



**OPTIMIZATION-BASED SIMULATION ALGORITHM FOR  
PREDICTIVE-REACTIVE JOB-SHOP SCHEDULING OF  
RECONFIGURABLE MANUFACTURING SYSTEMS**



**TAN JOE YEE**

**MASTER OF SCIENCE**

**2022**



**Faculty of Manufacturing Engineering**



**Tan Joe Yee**

**Master of Science**

**2022**

**OPTIMIZATION-BASED SIMULATION ALGORITHM FOR PREDICTIVE-  
REACTIVE JOB-SHOP SCHEDULING OF RECONFIGURABLE  
MANUFACTURING SYSTEMS**

**TAN JOE YEE**



**Faculty of Manufacturing Engineering**

**UNIVERSITI TEKNIKAL MALAYSIA MELAKA**

**2022**

## DECLARATION

I declare that this thesis entitled “Optimization-Based Simulation Algorithm for Predictive-Reactive Job-shop Scheduling of Reconfigurable Manufacturing Systems” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature



Supervisor Name : DR. ENG. PREL AZRUL AZWAN BIN AHMAD RAHMAN, LEND

Date

Signature :



Name :

TAN JOE YEE

Date :

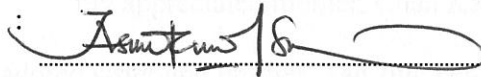
05/11/2022

اونيورسي تيكنيكل مليسيا ملاك  
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

## APPROVAL

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Master of Science.

Signature



Supervisor Name : IR. DR. -ING. AZRUL AZWAN BIN ABDUL RAHMAN CENG

Date

: 05/11/2022



## DEDICATION

Only

my beloved father, Tan Chee Kong

my appreciated mother, Chan Kam Ling

my adored sister and brother, Tan Jun Yen and Tan Joe Ven

for giving me moral support, encouragement and also understandings.



## ABSTRACT

Manufacturing industry is now moving forward rapidly towards reconfigurability and reliability to meet the hard-to-predict global business market, especially job-shop production. However, even there is a proper planned schedule for production, and there is also technique for scheduling in Reconfigurable Manufacturing System (RMS) but job-shop production will always come out with errors and disruption due to complex and uncertainty happening during the production process, hence fail to fulfill the due-date requirements. This study proposes a generic control strategy for piloting the implementation of a complex scheduling challenge in a RMS. This study is aimed to formulate an optimization-based algorithm with simulation tool to reduce the throughput time of complex RMS, which can comply with complex product allocations and flexible routings of the system. Predictive-reactive strategy was investigated, in which Genetic Algorithm (GA) and dispatching rules were used for predictive scheduling and reactivity controls. This research also provided some results in combining the rule-based simulation with optimization: first, a feasible schedule was computed and then fine-tuned with the rule-based simulation system, then tested with RMS which is the reactive part. Simulation experiments were run using different parameters to analyze the performance of the proposed algorithm with the system. The results showed that the proposed optimization-based algorithm had successfully reduce the throughput time of the system. In this case, the effectiveness and reliability of RMS is increase by combining the simulation with the optimization algorithm.

اونيورسيتي تيكنيكل مليسيا ملاك  
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

**ALGORITMA SIMULASI BERASASKAN PENGOPTIMUMAN UNTUK RAMALAN-  
BERTINDAKBALAS PENJADUALAN BENGGEL-KERJA BAGI KONFIGURASI  
SEMULA SISTEM PEMBUATAN**

**ABSTRAK**

*Industri pembuatan sedang menuju ke arah factor konfigurasi semula dan kebolehpercayaan untuk mencapai pasaran perniagaan secara global yang sukar diramalkan, terutamanya pengeluaran secara kerja bengkel. Walaupun jadual pengeluaran telah pun dirancang dan juga teknik penjadualan bagi system pembuatan konfigurasi semula telah dilaksanakan, namun terdapat juga masalah and gangguan yang disebabkan oleh kerumitan dan ketidakpastian dalam process pengeluaran, oleh itu sentiasa melebihi tempoh masa yang dituntukan. Kajian ini mencadangkan strategi kawalan generik untuk merintis pelaksanaan cabaran penjadualan kompleks dalam RMS. Kajian ini bertujuan untuk merumuskan algoritma berasaskan pengoptimuman dengan alat simulasi untuk mengurangkan masa pemprosesan RMS kompleks, dan boleh mematuhi peruntukan produk yang kompleks dan penghalaan yang fleksibel. Strategi ramalan-reaktif telah dianalisis, di mana Algoritma Genetik (GA) dan peraturan penghantaran digunakan untuk penjadualan ramalan dan kawalan kereaktifan. Penyelidikan ini juga memberikan keputusan dalam menggabungkan simulasi berasaskan peraturan dengan pengoptimuman: yang pertama, jadual yang boleh dilaksanakan telah dikira dan kemudian diperhalusi dengan sistem simulasi berasaskan peraturan, kemudian diuji dengan RMS yang merupakan bahagian reaktif. Eksperimen simulasi dijalankan menggunakan parameter yang berbeza untuk menganalisis prestasi algoritma yang dicadangkan. Keputusan menunjukkan bahawa algoritma berasaskan pengoptimuman yang dicadangkan telah berjaya mengurangkan masa pemprosesan sistem. Dalam kes ini, keberkesanan dan kebolehpercayaan RMS meningkat dengan menggabungkan simulasi dengan algoritma pengoptimuman.*



## ACKNOWLEDGEMENT

First, I would like to thank Universiti Teknikal Malaysia Melaka (UTeM) for providing the research platform. I would also like to express my gratitude to my supervisor, Ir. Dr.-Ing. Azrul Azwan bin Abdul Rahman CEng for his support and advice. His advice and guidance help to make this research project running smoothly and effectively. His encouragement and motivation are also highly appreciated throughout this project.

Also, special thanks to my co-supervisor, Ir. Dr. Hj. Muhamad Arfauz bin A Rahman CEng, who constantly supported my journey and all the help I received from him. Another party that I would like to thank is Encik Azwan, technician of the automation lab, who helped me a lot while I faced any technical issues during lab activities.

Other than that, I would like to thank my family who keep supporting and believing in me, especially my parents Tan Chee Kong and Chan Kam Ling. I also want to thank all my friends that helped me throughout the whole project. Finally, thank you to all the individual(s) who have provided me with the assistance, support and inspiration to embark on my study. All the contributions are greatly appreciated.



## TABLE OF CONTENTS

	PAGE
<b>DECLARATION</b>	
<b>APPROVAL</b>	
<b>DEDICATION</b>	
<b>ABSTRACT</b>	ii
<b>ABSTRAK</b>	iii
<b>ACKNOWLEDGEMENTS</b>	iv
<b>TABLE OF CONTENTS</b>	v
<b>LIST OF TABLES</b>	viii
<b>LIST OF FIGURES</b>	x
<b>LIST OF SYMBOLS AND ABBREVIATIONS</b>	X
<b>LIST OF APPENDICES</b>	xi
<b>LIST OF PUBLICATIONS</b>	xiii
<b>CHAPTER 1 INTRODUCTION</b>	
1.1 Background	1
1.2 Problem Statement	3
1.3 Research Objectives	5
1.4 Scope of Research	5
1.5 Contribution of Research	6
1.6 Thesis Outline	7
<b>CHAPTER 2 LITERATURE REVIEW</b>	
2.1 Introduction	9
2.2 Reconfigurable Manufacturing Systems	10
2.2.1 Material Handling System	12
2.2.2 Reconfigurable Material Handling System	15
2.3 Monorail System and Rail Guided Vehicles	17
2.4 Simulation	20
2.4.1 Computer Simulation Tool	22
2.4.2 Simulation-based Optimization	25
2.5 Job-shop Scheduling	28
2.5.1 Objective Function and Performance Measure	31
2.5.2 Dispatching Rules	34
2.5.3 Predictive-reactive Approach	36

2.6	Artificial Intelligence	40
2.6.1	Evolutionary Algorithms	40
2.6.2	Genetic Algorithms	41
2.7	Related Studies and Summary	43
2.7.1	State-of-the-art Research	45
2.7.2	State-of-the-art Implementation	51
<b>CHAPTER 3            METHODOLOGY</b>		
3.1	Introduction	55
3.2	Job-shop Scheduling Problem	57
3.2.1	Scheduling Procedure	58
3.3	Construction of Feasible Schedule	61
3.3.1	Process Plan	61
3.3.2	Workplace Operation Time Schedule	62
3.3.3	Due Date Schedule	63
3.4	Construction of Simulation Model	64
3.4.1	Methods	66
3.4.2	Source Release Control	69
3.4.3	Path Generations	70
3.4.4	Graphical User Interface Dialog	76
3.5	GA Setup and Control	81
3.5.1	Initialization of the Population of Chromosomes	83
3.5.2	Selection	83
3.5.3	Crossover	85
3.5.4	Mutation	87
3.6	Summary of the Chapter	88
<b>CHAPTER 4            RESULTS AND DISCUSSION</b>		
4.1	Introduction	89
4.2	Makespan	91
4.2.1	Number of Generations	91
4.2.2	Generation Size	94
4.2.3	Gantt Charts	96
4.3	Dispatching Rules	99
4.3.1	Number of Generations	99
4.3.2	Generation Size	101
4.4	Release Control Options and Complexity Levels	102
4.4.1	Number of Generations	103
4.4.2	Generation Size	106
4.5	Improvement Rate	110
4.5.1	Number of Generations	110
4.6	Summary of the chapter	113
<b>CHAPTER 5            CONCLUSION AND RECOMMENDATIONS</b>		
5.1	Conclusion	116
5.2	Recommendations	117
<b>REFERENCES</b>		<b>119</b>



## LIST OF TABLES

TABLE	TITLE	PAGE
Table 2.1	Comparison between DML and FMS Koren (2014).	10
Table 2.2	Types of transportation equipment using conveyor.	13
Table 2.3	JSS problem approaches and methods in literatures (Leusin et al., 2018).	30
Table 2.4	Summary of the state-of-the art research papers from 2016 to 2022.	45
Table 2.5	Summary of the state-of-the art implementation papers from 2016 to 2022.	51
Table 3.1	Objective functions that had been chosen for testing purpose.	59
Table 3.2	Dispatching rules that been considered for optimization purpose.	59
Table 3.3	Process plan for every product type.	62
Table 3.4	Workplace operation time schedule for every product type.	62
Table 3.5	Due date schedule for every product type.	63
Table 3.6	Objects that used in the simulation model.	65
Table 3.7	Initialization method used to initialize the simulation model.	66
Table 3.8	Control method used to control the simulation model.	68
Table 3.9	Defination for every release control option..	69
Table 3.10	Path generator complexity level options.	75
Table 3.11	Example of a population of chromosome representation based on product type and work order number.	83
Table 4.1	Parameters involved in the experiment.	90
Table 4.2	Percentage reduction in makespan for (a) normal scheduling and (b) rescheduling compared with initial makespan for number of generations = 5 and 10 with generation size = 6.	93
Table 4.3	Percentage reduction in makespan for (a) normal scheduling and (b) rescheduling compared with initial makespan for generation size = 6, 10 and 25 with generation number = 5.	95

Table 4.4 Improvement rate for normal scheduling and rescheduling of dispatching rules with number of generations = 5 and generation sizes = 6,10 and 25

111



## LIST OF FIGURES

FIGURE	TITLE	PAGE
Figure 1.1	RMS dual functionality of dedicated manufacturing system and flexible manufacturing system (Koren et.al., 2017).	2
Figure 1.2	Production scheme on parallel flexible injection machines of plastic components in the automotive supply chain (Andres et al., 2021).	4
Figure 1.3	The thesis outline.	8
Figure 2.1	Schematic diagram of a typical RMS (Koren, 2014).	11
Figure 2.2	Reconfigurable factors in a RMS (Han et al., 2020).	12
Figure 2.3	The reconfigurable factory testbed at the University of Michigan includes two flexible manufacturing cells and a conveyor for inter-cell material handling (Lee and Tilbury, 2008).	16
Figure 2.4	Example of RGV.	18
Figure 2.5	MONTRAC monorail material handling system.	19
Figure 2.6	Schematic illustration of MONTRAC monorail material handling system.	20
Figure 2.7	Procedure of simulation conduction (Siderska, 2016).	21
Figure 2.8	Historical evolution of simulation (Mourtzis et al., 2014).	21
Figure 2.9	The development of the computer simulation tools (Grabowik et al., 2018).	23
Figure 2.10	Comparative matrix of commercial simulation tools (Mourtzis et al., 2014).	25
Figure 2.11	Type of problem published from year 1991 to 2016 (Trigueiro et al., 2019).	26
Figure 2.12	Summary of SBO procedure on industrial engineering (Trigueiro et al., 2019).	27
Figure 2.13	Example of the schedule of $4 \times 3$ JSS problem (Piroozfard et al., 2016).	28

Figure 2.14	Objective functions of RMS considered in some relevant journal papers from 2006 to 2018 regarding to optimization problem (Yelles-Chaouche et al., 2020).	33
Figure 2.15	Percentage of objective function considered in JSS problem using AI strategy from 1997 to 2012 (Çalış and Bulkan, 2015).	34
Figure 2.16	Classification of production and maintenance scheduling approaches (Paprocka, Krenczyk and Burduk, 2021).	36
Figure 2.17	Behaviour of the different approaches in terms of uncertainty analysis and rescheduling (Iglesias-escudero et al., 2019).	37
Figure 2.18	Concept methodology of the proposed intelligence job scheduling system by Sobaszek et al. (2018).	39
Figure 2.19	The procedure of GA (Katoch et al., 2021).	42
Figure 2.20	Number of publications based on Scopus database score (Mourtzis, 2020).	47
Figure 3.1	Flow chart for research methodology.	55
Figure 3.2	Scheduling procedure.	60
Figure 3.3	The simulation model layout of the MONTRAC system.	64
Figure 3.4	The output generated by “Path_Generator” method in PathsTable.	70
Figure 3.7	Example of the path sequences generated by the method “Path_Generator”.	72
Figure 3.6	Flow chart for Path Generator method’s structure.	73
Figure 3.7	Permutation algorithm illustration.	74
Figure 3.8	List of auxiliary methods in the UI.	76
Figure 3.9	Settings tab in UI dialog.	77
Figure 3.10	Data tab in UI dialog.	79
Figure 3.11	Scheduling tab in UI dialog.	80
Figure 3.12	Evaluation tab in UI dialog.	81
Figure 3.13	GAWizard display view in (a)Define tab, (b)Run tab, (c)Evaluate tab.	82
Figure 3.14	Example of OX crossover between two parents and two children.	85



Figure 3.15	Example of PMX crossover for two parents and two children.	86
Figure 3.16	Example of mutation in a parent and a child.	87
Figure 4.1	Tree diagram for the combinations of number of generations and generation sizes for experiments.	90
Figure 4.2	Makespan for (a) normal scheduling and (b) rescheduling for number of generations = 5 and 10 with generation size = 6.	92
Figure 4.3	Makespan for (a) normal scheduling and (b) rescheduling for generation size = 6, 20 and 25 with number of generations = 5.	95
Figure 4.4	Gantt charts for makespan for every combination of generation sizes and number of generations.	98
Figure 4.5	The best fitness value in terms of dispatching rules for (a) normal scheduling and (b) rescheduling for number of generations = 5 and 10 with generation size = 6.	100
Figure 4.6	The best fitness value in terms of dispatching rules for (a) normal scheduling and (b) rescheduling for generation sizes = 6, 10 and 25 with number of generations = 5.	102
Figure 4.7	The release control options and path complexity levels comparisons for normal scheduling for (a) generations number = 5 and (b) generations number = 10 with the generations size = 6.	104
Figure 4.8	The release control options and path complexity levels comparisons for rescheduling for (a) generations number = 5 and (b) generations number = 10 with the generations size = 6.	105
Figure 4.9	The release control options and path complexity levels comparisons for normal scheduling for (a) generations size = 6, (b) generations size = 10 and (c) generation size = 25 with the generations number = 5.	107
Figure 4.10	The release control options and path complexity levels comparisons for rescheduling for (a) generations size = 6, (b) generations size = 10 and (c) generation size = 25 with the generations number = 5.	110
Figure 4.11	Improvement rate for (a) normal scheduling and (b) rescheduling with the generations number = 5 and varied generation sizes.	112
Figure 4.12	Architecture of the predictive-reactive job-shop scheduling for RMS.	114

## LIST OF SYMBOLS AND ABBREVIATIONS

AI	-	Artificial Intelligence
dd	-	Day
DML	-	Dedicated Manufacturing Line
EA	-	Evolutionary algorithm
FMS	-	Flexible Manufacturing System
GA	-	Genetic Algorithm
JSS	-	Job-shop scheduling
Lv	-	Level
min	-	Minute
mm	-	Month
NP	-	Non-deterministic Polynomial-time
Op	-	Option
OX	-	Order crossover
PMX	-	Partially matched crossover
RGV	-	Rail Guided Vehicle
RMS	-	Reconfigurable Manufacturing System
SBO	-	Simulation-based optimization
UI	-	User Interface
VDI	-	Verein Deutscher Ingenieure
yy	-	Year

## LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	Full illustration of the simulation model in Tecnomatix Plant Simulation.	137
B	Initialization method: Create_Prod_List (source code).	138
C	Initialization method: Path_Generator_Transporters (source code).	139
D	Initialization method: FindShortestPath (source code).	141
E	Control method: Move (source code).	142
F	Control method: TrackStopper (source code).	146
G	Control method: ArenaEntrCtrl (source code).	148
H	Control method: Load (source code).	149
I	Control method: Unload (source code).	150
J	Control method: Call_Transporter (source code).	151
K	Control method: Trace (source code).	152
L	Control method: Logging (source code).	153
M	Control method: Proc_time (source code).	156
N	Data for makespan from simulation experiments based in the generation size =6 for (a) normal scheduling and (b) rescheduling.	161
O	Data for makespan from simulation experiments based in the generation number = 5 for (a) normal scheduling and (b) rescheduling.	163
P	Data for best fitness based on release control and complexity level options in generation number = 5 and generation size = 6 for (a) normal scheduling and (b) rescheduling.	165
Q	Data for best fitness based on release control and complexity level options in generation number = 10 and generation size = 6 for (a) normal scheduling and (b) rescheduling.	168

R	Data for best fitness based on release control and complexity level options in generation number = 5 and generation size = 10 for (a) normal scheduling and (b) rescheduling.	171
S	Data for best fitness based on release control and complexity level options in generation number = 5 and generation size = 25 for (a) normal scheduling and (b) rescheduling.	174
T	Data for optimization time for generation number = 5 and generation size = 6 for (a) normal scheduling and (b) rescheduling.	177
U	Data for optimization time for generation number = 5 and generation size = 10 for (a) normal scheduling and (b) rescheduling.	180
V	Data for optimization time for generation number = 5 and generation size = 25 for (a) normal scheduling and (b) rescheduling.	183



## LIST OF PUBLICATIONS

### Indexed Journal

**Tan, J. Y.**, Abdul Rahman, A. A., Arfauz, A. R., Salleh, M. R. and Bilge, P., 2020. Predictive-reactive Job-shop Scheduling for Flexible Production Systems with the Combination of Optimization and Simulation Based Algorithm. *Journal of Advanced Manufacturing Technology*, 14(3), pp. 81-93.

**Tan, J. Y.**, Abdul Rahman, A. A., Nadiah, A. and Arfauz, A. R., 2021. The Effect of Lateral Lifting Tasks on Hand Grip and Pinch Strength Measurements. *IIUM Engineering Journal*, 22(2), pp. 261-282.



# CHAPTER 1

## INTRODUCTION

### 1.1 Background

The contemporary market continues to drive all kinds of companies and businesses, particularly manufacturers, towards flexibility. However, the random input orders and non-standardized manufacturing methods, along with the growing number of goods and variations causes current manufacturing systems to become more complex (Asadzadeh, 2015; Niehues et al., 2015; Allahverdi et al., 2018). The complexity and limitations of manufacturing processes causes the products throughput time has greatly increase and unable to achieve due date requirements (Scholz-Reiter et al., 2015). Manufacturing sectors are forced to handle demand fluctuations, rapidly adopt new products and order changes to make sure that the products are finished a within specific time (Angkiriwang et al., 2014).

The first moving assembly line which invented by Henry Ford was installed at the Ford Highland Park plant in Michigan, the origin of notable inventions in manufacturing. The Ford Windsor Engine Plant was designed and built in 1998–2000, which contains total of 120 CNC machines which are arranged in a reconfigurable system architecture that consists of 20 stages (6 machines per stage). Ford Motor Co. called this system as Flexible, Reconfigurable Manufacturing System, where flexible is referred to the CNC machines in this system can produce multiple product variants. Koren (2014) is the first who researched on Reconfigurable Manufacturing System (RMS), and have proved that RMS is useful in this situation. RMS can imbibe newer technologies in the production process and an

optimally designed RMS has the capacity of DMS and functionality of FMS built into one single system as shown in Figure 1.1 as below (Singh et al., 2017).

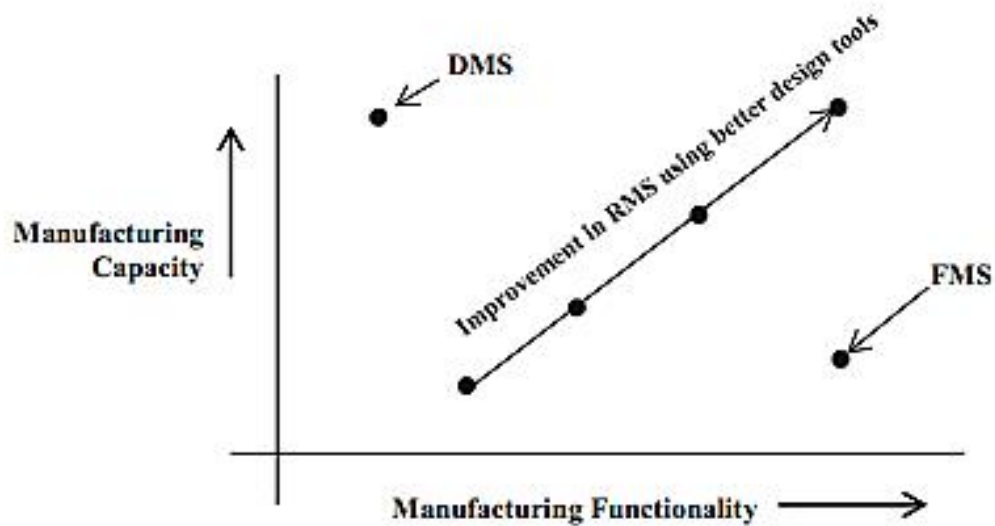


Figure 1.1 RMS dual functionality of dedicated manufacturing system and flexible manufacturing system (Koren et.al., 2017).

RMS is quite common in recent research works, and most algorithms, dispatching rules, and strategies have already been developed with RMS, but majority of studies in job scheduling concentrate on static scheduling constraints and not consider dynamic factors (Kundakci and Kulak, 2016). Conventional approaches suggest a high approximation of real systems and are complex in formulation; indeed, due to the complexity of the large number of variables and restrictions, most of the current algorithms do not give good result in a reasonable time (Nehzati, 2012; Choi and Xirouchakis, 2015; Wan and Yan, 2015; Niehues et al., 2016; Nasiri et al., 2017).

According to research, the predictive-reactive approach can adapted to rapid changes of shop floor's execution and provide a flexible schedule (Tang and Wang, 2008). While since it is very difficult to perform optimization process analytically during such complicated processes, simulation-based optimization is also useful in this scenario (Korytkowski et al., 2013). On the other hand, scheduling and controlling with simulation-

based optimization can increase the performance and efficiency of the output manufacturing systems, provide easy and fast evaluation of new layouts and schedules with direct production control (Fera et al., 2013; Doh et al., 2016; Leusin et al., 2018; Niehues et al., 2018b).

Due to dynamic job-shop scheduling problems are NP-hard combinatorial optimization problems, heuristic methods are useful for solving these types of problems (Kundakci and Kulak, 2016). Hence, this research focuses on modelling the simulation model for RMS that can provide versatility in system layout and product mix with flexible routing and production sequence, which is especially useful during the mass customization process in manufacturing industry.

The combination of simulation and optimization-based algorithm with the predictive-reactive approach for scheduling of the RMS under various optimization restrictions were studied through experiments. For the predictive part, the feasible schedule for RMS job-shop is predicted and decided. Rule-based simulation and optimization is then implemented into the schedule: first, a rough schedule was determined using optimization algorithm, then rule-based simulation systems were used to refine the schedule to obtain the most optimal results. For the reactive phase, the schedule obtained is adjusted and validated by MONTRAC monorail system. The results obtained from the experiments is compared and analysed to find out the effectivity of the proposed method structure, algorithms and architecture.

## **1.2 Problem Statement**

The RMS are getting more complex and facing more challenges due to the new evolution of market demands, causing the processing time for a product has increased and the products cannot complete on schedule, especially in job-shop productions (Allahverdi