2015

Multi-Period Cell Loading and Job Sequencing in a Cellular Manufacturing System

Gokhan Egilmez
University of New Haven, gegilmez@newhaven.edu

Gürsel A. Süer
Ohio University

Publisher Citation

Egilmez, G., & Süer, G. A. (2015). Multi-period cell loading and job sequencing in a cellular manufacturing system. International Journal of Advanced Operations Management, 7(2), 98-113.

Multi-period Cell Loading and Job Sequencing in a Cellular Manufacturing System

[1]Gokhan EGILMEZ and [2]Gürsel A. SÜER

[1]Assistant Professor, Department of Industrial and Manufacturing Engineering, North Dakota State University, Fargo ND
Tel: (701) 231-7286 Fax: (701) 231-7295
Address: 1410 14th Ave. N. Civil and Industrial Engineering Building, Room: 202K Fargo, ND 58102
(Corresponding author, email: gokhan.egilmez@ndsu.edu)

[2]Professor, Department of Industrial and Systems Engineering, Russ College of Engineering and Technology, Ohio University, Athens, OH, 45701 USA
Email: suer@ohio.edu, Phone: (740) 593-1542 Fax: (740) 593-0778

Author Bios:

Gokhan Egilmez serves as an assistant professor of Industrial and Manufacturing Engineering at North Dakota State University. He also worked as postdoctoral research associate in the dept. of Civil, Environmental and Construction Engineering at University of Central Florida prior to joining department of IME at NDSU. He obtained a doctorate degree in Mechanical and Systems Engineering and two master degrees in Industrial and Systems Engineering and Civil Engineering at Ohio University between 2007 and 2012. Prior to his higher education, in the United States, he received his BS in Industrial Engineering at Istanbul Technical University, Turkey in 2007. Gokhan has various peer-reviewed research articles, book chapter and conference proceedings related to sustainable development, manufacturing system design & control, supply chain management, transportation safety and predictive modeling & machine learning. For more information: http://gokhanegilmez.wordpress.com/

Gursel A. Suer is professor of Industrial and Systems Engineering at Ohio University. He has over 120 publications in various areas including cellular manufacturing systems, scheduling, supply chain management, and genetic algorithms. He has worked in University of Puerto Rico prior to joining Ohio University. Currently, he is manufacturing area editor of Computers and Industrial Engineering Journal. He is still working rigorously to conduct research in the aforementioned areas, mentoring graduate students and prospective scholars.

Multi-period Cell Loading and Job Sequencing in a Cellular Manufacturing System

Abstract

In this paper, a multi-period cell loading problem is addressed. The problem is observed in a thermo siphon manufacturing company. The objectives are to minimize the number of tardy jobs

(nT) in a multi-period planning horizon and optimize the scheduling of tardy jobs. Three cell loading and job scheduling strategies are proposed to determine the optimal cell loads and job sequences. To do so, two mixed integer programming-based mathematical models were developed and utilized in the experimentation. Additionally, three types of due dates (tight, medium and loose) were used to study the impact of tightness of due times. To study the impact of capacity requirements, three different demand levels were considered. Finally, two tardy job assignment methods were proposed to observe the impact on the performance measure, *nT*. Case problems were solved based on the primary performance measure (*nT*) and secondary performance measures (maximum tardiness, Tmax and total tardiness, TT). Finally, a cost sensitivity analysis was also performed to observe the performance of the proposed cell loading and job scheduling strategies. Results indicated that, the first strategy, (early start allowance and tardy job assignment after each period) performed better in terms of nT. For the secondary objectives, tradeoffs were observed among different strategies depending on the type of due date, demand level and tardy job assignment method.

Key words: Cellular manufacturing, number of tardy jobs, multi-period, cell loading, scheduling tardy jobs.

1. Introduction

Group Technology and Cellular Manufacturing have been important paradigms in the last quarter century of manufacturing design, planning and operation efforts worldwide. Group Technology (GT) is an approach used to identify products or parts with either similar design characteristics or similar manufacturing process routes and group them into product (part) families so as to increase the overall process similarity in manufacturing cells (Egilmez et al., 2011; Egilmez and Süer, 2013). In this regard, cellular manufacturing (CM) has been developed as a new manufacturing philosophy to deal with higher product variety and mid to low demand volume and successfully implemented worldwide as an application of GT philosophy to produce high variety of products more efficiently based on single unit flow rule.

Cellular manufacturing systems require two major decision making phases, namely: design (cell formation) and control (cell loading and scheduling) phases. Design phase deals with formation of product families and manufacturing cells, equipment and operator assignment problems (Egilmez and Süer, 2014). While design phase is completed as a result of more strategic and long term decision activity, control phase is more dynamic which requires short to mid-term operational and tactical level decisions. In addition to the strategic decisions associate with design phase, as a manufacturing control approach, cell loading and job scheduling has also been an integral part of CM in both industry and literature. Cell loading is the assignment of jobs to corresponding cells and job scheduling is the determining the sequence of jobs. While controlling a cellular manufacturing system where cell loading and job scheduling decisions are being made, several performance measures can be utilized depending on various factors such as assignment strategy, customer characteristics, due date, capacity requirements (Egilmez and Süer, 2013; Egilmez et al. 2012).

From internal manufacturing performance and external customer satisfaction performance, timelines in completing jobs is very critical in today's world. And, scheduling has an integral impact on the implementation of tactical and operational decision within a manufacturing system. Depending on the performance measurement focus area, several metrics have been used in scheduling literature including minimizing the number of tardy or late jobs, total tardiness, the maximum tardiness and earliness, etc. Among them, minimizing the number of tardy jobs has been a topic of interests in both academia and industry applications, since individual customer

satisfaction is directly related with the number of customers and their corresponding orders' delivery performance. In this regard, minimizing number of tardy jobs *(n_T)* is one of the widely used performance measures in machine scheduling and cellular manufacturing system control. A job is classified as "tardy" when its completion time (c_i) is greater than the due date (d_i); i.e. ($c_i > d_i$). Since the customer expectations and delivery performance are strongly correlated in today's highly competitive industrial world, companies have to satisfy their customers in terms of quality, cost and timeliness. In doing so, minimizing the number of tardy jobs is a significant performance measure for customer satisfaction (Egilmez and Suer, 2014).

The majority of scheduling literature dealt with scheduling problems for a certain period of time where multiple jobs are optimally ordered to be processed on resource(s). However, multi-period environment is indeed a critical aspect of the scheduling problem since each period that is considered for the scheduling problem can have a delaying effect on the jobs' schedule in the consecutive period. Therefore, in this study, the researchers addressed a cell loading and job scheduling problem is addressed in a multi-period environment. The primary objective is to minimize the number of tardy jobs in a cellular manufacturing system. Other performance measures, total tardiness and the maximum tardiness are also considered in the scope of study. The rest of paper is structured as follows. The related literature is provided in section 2. Section 3 introduces the problem statement. The methodology is described in section 4. Experimental setup is explained in section 5. Results are discussed in section 6. Conclusion and future remarks are given in section 7.

2. Literature Review

A job can be assigned to one of the available cells unless job splitting is allowed. In this regard, cell loading is similar to the classic parallel machine scheduling problem (Süer, 1997). Therefore, literature review section is grouped into two as parallel machine scheduling and cell loading and job scheduling.

2.1 Parallel Machine Scheduling:

Parallel machine scheduling literature is abundant with works where various performance measures are considered including minimizing n_T. Süer et al. (1993) developed an integer programming model and experimented with three heuristic procedures for minimizing n_T

objective. In another work, Ho and Chang (1995) proposed two heuristic methods for minimizing n_T objective in a parallel machine scheduling problem. Süer, Pico, and Santiago (1997) developed four mathematical models for the identical parallel machine scheduling problem to minimize n_T when job splitting is allowed. Gupta, Ruiz-Torres, and Webster, (2003) studied hierarchical criteria identical parallel machine problem where n_T is considered as the primary objective and minimum flow time is utilized as the secondary objective. As alternative approach, M'Hallah and Bulfin (2005) developed a branch and bound algorithm to minimize the weighted number of tardy jobs on identical and non-identical parallel machine systems. Several mathematical optimization-based and heuristic approaches have been proposed in the parallel machine scheduling literature. Some examples of the recent optimization approaches include uniform, unrelated and identical parallel machine systems with various objectives such as minimizing makespan, tardy jobs and additional parameters such as learning effect (e.g. Lee et al., (2012), Kaplan et al. (2013) Hsu et al. (2011), Chang et al. (2011), Vallada and Ruiz (2011), Lin et al. (2011), and Biskup (2008).

2.2 Cell Loading & Job Sequencing:

In spite of the similarity between cell loading and parallel machine scheduling, cell loading is different due to the involvement of part families with different processing requirements which makes cell loading task challenging due to the potential existence of cells that are not capable of processing all of the parts. Additionally, while processing times are used directly to build the schedules in parallel machine systems; in cell loading, first production rates are determined based on the routes and processing times information then cell loading and job sequencing tasks are performed (Süer, 1997). Greene and Sadowski (1983) argued pros and cons of utilizing cellular manufacturing systems. Süer (1997) developed two mixed integer mathematical models to minimize the number of tardy jobs in a multi-period environment. In another work, Süer and Bera (1998) developed an approach which simultaneously performs the cell loading and cell size determination in a labor intensive manufacturing system. Süer et al. (1999) presented manufacturing cell loading rules for multi-independent cells. Even though the cell loading and scheduling literature is not as abundant as it is in parallel machine scheduling, there are a few works published in recent years. For instance, Süer et al. (2013) proposed mathematical optimization and Genetic Algorithms to minimize the total tardiness in labor intensive manufacturing cells. In another work, Egilmez et al. (2014) focused on simultaneous manpower

allocation and cell loading. Additionally, integrated cellular design and control problem has also been recently addressed in the presence of probabilistic processing times and product demand (Egilmez and Süer, 2013). The most recent work addressed a stochastic mathematical optimization model for a set of cell loading and job scheduling problems in a single period environment (Egilmez and Süer, 2014). Even though, recent literature addressed interesting problems related to cellular design and control, multi-period environment has not been studied. Therefore, in this paper, minimizing the number of tardy jobs in a multi-period cellular manufacturing environment is studied and two mixed integer programming-based mathematical models are equipped with three cell loading and job scheduling strategies.

3. Problem Definition

A thermo-siphon body manufacturing system is taken as the case study for the problem. The manufacturing process consists of forming, welding and leak test. There are two identical and self-sufficient cells equipped to perform all operations for all jobs. A four-period horizon has been considered for experimentation where each planning period consists of one week with 40 hours of capacity, thus having a total production capacity of 80 hours per week. Each job is considered to have its own due date. There are seven products with varying unit processing times exist in manufacturing system.

4. Methodology

In an earlier work, Süer (1997) developed two mathematical models to minimize the number of tardy jobs in a multi-period time horizon. This study introduces, three heuristic cell loading and job sequencing strategies to optimize the job sequences in cells and assignment of tardy jobs. The first mathematical model minimizes n_T for all periods by allowing early start of jobs. On the other hand, the second mathematical model is used to minimize n_T when early start is not allowed. In this case, early start allows utilizing available capacity of previous period. In fact, the two mathematical models can be useful in different production planning systems. For example, in a manufacturing system where equipment and people utilization is very critical and due dates are very tight, it would be desirable to process the jobs earlier than needed if resources are available. On the other hand, in a Just in Time (JIT) environment, the timeliness of the production is more critical and inventory carrying is not desired.

4.1. Basic Information about the Proposed Models

Both mathematical models are mixed integer programming models. Prior to experimentation, all jobs are sorted by Earliest Due Date (*EDD*) thus obtaining $d_{[1]} \leq d_{[2]} \leq d_{[3]} \leq \ldots\ldots \leq d_{[n]}$. The notation and formulation of models are given as follows.

<u>Notation</u>

n	number of jobs
m	number of cells
$d_{[i]}$	due date of the job in the i^{th} order
$P_{[i]t}$	processing time of the job in the i^{th} order in period t
$X_{[i]j}$	1 if the job in the i^{th} order is assigned to cell j
	0 otherwise
CA	Capacity available per cell per period
T	The number of periods

<u>Indices</u>

i	Job index
j	Cell index
t	Period index

The following assumptions are made in both mathematical models:

i) A job can be assigned to only one cell.
ii) Each job is equally important.
iii) Cells are identical and independent.
iv) Each cell is capable of producing all jobs.
v) Overtime is not allowed.
vi) Customers accept late delivery (no lost sales)

4.2. Mathematical Model 1: Early Start is Allowed

The objective of this mathematical model is to maximize the number of early jobs which is equivalent to minimizing the number of tardy jobs. The objective function is shown in Equation (1). The first constraint forces early jobs to be completed by their due date as shown in Equation

(2). The second constraint (Equation 3) limits the assignment of a job to at most one cell. The decision variable takes only binary values as 0 or 1 which reflects the assignment of a job to a cell.

Objective function:

$$Max\ Z = \sum_{t=1}^{T}\sum_{i=1}^{n}\sum_{j=1}^{m} X_{[i]jt} \qquad (1)$$

Subject to:

$$\sum_{t=1}^{T}\sum_{i=1}^{k}\{P_{[i]t}X_{[i]jt}\} \le d_{[k]t} \qquad (2)$$

k = 1, 2, 3,…, n

j = 1, 2, 3,…, m

t = 1, 2, 3,…, T

$$\sum_{t=1}^{T}\sum_{j=1}^{m} X_{[i]jt} \le 1 \qquad (3)$$

i = 1, 2, 3,…, n

t = 1, 2, 3,…, T

$X_{[i]jt} \in (0, 1)$ for all *i, j* and *t*.

4.3. Mathematical Model 2: Early Start is not Allowed

In this model, jobs are not allowed to start early, which means every job is scheduled to the period they are due. The objective function is the same as in mathematical model 1, minimizing the number of tardy jobs. The first constraint in the previous mathematical model is modified to fit to this problem (Equation 4). A parameter, CA, is defined to denote the capacity available in a period which actually blocks the early start of jobs. All other constraints and assumptions are kept the same as in the previous mathematical model.

Subject to:

$$CA_{(t-1)} + \sum_{t=1}^{T}\sum_{i=1}^{k}\{I_{[i]t}\}X_{[i]jt} \le d_{[k]t} \qquad (4)$$

k = 1, 2, 3,…, n

j = 1, 2, 3,…, m

t = 1, 2, 3,…, T

4.4. Tardy Job Assignment Strategies

Minimizing the number of tardy jobs in a cellular manufacturing system is vital from the customer satisfaction and manufacturing system control performance perspectives. However, assignment of tardy jobs is another crucial task and is rarely addressed in scheduling and cellular control

literatures. Once the early jobs are scheduled to their corresponding cells, the next task is the assignment of tardy jobs. Three strategies are proposed to deal with this phase of the problem.

Strategy A: Early start is allowed and tardy jobs are added at the end of the period they were due. In this strategy, cells are loaded and job sequence is obtained based on "early start allowed" strategy. Early start allows processing a job in an earlier period. The tardy jobs are assigned after the last early job in the same period they were due.

Strategy B: Early start is allowed and tardy jobs are added at the end of planning horizon. In this strategy, early start approach is kept as the same as the previous strategy. However, the assignment of tardy jobs is different. Tardy jobs are added after the entire planning horizon, which is the 4^{th} period in this study.

Strategy C: Early start is not allowed and tardy jobs are added at the end of the period they were due. In this strategy, early start is not allowed and mathematical model 2 is used to minimize the number of tardy jobs. The assignment of tardy jobs is performed using Strategy A.

Allowing of early start means that as long as capacity is available (current load is less than 40 hours for one cell), following periods' jobs can be processed in advance. On the other hand, if early start is not allowed, a job can only be processed in the period it is due. Mathematical model 1 is used along with Strategy A and Strategy B. Mathematical model 2 is used for Strategy C. These strategies are illustrated Figure 1. Two rules are used to include the tardy jobs in the schedule, namely Earliest Due Date (EDD) and Shortest Processing Time (SPT).

4.5. A Numerical Example for the Strategies A, B and C

A 9-job numerical example is used to illustrate the methodology. The batch production times and due dates of the jobs in periods P1, P2, P3 and P4 are shown in Table 1.

Table 1: Example problem

Job	Due Date				Batch Production Time			
	Period 1	Period 2	Period 3	Period 4	Period 1	Period 2	Period 3	Period 4
1	12	14	13	12	12	14	13	12
2	6	8	10	8	3	4	5	4
3	14	14	12	12	7	7	6	6
4	10	6	6	8	5	3	3	4
5	12	18	15	12	4	6	5	4
6	6	4	6	8	3	2	3	4
7	8	10	8	9	8	10	8	9
8	10	10	10	10	5	5	5	5
9	20	24	20	24	5	6	5	6

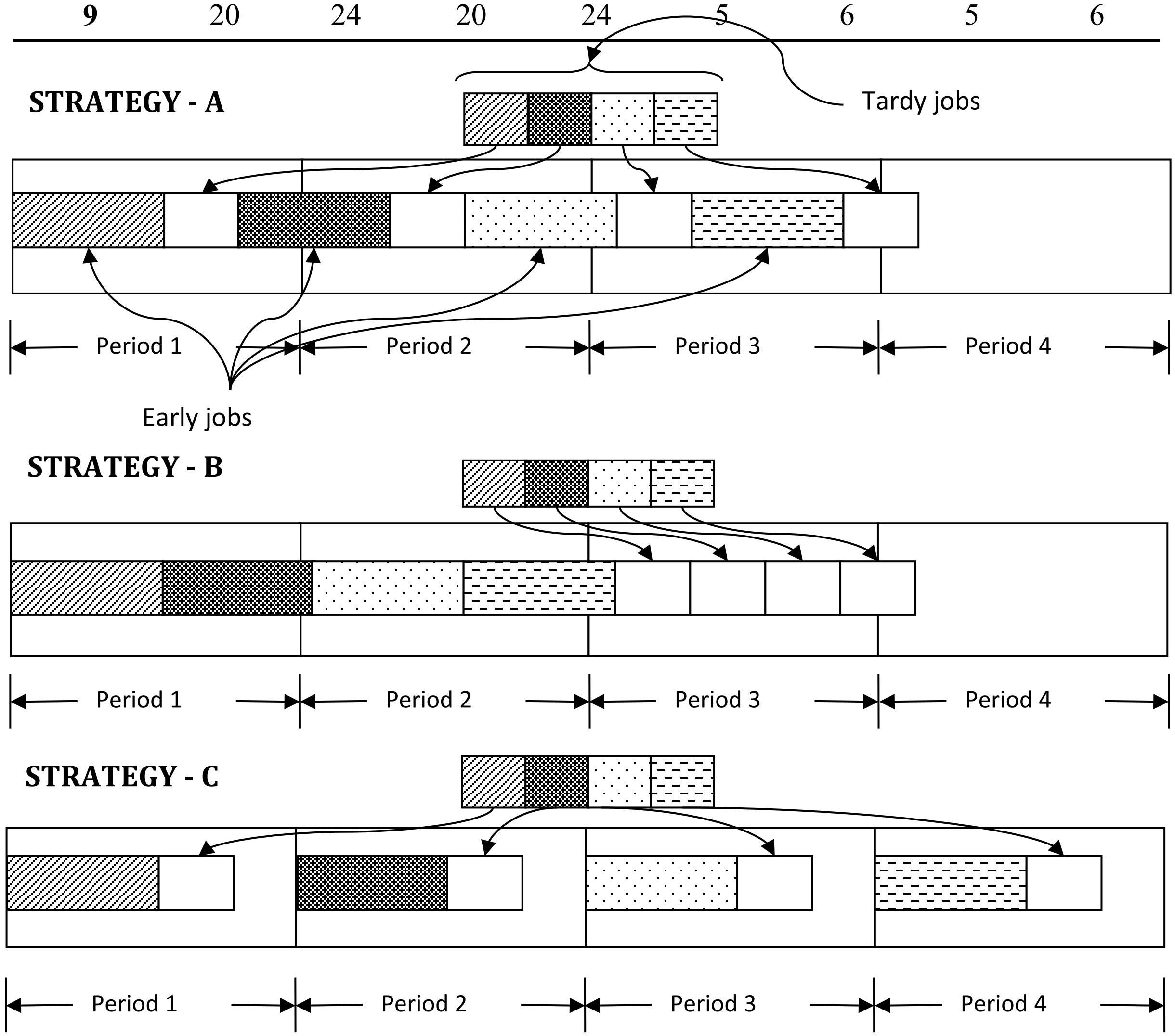


Figure 1. The illustration of three strategies

Solution with Strategy A: In this strategy, mathematical model 1 is used to solve the problem and the results are summarized in Table 2. Tardy jobs were added to the schedule after the period they were due. Tardy jobs are identified; T_{max} and TT values are also computed.

Table 2: Results of Strategy A for the Example Problem

Period	Period 1	Period 2	Period 3	Period 4
CELL1	4 8 9	2 1 9	4 6 2 8 3 1 5 9	2 4 6 7 8 1 3 5 9
CELL2	2 6 3	6 4 7 8 3 5	7	
TARDY	1 5 7			
n_T	3	0	0	0
$\sum n_T$	3			
T_{max}	25			
TT	63			

Solution with Strategy B: In this strategy, mathematical model 1 was used to optimize the number of tardy jobs. The tardy jobs are added at the end of planning horizon and the results are shown in Table 3.

Table 3: Results of Strategy B for the Example Problem

Periods	Period 1	Period 2	Period 3	Period 4
Cell 1-Early Jobs	4 8 9	1 2 9	1 2 3 4 5 6 8 9	1 2 3 4 5 6 7 8 9
Cell 2-Early Jobs	2 3 6	3 4 5 6 7 8		
Tardy Jobs	1 5 7	`		
nT	3	0	0	0
$\sum nT$	3			
T_{max}	66			
TT	182			

Solution with Strategy C: Mathematical model 2 is used since early start is not allowed in this strategy. The results are shown in Table 4.

Table 4: Results of Strategy C for the Example Problem

Period	Period 1	Period 2	Period 3	Period 4
Cell 1- Early jobs	3 8	4 5 8 9	3 4 6 9	2 3
Cell 2- Early jobs	2 4 5 9	2 3 6	2 5 8	4 5 9
Tardy jobs	1 6 7	1 7	1 7	1 6 7 8
n_T	3	2	2	4
$\sum n_T$	11			
T_{max}	20			
Total Tardiness	144			

5. Experimentation

The experimentation includes two sections as the initial data generation and the experimentation. It is carried out on a computer with 2-Gb memory and 1.7- Ghz dual core processor.

5.1. Data Generation

The processing times and due dates of jobs are generated randomly. Customer orders are generated for each period. Lot size (order quantities) for each job is generated from uniform distributions as shown in Table 5. Each product has a unit processing time as given in Table 6. According to table 1, products 1,2,3,4 and 5 used in 60 %, products 3,4,5 and 6 used in 80 % and products 4,5,6 and 7 used in 100 % capacity requirement level data generation. Capacity requirements for 25 jobs are generated from multiplying products' unit processing times and lot sizes. Capacity requirements are used as throughput times in cell loading and job sequencing. Job processing times are calculated by multiplying lot sizes and unit process times. Additionally, due dates are generated from uniform distributions as shown in Table 7.

Table 5: Statistical distributions used in data generation

Capacity Requirement	Lot sizes for each job ordered	Unit Process Times (Hrs)	Products Used In Generation
60%	Uniform Dist. (10, 30)	Uniform Dist. (0.07, 0.1)	Products 1,2,3,4,5
80%	Uniform Dist. (15, 35)	Uniform Dist. (0.09, 0.11)	Products 3,4,5,6
100%	Uniform Dist. (25, 35)	Uniform Dist. (0.1, 0.12)	Products 4,5,6,7

Table 6: Unit processing times

Product	Unit Process Time (Hrs)
1	0.07
2	0.08
3	0.09
4	0.1
5	0.1
6	0.11
7	0.12

Table 7: Distribution parameters used in due date generation

Due Date Type	Distribution Used (Hrs)
Tight	Uniform(0, 17)
Medium	Uniform(10, 27)
Loose	Uniform(20, 37)

5.2. Experimentation

Twenty seven cases are experimented with that includes three strategies (Strategies A, B and C), three types of due dates (tight, medium and loose) and three capacity requirement levels (60%, 80% and 100% of the system capacity) are experimented. Mathematical models are solved by using ILOG-OPL CPLEX optimization software. Earliest Due Date (EDD) and Shortest Processing Time (SPT) rules are used to schedule tardy jobs.

6. Results

The consolidated results are shown in Table 8. The results are grouped in four sections; comparison of strategies, comparison of due dates, comparison of demand levels, and comparison of scheduling rules for tardy jobs.

6.1. Analysis of results based on the selected performance measures: n_T, TT, T_{max}

In this section, the results are discussed considering the selected performance measures individually. The comparative discussions are made based on the proposed three cell loading and job sequencing strategies, the impacts of due dates, demand levels and tardy job assignment strategies as follows.

Table 8: Results of the Experimentation

Strategy A	Strategy	Due Date Type	Periods				Total	EDD	SPT	EDD	SPT
			1	2	3	4	n_T	T_{max}		TT	
60%	ES IS ALLOWED	TIGHT	6	0	0	0	6	40.95	44.45	235.83	234.46
		MEDIUM	0	0	0	0	0	0	0	0	0
		LOOSE	0	0	0	0	0	0	0	0	0
80%	ES IS ALLOWED	TIGHT	9	0	0	0	9	112.78	122.97	958.02	953.19
		MEDIUM	1	0	0	0	1	97.58	97.58	97.58	97.58
		LOOSE	0	0	0	0	0	0	0	0	0
100%	ES IS ALLOWED	TIGHT	13	0	0	0	13	141.6	147.86	963.92	949.49
		MEDIUM	5	0	0	0	5	136.3	141.51	667.47	667.1
		LOOSE	6	0	0	0	6	122.46	126.92	722.48	722.16

Strategy B	Strategy	Due Date Type	Periods				Total	EDD	SPT	EDD	SPT
			1	2	3	4	n_T	T_{max}		TT	
60%	ES IS ALLOWED	TIGHT	6	0	0	0	6	15.67	18.23	79.2	78.37
		MEDIUM	0	0	0	0	0	0	0	0	0
		LOOSE	0	0	0	0	0	0	0	0	0
80%	ES IS ALLOWED	TIGHT	9	8	5	3	22	17.54	26.56	227.97	231.57
		MEDIUM	1	0	0	0	1	19.4	19.4	19.4	19.4
		LOOSE	0	0	0	0	0	0	0	0	0
100%	ES IS ALLOWED	TIGHT	13	22	22	21	57	102.49	102.56	1056.03	1051.14
		MEDIUM	5	9	11	10	25	17.29	24.8	213	212.53
		LOOSE	6	6	5	1	17	11.02	11.04	90.45	93.39

Strategy C	Strategy	Due Date Type	Periods				Total	EDD	SPT	EDD	SPT
			1	2	3	4	n_T	T_{max}		TT	
60%	ES IS NOT ALLOWED	TIGHT	6	6	7	6	25	17.15	19.96	349.12	344.78
		MEDIUM	0	0	0	0	0	0	0	0	0
		LOOSE	0	0	0	0	0	0	0	0	0
80%		TIGHT	9	7	11	9	36	22.97	28.26	623.23	610.97

	ES IS NOT ALLOWED	MEDIUM	1	3	4	1	9	32.6	32.6	144.59	143.65
		LOOSE	0	0	0	0	0	0	0	0	0
100%	ES IS NOT ALLOWED	TIGHT	12	11	12	13	48	28.07	34.05	970.58	981.85
		MEDIUM	4	5	5	4	18	17.22	20.42	235.27	222.68
		LOOSE	5	1	2	2	10	14.1	14.1	47.08	42.3

6.1.1. Comparison of the proposed three cell loading and job sequencing strategies

Based on the objective of minimizing nT, strategy A provided the best solution for all demand levels and types of due dates. In terms of Tmax, strategy B provided the best solutions for all due dates and for 60 % and 80 % demand levels. In the case of 100 % demand level, there is a tradeoff observed between strategy A and B in terms of the type of due date. Additionally, EDD strategy worked slightly better than SPT in all cases. In terms of TT, there is no dominant strategy observed. Tradeoff occurs among strategies depending on the type of due date, demand level and tardy job assignment strategy. For example, strategy B is dominating others in 60 % demand level for the tight due date. On the other hand, strategy A is dominating others in 100 % demand level and tight due date.

6.1.2. Due date-based comparison

Results based on the type of due date revealed interesting conclusions about the performance of the proposed strategies. For instance, when due dates are tight, strategy A is the dominant in terms of nT (equivalency with strategy B is occurred in 60 % demand level). On the other hand, strategy B is observed as the dominant in terms of Tmax for 60 % and 80 % demand levels for the tight due dates. Strategy C is observed as the best strategy only for the 100 % demand level case.

In terms of medium due dates, strategy A is found to be the dominant strategy for minimizing nT objective (equivalency with strategy B is occurred in 60 % and 80 % demand levels). Besides, both of the strategies B and C worked better than A in terms of Tmax and there is no dominant strategy observed in this case. For the TT objective, strategy B is dominating other strategies for all demand levels and assignment strategies.In loose due date category, positive number of tardy jobs observed only in 100 % demand levels. In terms of nT, strategy A is dominating other

strategies. For the Tmax, strategy B is dominating other strategies and in terms of TT, strategy C is found as the dominant strategy compared to other strategies.

6.1.3. Demand level based comparison

Demand level has significant impact on system performance in terms of capacity requirements. Results indicated that when demand level is 60 % and 80 %; both of the strategies A and B are dominating C in terms of minimizing nT. For the same demand levels, strategy B is dominating others in terms of Tmax and TT. When demand level is 100 %, strategy A is dominating others in terms of nT and both strategies B and C are dominating A in terms of Tmax. However, there is no dominant strategy among B and C. All in all, there is no dominant strategy observed in terms of TT. In terms of the impact of due date, strategy A worked slightly better with tight due dates. On the other hand, strategy B worked slightly better with medium due dates and strategy C worked slightly better with loose due dates.

6.1.4. Tardy job assignment strategy-based comparison

In terms of tardy job assignment strategy, the impacts are evaluated based on the secondary performance measures (Tmax and TT). In terms of Tmax, EDD performed slightly better than SPT for all strategies. On the other hand, for the TT objective, SPT performed slightly better than EDD for strategy A. No dominance is observed for the strategies B and C.

6.2. Cost-based Result Analysis

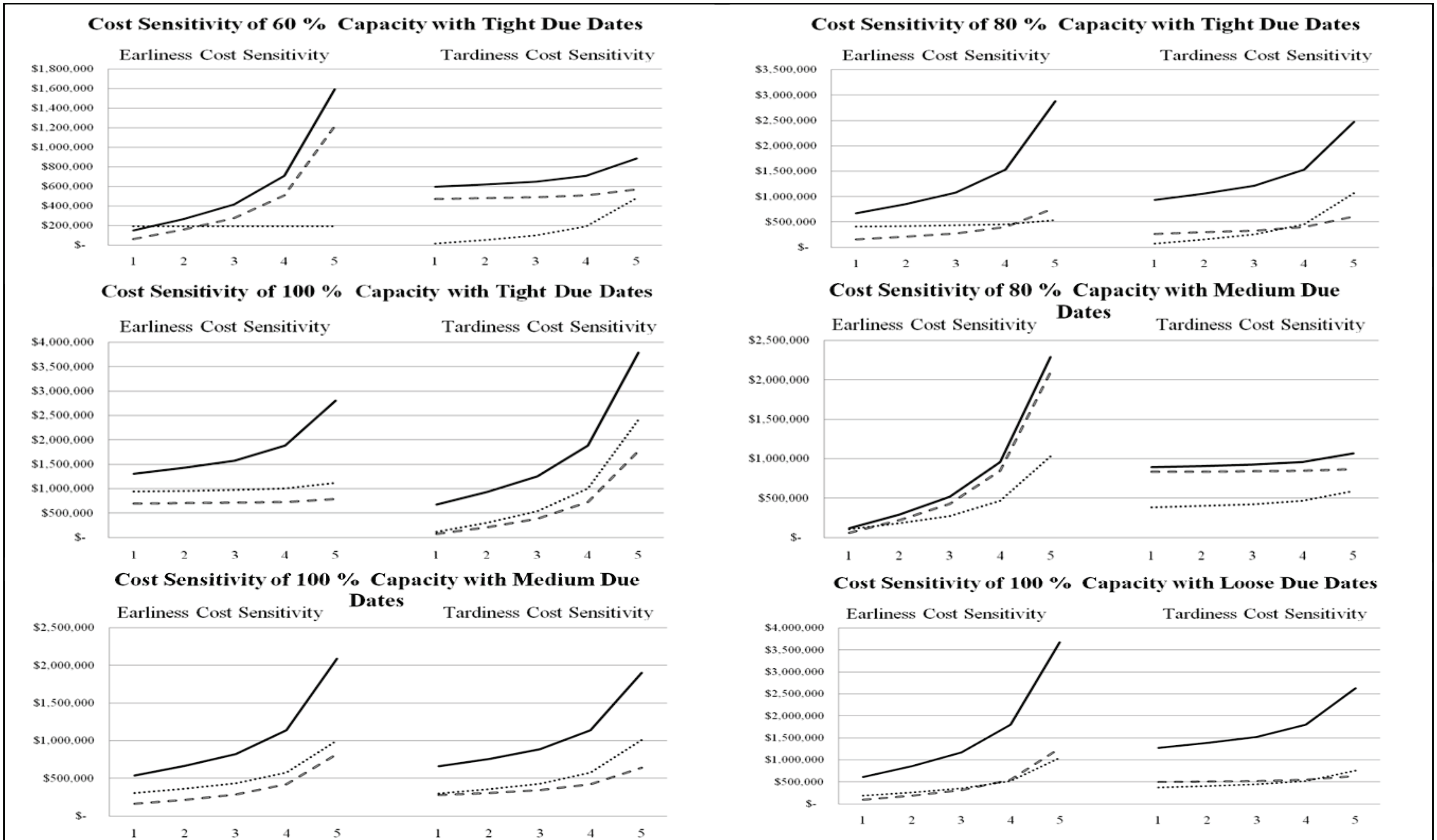
In this section a cost-based result analysis approach is utilized to compare the cell loading strategies performance as cost sensitivity graphs. The total cost function was defined as the combination of total earliness and total tardiness costs. Since there is a tradeoff between total earliness and total tardiness costs, the results are compared via cost sensitivity analysis. Cost sensitivity analysis is made based on a cost scale as shown in Table 9. Cost sensitivity of tardiness and earliness made with keeping each other's cost as constant value of $20. The results of cost-based comparison are shown in Figure 8. The vertical axis show the total cost based on the combination of the earliness and the tardiness costs shown in horizontal axis in the graphs, in Figure 2.

Table 9: Cost Sensitivity Scale

Earliness	Tardiness

Cost Scale	1	2	3	4	5	1	2	3	4	5
Earliness Cost	$ 1	$ 5	$ 10	$ 20	$ 50	$ 20	$ 20	$ 20	$ 20	$ 20
Tardiness Cost	$ 20	$ 20	$ 20	$ 20	$ 20	$ 1	$ 5	$ 10	$ 20	$ 50

According to Figure 2, both strategies B and C are less sensitive than strategy A to varying earliness and tardiness cost in all capacity levels and due dates in terms of total cost. In all due dates, strategy C is less sensitive than strategy B in lower capacity levels. However, in 100 % capacity level, strategy B is the least sensitive to varying cost. Strategy A provided the greatest total cost values in all capacity level and due date combinations. The total cost increases for all strategies as capacity level increases. In conclusion, strategy A, in other words, planning with allowing early start and assigning tardy jobs after the entire period is a good strategy when capacity levels are higher than 80 %. On the other hand, strategy C, planning without allowing



Type of Sensitivity	Earliness					Tardiness				
Cost Scale	1	2	3	4	5	1	2	3	4	5
Earliness Cost	$ 1	$ 5	$ 10	$ 20	$ 50	$ 20	$ 20	$ 20	$ 20	$ 20
Tardiness Cost	$ 20	$ 20	$ 20	$ 20	$ 20	$ 1	$ 5	$ 10	$ 20	$ 50

Strategy A
Strategy B
Strategy C

Figure 2: Cost Sensitivity Analysis of Earliness and Tardiness

early start and assigning tardy jobs after the related period is a good strategy when capacity levels are lower than 80 %.

7. Conclusions and Future Remarks

A multi-period cell loading problem on a thermo siphon manufacturing company is studied. Two mathematical models (proposed by Suer et al. 1996) are used to minimize the number of tardy jobs in a multi-cell and multi-period environment. The first mathematical model is used to minimize nT for all periods by allowing early start of jobs and the second mathematical model is used to minimize nT when early start is not allowed. After the optimal cell loads and job sequences are obtained, two different assignment strategies were used to schedule tardy jobs in multi-period environment.

Three different strategies (A, B and C) were proposed to deal with scheduling of tardy jobs. In the first strategy, the number of tardy jobs was minimized for all periods, in other words early start of a job is allowed and tardy jobs were assigned after the entire period (the 4th period). In the second strategy, the number of tardy jobs was minimized for each and every period separately, early start of a job was not allowed and tardy jobs were added after the related period. In the third strategy, tardy jobs were minimized for each and every period separately, early start of a job was not allowed and tardy jobs were added after the entire planning horizon (the 4th period).

The three strategies were experimented with mathematical models and the Gantt charts are drawn with respect to the results. Based on the obtained optimal schedules, Tmax and TT values are calculated. According to the results of the experimentation, strategy A provided best solution for nT in all cases. However, there is no dominant strategy observed for the objectives Tmax and TT. In other words, depending on the type of due date and demand level, the best strategy is varied. EDD is seemed as slightly better tardy job assignment strategy than SPT based on the objective of Tmax, tradeoff is occurred with TT. In terms of cost-based comparison, strategy A is found to be the most sensitive strategy to a change in tardiness cost. Allowance of early start is less costly for 80% or higher capacity utilization levels. For the remaining capacity levels, strategy C provided the least cost.

In conclusion, there is no unique strategy found which works best in all situations. Based on the planning strategy, whether it's forward or backward planning, early start allowance can be applied.

If a forward planning strategy is in use, early start should be allowed in planning as long as the BOM of the corresponding product does not prevent an early start or a there is a supplier restriction. Moreover, smaller number of tardy jobs with higher maximum tardiness and total tardiness values were obtained from strategy A. In the other strategies, greater number of tardy jobs with lower maximum tardiness and total tardiness were obtained with strategy B and C. Therefore, the comparison of results is strongly dependent on the scheduler's viewpoint whether less backorder with higher tardiness or more backorders with lower tardiness is preferred. In this case, it is strongly believed that customer profiles might have a crucial impact on the planning which is not studied in this paper. The problem studied can be extended with customer profiles which have different preference among the number of tardy jobs, maximum tardiness and total tardiness as a future work.

Acknowledgement

The researchers are grateful to the editors, Dr. Kannan Govindan, Dr. Mohammad Khadem, and Dr. Anwar Ashek Rahman and the anonymous reviewers for their valuable feedback and contribution in this study.

References

Azizoglu, M., Koksalan, M., & Koksalan, S. K. (2003). Scheduling to minimize maximum earliness and number of tardy jobs where machine idle time is allowed. *Journal of the Operational Research Society*, *54*(6), 661-664. Nature Publishing Group.

Biskup, D., 2008. A state-of-the-art review on scheduling with learning effects. *European Journal of Operational Research*, 188(2), pp.315–329.

Chang, P.-C. & Chen, S.-H., 2011. Integrating dominance properties with genetic algorithms for parallel machine scheduling problems with setup times. *Applied Soft Computing*, 11(1), pp.1263–1274.

Duffuaa, S. O., Raouf, A., Bendaya, M., & Makki, M. (1997). One-Machine Scheduling To Minimize Mean Tardiness With Minimum Number Tardy. *Production Planning and Control*, *8*(3), 226-230. Taylor Francis Ltd.

Egilmez, G., Erenay, B. & Süer, G.A., 2014. Stochastic skill-based manpower allocation in a cellular manufacturing system. *Journal of Manufacturing Systems*, p.(In Print).

Süer, G.A. & Eğilmez, G., 2014. Stochastic cell loading to minimize nT subject to maximum acceptable probability of tardiness. *Journal of Manufacturing Systems*, ((Accepted)).

Egilmez, G., Süer, G.A. & Ozguner, O., 2011. Stochastic Capacitated Cellular Manufacturing System Design with Hybrid Similarity Coefficient. In Dr. Faieza Abdul Aziz (Ed.), ed. *Manufacturing System*. Available at: http://www.intechopen.com/books/manufacturing-system/stochastic-capacitated-cellular-manufacturing-system-design-with-hybrid-similarity-coefficient.

Egilmez, G., Süer, G.A. & Huang, J., 2012. Stochastic cellular manufacturing system design subject to maximum acceptable risk level. *Computers & Industrial Engineering*, 63(4), pp.842–854.

Egilmez, G. & Süer, G., 2013. The impact of risk on the integrated cellular design and control. *International Journal of Production Research*, 52(5), pp.1–24.

Greene, T., & Sadowski, R. P. (1983). Cellular manufacturing control. *Journal of Manufacturing Systems*, *2*(2), 137-145.

Gupta, J., Ruiz-Torres, A., & Webster, S. (2003). Minimizing maximum tardiness and number of tardy jobs on parallel machines subject to minimum flow-time. *Journal of the Operational Research Society*, *54*(12), 1263–1274. Nature Publishing Group.

He, C., Lin, Y., & Yuan, J. (2010). A note on the single machine scheduling to minimize the number of tardy jobs with deadlines. *European Journal of Operational Research*, *201*(3), 966-970. Elsevier B.V. doi: 10.1016/j.ejor.2009.05.013.

Ho, J. C., & Chang, Y. L. (1995). Minimizing the number of tardy jobs for m parallel machines. *European Journal of Operational Research*, *84*(2), 343–355. Elsevier.

Hsu, C.-J., Kuo, W.-H. & Yang, D.-L., 2011. Unrelated parallel machine scheduling with past-sequence-dependent setup time and learning effects. *Applied Mathematical Modelling*, 35(3), pp.1492–1496.

Huo, Y., Leung, J., & Zhao, H. (2007). Bi-criteria scheduling problems: Number of tardy jobs and maximum weighted tardiness. *European Journal of Operational Research*, *177*(1), 116-134. doi: 10.1016/j.ejor.2005.06.067.

Kaplan, S. & Rabadi, G., 2013. Simulated annealing and metaheuristic for randomized priority search algorithms for the aerial refuelling parallel machine scheduling problem with due date-to-deadline windows and release times. *Engineering Optimization*, 45(1), pp.67–87.

Lee, W.-C., Chuang, M.-C. & Yeh, W.-C., 2012. Uniform parallel-machine scheduling to minimize makespan with position-based learning curves. *Computers & Industrial Engineering*, 63(4), pp.813–818.

Lin, Y.K., Pfund, M.E. & Fowler, J.W., 2011. Heuristics for minimizing regular performance measures in unrelated parallel machine scheduling problems. *Computers & Operations Research*, 38(6), pp.901–916.

Maxwell, W. L. (1970). On Sequencing N Jobs On One Machine To Minimize The Number Of Late Jobs. *Management Science*, *16*(5), 295–297. JSTOR.

Mhallah, R., & Bulfin, R. L. (2005). Minimizing the weighted number of tardy jobs on parallel processors. *European Journal of Operational Research*, *160*(2), 471-484. doi: 10.1016/j.ejor.2003.06.027.

Mhallah, R., & Bulfin, R. L. (2007). Minimizing the weighted number of tardy jobs on a single machine with release dates. *European Journal of Operational Research*, *176*(2), 727-744. doi: 10.1016/j.ejor.2005.08.013.

Moore, J. M. (1968). An n Job, One Machine Sequencing Algorithm for Minimizing the Number of Late Jobs. *Management Science*, *15*(1), 102-109.

Shanthikumar, J. (1983). Scheduling n jobs on one machine to minimize the maximum tardiness with minimum number. *Computers & Operations Research*, *10*(3), 255-266.

Soroush, H. (2007). Minimizing the weighted number of early and tardy jobs in a stochastic single machine scheduling problem. *European Journal of Operational Research*, *181*(1), 266-287. doi: 10.1016/j.ejor.2006.05.036.

Süer, G. (1997). Minimizing the number of tardy jobs in multi-period cell loading problems. *Computers & Industrial Engineering*, *33*(3-4), 721-724.

Süer, G. A., & Czajkiewicz, Z. (1992). A heuristic procedure to minimize number of tardy jobs and total tardiness in single machine scheduling. *Computers & Industrial Engineering*, *23*(1-4), 145-148.

Süer, G.A. & Arinsoy, A., 2014. Maximization of Delivery-Based Customer Satisfaction Considering Customer-Job Relationships in a Cellular Manufacturing Environment. In *Handbook of Research on Design and Management of Lean Production Systems*. IGI Global, p. 48.

Süer, G. A., & Bera, I. S. (1998). Multi-period cell loading and cell size determination. *Computers & Industrial Engineering*, *35*(1-2), 85-88.

Süer, G. A., Báez, E., & Czajkiewicz, Z. (1993). Minimizing the number of tardy jobs in identical machine scheduling. *Computers & Industrial Engineering*, *25*(1-4), 243-246.

Süer, G.A., Kamat, K., Mese, E and Huang, J., 2013. Minimizing total tardiness subject to manpower restriction in labor-intensive manufacturing cells. *Mathematical and Computer Modelling*, 57(3-4), pp.741–753.

Suer, G. A., Saiz, M., & Gonzalez, W. (1999). Evaluation of manufacturing cell loading rules for independent cells. *International Journal of Production Research*, *37*(15), 3445-3468. Taylor & Francis.

Süer, G. A., Pico, F., & Santiago, A. (1997). Identical machine scheduling to minimize the number of tardy jobs when lot-splitting is allowed. *Computers & Industrial Engineering*, *33*(1-2), 277-280.

Süer, G. A., & Sáiz, M. (1993). Cell loading in cellular manufacturing systems. *Computers & Industrial Engineering*, *25*(1-4), 247-250.

Trietsch, D., & Baker, K. R. (2007). Minimizing the number of tardy jobs with stochastically-ordered processing times. *Journal of Scheduling*, *11*(1), 71-73.

Vallada, E. & Ruiz, R., 2011. A genetic algorithm for the unrelated parallel machine scheduling problem with sequence dependent setup times. *European Journal of Operational Research*, 211(3), pp.612–622.