. Pallets cannot be shared among different types of parts even from the same part family. Table 37 provides the summary of part – pallet configurations possible in the case study.

Table 36 Pallet system allocation

Pallet configurations (at Load_In)		
2 same parts per pallet	2 L+R parts per pallet	1 part per pallet
(A0)	(BH)	(DH)
	(BH1)	(DH1)
	(FV)	(EH)
		(CH)
		(KV)
		(KV1)
		(GV)
Characteristics of configuration		
Double machining time	Double machining time	Single machining time
Separate Assembly ops	Separate assembly ops	Assembly linked between parts

Configuration 1 allows two of the same types of parts to be allocated on one pallet for machining. This means that two parts A0 will be allocated on pallet OP10A0 for machining and once it is out of FMS it will split into two parts to have manual operations performed on them.

Configuration 2 also requires two parts to be placed on one pallet. In this case, the parts are the mirror reflection of one another. For instance, the configuration for part BH would be BH Left and BH Right allocated on the OP10BH pallet. The part would also be split for manual operations for machining.

Configuration 3 allocates one part per pallet. In a manual operation area, one part per pallet is used.

7.4.3.3 Physical production system

The FMS system in this case study consists of 11 CNC machines with one loading and unloading station to facilitate part flow, internal MHR and assembly operations surround the system. There are 2 types of CNC machines – 9 that perform 4 axis machining and 2 that perform 5 axis machining. The model assumptions are summarised in Figure 57.

Assumptions

- All required parts produced (total of 11)
- Free flow model (100% utilisation)
- 9 x 4axis (M1)
- 2 x 5axix (M2)
- 1 x Wash machine (M3)
- Pallet system loading accurate
- Demand loaded in weekly (and it is fixed)
- Basic calculation for machines capacity
- Scheduling – based on parts arriving in FIFO rule
- Aim – to prove weekly production capacity
- Weekly demand is realised to the simulation every week
- Model calculates the KPI and not produced parts (if any)
- No shifts allocatted (labour)
- No downtime due to breakdowns
- No quality related rework/rejects

Figure 57 Assumption for model

The system produces 11 types of parts divided into 3 part clusters related to customers for the production line (A, BH-BH1-CH-DH-DH1-EH, FV-GV-KV-KV1) All clusters need to be produced in balanced quantities as specified in the operations data (illustrated in Table 38).

Table 37 Weekly part demand

Part cluster	Volume
A	320
H	46
V	56

Additionally part clusters need to be assembled together in the part-sets, which takes place in the assembly manual operation stage. The model is illustrated in Figure 58. The example of part flow is provided in Table 39. The model assumes fixed weekly demand of part-sets required for each part cluster.

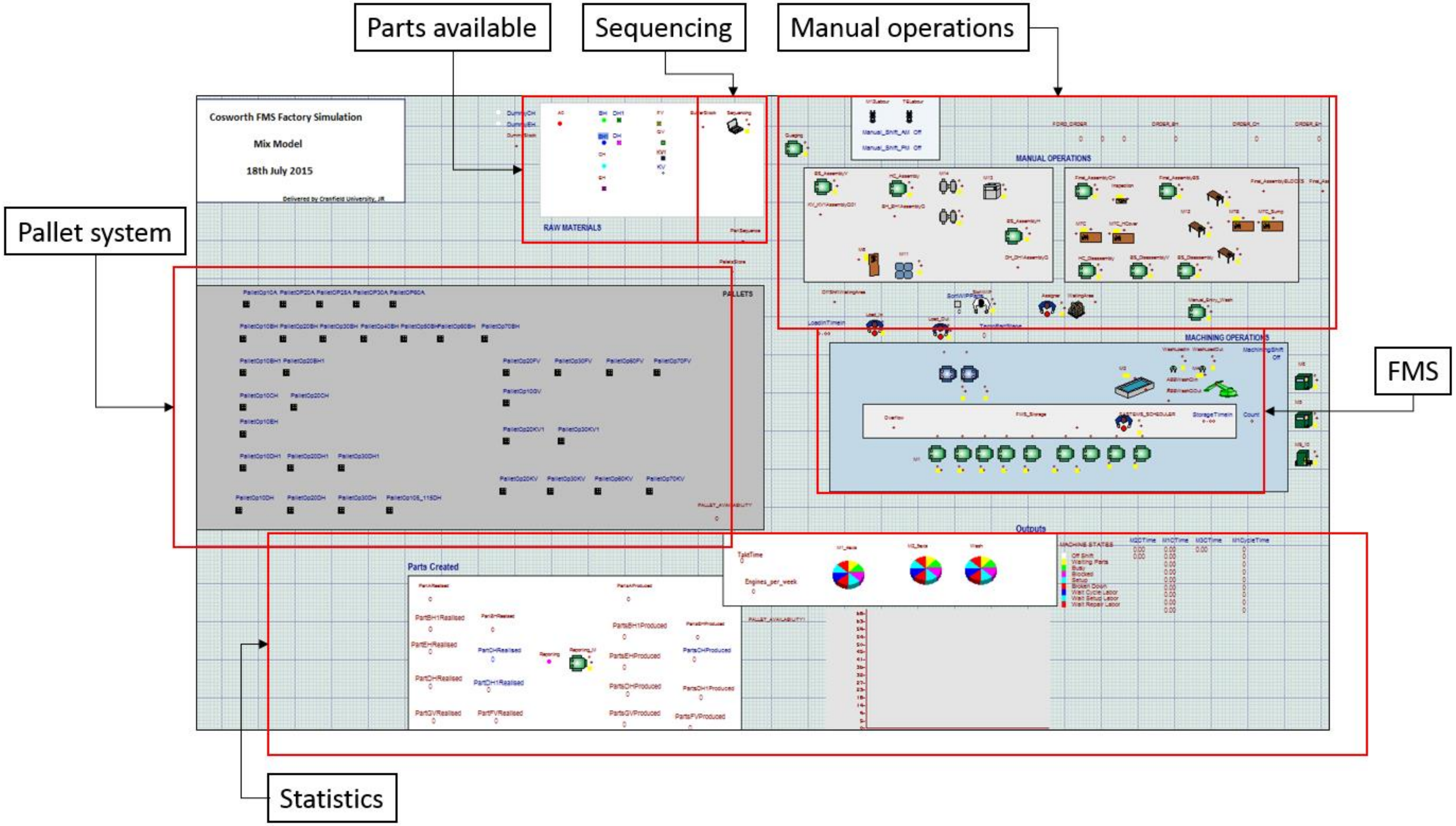


Figure 58 Mix-model simulation snapshot

Table 38 Part route in the FMS: Part index, cycle time

Number on machining operations	A0	CT	BH	CT	BH1	CT	CH	CT	EH	CT	DH1	CT	DH	CT	FV	CT	GV	CT	KV1	CT	KV	CT
1	10	30	10	35	10	35	10	10.13	10	25	10	35	10	35	20	65	10	32.5	20	32.5	20	32.5
2	20	55	20	35	20	35	20	26.45			20	35	20	35	30	65			30	32.5	30	32.5
3	25	30	30	35							30	35	30	35	60	65					60	32.5
4	60	55	40	35									95	13.4	70	65					70	32.5
5	65	30	50	35									105	13.4								
6	70	5	60	35									115	13.4								
7			70	25																		

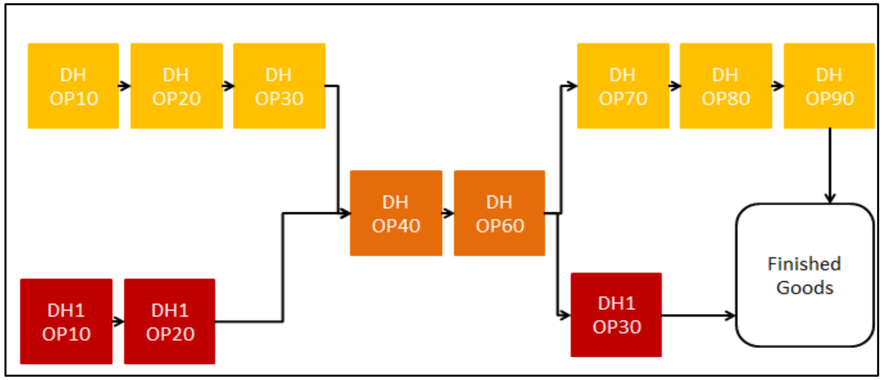


Figure 59 Example of part flow for DH cluster

7.4.3.4 Model verification

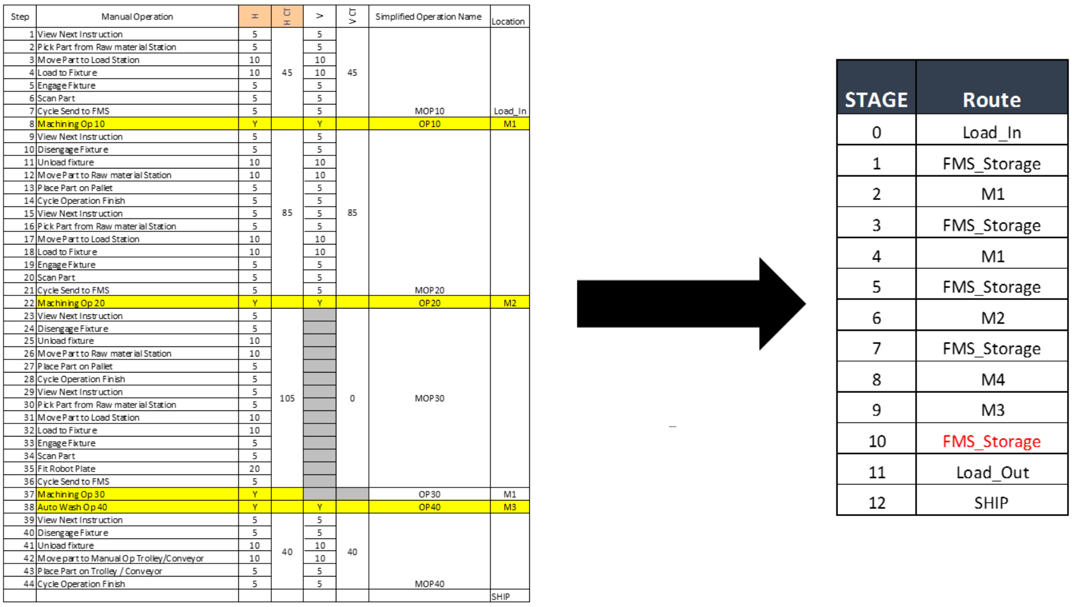
A WITNESS simulation model has been developed for this case study. The WITNESS software uses discrete event simulation for manufacturing applications. The data sources for different elements are outlined in the table below.

Table 39 Data sources for model development

Data Source	**Data Use**
Operation Matrix	Part flow – operations/machines
Factory layout	Visual reflection of the system and part flow understanding
OEE document	Scenario development – targets for scenario
Comments on a factory CAD drawing	General understanding of factory layout Stages of model development Basic assumptions
Line visit	Operation times Verification of original assumptions

The model has been verified through face validation checks: ensuring correct data inputs, observing part behaviour in the system, and comparing loading capacity provided by the industry to the modelling. Due to the high level of complex behaviours modelled in the system, it was not possible to verify loading capacity. In addition, due to the lack of available historical data, it was not possible to compare to model to real data sets. Although the verification was not quantifiable, it was possible to reach agreement on its correctness from industrial expert judgement based on loading calculations (Scenario 1).

Data input checks were made to ensure that data from industry is converted and modelled in the correct way. The example of such conversion is illustrated in Figure 60. The conversion was performed and agreed on with the industrial sponsor as well as crosschecks made to ensure correct data use.



Step	Manual Operation	H	H CT	V	V CT	Simplified Operation Name	Location
1	View Next Instruction	5	45	5	45	MOP10	Load_In
2	Pick Part from Raw material Station	5		5			
3	Move Part to Load Station	10		10			
4	Load to Fixture	10		10			
5	Engage Fixture	5		5			
6	Scan Part	5		5			
7	Cycle Send to FMS	5		5			
8	Machining Op 10	Y		Y		OP10	M1
9	View Next Instruction	5	85	5	85	MOP20	
10	Disengage Fixture	5		5			
11	Unload fixture	10		10			
12	Move Part to Raw material Station	10		10			
13	Place Part on Pallet	5		5			
14	Cycle Operation Finish	5		5			
15	View Next Instruction	5		5			
16	Pick Part from Raw material Station	5		5			
17	Move Part to Load Station	10		10			
18	Load to Fixture	10		10			
19	Engage Fixture	5		5			
20	Scan Part	5		5			
21	Cycle Send to FMS	5		5			
22	Machining Op 20	Y		Y		OP20	M2
23	View Next Instruction	5	105		0	MOP30	
24	Disengage Fixture	5					
25	Unload fixture	10					
26	Move Part to Raw material Station	10					
27	Place Part on Pallet	5					
28	Cycle Operation Finish	5					
29	View Next Instruction	5					
30	Pick Part from Raw material Station	5					
31	Move Part to Load Station	10					
32	Load to Fixture	10					
33	Engage Fixture	5					
34	Scan Part	5					
35	Fit Robot Plate	20					
36	Cycle Send to FMS	5					
37	Machining Op 30	Y				OP30	M1
38	Auto Wash Op 40	Y		Y		OP40	M3
39	View Next Instruction	5	40	5	40	MOP40	
40	Disengage Fixture	5		5			
41	Unload fixture	10		10			
42	Move part to Manual Op Trolley/Conveyor	10		10			
43	Place Part on Trolley / Conveyor	5		5			
44	Cycle Operation Finish	5		5			
							SHIP

STAGE	Route
0	Load_In
1	FMS_Storage
2	M1
3	FMS_Storage
4	M1
5	FMS_Storage
6	M2
7	FMS_Storage
8	M4
9	M3
10	FMS_Storage
11	Load_Out
12	SHIP

Figure 60 Data conversions from operation matrix for routing

Visual flow was verified through observation of the simulation model running and observing the expected behaviour in the model. This was key for machine allocation and for the order of parts entering FMS, as well as pallet allocation (ensuring that only number of parts dictated by number of pallets are in production at any given time the time). The first experimentations for the case study were a form of verification – these were based on comparisons of estimated production line capability to the simulation results and are presented in the next section.

7.4.4 **Parameter selection**

The parameter selection for case studies in flexibility has been an emergent process. The decision on the types of experiments to perform has been heavily embedded in the industrial context developed for evaluation of different aspects of flexibility in a FMS system based on the realistic challenges in a FMS system operational planning. Three scenarios have been included to explore flexibility:

1. Analysis of system performance with free flow (full system flexibility) and fixed number of pallets – 3 customers

The first experiment focused on providing validation of the simulation model where different demand and machine mixes were tested based on company development requirements. In further scenarios, the flexibility of route and shift were tested in an attempt to measure the FMS performance for the required demands. Loading capacity for various demands was calculated to verify whether the simulation can reach the capacity required by the industrial sponsor. This was the form of model verification.

2. Free flow vs dedicated production line – 2 customers

This section focused on comparisons of model performance in different flexibility set-ups driven by industrial input. After free flow scenario (1), the decision was made to not allow implementation of the mix-model production set-up in the FMS due to high complexity requirements and low control over the production operations inside the FMS. Use of a free flow approach would have created a knock-on effect on quality control in industrial context. Therefore, the scenarios developed reflect the strategies that can be practically adapted in the factory– from no flexibility to flexibility at Operation 10 for all parts. The idea of making early operations flexible was initiated from the assumption that during the busy periods of machines in early operations but while others are available, inputting early operation could increase used capacity and balance the production across the machines available.

3. Dedicated line but moving operations – 2 customers

Scenario 3 focused on dedicated production as based on previous scenarios, it was decided that better throughput could be achieved. Additionally, using dedicated machines allows for easier planning- it provides straightforward quality control and makes PLC input and part loading easier on the shop floor. Therefore, the next scenario has focused on testing improvement on the dedicated line configuration by moving one operation (OP40) from M4 to M6 in the simulation.

The experimentation requirements are presented in Table 41.

Table 40 Experimental design for flexibility simulation

Scenario	Scope	Purpose	Parameters	Route characteristic	Responses
1	3 customers (A,B,C)	Verification of production capacity for various demands	Number of machines Demand	Full flexibility	Throughput for individual parts
2	2 customers (B,C)	Testing how realistic route flexibility affects performance	Route change	Dedicated vs. partly flexible	Throughput Utilisation
3	2 customers (B,C)	Testing whether moving operation will improve performance	Demand Shift	Dedicated	Throughput Utilisation

The parameters for the first scenario focused on exploration of the system capacity under various demands. This study has explored a mix-model concept in free flow route. As the scenarios were developed as an exercise to understand rump-up to full production period, it took into account the changing machine availability and changing production demand. The responses focused on verification of whether it would be possible to deliver the production demand, hence individual part production has been considered as a response.

Scenario 2 focused directly on routing flexibility options for the FMS. However, the considerations for FMS routing were selected based on implications to other areas of business (for instance, free flow was not possible to implement due to implications to quality control). In consequence, the scenario considered the dedicated line FMS and the scenario where free flexibility on initial operations is provided (all OP10 for every part). For this scenario, the focus was on comparing system performance in terms of throughput and utilisation of machines.

Scenario 3 was an extension of scenario 2 exploration. Once the decision had been made on what type of routing guarantees better performance, the effort into testing if better result could be archived by moving operations. Additionally, the company could adapt two shift patterns: 24 hours over 5 days and 24 hours over 7 days.

7.4.5 **Decide type of experimentation**

Due to the complexity of the modelling, as well as different requirements from modelling from industry, the experimental set-up was not suitable to be used in the design of experiment format. The spread of scenarios and the output requirements meant that the case-by-case scenario development is more practical and appropriate for industry option. As a result, if analysis was used as a method to develop scenarios it allows a wide spread of experimentation that is informed by results from previous studies.

7.4.6 **Carry out experimentation**

The experimental results for the three case studies were introduced in this section. The experiments were carried out one after another. The reason being that results from the first experimentation influenced the direction of the experiments that followed.

7.4.6.1 Scenario 1 context and results

Scenario 1 experimentation focus was on understanding system capacity. Loads on M1, M2 and M3 machines at variable demands were done. The experiments summary is provided in Table 42. The simulation ran for 26 weeks. As it was deterministic, only one run per scenario was required.

Table 41 Experimentation for different load scenarios for mix-model

Experiment No	Corespondent production week Week	Number of machines			A	H	V
		M1	M2	M3			
		No req'd	No req'd	No req'd	Engs/Wk	Engs/Wk	Engs/Wk
1	31	3	1	1	74	10	0
2	32	3	1	1	94	10	0
3	33	5	1	1	150	10	12
4	34	5	1	1	200	10	12
5	35	8	1	1	220	10	36
6	36	8	1	1	320	10	48
7	37	9	2	1	320	10	48
8	38	9	2	1	320	10	48
9	39	9	2	1	320	10	48
10	40	9	2	1	320	10	48
11	41	10	2	1	320	10	52
12	42	10	2	1	320	10	52
13	43	10	2	1	320	10	52
14	44	10	2	1	320	10	52
15	45	10	2	1	320	10	52
16	46	10	2	1	320	10	52
17	47	10	2	1	320	10	52
18	48	10	2	1	320	10	52
19	49	10	2	1	320	10	52
20	50	10	2	1	320	10	56
21	51	10	2	1	320	10	56
22	52	10	2	1	320	10	56
23	1	15	2	2	320	46	56
24	1 (V110)	18	2	2	320	46	110

Loading capacity calculation was made for each scenario to act as a benchmark for results' comparisons. The results for the simulation cover the number of parts produced, compared to the maximum production capacity calculated. Part clusters (A, H, and F) were compared separately to the simulation results. The Figures 61 and 62 show that for A cluster and H cluster the production prediction is well matched inboth scenarios. It is not a case within F part cluster (summarised in Figure 63.). The results show that part KV was well matched to the prediction but part FV fell behind consistently (Figure 63). This is due to the limited number of pallets available for the FV production. As there were only two pallets and the overall production time is the longest, it is not possible to produce the required amount of parts.

When looking at individual scenarios, it is noticeable that scenarios 23 and 24 focused on highly increased demand and high machine availability. For all part clusters it is not possible to achieve higher throughput because the number of pallets available to process parts in FMS have not increased.

The scenarios allowed for verification of the model and to uncover the system limitations. Firstly, verification was achieved in a sense by proving the model’s consistent results when the capacity for the part-mix load in available. Secondly, it has been discovered that the number of pallets need to be appropriately selected to the production to be able to maintain the desired production levels for part clusters.

This scenario allowed the modeller and the industry to gain understanding of the FMS system behaviour in the free flow set-up and understand the limitations of pallets in the system, as well as build trust around the model behaviour and simulation results. Although the results were not revolutionary, their purpose was to verify and explore the mix-model in free flow environment and build understanding around a vital question in an applied context – is this going to work? What are the implications?

The next phase in mix-model experimentation was to focus on different scenarios selected that could explore the flexibility of FMS.

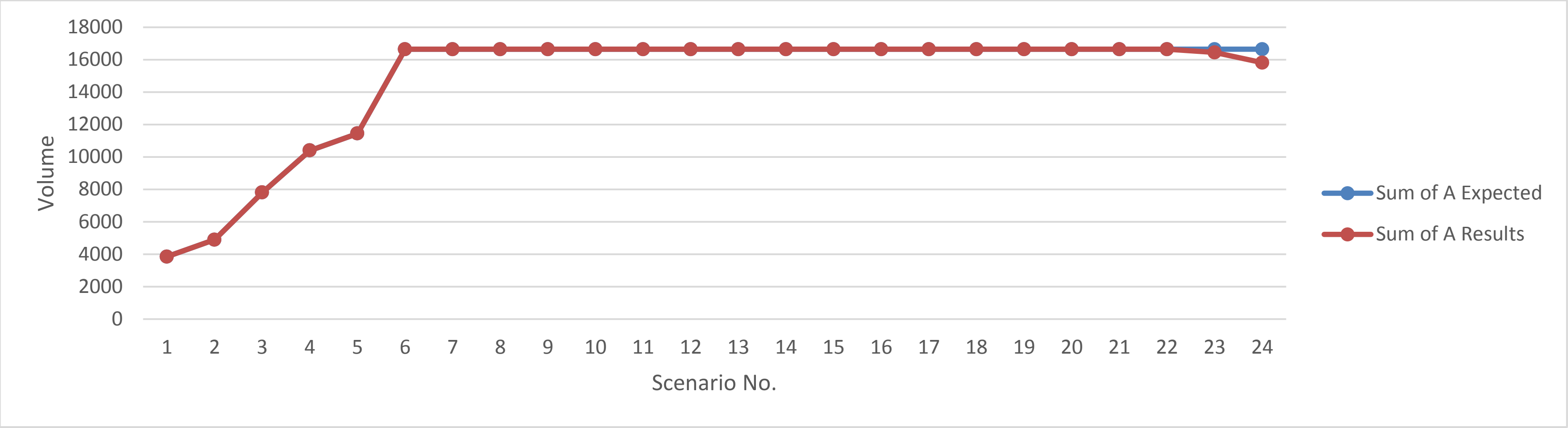


Figure 61 Results of demand of A cluster (legend: Expected – loading capacity calculation; Results – simulation results)

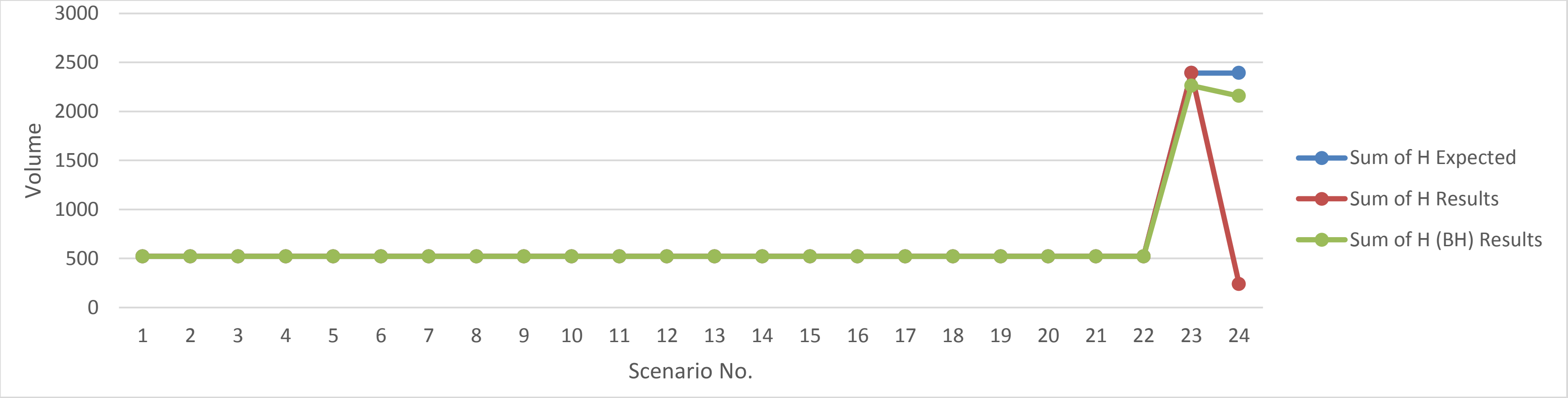


Figure 62 Results of demand of H cluster (legend: Expected – loading capacity calculation; Results – simulation results)

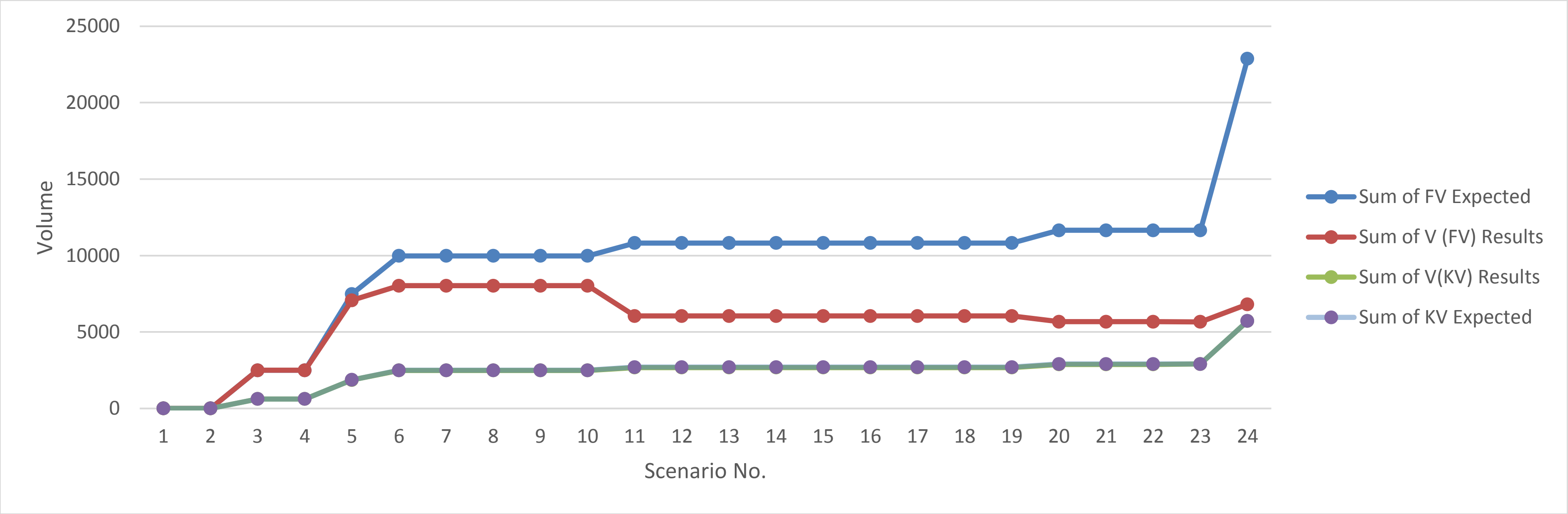


Figure 63 Results of demand of F cluster (legend: Expected – loading capacity calculation; Results – simulation results)

7.4.6.2 Scenario 2 experimentation

The focus of this scenario was on testing route flexibility scenarios for FMS. The physical environment in this case study is the same as in scenario 1, its specification is available in section 7.4.4. However, from this point, only part-sets H and F were considered. Table 43 provides pallet allocation to machines in the FMS. The cycle time was updated for the most recent production cycle times to reflect the real time per operation.

Table 42 Data input for the simulation machine allocation to operations, number of pallets and cycle times

Machine	Operation	Pallets	Cycle time
Machine 1	OP30 BH	1	1:31:46
Machine 1	OP90 DH	1	0:46:31
Machine 2	OP10 DH1	2	0:55:04
Machine 2	OP20 DH1	2	1:23:02
Machine 3	OP20 DH	2	1:29:45
Machine 3	OP10 BH	1	1:09:46
Machine 4	OP40 BH	1	0:51:14
Machine 4	OP90 BH	1	1:44:08
Machine 5	OP30 DH1	2	0:43:49
Machine 5	OP51 KV Assy	2	0:08:32
Machine 5	OP30 DH	2	0:43:53
Machine 5	OP150 BH	2	0:17:31
Machine 6	OP50 KV Assy	2	0:46:34
Machine 7	OP30 KV	2	1:07:36
Machine 8	OP20 KV1	1	0:34:25
Machine 8	OP30 KV1	1	0:31:03
Machine 9	OP20 KV	2	1:03:35
Machine 10	OP70 KV Assy	2	0:49:33
Machine 11	OP10 DH	2	1:37:15
Machine 11	OP20 BH	1	1:00:09

The scenarios considered are summarised in the Table 44. The production week has been set for 24h/5d set-up as it was considered appropriate for two part-sets being produced in the system. Utilisation and throughput were the desired KPIs to measure performance. As free flow was not accepted as a operation matrix, the two scenarios explored whether limited flexibility would be better for the line in comparison to dedicated operations machining.

Table 43 Experiment design for the flexibility scenarios

Assumptions	Experimental Factors	Responses
Shift 24h/7d 2 part-sets – H, F Demand on H – 40 Demand on F - 100	Dedicated machines Free flow on OP10 for all parts	Utilisation Throughput

The data results from both scenarios are illustrated in appendix D and the summary in shown in Figure 64.

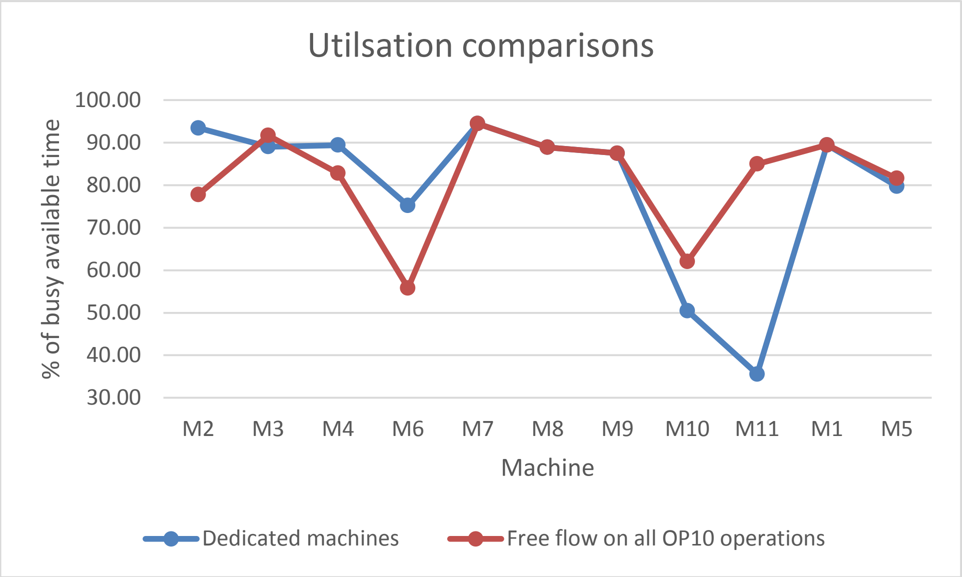


Figure 64 Comparisons of utilisation in given scenarios

The comparisons of the two scenarios demonstrated that Flexing OP scenario provided greater balance across the production in comparisons. For dedicated production, scenarios M11 and M10 have been heavily underutilised. The Flexing OP scenario used machines that are underutilised in dedicated scenario, while realising the load on busier machines (M2 and M4). However, M1, M3 and M7 have remained bottlenecks, whereas M10 remains underutilised and M6 has lost efficiency. The utilisation in M7, M8, M9 has not changed as there was no OP10 put on the machines.

In terms of throughput (Figure 65), a dedicated scenario has delivered better fulfilment of demand than a flexible, proving that a balancing line does not always indicate a better performance in terms of throughput. In a dedicated scenario, more parts have been completed in production overall. It is worth noting that Flexing OP scenario produced, on average, more H part-sets per week, but less 7 V part-sets. Subsequently, small benefit for H cluster means bigger loss for V. If we look at that from a percentage perspective, 3% compensation in overall production throughput for H means 9% benefit in overall production throughput for V.

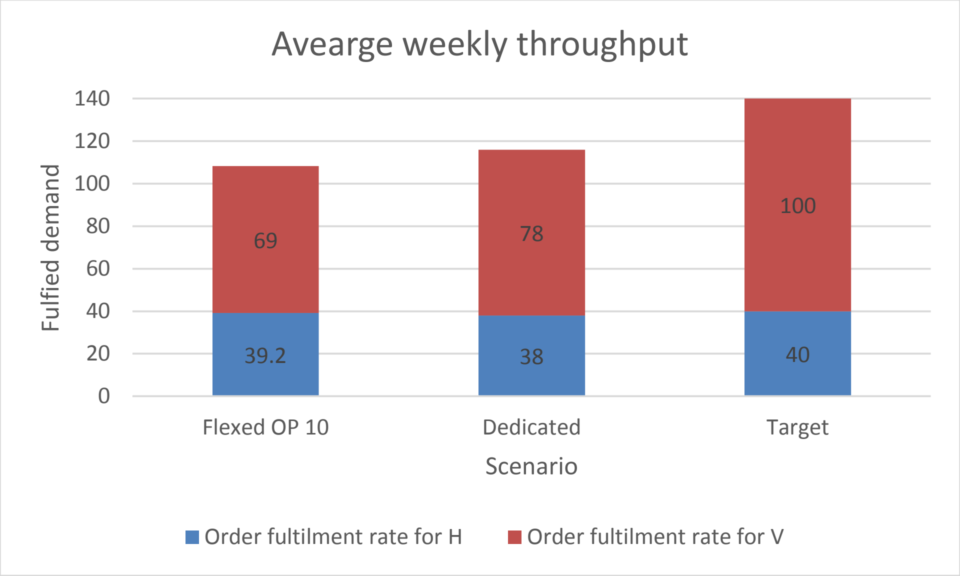


Figure 65 Comparisons of average weekly throughput in given scenarios

To sum up, although the balancing utilisation was better in the Flexing OP scenario, better throughput was achieved through dedicating operations. This unusual finding can be explained by unbalanced cycle times applied in production. OP 10 tend to be long operations, and giving priority to them has affected completion of operations that will proceed. The decision has been made to select dedicated machines strategy for the FMS system.

7.4.6.3 Scenario 3 experimentation

Once a dedicated line option was selected, the exploration was to improve performance of the chosen FMS configuration. Updated cycle times have been provided, along with proposed change in allocation of operation (OP 40BH moved to M6 instead of M4). Table 45 provides cycle time improvements. An overall reduction in cycle times across the matrix was 62.84 minutes, which should enable a reduction in overall system utilisation.

Table 44 Data input for the simulation machine allocation to operations and cycle times

Machine	Operation	Pallet time	NEW	OLD	Variance	Trend
Machine 1	OP30 BH	01:36:27	97.27	93	-4.27	↘
Machine 1	OP90 DH	00:38:50	38.5	49.24	10.74	↗
Machine 2	OP10 DH1	00:41:47	41.47	58.17	16.7	↗
Machine 2	OP20 DH1	01:18:23	78.23	83.43	5.2	↗
Machine 3	OP20 DH	01:16:31	76.31	89.44	13.13	↗
Machine 3	OP10 BH	01:21:35	81.35	83.23	1.88	↗
Machine 4	OP40 BH	00:53:32	53.32	51.17	-2.15	↘
Machine 4	OP90 BH	01:55:26	115.26	113.32	-1.94	↘
Machine 5	OP30 DH1	00:39:59	40	51.12	11.12	↗
Machine 5	OP51 KV Assy	00:08:32	8.32	8.19	-0.13	↘
Machine 5	OP30 DH	00:42:10	42.1	49.02	6.92	↗
Machine 5	OP150 BH	00:29:31	29.31	18.37	-10.94	↘
Machine 6	OP50 KV Assy	00:41:12	41.12	34.18	-6.94	↘
Machine 7	OP30 KV	01:04:12	64.12	60.58	-3.54	↘
Machine 8	OP20 KV1	00:31:48	31.48	36.06	4.58	↗
Machine 8	OP30 KV1	00:27:37	27.37	29.41	2.04	↗
Machine 9	OP20 KV	01:02:44	62.44	67.5	5.06	↗
Machine 10	OP70 KV Assy	00:47:34	47.37	52.42	5.05	↗
Machine 11	OP10 DH	01:22:39	82.39	93.14	10.75	↗
Machine 11	OP20 BH	01:05:42	65.42	65	-0.42	↘

On discovering that target throughput cannot be met by 24h/5d scenarios, it has been decided that 24h/7d shift will be more appropriate, but the demand range will be tested. The scenarios considered are summarised in the Table 46. The focus is on achieving 100 F and evaluate maximum H cluster part-sets. Baseline configuration of operations have been tested by moving OP40BH to M6.

Table 45 Experiment design for scenario 3

Assumptions	Experimental Factors	Responses
Shift 24h/7d 2 part-sets – H, F Demand on F – 110 All others- as set in precious case studies	Demand for H - 45, 50, 57	Utilisation Throughput
	Baseline dedication Vs. moving OP 40BH to M6	

Simulation run in WITNESS has been carried out running 26 weeks of production run with one week of warm up. The assumption for the model remains as specified in section 7.4.7.

The results from the experimentation are presented in Table 47. This shows that in 24/7 scenarios the average weekly throughput is met in scenarios with demand up to 50 parts; however, H production is only able to achieve an average of 55.3 part-sets per week in a maximum capacity in demand of 57. When comparing scenario 3 and 6 to one another it is clear that moving operation did not help to achieve better throughput and fulfill average weekly demand, but decreased V cluster production demand.

Table 46. Average weekly throughput results

Experiment Design			Average weekly throughput	
Scenario	Type	Demand	H	V
1	Baseline	45	45	110
2	Baseline	50	50	110
3	Baseline	57	55.2	110
4	Moving OP BH to M6	45	45	110
5	Moving OP BH to M6	50	50	110
6	Moving OP BH to M6	57	55.3	96.1

The utilisation results are demonstrated in Table 48. By moving OP scenarios, utilisation has decreased in M4 and increased in M6 as expected. After the change, M6 becomes a bottleneck and at highest demand; it reached maximum utilisation. The simulation has shown a lack of value in moving operation OP40BH to M6.

Table 47 Comparisons of utilisation in given scenarios

Experiment Design			Utilsation										
Scenario	Type	Demand	M2	M3	M4	M6	M7	M8	M9	M10	M11	M1	M5
1	Baseline	45	53.1	70.1	75	40.7	63.5	29.8	61.5	46.6	65.6	60.3	57.5
2	Baseline	50	59	77.9	83.3	40.7	63.5	29.8	61.5	46.6	72.9	67	63
3	Baseline	57	67.3	88.8	95.2	40.7	63.5	29.8	61.5	46.6	83.1	76.4	70.7
4	Moving OP 40 BH to M6	45	53.1	70.1	23.7	92	63.5	29.8	61.5	46.6	65.6	60.3	57.5
5	Moving OP 40 BH to M6	50	59	77.9	26.3	97.9	63.5	29.8	61.5	46.6	72.9	67	63
6	Moving OP 40 BH to M6	57	67.3	88.8	30	100	63.5	29.8	61.5	43.3	83.1	76.4	69.4

As the machines have been dedicated, moving operation has become as scenario testing strategy for FMS in terms of operation assignment to machines.

7.5 Discussion

Flexibility in FMS can be a source of competitive advantage; providing flexible production at various levels of planning production. The difficulty with the range of flexibility types available is the number of variants available and the selection of most appropriate level of flexibility for FMS. The chapter has provided insight into the importance of testing routing flexibility in FMS. The approach for tested flexibility has been proposed and tested through case study on routing flexibility in FMS with DES.

Selection of type flexibility is a key step in scoping the FMS production testing. The capability to select the type of flexibility provides a chance to explore different system flexibilities using the same approach. The selection of the type of flexibility when driven by industrial context depends on understanding the FMS potential as a system.

Selection of objectives defines what is the desired area of evaluation and set a goal for the simulation environment. In that way, different scenarios can be tested with the same objective in mind. This has been demonstrated through the three case studies. The scenarios could shape decision-making around flexibility by what-if scenario experimentation..

Defining FMS context shapes the boundary of modelling. It provides a test environment for experiments, and therefore it is important to define it clearly. The case study considered to demonstrate the approach has been very complex. An outline of different system elements has provided a clear boundary with obvious exclusions, assumptions and simplifications in the model. If the FMS context changes, the required experimentation changes. Within this case study, the FMS context was repurposed after every decision point. This has been a key to ensure appropriate context and up-to-date data available.

The decision on the type of experimentation is a consequence of the previous steps in the approach. The difficulty of modelling this case study was in its complexity and the spread of modelling objectives. That is why, analysis may have been an appropriate tool, but it may not be appropriate for different FMS contexts.

The experimentation process had to be well documented and justified for effective evaluation of flexibility. In the three case studies, details on the scope amendments and different directions have been provided. Verification of the model has been provided through scenario 1 and further tests have explored routing flexibility.

Through the case study, it was possible to validate this approach for modelling FMS flexibility with DES. The approach was designed with a wide scope of possible experimentation in mind, allowing choices for experimentation direction change.

7.6 Summary

The simulation model of mix-model FMS and the development of strategy for operation assignment has been demonstrated in the case study. The approach for testing flexibility has been introduced and three case studies have been presented, adapting what-if analysis. The simulation has provided a clear picture of impact of route assignment decision-making showing valuable and not valuable operational changes. Firstly, a free flow mix-model simulation has been introduced, proving a verification of model validity and a testing ground for operations planning in a free flow. As this strategy was found to be ineffective for the studied production, dedicated and semi-flexible operations assignment were tested. Surprisingly, it was discovered that although flexible production set-up provides better balancing, it is not reflection of the throughput. Further, decision-making in moving an operation to a different machine has been tested at different demand rates, based on the expected improvement to the process. Although the improvement was not achieved in this scenario, insights from the modelling have provided understanding of system modus operandi.

8 DES for Scheduling

This chapter focuses on supporting decision-making in scheduling for FMS. It explores the selection of parameters, introduces the simulation approach developed and provides scheduling case study.

8.1 Scheduling in FMS

FMS objective is to balance the flexibility versus the achievement of stable productivity (Upton, 1994) especially for medium-scale production. Scheduling is one of the key enablers to achieve efficient production in FMS set-up (Singh, Singh and Khan, 2016). Due to the number of combinations available, the complexity in FMS scheduling is much higher than in other manufacturing (Rifai, et al., 2016). It needs to take into consideration: routing, resource availability (i.e. number of pallets per operation) and capacity of the system.

The range of research on how simulation supports FMS scheduling has been outlined in section 2.3. The diversity of case studies demonstrates the spread of scope within FMS scheduling. Key case studies have focused on dispatching and scheduling rules in FMS (Basent, 2009), part flow and tool control with scheduling (Suresh Kumar and Sridharan, 2009), scheduling of AGV as part of FMS (Singh, Sarngadharan and Pal, 2011), and scheduling impact on performance (Abd, Abhary and Marian, 2014). DES have found useful ways to evaluate complex scheduling problems within a range of operational levels.

8.2 Scheduling parameters

Parameters associated with FMS scheduling experimentation have been outlined in this section. The main indicators of performance for simulation of scheduling in FMS are: utilisation, throughput and flow time. Figure 66 provides KPIs in scheduling DES.

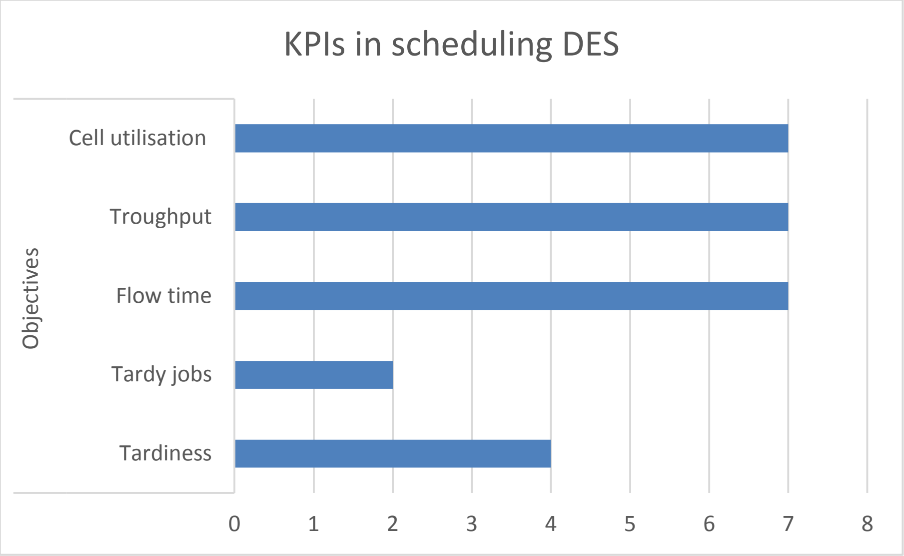


Figure 66 Objectives in scheduling DES, based on SLR

Experimental factors associated with scheduling identified from SLR have been illustrated in Figure 67. Dispatching and sequencing rules are the most common types of variables in the system focusing on schedule. Less obvious, are other variables affecting scheduling. Part related variables - like arrival rate, queue sizes and due date - have been regularly used. They have an impact on the speed and volume of the parts flow in the system. In addition, the number of machines have been used as a variable, which affects the capacity of the system. Other variables are: make span time, set-up times, cycle times, WIP level, traveling distance and batch size. These variables depend on the objective and scope of the simulation. It is important to note that as scheduling models frequently crossover with other themes (as showcased in the SLR), in many instances, the impact of two or three themes is measured. The decision on variable selection depends on the identification of "valuable" activities that affect performance. Therefore, when selecting variables, it is critical to capture those that encapsulate the simulation objectives.

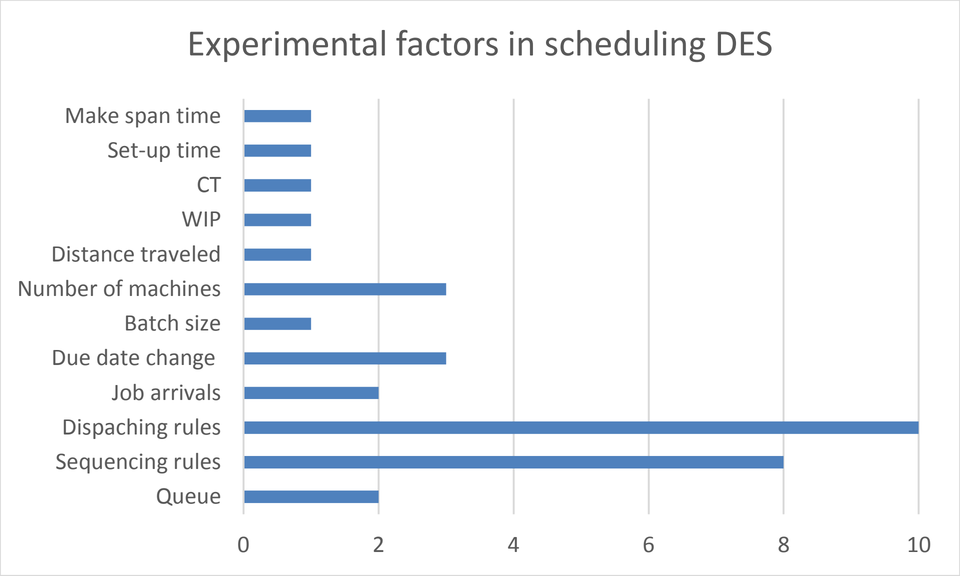


Figure 67 Experimental factors in scheduling DES, based on SLR

As the scope for FMS scheduling simulation is wide, there is a need for an approach dedicated to appropriate FMS scheduling simulation. The section below introduces an approach for schedule testing in the DES.

8.3 Approach for schedule testing

The approach introduced in this chapter has been designed for the schedule testing in FMS with the use of DES. It has been designed based on experience from building previous simulation models, with careful scoping dedicated to schedule testing in FMS set-up.

Firstly, it was identified that the approach needs to consider the following activities:

1. Setting model parameters – selection of FMS objective, variables and KPIs
2. Calculation of overall system performance – use of DES model to tests overall system performance under random schedule
3. Development of schedules – use of MatLab model to generate the possible schedule
4. Testing schedule and WIP in simulation – evaluation of schedule in DES Scheduler

Through iterative model development, it has been discovered that multiple model validation is required in the applied problem context and there are multiple loops for decision-making and amendments in FMS schedule testing. The reason for this is that establishing a common understanding and validating a basis for schedule development has been key for its successful application. WIP has been has also been identified as a possible variable due to the possible restrictions on storage in the FMS. In consequence, the introduced activities have been evolved into a modelling approach that is illustrated in Figure 68. The approach uses three simulation models: DES model for loading capacity evaluation, MatLab model for schedule generation and DES modelling for schedule testing. Matlab modelling has been carried out outside the scope of this PhD in partnership with Manufacturing Informatics PhD student. The considerations for the approach are further discussed in the next section.

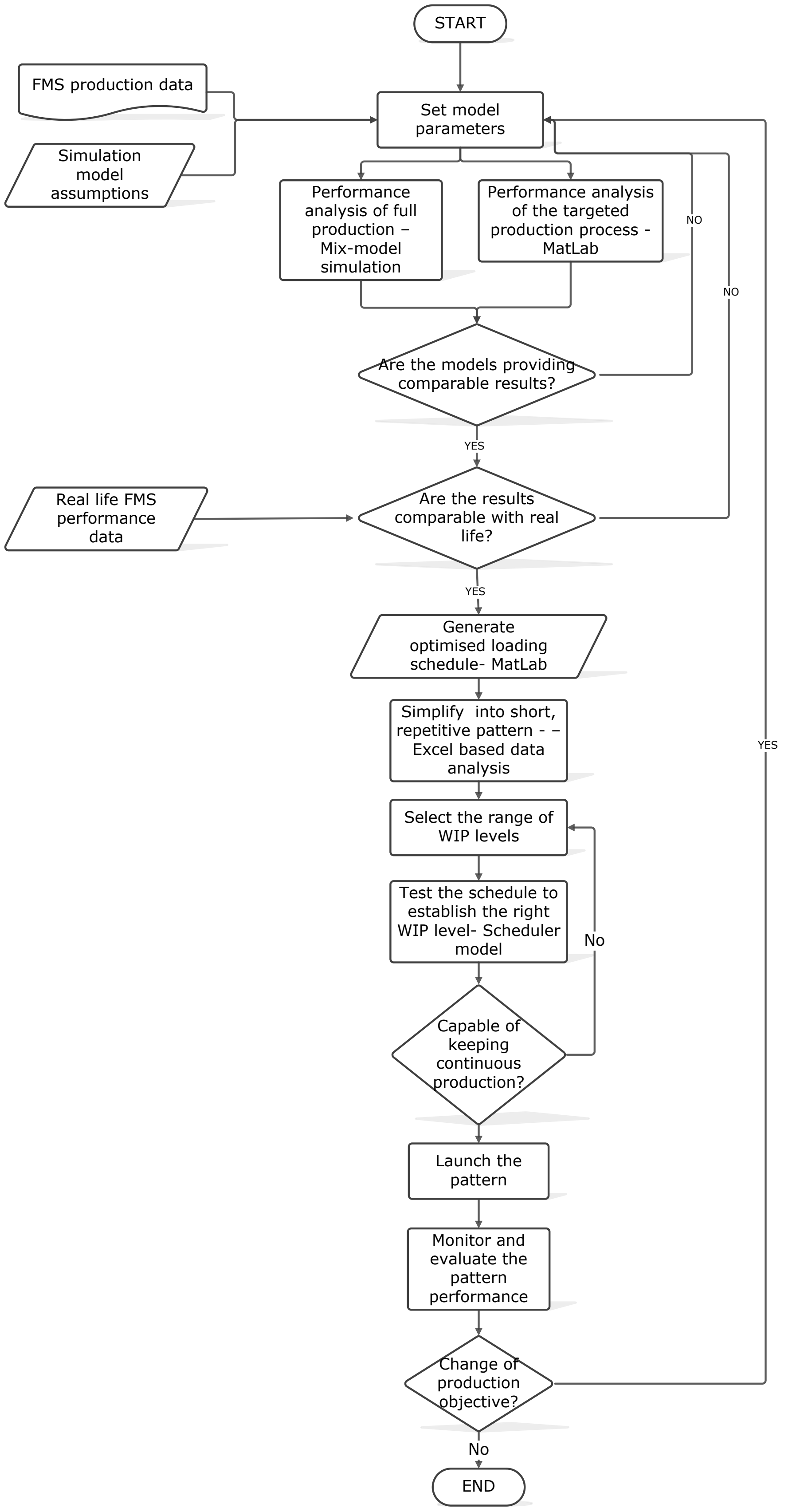


Figure 68 The framework for loading pattern generation and validation in FMS

8.3.1 **Parameter selection**

Parameters' selection helps to scope the boundary of modelling. Firstly, production data from FMS are collected to understand the current situation. For FMS scheduling, there are wide scoping possibilities. Therefore, when experimentation is carried out, it is important to consider the type of experimental set-up. The questions presented in Figure 69 allow to drive the variable selection for the simulation modelling. It links the requirements, data available and evaluation of usefulness to the results.

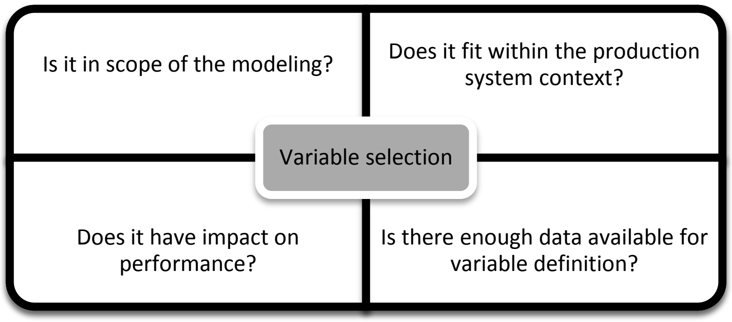


Figure 69 Questions for variable selection evaluation

8.3.2 **Calculation of overall system performance**

Next the capacity of the system is simulated with the use of DES, based on the whole system production to validate overall system production capacity. In parallel, MatLab model of the same FMS, analyses in detail, targeted production process and generates a schedule pattern associated with it. Model overlap is visualised in Figure 70.

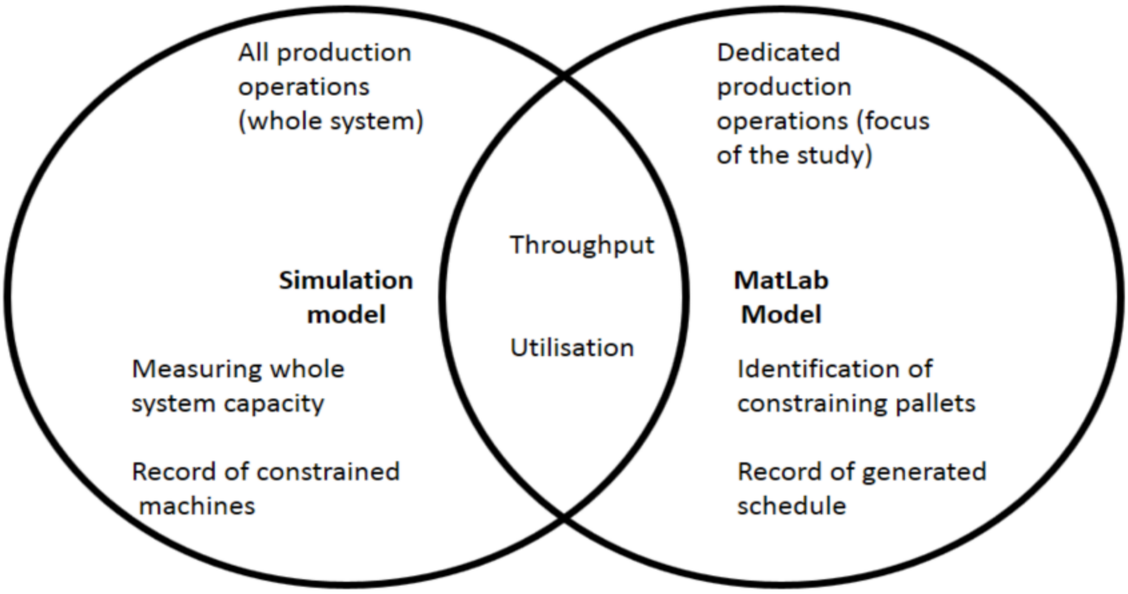


Figure 70 MatLab and DES - simulation models overlap

Both models focus on the same production system and share common datasets and scenarios; however, their objectives are different. In the simulation model, the aim is to understand the overall system capacity and any constraining elements; whereas MatLab model focuses on dedicated production mix, and aims to identify constraining pallets. The models can cross-reference the performance of the system as both models provide the same KPIs: machine utilisation and throughput. Results of both models are compared with real production data to verify their fit in terms of applicability to the studied system.

8.3.3 **Schedule generation**

The MatLab model has been designed to generate the schedule for FMS. After the model results have been validated, the schedule has been captured in the form of data-set. The provided data are then transformed into input pattern for scheduler model. Schedule generation has been part of wider research project and it is not included in this PhD work.

8.3.4 **Schedule evaluation with Scheduler**

The pattern generated in MatLab becomes an input schedule for the Scheduler model. The proposed model allows for testing the production capacity and throughput when applying different loading sequences to test their performance and establish an appropriate WIP level for the production system.

The model works on a simple set up process, similar to all simulation projects (as in Figure 71):

1. Set the parameters (choose the parameters that will be tested and the values of parameters)
2. Set simulation run (set up the simulation times horizon, warm-up time and starting parameters)
3. Run (select number of repetitions)
4. Collect the results (read results from excel file)

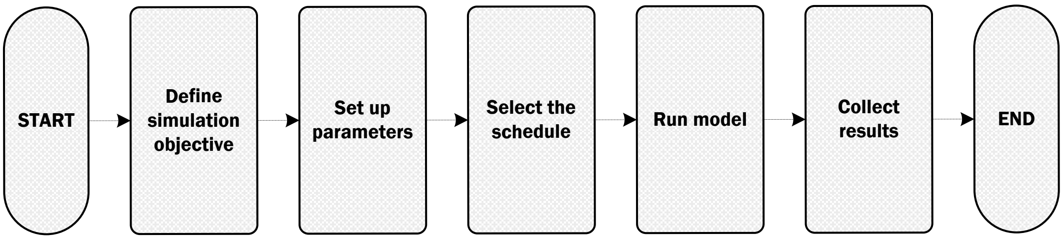


Figure 71 Simulation modelling for Scheduler

This process has been adapted for carrying out experiments with the use of the model.

After validating the schedule within a simulation environment, it is launched to the production line and tested in a real FMS system. In order to validate this approach, a case study of FMS scheduling has been carried out.

8.4 FMS scheduling case study

The case study of scheduling for automotive FMS has been introduced in this section. The simulation focuses on two variables that affect flow in FMS: schedule and WIP. This has been decided as schedule is considered main enabler for maximising production flow and WIP level regulates the flow rate.

8.4.1 **Case study context**

The case study focus on the FMS in automotive industry. Within the FMS, one part family production (A,B,C) has been a scheduling concern. After the production rate for parts A, B,C has been measured in the FMS, it was realised that the mean number loaded parts was 34 per week (as illustrated in Figure 72).

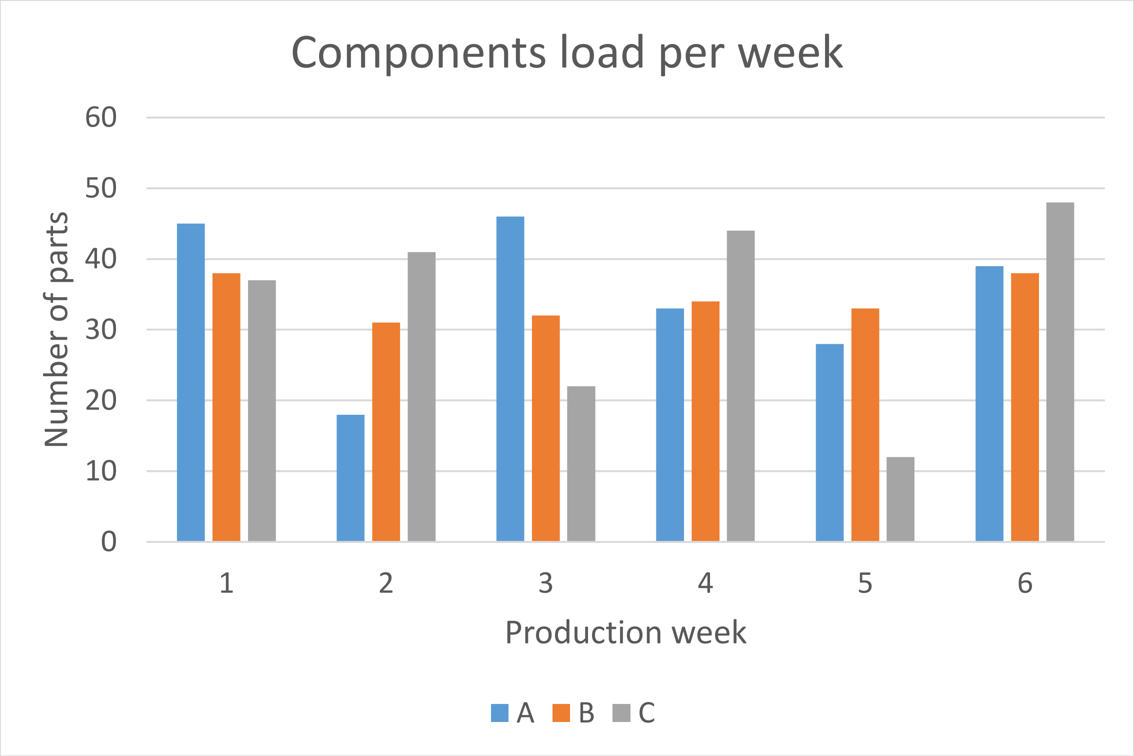


Figure 72 Load of parts in the FMS, based on company data

After investigation, it was ascertained that the full capacity had not been utilised due to the inconsistent and insufficient scheduling strategy dictated by the PLC. The loading at load station was driven by the internal PLC within the system, which was scheduling parts by due date objective. In consequence, the loading strategy prevented maximisation of production capacity as it followed the pattern illustrated in Figure 73.

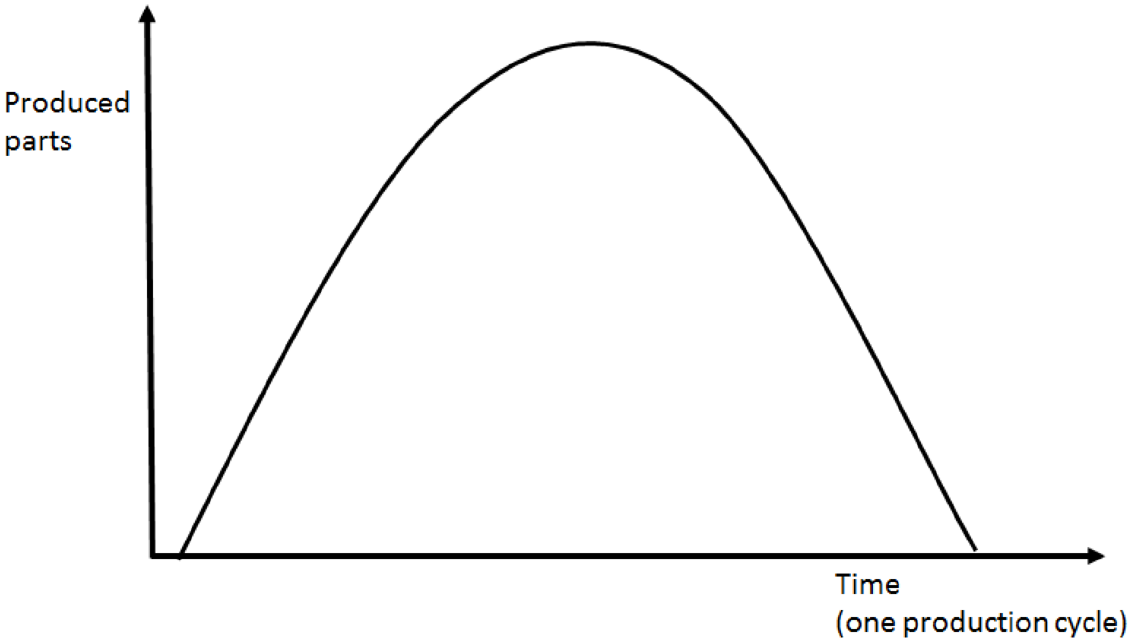


Figure 73 Production pattern achieved with use of PLC

To ensure production sustainability, the pattern should be able to deliver a consistent number of parts over time and maintain production at a sustainable continuous level. The concept of this is illustrated in Figure 74.

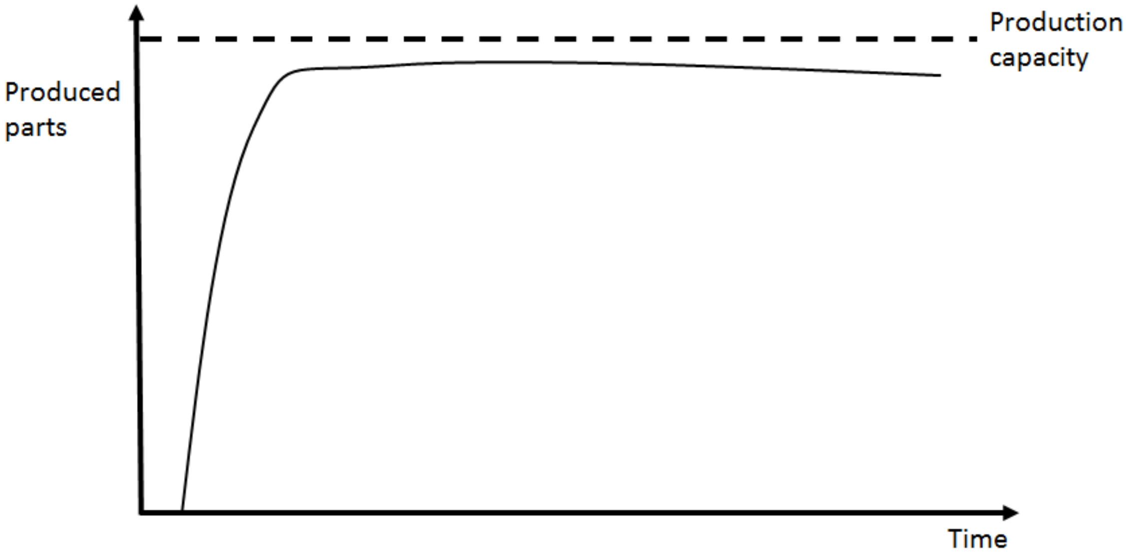


Figure 74 Production pattern for to-be production

With the use of the loading capacity calculation, it has been estimated that the production should be able to fulfil 57 engines per week based on historical production data (assuming: mean cycle times, infinite pallets, infinite tools, no downtime, no waiting for previous operations to complete). The FMS simulation approach was used, aiming to provide better schedule solution for the FMS.

8.4.2 **Parameter selection for FMS scheduling case study**

The model boundary is set to look at relationships between the WIP level and the schedule in relation to produced parts. The model represents the flexible manufacturing system, consisting of six CNC machines with dedicated operations. The model does not include workers, breakdowns, transportation of parts and setups. Table 49 defines the system boundary.

Table 48 FMS scheduling case study inclusion / exclusion of elements

Included in the model	Excluded from the model
3 types of parts	Labour
6 CNC machines connected by loading / unloading station	Statistical Breakdowns
WIP level buffers	Transportation of parts
Pallets allocated per operation	Set-up times

The model structure is presented in Figure 75. In the FMS model, the manufacturing process, scheduling mechanism, pallet allocation and WIP level control are the main building blocks. Several distinctive characteristics needed to be included to reflect the level of complexity: pallet system and part load, scheduling mechanism.

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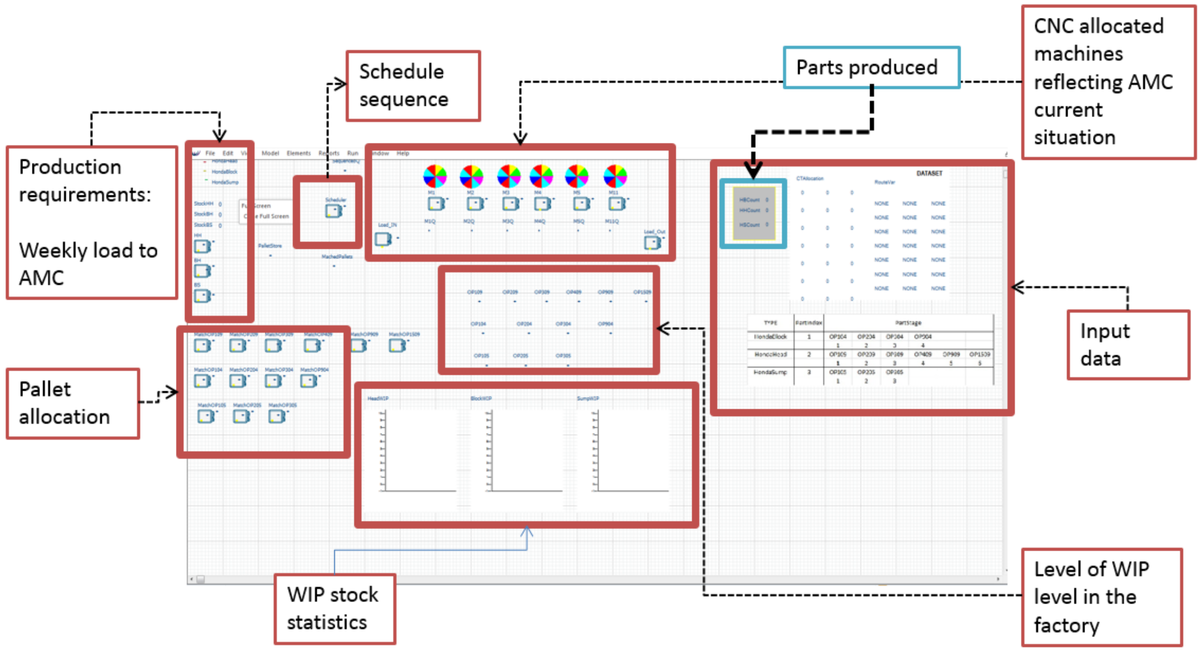


Figure 75 The scheduler model structure

8.4.2.1 Loading logic and pallet system

Part loading in the FMS is tied together with pallet allocation, as pallets are required for loading of every part in the system. Each operation requires pallets to carry parts from a particular machining task. The number of pallets is limited in the system, as well as, there are limited pallets per dedicated operation. As there is limited pallet availability, it can limit the system capacity if poorly managed. The pallet allocation per operation is summarised in Table 50.

Table 49 Pallet allocation to operations

OP No.	104	105	109	1509	204	205	209	304	305	309	409	904	909
No. of pallets	1	2	1	2	2	2	1	2	2	1	1	1	1

Also, the loading procedure is required to be captured in the valid way: it needs to be able to represent the actual pallet and part allocation to ensure real availability of pallets within the system. This relationship is demonstrated in Figure 76. Both pallet and part need to be present at load station to perform loading, part is taken away by MHR and moved to the appropriate machining operation; from there the MHR moves the part on the pallet back to loading station for unloading. The elements are separated, the pallet is made available for another operation and the part is allocated to go on the next consecutive operation assigned on the route.

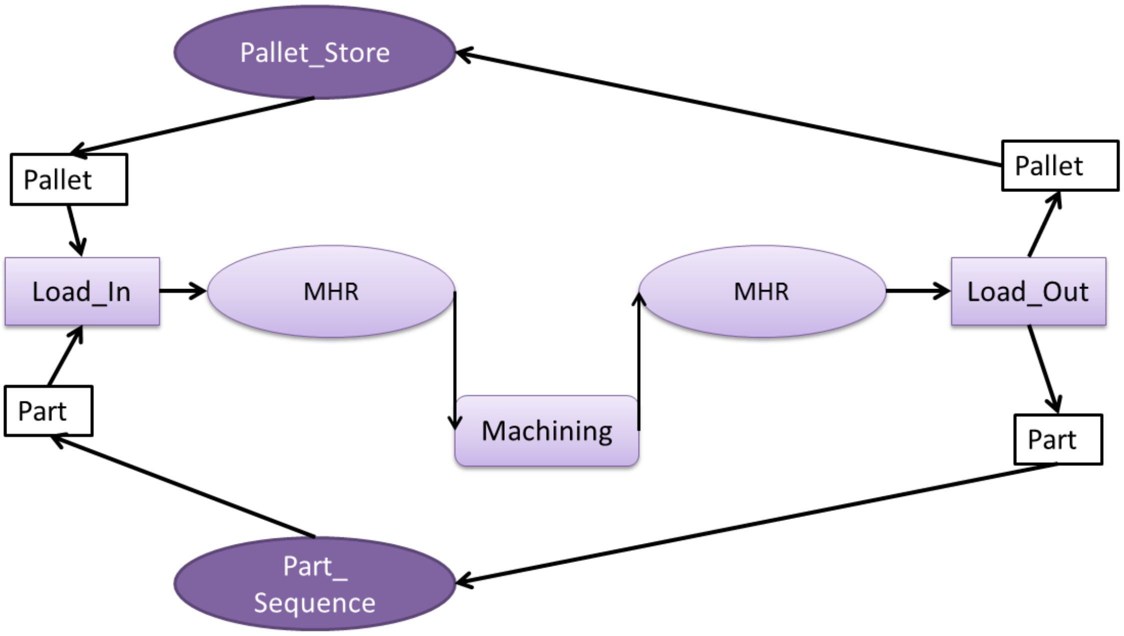


Figure 76 The conceptual model for parts production with limited pallets availability

8.4.2.2 Scheduling

Scheduling is a process where the sequence of flowing through the system is set-up. This process consists of establishing the decision-making points as well as rules of the flow. The aim of the modelling is to evaluate whether it is possible to achieve the production targets with the given schedule and the minimum WIP necessary to maintain the production rate.

The simulation aims to model three types of parts - A, B and C. The production requirement is to achieve balanced quantities and maintain continuous part load to the FMS. There are six main processing machines (M1, M2, M3, M4, M5, and M11) and the operations are dedicated to specific machines with strict requirement to follow the operation processes. The cycle times for the processes are not balanced across the production and the schedule for the production needs to take this variance into account. Tables 51 and 52 represent the part locations and cycle times per operation.

Table 50 The part allocation to machines for parts A,B,C

STAGE	A	B	C
1	M11	M3	M2
2	M3	M11	M2
3	M5	M1	M5
4	M1	M4	
5		M4	
6		M5	

Table 51 The cycle times for processing parts A,B,C

STAGE	A	B	C
1	94	84	59
2	90	65	84
3	50	94	52
4	50	52	
5		114	
6		19	

Next, each operation has been allocated an index number that will represent the operation in the simulation (represented in the Table 53). This allows to create (PartIndex, PartStage) relationship which will drive the simulation schedule. PartIndex represents the type of part, and PartStage represents the operation that needs to be performed. For example OP104 is represented by values (1,1) which means (Part A, Stage 1) and so on.

Table 52 Part index allocation for production set-up

TYPE	Part Index	Part Stage					
A	1	OP104	OP204	OP304	OP904		
		1	2	3	4		
B	2	OP109	OP209	OP309	OP409	OP909	OP1509
		1	2	3	4	5	6
C	3	OP105	OP205	OP305			
		1	2	3			

Additional complexity in production lays in the nature of the production process. In order to produce one full production, all three parts need to be available for assembly (A-B-C). This means that batch size production is not appropriate. Also, to be able to maximise the number of finished products, the balanced quantities need to be produced.

8.4.3 Calculation of performance for the FMS case study

The whole FMS system simulation has been run to foresee if the capacity will be constrained by other variables (i.e. number of pallets, operations flow, machine availability) for the scenarios considered (snapshot of results are presented in Appendix E).

Once this was validated as capable of production, the Matlab model simulation verified that 50 sets of engines (assuming 165-hour week) can be loaded in a system if the specific pattern is maintained.

8.4.4 **Schedule generation for the FMS case study**

The pattern is fed into the Scheduler model as a loading sequence. The example of generated pattern is provided in Table 54 The pattern addresses the production requirements (balanced parts production) and takes into account limitations (number of pallets).

Table 53 Loading pattern for the FMS generated by MatLab model

Loading Pattern	OP 209	OP 204	OP 909	OP 305	OP 309	OP 105	OP 109	OP 104	OP 304	OP 205	OP 904	OP 1509	OP 409

8.4.5 **Schedule evaluation for the FMS case study**

Based on the above set-up, MatLab model generated a schedule pattern. The schedule pattern was simulated in the DES based Scheduler. The objectives for generated schedule evaluation were to achieve balanced quantities of parts in production, fulfil the production order and to maintain minimum WIP level per operation. The parameters and responses for the simulation experimentation are summarised in Table 55.

Table 54 Model parameters and responses

Inputs	Experimental factors	Results
Weekly product load	Schedule sequence	Level of WIP
Number of fixtures per operation		Part-sets produced
WIP per operation	Degree of freedom for skipping schedule	
Shift time		

The production objective was to evaluate if the production targets can be fulfilled across one year production period. The planned demand was 40 parts over 5 days or 50 parts over 7 days with the WIP of 3 per operation. Two shifts and load to the production system were the main experimental factors set up. The simulation model ran for 10 production weeks (with warm-up time of one week) with no repetition as model was taking into account variable elements. The model started with the required level of WIP in the system at the simulation model. The experimental design is summarised in Table 56.

Table 55 Experimental design

Scenario	Load	Shift	WIP per operation	Fixtures
1	60	24//7	3	As defined in Table 37
2	50	24//7	3	
3	40	24//7	3	
4	60	24//5	3	
5	50	24//5	3	
6	40	24//5	3	

8.4.5.1 Results validation

Firstly, for the purpose of validation, the results of the industry loading capacity calculation have been compared with scenario 1, which corresponded to the expected loading system capability at no constraint level (summarised in Figure 77).

The comparisons have shown a match with the expected capacity loading. Machine 5 has displayed a slightly lower result because this machine processed operations for two part families, and one operation has been excluded from the simulation study as irrelevant to the examined part family.

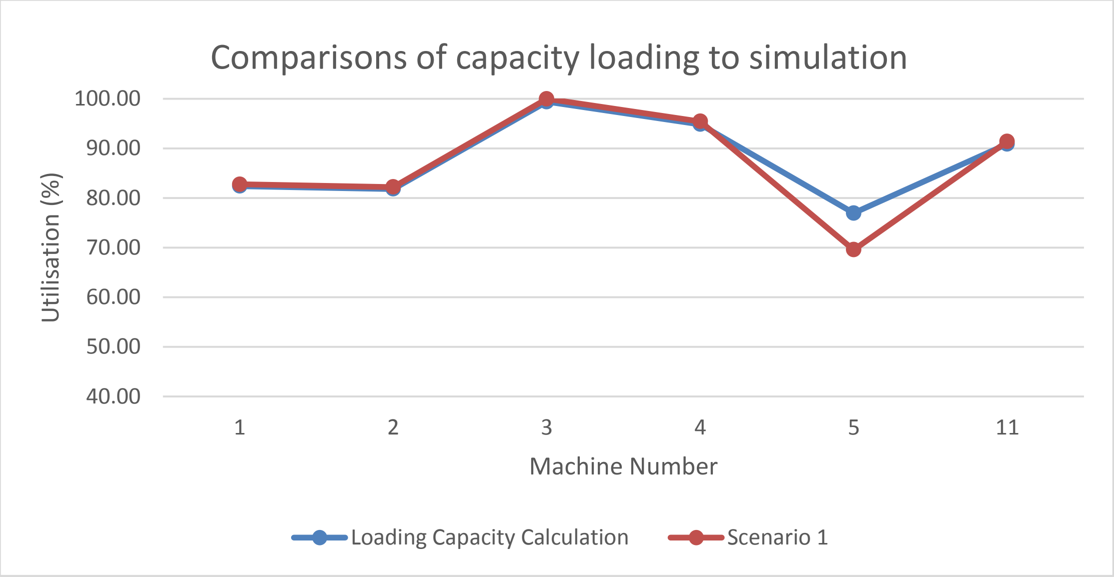


Figure 77 Comparisons of capacity loading to Scenario 1 simulation

They key evaluation elements were: the reflection of utilisation proportions in line balancing; and error between the simulated and expected utilisation. The results have been evaluated by the industrial partner, and it has been concluded that the level of error was acceptable. The results represented well the expert’s predictions as well as reflected the performance of the real system. This evaluation provided confidence in the simulation results.

8.4.5.2 Results for scheduling scenarios

As mentioned previously the aim of the experimentation was to evaluate the production schedule and WIP in terms of achievable capacity and throughput. The full simulation results for the scenarios are provided in Appendix F.

From the throughput experimentation (Figure 78), it is clear that in 24/5 shift maximum system throughput is 41 part-sets, as the throughput did not increase with the load. For 24/7 scenarios, it has been observed that loading increases proportionally, achieving maximum capacity of 58 part-sets.

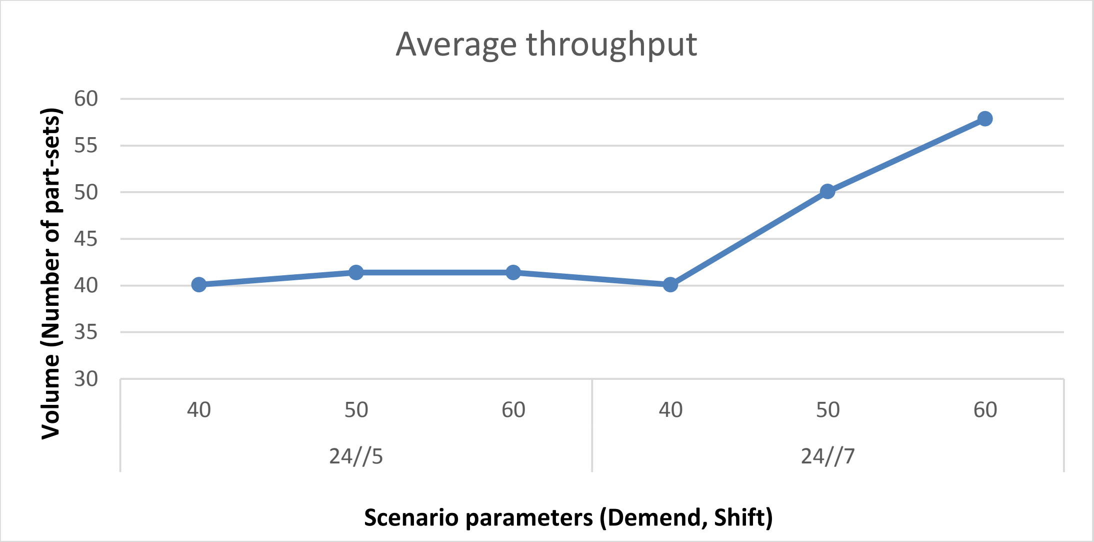


Figure 78 Average throughput per scenario experimentation

In the case of utilisation, the assumption was that no breakdowns and downtimes demonstrated the maximum potential system capability and this is not realistic view in the real life applications. Therefore, OEE of 65% for M5 and 90% for remaining machines has been considered as a safeguard against over expectation. Figure 79 represents the results for utilisation of machines in the experimented scenarios.

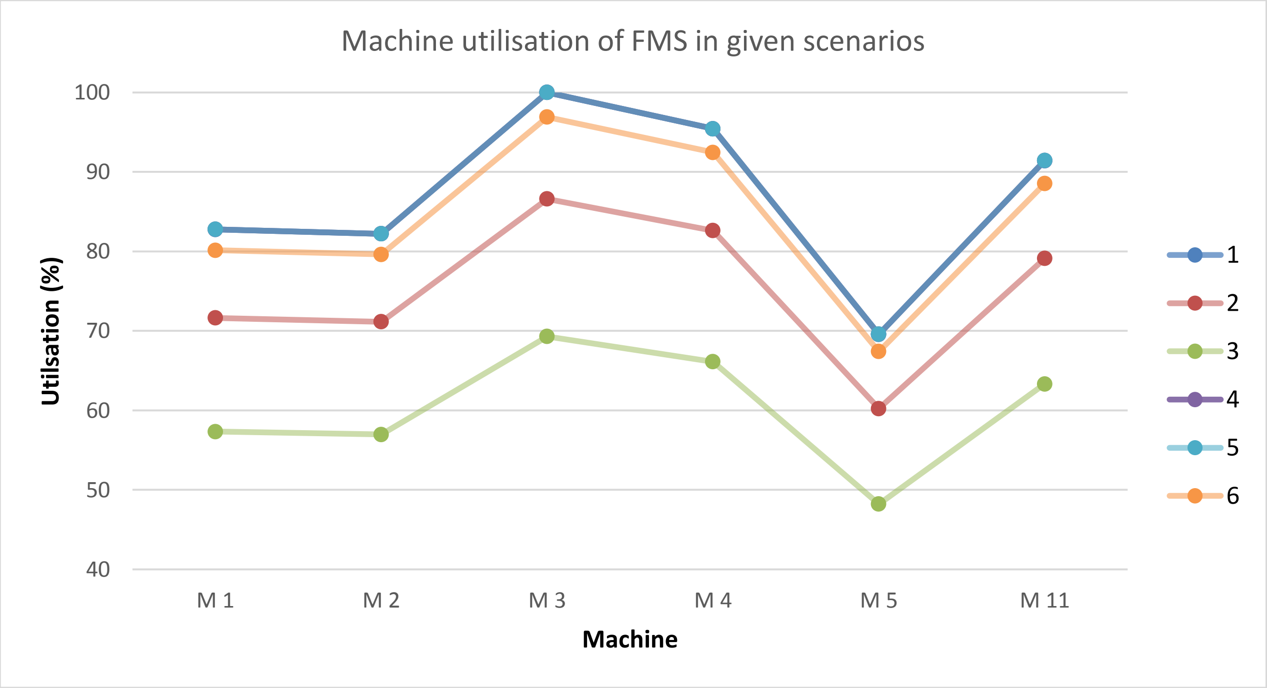


Figure 79 Results on percentage utilisation of FMS in given scenarios

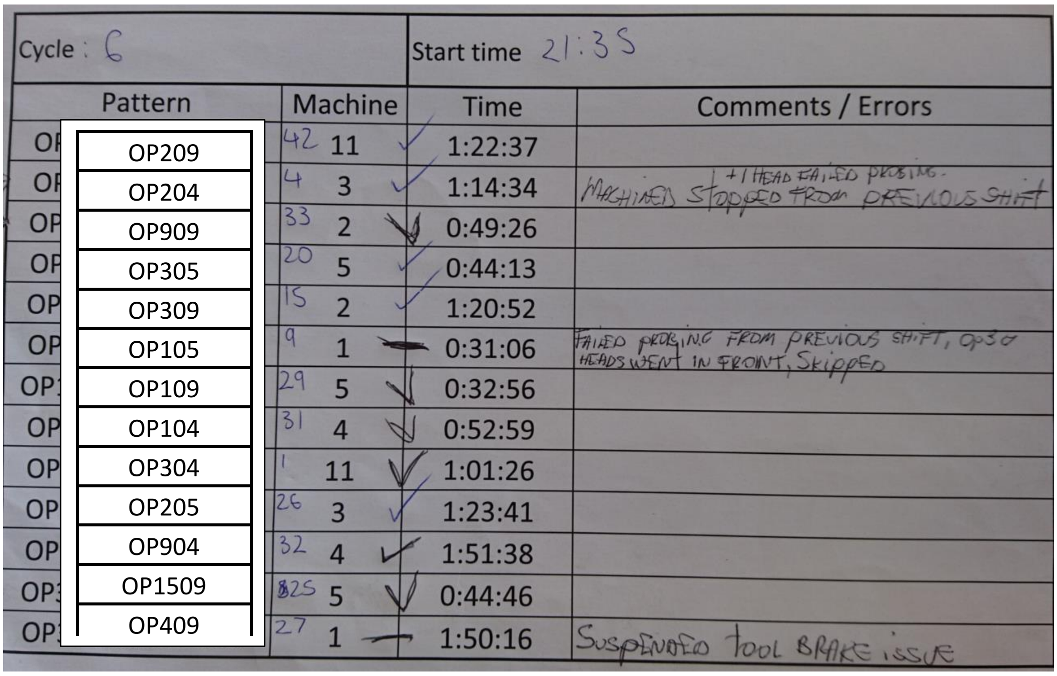
Scenario 6 evaluates load of 40 parts over 5 days. It is visible that M3 and M4 are the most utilised machines in the system and capable of producing on average 40 part sets per week. However, as machine utilisation was beyond 90% OEE it would be risky to assume that production could consistently deliver. This is especially true if breakdowns occur in M3, M4 and even M11. Scenario 4 and 5 display 100% utilisation in M3, suggesting a bottleneck in production affecting further machines utilisation. Although utilisation has increased, the output from the system did not increase.

Scenarios 3, 2 and 1 that focus on 24/7 shift. Increasing demand has shown consistent increase of utilisation and throughput. This demonstrated that the system capacity can deliver required throughput. As scenario 1 has reached 100% utilisation for M3, over 95% in M4 and over 69% utilisation on M5, it is considered unsafe for production utilisation level if downtime is required. Scenario 2 has been evaluated as acceptable within the established boundaries and scenario 3 has shown underutilisation of the system. Scenario 3 demonstrates the lowest overall utilisation, as the system has capability to deliver more parts in the current configuration.

It is a safe assumption that increasing machining provides more capacity. However, evaluation of the best production configuration depends on the balance of requirements and limitations of the system. The maximum capacity has been confirmed to be 58 part-sets per week in the 24/7 configuration. But, when assuming 60% OEE on M5 and 90% OEE on remaining machines, 50 part-sets is an achievable consistent production environment.

8.4.5.3 Validation of case study results

Once it is established that the pattern has capability to deliver 58 parts, the physical validation of the schedule has been performed. The test has been set-up on the FMS line and the schedule has been maintained for over 72 hours without disruption. The pattern has provided planned estimate to produce 1 engine set every 3 hours. The validation has been monitored through a designed pattern sheet (as illustrated in Figure 80) which has been a guidance for workers loading the parts to the FMS system. The maximum achieved capacity was 58 engines per week, when no downtime has been present.



Cycle : 6		Start time 21:35	
Pattern	Machine	Time	Comments / Errors
OP209	42 11 ✓	1:22:37	
OP204	4 3 ✓	1:14:34	MACHINED STOPPED FROM PREVIOUS SHIFT + 1 HEAD FAILED PROBING.
OP909	33 2 ✓	0:49:26	
OP305	20 5 ✓	0:44:13	
OP309	15 2 ✓	1:20:52	
OP105	9 1 —	0:31:06	FAILED PROBING FROM PREVIOUS SHIFT, OP30 HEADS WENT IN FRONT, SKIPPED
OP109	29 5 ✓	0:32:56	
OP104	31 4 ✓	0:52:59	
OP304	1 11 ✓	1:01:26	
OP205	26 3 ✓	1:23:41	
OP904	32 4 ✓	1:51:38	
OP1509	25 5 ✓	0:44:46	
OP409	27 1 —	1:50:16	SUSPENDED TOOL BRAKE ISSUE

Figure 80 Physical validation of sequence using pattern sheet

8.5 Discussion

Scheduling is one of the most important aspects in FMS, as the ability to reconfigure schedule can be a source of competitive advantage. Due to the levels of complexity in scheduling for FMS, decision support tools are needed to be able to fully utilise FMS potential. Within this chapter, an approach for scheduling for FMS with DES has been introduced and validated through an automotive case study.

During the development of the approach, the key activities for FMS scheduling in DES has been identified as: parameters definition, overall system capacity simulation, schedule generation and schedule evaluation. The understanding of key steps allowed definition of methods required for FMS scheduling with DES. The approach itself has been built based on experiences from previous simulation modelling, as well as industry requirements. The approach proposes use of three simulation tools; loading capacity model for system performance, MatLab model for schedule generation and DES Scheduler model for schedule verification. The reason why the three models were used together is in the cross-reference capability. By completing the first activity it was possible to define and verify the simulated environment. Based on the results from the first activity, it was possible to generate the schedule for the defined environment. Finally, by testing within the scheduler, it was possible to verify the schedule in a practical context – by testing the required schedule capability to withstand continuous production. Undergoing this process has built confidence in applying the proposed schedule in the FMS line with a successful result.

The amount of computation within this work has been very high, requiring collaboration of, not only researchers but also with the industrial sponsor. Aside from collaboration, there are other enablers required for the application of this approach. From a technical perspective, data confidence and careful DES model scoping are essential for applying this approach in an industrial context.

The future work for the research could focus on an in-depth study of disruptions on the FMS schedule. For example, once the schedule sequence has been established, there is possibility for investigation into the schedule resilience. In addition, investigation into the effect of FMS set-up change on pattern would be efforts in the area of FMS re-configurability. This work has been started and is included in Appendix G.

8.6 Summary

This chapter focused on proposing schedule testing method for FMS with use of DES. The scheduling parameters has been identified as a base of investigation. Approach for scheduling in FMS has been proposed and scheduler DES structure based on the findings from industry and literature has been constructed. In validation of the model, a case study of scheduling for FMS and pattern evaluation has been carried out and validated through application in the industrial production line.

9 Discussion and conclusions

This section focuses on discussion of findings and evaluation of the conceptual framework for FMS decision support. It covers the key research findings and considers their implications. Further, research contributions are outlined, research limitations are considered and discussed and finally, future work is suggested for developments in the field of FMS decision support.

9.1 Key research findings

Within this section key findings and its implications are outlined.

9.1.1 **Decision support for FMS with DES**

Whereas definition of FMS as a physical system is defined in literature (Kostal and Velisek, 2011); the definitions of FMS complexity have been diverse, depending on context. It has been found that FMS design is a complex research ground requiring different levels of detail and requirements, from multiple areas, of manufacturing operation and systems engineering.

DES has been known to be valuable tool in supporting decision-making in FMS, as it can capture and represent the nature of manufacturing systems in a format acceptable to researchers and manufacturers, providing the “picture” of the system at the right level of detail. Further, it provides a tool for testing and evaluating the “picture” at different levels.

A systematic literature review (SLR) has been performed, finding 67 papers relevant to decision support for FMS design using DES. The majority of case studies identified in the SLR have not been applied in industry. Few industrial case studies found have been very specific to the modelling objectives, reflecting the true picture of simulation requirements- they need to be focused and specific to be applicable. This PhD work has focused on provision of general conceptual framework for FMS design, focusing on key FMS elements as a basis of investigation. In addition, within this work unique case study was explored- automotive FMS line focused on mid-volume production.

From the literature, 16 FMS case studies have been identified and 51 manufacturing system case studies have been found relevant to the FMS context. For instance, AGV simulation has been found relevant to scheduling in FMS, whereas job shop simulation has been found useful for flexibility related exploration.

The main decision-making clusters discovered from the SLR are: strategy, layout testing, set-up configuration, scheduling, PLC control and methods in building simulation models. It has been found that set-up, flexibility and scheduling have strong cross-references in FMS modelling. These three aspects of FMS form building blocks for FMS design.

9.1.2 **Methods used in this PhD**

Conceptual framework (CF) has been found to be the appropriate form of capturing the concepts to support decision-making in FMS with DES. This visual form of conceptualisation allows for capturing different production elements, as well as considering different aspects of decision-making in a clear way. The CF has been described at a high level of abstraction. The purpose of it is to identify key areas for decision-making in FMS, and concentrate on needs of the system in detail in the applied context. Capturing requirements has been a key element in defining the key areas for decision-making in FMS. This stage allows to explore how available data and company requirements can set the context for FMS development. The reflection on this process is that there is need for overall FMS requirements definition, but also in every case study, requirements need to be evaluated and re-purposed to fit within the scope of simulation problem. This is captured in individual case studies.

Case studies have been found an appropriate means of studying decision-making for FMS with DES. The conceptual framework was constructed around conceptual modelling and simulation tools as means to structure case studies. The strength of this method was the ability to consider applied FMS context; and study it in depth to explore the requirements of decision-making and provide a structured method to reach informed decision-making options.

9.1.3 **Approach for data collection for FMS simulation**

The data collection and transformation have been present across the conceptual framework. Chapter 5 on data driven FMS simulation, addresses problems of data capture and transformation in simulation for FMS. The material handling robot (MHR) behaviour has been studied with videoing to capture machine behaviour and collect cycle times. Although understanding of MHR was not part of this PhD requirements, it served an excellent case study for testing approach for data collection from the shop floor.

It has been found that two types of data are required for simulation – conceptual behaviour of the system, as well as quantitative data that defines the behaviour in discrete time. The MHR behaviour has been coded using behavioural coding into “load” and “move” actions. Further, those actions have been captured and transformed into useful time distribution curves that could be used as cycle times in the simulation study. The case study of MHR in FMS has been built in simulation to test the collected data versus the estimated cycle times provided by industry. The results were compared against the industry standard tool – loading capacity analysis – proving that distribution-based cycle times achieved a better fit to estimated performance.

Although this case study considered one element of FMS, it has been important to model this accurately in the simulation. This is because the MHR has been identified as critical for production flow. In the case of a bottleneck, the whole system performance could deteriorate. The case study resulted in more accurate simulation modelling and building trust between the modeller and the industry, around the usefulness of the simulation for FMS decision-making. As this approach has not been used in FMS before, this case study has validated the data collection approach for FMS application.

As there is a lack of specific data collection methods for simulation, this approach provided a mechanism to record, systematise and test machine behaviour for simulation applications. The novelty of this approach lies in integration of data analysis to validate the required datasets, as well as using them to improve simulation results.

9.1.4 **DES-based approach for evaluation of production set-ups in FMS**

Chapter 6 explored the first step of conceptual framework considerations – the set-up of FMS production line. Set-up has been found to cover a wide range of elements in production systems, depending on modelling objectives; however; the common focus is on establishing the best physical system configuration. An approach for FMS set-up modelling with DES has been introduced and validated with the automotive case study. In the set-up case study, design of experiment was carried out, evaluating the best configuration between the number of machines, number of pallets and part sequence in the real FMS system. The optimal combination of the three parameters has been selected based on maximum throughput and machine utilisation. In addition, it has been discovered that sequencing has high impact on performance of FMS capacity. Further, miscalculating of the number of pallets in the system has high impact on FMS performance as its shortage can lead to FMS starvation, and its over provision creates bottlenecks (queues) in the system affecting throughput. Although decision making for set-up in FMS with DES has been studied before, it has not been considered in the applied automotive context.

9.1.5 **DES-based approach for addressing different levels of flexibility in FMS**

Flexibility in FMS has been explored in Chapter 7. For FMS there are multiple areas for exploring flexibility, as this is the main advantage over other production systems. Within the chapter, an approach for evaluating FMS flexibility with DES has been proposed and validated with an automotive case study. The focus of the case study has been on route flexibility, which has also been identified in the literature as the most impactful area of FMS capacity potential (Joseph and Sridharan, 2011a). A high level of complexity has been investigated in the FMS modelling as a range of system behaviours had to be captured: pallet system, mix-model part matrix and dedicated pallet allocation. The scenarios considered were fit for decision-making that has emerged from industry requirement to test possible production system routes. In this case, what-if analysis proved to be an appropriate tool for the experimentation. Three phases of experimentation have been done: exploration of pallet system in a free flow set up, comparing free flow versus dedicated line production and finally moving operations in dedicated scenarios.

The experimentation process has been emergent. This means that the first scenario acted as a validation and system performance benchmark. It focused on evaluation of capacity in FMS based on forecast production requirements. Further, Scenario 2 has compared improvement of performance in chosen set-ups. Subsequently once a dedicated line is chosen as a preferable option, the efforts are focused on testing if improvement could be made by moving operations across to different machines in Scenario 3. The findings from case study experimentation have been unexpected but insightful. Scenario 1 provides FMS capability of fulfilling demand requirements. Scenario 2 shows that although flexible production set-up provides better line balancing, it does not reflect better throughput. Further, in Scenario 3, moving the operation to a different machine has been tested at different demand rates. Even though the improvement was not achieved in this scenario, insights from modelling have provided understanding of system modus operandi and ensured that changes that intuitively seem to improve the system might not necessarily be doing so. This implies that simulation modelling for scenario testing could be essential in routing changes in FMS.

The challenge in model development in a flexibility case study was that there was a high level of complex behaviour included. As a consequence, it was very difficult to track the impact on performance of single variables. The model was effective in showing overall impact of parameter changes on throughput and utilisation.

Validation of the model has proven difficult, because there was a lack of real life or historical data for comparison, and at the same time, the level of complex behaviour in the model was preventing identifying elements that impact the system-level complex behaviours. For example, pallet availability and complex part routing could not be viewed separately. The model however proved a very useful tool for comparison of scenarios where there were no constraints (i.e.

breakdowns). Loading capacity for this model was only partial validation as the tool was not able to capture pallet limitation and therefore did not reflect the expected throughput results; it was able to provide indication of what maximum production was achievable in the set configurations.

The novelty of this approach is in provision of structured tactic for addressing flexibility levels in FMS across different flexibility measures. Although flexibility has been studied before, consideration of flexibility in stages to achieve improved system configuration has not been attempted before. The case study presented within this chapter is a demonstration of range of scenarios that was developed to demonstrate the approach application.

9.1.6 DES-based approach for testing schedules in FMS

Chapter 8 has focused on development of an approach for scheduling in FMS with the use of DES. From the case study in set-up, scheduling was identified to have a significant impact on FMS performance. In addition, among industrial challenges it has been shown to be an area of potential improvement. FMS scheduling approach has been proposed and validated in this chapter. A case study of automotive FMS schedule improvement has been a basis for validation. The approach allowed to cross-reference results from three simulation models (capacity model, scheduling model and schedule evaluation) to obtain confidence in the proposed scheduling sequence. Through the case study development it was possible to implement the prescribed schedule on the studied FMS line with successful resulted - the FMS production rate has been improved from 34 to 58 parts per week when no downtime was accounted.

As scheduling in FMS context is highly difficult due to the levels of complexity and nature of the FMS system, this novel approach focused on proposing schedule testing method for FMS with use of DES that can be cross-referenced with other tools to provide accurate schedules that are implementable in the production context.

9.2 Research contributions

The main research contribution of this study is to develop a decision support framework for FMS development with the use of DES. The framework development has been based on systematic literature findings and automotive industry requirements for FMS development. The proposed conceptual framework has been validated through the use of industrial case studies addressing framework components.

The sub-contributions that emerged from this PhD are:

1. Data collection method for accurate modelling of FMS in simulation
2. An approach for set-up evaluation in FMS
3. An approach for flexibility testing in FMS
4. As approach for scheduling testing in FMS

9.3 Conceptual framework development

The difficulty of this research was to capture the idea of defining the FMS at various levels to provide decision-making for FMS development with DES holistically. The conceptual framework acted as structured approach for FMS development, exploring the order of FMS design and development (what needs to be done first, second, etc.), as well as different objectives.

Set-up, flexibility and scheduling has been identified as the most cross-referenced areas. The FMS definition requires the coverage of a group of machines, loading/unloading station, material handling robot (MHR) and PLC system logic. Therefore, the assumption was that three key areas need to include the key system elements (set-up), as well as understanding their behaviour (flexibility) and order of flow (scheduling). Within the conceptual framework, those elements proved to be able to support decision-making of FMS development at different levels.

The conceptual framework is a flow chart to highlight the order of simulation studies required, as well as provide a clear visual communication tool. The framework remains a high-level snapshot of steps to consider while developing

FMS. The specification of each simulation element has been developed as a case study using simulation-modelling methods. Every case study has followed a defined set of methods. A conceptual model has been used as a building block in every case of the modelled environment. This allowed creation of a set of information where requirements, objectives and data could be systematised and communicated with the stakeholders.

The context for the decision support framework was the development of FMS system for an automotive company. The framework was tested through the development of case studies in different decision areas, which allowed in depth system understanding. The drawback of this approach is that the framework was tested on one industrial sector, so more extensive studies applied to other industries would be essential in the future. Other industries will have different manufacturing challenges with FMS.

Although the general areas for decision-making were established through systematic literature review, the order of decision-making is related to the context of the research. The FMS development process was reflected in simulation studies. The set-up was considered before the implementation of factory set-up and flexibility has been studied once machines have been installed and first parts has been proved in production process, whereas schedule has been studied once there was rump-up of production. Through case studies development, it has been proved that the order of simulation models development for decision-making is an appropriate assumption.

Throughout the conceptual framework development, it emerged that keeping the same KPIs for measuring FMS performance is a useful indicator for consistency of modelling and communication with industry. In case studies throughput and machine utilisation have been identified as main KPIs, as the focus of the case studies was directed at improvement of capacity in the FMS.

9.4 Data availability considerations

Data availability is essential for building effective simulation models. Moreover, trust in data and its validity for modelling is key to the usability of simulation studies in the industrial context. Within this PhD work, the level of accuracy in data has improved as the project progressed. From how simulation models have been developed, the level of accuracy has increased with the simulation development. Table 57 provides a reflection on how data and system modelling have emerged throughout the research. The set-up case study worked on assumptions and estimated data, due to the fact that no data was available. At the time of the flexibility case study development, some production data became available, as well as it was possible to view the production system behaviour and verify the modelling based on the observation. The scheduling case study was developed in a data-rich environment where many data sets were available and the system behaviour understanding was deep. The modelling process was improved, not only as data improved but also as understanding of system behaviour improved. The difficulties faced in model development have been a learning curve in model scoping. Consequently, at the scheduling case study, the simulation model has been sufficiently complex to capture the production behaviour.

Model	Set-up	Flexibility	Scheduling
Scope	Assumptions	Observed and estimated	Observed
Data	Estimated	Partially estimated	Historical/ Real time

Table 56 Relationship between data availability and system behaviour capture in simulation work

9.5 Validation

To ensure validity of the proposed conceptual framework, triangulation of multiple data have been used: systematic literature review as a basis for FMS building blocks, documentation from case studies to capture the requirements of FMS as well as operational data and project meetings where FMS practical implications have been captured. In order to ensure reliability of the research, every building block (case study) in the conceptual framework has had a defined research approach that has been guiding the research and ensuring the flow of information from case to case.

The conceptual framework validation has been done through case study approach. With emergent themes to form conceptual framework, it is possible to apply it in any FMS context. The conceptual framework considers FMS development as a process, focusing on important decision-making areas: set-up, flexibility and scheduling. From the case studies, it is evident that although the areas overlap, considering them separately provides insight into FMS behaviour and allows informed choices to be made. Within this PhD, the case studies have demonstrated the use of the conceptual framework in an automotive context, demonstrating that planned and emergent scenarios play equally important roles in the process.

Through the case studies, it has been verified that conceptual framework is a valid approach to support decision-making in FMS with the use of DES in the context of automotive production. The use of DES provides not only experimentation space for FMS but also builds understanding of system behaviour. This is key to operational decision-making.

9.6 Research limitations

This PhD study has been developed with the following limitations:

1. The PhD has considered only DES tools in supporting FMS decision-making. As one approach towards decision support has been explored, there is potential for other approaches and methods delivering FMS support. The SLR has found that hybrid models (set of approaches and methods) are popular research tools for FMS support, suggesting that other modelling approaches and tools could be appropriate for FMS support. Exploration of how other tools could support FMS decision-making within the key decision-making areas could be future research direction.
2. This PhD work has focused on studying one in-depth case study of FMS development in the automotive industry for framework validation through case studies. What has applied to automotive industries might not be appropriate for other industries. Therefore, testing the conceptual framework with different industries is a consideration for future research.

3. The simulation model development has been challenging from the modelling perspective. Due to a number of assumptions and simplifications, it was not possible to model all complexities prescribed from industry requirements. The scope had to be as relevant to the problem and objective of modelling as possible. Keeping it simple made it easier for modeller to communicate the model, as well as demonstrate valuable decision-making feedback. In consequence, some aspects of FMS could not be considered. For instance, in scheduling simulation the flexibility could be part of experimentation but in limited form as the computation time has been too long for experimentation.
4. Lack of operational data within the set-up case study made validation and verification of the results a difficult challenge. It was based on limited expertise within the company, as FMS was a novel environment. In order to ensure that model validation, advice from experts from external partner had to be acquired. Although useful, they could not be informed about the case study sensitive commercial details. As the models development progressed and the production have been ramping up, more understanding and data were available for validation of the models.

9.7 Future work

The current research landscape in DES and FMS is widening. Although separately both areas has been studied, there is limited number of studies on decision support in FMS development by DES. This research open up the opportunities for further development, This is also important as FMS based systems gain popularity in the UK in automotive industry. The conceptual framework does not consider the impact of disruptions on the FMS performance. Considering impact of disruptions on various aspects of FMS would deepen the understanding of sensitive performance parameters as well as support resilience of FMS in operational context.

As the conceptual framework has been tested within the automotive sector, future work should focus on validation of conceptual framework for other industries. Development of FMS in pharmaceutical sector could be another suitable application, for instance, in customised drug production (Personalized Medicine Coalition, 2017) where new manufacturing solutions are explored.

Another angle for extending the research could focus on the exploration of the methods for FMS development using other approaches and methods. DES has been successful in decision support for FMS development; however mixing methods could provide variety of benefits for FMS environment. For example, with use of DES and meta-modelling it would be possible to simplify experimentation in FMS development and provide faster results (Kumar and Sridharan, 2010). Also, looking at how FMS is advancing within Industry 4.0 concepts could make DES not suitable within certain contexts. For example, Ciufudean and Buzduga (2016) has looked into diagnosis on Internet of Things controlled FMS with Markov models based on discrete events.

Also, development of methods for improving data accuracy in simulation model development for decision support could be taken to another level. For example, research into linking the actual production data to simulation in a real time could provide capacity for instant system reconfiguration in case of breakdowns or other production disruptions. In addition, linking simulation with optimisation could speed up the reconfiguration of FMS processes (Song et.al, 2016).

9.8 Conclusions

Flexible manufacturing systems have the capability to provide efficient production plants, minimising resources and maximising capacity especially where there is a need for product range diversification. The benefits of FMS relay on the capability to configure a production line so it delivers the best performance for changing production requirements. However, making informed decisions about changing production can be difficult. Discrete event simulation is a tool that is capable of capturing complexity and constraints associated with FMS. The aim of this research is to develop a decision support framework for flexible manufacturing systems using discrete event simulation.

The research aim and objectives defined in Chapter 3 have been addressed as follows:

1. To develop a conceptual framework for the decision support in FMS using DES

The conceptual framework development process and definition is provided in Chapter 4. Its development has been addressed in three stages. Firstly, the systematic literature review and industrial input has provided a basis for identification of key decision-making areas for FMS development and for framework scoping. Secondly, the conceptual framework has been defined through discussions and industrial meetings and finally it has been evaluated though a case study approach.

2. To develop an approach for simulation of FMS based on the use of primary data collected from the industrial shop floor

This research objective has been addressed in Chapter 5 and it has focused on the development of a method for data collection for FMS simulation. The method has been evaluated through modelling MHR in FMS. A case study of MHR used in FMS has been developed where data from the factory floor has been collected through videoing, and then systematised and transformed to provide the most accurate data input for simulation. The study has been validated against capacity loading evaluation, resulting in achieving better data fit than estimated figures.

3. To develop a DES-based approach for evaluation of production set-ups in FMS

This research objective was met by demonstration and validation of a DES-based approach for set-up in FMS decision-making. It has been developed in Chapter 6 of this thesis. The approach has been outlined and validated with an industrial case study. A case study of an existing FMS system has been used to experiment with the number of machines, number of pallets and sequence to improve performance. The simulation provided an evidence based optimal configuration, as well as provided insights into understanding FMS behaviour.

4. To develop a DES-based appraoch for addressing different levels of flexibility in FMS

This research objective has been met by the development of an approach to address flexibility in FMS using DES. A mix-model simulation case study (described in Chapter 7) has been used for validation. What-if analysis had been used for a range of experimentation tailored to industrial FMS.

5. To develop a DES- based approach for testing schedules in FMS

This objective has been realised in Chapter 8. The approach for FMS scheduling with DES has been introduced and validated with the case study approach. A case study of industrial FMS has been considered where performance improvement through FMS scheduling has been demonstrated. Scheduling simulation has provided improvements in FMS performance.

6. To validate the conceptual framework and the proposed approaches through case studies on FMS

This objective has been met through demonstration of case studies developed in chapters 5-8, as well as reflection on conceptual framework development provided in section 9.3.

Through this research, the following contributions to knowledge have been discovered:

- There are three key building blocks for FMS development: set-up, flexibility and scheduling
- In every FMS case study, requirements for decision-making need to be evaluated and re-purposed to fit within the scope of simulation
- Through case studies, it has been confirmed that there are key parameters, such as routing and number of pallets, for capacity improvement in FMS
- A method for primary data collection based on videoing and behavioural coding has been introduced and validated
- DES based approaches for set-up, flexibility and scheduling in FMS have been introduced and validated

To sum up, this PhD work has contributed to the development of a systematic approach for decision-making for FMS development using DES. The approach provided tools for evidence-based decision-making in FMS.

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APPENDICES

APPENDIX	TITLE
A	DOE on MHR capacity
B	Capacity loading for validation of MHR scenarios
C	Set-up simulation results
D	2nd phase experimentation results on flexibility
E	Capacity loading for scenarios in Scheduler
F	Scheduler experimentation results
G	Machine utilisation dataset for breakdowns in scheduler model
H	Pattern testing scenario results

Appendix A DOE on MHR capacity

Table A1. MHR 1 Sigma Study; 2 movements per operation

Scenario	Load times	Unload	Move	A	B	C	D	E	F	G	H	Movement per operation	A-E Volume	F-H Volume	Total	Total CT	CT*Volume	Utilisation
1	15	15	10	6	4	2	2	3	4	5	2	2	680	1100	3560	40	142400	33%
2	22	15	10	6	4	2	2	3	4	5	2	2	680	1100	3560	47	167320	39%
3	29	15	10	6	4	2	2	3	4	5	2	2	680	1100	3560	54	192240	45%
4	15	22	10	6	4	2	2	3	4	5	2	2	680	1100	3560	47	167320	39%
5	22	22	10	6	4	2	2	3	4	5	2	2	680	1100	3560	54	192240	45%
6	29	22	10	6	4	2	2	3	4	5	2	2	680	1100	3560	61	217160	50%
7	15	29	10	6	4	2	2	3	4	5	2	2	680	1100	3560	54	192240	45%
8	22	29	10	6	4	2	2	3	4	5	2	2	680	1100	3560	61	217160	50%
9	29	29	10	6	4	2	2	3	4	5	2	2	680	1100	3560	68	242080	56%
10	15	15	17	6	4	2	2	3	4	5	2	2	680	1100	3560	47	167320	39%
11	22	15	17	6	4	2	2	3	4	5	2	2	680	1100	3560	54	192240	45%
12	29	15	17	6	4	2	2	3	4	5	2	2	680	1100	3560	61	217160	50%
13	15	22	17	6	4	2	2	3	4	5	2	2	680	1100	3560	54	192240	45%
14	22	22	17	6	4	2	2	3	4	5	2	2	680	1100	3560	61	217160	50%
15	29	22	17	6	4	2	2	3	4	5	2	2	680	1100	3560	68	242080	56%
16	15	29	17	6	4	2	2	3	4	5	2	2	680	1100	3560	61	217160	50%
17	22	29	17	6	4	2	2	3	4	5	2	2	680	1100	3560	68	242080	56%
18	29	29	17	6	4	2	2	3	4	5	2	2	680	1100	3560	75	267000	62%
19	15	15	24	6	4	2	2	3	4	5	2	2	680	1100	3560	54	192240	45%
20	22	15	24	6	4	2	2	3	4	5	2	2	680	1100	3560	61	217160	50%
21	29	15	24	6	4	2	2	3	4	5	2	2	680	1100	3560	68	242080	56%
22	15	22	24	6	4	2	2	3	4	5	2	2	680	1100	3560	61	217160	50%
23	22	22	24	6	4	2	2	3	4	5	2	2	680	1100	3560	68	242080	56%
24	29	22	24	6	4	2	2	3	4	5	2	2	680	1100	3560	75	267000	62%
25	15	29	24	6	4	2	2	3	4	5	2	2	680	1100	3560	68	242080	56%
26	22	29	24	6	4	2	2	3	4	5	2	2	680	1100	3560	75	267000	62%
27	29	29	24	6	4	2	2	3	4	5	2	2	680	1100	3560	82	291920	68%

Table A2. MHR 3 Sigma Study; 2 movements per operation

Scenario	Load times	Unload	Move	A	B	C	D	E	F	G	H	Movement per operation	A-E Volume	F-H Volume	Total	Total CT	CT*Volume	Utilisation
1	15	15	10	6	4	2	2	3	4	5	2	2	680	1100	3560	40	142400	33%
2	22	15	10	6	4	2	2	3	4	5	2	2	680	1100	3560	47	167320	39%
3	40	15	10	6	4	2	2	3	4	5	2	2	680	1100	3560	65	231400	54%
4	15	22	10	6	4	2	2	3	4	5	2	2	680	1100	3560	47	167320	39%
5	22	22	10	6	4	2	2	3	4	5	2	2	680	1100	3560	54	192240	45%
6	40	22	10	6	4	2	2	3	4	5	2	2	680	1100	3560	72	256320	59%
7	15	40	10	6	4	2	2	3	4	5	2	2	680	1100	3560	65	231400	54%
8	22	40	10	6	4	2	2	3	4	5	2	2	680	1100	3560	72	256320	59%
9	40	40	10	6	4	2	2	3	4	5	2	2	680	1100	3560	90	320400	74%
10	15	15	17	6	4	2	2	3	4	5	2	2	680	1100	3560	47	167320	39%
11	22	15	17	6	4	2	2	3	4	5	2	2	680	1100	3560	54	192240	45%
12	40	15	17	6	4	2	2	3	4	5	2	2	680	1100	3560	72	256320	59%
13	15	22	17	6	4	2	2	3	4	5	2	2	680	1100	3560	54	192240	45%
14	22	22	17	6	4	2	2	3	4	5	2	2	680	1100	3560	61	217160	50%
15	40	22	17	6	4	2	2	3	4	5	2	2	680	1100	3560	79	281240	65%
16	15	40	17	6	4	2	2	3	4	5	2	2	680	1100	3560	72	256320	59%
17	22	40	17	6	4	2	2	3	4	5	2	2	680	1100	3560	79	281240	65%
18	40	40	17	6	4	2	2	3	4	5	2	2	680	1100	3560	97	345320	80%
19	15	15	35	6	4	2	2	3	4	5	2	2	680	1100	3560	65	231400	54%
20	22	15	35	6	4	2	2	3	4	5	2	2	680	1100	3560	72	256320	59%
21	40	15	35	6	4	2	2	3	4	5	2	2	680	1100	3560	90	320400	74%
22	15	22	35	6	4	2	2	3	4	5	2	2	680	1100	3560	72	256320	59%
23	22	22	35	6	4	2	2	3	4	5	2	2	680	1100	3560	79	281240	65%
24	40	22	35	6	4	2	2	3	4	5	2	2	680	1100	3560	97	345320	80%
25	15	40	35	6	4	2	2	3	4	5	2	2	680	1100	3560	90	320400	74%
26	22	40	35	6	4	2	2	3	4	5	2	2	680	1100	3560	97	345320	80%
27	40	40	35	6	4	2	2	3	4	5	2	2	680	1100	3560	115	409400	95%

Table A3. MHR 1 Sigma Study; 3 movements per operation

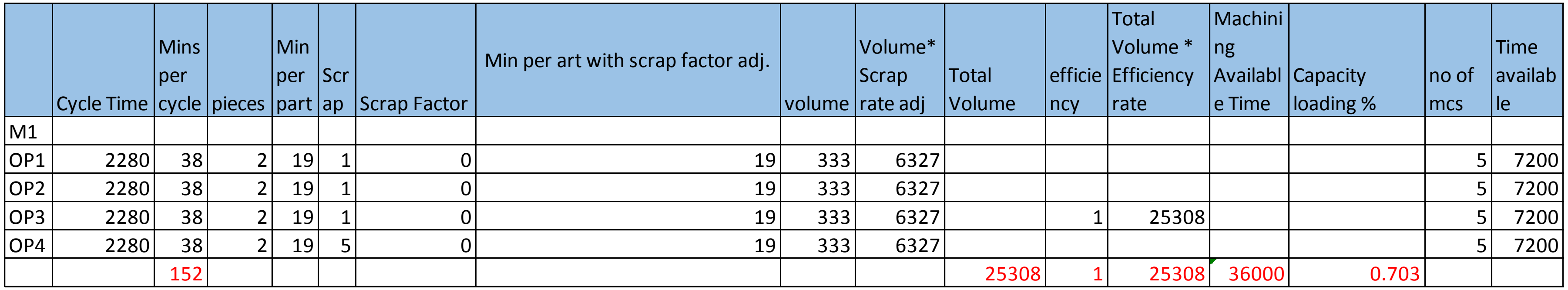
Scenario	Load times	Unload	Move	A	B	C	D	E	F	G	H	Movement per operation	A-E Volume	F-H Volume	Total	Total CT	CT*Volume	Utilisation
1	15	15	10	6	4	2	2	3	4	5	2	3	680	1100	5340	40	213600	49%
2	22	15	10	6	4	2	2	3	4	5	2	3	680	1100	5340	47	250980	58%
3	29	15	10	6	4	2	2	3	4	5	2	3	680	1100	5340	54	288360	67%
4	15	22	10	6	4	2	2	3	4	5	2	3	680	1100	5340	47	250980	58%
5	22	22	10	6	4	2	2	3	4	5	2	3	680	1100	5340	54	288360	67%
6	29	22	10	6	4	2	2	3	4	5	2	3	680	1100	5340	61	325740	75%
7	15	29	10	6	4	2	2	3	4	5	2	3	680	1100	5340	54	288360	67%
8	22	29	10	6	4	2	2	3	4	5	2	3	680	1100	5340	61	325740	75%
9	29	29	10	6	4	2	2	3	4	5	2	3	680	1100	5340	68	363120	84%
10	15	15	17	6	4	2	2	3	4	5	2	3	680	1100	5340	47	250980	58%
11	22	15	17	6	4	2	2	3	4	5	2	3	680	1100	5340	54	288360	67%
12	29	15	17	6	4	2	2	3	4	5	2	3	680	1100	5340	61	325740	75%
13	15	22	17	6	4	2	2	3	4	5	2	3	680	1100	5340	54	288360	67%
14	22	22	17	6	4	2	2	3	4	5	2	3	680	1100	5340	61	325740	75%
15	29	22	17	6	4	2	2	3	4	5	2	3	680	1100	5340	68	363120	84%
16	15	29	17	6	4	2	2	3	4	5	2	3	680	1100	5340	61	325740	75%
17	22	29	17	6	4	2	2	3	4	5	2	3	680	1100	5340	68	363120	84%
18	29	29	17	6	4	2	2	3	4	5	2	3	680	1100	5340	75	400500	93%
19	15	15	24	6	4	2	2	3	4	5	2	3	680	1100	5340	54	288360	67%
20	22	15	24	6	4	2	2	3	4	5	2	3	680	1100	5340	61	325740	75%
21	29	15	24	6	4	2	2	3	4	5	2	3	680	1100	5340	68	363120	84%
22	15	22	24	6	4	2	2	3	4	5	2	3	680	1100	5340	61	325740	75%
23	22	22	24	6	4	2	2	3	4	5	2	3	680	1100	5340	68	363120	84%
24	29	22	24	6	4	2	2	3	4	5	2	3	680	1100	5340	75	400500	93%
25	15	29	24	6	4	2	2	3	4	5	2	3	680	1100	5340	68	363120	84%
26	22	29	24	6	4	2	2	3	4	5	2	3	680	1100	5340	75	400500	93%
27	29	29	24	6	4	2	2	3	4	5	2	3	680	1100	5340	82	437880	101%

Table A4. MHR 3 Sigma Study; 3 movements per operation

Scenario	Load times	Unload	Move	A	B	C	D	E	F	G	H	Movement per operation	A-E Volume	F-H Volume	Total	Total CT	CT*Volume	Utilisation
1	15	15	10	6	4	2	2	3	4	5	2	3	680	1100	5340	40	213600	49%
2	22	15	10	6	4	2	2	3	4	5	2	3	680	1100	5340	47	250980	58%
3	40	15	10	6	4	2	2	3	4	5	2	3	680	1100	5340	65	347100	80%
4	15	22	10	6	4	2	2	3	4	5	2	3	680	1100	5340	47	250980	58%
5	22	22	10	6	4	2	2	3	4	5	2	3	680	1100	5340	54	288360	67%
6	40	22	10	6	4	2	2	3	4	5	2	3	680	1100	5340	72	384480	89%
7	15	40	10	6	4	2	2	3	4	5	2	3	680	1100	5340	65	347100	80%
8	22	40	10	6	4	2	2	3	4	5	2	3	680	1100	5340	72	384480	89%
9	40	40	10	6	4	2	2	3	4	5	2	3	680	1100	5340	90	480600	111%
10	15	15	17	6	4	2	2	3	4	5	2	3	680	1100	5340	47	250980	58%
11	22	15	17	6	4	2	2	3	4	5	2	3	680	1100	5340	54	288360	67%
12	40	15	17	6	4	2	2	3	4	5	2	3	680	1100	5340	72	384480	89%
13	15	22	17	6	4	2	2	3	4	5	2	3	680	1100	5340	54	288360	67%
14	22	22	17	6	4	2	2	3	4	5	2	3	680	1100	5340	61	325740	75%
15	40	22	17	6	4	2	2	3	4	5	2	3	680	1100	5340	79	421860	98%
16	15	40	17	6	4	2	2	3	4	5	2	3	680	1100	5340	72	384480	89%
17	22	40	17	6	4	2	2	3	4	5	2	3	680	1100	5340	79	421860	98%
18	40	40	17	6	4	2	2	3	4	5	2	3	680	1100	5340	97	517980	120%
19	15	15	35	6	4	2	2	3	4	5	2	3	680	1100	5340	65	347100	80%
20	22	15	35	6	4	2	2	3	4	5	2	3	680	1100	5340	72	384480	89%
21	40	15	35	6	4	2	2	3	4	5	2	3	680	1100	5340	90	480600	111%
22	15	22	35	6	4	2	2	3	4	5	2	3	680	1100	5340	72	384480	89%
23	22	22	35	6	4	2	2	3	4	5	2	3	680	1100	5340	79	421860	98%
24	40	22	35	6	4	2	2	3	4	5	2	3	680	1100	5340	97	517980	120%
25	15	40	35	6	4	2	2	3	4	5	2	3	680	1100	5340	90	480600	111%
26	22	40	35	6	4	2	2	3	4	5	2	3	680	1100	5340	97	517980	120%
27	40	40	35	6	4	2	2	3	4	5	2	3	680	1100	5340	115	614100	142%

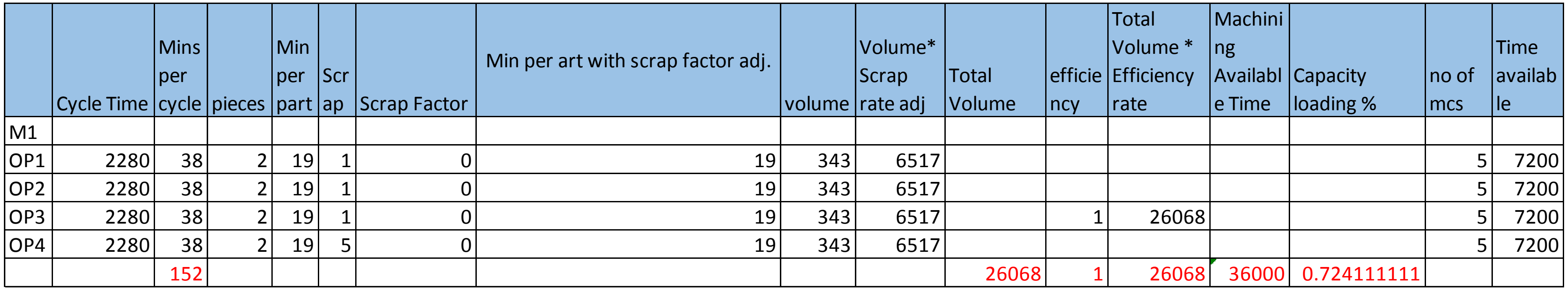
Appendix B Loading capacity for validation of MHR scenarios

Table B1. Loading capacity for MHR at Volume = 333



	Cycle Time	Mins per cycle	pieces	Min per part	Scrap	Scrap Factor	Min per art with scrap factor adj.	volume	Volume* Scrap rate adj	Total Volume	efficiency	Total Volume * Efficiency rate	Machining Available Time	Capacity loading %	no of mcs	Time available
M1																
OP1	2280	38	2	19	1	0	19	333	6327						5	7200
OP2	2280	38	2	19	1	0	19	333	6327						5	7200
OP3	2280	38	2	19	1	0	19	333	6327		1	25308			5	7200
OP4	2280	38	2	19	5	0	19	333	6327						5	7200
		152								25308	1	25308	36000	0.703		

Table B2. Loading capacity for MHR at Volume = 343



	Cycle Time	Mins per cycle	pieces	Min per part	Scrap	Scrap Factor	Min per art with scrap factor adj.	volume	Volume* Scrap rate adj	Total Volume	efficiency	Total Volume * Efficiency rate	Machining Available Time	Capacity loading %	no of mcs	Time available
M1																
OP1	2280	38	2	19	1	0	19	343	6517						5	7200
OP2	2280	38	2	19	1	0	19	343	6517						5	7200
OP3	2280	38	2	19	1	0	19	343	6517		1	26068			5	7200
OP4	2280	38	2	19	5	0	19	343	6517						5	7200
		152								26068	1	26068	36000	0.724111111		

Appendix C Set-up simulation results

Table C1. Results for Set-up simulation

Scenario	Parameters			Results		
No.	Sequence	Number of pallets	Number of machines	Average Throughput	M1 Utilisation %	M2 Utilisation %
Base Case	1	3	4	310	99.8	75.6
1	2	3	4	167	60.9	42.8
2	1	2	4	231	74.1	56.1
3	2	2	4	167	61.2	44.7
4	1	4	4	310	99.9	75.7
5	2	4	4	153	58.6	41.9
6	1	3	3	233	100.0	56.7
7	2	3	3	167	80.9	44.8
8	1	2	3	218	93.6	53.1
9	2	2	3	167	81.2	45.5
10	1	4	3	233	99.9	56.7
11	2	4	3	167	80.4	44.8

Appendix D 2nd phase experimentation results

Dedicated machines scenario

Table D1. Utilisation for dedicated machines scenario

UTILISATION	% of Busy from available time
M2	77.78
M3	91.67
M4	82.78
M6	55.83
M7	94.44
M8	88.88
M9	87.50
M10	62.02
M11	84.99
M1	89.44
M5	81.59

Table D2. Throughput for dedicated machines scenario

Name	No Entered	No. Shipped	No. Scrapped	WIP
BH	1520	720	0	80
BH1	1520	720	0	80
CH	760	0	0	40
DH	760	0	0	40
DH1	760	0	0	40
FV	3894	3026	0	868
KV	1947	1513	0	434
KV1	1947	1513	0	434
Order fulfilment rate for H			95%	
Order fulfilment rate for V			78%	

Free flow for OP 10 on all parts

Table D3. Utilisation for free flow for OP 10 on all parts scenario

UTILISATION	% of Busy from available time
M2	93.45
M3	89.05
M4	89.40
M6	75.18
M7	94.44
M8	88.88
M9	87.50
M10	50.47
M11	35.56
M1	89.44
M5	79.74

Table D4. Throughput for free flow for OP 10 on all parts scenario

Name	No Entered	No. Shipped	No. Scrapped	WIP
BH	1520	746	0	28
BH1	1520	746	0	28
CH	760	0	0	14
DH	760	0	0	14
DH1	760	0	0	14
FV	3898	2688	0	1210
KV	1949	1344	0	605
KV1	1949	1344	0	605
Order fulfilment rate for H			98%	
Order fulfilment rate for V			69%	

Appendix E Loading capacity for scenarios in Scheduler

DATA

UTILISATION	Name	% Busy	% Off-Shift	% Idle	No. Of Operations
M2	M1(1)	55.95	28.57	15.48	2000
M3	M1(2)	68.25	28.57	3.17	2000
M4	M1(3)	64.97	28.57	6.46	1997
M6	M1(4)	33.73	28.57	37.7	2500
M7	M1(5)	60.52	28.57	10.91	2500
M8	M1(6)	64.48	28.57	6.94	5000
M9	M1(7)	67.46	28.57	3.97	2500
M10	M1(8)	51.59	28.57	19.84	2500
M11	M1(9)	62.7	28.57	8.73	2000
M1	M2(1)	56.26	28.57	15.17	1998
M5	M2(2)	54.7	28.57	16.72	5498

TIME 26weeks

Engines

Name	No Entere	No. Shippe	No.Scrappe	WIP
BH	2000	991	0	18
BH1	2000	991	0	18
CH	1000	0	0	9
DH	1000	0	0	9
DH1	1000	0	0	9
FV	5000	5000	0	0
KV	2500	2500	0	0
KV1	2500	2500	0	0
Order fultilment rate Honda			99%	
Order fultilment rate Victoria			100%	

Assumptions

100% availability on machines

No scrap

ony CMM that is o the critical path

CT for machining from 24/06/2016

5 days/week

Pallets as currently available 26/06/2016

Figure E1. 40 parts on 24/5 shift scenario

DATA

UTILISATION	Name	% Busy	% Off-Shift	% Idle	No. Of Operations
M2	M1(1)	69.94	1.79	28.27	2500
M3	M1(2)	85.32	1.79	12.9	2500
M4	M1(3)	81.45	1.79	16.77	2503
M6	M1(4)	33.73	1.79	64.48	2500
M7	M1(5)	60.52	1.79	37.7	2500
M8	M1(6)	64.48	1.79	33.73	5000
M9	M1(7)	67.46	1.79	30.75	2500
M10	M1(8)	51.59	1.79	46.63	2500
M11	M1(9)	78.37	1.79	19.84	2500
M1	M2(1)	70.44	1.79	27.78	2500
M5	M2(2)	66.48	1.79	31.73	6252

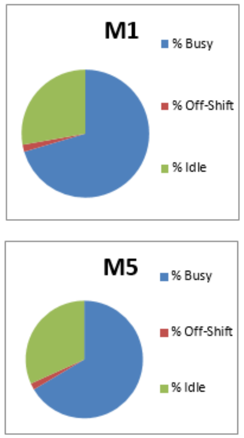
TIME 26 weeks

Engines

Name	No Enterec	No. Shippe	No.Scrappec	WIP
BH	2514	1252	0	10
BH1	2514	1252	0	10
CH	1257	0	0	5
DH	1257	0	0	5
DH1	1257	0	0	5
FV	5000	5000	0	0
KV	2500	2500	0	0
KV1	2500	2500	0	0
Order fultilment rate Honda			100%	
Order fultilment rate Victoria			100%	

Assumptions
100% availability on machines
No scrap
ony CMM that is o the critical path
CT for machining from 24/06/2016
7 days/week
Pallets as currently available 26/06/2016

5 AXIS



4 AXIS

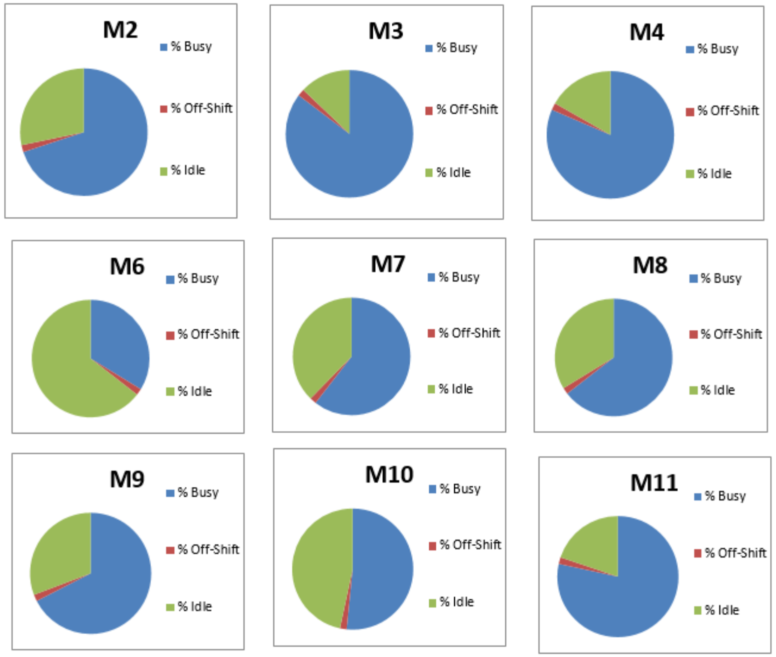


Figure E2. 50 parts on 24/7 shift scenario

Appendix F Scheduler experimentation results

Table F1. Average utilisation results

Scenario	Load	Shift	WIP	M1	M2	M3	M4	M5	M11
1	60	24//7	3	82.76	82.21	100	95.43	69.57	91.41
2	50	24//7	3	71.64	71.16	86.6	82.62	60.23	79.12
3	40	24//7	3	57.33	56.96	69.31	66.13	48.21	63.33
4	60	24//5	3	82.77	82.22	100	95.44	69.58	91.42
5	50	24//5	3	82.77	82.22	100	95.44	69.58	91.42
6	40	24//5	3	63.33	57.33	56.96	69.31	66.13	48.21

Table F2. Average throughput – simulation results

Scenario	Load	Shift	WIP	A	B	C
1	60	24//7	3	57.8	57.8	57.9
2	50	24//7	3	50.1	50.1	50.1
3	40	24//7	3	40.1	40.1	40.1
4	60	24//5	3	41.4	41.4	41.4
5	50	24//5	3	41.4	41.4	41.4
6	40	24//5	3	40.1	40.1	40.1

Appendix G Future work for FMS scheduling simulation

FMS Scheduler further scenarios - breakdowns

Base scenario, from case study presented in chapter 8.5 has been used, but this time the experimental design has focused on impact of breakdowns on production system performance. Previous assumptions were using assumed OEE as utilisation benchmark for assessing the solutions whereas in this case study breakdown distribution data are used.

The specific machines used in production were new and limited data has been available, however through expert feedback and historical production data from different manufacturing plant with similar production set up it has been possible to identify breakdown rate as well as repair time that can be applied in the simulation model. The breakdown distribution was set to be negative exponential distribution at average rate on 270 minutes [NegExp(270)]. Repair rate has been based on data from industry sourced from similar in profile manufacturing plant and it is presented in Figure G1. The assumptions made for this case study limit machines actual availability by around 8-10% per machine reflecting the idea of having machines working on 90% OEE.

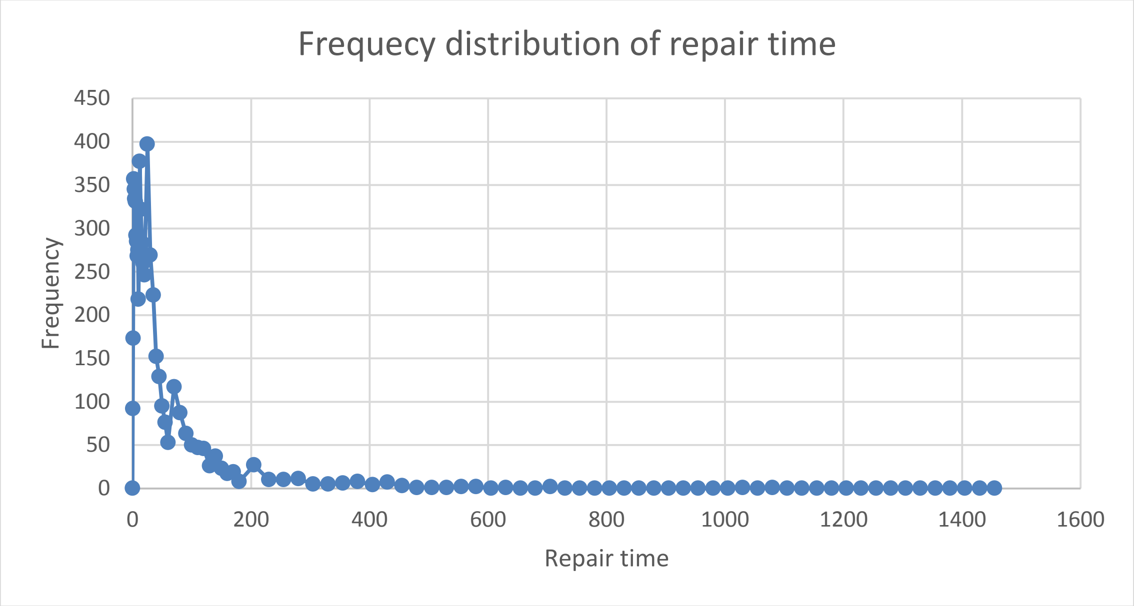


Figure G1. Frequency distribution for repair time

The run scenarios are the same as in Table 56 – experimental design in section 8.6. The difference for the modelling has changed as there is a variable elements in the model- it is stochastic in nature. This means that replication is required and 50 replication of each scenario has been performed. Standard deviation of the responses is measured to observe the variance in the responses.

The model has been run for 26 weeks of production with no warm up time and the model starts with WIP of 3 parts in the system (through using ImportState function). The experimenter in WITNESS simulation software has been used to carry out experiments. The results were visually verified through sensitivity analysis on parameters. The example of visual verification on part B has been illustrated in Figure G2.

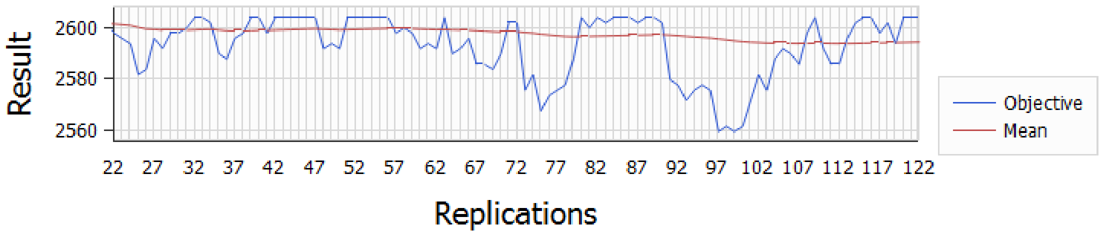


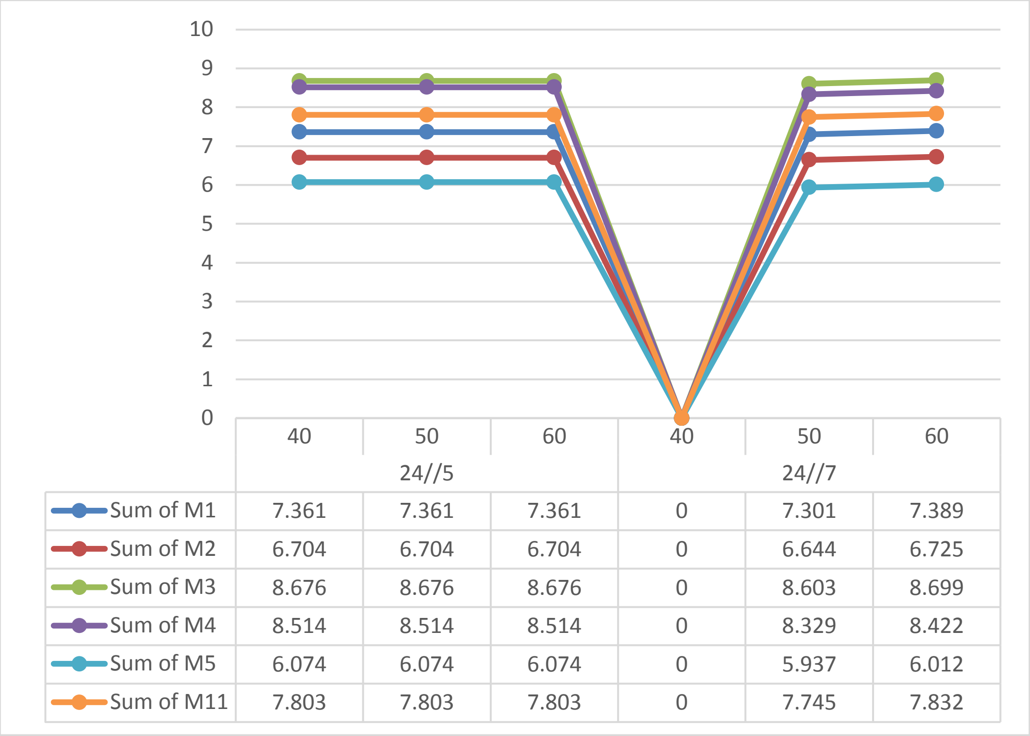
Figure G2. Visual verification of parameters showcased on part B total throughput.

The results from weekly throughput the simulation provide very low standard deviation (from 0 – 0.3) suggesting that the simulation runs results has been very consistent from run to run (table G1).

Table G1. Parts production results per week (for 50 scenarios)

Parameters			A			B			C		
DOE	Shift	Demand	**Mean**	**SD**	**Best**	**Mean**	**SD**	**Best**	**Mean**	**SD**	**Best**
1	24//5	40.0	33.8	0.3	34.4	33.8	0.3	34.4	33.9	0.3	34.4
2	24//5	50.0	33.8	0.3	34.4	33.8	0.3	34.4	33.9	0.3	34.4
3	24//5	60.0	33.8	0.3	34.4	33.8	0.3	34.4	33.9	0.3	34.4
4	24//7	40.0	40.1	0.0	40.1	40.1	0.0	40.1	40.1	0.0	40.1
5	24//7	50.0	49.9	0.1	50.1	49.9	0.1	50.1	50.0	0.1	50.1
6	24//7	60.0	50.5	0.3	51.2	50.5	0.3	51.2	50.6	0.3	51.2

As expected with use of breakdowns the output of the parts has decreased with additional limitation (Figure G3) suggesting that with overall breakdown rates of 6-9% in all machines the maximum load for 24/7 scenarios is 50 part-sets on average. The interesting finding is that in 24/5 scenarios due to availability and pattern use 33 part-sets on average are maximum what is possible to achieve within that production set-up.



	40	50	60	40	50	60
	24//5			24//7		
Sum of M1	7.361	7.361	7.361	0	7.301	7.389
Sum of M2	6.704	6.704	6.704	0	6.644	6.725
Sum of M3	8.676	8.676	8.676	0	8.603	8.699
Sum of M4	8.514	8.514	8.514	0	8.329	8.422
Sum of M5	6.074	6.074	6.074	0	5.937	6.012
Sum of M11	7.803	7.803	7.803	0	7.745	7.832

Figure G3. Machine utilisation in breakdown state for breakdown scenarios

Machines utilisation data (Figure G4) demonstrate that in 24/5 scenarios as limit of throughput has been restrained the machine utilisation stays the same (and standard deviation for each machine remains the same – Figure 85). Within 24/7 scenarios with when load is 40 the capacity of the system is not fully used and as WIP does not build beyond unnecessary limit the SD is 0. In scenarios considering demand of 50 and 60 parts, the system reaches close to the maximum load and build-up of WIP in the system causes the SD to increase with the increase of load. Nonetheless, standard deviation for machine utilisation (in variance of time) within the system remains small (from 0 – 0.66

minutes per machine) suggesting very consistent results pool within this simulation experimentation.

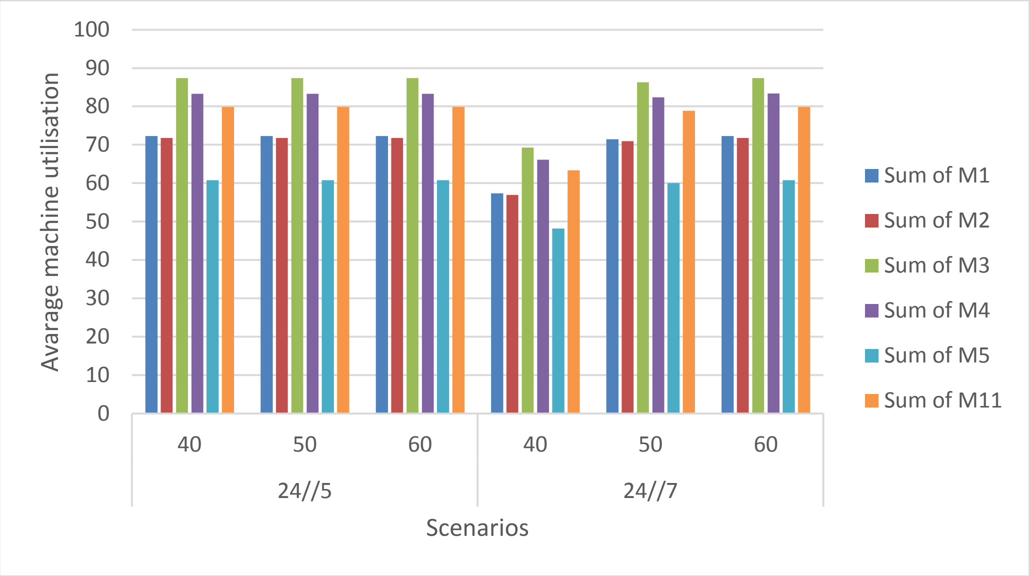


Figure G4. Machine utilisation in busy state for breakdown scenarios

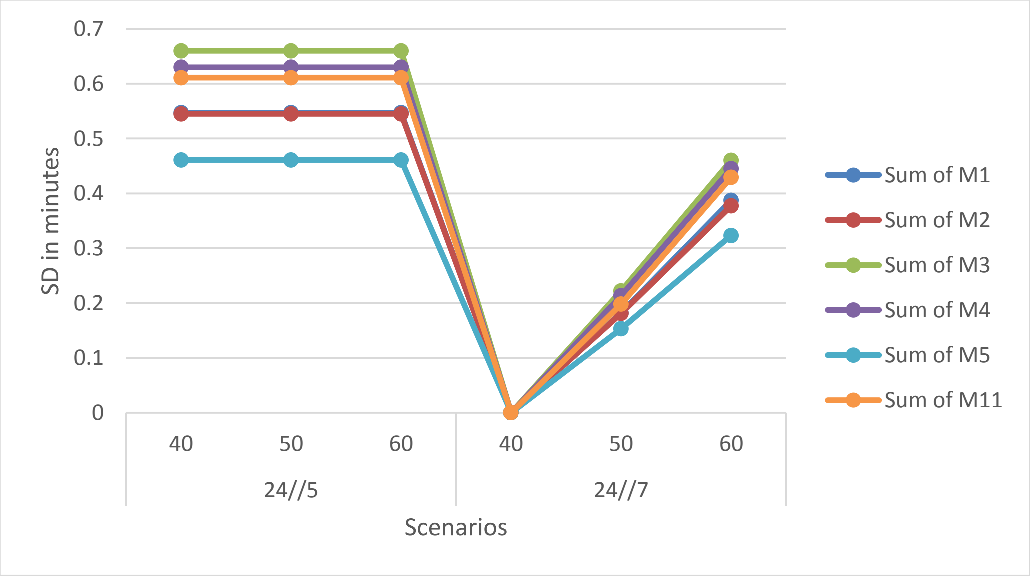


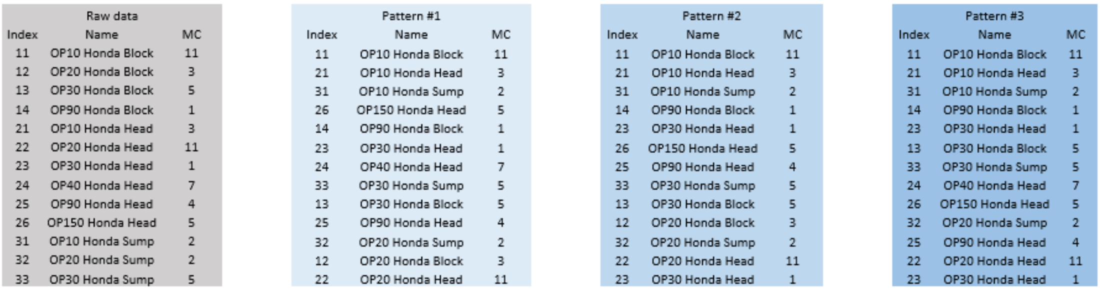
Figure G5. Standard deviation for machine utilisation busy state for breakdown scenarios (in time units)

In case of scenario of production of 40 parts over 24/7 shift, the production is not affected by breakdowns as plenty of time is available for production of required part-sets (Figure G5). This also means that WIP is minimal, not creating queues or bottlenecks. On the downside, the system is not efficiently used and highest utilised machine (M3) reaches under 70% of utilisation.

The general observation from adding additional constraint to the simulation system provides insight into how the system is behaving under such constraints. In case of breakdowns overall the throughput has decreased significantly from 40 to 33 in 24/5 scenarios and from 57 to 50 in 24/7 scenarios corresponding to 82.5% and 87.7% of previous production capacity suggesting that less than 6-9% overall breakdown rate in FMS can have impact on 12-17.5% decrease in throughput. As FMS system need to deliver things in coordination, breakdowns will have greater impact on production performance.

Further scenarios- pattern testing and moving operations

The second avenue of testing the scenarios has raised from looking at pattern robustness in the simulation when there is requirement to change operations to different machines. The scenario has been provided by the industrial sponsor as a test of planned operational change of moving OP409 to additional machine (M6). From the MatLab model 3 additional patterns has been provided (as seen in Figure G6). Base pattern used in initial case study was used as a benchmark and four additional patterns has been tested. Raw data was referring to the critical path pattern following parts from in part relevant production sequence and the three additional patterns has been generated by MatLab simulation.



Raw data

Index	Name	MC
11	OP10 Honda Block	11
12	OP20 Honda Block	3
13	OP30 Honda Block	5
14	OP90 Honda Block	1
21	OP10 Honda Head	3
22	OP20 Honda Head	11
23	OP30 Honda Head	1
24	OP40 Honda Head	7
25	OP90 Honda Head	4
26	OP150 Honda Head	5
31	OP10 Honda Sump	2
32	OP20 Honda Sump	2
33	OP30 Honda Sump	5

Pattern #1

Index	Name	MC
11	OP10 Honda Block	11
21	OP10 Honda Head	3
31	OP10 Honda Sump	2
26	OP150 Honda Head	5
14	OP90 Honda Block	1
23	OP30 Honda Head	1
24	OP40 Honda Head	7
33	OP30 Honda Sump	5
13	OP30 Honda Block	5
25	OP90 Honda Head	4
32	OP20 Honda Sump	2
12	OP20 Honda Block	3
22	OP20 Honda Head	11

Pattern #2

Index	Name	MC
11	OP10 Honda Block	11
21	OP10 Honda Head	3
31	OP10 Honda Sump	2
14	OP90 Honda Block	1
23	OP30 Honda Head	1
26	OP150 Honda Head	5
25	OP90 Honda Head	4
33	OP30 Honda Sump	5
13	OP30 Honda Block	5
12	OP20 Honda Block	3
32	OP20 Honda Sump	2
22	OP20 Honda Head	11
23	OP30 Honda Head	1

Pattern #3

Index	Name	MC
11	OP10 Honda Block	11
21	OP10 Honda Head	3
31	OP10 Honda Sump	2
14	OP90 Honda Block	1
23	OP30 Honda Head	1
13	OP30 Honda Block	5
33	OP30 Honda Sump	5
24	OP40 Honda Head	7
26	OP150 Honda Head	5
32	OP20 Honda Sump	2
25	OP90 Honda Head	4
22	OP20 Honda Head	11
23	OP30 Honda Head	1

Figure G6. Patterns required for testing

Additionally, new cycle time data has been given (see table G2).

Table G2. Cycle time updated (data from the company)

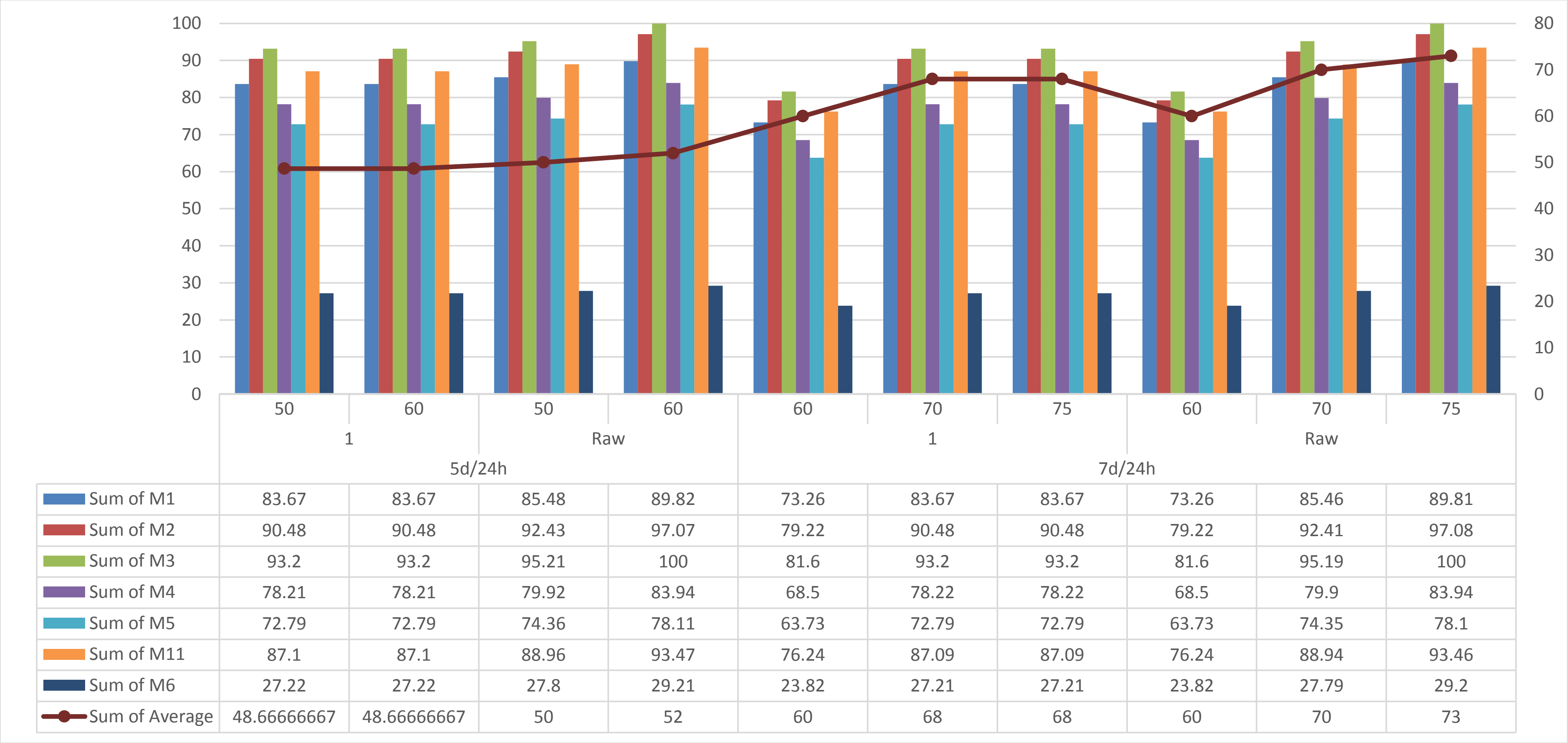
Enter start	20/11/2016 18:00				
Enter finish	21/11/2016 10:00				
Machine	Operation	Pallet time (h:mm:ss)	Pallet time (Dec)	MC Loading (h:mm:ss)	MC Loading (Dec)
Machine 1	OP30 BH	1:25:32	85.53	2:02:30	122.49
Machine 1	OP90 DH	0:36:58	36.96		
Machine 2	OP10 DH1	0:51:27	51.46	2:12:17	132.28
Machine 2	OP20 DH1	1:20:49	80.82		
Machine 3	OP20 DH	1:18:26	78.43	2:16:22	136.36
Machine 3	OP10 BH	0:57:56	57.93		
Machine 6	OP40 BH	0:39:08	39.13	2:34:00	154.00
Machine 4	OP90 BH	1:54:52	114.87		
Machine 5	OP30 DH1	0:39:47	39.78	2:09:12	129.21
Machine 5	OP51 KV Assy	0:09:14	9.23		
Machine 5	OP30 DH	0:41:19	41.31		
Machine 5	OP150 BH	0:25:02	25.03		
Machine 6	OP50 KV Assy	0:41:05	41.09		
Machine 7	OP30 KV	1:05:43	65.71		
Machine 8	OP20 KV1	0:31:49	31.82		
Machine 8	OP30 KV1	0:27:00	27.00		
Machine 9	OP20 KV	1:02:48	62.80		
Machine 10	OP70 KV Assy	0:47:05	47.08		
Machine 11	OP10 DH	1:23:29	83.48	2:07:29	127.48
Machine 11	OP20 DH	0:44:00	44.00		

The experimentation for this case study has focus on pattern robustness and therefore breakdowns were not considered. The experiment design has been designed in 19 experiments starting from looking at base pattern generated in the first case study and following the 4 patterns looking a different demand and shift patterns (table G3).BASE experiments were considered a basic benchmark to ensure that experimentation set-up is correct and further experiments focused on different scenarios considerations. The experiments were set-up based on the emerging results from previous experimentation – for example decision has been made to not consider further scenarios with shift 24/5 and demand above 60 in Raw pattern as the utilisation of M3 has already reached 100% and therefore maximum capacity has been achieved in the configuration.

Table G3. Experiment design for pattern testing

Experimental design					
Run	**OPS**	**Run time (weeks)**	**Demand**	**Shift**	**Pattern**
1	STANDARD	26	50	7d/24h	BASE
2	STANDARD	26	50	5d/24h	BASE
3	OPH40 from M4 to M6	26	50	5d/24h	BASE
4	OPH40 from M4 to M6	26	50	7d/24h	BASE
5	OPH40 from M4 to M6	26	50	5d/24h	Raw
6	OPH40 from M4 to M6	26	60	5d/24h	Raw
7	OPH40 from M4 to M6	26	60	7d/24h	Raw
8	OPH40 from M4 to M6	26	70	7d/24h	Raw
9	OPH40 from M4 to M6	26	75	7d/24h	Raw
10	OPH40 from M4 to M6	26	50	5d/24h	1
11	OPH40 from M4 to M6	26	60	5d/24h	1
12	OPH40 from M4 to M6	26	60	7d/24h	1
13	OPH40 from M4 to M6	26	70	7d/24h	1
14	OPH40 from M4 to M6	26	75	7d/24h	1
15	OPH40 from M4 to M6	26	50	5d/24h	2
16	OPH40 from M4 to M6	26	50	5d/24h	3

17	OPH40 from M4 to M6	26	50	5d/24h	3
18	OPH40 from M4 to M6	26	50	5d/24h	3



	5d/24h				7d/24h					
	1		Raw		1			Raw		
	50	60	50	60	60	70	75	60	70	75
Sum of M1	83.67	83.67	85.48	89.82	73.26	83.67	83.67	73.26	85.46	89.81
Sum of M2	90.48	90.48	92.43	97.07	79.22	90.48	90.48	79.22	92.41	97.08
Sum of M3	93.2	93.2	95.21	100	81.6	93.2	93.2	81.6	95.19	100
Sum of M4	78.21	78.21	79.92	83.94	68.5	78.22	78.22	68.5	79.9	83.94
Sum of M5	72.79	72.79	74.36	78.11	63.73	72.79	72.79	63.73	74.35	78.1
Sum of M11	87.1	87.1	88.96	93.47	76.24	87.09	87.09	76.24	88.94	93.46
Sum of M6	27.22	27.22	27.8	29.21	23.82	27.21	27.21	23.82	27.79	29.2
Sum of Average	48.66666667	48.66666667	50	52	60	68	68	60	70	73

Figure G7. Results from experimentation visualisation

The experimental results has demonstrated that pattern 2 and 3 are not able to maintain continuous production due to missing operations, which prevented production of part-sets. Adjustment of the patterns to accommodate the missing operations could rectify that, however it has not been possible during the experimentation. Therefore, Raw pattern and Pattern 1 has been suitable for further analysis (Figure G7 and Table G4). In scenarios considering 24/5 shift maximum throughput has been achieved with Raw pattern with M3 becoming a bottleneck for the system suggesting maximum achievable capacity of 52. On the other hand, in this configuration Pattern 1 is only capable of outputting maximum of 48 part-sets per week regardless the demand. In scenarios considering 24/7 shift Raw pattern performs better than Pattern 1 with maximum throughput achieved as 73 part-sets versus 70. This is significant for decision-making as it demonstrates how decision making in scheduling has impact on the factory performance.

Table G4. Utilisation statistics

Run	Demand	Shift	Pattern	M1	M2	M3	M4	M5	M11	M6
5	50	5d/24h	Raw	85.48	92.43	95.21	79.92	74.36	88.96	27.8
6	60	5d/24h	Raw	89.82	97.07	100	83.94	78.11	93.47	29.21
7	60	7d/24h	Raw	73.26	79.22	81.6	68.5	63.73	76.24	23.82
8	70	7d/24h	Raw	85.46	92.41	95.19	79.9	74.35	88.94	27.79
9	75	7d/24h	Raw	89.81	97.08	100	83.94	78.1	93.46	29.2
10	50	5d/24h	1	83.67	90.48	93.2	78.21	72.79	87.1	27.22
11	60	5d/24h	1	83.63	90.48	93.2	78.21	72.79	87.1	27.22
12	60	7d/24h	1	73.26	79.22	81.6	68.5	63.73	76.24	23.82
13	70	7d/24h	1	83.67	90.48	93.2	78.22	72.79	87.09	27.21
14	75	7d/24h	1	83.67	90.48	93.2	78.22	72.79	87.09	27.21

By moving OP409 to additional machine, the system has gained more capability in terms of utilisation. It is visible however that Raw pattern use provides higher overall system utilisation for maximum throughput but at demand set at 60 in 7/24 scenario both patterns perform the same utilisation and throughput. It can be concluded that load of 60 parts within this configuration is sustainable in production.