

BOTTLENECK ADJACENT MATCHING HEURISTICS FOR SCHEDULING A
RE-ENTRANT FLOW SHOP WITH DOMINANT MACHINE PROBLEM

SH SALLEH BIN SH AHMAD

A thesis submitted in
fulfilment of the requirement for the award of
Doctor of Philosophy

Faculty of Mechanical and Manufacturing Engineering
Universiti Tun Hussein Onn Malaysia

JULY, 2009

In the name of
ALLAH,
Most Gracious,
Most Merciful.

To my beloved parents Sh Ahmad bin Omar Bareduan and Maznah binti Ali Al-Qasam.

Also my loving wife Sharifah Hamidah binti Syed Hassan Al-Jahsyi.

And cheering children Nazhif, Haniff, Nadhirah,
Muhammad and Ibrahim.



PTTA UTHM
PERPUSTAKAAN TUN AMINAH

ACKNOWLEDGEMENT

“Alhamdulillah”, all praise to **ALLAH**, the most gracious and the most merciful, for all the strength and will provided to the author in completing the research. Without “the mercy”, the author is just an ordinary person who may not even understand what the research topic is all about.

The author would like to express utmost appreciation and gratitude to the research supervisor, Prof. Dr. Sulaiman bin Hj Hasan for his guidance, persistent encouragement and associated aid throughout the research period. His understanding and patience during the tough period are forever appreciated.

Heartiest thanks are due to the senior technician at the Cyber Manufacturing Centre, UTHM for his full cooperation for the research. Appreciation is also dedicated to those who contributed directly or indirectly towards the success of this thesis.

Finally, sincere thanks are dedicated to the author’s parents and family for their consistent prays, patience and never-ending support. May **ALLAH** bless all of us.

ABSTRACT

The re-entrant flow shop environment has become prominent in the manufacturing industries and has recently attracted researchers attention. Typical examples of re-entrant flow shops are the printed circuit board manufacturing and furniture painting processes where components or processed parts enter some specific machines more than once. Similar with other manufacturing environment, identifying appropriate scheduling methodologies to ensure high output rate is very much desirable. The problem explored and investigated in this research is a special type of scheduling problem found in a re-entrant flow shop where two of its processes have high tendency of exhibiting bottleneck characteristics. The scheduling problem resembles a four machine permutation re-entrant flow shop with the routing of $M1, M2, M3, M4, M3, M4$ where $M1$ and $M4$ have high tendency of being the dominant machines. The main objective of this research is to take advantage of the bottleneck characteristics at the re-entrant flow shop and use it to develop heuristics that can be used to solve its scheduling problems. There are four major concentrations in this research. First, basic mathematical properties or conditions that explain the behaviour of the bottleneck processes were developed to give an insight and clearer understanding of the re-entrant flow shop with dominant machines. Second, four new and effective scheduling procedures which were called BAM1 (Bottleneck Adjacent Matching 1), BAM2, BAM3 and BAM4 heuristics were developed. Third, bottleneck approach was utilised in the study and the analysis using Visual Basic macro programming indicated that this method produced good results. Fourth, the Bottleneck Scheduling Performance (BSP) indexes introduced in the BAM heuristics procedure could be used to ascertain that some specific generated job arrangements are the optimum schedule. As a general conclusion, this research has achieved the objectives to develop bottleneck-based makespan algorithms and heuristics applicable for re-entrant flow shop environment. The experimental results demonstrated that the BAM heuristics generated good performances within specific $P1$ (first process) bottleneck dominance level and when the number of jobs increases. Within the medium to large-sized problems, BAM2 is the best at weak $P1$ dominance level whereas BAM4 is the best at strong $P1$ dominance level.

ABSTRAK

Aliran masuk semula merupakan persekitaran yang biasa ditemui di industri pengeluaran dan ianya telah menarik perhatian ramai penyelidik. Contoh tipikal bagi persekitaran ini ialah proses pembuatan papan litar tercetak dan pengecatan perabot di mana komponen produk melalui mesin tertentu lebih dari sekali. Seperti persekitaran pembuatan yang lain, mengenalpasti kaedah penjadualan yang dapat memaksimumkan pengeluaran sangat diperlukan. Masalah yang diterokai dan diselidiki dalam kajian ini merupakan masalah penjadualan yang khusus bagi sebuah aliran masuk semula di mana dua daripada prosesnya berpotensi tinggi memiliki ciri-ciri kejejalan. Masalah penjadualan ini digambarkan sebagai satu aliran masuk semula yang dilengkapi dengan empat mesin. Perjalanan prosesnya pula melalui M1,M2,M3,M4,M3,M4 di mana M1 dan M4 memiliki ciri-ciri kejejalan. Objektif kajian ini adalah untuk menggunakan ciri-ciri kejejalan tersebut bagi membangunkan beberapa heuristik yang boleh digunakan untuk menyelesaikan masalah penjadualan aliran masuk semula. Terdapat empat penekanan utama dalam kajian ini. Pertama, ciri-ciri matematik asas untuk menerangkan sifat-sifat kejejalan proses telah dibangunkan bagi memperolehi kefahaman yang mendalam tentang aliran masuk semula ini. Kedua, empat heuristik baru yang dinamakan BAM1 (*Bottleneck Adjacent Matching 1*), BAM2, BAM3 dan BAM4 telah dibangunkan. Ketiga, pendekatan menggunakan ciri-ciri kejejalan telah digunakan dalam kajian ini dan keputusan analisis menggunakan pengaturcaraan makro Visual Basic menunjukkan kaedah ini sangat berkesan. Keempat, indeks prestasi penjadualan kejejalan (*Bottleneck Scheduling Performance (BSP) indexes*) yang diperkenalkan dalam heuristik BAM boleh digunakan untuk mengesahkan bahawa suatu susunan jadual yang dihasilkan merupakan penyelesaian yang optimum. Sebagai kesimpulan umum, kajian ini telah berjaya mencapai objektif untuk membangunkan algoritma tempoh siap keseluruhan kerja berasaskan konsep kejejalan beserta heuristik yang sesuai digunakan untuk aliran masuk semula. Keputusan eksperimen menunjukkan heuristik BAM menghasilkan prestasi yang baik pada paras kejejalan $P1$ (proses pertama) tertentu dan apabila bilangan kerja meningkat. Pada paras kejejalan $P1$ rendah, BAM2 merupakan heuristik yang terbaik manakala pada paras kejejalan $P1$ tinggi, BAM4 menghasilkan keputusan yang terbaik.

CONTENTS

RESEARCH TITLE	i
DECLARATION	ii
DEDICATION	iii
ACKNOWLEDGEMENT	iv
ABSTRACT	v
CONTENTS	vii
LIST OF TABLES	xii
LIST OF FIGURES	xviii
LIST OF ABBREVIATIONS	xx
LIST OF APPENDIXES	xxiii
CHAPTER 1 INTRODUCTION	1
1.1 Sequencing and Scheduling	1

1.2	Cyber Manufacturing System	3
1.3	Re-entrant Flow Shop	5
1.4	Problem Description	7
1.5	Research Objectives	8
1.6	Scope Of The Study	9
1.7	Significance Of Research	9
1.8	Structure Of Thesis	10
CHAPTER 2 LITERATURE REVIEW		12
2.1	Permutation Flow Shops With Makespan Objective	12
2.2	Re-entrant Permutation Flow Shop	31
2.3	Flow Shops With Bottleneck or Dominant Machine	37
2.4	Petri Net And Collaborative Process Modelling	46
2.5	Summary	53
CHAPTER 3 METHODOLOGY		54
3.1	CMC Activities Modelling	56
3.2	CMC Schedule Modelling	57

3.3	CMC Makespan Algorithm	57
3.4	Alternative Makespan Algorithms Using Bottleneck Approach	58
3.5	Bottleneck-based Heuristics for the CMC	60
3.6	Simulation Experimental Design	61
3.7	Summary	65

CHAPTER 4 CMC MAKESPAN COMPUTATIONS USING BOTTLENECK APPROACH

		66
4.1	Modelling The CMC With Petri Net	66
4.2	CMC Makespan Algorithm 1	71
4.3	Makespan Algorithm Using CNC Machine As Bottleneck	78
4.4	Makespan Algorithm Using CAD As Bottleneck	97
4.5	Summary	116

CHAPTER 5 BOTTLENECK ADJACENT MATCHING (BAM) HEURISTICS WITH CNC MACHINE AS THE DOMINANT MACHINE

5.1	Bottleneck Dominance Level Measurement	118
-----	--	-----

5.2	Bottleneck Adjacent Matching 1 (BAM1) Heuristic	122
5.3	BAM1 Heuristic Performance Evaluation	135
5.4	Bottleneck Adjacent Matching 2 (BAM2) Heuristic	143
5.5	BAM2 Heuristic Performance Evaluation	154
5.6	Summary	159

**CHAPTER 6 BOTTLENECK ADJACENT MATCHING (BAM)
HEURISTICS WITH CAD AS THE DOMINANT MACHINE** **161**

6.1	Bottleneck Adjacent Matching 3 (BAM3) Heuristic	161
6.2	BAM3 Heuristic Performance Evaluation	173
6.3	Bottleneck Adjacent Matching 4 (BAM4) Heuristic	178
6.4	BAM4 Heuristic Performance Evaluation	189
6.5	Summary	194

CHAPTER 7 DATA ANALYSIS AND FINDINGS **195**

7.1	Introduction	195
7.2	Results of Experiment and Discussions	197

7.2.1	Results of Experiment and Discussions at Weak $P1$ Dominance Level	198
7.2.2	Results of Experiment and Discussions at Medium $P1$ Dominance Level	200
7.2.3	Results of Experiment and Discussions at Strong $P1$ Dominance Level	203
7.2.4	Results of Experiment and Discussions on BSP Index	206
7.3	Summary	209

CHAPTER 8 CONCLUSIONS AND FUTURE RESEARCH 211

8.1	Conclusions	211
-----	-------------	-----

8.2	Future Research	213
-----	-----------------	-----

REFERENCES	215
-------------------	------------

APPENDIX	226
-----------------	------------



PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

LIST OF TABLES

TABLE NO.	TITLE	PAGE
2.1.1	Permutation flow shops heuristics using index development and $F_2//C_{max}$ analogy (Framinan <i>et al.</i> , 2004)	15
2.1.2	Heuristic concept used in Phase II: Solution Construction	24
2.1.3	Heuristics in Phase III: Solution Improvement	30
2.1.4	Metaheuristics in Phase III: Solution Improvement	30
2.2.1	Heuristics and metaheuristics in re-entrant flow shop studies	37
2.3.1	Researches on flow shop with bottleneck or dominant machines	45
4.2.1	Processing time range (hr)	71
4.2.2	Processing time data (hr)	71
4.2.3	Start and stop time for each task with DACB job sequence	74
4.2.4	Makespan from different job sequences using Algorithm 1	76
4.2.5	Makespan from different job sequences using Petri net	76
4.3.1	Processing time ($P(i, j)$) (hr)	79
4.3.2	Condition 4.1, Condition 4.2 and Condition 4.3 observations	84
4.3.3	Accuracy of Equation 4.1 at various conditions	85
4.3.4	Makespan of AXXX using Algorithm1 and Equation 4.1	89
4.3.5	AXXX job sequences versus Conditions 4.4, 4.5 and 4.6	89
4.3.6	Processing time data and BCF value	90
4.3.7	Summary of the developed makespan and completion time equations for CNC machine as bottleneck	96
4.4.1	Processing time range (hr)	97
4.4.2	Processing time data (hr)	97

4.4.3	Different job sequences with equal makespan	98
4.4.4	Condition 4.7, Condition 4.8 and Condition 4.9 observations	102
4.4.5	Accuracy of Equation 4.7 at various conditions	104
4.4.6	Condition 4.9 violations	104
4.4.7	Makespan computation using Algorithm 1	105
4.4.8	Makespan computation using Equation 4.7	105
4.4.9	Table for makespan computation	109
4.4.10	Summary of the developed makespan and completion time equations	116
5.1.1	Process time data	119
5.1.2	Comparison of $P(1,j)+P(2,j)+P(3,j)$ and $P(2,j)+P(3,j)+P(4,j)+P(5,j)+P(6,j)$	120
5.1.3	Occurrence of $P(1,j)+P(2,j)+P(3,j)$ greater than $P2 + P3 + P4 + P5 + P6$ of other job	120
5.1.4	BCF value for ABCDEF job arrangement	121
5.1.5	Start and stop time for ABCDEF job sequence using Algorithm 1	121
5.2.1	Data for $P(1,j) + P(2,j) + P(3,j)$	125
5.2.2	BAM1 index computation for second job	126
5.2.3	BAM1 index computation for third job	127
5.2.4	BAM1 index computation for fourth job	127
5.2.5	BAM1 index computation for fifth job	128
5.2.6	Start and stop time for BEDACF job sequence using Algorithm 1	128
5.2.7	Process time data for BEDACF job sequence	129
5.2.8	BSP1 index evaluation	130
5.2.9	BAM1 index computation for second job (first job = Job C)	130
5.2.10	BAM1 index computation for third job (first job = Job C)	131
5.2.11	BAM1 index computation for fourth job (first job = Job C)	131
5.2.12	BAM1 index computation for fifth job (first job = Job C)	132

5.2.13	Start and stop time for CEDABF job sequence using Algorithm 1	132
5.2.14	BAM1 list of scheduling sequences	133
5.2.15	Start and stop time for BEDACF job sequence using Algorithm 1	134
5.3.1	$P1$ dominance level groups	136
5.3.2	Process time data range (hours)	136
5.3.3	BAM1 heuristic performance for 6 job problems	137
5.3.4	NEH heuristic performance for 6 job problems	139
5.3.5	BAM1 vs NEH makespan performance for 6 job problems	140
5.3.6	BAM1 vs NEH makespan performance for 10 job problems	140
5.3.7	BAM1 vs NEH makespan performance for 20 job problems	141
5.3.8	BAM1 vs NEH makespan performance for 20 job problems (test 2)	142
5.3.9	BAM1 vs NEH makespan performance for 20 job problems (test 3)	143
5.4.1	Process time data	147
5.4.2	Data for $P(1,j) + P(2,j) + P(3,j)$	147
5.4.3	BAM2 index for second job	148
5.4.4	BAM2 index for third job	148
5.4.5	BAM2 index for fourth job	148
5.4.6	BAM2 index for fifth job	149
5.4.7	Process time data	149
5.4.8	BCF value for BEDACF job arrangement	150
5.4.9	BSP2 index computation for BEDACF job arrangement	150
5.4.10	BSP2 index evaluation	151
5.4.11	BAM2 index for second job (first job = Job C)	151
5.4.12	BAM2 index for third job (first job = Job C)	152
5.4.13	BAM2 index for fourth job (first job = Job C)	152
5.4.14	BAM2 index for fifth job (first job = Job C)	152
5.4.15	Process time data	153

5.4.16	BCF value for CEDABF job arrangement	153
5.4.17	BAM2 list of scheduling sequences	154
5.5.1	Process time data range (hours)	155
5.5.2	BAM2 heuristic performance for 6 job problems	155
5.5.3	BAM2 vs NEH makespan performance for 6 job problems	156
5.5.4	BAM2 vs NEH makespan performance for 10 job problems	157
5.5.5	BAM2 vs NEH makespan performance for 20 job problems	158
5.5.6	BAM2 vs NEH makespan performance for 20 job problems (test 2)	158
5.5.7	BAM2 vs NEH makespan performance for 20 job problems (test 3)	159
6.1.1	Process time data	164
6.1.2	Data for $P(2,j) + P(3,j) + P(4,j) + P(5,j) + P(6,j)$	165
6.1.3	BAM3 index computation for 5 th job	166
6.1.4	BAM3 index computation for 4 th job	167
6.1.5	BAM3 index computation for 3 rd job	167
6.1.6	BAM3 index computation for 2 nd job	168
6.1.7	Process time data	168
6.1.8	Start and stop time for CFDBAE job sequence using Algorithm 1	169
6.1.9	BSP3 index evaluation	170
6.1.10	BAM3 index computation for 5 th job (last job = Job A)	170
6.1.11	BAM3 index computation for 4 th job (last job = Job A)	171
6.1.12	BAM3 index computation for 3 rd job (last job = Job A)	171
6.1.13	BAM3 index computation for 2 nd job (last job = Job A)	172
6.1.14	Start and stop time for ECFDBA job sequence using Algorithm 1	172
6.2.1	Process time data range (hours)	173
6.2.2	BAM3 heuristic performance for 6 job problems	173
6.2.3	BAM3 vs NEH makespan performance for 6 job problems	174
6.2.4	BAM3 vs NEH makespan performance for 10 job problems	175

6.2.5	BAM3 vs NEH makespan performance for 20 job problems	176
6.2.6	BAM3 vs NEH makespan performance for 20 job problems (test 2)	177
6.2.7	BAM3 vs NEH makespan performance for 20 job problem (test 3)	177
6.3.1	Process time data	181
6.3.2	Data for $P(2,j) + P(3,j) + P(4,j) + P(5,j) + P(6,j)$	181
6.3.3	BAM4 index for 5 th job selection	182
6.3.4	BAM4 index for 4 th job selection	182
6.3.5	BAM4 index for 3 rd job selection	183
6.3.6	BAM4 index for 2 nd job selection	183
6.3.7	Process time data for FEBADC	184
6.3.8	$VP(2,j)$, $VP(3,j)$ and $VP(4,j)$ computations for FEBADC	184
6.3.9	Start and stop time for FEBADC job sequence using Algorithm 1	185
6.3.10	BSP4 index evaluation	186
6.3.11	BAM4 index computation for 5 th job (last job = Job A)	187
6.3.12	BAM4 index computation for 4 th job (last job = Job A)	187
6.3.13	BAM4 index computation for 3 rd job (last job = Job A)	188
6.3.14	BAM4 index computation for 2 nd job (last job = Job A)	188
6.3.15	Listed scheduling sequences using BAM4 heuristic	189
6.4.1	Process time data range (hours)	189
6.4.2	BAM4 heuristic performance for 6 job problems	190
6.4.3	BAM4 vs NEH makespan performance for 6 job problems	191
6.4.4	BAM4 vs NEH makespan performance for 10 job problems	191
6.4.5	BAM4 vs NEH makespan performance for 20 job problems	192
6.4.6	BAM4 vs NEH makespan performance for 20 job problems (test 2)	193
6.4.7	BAM4 vs NEH makespan performance for 20 job problems (test 3)	193
7.1.1	Number of simulated cases	196

7.1.2	Criteria for $P1$ dominance level classifications	197
7.2.1	Percentage of accurate makespan results at weak $P1$ dominance level	198
7.2.2	Percentage of accurate makespan ranking at weak $P1$ dominance level	198
7.2.3	Average makespan ratio at weak $P1$ dominance level	198
7.2.4	Average makespan ratio ranking at weak $P1$ dominance level	198
7.2.5	Percentage of accurate makespan results at medium $P1$ dominance level	200
7.2.6	Percentage of accurate makespan ranking at medium $P1$ dominance level	201
7.2.7	Average makespan ratio at medium $P1$ dominance level	201
7.2.8	Average makespan ratio ranking at medium $P1$ dominance level	201
7.2.9	Percentage of accurate makespan results at strong $P1$ dominance level	203
7.2.10	Percentage of accurate makespan ranking at strong $P1$ dominance level	203
7.2.11	Average makespan ratio at strong $P1$ dominance level	203
7.2.12	Average makespan ratio ranking at strong $P1$ dominance level	204
7.2.13	BSP index value that generates optimum makespan	206

LIST OF FIGURES

1.2.1	CMC process flow	5
2.1.1	Classification of scheduling delays	18
2.4.1	Example of PN model (Proth and Xie, 1996)	47
2.4.2	Status of the example PN in Figure 2.4.1 after firing T2	48
2.4.3	Status of the PN in Figure 2.4.2 after firing T5	49
2.4.4	An elementary object system for IOWF-net (Ling and Loke, 2002)	50
2.4.5	Sub-assembly body collaborative design synchronized coloured network (Ding <i>et al.</i> , 2005).	52
3.1	Flow diagram for research methodology	55
4.1.1	Cyber manufacturing centre information flow model	67
4.1.2	Conceptual Petri net modelling for CMC	69
4.1.3	Modified PN model for scheduling purposes	70
4.2.1	PN model of first-come-first-served schedule arrangement	72
4.2.2	PN model for searching the optimum job arrangement	73
4.2.3	PN model for optimum job arrangement with DACB job sequence	74
4.2.4	PN model for user selected job sequence	77
4.3.1	Scheduling Gantt chart for DACB job sequence (process focused)	80
4.3.2	Scheduling Gantt chart for DACB job sequence (resource focused)	80
4.3.3	Example schedule that fulfils Condition 4.1,4.2 and 4.3	81

4.3.4	Example schedule that fulfils Condition 4.2 and its assumptions	82
4.3.5	Example schedule that fulfils Condition 4.3 and its assumptions	83
4.4.1	Gantt chart for ABCD job sequence	98
4.4.2	Example schedule that fulfils Conditions 4.7, 4.8 and 4.9	101
4.4.3	Example schedule that violates Condition 4.10	106
4.4.4	Example schedule that violates Condition 4.11	107
4.4.5	Example schedule that violates Condition 4.12	108
5.2.1	Flow diagram for BAM1 heuristic	124
5.2.2	Gantt chart illustrating the discontinuity period between $P65$ and $P46$	135
5.4.1	Flow diagram for BAM2 heuristic	146
6.1.1	Flow diagram for BAM3 heuristic	164
6.3.1	Flow diagram for BAM4 heuristic	180



LIST OF ABBREVIATIONS

APA	-	Average performance advantage
API	-	Average percentage improvement
BAM	-	Bottleneck Adjacent Matching
BAM1	-	Bottleneck Adjacent Matching 1
BAM2	-	Bottleneck Adjacent Matching 2
BAM3	-	Bottleneck Adjacent Matching 3
BAM4	-	Bottleneck Adjacent Matching 4
<i>BCF</i>	-	Bottleneck correction factor
BMI	-	Bottleneck minimal idleness heuristic developed by Kalir and Sarin
BSP1	-	Bottleneck scheduling performance 1
BSP2	-	Bottleneck scheduling performance 2
BSP3	-	Bottleneck scheduling performance 3
BSP4	-	Bottleneck scheduling performance 4
CAD	-	Computer aided design
CDS	-	Heuristic developed by Campbell, Dudek and Smith
C_j	-	Completion time for each job
C_{max}	-	Makespan
CMC	-	Cyber manufacturing centre
CNC	-	Computer numerical control
<i>d_{dm}</i>	-	Decreasing dominating machines
<i>DL</i>	-	Dominance level
DM	-	Decomposition method
$F_2//C_{max}$	-	2-machine flow shop, makespan objective

$F_3//C_{max}$	-	3-machine flow shop, makespan objective
FCFS	-	First-come-first-served
$F_m/prmu/C_{max}$	-	m -machine flow shop, permutation rule, makespan objective
GA	-	Genetic algorithm
idm	-	Increasing dominating machines
INA	-	Integrated Net Analyser software
k	-	The recurring loops
LB	-	Lower bound
LPT	-	Longest processing time first
m	-	Number of machines or stages
Max	-	Maximum
Min	-	Minimum
n	-	Number of jobs
NEH	-	Heuristic developed by Nawaz, Ensore and Ham
$nmit$	-	No machine idle time
NP-hard	-	Non-polynomial time algorithm
$nwip$	-	No-wait in process
$P(i,j)$	-	Processing time of the j^{th} job at i^{th} process
$P1BCF$	-	Process 1 bottleneck correction factor
PA	-	Performance advantage
PCB	-	Printed circuit board
PI	-	Percentage improvement
PN	-	Petri net
PO	-	Heuristic developed by Pour
RA	-	Random Access heuristic developed by Dannenbring
R_k	-	Non-scheduled jobs
SA	-	Simulated annealing
S_k	-	Partially arranged scheduled jobs
SME	-	Small and medium enterprise
SPT	-	Shortest processing time first
TS	-	Tabu search

TSP	-	Travelling salesman problem
UTHM	-	Universiti Tun Hussein Onn Malaysia
<i>VP</i>	-	Virtual processing time



PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

LIST OF APPENDIXES

APPENDIX	TITLE	PAGE
A	BAM2 Index Computation for Second Job Position	227
B	BAM2 Index Computation for Third Job Position	231
C	BAM4 Index Computation for $(n-1)^{\text{th}}$ or Second Last Job Position	234
D	BAM4 Index Computation for $(n-2)^{\text{th}}$ Job Position	239



CHAPTER 1

INTRODUCTION

This chapter provides introduction and overview to the field of study which include sequencing and scheduling, cyber manufacturing system, re-entrant flow shop, problem description, research objectives, scope of the study, and significance of research.

1.1 Sequencing and Scheduling

Sequencing and scheduling play crucial roles in production planning and control. In the current competitive environment, effective scheduling has become a necessity for survival in the marketplace. Companies must ensure the meeting of delivery dateline committed to customers, as failure to do so may result in a significant loss of goodwill and vital businesses. At the same time, they also have to schedule the resources availability in the most effective manner. In production operations that involve many processes and resources, finding the optimal schedule involves complex and tedious steps. Very often, the schedules are normally obtained either by using simple heuristics (solution guidelines or rule of thumb that find feasible but not necessarily the optimum results) or through time consuming simulations.

Scheduling began to be considered seriously in manufacturing with the work of Henry Gantt during World War I (Pinedo, 2002). By using graphical techniques, he made a significant contribution to the field of scheduling which was considered as one of the oldest techniques available for operations scheduling (Turner *et al.*, 1993). Later, during

the World War II the field of operations research established its advancement. It involves intensive mathematical approach to develop scientific model of operating system, incorporating measurement of factors such as chance and risk in order to predict and compare the outcomes of alternative decisions, strategies, or control. In 1954, S. M. Johnson introduced the algorithm for optimal scheduling of a two-stage flow shop environment which is famously known as Johnson's rule (Pinedo, 2002). This work was followed and expanded by other researchers in solving scheduling problems from various fields and complexity.

Beginning of 1980's, large scale manufacturing industries such as the petrochemical, steel, paper, and glass industries have ventured into formal scheduling techniques. In these industries, the principle production machineries and ancillary equipments are very costly, so maximising the utilisations are very much desired in order to have the most economical and efficient operations. Developing schedules that maximise throughput, in other words, minimise the schedule makespan (completion time of the last job), is consistent with the goal of reducing manufacturing cost (Lee, 2000).

Scheduling provides the anticipated start times of each job on each resource (Hopp and Spearman, 2008). In typical manufacturing industries, the resources are normally the machines and the jobs or tasks are the operations in the production processes (Pinedo, 2002). In general, scheduling is a decision making process with the goal of one or more objectives to ensure profitable operations. This research was devoted to the study of one particular manufacturing scheduling environment. The environment under study is the re-entrant flow shops with dominant machine characteristics. A dominant or bottleneck is an operation that has the lowest capacity of any operation in the process and thus limits a system's output (Krajewski and Ritzman, 2005). In particular, the manufacturing environment in this study is a part of the Cyber Manufacturing System available at Universiti Tun Hussein Malaysia (UTHM). Here, top performance and accurate scheduling is very critical in order to meet the ever demanding customer requirements.

REFERENCES

- Adams, J., Balas, E. and Zawack, D. (1988). "Shifting Bottleneck Procedure For Job Shop Scheduling." *Management Science*. 34(3). 391-401.
- Bareduan, Salleh Ahmad, Sulaiman Hj Hasan and Saporudin Ariffin (2008). "Finite Scheduling of Collaborative Design And Manufacturing Activity: A Petri Net Approach." *Journal of Manufacturing Technology Management*. 19(2). 274-288.
- Bareduan, Salleh Ahmad, Sulaiman Hj Hasan, Noor Hakim Rafai and Muhammad Farid Shaari (2006). "Cyber Manufacturing System for Small and Medium Enterprises: A Conceptual Framework." *Transactions of North American Manufacturing Research Institution for Society of Manufacturing Engineers*. 34. 365-372.
- Ben-Daya, M. and Al-Fawzan, M. (1998). "A Tabu Search Approach For The Flow Shop Problem." *European Journal of Operational Research*. 109. 88-95.
- Bozejko, W. and Wodecki, M. (2004). "The New Concepts In Parallel Simulated Annealing Method." *Artificial Intelligent and Soft Computing*. 3070. 853-859.
- Campbell, H.G., Dudek, R.A. and Smith, M.L. (1970). "Heuristic Algorithm For The N Job, M Machine Sequencing Problem." *Management Science*. 16(10). 630-637.
- Cepek, O., Okada, M. and Vlach, M. (2002). "Nonpreemptive Flowshop Scheduling With Machine Dominance." *European Journal of Operational Research*. 139. 245-261.

- Chen, J.S., Pan, J.C.H. and Wu, C.K. (2008a). "Hybrid Tabu Search For Re-entrant Permutation Flow-Shop Scheduling Problem." *Expert Systems with Applications*. 34(3). 1924-1930.
- Chen, J.S., Pan, J.C.H. and Lin, C.M. (2008b). "Hybrid Genetic Algorithm For The Re-entrant Flow-Shop Scheduling Problem." *Expert Systems with Applications*. 34. 570-577.
- Chen, C.L., Vempati, V.S. and Aljaber, N. (1995). "An Application Of Genetic Algorithms For Flow Shop Problems." *European Journal of Operational Research*. 80. 389-396.
- Chen, J.S. (2006). "A Branch And Bound Procedure For The Reentrant Permutation Flow-Shop Scheduling Problem." *International Journal of Advanced Manufacturing Technology*. 29. 1186-1193.
- Cheng, M.B., Sun, S.J. and He, L.M. (2007). "Flow Shop Scheduling Problems With Deteriorating Jobs On No-Idle Dominant Machines." *European Journal of Operational Research*. 183. 115-124.
- Choi, B.C., Yoon, S.H. and Chung, S.J. (2007). "Minimizing Maximum Completion Time In A Proportionate Flow Shop With One Machine Of Different Speed." *European Journal of Operational Research*. 176(2). 964-976.
- Choi, S.W., Kim, Y.D. and Lee, G.C. (2005). "Minimizing Total Tardiness Of Orders With Reentrant Lots In A Hybrid Flowshop." *International Journal of Production Research*. 43(11). 2149-2167.
- Choi, S.W. and Kim, Y.D. (2007). "Minimizing Makespan On A Two-Machine Reentrant Flowshop." *Journal of The Operational Research Society*. 58. 972-981.

- Choi, S.W. and Kim, Y.D. (2008). "Minimizing Makespan On An m -Machine Reentrant Flowshop.." *Computers & Operations Research*. **35**(5). 1684-1696.
- Dannenbring, D.G. (1977). "Evaluation Of Flow Shop Sequencing Heuristics." *Management Science*. **23**(11). 1174-1182.
- Demirkol, E. and Uzsoy, R. (2000). "Decomposition Methods For Reentrant Flow Shops With Sequence-Dependent Setup Times." *Journal of Scheduling*. **3**(3). 155-177.
- Desrochers, A. A. and Al-Jaar, R. Y. (1995). "Application of Petri Nets in Manufacturing Systems: Modeling, Control, and Performance Analysis." New York: IEEE Press.
- Drath, R. (2003). "Visual Object Net ++." TU-Ilmenau (Germany): http://www.informatik.uni-hamburg.de/TGI/PetriNets/tools/complete_db.
- Drobouchevitch, I.G. and Strusecich, V.A. (1999). "A Heuristic Algorithm For Two-Machine Re-entrant Shop Scheduling." *Annals of Operations Research*. **86**(1). 417-439.
- Framinan, J.M., Gupta, J.N.D. and Leisten, R. (2004). "A Review And Classification Of Heuristics For Permutation Flow-Shop Scheduling With Makespan Objective." *Journal of The Operational Research Society*. **55**. 1243-1255.
- Framinan, J.M., Leisten, R. and Rajendran, C. (2003). "Different Initial Sequences For The Heuristic Of Nawaz, Enscore And Ham To Minimize Makespan, Idletime Or Flowtime In The Static Permutation Flowshop Sequencing Problem." *International Journal of Production Research*. **41**(1). 121-148.
- Framinan, J.M., Leisten, R. and Ruiz-Usano, R. (2002). "Efficient Heuristics For Flowshop Sequencing With The Objectives Of Makespan And Flowtime Minimisation." *European Journal of Operational Research*. **141**. 559-569.

- Garey, M.R., Johnson, D.S. and Sethi, R. (1976). "Complexity Of Flowshop And Jobshop Scheduling." *Mathematics of Operations Research*. 1(2). 117-129.
- Grabowski, J. and Pempera, J. (2000). "Sequencing Of Jobs In Some Production System." *European Journal of Operational Research*. 125. 535-550.
- Graves, S.C., Meal, H.C., Stefek, D. and Zeghmi, A.H. (1983). "Scheduling Of Reentrant Flow Shops." *Journal of Operations Management*. 3(4). 197-207.
- Haouari, M. and Ladhari, T. (2003). "A Branch-And-Bound-Based Local Search Method For The Flow Shop Problem." *Journal of The Operational Research Society*. 54(10). 1076-1084.
- Ho, J.C. and Chang, Y.L. (1991). "New Heuristic For The n-Job, M-Machine Flow-Shop Problem." *European Journal of Operational Research*. 52(2). 194-202.
- Ho, J.C. and Gupta, J.N.D. (1995). "Flowshop Scheduling With Dominant Machines." *Computers and Operations Research*. 22(2). 237-246.
- Hopp, W.J. and Spearman, M.L. (2008). "Factory Physics." 3rd. ed. New York: McGraw-Hill/Irwin. 516-529.
- Hwang, H. and Sun, J.U. (1997). "Production Sequencing Problem With Reentrant Work Flows And Sequence Dependent Setup Times." *Computers and Industrial Engineering*. 33(3-4). 773-776.
- Ishibuchi, H., Misaki, S. and Tanaka, H. (1995). "Modified Simulated Annealing Algorithms For The Flow Shop Sequencing Problem." *European Journal of Operational Research*. 81. 388-398.

- Kalczynski, P.J. and Kamburowski, J. (2007). "On The NEH Heuristic For Minimizing The Makespan In Permutation Flow Shops." *The International Journal of Management Science (OMEGA)*. **35**. 53-60.
- Kalczynski, P.J. and Kamburowski, J. (2005). "A Heuristic For Minimizing The Makespan In No-Idle Permutation Flow Shops." *Computers and Industrial Engineering*. **49**. 146-154.
- Kalir, A.A. and Sarin, S.C. (2001). "A Near-Optimal Heuristic For The Sequencing Problem In Multiple-Batch Flow-Shops With Small Equal Sublots." *The International Journal of Management Science (OMEGA)*. **29**. 577-584.
- King, J.R. and Spachis, A.S. (1980). "Heuristics For Flow-Shop Scheduling." *International Journal of Production Research*. **18**(3). 345-357.
- Koulamas, C. (1998). "A New Constructive Heuristic For The Flow Shop Scheduling." *European Journal of Operational Research*. **105**. 66-71.
- Koulamas, C. and Kyparisis, G.J. (2008). "A Note On The Proportionate Flow Shop With A Bottleneck Machine." *European Journal of Operational Research*.
doi:10.1016/j.ejor.2008.01.031.
- Kubiak, W., Lou, S.X.C. and Wang, Y. (1996). "Mean Flow Time Minimization In Reentrant Job Shops With A Hub." *Operations Research*. **44**(5). 764-776.
- Lee, L. (2000). "Zero Wait Flow Shop With Multiple Processors With Heuristics, Algorithm, And Mathematical Concepts." University of Houston: Ph.D. Thesis.
- Lian, Z., Gu, X. and Jiao, B. (2008). "A Novel Particle Swarm Optimization Algorithm For Permutation Flow-Shop Scheduling To Minimize Makespan." *Chaos, Solitons and Fractals*. **35**(5). 851-861.

- Lai, T.C. (1996). "Note On Heuristics Of Flow Shop Scheduling." *Operations Research*, 44(4). 648-652.
- Ling, S. and Loke, S. W. (2002). "Advanced Petri Nets for Modeling Mobile Agent Enabled Interorganizational Workflows." Proceedings of the 9th Annual IEEE International Conference and Workshop on the Engineering of Computer-Based Systems (ECBS'02)
- Lourenco, H.R. (1996). "Sevast'yanov's Algorithm For The Flow-Shop Scheduling Problem." *European Journal of Operational Research*, 91. 176-189.
- McCormick, S.T., Pinedo, M.L., Shenker, S. and Wolf, B. (1989). "Sequencing In An Assembly Line With Blocking To Minimize Cycle Time." *Operations Research*, 37(6). 925-935.
- Moccellin, J.V. (1995). "New Heuristic Method For The Permutation Flow Shop Scheduling." *Journal of The Operational Research Society*, 46(7). 883-886.
- Mukherjee, S. and Chatterjee, A.K. (2006). "Applying Machine Based Decomposition In 2-Machine Flow Shops." *European Journal of Operational Research*, 169. 723-741.
- Murata, T., Ishibuchi, H. and Tanaka, H. (1996). "Genetic Algorithms For Flowshop Scheduling Problems." *Computers and Industrial Engineering*, 30(4). 1061-1071.
- Nawaz, M., Enscore, E.E. and Ham, I. (1983). "A Heuristic Algorithm For The m -Machine, n -Job Flow Shop Sequencing Problem." *The International Journal of Management Science (OMEGA)*, 11. 91-95.
- Nearchou, A.C. (2004). "Flow-Shop Sequencing Using Hybrid Simulated Annealing." *Journal of Intelligent Manufacturing*, 15(3). 317-328.

- Nouweland, V.D.A., Krabbenborg, M. and Potters, J. (1992). "Flow-Shops With A Dominant Machine." *European Journal of Operational Research*. 62(1). 38-46.
- Nowicki, E. and Smutnicki, C. (1996). "A Fast Tabu Search Algorithm For The Permutation Flow Shop Problem." *European Journal of Operational Research*. 91. 160-175.
- Ogbu, F.A. and Smith, D.K. (1990). "The Application Of The Simulated Annealing Algorithm To The Solution Of The $n/m/C_{max}$ Flowshop Problem." *Computers and Operations Research*. 17(3). 243-253.
- Onwubolu, G.C. (1996). "A Flow-shop Manufacturing Scheduling System With Interactive Computer Graphics." *International Journal of Operations & Production Management*. 16(9). 74-84
- Osman, I.H. and Potts, C.N. (1989). "Simulated Annealing For Permutation Flow-Shop Scheduling." *The International Journal of Management Science (OMEGA)*. 17(6). 551-557.
- Pan, J.C.H., Chen, J.S. and Chao, C.M. (2002). "Minimizing Tardiness In A Two-Machine Flow-Shop." *Computers and Operations Research*. 29. 869-885.
- Pan, J.C.H. and Chen, J.S. (2003). "Minimizing Makespan In Re-Entrant Flow-Shop." *Journal of The Operational Research Society*. 54. 642-653.
- Pearn, W.L., Chung, S.H., Chen, A.Y. and Yang, M.H. (2004). "A Case Study On The Multistage IC Final Testing Scheduling Problem With Reentry." *International Journal of Production Economics*. 88. 257-267.

- Pinedo, M. (2002). "Scheduling: Theory, Algorithms, And Systems." Upper Saddle River, New Jersey.:Prentice-Hall.
- Ponnambalam, S.G., Aravindan, P. and Chandrasekaran, S. (2001). "Constructive And Improvement Flow Shop Scheduling Heuristics: An Extensive Evaluation." *Production Planning and Control*. **12**(4). 335-344.
- Pour, H.D. (2001). "A New Heuristic For The n -Job, m -Machine Flow-Shop Problem." *Production Planning and Control*. **12**(7). 648-653.
- Prabhakaran, G., Khan, B.S.H. and Rakesh, L. (2006). "Implementation Of Grasp In Flow Shop Scheduling." *International Journal of Advanced Manufacturing Technology*. **30**(11-12). 1126-1131.
- Proth, J. M. and Xie, X. (1996). "Petri Nets: A Tool for Design and Management of Manufacturing System." West Sussex, England: John Wiley.
- Rajendran, C. (1993). "Heuristics Algorithm For Scheduling In A Flowshop To Minimize Total Flowtime." *International Journal of Production Economics*. **29**(1). 65-73.
- Raman, N. (1995). "Minimum Tardiness Scheduling In Flow Shops: Construction And Evaluation Of Alternative Solution Approaches." *Journal of Operations Management*. **12**. 131-151.
- Reeves, C.R. (1995). "A Genetic Algorithm For Flowshop Sequencing." *Computers and Operations Research*. **22**(1). 5-13.
- Reeves, C.R. (1993). "Improving The Efficiency Of Tabu Search For Machine Sequencing Problems." *Journal of The Operational Research Society*. **44**(4). 375-382.

- Roth, S. and Starke, P.H. (2003). "INA: Integrated Net Analyser Version 2.2." Berlin: Humboldt-Universitat. <http://www2.informatik.hu-berlin.de/~starke/ina.html>
- Ruiz, R. and Maroto, C. (2005). "A Comprehensive Review And Evaluation Of Permutation Flowshop Heuristics." *European Journal of Operational Research*. **165**. 479-494.
- Ruiz, R. and Stutzle, T. (2007). "A Simple And Effective Iterated Greedy Algorithm For The Permutation Flowshop Scheduling Problem." *European Journal of Operational Research*. **177**. 2033-2049.
- Sarin, S. and Lefoka, M. (1993). "Scheduling Heuristic For The n -Job, m -Machine Flow Shop." *The International Journal of Management Science (OMEGA)*. **21**(2). 229-234.
- Sevast'Janov, S. (1995). "Vector Summation In Banach Space And Polynomial Algorithms For Flow Shops And Open Shops." *Mathematics of Operations Research*. **20**(1). 90-103.
- Stinson, J.P. and Smith, A.W. (1982). "Heuristic Programming Procedure For Sequencing The Static Flowshop." *Production Research*. **20**(6). 753-764.
- Suliman, S.M.A. (2000). "A Two-Phase Heuristic Approach To The Permutation Flow-Shop Scheduling Problem." *International Journal of Production Economics*. **64**. 143-152.
- Taillard, E. (1990). "Some Efficient Heuristic Methods For The Flow Shop Sequencing Problem." *European Journal of Operational Research*. **47**(1). 65-74.
- Turner, W.C., Mize, J.H., Case, K.E. and Nazemetz, J.W. (1993). "Introduction To Industrial And Systems Engineering." 3rd. ed. Englewood Cliffs, New Jersey.: Prentice-Hall. 14.

- Wang, J.B. (2007). "Flow Shop Scheduling Problems With Decreasing Linear Deterioration Under Dominant Machines." *Computers and Operations Research*, **34**, 2043-2058.
- Wang, J.B. and Xia, Z.Q. (2005). "No-Wait Or No-Idle Permutation Flowshop Scheduling With Dominating Machine." *Journal of Applied Mathematics and Computing*." **17**(1-2), 419-432.
- Wang, J.B., Shan, F., Jiang, B. and Wang, L.Y. (2006). "Permutation Flow Shop Scheduling With Dominant Machines To Minimize Discounted Total Weighted Completion Time." *Applied Mathematics and Computation*." **182**(1), 947-957.
- Wang, L., Wu, H. and Zheng, D.Z. (2005). "A Quantum-Inspired Genetic Algorithm For Scheduling Problems." *Lecture Notes in Computer Science: Advances in Natural Computation*. **3612**(3), 417-423.
- Wang, L. and Zheng, D.Z. (2003). "An Effective Hybrid Heuristic For Flow Shop Scheduling." *International Journal of Advanced Manufacturing Technology*. **21**(1), 38-44.
- Wang, M.Y., Sethi, S.P. and Van de Velde, S.L. (1997). "Minimizing Makespan In A Class Of Reentrant Shops." *Operations Research*, **45**(5), 702-712.
- Werner, F. (1993). "On The Heuristic Solution Of The Permutation Flow Shop Problem By Path Algorithms." *Computers and Operations Research*, **20**(7), 707-722.
- Widmer, M. and Hertz, A. (1989). "New Heuristic Method For The Flow Shop Sequencing Problem." *European Journal of Operational Research*. **41**(2), 186-193.

- Woo, H.S. and Yim, D.S. (1998). "A Heuristic Algorithm For Mean Flow Time Objective In Flowshop Scheduling." *Computers and Operations Research*, **25**(3). 175-182.
- Xiang, S., Tang, G. and Cheng, T.C.E. (2000). "Solvable Cases Of Permutation Flowshop Scheduling With Dominant Machines." *International Journal of Production Economics*. **66**. 53-57.
- Yamada, T. and Reeves, C.R. (1998). "Solving The C_{sum} Permutation Flowshop Scheduling Problem By Genetic Local Search." Proc. of the IEEE Conference on Evolutionary Computation, ICEC 1998. 230-234.
- Yang, D.L., Kuo, W.H. and Chern, M.S. (2008). "Multi-Family Scheduling In A Two-Machine Reentrant Flow Shop With Setups." *European Journal of Operational Research*. **187**(3). 1160-1170.
- Ying, K.C. and Liao, C.J. (2004). "An Ant Colony System For Permutation Flow Shop Sequencing." *Computers and Operations Research*, **31**. 791-801.
- Zegordi, S.H., Itoh, K. and Enkawa, T. (1995). "Minimizing Makespan For Flow Shop Scheduling by Combining Simulated Annealing With Sequencing Knowledge." *European Journal of Operational Research*. **85**. 515-531.