Operator Assignment Decisions in a Highly Dynamic Cellular Environment

A thesis presented to
the faculty of
the Russ College of Engineering and Technology of Ohio University

In partial fulfillment
of the requirements for the degree
Master of Science

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November 2008

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ABSTRACT

ALHAWARI, OMAR IBRAHIM, M.S. November 2008, Industrial and Systems
Engineering

Operator Assignment Decisions in a Highly Dynamic Cellular Environment (130 pp.)

Director of Thesis: Gürsel A. Süer

Operators are assigned to operations in labor-intensive manufacturing cells using two assignment approaches: Max-Min and Max. The major concern is to see how these two approaches impact operators' skill levels, makespan and total processing time among cells. The impact is discussed under chaotic environment where sudden changes in product mix with different operation times are applied and under non-chaotic environment where same product mix is run period after period. In this thesis, operator's skill levels are affected by learning and forgetting rates. Max-Min improved operators' skill levels more significantly than Max in this multi-period study; particularly in chaotic environment. This eventually improved makespan and total processing times as well.

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ACKNOWLEDGEMENTS

It is enormous pleasure to thank the many people who have helped me with this thesis and made it possible. It was an emotional experience reliving those tiring times on one hand, and wonderful, wise, motivating, and warm presence of my advisor Dr. Gürsel A. Süer on the other hand. It is my profound gratitude and enormous honor to be guided by him throughout my masters. He provided encouragement, advise, good company and ability to explain things clearly and simply. His eagerness to produce high quality graduate students has been always inspirational and impressive. I personally can not thank him enough since he has been a wonderful influence in my life (which I badly needed).

I am grateful and appreciative to the wonderful committee members, Dr. George A. Johanson, Dr. Gary Weckman and Dr. Diana J. Schwerha for their time and helpful suggestions for future research in this field. Their useful input has been highly valuable and encouraging. They indeed deserve special thanks for their assistance and encouragement that helped in significant ways.

I thank the department of Industrial and Systems Engineering at Ohio University for giving me the opportunity to gain precious education and experience. I thank all my friends in Jordan and USA who have supported me emotionally.

Lastly and most importantly, I am really happy to express my deep appreciation to my family members; in particular my parents, for their love, support and prayers through the difficult times. Remembering myself what they have sacrificing for me has kept me moving forward.

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CHAPTER 1 INTRODUCTION

This chapter introduces general definition of a manufacturing system, different manufacturing layout types, group technology versus cellular manufacturing, labor-intensive cells versus machine-intensive cells, skill levels, mathematical programming model, performance measures, manpower allocation and thesis objective.

1.1 Manufacturing System

The common meaning of manufacturing can be given as the making of products by manual labor or by machinery. “Manufacturing is the transformation of raw material into useful products through the use of the easiest and least expensive methods. It must be mentioned that not only must the product be manufactured by the easiest and least expensive method, but also it must have the desired quality in performance as well as reliability” (Stephano & Spiegl, 1992, p.27). Figure 1.1 illustrates a typical manufacturing system.

Figure 1.1 A typical manufacturing system

Figure 1.2 Manufacturing system layouts

Figure 1.2 shows different layout types of a manufacturing system (Irani, 1999, p.2). Product layout is designed to process a single product through dissimilar machines in one flow direction, cellular layout is formed when dissimilar machines are allocated to process similar parts, and functional (process) layout is established when similar machines are allocated in each department to perform similar processes (Askin & Standridge, 1993, pp. 9-11). There is one more layout type called fixed layout and this is used in processing large products, where parts are fixed and machines move around (Askin & Standridge, 1993, p.9).

In today's market, the environment of different layouts: product, process and cellular can be summarized by volume-variety combination. Figure 1.3 shows where each layout stands concerning product demand volume and variety of products (Askin &

Skandridge, 1993, p.11). It is noticeable that each layout is sensitive to the changes in the demand for products and the product mix. A process layout is preferred in the case of having high product variety and low parts production volume since higher manufacturing flexibility is needed. Product layout is suitable when production volume is high and product variety is low as production since flexibility is not required at all. Cellular layout is preferred when higher flexibility is needed as it has advantages of both product and process layouts as product flexibility is medium-high.

Figure 1.3 Volume versus variety

The different types of manufacturing layouts are summarized in table 1.1 (Askin & Skandridge, 1993, p.11), to show how they usually fit manufacturing environment. For example, work-in- process is higher in process layout, whereas it is lower in product and cellular layout.

Table 1.1 General characteristics of layout types

Characteristics	Product	Process(functional)	Cellular	Fixed
Throughput time	Low	High	Low	Medium
Work-in-process	Low	High	Low	Medium
Skill level	Choice	High	Medium-high	Mixed
Product flexibility	Low	High	Medium-high	High
Demand flexibility	Medium	High	Medium	Medium
Machine utilization	High	Medium-low	Medium-high	Medium
Worker utilization	High	High	High	Medium
Unit production cost	low	High	low	High

1.2 Group Technology versus Cellular Manufacturing

“Group technology (GT) is a manufacturing concept that seeks to identify and group similar parts to take advantage of their similarities in manufacturing and design processes. A modern definition of GT is the realization that many problems are similar, and that by grouping them, a single solution can be found to a set of problems, thus saving time and effort” (Irani, 1999, p.1). Researchers have derived an application of group technology, which is known as cellular manufacturing (CM), and this includes gathering and processing similar parts on manufacturing processes. Cellular

manufacturing is also considered as a set of manufacturing cells that is dedicated to manufacture part families, or assembly cells that is dedicated to process product families (Askin & Skandridge, 1993, p.163). “Cellular manufacturing has some typical benefits:

- Reducing lead times and setup times
- Reducing the work-in-process inventory
- Lowering material handling costs
- Better output quality and easier quality control
- Increasing individual accountability
- Reducing labor costs
- Increasing job satisfaction

On the other hand, there are some problems with cellular manufacturing as well:

- Relocating machines
- Load balancing problems among individual cells
- Resistance to one operator-multiple machines
- Traditional commitment to dedicated set-ups” (Hyer, 1984, p.26).

1.3 Labor-Intensive Cells versus Machine-Intensive Cells

The cellular manufacturing systems can be machine-intensive or labor-intensive. In labor-intensive cells, it is easier to reconfigure cells when a product is ready to be processed. Moreover, moving equipment is much easier than it is in machine-intensive cells (Süer & Tummaluri, 2008). Labor-intensive manufacturing cells have been observed in apparel, jewelry manufacturing, electromechanical assembly, sewing, shoe manufacturing, medical devices, and car seat manufacturing industries. Basically, in

labor-intensive cells, most of the operations require light weight, and small machines as well as equipment that requires continuous operator attendance and involvement (Süer & Tummaluri, 2008). The operator's role in machine-intensive cells is very limited due to the presence of automatic machines. On the other hand, the operator has a key role in labor-intensive cells, and the number of operators and their assignment to operations has a great impact on the cell's production rate. In some cases, the number of operations is less than the number of operators. This creates the possibility that multiple operators are assigned to perform operations. It is important to control operator assignments; however, when the number of cells and the number of operators increase, keeping track of operator assignment becomes difficult.

1.4 Skill Levels

In a decision making world, particularly in an industrial environment, performance rating plays an important role to expand the knowledge in assigning operators to operations. Operators are different in their performance due to many reasons such as experience, training issues, learning and forgetting rate, etc. Performance differs between operators in which an operator who is low skilled will spend longer time to perform an operation than a highly skilled operator.

In this thesis, concepts such as learning and forgetting rates are discussed to show how operator skill level varies from time to time; thus, the assignment decision is affected. Forgetting and learning rates affect the operator's skills and they are determined by their current skills. Learning takes place when the operator performs an operation continuously for a period of time, consequently, the operator will be familiar with

performing an operation. On the other hand, forgetting happens when the operator does not perform an operation continuously for a period of time. “Cells performance is not only affected by how the cells are loaded but it is also affected by the performance of the operators” (Süer and Tummaluri, 2008).

1.5 Mathematical Models

A mathematical model typically consists of an objective function and constraints. The relations between variables are established in the objective function and constraints. The output of these variables can be expressed either as real or integer numbers. Mathematical programming model such as linear programming is used for different problem formulations. Linear programming is very important for optimization problems. It can be used in many areas, such as business management, economics, transportation, manufacturing systems, telecommunications, diverse industries ...etc. The ultimate goal of applying a linear programming model is to attain the best results or outcomes, for example: maximum profits, maximum production rate, minimum costs, minimum efforts and minimum number of operators. “A Linear programming problem is a problem of minimizing or maximizing a linear function in the presence of linear constraints of the inequality and/or equality type” (Bazaraa & Jarvis, 1943, p.2). Linear programming has been well known and its popularity can be addressed in ability to model large and complex problems. The linear programming model is solved using software known as ILOG/OPL in this thesis. In this thesis, models are of mixed-integer programming type.

1.6 Performance Measures

The cell loading and product sequencing issues have been studied in cellular manufacturing environments. Cell loading means assigning products to cells. This can be done in two ways – allowing lot splitting and not allowing lot splitting between cells. In this study, lot-splitting is not allowed to simplify lot tracking on the shop floor and to avoid the complications for downstream operations. The cell loading can be performed to minimize makespan, number of tardy jobs, total tardiness, etc. Makespan is the maximum of completion times on cells and is the major focus in this thesis. However, we also measured total processing times on cells in some cases. Another issue that usually comes after cell loading is product sequencing in which products are arranged in such a way that some other performance measures are targeted such as minimizing average flow time, minimizing intra-cell manpower transfers, etc. Product sequencing is done for each cell independently. Average flow time measures how long a job remains in the system and the shortest processing time rule (SPT) finds the optimal solution for minimizing average flow time in the case of zero ready times (Süer, Vazquez, & Santos, 2003) in a cell.

Other performance measures are used when assigning operators into operations such that to maximize the output and re-assigns other operators to non-bottleneck operations to minimize total skills such that the optimal output rate is maintained.

1.7 Objectives of this Thesis

The objectives of this study are listed below:

- Improving manpower assignments such that makespan will be reduced.

- Developing models to apply skill-based times as opposed to a previous work which considered only skill levels in models. New models resulted in more accurate estimation of bottleneck and production rates, and thus better manpower assignment.
- Comparing Max and Max-Min approaches under a chaotic environment where sudden changes in the product mix with different operation times are applied.

CHAPTER 2 LITERATURE REVIEW

Researchers have addressed areas related to this subject such as cell loading, operator assignment or allocation. Süer (1996) discussed, in his paper, the subject of optimal operator assignment and cell loading in labor-intensive manufacturing cells. He stated that the operator assignment to cells influences production rate that each cell can produce. He proposed a two-phase methodology. In phase 1, he generated operator assignments for alternative manpower levels by using a mixed integer mathematical model. In phase 2, he found the optimal manpower levels for each cell and optimal product assignment to cells. He also proposed an integer programming model to solve phase 2 problem. He mentioned that as long as the processing times remain the same, the mathematical model used for phase 1 is run just once. On the other hand, the mathematical model used in phase 2 is required to be re-run due to changing demand in different periods.

Süer and Dagli (2005) discussed manpower decisions in their paper. They considered two issues; product sequencing in a cell and cell loading. For the first issue, they targeted to minimize intra-cell manpower transfers. A three-phase methodology was proposed, in which optimal manpower level for each operation was found by using a mathematical model, a matrix for manpower transfers between products was formed, and traveling salesman problem was solved. For the second issue, they aimed to find the optimal assignment of products to cells. Their objective was to minimize makespan and number of machines.

Cesani and Steudel (2005) presented a research concerning labor assignment strategies, and their impact on the cell performance in cellular manufacturing

environment. The term labor flexibility was discussed and referred to the movement of operators between cells and inside the same cell. Labor assignments, such as dedicated assignment, in which an operator is assigned to one or more machines, shared assignment in which two operators or more are assigned to one or more machines, and combined in which an operator is assigned as dedicated and shared together. They made their discussions based on workload sharing, workload balancing and bottleneck operations. Experiments and simulation models were implemented and discussed. They concluded based on results, that the balance in the operators' workload and the level of machine sharing are important factors to determine cell performance and behavior. They also referred to the importance of cross-training issue in improving cell performance.

Süer and Tummaluri (2008) discussed the problem of operator assignment to operations in labor-intensive cells. The operators are assigned to operations in multi-period context considering their skill levels, forgetting and learning rates. They developed a three- phase hierarchical methodology to solve this problem. The first phase is generating alternative operator levels for each product using operation standard times. The second phase is determining cell loads and cell sizes using standard times. The third phase is assigning operators to operations. A mixed integer mathematical model is used in all phases. Two different approaches (Max and MaxMin) are proposed for solving the operator assignment in the third phase. The results showed that when Max approach is used, lower makespan allocation values are obtained, whereas Max-Min improved the skill levels more regularly. The work undertaken in this thesis is an extension of work by Süer and Tummaluri (2008). They found that Max-Min is superior to Max approach in terms of improving operator skill levels; however, they could not show that Max-Min

approach is better in minimizing makespan as a result of improved skill levels. Their work also showed that some non-bottleneck operations became bottleneck after assigning operators. Moreover, their work assumed a static cellular environment, in which they assumed that there are no new hiring and quitting of operators when performing the multi-period analysis, and there are no new products entering the system (i.e. product mix remained the same throughout the study). Thus, in this study, we intend to introduce a highly dynamic cellular environment, in which new products with different processing times will enter the system and some other products will leave.

Bhaskar and Srinivasan (1997) discussed both static and dynamic operator allocation problem. First, they considered static operator allocation when a single product is produced on many cells. Later, they considered the situation in which a cell can produce the next variety of products with the current operator allocation, i.e., dynamic variety allocation problem. This situation may result in the problem of idle time, when a cell should wait until another cell is ready to process next variety. The authors formulated a linear mathematical model to represent the nature of the problem, with the objective of minimizing the difference between the maximum and minimum load. Regarding the dynamic allocation problem, they developed a strategy that says when all operators finish the processing of the first variety in a cell; they should join other cells to help in reducing the processing time of the next variety. They represented the problem in a non-linear model, and then developed heuristics for the strategy to reduce the makespan of the dynamic problem. All algorithms are then demonstrated and analyzed. Results showed that heuristics proposed are getting desired results, in terms of allocating operators for such problems in cellular manufacturing environment.

McDonald (2004) discussed some of operator assignment policies on production line by using multi-skilled workforce in his dissertation. He proposed a new mathematical model to assign operators to operations or tasks, and to determine operators' skill levels. The mathematical model contains many objectives such as assigning operators, determining training cost, and scheduling of job rotation. He applied some measures of performance, average flow time and work-in-process. The model is solved and then results are interpreted. He concluded that the effect of job rotation is not the same at all levels of multi-skilling. The performance of a cell is really affected by job rotation and levels of multi-skilling. There are a significant impact of worker assignment on performance measures.

Some researchers addressed areas related to this subject such as learning and forgetting rate and product sequencing. Nembhard and Osothsip (2002) discussed, in their paper, the operator behavior in terms of learning and forgetting rates; particularly, in the case of performing complex tasks. A study was conducted at a textile manufacturing plant, where different manual sewing tasks were available. Data was collected by studying the behavior of each worker over a period of one year. They used a model of individual learning and forgetting rate, which was introduced first by Nembhard and Uzumeri (2000) in order to measure the productivity rate. This model was applied to each operator, and operator learning and forgetting parameters were considered as dependent variables, whereas task complexity was considered as independent variable. Results were captured and then statistical analysis was done to find if there is a relationship between the variability of learning and forgetting rates with task complexity. Results indicated task complexity significantly affects the variance of worker learning and forgetting rates.

For higher task complexities, workers are more varied in their learning and forgetting rate than they are at lower task complexities. The impact of task complexities on worker learning and forgetting affects worker assignment and productivity. A worker skill level increases when he performs an operation for many consecutive periods. In the same manner, the length of interruption interval affects the skill levels adversely; hence, if an operator does not perform a certain operation for a number of consecutive periods, his skill level decreases.

Wu and Sun (2006) discussed, in their paper, the problems of manpower allocation and project scheduling, taking into consideration the learning effect. The nature of the problem, they mentioned, is that every project consists of certain number of periods, in which many operators perform different tasks. These operators should be reassigned to different tasks at the end of each period of the project. The reassigning strategy should consider the learning effect. The authors formulated the problem in the form of non-linear programming model, and objective function minimized the outsourcing costs. They resorted to Genetic Algorithm as a problem solver, and applied GA to the problem considered. The manpower allocation decisions were represented in the form of chromosome and then GA parameters were set and implemented to obtain solutions. Various sizes of this type of problem were solved by using GA.

Some researchers addressed areas such as cross-training. Slomp et al. (2005) discussed cross-training decisions in a cellular manufacturing environment. They wanted to minimize the load of the bottleneck worker. In their study, they presented an integer programming model to calculate which workers have to be trained for which machines. Based on this model, they discussed the trade-off between the operating costs of the

manufacturing cell, the costs of cross-training, and the workload among workers, they showed that the connection between workers and machines is really important to form chaining and this produces an efficient cross-training situation. In this case, workload can be shifted from heavier loaded worker to less loaded worker. Labor flexibility is needed in these environments. Unbalanced load may give feelings of unfairness in a team.

Bidanda et al. (2003) presented the importance of focusing not only on technical issues, but also human issues in cellular manufacturing environments. Technical issues include cell formation and cell design, whereas human issues involve such as worker assignment strategies, skill identification, training, communication, autonomy, reward system, conflict management, and teamwork. They conducted a survey to show the importance of human issues in cellular manufacturing. The number of participants in the survey was 40, and consisted of workers, managers and academicians. They were asked to rank the human issues. Their response was analyzed. The results showed that three major human issues in cellular manufacturing are communication, teamwork and training. The degree of autonomy was found the least important among all. The reward system was in the middle. The assignment strategies were found significant among academicians. The skill identification was found significant among managers and academicians whereas conflict management is significant among workers.

Some researchers addressed areas related to this subject such as skills. Suksawat et al. (2005) discussed the concept of evaluating the skill levels of workers. They developed a skilled worker-based scheduling method based on the skill evaluation and genetic algorithm application. They focused on the objective of improving the production rate by considering workers' skill levels.

Some researchers addresses areas related to the impact of operator on manufacturing cells Gregor and Nyhuis (2004) discussed the impact of operators on the logistic behavior of manufacturing cells. They evaluated the human influence on logistic performance of manufacturing cells through a modeling strategy. They also presented a mathematical equation that describes the human influence on the behavior of manufacturing cells. the relations between human operators in manufacturing cells and how the operator becomes a bottleneck of cell are discussed. They concluded that the variation of operator assignments and different cell configurations results in various logistics. Operator assignment is evaluated when operator processing time or cycle time is known.

Shirase et al. (2001) developed a system of distributed production system which consists of some cell groups. They discussed a dynamic operator assignment method. In this cooperative method, they considered that whenever any cell in a group of cells is unable to meet the due date of certain part, it has the option to ask for one operator as a support from other groups. Eventually, cooperation is taking place between cell groups until all due dates are met. They generalized the idea in which some disturbances in a production system can be treated by cooperation between subsystems.

Wirojanagud, et al (2005) discussed a strategic way to model worker differences for workforce planning. Impact of individual differences on management decisions is considered and then discussed. A problem of job shop environment has been formulated in a form of a mixed integer programming model. The major concern was to identify number of workers who will be hired, fired and cross-trained at a minimum cost.

Experiments are run and then results are analyzed. Workers differences are playing a major role in making decisions in manufacturing system environment.

Bokhorst, Slomp, Gaalman(2004) Presented a study that aims to discuss the impact of labor assignment rule on Dual Resource Constrained(DRC) systems, in limited labor and machine environment. The assignment rule is known as a who-rule that implies to find a way to select one worker among many workers, and then send him or her to a machine to perform an operation. In addition to, this rule is important in worker assignment strategy. They applied the who-rule in some simulation studies. Results have shown the influence of this rule on DRC systems where worker differences are considered.

Shing and Gassmann(1997) discussed allocation functions between worker and machines could influence the performance of manufacturing cells over a long period of time considered as 15 months. They concluded that skills development and knowledge are really important for keeping long-term competitiveness. Allocation of functions has an impact on the long term performance, in which the long period will give more vision to make the work smooth through absorbing the complexity of the nature of manufacturing environment.

Nembhard (2001) discussed a heuristic approach for assigning workers to task based on individual learning rate. Basically, he run experiments based on two conditions: a long production run and a short production run. Results were interpreted and showed that the heuristic approach have an impact on overall productivity. Best results were found when workers learn more gradually.

CHAPTER 3 PROBLEM CONSIDERED

In this chapter, several issues are discussed such as problem statement, the approaches used, dynamic cellular environment, cell loading and product sequencing. The aim of this study is to compare two operator assignment approaches in highly dynamic cellular environments; (1) Max approach, (2) Max-Min approach. These two approaches are used to assign operators to operations, which may affect operators' skill levels, and eventually the performance of cells.

3.1 Problem Statement

An example is provided to show how these two approaches work. Table (3.1) shows the standard times for operations of product X2 for all six operations. The skill levels are divided into seven categories where 7 is the best, 1 is the worst and 4 is the average. It is assumed that there are 12 operators in the cell and each operator can perform 3 operations with skill levels given in table 3.2. The higher the skill level, the lower the processing time. The operation times based on corresponding skills are given in table (3.3).

Table 3.1 The standard times for operations

Product	Operation					
	Op.1	Op.2	Op.3	Op.4	Op.5	Op.6
X2	0.05 (min/unit)	0.29 (min/unit)	0.62 (min/unit)	0.74 (min/unit)	0.38 (min/unit)	0.55 (min/unit)

Table 3.2 The skill levels for operators

Operator	Operation					
	Op.1	Op.2	Op.3	Op.4	Op.5	Op.6
1	5		5	4		
2		3	4	4		
3	3	5	3			
4				4	3	4
5	2	3			5	
6			5	6		4
7	4				4	3
8	4		4	4		
9		4			4	4
10	4		3	4		
11	4			1		3
12		3	4		5	

Table 3.3 The skill-based operation times matrix

Operator	Operation					
	Op.1	Op.2	Op.3	Op.4	Op.5	Op.6
1	0.0475 (min/unit)		0.589 (min/unit)	0.74 (min/unit)		
2		0.3045 (min/unit)	0.62 min/unit)	0.74 (min/unit)		
3	0.0525 (min/unit)	0.2755 (min/unit)	0.651 (min/unit)			
4				0.74 (min/unit)	0.399 (min/unit)	0.55 (min/unit)
5	0.055 (min/unit)	0.3045 (min/unit)			0.361 (min/unit)	
6			0.589 (min/unit)	0.666 (min/unit)		0.55 (min/unit)
7	0.05 (min/unit)				0.38 (min/unit)	0.5775 (min/unit)
8	0.05 (min/unit)		0.62 (min/unit)	0.74 (min/unit)		
9		0.29 (min/unit)			0.38 (min/unit)	0.55 (min/unit)
10	0.05 (min/unit)		0.651 (min/unit)	0.74 (min/unit)		
11	0.05 (min/unit)			0.851 (min/unit)		0.5775 (min/unit)
12		0.3045 (min/unit)	0.62 (min/unit)		0.361 (min/unit)	

3.2 Approaches Used

In this section, how Max and Max-Min strategies work is described.

3.2.1 Max Approach

The Max strategy uses the skill-based times to assign operators to operations such that maximum output is achieved. An integer mathematical model is used to assign operators and it is solved by using ILOG/OPL. Figure (3.1) shows the optimal operator assignment to each operation for the example problem.

Figure 3.1 The optimal operator assignment using the Max Approach

Table (3.4) shows the output for each operation. The reader can easily observe that operation 2 is the bottleneck operation among all operations with an output of (217.79 units/hr).

Table 3.4 The output rate for each operation

Operation	Op.1	Op.2	Op.3	Op.4	Op.5	Op.6
Output	1200	217.79	295.42	243.24	324.1	218.18
rate	(units/hr)	(units/hr)	(units/hr)	(units/hr)	(units/hr)	(units/hr)

3.2.2 Max-Min Approach

The Max-Min strategy also uses the skill-based times given in table (3.3) to find the optimal operator assignment to maximize the output. In this approach, first the slowest operation, bottleneck operation, is identified. The bottleneck operation is operation 2 and is performed by operator 3 who is the most skilled operator to perform operation 2 based on times provided in table (3.3). The Max-Min approach keeps the operators assigned to the bottleneck operation unchanged as shown in figure (3.2). However, it re-assigns other operators to non-bottleneck operations to minimize total skills such that the optimal output rate is maintained. The solution obtained by using the Max-Min approach is given in figure (3.3). This gives operators the opportunity to perform operations that they are not very skilled at and this will eventually help increase their skill levels. Even though the output rates for some operations (op.1, op.4 and op.5) are adversely affected from this arrangement, the bottleneck operation remains the same (217.79 units/hr) as shown in table (3.5).

Figure 3.2 The bottleneck operation 2 is performed by operator 3

Figure 3.3 The optimal operator assignment using the Max-Min Approach

Table 3.5 The output rate for each operation after re-assignment

Operation	Op.1	Op.2	Op.3	Op.4	Op.5	Op.6
Output rate	1090.90	217.79	295.42	232.66	308.27	218.18
	(units/hr)	(units/hr)	(units/hr)	(units/hr)	(units/hr)	(units/hr)

3.3 Dynamic Cellular Environment

The problem is considered dynamic because a new product set will be released to the shop after a certain number of periods. This new product set will have different standard times and manpower requirements space will be different than existing products.

3.4 Cell Loading and Sequencing

Cell loading means assigning products to cells. Product sequencing usually comes after cell loading in which products are arranged by using a particular sequencing rule. Figure (3.4) shows a simple example of 10 products of type X assigned to two cells and then sequenced by SPT on each cell. In this thesis, (SPT) has been used since one of the objectives is minimizing average flow time.

Figure 3.4 The cell loading and product sequencing

3.5 Experimentation Performed

In this thesis, several experiments are conducted to solve the problem of operator assignment, considering (N_x) products of type X and (N_y) products of type Y and (M) operations for each product. Each operator is assumed to perform (P) operations. These (R) operators are divided into (S) different cells. Experimentation is performed to see how Max and Max-Min approaches will cope with significant changes in the cellular system. Süer and Tummaluri (2008) used the standard times for initial operator assignment mathematical models. They considered operator skill levels afterwards and then modified output rates accordingly. On the other hand, in this study, skill-based times are used directly in mathematical models.

CHAPTER 4 METHODOLOGY

In this chapter, several issues are discussed such as multi-period methodology, the general overview of the methodology, performance measures, skill levels, the learning and forgetting rates and the dynamic cellular environment considerations.

4.1 Multi-period Methodology

The study is carried out in a multi-period environment. The number of periods included in this study is 16 and each period represents a week. This allows us to see the impact of the approaches in the long-term. Based on the assignments made in previous periods, an operator's skill level may be adjusted. Figure (4.1) includes the multi-period methodology in which the proposed approach is implemented and the results are captured. These results may affect the operator skill levels; hence, they need to be revised each period. Once all periods are considered for the 1st approach, then the same procedure is applied for the second approach, and finally the results are compared.

Figure 4.1 Multi-period methodology

4.2 General Overview of the Approaches

In this study, we use Max and Max-Min approaches by following the flowcharts in figure 4.2. The major steps for the Max strategy are: (1) find optimal operator assignment using an integer mathematical model, (2) determine cell loads to minimize makespan by using an integer mathematical model, (3) determine product sequence in each cell using a simple scheduling rule. The sequence of products is determined by using the shortest processing time (SPT) rule since the objective is to minimize the average flow time. The first three steps of the Max-Min approach is similar to the Max approach. However, two more steps are included in the Max-Min approach, and they are: (4) identify bottleneck and non-bottleneck operations for each product in the cell, (5) re-assign low-skilled operators to non-bottleneck operations using the Min-skill principle. By doing this, we expect that operators with low skills will get a chance to perform these operations and eventually improve their skill levels.

Figure 4.2 The general overview of the approaches

4.3 Performance Measures

Each task in figure 5 has its own objective as given in table (4.1).

Table 4.1 The performance measures used

	Max Approach	Max-Min Approach
Operator assignment	maximize production rate	maximize production rate
Cell Loads	minimize makespan	minimize makespan
Product sequence	minimize average flow time	minimize average flow time
Re-assigning low skilled operators	—	minimize total skills without violating original production rate

4.4 Skill Levels

In this study, each operator is assumed to have a skill level for each operation he performs. These skill levels follow the normal distribution, in which μ represents the mean value and σ represents the standard deviation. Figure (4.3) shows the normal distribution curve of skill levels. The skill levels are divided into seven categories and their corresponding probabilities are shown in table (4.2). Level 4 represents the average skill, level 7 represents the best and level 1 is the worst. This is an assumption used in this study. Süer and Tummaluri (2008) also used a similar classification except they used

9 skills as opposed to 7 suggested here. No empirical work has been done to verify these results.

Table 4.2 The Skill levels and probability

Skill Level	Time	probability
1	$\mu+3\sigma$	0.0062
2	$\mu+2\sigma$	0.0606
3	$\mu+\sigma$	0.2417
4	μ	0.383
5	$\mu-\sigma$	0.2417
6	$\mu-2\sigma$	0.0606
7	$\mu-3\sigma$	0.0062

Figure 4.3 The normal distribution curve for skill levels

4.5 Operation Times

Operation times are calculated according to the operator skill levels. The standard processing time for each operation is considered to be the average time, hence, the operator with skill level 4 is considered to have the average operation time. Other skills below or over will follow the normal distribution. Table (4.3) provides an example for product X1 with operation times for different skill levels with a standard deviation of 5% of the mean. The σ for operation 1 for product X1 is 0.0035 ($= .07 \times .05$). As the skill level decreases by 1 level (4 $\rightarrow$ 3), the operator skilled-based time increases to 0.0735 ($= .07 + \sigma$).

Table 4.3 The operation times for different skill levels with $\sigma = 5\%$ of the mean

	Operation					
	Op.1	Op.2	Op.3	Op.4	Op.5	Op.6
Product X1	0.07	0.045	0.37	0.88	0.38	0.21
Std. Dev	0.0035	0.0225	0.0185	0.044	0.019	0.0105
Skill level						
7	0.0595	0.3825	0.3145	0.7480	0.3230	0.1785
6	0.0630	0.4050	0.3330	0.7920	0.3420	0.1890
5	0.0665	0.4275	0.3515	0.8360	0.3610	0.1995
4	0.0700	0.4500	0.3700	0.8800	0.3800	0.2100
3	0.0735	0.4725	0.3885	0.9240	0.3990	0.2205
2	0.0770	0.4950	0.4070	0.9680	0.4180	0.2310
1	0.0805	0.5175	0.4255	1.0120	0.4370	0.2415

4.6 Learning and Forgetting Rates

In this study, a skill level is affected by learning and forgetting rates. An operator's skill level increases when he performs an operation for many consecutive periods. In the same manner, the length of interruption interval affects the skill levels adversely; hence, if an operator does not perform a certain operation for a number of consecutive periods, his skill level decreases. Table (4.4) shows the assumed number of required periods for improving or lowering skill level, and it also shows the probability for that skill to change. The probability values follow the notion that an operator who has been performing an operation for a long time, will become more experienced operator, and it will take longer for that skill to deteriorate. As shown in table 10, a skill level can be improved from 1 to 2 with a probability of 0.7, if an operator keeps performing the same operation for 3 periods consecutively. On the other hand, improving skill level from 6 to 7 requires an operator to perform the operation for 6 periods consecutively (with a probability of 0.3). Meanwhile, an operator's skill level can deteriorate from 2 to 1 with a probability of 0.7, if he does not perform the operation for 4 periods consecutively. Similarly, if he does not perform the operation for 7 periods consecutively, his skill will decrease from 7 to 6 with a probability of 0.3. No empirical study has been done to validate these assumptions due to time restrictions. However, it is believed that these numbers reflect the relations between learning and forgetting rates of workers at different skill levels along with associated probabilities reasonably well. The operator skill matrix is revised on learning and forgetting rates at the end of every period.

Table 4.4 The learning and forgetting rates

Learning				Forgetting			
Skill level		periods	Prob.	Skill level		periods	Prob.
From	To			From	To		
1	2	3	0.70	2	1	4	0.70
2	3	3	0.65	3	2	4	0.65
3	4	4	0.6	4	3	5	0.6
4	5	4	0.5	5	4	5	0.5
5	6	5	0.4	6	5	6	0.4
6	7	6	0.3	7	6	7	0.3

4.7 Mathematical Model for Max Approach

The Max strategy uses the skill-based times to assign operators into operations such that maximum output is achieved. An integer mathematical model is used to assign operators. The mathematical model is formulated with the objective function of maximizing the production rate as shown in equation (1). Equation (2) determines which operators have to be assigned to each operation. Equation (3) ensures that each operator is assigned to only one operation within a cell. Equation (4) shows that y_{kj} is a binary variable. The mathematical programming model is given below:

Objective function

$$MaxZ = R \dots\dots\dots(1)$$

Subject to:

$$\sum_{k \in f_j} (a_{kj} y_{kj}) - R \geq 0 \dots\dots\dots (j = 1, 2, 3 \dots m) \dots\dots\dots (2)$$

$$\sum_{j \in f_k} y_{kj} = 1 \dots\dots\dots (k = 1, 2, 3 \dots n) \dots\dots\dots (3)$$

$$y_{kj} \in (0, 1) \dots\dots\dots (4)$$

Decision variables

R Production rate

y_{kj} 1 if operator k is assigned to operation j , 0 otherwise

Parameters

a_{kj} Number of units operator k can process if assigned to operation j

m Number of operations in the cell

f_k Set of operations that operator k can perform (be assigned to)

f_j Set of operators who can perform operation j

k Operator index

j Operation index

n Number of operators

This assignment model is run for each product by using ILOG OPL software. Appendix

A1 shows an example of the mathematical model run for product 1 in period 1.

4.8 Mathematical Model for Max-Min Approach

The Max-Min strategy also uses the skill-based times to find the optimal operator assignment to maximize the output. In this approach, first the slowest operation,

bottleneck operation, is identified. The same integer mathematical model is used to assign operators and it is solved by using ILOG/OPL. However, another constraint is added to determine production rate for each operation as in equation (5).

$$R_j = \sum_{k \in fj} (a_{kj} y_{kj}) \dots \dots \dots (j = 1, 2, 3 \dots m) \dots \dots \dots (5)$$

Obviously, the lowest production rate operation is identified as the bottleneck operation as shown in equation (6)

$$R_b = \min(R_j / j = 1, 2, 3 \dots m) \dots \dots \dots (6)$$

The Max-Min approach keeps the operators assigned to the bottleneck operation the same; however, it re-assigns other operators to non-bottleneck operations to minimize total skills such that the optimal output rate is maintained. A mathematical programming model is used where the objective function is to minimize the total skills for the remaining low skilled operators as given in equation (7). Equation (8) guarantees that the original production rate is not violated. Equation (9) shows a constraint in which each operator is assigned to one operation within each cell. Equation (10) shows that y_{kj} is a binary variable. Appendix A2 shows an example of the math models for product 1 in period 1.

The math model used is as follows:

Objective function

Minimize,

$$MinZ = \sum_{k \in fj} \sum_{j \in fk} (s_{kj} y_{kj}) \dots \dots \dots (7)$$

Subject to:

$$\sum_{k \in fj} (a_{kj} y_{kj}) \geq R_b \dots \dots \dots (j = 1, 2, 3 \dots m) \dots \dots \dots (8)$$

$$\sum_{j \in fk} y_{kj} = 1 \dots \dots \dots (k = 1, 2, 3 \dots n) \dots \dots \dots (9)$$

$$y_{kj} \in (0, 1) \dots \dots \dots (10)$$

Where,

s_{kj} Skill level of operator k for operation j

R_b Production rate of bottleneck operation

4.9 Cell Loading and Product Sequencing

The cell loading issue has been studied in cellular manufacturing environments. Cell loading means assigning products to cells. A mathematical model is used to assign products to cells and the objective function is to minimize the makespan for each cell. Makespan means the maximum completion time among all cells. Equation (11) shows the objective function, minimizing makespan. Equation (12) shows that the total processing time in each cell should be equal or greater the makespan. Equation (13) ensures that each product is assigned to a cell. Equation (14) shows the sign restriction.

Objective function

$$\text{Min} Z = MS \dots\dots\dots (11)$$

Subject to:

$$MS - \sum_{i=1}^n p_{ij} x_{ij} \geq 0 \dots\dots\dots (1 \leq j \leq c) \dots\dots\dots (12)$$

$$\sum_{j=1}^c x_{ij} = 1 \dots\dots\dots (1 \leq i \leq n) \dots\dots\dots (13)$$

$$x_{ij} \in (0,1) \dots\dots\dots (14)$$

Where,

x_{ij} 1 if product i is assigned to cell j , 0 otherwise

p_{ij} Processing time of product i in cell j

c Number of cells

n Number of products

The above model is solved in ILOG OPL. Appendix A3 shows an example of this model run in period 1.

Product sequencing usually comes after cell loading in which products are arranged in such a way, that a selected performance measure is completed. In this thesis, average flow time is considered as a measure and it is minimized by using the shortest processing time technique (SPT). SPT denotes that jobs are ordered in the increasing order of processing times. Table (4.5) shows as an example of 10 products with their processing times. Figure (4.3) shows the products assigned to two cells. These product are arranged by using (SPT) and represented by Gantt chart as shown in figure (4.4).

Table 4.5 The processing times for products

Processing time	Product									
	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Pi (cell1)	12.7 9	34.4 4	16.2 9	11.7 6	8.72	20.2 7	16.3 9	9.75	11.8 3	18.75
Pi (cell2)	8.47	20.5 9	9.66	6.69	5.2	11.8 1	8.78	4.91	6.19	10.21

Cell 1	X1 12.79	X3 29.08	X5 37.8	X6 58.07		
Cell 2	X2 20.59	X4 27.28	X7 36.06	X8 40.97	X9 47.16	X10 57.37

Figure 4.3 Gantt chart for cell loading

Cell 1	X5 8.72	X1 21.51	X3 37.8	X6 58.07		
Cell 2	X8 4.91	X9 11.10	X4 17.79	X7 26.51	X10 36.78	X2 57.37

Figure 4.4 Gantt chart for product sequencing

CHAPTER 5 EXPERIMENTS AND RESULTS

In this chapter, the data used and various experiments carried out are discussed in detail.

5.1 Operator Skill Levels

In this thesis, several experiments are conducted using 10 products of type X and 10 products of type Y and 6 operations for each product and they are:

- 1) periods 1-14 (no chaos)
- 2) periods 10-11 (chaos)
- 3) periods 15-16 (chaos)
- 4) period 15 (chaos with new standard deviation)

The total number of operators included in the study is 30. Each operator is assumed capable of performing 3 operations. These operators are divided into two cells with 12 operators in cell 1 and 18 operators in cell 2. Table (5.1) shows the individual and cumulative probability for each skill level.

Table 5.1 The individual and cumulative probability for skill levels

probability	Cumulative probability	Skill level
0.0062	0.0010 – 0.0062	1
0.0606	0.0063 - 0.0668	2
0.2417	0.0669 - 0.3085	3
0.383	0.3056 - 0.6915	4
0.2417	0.6916 - 0.9332	5
0.0606	0.9332 - 0.9938	6
0.0062	0.9939 - 1	7

The total number of skill levels is 90 ($30 \times 3 = 90$); thus, 90 numbers are generated randomly to form the matrix of operator skill levels as in table (5.2). These numbers were established considering a jewelry manufacturing company but at a smaller scale to simplify computations and allow us to compare Max-Min vs. Max strategies under chaotic environment.

Table 5.2 Operator skill levels

Operator	operation					
	op.1	op.2	op.3	op.4	op.5	op.6
1	5		5	4		
2		3	4	4		
3	3	5	3			
4				4	3	4
5	2	3			5	
6			5	6		4
7	4				4	3
8	4		4	4		
9		4			4	4
10	4		3	4		
11	4			1		3
12		3	4		5	
13	4	5		4		
14		5	5	5		
15	3		3		5	
16		3	3		5	
17	5			4		3
18	5	5		5		
19		5		5		4
20	5		3		6	
21	4			3		2
22		3	5		3	
23	3		4			5
24	4			5	3	
25			4	3		6
26		3	1			7
27	3			3	5	
28		4	2		4	
29	5		4			4
30	5				4	5

5.2 Standard Times

The standard times for operations correspond to a skill level of 4. The standard times for products X and Y are randomly generated from a random uniform distribution in the intervals shown in table (5.3). Table (5.4) below shows the generated times for all products. Appendices B1 and B2 show the operation-operator times for products X and Y, respectively.

Table 5.3 Uniform distribution intervals for standard operations times for products X and Y

product	Operation					
	OP.1	OP.2	OP.3	OP.4	OP.5	OP.6
X	[0.04-0.09]	[0.28-0.45]	[0.37-1.18]	[0.47-0.88]	[0.18-0.45]	[0.20-0.80]
Y	[1.10-1.30]	[1.20-1.40]	[0.09-0.15]	[0.04-0.09]	[1.00-1.20]	[0.04-0.08]

Table 5.4 Standard times for all products

Product	operation					
	1	2	3	4	5	6
X1	.07	.45	.37	.88	.38	.21
X2	.05	.29	.62	.74	.38	.55
X3	.06	.29	1.18	.86	.18	.56
X4	.04	.31	.55	.47	.4	.71
X5	.08	.41	.43	.74	.43	.44
X6	.07	.32	1.18	.55	.45	.39
X7	.09	.37	.46	.49	.26	.26
X8	.08	.28	.49	.61	.29	.55
X9	.04	.34	.81	.62	.34	.65
X10	.07	.43	.74	.87	.43	.75
Y1	1.12	1.3	0.15	0.09	1	0.08
Y2	1.18	1.23	0.11	0.04	1.12	0.05
Y3	1.23	1.34	0.11	0.06	1.13	0.05
Y4	1.11	1.39	0.13	0.05	1.2	0.07
Y5	1.15	1.4	0.1	0.04	1.15	0.07
Y6	1.2	1.29	0.14	0.07	1.15	0.04
Y7	1.29	1.21	0.15	0.09	1.19	0.08
Y8	1.22	1.26	0.1	0.05	1.11	0.04
Y9	1.12	1.29	0.09	0.04	1.14	0.08
Y10	1.1	1.35	0.12	0.08	1.17	0.06

5.3 Product Demand

The product demand for all products is randomly generated from the uniform distribution in the interval of [2200, 8500] for all periods. Table (5.5) shows these demand values.

Table 5.5 Product demand and total demand for each period

Period	Product Demand										Total Demand
	1	2	3	4	5	6	7	8	9	10	
1	3500	7500	3400	2700	2200	4000	4500	2200	2300	3000	35300
2	3500	7500	3700	2900	2200	4300	4600	2200	2500	3000	36400
3	3700	7500	3700	3000	2400	4300	4600	2400	2500	3100	37200
4	3100	6500	3700	2750	2150	3500	4400	1900	2500	3100	33600
5	3100	6750	3700	2750	2400	3900	4200	1900	2500	3300	34500
6	4200	8000	3700	3000	2500	4300	4800	2400	2500	3100	38500
7	2800	6400	3700	2250	2150	3200	4400	1900	2300	3100	32200
8	2800	6300	3700	2250	2000	3200	4250	1900	2300	3100	31800
9	3100	7750	3700	2750	2400	3900	4200	1900	2500	3300	35500
10	3300	8450	3700	3050	2600	3900	4400	2000	2500	3500	37400
11	2900	6400	3700	2300	2150	3250	4400	1900	2300	3200	32500
12	3500	7600	3400	3200	2200	3500	4500	2200	2300	3000	35400
13	4100	7700	3500	2500	2400	4800	4000	2400	2500	3400	37300
14	2800	6800	3450	2500	2150	3200	4200	2100	2300	3100	32600
15	3600	6750	3700	3000	2400	3900	4200	1900	2750	3500	35700
16	3400	6900	3700	2900	2200	4300	4600	2200	2500	3600	36300

5.4 Experiment 1

This experiment includes runs using Max and Max-Min approaches starting from period 1 to period 14. The results are analyzed below:

5.4.1 Optimal Production Rates

The two approaches are used to assign operators to different operations. Tables (5.6) and (5.7) provide an example of the results of optimal production rates obtained in period 14 using Max-Min and Max approaches, respectively. Max-Min led to higher production rates in cell 2 for X1, cell 1 for X3, cell 1 for X4, cell 1 for X7, cell 2 for X7 and cell 2 for X9, while the rest remained the same.

Table 5.6 The optimal production rate for X products when Max-Min is used in period 14

	Product									
	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
O_i (Cell1)	305.01	242.42	<u>232.64</u>	<u>256.68</u>	275.57	220.59	<u>306.91</u>	252.1	207.61	177.78
O_i (Cell 2)	<u>463.46</u>	385.03	378.15	450.56	471.65	361.99	<u>561.74</u>	486.82	<u>415.22</u>	328.32
Demand	2800	6800	3450	2500	2150	3200	4200	2100	2300	3100
P_i (cell1)	9.18	28.05	14.83	9.74	7.8	14.51	13.68	8.33	11.08	17.44
P_i (cell2)	6.04	17.66	9.12	5.55	4.56	8.84	7.48	4.31	5.54	9.44

Table 5.7 The optimal production rate for X products when Max is used in period 14

	Product									
	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
O_i (Cell1)	305.01	242.42	<u>229.31</u>	<u>249.55</u>	275.57	220.59	<u>298.38</u>	252.1	207.61	177.78
O_i (Cell 2)	<u>454.08</u>	385.03	378.15	450.56	471.65	361.99	<u>560.22</u>	486.82	<u>412.98</u>	328.32
Demand	2800	6800	3450	2500	2150	3200	4200	2100	2300	3100
P_i (cell1)	9.18	28.05	15.05	10.02	7.8	14.51	14.08	8.33	11.08	17.44
P_i (cell2)	6.17	17.66	9.12	5.55	4.56	8.84	7.5	4.31	5.57	9.44

Where,

O_i optimal production rate for product i

P_i processing time for product i

Appendices C1 and C2 show the optimal production rates for all periods when Max-Min and Max were used, respectively. Table (5.8) shows the summary of these appendices.

The results show the production rates were higher with Max-Min after period 9.

Table 5.8 Comparison of Max-Min and Max in terms of production rates

	period	Number of Production rates in which Max-Min is better than Max.	Number of Production rates in which Max is better than Max-Min.
Exp.1	1	0	0
	2	0	0
	3	0	0
	4	0	0
	5	0	0
	6	0	0
	7	0	0
	8	0	0
	9	0	0
	10	1	0
	11	1	0
	12	1	0
	13	4	0
	14	6	0

5.4.2 Number of Operations Performed and Missed

Max and Max-Min approaches are used to assign operators to operations, which may affect operators' skill levels, and eventually the performance of cells. Tables (5.9) and (5.10) provide an example that shows all operations performed or missed by each operator in cell 1 in period 14, when Max-Min and Max approaches are used, respectively. Operators have missed fewer operations when Max-min assignment approach is used; this shows that operators were used more evenly across operations under this policy. Appendices D1 and D2 show all of the results obtained for all periods. Tables 5.11 and 5.12 show the summary of appendices for Max and Max-Min, respectively. The results show that the observation made for period 14 remains true in other periods as well.

Table 5.9 Operations performed and missed by each operator when Max is used

Period 14						
Cell 1	Product				operations performed	operations missed
Operator	X1	X3	X4	X6		
1	3	3	3	3	3	1,4
2	4	4	2	3	2,3,4	-
3	2	2	2	2	2	1,3
4	6	6	6	6	6	4,5
5	5	1	1	5	1,5	2
6	4	3	4	4	3,4	6
7	5	5	5	5	5	1,6
8	4	3	3	3	3,4	1
9	2	6	6	6	2,6	5
10	4	4	4	1	1,4	3
11	1	4	6	4	1,4,6	-
12	3	3	5	3	3,5	2
Total					22	14

Table 5.10 Operations performed and missed by each operator when Max-Min is used

Period 14						
Cell 1	Product				operations performed	operations missed
Operator	X1	X3	X4	X6		
1	3,4	3	3	3,4	3,4	1
2	4	3	4,2	4,3	2,3,4	-
3	2	2	2,1	2	1,2	3
4	4	4	6	5	4,5,6	-
5	1	1	5,2	5,1	1,2,5	-
6	4	3	3	4,6	3,4,6	-
7	5	6	6	6	5,6	1
8	4,3	4	1,4	3	1,3,4	-
9	2	6	2,5	6	2,5,6	-
10	3	3	4	3	3,4	1
11	6	4	6	1,4	1,4,6	-
12	5	5	5	3	3,5	2
Total					31	5

Table 5.11 Number of operations missed and performed when Max is used

period	Number of operations Max Approach			
	missed in cell 1	performed in cell 1	missed in cell 2	performed in cell 2
1	14	22	13	41
2	14	22	14	40
3	14	22	14	40
4	15	21	15	39
5	15	21	14	40
6	15	21	15	39
7	16	20	21	33
8	17	19	20	34
9	18	18	19	35
10	16	20	17	37
11	17	19	16	38
12	18	18	19	35
13	17	19	18	36
14	14	22	16	38

Table 5.12 Number of operations missed and performed when Max-Min is used

	Number of operations Max-Min Approach			
period	missed in cell 1	performed in cell 1	missed in cell 2	performed in cell 2
1	5	31	10	44
2	9	27	11	43
3	9	27	11	43
4	5	31	9	45
5	4	32	8	46
6	7	29	5	49
7	5	31	9	45
8	4	32	8	46
9	5	31	6	48
10	7	29	7	47
11	5	31	7	47
12	6	30	7	47
13	8	28	5	49
14	5	31	10	44

5.4.3 Impact on Operator Skill Levels

It was found that Max-Min improves operator skill levels more significantly than Max did. Benefits come from the Max-Min assignment strategy in which it finds the optimal operator assignment to maximize the output and then it holds the skilled operators and keep them un-assigned, and re-assign low skilled operators to non-bottleneck operations. This strategy allows an operator to perform an operation that he or she is not skilled at; hence his or her skill does not deteriorate and certainly improves. Tables (5.13) and (5.14) show the comparison of these two approaches at the end of period 14 in terms of average operator skill levels for cells 1 and 2, respectively. In cell 1, it was found that not only the average operator skill levels is greater than the initial average skill levels when Max-Min was used, but also is greater than operators average

skill levels when Max was used. On the other hand, when Max was used, 5 operators had an average skill levels greater than their initial ones, 3 operators kept the same average and 4 operators were found having lower average skill levels.

Table 5.13 Comparison of two approaches in cell 1 at the end of period 14

Cell 1		Average operator skill levels (at the end of Period 14)	
operator	Initial average skill level	Max-Min Approach	Max-Approach
1	4.67	5.67	4.67
2	3.67	5.33	4.67
3	3.67	4.67	3
4	3.67	6	3.67
5	3.33	5.33	3.67
6	5	6.33	4.67
7	3.67	5.33	3.37
8	4	5	4.33
9	4	5.67	4.33
10	3.67	5.33	3.67
11	2.5	5.67	3.67
12	4	5.33	3.67

In cell 2, it was found that the average operator skill levels is greater than the initial average skill levels when Max-Min was used. However, 15 operators had greater average skill levels than when Max was used, but 2 operators had the same average skill levels and 1 operator had lower average skill levels. As to Max strategy, 14 operators had an average skill levels greater than their initial ones, 1 operator kept the same average and 3 operators were found having lower average skill levels than their initial ones.

Table 5.14 Comparison of two approaches in cell 2 at the end of period 14

Cell 2		Average operator skill levels (at the end of Period 14)	
operator	Initial average skill level	Max-Min Approach	Max-Approach
13	4.33	5.33	4.33
14	5	7	6
15	3.67	6.33	5.67
16	3.67	6.33	5.33
17	4	5.33	4.67
18	5	6	5.33
19	4.67	5.67	5
20	4.67	6	5
21	3	5.67	5.67
22	3.67	5.33	3.33
23	4	6	5
24	4	5	3.67
25	4.33	6.33	5.33
26	3.67	4	3
27	3.67	6	5.33
28	3.33	5.33	5.33
29	4.33	5.33	4.67
30	4.67	6	6.67

5.4.4 Impact on Operations

Max-Min approach improved operator skill levels on each operation more apparently than Max did. Table (5.15) shows average skill levels on each operation. It was found that operation 1 deteriorated when Max was used; however average operator skills on all operations were greater when Max-Min was used.

Table 5.15 Average skill levels on each operation

		Average operator skill levels (at the end of period 14)	
Operation	Initial average skill level	Max-Min Approach	Max-Approach
Op.1	4	4.39	3.44
Op.2	3.92	5.23	4.23
Op.3	3.65	6	4.89
Op.4	4	6.25	5.63
Op.5	4.31	6.15	4.62
Op.6	4.25	5.92	4.62

5.4.5 Impact on Makespan

The results have shown that both approaches were tied in terms of makespan for the first 11 periods. Starting period 12, Max-Min performed better in minimizing makespan by 0.2 %, 0.2% and 0.1% compared to Max approach in periods 12, 13 and 14, respectively. Table (5.16) shows the comparison of these two approaches in terms of makespan from period 1 to period 14.

Table 5.16 The makespan from period 1 to period 14

period	Max-Min	Max	Difference(%)
1	58.07	58.07	0.0%
2	59.84	59.84	0.0%
3	61	61	0.0%
4	53.13	53.13	0.0%
5	55.92	55.92	0.0%
6	60.07	60.07	0.0%
7	50.23	50.23	0.0%
8	49.684	49.684	0.0%
9	55.76	55.76	0.0%
10	57.9	57.9	0.0%
11	50.64	50.64	0.0%
12	53.19	53.1	0.2%
13	56.25	56.15	0.2%
14	49.04	48.99	0.1%

5.4.6 Impact on Total Time

The results have shown that both approaches were tied in terms of total time for the first 11 periods. Similar to previous section, Max-Min performed slightly better in minimizing total time by 0.1 %, 0.3% and 0.6% compared to Max approach in periods 12, 13 and 14, respectively. Table (5.17) summarizes the results obtained.

Table 5.17 The total time from period 1 to period 14

period	Max-Min	Max	Difference(%)
1	115.44	115.44	0%
2	119.07	119.07	0%
3	121.5	121.5	0%
4	104.79	104.79	0%
5	111.7	111.7	0%
6	119.05	119.05	0%
7	100.2	100.2	0%
8	99.094	99.094	0%
9	111.07	111.07	0%
10	115.23	115.23	0%
11	100.2	100.2	0%
12	103.91	104	0.1%
13	111.09	111.47	0.3%
14	97.25	97.8	0.6%

5.5 Experiment 2

In this section, chaos is applied in periods 10 and 11 and results are analyzed below:

5.5.1 Impact on Makespan under Chaos

The chaos is applied in periods 10 and 11 to create a big shock in the system to see how both approaches behave in terms of makespan. This is accomplished by introducing new products with very different processing times. The results have shown that when 5 products of type Y entered the system and 5 products of type X left the system, Max-Min gave better results (with 0.4% reduction in makespan) in period 10. In period 11, the entire set of products of type Y is manufactured (no product X in the system). Max-Min still worked better (with 0.4% improvement in makespan). Table 5.18

shows the results of makespan using these two approaches in periods 10 and 11. Table 5.19 shows another chaotic scenario by entering all products of type Y and releasing all products of type X in period 10. In this case, the improvement with Max-Min over Max was 0.7%.

Table 5.18 Impact on makespan under chaos in periods 10 and 11

	Max-Min	Max	Difference (%)
Period 10 (5 products)	71.15	71.43	0.4%
Period 11 (5 + 5) products)	81.68	82.02	0.4%

Table 5.19 Impact on makespan under chaos in period 10

	Max-Min	Max	Difference (%)
Period 10 (10 products)	94.3	94.92	0.7%

5.5.2 Impact on Total Time under Chaos

Max-Min performed better in minimizing total time by 0.2 % and 0.4% compared to Max approach in periods 10 and 11, respectively. Table (5.20) shows the comparison of these two approaches in terms of total time from periods 10 and 11. Table (5.21) shows that Max-Min-Min is better by 0.5% when all Y products are in period 10.

Table 5.20 Impact on total time under chaos in periods 10 and 11

	Max-Min	Max	Difference (%)
period 10 (5 products)	142.25	142.53	0.2%
period 11 (5 + 5) products)	163.11	163.81	0.4%

Table 5.21 Impact on total time under chaos in period 10

	Max-Min	Max	Difference (%)
Period 10 (10 products)	188.66	189.58	0.5%

5.6 Experiment 3

In this section, chaos is applied in periods 15 and 16 and results are analyzed below:

5.6.1 Impact on Makespan under Chaos.

The chaos was applied in periods 15 and 16 as we did in experiment 2. The results have shown that when 5 products of type Y entered the system and 5 products of type X left the system, Max-Min gave better results (with 1.7% reduction in makespan) in period 15. In period 16, the entire set of products of type Y is manufactured (no product X in the system). Max-Min still worked better (with 1.2% improvement in makespan). Table 5.22 shows the results of makespan using these two approaches in periods 15 and 16. Table 5.23 shows another chaotic scenario by entering all products of type Y and releasing all products of type X in period 15. In this case, the improvement with Max-Min over Max was 2.2%.

Table 5.22 Impact on makespan under chaos in periods 15 and 16

	Max-Min	Max	Difference (%)
period 15 (5 products)	66.48	67.6	1.7%
period 16 (5+5) products)	88.6	89.7	1.2%

Table 5.23 Impact on makespan under chaos in period 15

	Max-Min	Max	Difference (%)
Period 15 (10 products)	86.81	89.01	2.2%

5.6.2 Impact on Total Time under Chaos

Not only Max-Min performs better in minimizing makespan in periods 15 and 16, but also in minimizing the total time. Max-Min is better by 2.2 % and 1.1% compared to Max approach in periods 15 and 16, respectively. Table (5.24) shows the comparison of these two approaches in terms of total time from periods 15 and 16. Table (5.25) shows that Max-Min is better by 2.3% when all Y products are in period 15.

Table 5.24 Impact on total time under chaos in periods 15 and 16

	Max-Min	Max	Difference (%)
period 15 (5 products)	132.04	134.95	2.2%
period 16 (5+5) products)	177.19	179.181	1.1%

Table 5.25 Impact on total time under chaos in period 15

	Max-Min	Max	Difference (%)
Period 15 (10 products)	173.35	177.4	2.3%

5.7 Experiment 4

In this phase, we wanted to show that the improvement in operators' skill levels should have better impact than what happened in pervious experiments. We changed the standard deviation from (0.05μ) to (0.2μ) to extend the gap of operator-operation times, and then we applied these new times in period 15 by entering all products of type Y in the system. Results have shown that there was better gain in terms of minimizing makespan and total time. Max-Min performed better by 5% than Max approach. Tables 5.26 and 5.27 show these results.

Table 5.26 Impact on makespan under chaos in period 15

	Max-Min	Max	Difference (%)
period 15 (10 products) (SD = 0.2)	55.23	58.02	5%

Table 5.27 Impact on total time under chaos in period 15

	Max-Min	Max	Difference (%)
period 15 (10 products) (SD = 0.2)	109.7	115.55	5 %

CHAPTER 6 CONCLUSIONS AND FUTURE WORK

This chapter concludes the thesis by summarizing the results obtained from the experimentation and suggests any future research in the field.

6.1 Conclusions

In this study, operators were assigned to operations to maximize the production rate using two assignment approaches: Max-Min and Max. The major concern is to see how these two approaches impact operators' skill levels, as well as impact on makespan and total time among cells. The impact is discussed under a chaotic environment where sudden changes in product mix with different operation times are applied and under a non-chaotic environment where the same product mix is run period after period. In this thesis, a skill level is affected by learning and forgetting rates. An operator's skill level increases when he performs an operation for many consecutive periods; on the other hand, if an operator does not perform a certain operation for a number of consecutive periods, his skill level decreases. Max-Min did improve operators' overall skill levels more significantly than Max in multi-periods. This is due to the fact that Max-Min does not only assign operators to maximize production rate, but also it re-assigns operators to operations where they are not very skilled; thus, operator's skill levels continue to improve. On the other hand, Max is only assigning operators to operations to maximize production rate.

More importantly, Max-Min has achieved better results in terms of minimizing makespan under non-chaotic experiments. This gain is significant because the work undertaken in this thesis is an extension of a previous work by Süer and Tummaluri

(2008). They found that Max-Min is superior to Max approach in terms of improving operator skill levels; however, they could not show that Max-Min approach is better in minimizing makespan as a result of improved skill levels. Their work also showed that some non-bottleneck operations became bottleneck after assigning operators, whereas we solved this problem by adding a constraint that prevents violating the original production rate the in the mathematical model used by Max-min.

Moreover, the previous work assumed a stable cellular environment, in which they assumed that there are no new products entering the system. Thus, in this thesis, we introduced a highly dynamic cellular environment, in which new products with different processing times entered the system and other products left the system. Max-Min acts well under chaotic environment because it increases operators' skill levels well enough to face the shock applied, where the shock contains products with new processing times and this requires different manpower allocation.

Süer and Tummaluri (2008) used the standard times for initial operator assignment to operations by using mathematical models. They considered operator skill levels afterwards and then modified output rates accordingly. On the other hand, in this thesis, skill-based times are used directly in mathematical models for operator assignment. They also considered 9 categories of operator's skill levels, where 9 is the worst, 1 is the best and 5 is the average; however we considered 7 categories where 7 is the best, 1 is the worst and 4 is the average.

We also concluded that the standard deviation used in operator time matrix, is an important factor for helping Max-Min approach to expand the gain in terms of minimizing makespan and total time. A standard deviation of 5% of the mean is used in

operator matrix for all experimentations. In period 15, when we replaced the whole set of products of type X with products of type Y, we found the highest gain that shows Max-Min is better in minimizing makespan and total time among all periods. This gain was captured using a standard deviation of (0.05μ) ; however, when we used a standard deviation of (0.2μ) , we found that the gain is higher than using (0.05μ) .

6.2 Future Work

This thesis can be extended by considering the following issues:-

- Applying Operator preference concept, in which they choose the operation they would like to perform. This will increase their job satisfaction and their loyalty to the company.
- New hiring and quitting of operators. Some operators will leave the company and the others will be hired and this will affect the current skill pool. Once again, keeping the skill levels of current employees high is expected to benefit the company in the long term.
- Creating chaotic environment by assuming new products entering the system and others leave while new operators will join and others will leave simultaneously.
- Experimenting with different standard deviations.
- Skill levels can be combined by traditional learning curve computations where processing time of an operation decreases as more units are manufactured by the same operator.
- Allowing lot-splitting during cell loading process. Makespan will get a lower value than when lot splitting is not allowed, but planning efforts get complicated

since now there might be more products to build per cell. Figures 6.1 and 6.2 show the Gantt charts for cell loading when lot splitting is not allowed and also when lot splitting is allowed, respectively.

Cell 1	X5 8.72	X1 21.51		X3 37.8		X6 58.07	
Cell 2	X8 4.91	X9 11.10	X4 17.79	X7 26.51	X10 36.78	X2 57.37	

Figure 6.1 Gantt chart for cell loading-lot splitting is not allowed

Cell 1	X5 8.72	X1 21.51		X3 37.8		X6 57.72	
Cell 2	X8 4.91	X9 11.10	X4 17.79	X7 26.51	X10 36.78	X2 57.37	X6' 57.72

Figure 6.2 Gantt chart for cell loading-lot splitting is allowed

- Allowing operator sharing among operations in the same cell. Production rate will get a higher value than when operator sharing is not allowed. For example; product X1 in cell 1 in period 1 has a production rate of (273.68 units/hr) when each operator is assigned to only one operation. However, when operator sharing is allowed, this cell produces (310.72 units/hr). In this case, 3 operators are assigned to 2 operations, 1 operator is assigned to 3 operations, and the rest of operators are assigned to one operation.

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APPENDIX A: THE MATHEMATICAL MODELS USED FOR PRODUCT 1 IN PERIOD 1

A1. Mathematical Model when Max Approach was used.

//operation 1

```
dvar int+ Y011 in 0..maxint;
dva int+ Y031 in 0..maxint;
dvar int+ Y051 in 0..maxint;
dvar int+ Y071 in 0..maxint;
dvar int+ Y081 in 0..maxint;
dvar int+ Y101 in 0..maxint;
dvar int+ Y111 in 0..maxint;
```

//operation 2

```
dvar int+ Y022 in 0..maxint;
dvar int+ Y052 in 0..maxint;
dvar int+ Y032 in 0..maxint;
dvar int+ Y092 in 0..maxint;
dvar int+ Y122 in 0..maxint;
```

//operation 3

```
dvar int+ Y013 in 0..maxint;
dvar int+ Y023 in 0..maxint;
dvar int+ Y033 in 0..maxint;
dvar int+ Y063 in 0..maxint;
dvar int+ Y083 in 0..maxint;
dvar int+ Y103 in 0..maxint;
dvar int+ Y123 in 0..maxint;
```

//operation 4

```
dvar int+ Y014 in 0..maxint;
dvar int+ Y024 in 0..maxint;
dvar int+ Y044 in 0..maxint;
dvar int+ Y064 in 0..maxint;
dvar int+ Y084 in 0..maxint;
dvar int+ Y104 in 0..maxint;
dvar int+ Y114 in 0..maxint;
```

//operation 5

```
dvar int+ Y045 in 0..maxint;
dvar int+ Y055 in 0..maxint;
dvar int+ Y075 in 0..maxint;
dvar int+ Y095 in 0..maxint;
dvar int+ Y125 in 0..maxint;
```

//operation 6

```
dvar int+ Y046 in 0..maxint;
dvar int+ Y066 in 0..maxint;
dvar int+ Y076 in 0..maxint;
dvar int+ Y096 in 0..maxint;
dvar int+ Y116 in 0..maxint;
```

```
//defining Z as the value of R where R is the production rate
dvar float+ Z in 0..maxint;
dvar float+ R in 0..maxint;
```

```

maximize Z; // objective function to find the maximum production rate
subject to
{
Z==R;
((60/.0665)*Y011+ (60/0.0735)*Y031+ (60/0.077)*Y051+ (60/0.07)*Y071+
(60/0.07)*Y081+ (60/0.07)*Y101+ (60/0.07)*Y111)-R>=0;// finding máximo

((60/0.4725)*Y022+ (60/0.4275)*Y032+ (60/0.4725)*Y052+ (60/0.45)*Y092+
(60/0.4725)*Y122)- R>=0;// op.2

((60/0.3515)*Y013+ (60/0.37)*Y023+ (60/0.3885)*Y033+ (60/0.3515)*Y063+
(60/0.37)*Y083+ (60/0.3885)*Y103+ (60/0.37)*Y123)- R >=0;// op.3

((60/0.88)*Y014+ (60/0.88)*Y024+ (60/0.88)*Y044+ (60/0.792)*Y064+
(60/0.88)*Y084+ (60/0.88)*Y104+ (60/1.012)*Y114)- R>=0;//op.4

((60/0.399)*Y045+ (60/0.361)*Y055+ (60/0.38)*Y075+ (60/0.38)*Y095+
(60/0.361)*Y125)- R>=0;//op.5

((60/0.21)*Y046+ (60/0.21)*Y066+ (60/0.2205)*Y076+ (60/0.21)*Y096+
(60/0.2205)*Y116)- R>=0;//op.6

Y011+ Y013+Y014 == 1;
Y022+ Y023+ Y024 == 1;
Y031+ Y032+ Y033 == 1;
Y044+ Y045+ Y046 == 1;
Y051+ Y052+ Y055 == 1;
Y063+ Y064 + Y066 == 1;
Y071+ Y075 + Y076 == 1;
Y081+ Y083 + Y084 == 1;
Y092+ Y095 + Y096 == 1;
Y101+ Y103 + Y104 == 1;
Y111+ Y114 + Y116 == 1;
Y122+ Y123 + Y125 == 1;

};

```

Final solution with objective = 273.68:

```

Z = 273.68;
R = 273.68;
Y011 = 0;
Y031 = 0;
Y051 = 0;
Y071 = 0;
Y081 = 0;

```

Y101 = 0;
Y111 = 1;
Y022 = 0;
Y032 = 1;
Y052 = 0;
Y092 = 1;
Y122 = 0;
Y013 = 1;
Y023 = 0;
Y033 = 0;
Y063 = 0;
Y083 = 0;
Y103 = 0;
Y123 = 1;
Y014 = 0;
Y024 = 1;
Y044 = 0;
Y064 = 1;
Y084 = 1;
Y104 = 1;
Y114 = 0;
Y045 = 0;
Y055 = 1;
Y075 = 1;
Y095 = 0;
Y125 = 0;
Y046 = 1;
Y066 = 0;
Y076 = 0;
Y096 = 0;
Y116 = 0;

A1. Mathematical Model when Max-Min Approach was used

A 2.1 Mathematical model for finding bottleneck operations.

```

//operation 1

dvar int+ Y011 in 0..maxint;
dva int+ Y031 in 0..maxint;
dvar int+ Y051 in 0..maxint;
dvar int+ Y071 in 0..maxint;
dvar int+ Y081 in 0..maxint;
dvar int+ Y101 in 0..maxint;
dvar int+ Y111 in 0..maxint;


//operation 2

dvar int+ Y022 in 0..maxint;
dvar int+ Y052 in 0..maxint;
dvar int+ Y032 in 0..maxint;
dvar int+ Y092 in 0..maxint;
dvar int+ Y122 in 0..maxint;


//operation 3

dvar int+ Y013 in 0..maxint;
dvar int+ Y023 in 0..maxint;
dvar int+ Y033 in 0..maxint;
dvar int+ Y063 in 0..maxint;
dvar int+ Y083 in 0..maxint;
dvar int+ Y103 in 0..maxint;
dvar int+ Y123 in 0..maxint;


//operation 4

dvar int+ Y014 in 0..maxint;
dvar int+ Y024 in 0..maxint;
dvar int+ Y044 in 0..maxint;
dvar int+ Y064 in 0..maxint;
dvar int+ Y084 in 0..maxint;
dvar int+ Y104 in 0..maxint;
dvar int+ Y114 in 0..maxint;


//operation 5

dvar int+ Y045 in 0..maxint;
dvar int+ Y055 in 0..maxint;
dvar int+ Y075 in 0..maxint;
dvar int+ Y095 in 0..maxint;
dvar int+ Y125 in 0..maxint;


//operation 6

dvar int+ Y046 in 0..maxint;
dvar int+ Y066 in 0..maxint;
dvar int+ Y076 in 0..maxint;
dvar int+ Y096 in 0..maxint;
dvar int+ Y116 in 0..maxint;


//defining Z as the value of R where R is the production rate
dvar float+ Z in 0..maxint;
dvar float+ R in 0..maxint;
dvar float+ R1 in 0..maxint;
dvar float+ R2 in 0..maxint;
dvar float+ R3 in 0..maxint;
dvar float+ R4 in 0..maxint;

```

```

dvar float+ R5 in 0..maxint;
dvar float+ R6 in 0..maxint;

maximize Z; // objective function to find the maximum production rate
subject to
{
Z==R;
((60/.0665)*Y011+ (60/0.0735)*Y031+ (60/0.077)*Y051+ (60/0.07)*Y071+
(60/0.07)*Y081+ (60/0.07)*Y101+ (60/0.07)*Y111)-R>=0;// finding máximo

((60/0.4725)*Y022+ (60/0.4275)*Y032+ (60/0.4725)*Y052+ (60/0.45)*Y092+
(60/0.4725)*Y122)- R>=0;// op.2

((60/0.3515)*Y013+ (60/0.37)*Y023+ (60/0.3885)*Y033+ (60/0.3515)*Y063+
(60/0.37)*Y083+ (60/0.3885)*Y103+ (60/0.37)*Y123)- R >=0;// op.3

((60/0.88)*Y014+ (60/0.88)*Y024+ (60/0.88)*Y044+ (60/0.792)*Y064+
(60/0.88)*Y084+ (60/0.88)*Y104+ (60/1.012)*Y114)- R>=0;//op.4

((60/0.399)*Y045+ (60/0.361)*Y055+ (60/0.38)*Y075+ (60/0.38)*Y095+
(60/0.361)*Y125)- R>=0;//op.5

((60/0.21)*Y046+ (60/0.21)*Y066+ (60/0.2205)*Y076+ (60/0.21)*Y096+
(60/0.2205)*Y116)- R>=0;//op.6

R1==((60/.0665)*Y011+ (60/0.0735)*Y031+ (60/0.077)*Y051+ (60/0.07)*Y071+
(60/0.07)*Y081+ (60/0.07)*Y101+ (60/0.07)*Y111);
R2==((60/0.4725)*Y022+ (60/0.4275)*Y032+ (60/0.4725)*Y052+ (60/0.45)*Y092+
(60/0.4725)*Y122);
R3==((60/0.3515)*Y013+ (60/0.37)*Y023+ (60/0.3885)*Y033+ (60/0.3515)*Y063+
(60/0.37)*Y083+ (60/0.3885)*Y103+ (60/0.37)*Y123);
R4==((60/0.88)*Y014+ (60/0.88)*Y024+ (60/0.88)*Y044+ (60/0.792)*Y064+
(60/0.88)*Y084+ (60/0.88)*Y104+ (60/1.012)*Y114);
R5==((60/0.399)*Y045+ (60/0.361)*Y055+ (60/0.38)*Y075+ (60/0.38)*Y095+
(60/0.361)*Y125);
R6==((60/0.21)*Y046+ (60/0.21)*Y066+ (60/0.2205)*Y076+ (60/0.21)*Y096+
(60/0.2205)*Y116);

Y011+ Y013+Y014 == 1;
Y022+ Y023+ Y024 == 1;
Y031+ Y032+ Y033 == 1;
Y044+ Y045+ Y046 == 1;
Y051+ Y052+ Y055 == 1;
Y063+ Y064 + Y066 == 1;
Y071+ Y075 + Y076 == 1;
Y081+ Y083 + Y084 == 1;

```

```
Y092+ Y095 + Y096 == 1;  
Y101+ Y103 + Y104 == 1;  
Y111+ Y114 + Y116 == 1;  
Y122+ Y123 + Y125 == 1;  
  
};
```

Final solution with objective = 273.68:

$$Z = 273.68;$$

$$R = 273.68;$$

$$Y011 = 0;$$

$$Y031 = 0;$$

$$Y051 = 0;$$

$$Y071 = 0;$$

$$Y081 = 0;$$

$$Y101 = 0;$$

$$Y111 = 1;$$

$$Y022 = 0;$$

$$Y032 = 1;$$

$$Y052 = 0;$$

$$Y092 = 1;$$

$$Y122 = 0;$$

$$Y013 = 1;$$

$$Y023 = 0;$$

$$Y033 = 0;$$

$$Y063 = 0;$$

$$Y083 = 0;$$

$$Y103 = 0;$$

$$Y123 = 1;$$

$$Y014 = 0;$$

$$Y024 = 1;$$

$$Y044 = 0;$$

$$Y064 = 1;$$

$$Y084 = 1;$$

$$Y104 = 1;$$

$$Y114 = 0;$$

$$Y045 = 0;$$

$$Y055 = 1;$$

$$Y075 = 1;$$

$$Y095 = 0;$$

$$Y125 = 0;$$

$$Y046 = 1;$$

$$Y066 = 0;$$

$$Y076 = 0;$$

$$Y096 = 0;$$

$$Y116 = 0;$$

$$R1 = 857.14;$$

$$R2 = 273.68;$$

$$R3 = 332.86;$$

$$R4 = 280.3;$$

$$R5 = 324.1;$$

$$R6 = 285.71;$$

A 2.2 Mathematical model for re-assigning low-skilled operators to non-bottleneck operations

//operation 1

```
dvar int+ Y011 in 0..maxint;
dvar int+ Y031 in 0..maxint;
dvar int+ Y051 in 0..maxint;
dvar int+ Y071 in 0..maxint;
dvar int+ Y081 in 0..maxint;
dvar int+ Y101 in 0..maxint;
dvar int+ Y111 in 0..maxint;
```

//operation 2

```
dvar int+ Y022 in 0..maxint;
dvar int+ Y052 in 0..maxint;
dvar int+ Y032 in 0..maxint;
dvar int+ Y092 in 0..maxint;
dvar int+ Y122 in 0..maxint;
```

//operation 3

```
dvar int+ Y013 in 0..maxint;
dvar int+ Y023 in 0..maxint;
dvar int+ Y033 in 0..maxint;
dvar int+ Y063 in 0..maxint;
dvar int+ Y083 in 0..maxint;
dvar int+ Y103 in 0..maxint;
dvar int+ Y123 in 0..maxint;
```

//operation 4

```
dvar int+ Y014 in 0..maxint;
dvar int+ Y024 in 0..maxint;
dvar int+ Y044 in 0..maxint;
dvar int+ Y064 in 0..maxint;
dvar int+ Y084 in 0..maxint;
dvar int+ Y104 in 0..maxint;
dvar int+ Y114 in 0..maxint;
```

//operation 5

```
dvar int+ Y045 in 0..maxint;
dvar int+ Y055 in 0..maxint;
dvar int+ Y075 in 0..maxint;
dvar int+ Y095 in 0..maxint;
dvar int+ Y125 in 0..maxint;
```

//operation 6

```
dvar int+ Y046 in 0..maxint;
dvar int+ Y066 in 0..maxint;
dvar int+ Y076 in 0..maxint;
dvar int+ Y096 in 0..maxint;
dvar int+ Y116 in 0..maxint;
```

```
dvar float+ Z in 0..maxint;
//dvar float+ R in 0..maxint;
```

```
minimize Z; // objective function to find the minimum skill
subject to
{
```

$Z = 5*Y_{011} + 5*Y_{013} + 4*Y_{014} + 4*Y_{023} + 4*Y_{024} + 4*Y_{044} + 3*Y_{045} + 4*Y_{046} + 2*Y_{051} + 5*Y_{055} + 5*Y_{063} + 6*Y_{064} + 4*Y_{066} + 4*Y_{071} + 4*Y_{075} + 3*Y_{076} + 4*Y_{081} + 4*Y_{083} + 4*Y_{084} + 4*Y_{101} + 3*Y_{103} + 4*Y_{104} + 4*Y_{111} + 1*Y_{114} + 3*Y_{116} + 4*Y_{123} + 5*Y_{125};$

$((60/0.0665)*Y_{011} + (60/0.077)*Y_{051} + (60/0.07)*Y_{071} + (60/0.07)*Y_{081} + (60/0.07)*Y_{101} + (60/0.07)*Y_{111}) \geq 273.68;$

$((60/0.3515)*Y_{013} + (60/0.37)*Y_{023} + (60/0.3515)*Y_{063} + (60/0.37)*Y_{083} + (60/0.3885)*Y_{103} + (60/0.37)*Y_{123}) \geq 273.68;$

$((60/0.88)*Y_{014} + (60/0.88)*Y_{024} + (60/0.88)*Y_{044} + (60/0.792)*Y_{064} + (60/0.88)*Y_{084} + (60/0.88)*Y_{104} + (60/1.012)*Y_{114}) \geq 273.68;$

$((60/0.399)*Y_{045} + (60/0.361)*Y_{055} + (60/0.38)*Y_{075} + (60/0.361)*Y_{125}) \geq 273.68;$

$((60/0.21)*Y_{046} + (60/0.21)*Y_{066} + (60/0.2205)*Y_{076} + (60/0.2205)*Y_{116}) \geq 273.68;$

$Y_{011} + Y_{013} + Y_{014} == 1;$
 $Y_{023} + Y_{024} == 1;$
 $Y_{044} + Y_{045} + Y_{046} == 1;$
 $Y_{051} + Y_{055} == 1;$
 $Y_{063} + Y_{064} + Y_{066} == 1;$
 $Y_{071} + Y_{075} + Y_{076} == 1;$
 $Y_{081} + Y_{083} + Y_{084} == 1;$
 $Y_{101} + Y_{103} + Y_{104} == 1;$
 $Y_{111} + Y_{114} + Y_{116} == 1;$
 $Y_{123} + Y_{125} == 1;$

};

Final solution with objective = 42:

$$Z = 42;$$

$$Y_{011} = 0;$$

$$Y_{013} = 0;$$

$$Y_{014} = 1;$$

$$Y_{023} = 0;$$

$$Y_{024} = 1;$$

$$Y_{044} = 0;$$

$$Y_{045} = 0;$$

$$Y_{046} = 1;$$

$$Y_{051} = 0;$$

$$Y_{055} = 1;$$

$$Y_{063} = 0;$$

$$Y_{064} = 1;$$

$$Y_{066} = 0;$$

$$Y_{071} = 0;$$

$$Y_{075} = 1;$$

$$Y_{076} = 0;$$

$$Y_{081} = 0;$$

$$Y_{083} = 0;$$

$$Y_{084} = 1;$$

$$Y_{101} = 0;$$

$$Y_{103} = 1;$$

$$Y_{104} = 0;$$

$$Y_{111} = 1;$$

$$Y_{114} = 0;$$

$$Y_{116} = 0;$$

$$Y_{123} = 1;$$

$$Y_{125} = 0$$

A3. Mathematical Model used for Cell Loading

```

//CELL 1
dvar int+ x011 in 0..1;
dvar int+ x021 in 0..1;
dvar int+ x031 in 0..1;
dvar int+ x041 in 0..1;
dvar int+ x051 in 0..1;
dvar int+ x061 in 0..1;
dvar int+ x071 in 0..1;
dvar int+ x081 in 0..1;
dvar int+ x091 in 0..1;
dvar int+ x101 in 0..1;

//CELL 2
dvar int+ x012 in 0..1;
dvar int+ x022 in 0..1;
dvar int+ x032 in 0..1;
dvar int+ x042 in 0..1;
dvar int+ x052 in 0..1;
dvar int+ x062 in 0..1;
dvar int+ x072 in 0..1;
dvar int+ x082 in 0..1;
dvar int+ x092 in 0..1;
dvar int+ x102 in 0..1;

//defining Z as the value of MS where MS is the makespan
dvar float+ Z in 0..maxint;
dvar float+ MS in 0..maxint;

minimize Z; // objective function to minimize makespan

subject to

{

MS
>=(12.79*x011+34.44*x021+16.29*x031+11.76*x041+8.72*x051+20.27*x061+16.39*
x071+9.75*x081+11.83*x091+17.81*x101);
MS
>=(8.47*x012+20.59*x022+9.60*x032+6.60*x042+5.20*x052+11.81*x062+8.72*x072
+4.91*x082+6.19*x092+10.21*x102);

Z==MS;

MS
>=(12.79*x011+34.43*x021+16.29*x031+11.76*x041+8.72*x051+20.27*x061+16.39*x0
71+9.50*x081+11.83*x091+17.81*x101);
MS
>=(8.47*x012+20.59*x022+9.50*x032+6.69*x042+5.20*x052+11.81*x062+8.78*x072+4.
91*x082+6.19*x092+10.21*x102);

x011+x012==1;//
x021+x022==1;
x031+x032==1;
x041+x042==1;
x051+x052==1;

```



```
x061+x062==1;  
x071+x072==1;  
x081+x082==1;  
x091+x092==1;  
x101+x102==1;
```

```
};
```

Final solution with objective = 58.07:

Z = 58.07;

MS = 58.07;

x011 = 1;

x021 = 0;

x031 = 1;

x041 = 0;

x051 = 1;

x061 = 1

x071 = 0;

x081 = 0;

x091 = 0;

x101 = 0;

x012 = 0;

x022 = 1;

x032 = 0;

x042 = 1;

x052 = 0;

x062 = 0;

x072 = 1;

x082 = 1;

x092 = 1;

x102 = 1;

APPENDIX B: OPERATION-OPERATOR TIMES FOR PRODUCTS X AND Y

B1. Operation-operator Times for Product of Type X

	Op.1	Op.2	Op.3	Op.4	Op.5	Op.6
X1	0.07	0.45	0.37	0.88	0.38	0.21
Std. Dev.	0.0035	0.0225	0.0185	0.044	0.019	0.0105
skill level						
7	0.0595	0.3825	0.3145	0.748	0.323	0.1785
6	0.063	0.405	0.333	0.792	0.342	0.189
5	0.0665	0.4275	0.3515	0.836	0.361	0.1995
4	0.07	0.45	0.37	0.88	0.38	0.21
3	0.0735	0.4725	0.3885	0.924	0.399	0.2205
2	0.077	0.495	0.407	0.968	0.418	0.231
1	0.0805	0.5175	0.4255	1.012	0.437	0.2415
X2	0.05	0.29	0.62	0.74	0.38	0.55
Std. Dev.	0.0025	0.0145	0.031	0.037	0.019	0.0275
skill level						
7	0.0425	0.2465	0.527	0.629	0.323	0.4675
6	0.045	0.261	0.558	0.666	0.342	0.495
5	0.0475	0.2755	0.589	0.703	0.361	0.5225
4	0.05	0.29	0.62	0.74	0.38	0.55
3	0.0525	0.3045	0.651	0.777	0.399	0.5775
2	0.055	0.319	0.682	0.814	0.418	0.605
1	0.0575	0.3335	0.713	0.851	0.437	0.6325

	Op.1	Op.2	Op.3	Op.4	Op.5	Op.6
X3	0.06	0.29	1.18	0.86	0.18	0.56
Std. Dev.	0.003	0.0145	0.059	0.043	0.009	0.028
skill level						
7	0.051	0.2465	1.003	0.731	0.153	0.476
6	0.054	0.261	1.062	0.774	0.162	0.504
5	0.057	0.2755	1.121	0.817	0.171	0.532
4	0.06	0.29	1.18	0.86	0.18	0.56
3	0.063	0.3045	1.239	0.903	0.189	0.588
2	0.066	0.319	1.298	0.946	0.198	0.616
1	0.069	0.3335	1.357	0.989	0.207	0.644
X4	0.04	0.31	0.55	0.47	0.4	0.71
Std. Dev.	0.002	0.0155	0.0275	0.0235	0.02	0.0355
skill level						
7	0.034	0.2635	0.4675	0.3995	0.34	0.6035
6	0.036	0.279	0.495	0.423	0.36	0.639
5	0.038	0.2945	0.5225	0.4465	0.38	0.6745
4	0.04	0.31	0.55	0.47	0.4	0.71
3	0.042	0.3255	0.5775	0.4935	0.42	0.7455
2	0.044	0.341	0.605	0.517	0.44	0.781
1	0.046	0.3565	0.6325	0.5405	0.46	0.8165
X5	0.08	0.41	0.43	0.74	0.43	0.44
Std. Dev.	0.004	0.0205	0.0215	0.037	0.0215	0.022
skill level						
7	0.068	0.3485	0.3655	0.629	0.3655	0.374
6	0.072	0.369	0.387	0.666	0.387	0.396
5	0.076	0.3895	0.4085	0.703	0.4085	0.418
4	0.08	0.41	0.43	0.74	0.43	0.44
3	0.084	0.4305	0.4515	0.777	0.4515	0.462
2	0.088	0.451	0.473	0.814	0.473	0.484
1	0.092	0.4715	0.4945	0.851	0.4945	0.506
X6	0.07	0.32	1.18	0.55	0.45	0.39
Std. Dev.	0.0035	0.016	0.059	0.0275	0.0225	0.0195
skill level						
7	0.0595	0.272	1.003	0.4675	0.3825	0.3315
6	0.063	0.288	1.062	0.495	0.405	0.351
5	0.0665	0.304	1.121	0.5225	0.4275	0.3705
4	0.07	0.32	1.18	0.55	0.45	0.39
3	0.0735	0.336	1.239	0.5775	0.4725	0.4095
2	0.077	0.352	1.298	0.605	0.495	0.429
1	0.0805	0.368	1.357	0.6325	0.5175	0.4485

	Op.1	Op.2	Op.3	Op.4	Op.5	Op.6
X7	0.09	0.37	0.46	0.49	0.26	0.26
Std. Dev.	0.0045	0.0185	0.023	0.0245	0.013	0.013
skill level						
7	0.0765	0.3145	0.391	0.4165	0.221	0.221
6	0.081	0.333	0.414	0.441	0.234	0.234
5	0.0855	0.3515	0.437	0.4655	0.247	0.247
4	0.09	0.37	0.46	0.49	0.26	0.26
3	0.0945	0.3885	0.483	0.5145	0.273	0.273
2	0.099	0.407	0.506	0.539	0.286	0.286
1	0.1035	0.4255	0.529	0.5635	0.299	0.299
X8	0.08	0.28	0.49	0.61	0.29	0.55
Std. Dev.	0.004	0.014	0.0245	0.0305	0.0145	0.0275
skill level						
7	0.068	0.238	0.4165	0.5185	0.2465	0.4675
6	0.072	0.252	0.441	0.549	0.261	0.495
5	0.076	0.266	0.4655	0.5795	0.2755	0.5225
4	0.08	0.28	0.49	0.61	0.29	0.55
3	0.084	0.294	0.5145	0.6405	0.3045	0.5775
2	0.088	0.308	0.539	0.671	0.319	0.605
1	0.092	0.322	0.5635	0.7015	0.3335	0.6325

	Op.1	Op.2	Op.3	Op.4	Op.5	Op.6
X9	0.04	0.34	0.81	0.62	0.34	0.65
Std. Dev.	0.002	0.017	0.0405	0.031	0.017	0.0325
skill level						
7	0.034	0.289	0.6885	0.527	0.289	0.5525
6	0.036	0.306	0.729	0.558	0.306	0.585
5	0.038	0.323	0.7695	0.589	0.323	0.6175
4	0.04	0.34	0.81	0.62	0.34	0.65
3	0.042	0.357	0.8505	0.651	0.357	0.6825
2	0.044	0.374	0.891	0.682	0.374	0.715
1	0.046	0.391	0.9315	0.713	0.391	0.7475
X10	0.07	0.43	0.74	0.87	0.43	0.75
Std. Dev.	0.0035	0.0215	0.037	0.0435	0.0215	0.0375
skill level						
7	0.0595	0.3655	0.629	0.7395	0.3655	0.6375
6	0.063	0.387	0.666	0.783	0.387	0.675
5	0.0665	0.4085	0.703	0.8265	0.4085	0.7125
4	0.07	0.43	0.74	0.87	0.43	0.75
3	0.0735	0.4515	0.777	0.9135	0.4515	0.7875
2	0.077	0.473	0.814	0.957	0.473	0.825
1	0.0805	0.4945	0.851	1.0005	0.4945	0.8625

B2. Operation-operator Times for Product of Type Y

	Op.1	Op.2	Op.3	Op.4	Op.5	Op.6
Y1	1.12	1.3	0.15	0.09	1	0.08
Std. Dev.	0.056	0.065	0.0075	0.0045	0.05	0.004
skill level						
7	0.952	1.105	0.1275	0.0765	0.85	0.068
6	1.008	1.17	0.135	0.081	0.9	0.072
5	1.064	1.235	0.1425	0.0855	0.95	0.076
4	1.12	1.3	0.15	0.09	1	0.08
3	1.176	1.365	0.1575	0.0945	1.05	0.084
2	1.232	1.43	0.165	0.099	1.1	0.088
1	1.288	1.495	0.1725	0.1035	1.15	0.092
Y2	1.18	1.23	0.11	0.04	1.12	0.05
Std. Dev.	0.059	0.0615	0.0055	0.002	0.056	0.0025
skill level						
7	1.003	1.0455	0.0935	0.034	0.952	0.0425
6	1.062	1.107	0.099	0.036	1.008	0.045
5	1.121	1.1685	0.1045	0.038	1.064	0.0475
4	1.18	1.23	0.11	0.04	1.12	0.05
3	1.239	1.2915	0.1155	0.042	1.176	0.0525
2	1.298	1.353	0.121	0.044	1.232	0.055
1	1.357	1.4145	0.1265	0.046	1.288	0.0575

	Op.1	Op.2	Op.3	Op.4	Op.5	Op.6
Y3	1.23	1.34	0.11	0.06	1.13	0.05
Std. Dev.	0.0615	0.067	0.0055	0.003	0.0565	0.0025
skill level						
7	1.0455	1.139	0.0935	0.051	0.9605	0.0425
6	1.107	1.206	0.099	0.054	1.017	0.045
5	1.1685	1.273	0.1045	0.057	1.0735	0.0475
4	1.23	1.34	0.11	0.06	1.13	0.05
3	1.2915	1.407	0.1155	0.063	1.1865	0.0525
2	1.353	1.474	0.121	0.066	1.243	0.055
1	1.4145	1.541	0.1265	0.069	1.2995	0.0575
Y4	1.11	1.39	0.13	0.05	1.2	0.07
Std. Dev.	0.0555	0.0695	0.0065	0.0025	0.06	0.0035
skill level						
7	0.9435	1.1815	0.1105	0.0425	1.02	0.0595
6	0.999	1.251	0.117	0.045	1.08	0.063
5	1.0545	1.3205	0.1235	0.0475	1.14	0.0665
4	1.11	1.39	0.13	0.05	1.2	0.07
3	1.1655	1.4595	0.1365	0.0525	1.26	0.0735
2	1.221	1.529	0.143	0.055	1.32	0.077
1	1.2765	1.5985	0.1495	0.0575	1.38	0.0805

	Op.1	Op.2	Op.3	Op.4	Op.5	Op.6
Y5	1.15	1.4	0.1	0.04	1.15	0.07
Std. Dev.	0.0575	0.07	0.005	0.002	0.0575	0.0035
skill level						
7	0.9775	1.19	0.085	0.034	0.9775	0.0595
6	1.035	1.26	0.09	0.036	1.035	0.063
5	1.0925	1.33	0.095	0.038	1.0925	0.0665
4	1.15	1.4	0.1	0.04	1.15	0.07
3	1.2075	1.47	0.105	0.042	1.2075	0.0735
2	1.265	1.54	0.11	0.044	1.265	0.077
1	1.3225	1.61	0.115	0.046	1.3225	0.0805
Y6	1.2	1.29	0.14	0.07	1.15	0.04
Std. Dev.	0.06	0.0645	0.007	0.0035	0.0575	0.002
skill level						
7	1.02	1.0965	0.119	0.0595	0.9775	0.034
6	1.08	1.161	0.126	0.063	1.035	0.036
5	1.14	1.2255	0.133	0.0665	1.0925	0.038
4	1.2	1.29	0.14	0.07	1.15	0.04
3	1.26	1.3545	0.147	0.0735	1.2075	0.042
2	1.32	1.419	0.154	0.077	1.265	0.044
1	1.38	1.4835	0.161	0.0805	1.3225	0.046

	Op.1	Op.2	Op.3	Op.4	Op.5	Op.6
Y7	1.29	1.21	0.15	0.09	1.19	0.08
Std. Dev.	0.0645	0.0605	0.0075	0.0045	0.0595	0.004
skill level						
7	1.0965	1.0285	0.1275	0.0765	1.0115	0.068
6	1.161	1.089	0.135	0.081	1.071	0.072
5	1.2255	1.1495	0.1425	0.0855	1.1305	0.076
4	1.29	1.21	0.15	0.09	1.19	0.08
3	1.3545	1.2705	0.1575	0.0945	1.2495	0.084
2	1.419	1.331	0.165	0.099	1.309	0.088
1	1.4835	1.3915	0.1725	0.1035	1.3685	0.092
Y8	1.22	1.26	0.1	0.05	1.11	0.04
Std. Dev.	0.061	0.063	0.005	0.0025	0.0555	0.002
skill level						
7	1.037	1.071	0.085	0.0425	0.9435	0.034
6	1.098	1.134	0.09	0.045	0.999	0.036
5	1.159	1.197	0.095	0.0475	1.0545	0.038
4	1.22	1.26	0.1	0.05	1.11	0.04
3	1.281	1.323	0.105	0.0525	1.1655	0.042
2	1.342	1.386	0.11	0.055	1.221	0.044
1	1.403	1.449	0.115	0.0575	1.2765	0.046

	Op.1	Op.2	Op.3	Op.4	Op.5	Op.6
Y9	1.12	1.29	0.09	0.04	1.14	0.08
Std. Dev.	0.056	0.0645	0.0045	0.002	0.057	0.004
skill level						
7	0.952	1.0965	0.0765	0.034	0.969	0.068
6	1.008	1.161	0.081	0.036	1.026	0.072
5	1.064	1.2255	0.0855	0.038	1.083	0.076
4	1.12	1.29	0.09	0.04	1.14	0.08
3	1.176	1.3545	0.0945	0.042	1.197	0.084
2	1.232	1.419	0.099	0.044	1.254	0.088
1	1.288	1.4835	0.1035	0.046	1.311	0.092
Y10	1.1	1.35	0.12	0.08	1.17	0.06
Std. Dev.	0.055	0.0675	0.006	0.004	0.0585	0.003
skill level						
7	0.935	1.1475	0.102	0.068	0.9945	0.051
6	0.99	1.215	0.108	0.072	1.053	0.054
5	1.045	1.2825	0.114	0.076	1.1115	0.057
4	1.1	1.35	0.12	0.08	1.17	0.06
3	1.155	1.4175	0.126	0.084	1.2285	0.063
2	1.21	1.485	0.132	0.088	1.287	0.066
1	1.265	1.5525	0.138	0.092	1.3455	0.069

APPENDIX C: OPTIMAL PRODUCTION RATES WHEN MAX AND MAX-MIN WERE USED

C1. Optimal Production Rates when Max-Min was used.

period 1

Product	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Cell1	273.68	217.79	208.74	229.67	252.25	197.37	274.6	225.56	194.33	160
Cell 2	413.36	364.39	351.82	403.14	422.48	338.67	512.09	447.67	371.52	293.76
Demand	3500	7500	3400	2700	2200	4000	4500	2200	2300	3000
Procesing time (cell1)	12.79	34.44	16.29	11.76	8.72	20.27	16.39	9.75	11.83	18.75
Procesing time (cell2)	8.47	20.59	9.66	6.69	5.2	11.81	8.78	4.91	6.19	10.21

period 2

Product	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Cell1	273.68	217.79	208.74	229.67	252.25	197.37	274.6	225.6	194.33	160
Cell 2	413.36	364.39	351.82	403.14	422.48	338.67	512.09	447.67	371.52	293.76
Demand	3500	7500	3700	2900	2200	4300	4600	2200	2500	3000
Procesing time (cell1)	12.79	34.43	17.72	12.62	8.72	21.78	16.75	9.75	12.86	18.75
Procesing time (cell2)	8.47	20.59	10.52	7.19	5.2	12.69	8.98	4.91	6.72	10.21

period 3

Product	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Cell1	273.68	217.79	208.74	229.67	252.25	197.37	274.6	225.6	194.33	160
Cell 2	413.36	364.39	351.82	403.14	422.48	338.67	512.09	447.67	371.52	293.76
Demand	3700	7500	3700	3000	2400	4300	4600	2400	2500	3100
Procesing time (cell1)	13.51	34.43	17.72	13.06	9.51	21.78	16.75	10.64	12.86	19.37
Procesing time (cell2)	8.95	20.59	10.52	7.44	5.68	12.69	8.98	5.36	6.72	10.55

period 4

Product	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Cell1	273.68	217.79	208.74	229.67	252.25	197.37	274.6	225.56	194.33	160
Cell 2	413.36	364.39	354.02	403.14	422.48	338.76	512.09	447.67	371.52	293.76
Demand	3100	6500	3700	2750	2150	3500	2200	1900	2500	3100
Procesing time (cell1)	11.32	29.84	17.72	11.97	8.52	17.73	8.01	8.42	12.86	19.37
Procesing time (cell2)	7.49	17.83	10.45	6.82	5.08	10.33	4.29	4.24	6.72	10.55

period 5

Product	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Cell1	280.7	217.79	214.09	229.67	260.79	197.37	274.6	229.67	194.33	168.42
Cell 2	421.05	364.39	357.88	403.14	426.74	344.5	515.57	447.67	371.52	293.76
Demand	3100	6750	3700	2750	2400	3900	4200	1900	2500	3100
Procesing time (cell1)	11.04	30.99	17.28	11.97	9.2	19.76	15.29	8.27	12.86	18.4
Procesing time (cell2)	7.36	18.52	10.34	6.82	5.62	11.32	8.15	4.24	6.73	10.55

period 6

Product	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Cell1	288.5	229.67	220.04	242.42	260.79	208.33	289.86	238.1	196.08	168.42
Cell 2	435.41	370.77	364.15	425.53	445.71	351.94	531.06	459.77	391.1	310.08
Demand	4200	8000	3700	3000	2500	4300	4800	2400	2500	3100
Procesing time (cell1)	11.56	34.83	16.82	12.38	9.59	20.64	16.56	10.08	12.75	18.4
Procesing time (cell2)	9.64	21.58	10.16	7.05	5.61	12.22	9.04	5.22	6.39	9.99

period 7										
Product	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Cell1	288.5	229.67	220.04	242.42	266.09	208.33	289.86	238.1	196.08	168.42
Cell 2	435.41	377.9	370.37	425.53	445.71	357.26	540.54	473.29	392.16	310.08
Demand	2800	6400	3700	2250	2150	3200	4400	1900	2300	3100
	9.71	27.87	16.82	9.28	8.08	15.36	15.18	7.98	11.73	18.4
	6.43	16.94	9.99	5.29	4.82	8.96	8.14	4.01	5.86	9.99

period 8										
Product	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Cell1	288.5	229.67	220.04	242.42	266.09	208.33	289.86	238.1	196.08	168.42
Cell 2	435.41	377.9	371.15	425.53	445.71	357.26	540.54	473.29	392.16	310.08
Demand	2800	6300	3700	2250	2000	3200	4250	1900	2300	3100
	9.71	27.43	16.82	9.28	7.52	15.36	14.66	7.98	11.73	18.4
	6.43	16.67	9.97	5.29	4.49	8.96	7.86	4.01	5.86	9.99

period 9										
Product	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Cell1	288.5	229.67	220.04	242.42	266.09	208.33	289.86	238.1	196.08	168.42
Cell 2	438.6	377.9	371.15	425.53	445.71	357.26	540.54	473.29	392.16	310.08
Demand	3100	7750	3700	2750	2400	3900	4200	1900	2500	3300
Procesing time (cell1)	10.75	33.74	16.82	11.34	9.02	18.72	14.49	7.98	12.75	19.59
Procesing time (cell2)	7.07	20.51	9.97	6.46	5.38	10.92	7.77	4.01	6.37	10.64

period 10										
Product	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Cell1	296.3	229.89	225.99	242.42	275.57	208.33	289.86	242.42	205.13	177.78
Cell 2	442.58	377.9	371.15	425.53	450.45	361.99	542.99	473.29	392.16	310.08
Demand	3300	8450	3700	3050	2600	3900	4400	2000	2500	3500
Procesing time (cell1)	11.14	36.76	16.37	12.58	9.43	18.72	15.18	8.25	12.19	19.69
Procesing time (cell2)	7.46	22.36	9.97	7.17	5.77	10.77	8.1	4.23	6.37	11.29

Period 11										
Product	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Cell1	296.3	229.89	225.99	242.42	275.57	208.33	289.86	242.42	205.13	177.78
Cell 2	442.58	377.9	371.15	425.53	450.45	361.99	542.99	473.29	392.16	310.08
Demand	2900	6400	3700	2300	2150	3250	4400	1900	2300	3200
Procesing time (cell1)	9.79	27.84	16.37	9.49	7.8	15.6	15.18	7.84	11.21	18
Procesing time (cell2)	6.55	16.94	9.97	5.41	4.77	8.98	8.1	4.01	5.86	10.32

period 12										
Product	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Cell1	305.01	242.42	229.31	249.55	275.57	220.59	298.38	252.1	207.61	177.78
Cell 2	454.08	385.03	378.15	450.56	471.65	361.99	553.06	486.82	415.22	328.32
Demand	3500	7600	3400	3200	2200	3500	4500	2200	2300	3000
Procesing time (cell1)	11.48	31.35	14.83	12.82	7.98	15.87	15.08	8.73	11.08	16.87
Procesing time (cell2)	7.71	19.74	8.99	7.1	4.66	9.67	8.14	4.52	5.54	9.14

period 13

Product	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Cell1	305.01	242.42	232.64	256.68	275.57	220.59	306.91	252.1	207.61	177.78
Cell 2	454.08	385.03	378.15	450.56	471.65	361.99	553.06	486.82	415.22	328.32
Demand	4100	7700	3500	2500	2400	4800	4000	2400	2500	3400
Procesing time (cell1)	13.44	31.76	15.04	9.74	8.71	21.76	13.03	9.52	12.04	19.12
Procesing time (cell2)	9.03	20	9.26	5.55	5.09	13.26	7.23	4.93	6.02	10.36

period 14

Product	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Cell1	305.01	242.42	232.64	256.68	275.57	220.59	306.91	252.1	207.61	177.78
Cell 2	463.46	385.03	378.15	450.56	471.65	361.99	561.74	486.82	415.22	328.32
Demand	2800	6800	3450	2500	2150	3200	4200	2100	2300	3100
Procesing time (cell1)	9.18	28.05	14.83	9.74	7.8	14.51	13.68	8.33	11.08	17.44
Procesing time (cell2)	6.04	17.66	9.12	5.55	4.56	8.84	7.48	4.31	5.54	9.44

C1. Optimal Production Rates when Max was used.

period 1

Product	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Cell1	273.68	217.79	208.74	229.67	252.25	197.37	274.6	225.56	194.33	160
Cell 2	413.36	364.39	351.82	403.14	422.48	338.67	512.09	447.67	371.52	293.76
Demand	3500	7500	3400	2700	2200	4000	4500	2200	2300	3000
Procesing time (cell1)	12.79	34.44	16.29	11.76	8.72	20.27	16.39	9.75	11.83	18.75
Procesing time (cell2)	8.47	20.59	9.66	6.69	5.2	11.81	8.78	4.91	6.19	10.21

period 2

Product	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Cell1	273.68	217.79	208.74	229.67	252.25	197.37	274.6	225.6	194.33	160
Cell 2	413.36	364.39	351.82	403.14	422.48	338.67	512.09	447.67	371.52	293.76
Demand	3500	7500	3700	2900	2200	4300	4600	2200	2500	3000
Procesing time (cell1)	12.79	34.43	17.72	12.62	8.72	21.78	16.75	9.75	12.86	18.75
Procesing time (cell2)	8.47	20.59	10.52	7.19	5.2	12.69	8.98	4.91	6.72	10.21

period 3

Product	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Cell1	273.68	217.79	208.74	229.67	252.25	197.37	274.6	225.6	194.33	160
Cell 2	413.36	364.39	351.82	403.14	422.48	338.67	512.09	447.67	371.52	293.76
Demand	3700	7500	3700	3000	2400	4300	4600	2400	2500	3100
Procesing time (cell1)	13.51	34.43	17.72	13.06	9.51	21.78	16.75	10.64	12.86	19.37
Procesing time (cell2)	8.95	20.59	10.52	7.44	5.68	12.69	8.98	5.36	6.72	10.55

period 4

Product	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Cell1	273.68	217.79	208.74	229.67	252.25	197.37	274.6	225.56	194.33	160
Cell 2	413.36	364.39	354.02	403.14	422.48	338.76	512.09	447.67	371.52	293.76
Demand	3100	6500	3700	2750	2150	3500	2200	1900	2500	3100
Procesing time (cell1)	11.32	29.84	17.72	11.97	8.52	17.73	8.01	8.42	12.86	19.37
Procesing time (cell2)	7.49	17.83	10.45	6.82	5.08	10.33	4.29	4.24	6.72	10.55

period 5

Product	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Cell1	280.7	217.79	214.09	229.67	260.79	197.37	274.6	229.67	194.33	168.42
Cell 2	421.05	364.39	357.88	403.14	426.74	344.5	515.57	447.67	371.52	293.76
Demand	3100	6750	3700	2750	2400	3900	4200	1900	2500	3100
Procesing time (cell1)	11.04	30.99	17.28	11.97	9.2	19.76	15.29	8.27	12.86	18.4
Procesing time (cell2)	7.36	18.52	10.34	6.82	5.62	11.32	8.15	4.24	6.73	10.55

period 6

Product	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Cell1	288.5	229.67	220.04	242.42	260.79	208.33	289.86	238.1	196.08	168.42
Cell 2	435.41	370.77	364.15	425.53	445.71	351.94	531.06	459.77	391.1	310.08
Demand	4200	8000	3700	3000	2500	4300	4800	2400	2500	3100
Procesing time (cell1)	11.56	34.83	16.82	12.38	9.59	20.64	16.56	10.08	12.75	18.4
Procesing time (cell2)	9.64	21.58	10.16	7.05	5.61	12.22	9.04	5.22	6.39	9.99

period 7

Product	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Cell1	288.5	229.67	220.04	242.42	266.09	208.33	289.86	238.1	196.08	168.42
Cell 2	435.41	377.9	370.37	425.53	445.71	357.26	540.54	473.29	392.16	310.08
Demand	2800	6400	3700	2250	2150	3200	4400	1900	2300	3100
	9.71	27.87	16.82	9.28	8.08	15.36	15.18	7.98	11.73	18.4
	6.43	16.94	9.99	5.29	4.82	8.96	8.14	4.01	5.86	9.99

period 8

Product	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Cell1	288.5	229.67	220.04	242.42	266.09	208.33	289.86	238.1	196.08	168.42
Cell 2	435.41	377.9	371.15	425.53	445.71	357.26	540.54	473.29	392.16	310.08
Demand	2800	6300	3700	2250	2000	3200	4250	1900	2300	3100
	9.71	27.43	16.82	9.28	7.52	15.36	14.66	7.98	11.73	18.4
	6.43	16.67	9.97	5.29	4.49	8.96	7.86	4.01	5.86	9.99

period 9

Product	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Cell1	288.5	229.67	220.04	242.42	266.09	208.33	289.86	238.1	196.08	168.42
Cell 2	438.6	377.9	371.15	425.53	445.71	357.26	540.54	473.29	392.16	310.08
Demand	3100	7750	3700	2750	2400	3900	4200	1900	2500	3300
Procesing time (cell1)	10.75	33.74	16.82	11.34	9.02	18.72	14.49	7.98	12.75	19.59
Procesing time (cell2)	7.07	20.51	9.97	6.46	5.38	10.92	7.77	4.01	6.37	10.64

period 10

Product	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Cell1	296.3	229.89	225.99	242.42	275.57	208.33	289.86	242.42	205.13	177.78
Cell 2	439	377.9	371.15	425.53	450.45	361.99	542.99	473.29	392.16	310.08
Demand	3300	8450	3700	3050	2600	3900	4400	2000	2500	3500
Procesing time (cell1)	11.14	36.76	16.37	12.58	9.43	18.72	15.18	8.25	12.19	19.69
Procesing time (cell2)	7.51	22.36	9.97	7.17	5.77	10.77	8.1	4.23	6.37	11.29

period 11

Product	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Cell1	296.3	229.89	225.99	242.42	275.57	208.33	289.86	242.42	205.13	177.78
Cell 2	439	377.9	371.15	425.53	450.45	361.99	542.99	473.29	392.16	310.08
Demand	2900	6400	3700	2300	2150	3250	4400	1900	2300	3200
Procesing time (cell1)	9.79	27.84	16.37	9.49	7.8	15.6	15.18	7.84	11.21	18
Procesing time (cell2)	6.61	16.94	9.97	5.41	4.77	8.98	8.1	4.01	5.86	10.32

period 12

Product	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Cell1	305.01	242.42	229.31	249.55	275.57	220.59	298.38	252.1	207.61	177.78
Cell 2	454.08	385.03	378.15	450.56	471.65	361.99	553.06	486.82	408.64	328.32
Demand	3500	7600	3400	3200	2200	3500	4500	2200	2300	3000
Procesing time (cell1)	11.48	31.35	14.83	12.82	7.98	15.87	15.08	8.73	11.08	16.87
Procesing time (cell2)	7.71	19.74	8.99	7.1	4.66	9.67	8.14	4.52	5.63	9.14

period 13

Product	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Cell1	305.01	242.42	229.31	249.55	275.57	220.59	298.38	252.1	207.61	177.78
Cell 2	454.08	385.03	378.15	450.56	471.65	361.99	553.06	486.82	408.64	328.32
Demand	4100	7700	3500	2500	2400	4800	4000	2400	2500	3400
Procesing time (cell1)	13.44	31.76	15.26	10.02	8.71	21.76	13.41	9.52	12.04	19.12
Procesing time (cell2)	9.03	20	9.26	5.55	5.09	13.26	7.23	4.93	6.12	10.36

period 14

Product	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Cell1	305.01	242.42	229.31	249.55	275.57	220.59	298.38	252.1	207.61	177.78
Cell 2	454.08	385.03	378.15	450.56	471.65	361.99	560.22	486.82	412.98	328.32
Demand	2800	6800	3450	2500	2150	3200	4200	2100	2300	3100
Procesing time (cell1)	9.18	28.05	15.05	10.02	7.8	14.51	14.08	8.33	11.08	17.44
Procesing time (cell2)	6.17	17.66	9.12	5.55	4.56	8.84	7.5	4.31	5.57	9.44

APPENDIX D: OPERATIONS PERFORMED AND MISSED BY EACH OPERATOR WHEN MAX-MIN AND MAX WERE USED

D1. Operations Performed and Missed by each Operator when Max- Min was used.

Period 1						
Cell 1	Product				operations performed	operations missed
Operator	X1	X3	X5	X6		
1	3,4	3	3	3	3,4	1
2	4	4	3	3,2	2,3,4	-
3	2	2	2	3,2	2,3	1
4	6	6,5	6,4	4	4,5,6	-
5	5	5,1	5	5,1	1,5	2
6	4	3	4,6	4	3,4,6	-
7	5	1,6	5	1,6	1,5,6	-
8	4	3	3	4	3,4	1
9	2	6	6	2,5	2,5,6	-
10	4,3	4	4	4	3,4	1
11	1	4	1	6	1,4,6	-
12	3	3	3	5,2	2,3,5	-

Period 1								
Cell 2	Product						operations performed	operations missed
Operator	X2	X4	X7	X8	X9	X10		
13	4	2	2	4	4	2	2,4	1
14	3	4	3	3	3	4	3,4	2
15	5	3	5	3	1	3	1,3,5	-
16	2	3	5	2	3	5	2,3,5	-
17	4	1,6	4	4	4,6	4	1,4,6	-
18	2,4	4	2	4	2	4	2,4	1
19	4,2	2	2	2	2	2	2,4	6
20	5	3,5	5,1	5	5	5	1,3,5	-
21	4	6	4	6	6,4	6	4,6	1
22	3	5,3	3	3	3	3	3,5	2
23	3	6,3	6	6	3	6	,3,6	1
24	4	4	4	4	4	1	1,4	5
25	6	6	4	6	3	4	3,4,6	-
26	6	6,3	6	6	6	6	3,6	2
27	1	5,1	4	5	4	4	1,4,5	-
28	5	5	3	2	5	3	2,3,5	-
29	3	6	3	3	6	3	3,6	1
30	6	6,5	1,5	1	6	5	1,5,6	-

Period 2					
Cell 1	Product			operations performed	operations missed
Operator	X1	X2	X4		
1	3,4	4	3	3,4	1
2	4	4,3	2	2,3,4	-
3	2	2	2	2	1,3
4	6	6,5	4	4,5,6	-
5	5	5,1	1	1,5	2
6	4	3,6	3	3,4,6	-
7	5	5	6	5,6	1
8	4	3,4	4	3,4	1
9	2	6	6	2,6	5
10	4,3	4,3	4	4,3	1
11	1	1,4	6	1,4,6	-
12	3	3	5	,3,5	2

Period 2									
Cell 2	Product							operations performed	operations missed
Operator	X3	X5	X6	X7	X8	X9	X10		
13	2	2	2	2	4	4	2	2,4	1
14	3	4	3	3	3	3	4	3,4	2
15	3	5	5,3	5	3	1	3	1,3,5	-
16	3	2	3	5	2	3	5	2,3,5	-
17	4	4	4	4	4	4,6	4	4,6	1
18	4,2	4	4	2	4	2	4	2,4	1
19	2,4	4	2	2	2	2	2	2,4	6
20	5	5	5,3	5,1	5	5	5	1,3,5	-
21	4,1	1	1	4	6	6,4	6	1,4,6	-
22	3	5	3,5	3	3	3	3	3,5	2
23	3	3	3,6	6	6	3	6	3,6	1
24	4	4	4	4	4	4	1	1,4	5
25	6	6	3	4	6	3	4	3,4,6	-
26	6	6	6	6	6	6	6	6	2,3
27	1	5	5	4	5	4	4	1,4,5	-
28	3	2	3	3	2	5	3	2,3,5	-
29	3	3	3	3	3	6	3	3,6	1
30	6	6	6,5	1,5	1	6	5	1,5,6	-

Period 3					
Cell 1	Product			operations performed	operations missed
Operator	X1	X2	X4		
1	3,4	4	3	3,4	1
2	4	4,3	2	2,3,4	-
3	2	2	2	2	1,3
4	6	6,5	4	4,5,6	-
5	5	5,1	1	1,5	2
6	4	3,6	3	3,4,6	-
7	5	5	6	5,6	1
8	4	3,4	4	3,4	1
9	2	6	6	2,6	5
10	4,3	4,3	4	4,3	1
11	1	1,4	6	1,4,6	-
12	3	3	5	,3,5	2

Period 3									
Cell 2	Product							operations performed	operations missed
Operator	X3	X5	X6	X7	X8	X9	X10		
13	2	2	2	2	4	4	2	2,4	1
14	3	4	3	3	3	3	4	3,4	2
15	3	5	5,3	5	3	1	3	1,3,5	-
16	3	2	3	5	2	3	5	2,3,5	-
17	4	4	4	4	4	4,6	4	4,6	1
18	4,2	4	4	2	4	2	4	2,4	1
19	2,4	4	2	2	2	2	2	2,4	6
20	5	5	5,3	5,1	5	5	5	1,3,5	-
21	4,1	1	1	4	6	6,4	6	1,4,6	-
22	3	5	3,5	3	3	3	3	3,5	2
23	3	3	3,6	6	6	3	6	3,6	1
24	4	4	4	4	4	4	1	1,4	5
25	6	6	3	4	6	3	4	3,4,6	-
26	6	6	6	6	6	6	6	6	2,3
27	1	5	5	4	5	4	4	1,4,5	-
28	3	2	3	3	2	5	3	2,3,5	-
29	3	3	3	3	3	6	3	3,6	1
30	6	6	6,5	1,5	1	6	5	1,5,6	-

Period 4					
Cell 1	Product			operations performed	operations missed
Operator	X1	X2	X4		
1	3,4	4	3	3,4	1
2	4	4,3	2	2,3,4	-
3	2	2	2,1	1,2	3
4	6	6,5	6,4	4,5,6	-
5	5	5,1	1,5	1,5	2
6	4	3,6	3	3,4,6	-
7	1	5	6	1,5,6	-
8	4	3,4	4,1	1,3,4	-
9	2	6	6	2,6	5
10	4,3	4,3	4	3,4	1
11	4	1,4	1,6	1,4,6	-
12	5	3	5,2	2,3,5	-

Period 4									
Cell 2	Product							operations performed	operations missed
Operator	X3	X5	X6	X7	X8	X9	X10		
13	2	2	2	2	2,4	2	4	2,4	1
14	3	4	3	3	4	3	2	2,3,4	-
15	3	5	5,3	5	3	5,1	1,5	1,3,5	-
16	3	2,5	3	5	2	3	5,3	2,3,5	-
17	4	4	4	4	4	4,6	4,6	4,6	1
18	4,2	4	4	2	4,2	2	4	2,4	1
19	2,4	4	2	2	4	4	2	2,4	6
20	5	5,3	5,3	5,1	5	1,5	5	1,3,5	-
21	4	1,6	1	4	6	6,4	6	1,4,6	-
22	3	3,5	3,5	3	3	3	3	3,5	2
23	3	6	3,6	6	1	3	6,3	3,6	1
24	4	4	4	4	4	4	4	4	1,5
25	6	3	3	4	6	3	3	3,4,6	-
26	6	6,2	6	6	6,3	6	6	2,3,6	-
27	1	5,1	5	4	5	4	4	1,4,5	-
28	3	2,3	3	3	3	5	3	2,3,5	-
29	3	3,6	3	3	3,6	6	3,6	3,6	1
30	6	6	6,5	1,5	6	6	6	1,5,6	-

Period 5						
Cell 1	Product				operations performed	operations missed
Operator	X1	X3	X5	X10		
1	4	4	3	4,3	3,4	1
2	3,4	3	2	3,2	2,3,4	-
3	2	2	2,3	2,1	1,2,3	-
4	6,5	6,5	4	6	4,5,6	-
5	5,1	5,1	5,1	5,2	1,2,5	-
6	4	3	4	4	4,3	6
7	5,6	1,6	5	5	1,5,6	-
8	4,3	3	4	3	3,4	1
9	2	6	6,5	6	2,5,6	-
10	4,3	4	4	4	3,4	1
11	1,4	4	1,6	1,4	1,4,6	-
12	3,5	3	3,2	2,5	2,3,5	-

Period 5								
Cell 2	Product						operations performed	operations missed
Operator	X2	X6	X7	X9	X4	X8		
13	2,4	4	2	4	4	4,2	2,4	1
14	2,3	3	4	3	4	3	2,3,4	-
15	3	3	3	3,1	3,5	3	1,3,5	-
16	3,2	3	5	3	3	5	2,3,5	-
17	4	4	4	4,6	6	1,4	1,4,6	---
18	4	4	2	4	4	4	2,4	1
19	4	2	4	2	2	2,4	2,4	6
20	3	3	3	5	5,3	5	3,5	1
21	4	1	1	1,6	6	4,6	1,4,6	-
22	3,2	3,2	2	3	5,3	3	2,3,5	-
23	1	3	3	6	3,1	6	1,3,6	-
24	4,5	5	4	4,5	1,5	4	1,4,5	-
25	6	6	6	6,4	6,3	6	3,4,6	-
26	6	6	6	6,3	3,6	,6	3,6	2
27	5	5	5	5,4	5	4	4,5	1
28	5,3	2,3	2	2	2	2	2,3,5	-
29	6	3	3	3	6	3	3,6	1
30	5	5	5	6	6	6	5,6	1

Period 6					
Cell 1	Product			operations performed	operations missed
Operator	X1	X2	X5		
1	3,4	3,4	3,1	1,3,4	-
2	4	4	2,3	2,3,4	-
3	2	2	2,3	2,3	1
4	6	4,5	6,5	4,5,6	-
5	5	5,1	5,1	1,5	2
6	4	6	4	4,6	3
7	5	5	5,6	5,6	1
8	4	3	4	3,4	1
9	2	6	6,5	2,5,6	-
10	4,3	4,3	4	3,4	1
11	1	1,4	1,6	1,4,6	-
12	3	3	3,2	2,3	5

Period 6									
Cell 2	Product							operations performed	operations missed
Operator	X3	X4	X6	X7	X8	X9	X10		
13	4	2	2	2	2,4	2,4	4	2,4	1
14	3	5	3	4	3,2	3	4	2,3,4	-
15	3	5,1	5,3	5,1	3	1	5	1,3,5	-
16	2,3	5,3	5,3	3	5	5	3	2,3,5	-
17	4	6	4	4	4	6	6	4,6	1
18	2,4	4	4	4	4,2	4,2	2	2,4	1
19	4,2	2	2,4	2	4,6	2	2	2,4,6	-
20	3	1,3	3,5	3	5	5	5	1,3,5	-
21	1	6	1	6	1,4	4,6	4,6	1,4,6	-
22	3,2	3,5	3,2	5	3	3	3	2,3,5	-
23	6	3	3	3	6	3	6,1	1,3,6	-
24	4	4	4,5	4	4,1	4	4	1,4,5	-
25	3	3,6	3	3	6,4	6,4	4	3,4,6	-
26	6	6,3	6	6	6,3	6	6,3	3,6	2
27	5	5	5	5	4	4	1,4	1,4,5	-
28	3	3,5	3	2	2,3	3	3	2,3,5	-
29	3	6	3	6	3,6	3	3,6	3,6	1
30	6	6	6	1,5	6	6	6	1,5,6	-

Period 7						
Cell 1	Product				operations performed	operations missed
Operator	X1	X3	X5	X6		
1	3,4	3	3,1	4	1,3,4	-
2	4,3	3	3	3	3,4	2
3	2	2	2,3	2	2,3	1
4	6	6	6,5	4,5	4,5,6	-
5	5,1	1	5,2	5,1	1,2,5	-
6	4	3	4	3,6	3,4,6	-
7	5,1	5	1,6	1,6	1,5,6	-
8	3,4	4	4	3	3,4	1
9	2	6	2,5	6,5	2,5,6	--
10	4,3	4	4	3	3,4	1
11	4	4	6	6,4	4,6	1
12	5	3	5,2	5,3	2,3,5	-

Period 7								
Cell 2	Product						operations performed	operations missed
Operator	X2	X4	X7	X8	X9	X10		
13	2,4	2	2	2,4	2	2	2,4	1
14	3,2	4	4	3,4	3	4	2,3,4	-
15	1,3	3	5	5	1	1,3	1,3,5	-
16	5,2	3	5,3	3	3	5	2,3,5	-
17	4	6	4	4,6	6	4,6	4,6	1
18	4,1	4	2	4,2	4	2	1,2,4	-
19	4	2	2	2	2	6	2,6	4
20	5,3	5,3	5,3	5	5	5	3,5	1
21	4	1,6	4	4	4	4	1,4,6	-
22	3,5	3,5	3	3	3	3	3,5	2
23	3	6,1	3,1	6,1	3	3,1	1,3,6	-
24	5	4	4	4	4	4	,4,5	1
25	6	3,6	6	6	6,3	6,4	3,4,6	-
26	6	6,3	6	6,3	6	6,3	3,6	2
27	4	5	4	4	4	4	4,5	1
28	2,5	5	3,5	3	5	3	2,3,5	-
29	3	6	3	6	3,6	3,6	3,6	1
30	6	6	1,5	1,6	6	6	1,5,6	-

Period 8						
Cell 1	Product				operations performed	operations missed
Operator	X1	X3	X5	X6		
1	3,4	3	3,1	4	1,3,4	-
2	3,4	3	3	3	3,4	2
3	2	2	2,3	2	2,3	1
4	6	6	6,5	4,5	4,5,6	-
5	5	5,1	5,2	5,1	1,2,5	-
6	4	3	4	3,6	3,4,6	-
7	1,5	1,5	1,6	1,6	1,5,6	-
8	4,1	4	4	3	1,3,4	-
9	2	6	2,5	6	2,5,6	-
10	4,3	4	4	3	3,4	1
11	4	4	6	6,4	4,6	1
12	5,3	3	5,2	5,3	2,3,5	-

Period 8								
Cell 2	Product						operations performed	operations missed
Operator	X2	X4	X7	X8	X9	X10		
13	2,1	2	2	1,2	2	2	1,2	4
14	3,2	4	4	4	3	4	2,3,4	-
15	1,3	5,3	5	3	1	5	1,3,5	-
16	5,2	3	5,3	5	5,3	3	2,3,5	-
17	4	6	4	4	6	6	4,6	1
18	4	4	2	2	4	4	2,4	1
19	2,4	2	2	2,6	2	2	2,4,6	-
20	5,3	3	1,3	5	5	3,1	1,3,5	-
21	4	1,6	4	6,4	4,6	4	1,4,6	-
22	3,5	3,5	3	3	3	3	,3,5	2
23	3	6	3,1	6	3	1,6	1,3,6	-
24	4,5	4	4	4	4	4	,4,5	1
25	6	3,6	6	6	6,4	4	3,4,6	-
26	6	6,3	6	6,3	6	6,3	3,6	2
27	4	5,1	4	4	4	5	1,4,5	-
28	5	5	3,5	3	3,5	3	3,5	2
29	3	6	3	6	3	6	3,6	1
30	6	6,5	5	1,6	6	6	1,5,6	-

Period 9						
Cell 1	Product				operations performed	operations missed
Operator	X1	X3	X5	X6		
1	3,4	3	3	3,4	3,4	1
2	3	4	3,2	3	2,3,4	-
3	2	2	2,3	2	,2,3	1
4	4,6	6	4	5,6	4,5,6	-
5	5	1	5,2	1	1,2,5	-
6	4	3	4	4,6	3,4,6	-
7	1,5	5,6	6	6,5	1,5,6	-
8	4	4	4	4,3	3,4	1
9	2	6,5	2,5	5	2,5,6	-
10	4,1	3	1	3	1,3,4	-
11	6,4	4	6	6,4	4,6	1
12	5,3	3	5	3	3,5	2

Period 9								
Cell 2	Product						operations performed	operations missed
Operator	X2	X4	X7	X8	X9	X10		
13	2,1	2	2	4	2	1,4	1,2,4	-
14	4,3	2	4	2,4	3	4	2,3,4	-
15	3,5	5	5	3,1	3	3	1,3,5	-
16	5,2	3,5	3	3	3	5,3	2,3,5	-
17	4	6	4	4	6,4	6,4	4,6	1
18	4	4	2	2	4	2	2,4	1
19	2,4	4	2	4,2	2	2	2,4	6
20	5,3	3	3	5	5	5	,3,5	1
21	4	1,6	4	4	4,6	4,6	1,4,6	-
22	3,2	3,5	5	3	3	3,5	2,3,5	-
23	3	6	3,1	6	3	6	1,3,6	--
24	4,5	4	4	4	4,1	4,1	1,4,5	-
25	6	3,6	6	6	6,4	4	3,4,6	-
26	6	6,3	6	6	6	6,3	3,6	2
27	1,4	5,1	4	5	4	4	1,4,5	-
28	5	5,3	5,3	3	5,3	3	3,5	2
29	3	3,6	3	1,3	3,6	3,6	1,3,6	-
30	6	6	1,5	6	1,5	6	1,5,6	-

Period 10					
Cell 1	Product			operations performed	operations missed
Operator	X1	X2	X5		
1	3,4	3,4	3,1	1,3,4	-
2	4,3	4,3	3,2	2,3,4	-
3	2	3,1	2,3	1,2,3	-
4	6,5	6	6,5	5,6	4
5	5	5	5,2	,2,5	1
6	4	4,3	4	3,4	6
7	5,6	6	6	,5,6	1
8	4	3,4	4	3,4	1
9	2	2	2,5	2,5	6
11	1,4	1,4	1,6	1,4,6	-
12	3	5	5,3	,3,5	2

Period 10									
Cell 2	Product							operations performed	operations missed
Operator	X10	X4	X7	X8	X3	X9	X6		
13	2	2	2	2,4	2,4	2	2	,2,4	1
14	3,4	3,2	2,4	2,4	3	3	3,4	2,3,4	-
15	1,3	3,5	3	1	3	5	1,3	1,3,5	-
16	3	3	2	3	3	5	3	2,3,5	-
17	4	4	4	4,6	4	4,6	4	4,6	1
18	2	2,1	4	4,2	4,2	4,1	2	2,4,1	
19	4,6	4	4	4,2	2	2	4,6	2,4,6	-
20	5	5,3	5,3	5	5	3	5	,3,5	1
21	4,6	1,6	1	4	4	4	4,6	1,4,6	-
22	3,5	3,5	3,2	3	3	3	3,5	2,3,5	-
23	3,1	6	3	3,6	3	3	3,1	1,3,6	-
24	4	4	4,5	4	4,1	4	4	1,4,5	
25	6,4	6	6	6,4	6	6,4	6,4	,4,6	3
26	6,3	6,3	6	6,3	6	6	6,3	3,6	2
27	4	5	5	5	1,4	1,4	4	1,4,5	-
28	5,3	5,3	2	3	3	3	5,3	2,3,5	-
29	6	6	3	6	3	6	6	3,6	1
30	6	6	5	6	6	6	6	,5,6	1

Period 11						
Cell 1	Product				operations performed	operations missed
Operator	X1	X3	X5	X6		
1	3,4	4	3,1	3,4	1,3,4	
2	4,3	3	2	4,3	2,3,4	
3	2	2	2,3	2	2,3	1
4	6,5	6	6,5	6,5	5,6	4
5	5	5,1	5,2	5,1	1,2,5	-
6	4	3	4	3,6	3,4,6	-
7	5,6	1,6	5,6	5,6	1,5,6	-
8	4	3	4	3	3,4	1
9	2	6,5	6,5	6,5	2,5,6	-
10	4,1	4	4	1,3	1,3,4	-
11	1,4	4	1,6	4	1,4,6	
12	3	3	3	3	3	2,5

Period 11								
Cell 2	Product						operations performed	operations missed
Operator	X2	X4	X7	X8	X9	X10		
13	2	2	2	,4	4	2	2,4	1
14	3,4	3,2	2,4	2,	3	3	2,3,4	-
15	1,3	3,5	3	3	3,5	5	1,3,5	-
16	3	3	3,2	3	2	5	2,3,5	-
17	4	4	4	4,	4	4,6	4,6	1
18	2	2,1	4	2	4,1	4,1	2,4,1	-
19	4,6	4	4	4,6	2,4	2	2,4,6	-
20	5	5,3	5,3	5	3	3	3,5	1
21	4,6	1,6	1	1,4	4	4	1,4,6	-
22	3,5	3,5	2	3	3,2	3	2,3,5	-
23	3,1	6	3	3,1	6	3	1,3,6	-
24	4	4	4,5	4	4,5	4	4,5	1
25	6,4	6	6	6,	6	6,4	4,6	3
26	6,3	6,3	6	6,3	6	6	3,6	2
27	4	5	5	4	5,4	1,4	1,4,5	-
28	5,3	5,3	2	5	5,3	3	2,3,5	-
29	6	6	3	6	1,3	6	1,3,6	-
30	6	6	5	6	5	6	5,6	1

Period 12					
Cell 1	Product			operations performed	operations missed
Operator	X1	X2	X5		
1	3,4	3,4	3,1	1,3,4	-
2	4	3,4	4	3,4	2
3	2	2	2,3	3,2	1
4	6	6	6,5	6,5	4
5	5	5,1	5,2	1,2,5	-
6	4	4,3	4	4,3	6
7	5	5	5,6	5,6	1
8	4	4,3	4	3,4	1
9	2	6	2,5	2,6,5	-
10	4,3	4,3	1,3	1,3,4	-
11	1	1,4	6	1,6,4	-
12	2	3,5	3,2	3,2,5	-

Period 12									
Cell 2	Product							operations performed	operations missed
Operator	X3	X4	X6	X7	X8	X9	X10		
13	2,4	2	2,1	2	2,4	2	1,4	1,2,4	-
14	3	4	3,2	4	4,2	3	4	2,3,4	-
15	3	3	5,3	1,3	5	1	5	1,3,5	-
16	2,3	5,3	5,3	5,3	5	5	5	2,3,5	-
17	4	1,6	4	4	4,6	4,6	4,6	1,4,6	----
18	4,2	2	4	2	4,2	4	2	2,4	1
19	4	4	2	2	2,4	2	2	2,4	6
20	3	5,3	3	5	3	5	3	3,,5	1
21	1,4	6	1,4	6	1,4	6,4	4	1,4,6	-
22	3,2	3,5	3,5	3,5	3	3	3	2,3,5	-
23	6	6,1	3	3,6	6	6,3	6	1,3,6	-
24	4,1	4	4,5	4	4,1	4	4,1	4,1,5	-
25	6	3,6	3	3	6,4	3	6,4	,3,6,4	-
26	3	6	6	6	6,3	6	6,3	6,3	2
27	5	5	5	4	4	4	4	,5,4	1
28	3	3	3	5,3	3	3	3	,3,5	2
29	3	6	3	3,1	3,6	3,6	3,6	1,3,6	-
30	6	6,5	6	6,5	6	6	6	,5,6	1

Period 13					
Cell 1	Product			operations performed	operations missed
Operator	X1	X2	X4		
1	3,4	4	3	3,4	1
2	4	3	2	2,3,4	-
3	2	2	1	1,2	3
4	6	6	6,5	5,6	4
5	5	5,1	5,2	1,2,5	-
6	4	4	3	3,4	6
7	5	5	5,6	5,6	1
8	4	4,3	4	3,4	1
9	2	6	6	2,6	5
10	4,3	3	4	3,4	1
11	1	1,4	6	1,4,6	-
12	2	3,5	2,5	2,3,5	-

Period 13									
Cell 2	Product							operations performed	operations missed
Operator	X3	X5	X6	X7	X8	X9	X10		
13	2,4	2	2,1	2	2,4	2	2	1,2,4	-
14	3	4	3,2	4	4,2	3	3,4	2,3,4	-
15	3	5	5,3	1,5	5	1	5	1,3,5	-
16	3	2	5,3	5,3	5	5	5	2,3,5	-
17	1,4	4	4	4	4,6	4,6	4,6	1,4,6	-
18	4,1	4	4	2	4,2	4	4,1	2,4,1	-
19	2	4	2	2	2,4	2	2	2,4	6
20	3	5	3	5,3	3	5	1,3	1,3,5	-
21	4	1	1,4	6	1,4	6,4	4	1,4,6	-
22	3,2	3	3,5	3,5	3	3	3	2,3,5	-
23	6	3	3	3,1	6	6,3	6	1,3,6	-
24	4	4	4,5	4	4,1	4	4	4,1,5	-
25	4,3	6,3	3	6,3	6,4	3	6,4	3,6,4	-
26	6	6	6	3,6	6,3	6	6,3	3,6	2
27	5	5	5	4	4	4	4	5,4	1
28	3	2	3	5,3	3	3	3	2,3,5	-
29	3	3,6	3	3,6	3,6	3,6	3,6	3,6	1
30	6	6	6	6,5	6	6	6	5,6	1

Period 14						
Cell 1	Product				operations performed	operations missed
Operator	X1	X3	X4	X6		
1	3,4	3	3	3,4	3,4	1
2	4	3	4,2	4,3	2,3,4	-
3	2	2	2,1	2	1,2	3
4	4	4	6	5	4,5,6	-
5	1	1	5,2	5,1	1,2,5	-
6	4	3	3	4,6	3,4,6	-
7	5	6	6	6	5,6	1
8	4,3	4	1,4	3	1,3,4	-
9	2	6	2,5	6	2,5,6	-
10	3	3	4	3	3,4	1
11	6	4	6	1,4	1,4,6	-
12	5	5	5	3	3,5	2

Period 14								
Cell 2	Product						operations performed	operations missed
Operator	X2	X5	X7	X8	X9	X10		
13	4	2	2	4	2	2	2,4	1
14	4	4	4	3,2	3	3,4	2,3,4	-
15	3	3,5	3,5	1,3	5	5	1,3,5	-
16	2	2	2	5	5	5	2,5	3
17	4	4	4,1	4	1,4	4	1,4	6
18	4,2	4	2	2	4,1	4,1	2,4,1	-
19	2,4	4	4	2,6	2	2	2,4,6	-
20	3	5,3	5,3	5	3	3	3,5	1
21	1	1	6	4	4,6	4,6	1,4,6	-
22	5	3	5,3	3	3	3	3,5	2
23	6	6	3,6	6	6	6	3,6	1
24	4	4	4	4	4	4	4	1,5
25	3	6,3	6,3	6	6,4	6,4	3,4,6	-
26	6	6	6,3	6,3	6	6,3	6,3	2
27	5	5	5,4	4	4	4	4,5	1
28	5	2	3,5	3	3	3	2,3,5	-
29	3	3,6	3,6	3,1	3	1,6	1,3,6	-
30	6	5	1,5	6	6	6	1,5,6	-

D2. Operations Performed and Missed by each Operator when Max was used.

Period 1						
Cell 1	Product				operations performed	operations missed
Operator	X1	X3	X5	X6		
1	3	3	3	3	3	1,4
2	4	4	3	3	3,4	2
3	2	2	2	3	2,3	1
4	6	6	6	4	4,6	5
5	5	5	5	5	5	1,2
6	4	3	4	4	3,4	6
7	5	1	5	1	1,5	6
8	4	3	3	4	3,4	1
9	2	6	6	2	2,6	5
10	4	4	4	4	4	1,3
11	1	4	1	6	1,4,6	-
12	3	3	3	5	3,5	2

Period 1								
Cell 2	Product						operations performed	operations missed
Operator	X2	X4	X7	X8	X9	X10		
13	4	2	2	4	4	2	2,4	1
14	3	4	3	3	3	4	3,4	2
15	5	3	5	3	1	3	1,3,5	-
16	2	3	5	2	3	5	2,3,5	-
17	4	1	4	4	4	4	1,4	6
18	2	4	2	4	2	4	2,4	1
19	4	2	2	2	2	2	2,4	6
20	5	3	5	5	5	5	3,5	1
21	4	6	4	6	6	6	4,6	1
22	3	5	3	3	3	3	3,5	2
23	3	6	6	6	3	6	3,6	1
24	4	4	4	4	4	1	1,4	5
25	6	6	4	6	3	4	3,4,6	-
26	6	6	6	6	6	6	6	2,3
27	1	5	4	5	4	4	1,4,5	-
28	5	5	3	2	5	3	2,3,5	-
29	3	6	3	3	6	3	3,6	1
30	6	6	1	1	6	5	1,5,6	-

Period 2					
Cell 1	Product			operations performed	operations missed
Operator	X1	X2	X4		
1	3	4	3	3,4	1
2	4	4	2	2,4	3
3	2	2	2	2	1,3
4	6	6	4	4,,6	5
5	5	5	1	1,5	2
6	4	3	3	3,4	6
7	5	5	6	5,6	1
8	4	3	4	3,4	1
9	2	6	6	2,6	5
10	4	4	4	4	1,3
11	1	1	6	1,6	4
12	3	3	5	3,5	2

Period 2									
Cell 2	Product							operations performed	operations missed
Operator	X3	X5	X6	X7	X8	X9	X10		
13	2	2	2	2	4	4	2	2,4	1
14	3	4	3	3	3	3	4	3,4	2
15	3	5	5	5	3	1	3	1,3,5	-
16	3	2	3	5	2	3	5	2,3,5	-
17	4	4	4	4	4	4	4	4	1,6
18	4	4	4	2	4	2	4	2,4	1
19	2	4	2	2	2	2	2	2,4	6
20	5	5	5	5	5	5	5	5	1,3
21	4	1	1	4	6	6	6	1,4,6	-
22	3	5	3	3	3	3	3	3,5	2
23	3	3	3	6	6	3	6	3,6	1
24	4	4	4	4	4	4	1	1,4	5
25	6	6	3	4	6	3	4	3,4,6	-
26	6	6	6	6	6	6	6	6	2,3
27	1	5	5	4	5	4	4	1,4,5	-
28	3	2	3	3	2	5	3	2,3,5	-
29	3	3	3	3	3	6	3	3,6	1
30	6	6	6	1	1	6	5	1,5,6	-

Period 3					
Cell 1	Product			operations performed	operations missed
Operator	X1	X2	X4		
1	3	4	3	3,4	1
2	4	4	2	2,4	3
3	2	2	2	2	1,3
4	6	6	4	4,6	5
5	5	5	1	1,5	2
6	4	3	3	3,4	6
7	5	5	6	5,6	1
8	4	3	4	3,4	1
9	2	6	6	2,6	5
10	4	4	4	4	1,3
11	1	1	6	1,6	4
12	3	3	5	3,5	2

Period 3									
Cell 2	Product							operations performed	operations missed
Operator	X3	X5	X6	X7	X8	X9	X10		
13	2	2	2	2	4	4	2	2,4	1
14	3	4	3	3	3	3	4	3,4	2
15	3	5	5	5	3	1	3	1,3,5	-
16	3	2	3	5	2	3	5	2,3,5	-
17	4	4	4	4	4	4	4	4	1,6
18	4	4	4	2	4	2	4	2,4	1
19	2	4	2	2	2	2	2	2,4	6
20	5	5	5	5	5	5	5	5	1,3
21	4	1	1	4	6	6	6	1,4,6	-
22	3	5	3	3	3	3	3	3,5	2
23	3	3	3	6	6	3	6	3,6	1
24	4	4	4	4	4	4	1	1,4	5
25	6	6	3	4	6	3	4	3,4,6	-
26	6	6	6	6	6	6	6	6	2,3
27	1	5	5	4	5	4	4	1,4,5	-
28	3	2	3	3	2	5	3	2,3,5	-
29	3	3	3	3	3	6	3	3,6	1
30	6	6	6	1	1	6	5	1,5,6	-

Period 4					
Cell 1	Product			operations performed	operations missed
Operator	X1	X2	X4		
1	3	4	3	3,4	1
2	4	4	2	2,4	3
3	2	2	2	2	1,3
4	6	6	4	4,6	4,5
5	5	5	1	1,5	2
6	4	3	3	3,4	6
7	5	5	6	5,6	1
8	4	3	4	3,4	1
9	2	6	6	2,6	5
10	4	4	4	4	1,3
11	1	1	6	1,6	4
12	3	3	5	3,5	2

Period 4									
Cell 2	Product							operations performed	operations missed
Operator	X3	X5	X6	X7	X8	X9	X10		
13	2	2	2	2	2	2	4	2,4	1
14	3	4	3	3	4	3	2	2,3,4	-
15	3	5	5	5	3	5	1	,1,3,5	-
16	3	2	3	5	2	3	5	2,3,5	-
17	4	4	4	4	4	4	4	4	1,6
18	4	4	4	2	4	2	4	,2,4	1
19	2	4	2	2	4	4	2	2,4	6
20	5	5	5	5	5	1,	5	1,5	3
21	4	1	1	4	6	6	6	1,4,6	-
22	3	3	3	3	3	3	3	3,	2,5
23	3	6	3	6	1	3	6	3,6	1
24	4	4	4	4	4	4	4	4	1,5
25	6	3	3	4	6	3	3	3,4,6	-
26	6	6	6	6	6	6	6	6	2,3
27	1	5	5	4	5	4	4	1,4,5	-
28	3	2	3	3	3	5	3	2,3,5	-
29	3	3	3	3	3	6	3	,3,6	1
30	6	6	6	1	6	6	6	1,,6	5

Period 5						
Cell 1	Product				operations performed	operations missed
Operator	X1	X3	X5	X10		
1	3	3	3	4	3,4	1
2	4	4	4	2	2,4	3
3	2	2	2	2	2	1,3
4	6	6	6	6	6	4,5
5	5	1	5	5	1,5	2
6	4	3	4	4	4,3	6
7	5	5	5	5	5	1,6
8	4	3	4	3	3,4	1
9	2	6	2	6	2,6	5
10	4	4	1	4	1,4	3
11	1	4	6	1	1,4,6	-
12	3	3	3	3	3	2,5

Period 5								
Cell 2	Product						operations performed	operations missed
Operator	X2	X6	X7	X9	X4	X8		
13	4	2	4	4	4	4	2,4	1
14	4	3	2	3	3	3	2,3,4	-
15	3	3	5	3	3	3	3,5	1
16	3	3	3	3	5	5	3,5	2
17	4	4	4	4	6	1	1,4,6	-
18	2	4	4	4	4	4	2,4	1
19	2	4	2	2	2	2	2,4	6
20	5	3	3	5	5	5	3,5	1
21	4	1	1	1	6	4	1,4,6	-
22	3	3	2	3	5	3	2,3,5	-
23	3	3	3	6	3	6	3,6	1
24	5	5	4	4	4	4	4,5	1
25	6	6	6	6	6	6	6	3,4
26	6	6	6	6	6	6	6	2,3
27	4	5	5	5	1	4	1,4,5	-
28	5	2	2	2	2	2	2,5	3
29	6	3	3	3	3	3	3,6	1
30	1	5	5	6	6	6	1,5,6	-

Period 6					
Cell 1	Product			operations performed	operations missed
Operator	X1	X2	X5		
1	4	3	4	3,4	1
2	3	4	3	3,4	2
3	2	2	2	2	1,3
4	6	6	4	4,6	5
5	5	5	5	5	1,2
6	4	4	4	4	3,6
7	5	5	5	5	1,6
8	4	3	1	1,3,4	-
9	2	6	6	2,6	5
10	4	4	3	3,4	1
11	1	1	6	1,6	4
12	3	3	2	2,3	5

Period 6									
Cell 2	Product							operations performed	operations missed
Operator	X3	X4	X6	X7	X8	X9	X10		
13	2	2	2	2	2	2	4	2,4	1
14	3	4	3	4	3	3	4	,3,4	2
15	3	3	5	3	3	5	3	,3,5	1
16	2	3	3	5	3	5	5	2,3,5	-
17	4	1	4	4	4	6	1	1,4,6	-
18	4	4	4	4	4	4	2	4	1,2
19	4	2	2	2	4	2	2	2,4	6
20	3	5	5	3	5	1	5	1,3,5	-
21	1	6	1	6	4	4	6	1,4,6	--
22	3	3	3	3	3	3	3	3	2,5
23	3	6	3	1	6	3	3	1,3,6	-
24	4	4	4	4	4	4	4	4	1,5
25	6	6	3	3	6	3	4	3,6	4
26	6	6	6	6	6	6	6	6	3,2
27	5	5	5	5	5	4	4	4,5	1
28	3	5	3	2	2	3	3	2,3,5	---
29	3	3	3	6	1	6	6	1,3,6	-
30	6	6	6	5	6	6	6	5,6	1

Period 7						
Cell 1	Product				operations performed	operations missed
Operator	X1	X3	X5	X6		
1	3	3	3	3	3	4,1
2	4	4	2	4	2,4	3
3	2	2	2	2	2	1,3
4	6	6	6	5	5,6	4
5	5	5	5	5	5	2,1
6	4	3	4	3	3,4	6
7	5	1	5	6	1,5,6	-
8	4	3	4	3	3,4	1
9	2	6	6	6	2,6	5
10	4	4	4	4	4	3,1
11	1	4	1	1	1,4	6
12	3	3	3	3	3	2,5

Period 7								
Cell 2	Product						operations performed	operations missed
Operator	X2	X4	X7	X8	X9	X10		
13	4	2	2	2	2	2	4,2	1
14	3	4	4	4	3	4	4,3	2
15	3	1	3	3	1	1	1,3	5
16	5	5	5	5	3	5	3,5	2
17	4	6	4	6	4	4	4,6	1
18	2	4	2	4	4	2	2,4	1
19	2	2	2	2	2	4	2,4	6
20	1	5	1	5	5	5	5,1	3
21	4	6	4	4	6	4	4,6	1
22	3	3	3	3	3	3	3	2,5
23	6	3	3	1	6	3	1,3,6	-
24	4	4	4	4	4	4	4	1,5
25	6	6	6	6	3	6	3,6	4
26	6	6	6	6	6	6	6	2,3
27	4	5	4	4	4	4	4,5	1
28	5	3	5	3	5	3	3,5	2
29	3	3	3	3	3	3	3	1,6
30	5	6	5	6	6	6	5,6	1

Period 8						
Cell 1	Product				operations performed	operations missed
Operator	X1	X3	X5	X6		
1	3	3	3	3	3	4,1
2	4	4	2	4	2,4	3
3	2	2	2	2	2	1,3
4	6	6	6	5	5,6	4
5	5	5	5	5	5	2,1
6	4	3	4	3	3,4	6
7	5	1	5	6	1,5,6	-
8	4	3	4	3	3,4	1
9	2	6	6	6	2,6	5
10	4	4	4	4	4	3,1
11	1	4	1	1	1	4,6
12	3	3	3	3	3	2,5

Period 8								
Cell 2	Product						operations performed	operations missed
Operator	X2	X4	X7	X8	X9	X10		
13	4	2	2	4	2	4	4,2	1
14	4	4	4	4	3	3	4,3	2
15	3	3	3	3	1	1	1,3	5
16	5	5	3	3	3	3	3,5	2
17	4	6	4	4	4	4	4,6	1
18	2	4	2	2	2	2	2,4	1
19	2	2	2	2	4	2	2,4	6
20	1	5	5	5	5	5	5,1	3
21	4	6	4	4	6	6	4,6	1
22	3	3	3	3	3	3	3	2,5
23	3	6	3	6	3	3	3,6	1
24	4	4	4	4	4	4	4	1,5
25	6	6	6	6	6	4	4,6	3
26	6	6	6	6	6	6	6	2,3
27	5	5	4	5	4	4	4,5	1
28	5	3	5	3	5	5	3,5	2
29	3	3	1	1	3	6	1,3,6	-
30	6	1	5	6	6	6	5,6	1

Period 9						
Cell 1	Product				operations performed	operations missed
Operator	X1	X3	X5	X6		
1	3	3	3	3	3	4,1
2	4	4	3	3	3,4	2
3	2	2	2	2	2	1,3
4	6	6	6	6	6	4,5
5	5	1	5	5	1,5	2
6	4	3	4	4	3,4	6
7	5	5	5	5	5	1,6
8	4	3	4	3	3,4	1
9	2	6	6	6	2,6	5
10	4	4	4	4	4	3,1
11	1	4	1	1	1,4	6
12	3	3	3	3	3	2,5

Period 9								
Cell 2	Product						operations performed	operations missed
Operator	X2	X4	X7	X8	X9	X10		
13	2	2	2	2	2	2	2	1,4
14	3	4	4	4	3	3	3,4	2
15	5	3	5	1	3	5	1,3,5	-
16	3	3	3	3	3	3	3	2,5
17	4	1	4	4	4	4	1,4	6
18	4	4	2	2	4	2	2,4	1
19	4	2	2	4	2	4	2,4	6
20	5	5	5	5	5	5	5	1,3
21	4	6	4	4	4	4	4,6	1
22	3	3	3	3	3	3	3	2,5
23	6	6	3	6	6	6	3,6	1
24	4	4	4	4	4	4	4	1,5
25	6	6	6	6	3	6	6,3	4
26	6	6	6	6	6	6	6	3,2
27	4	5	4	5	1	4	1,4,5	-
28	2	5	5	3	5	3	2,3,5	-
29	3	3	3	3	6	1	1,3,6	-
30	5	6	1	6	6	6	1,5,6	-

Period 10					
Cell 1	Product			operations performed	operations missed
Operator	X1	X2	X5		
1	3	4	3	3,4	1
2	4	3	2	2,3,4	-
3	3	3	2	3,2	1
4	6	6	6	6	4,5
5	5	5	5	5	1,2
6	4	3	4	3,4	6
7	5	5	5	5	1,6
8	4	4	4	4	1,3
9	2	6	6	2,6	5
10	4	1	4	1,4	3
11	1	4	1	1,4	6
12	3	3	3	3	2,5

Period 10									
Cell 2	Product							operations performed	operations missed
Operator	X10	X4	X7	X8	X3	X9	X6		
13	2	2	2	2	2	2	2	2	4,1
14	3	3	4	4	3	3	3	3,4	2
15	1	3	3	3	3	3	3	1,3,	6
16	3	5	2	3	3	5	3	2,3,5	-
17	4	4	4	4	4	4	4	4	1,6
18	4	4	2	4	2	2	2	2,4	1
19	2	2	4	2	4	4	4	2,4	6
20	5	5	5	5	5	5	3	3,5	1
21	4	6	1	4	4	4	1	1,4,6	--
22	3	3	2	3	3	3	3	2,3,	5
23	6	6	3	6	3	6	3	3,6	1
24	4	4	4	4	4	4	5	4,5	1
25	6	6	6	6	6	6	6	6	3,4
26	6	6	6	6	6	6	6	6	2,3
27	4	1	5	5	1	1	5	1,4,5	-
28	5	5	3	3	3	3	2	2,3,5	-
29	3	3	3	6	3	3	3	3,6	1
30	6	6	5	1	6	6	5	1,5,6	-

Period 11						
Cell 1	Product				operations performed	operations missed
Operator	X1	X3	X5	X6		
1	3	3	3	3	3	1,4
2	4	2	4	4	2,4	3
3	3	2	2	2	3,2	1
4	6	6	6	6	6	4,5
5	5	5	1	5	1,5	2
6	4	4	3	3	3,4	6
7	5	5	5	5	,5	1,6
8	4	4	3	3	3,4	1
9	2	6	6	6	2,6	5
10	4	4	4	4	4	3,1
11	1	1	4	1	1,4	6
12	3	3	3	3	3	2,5

Period 11								
Cell 2	Product						operations performed	operations missed
Operator	X2	X4	X7	X8	X9	X10		
13	2	2	2	2	4	2	2,4	1
14	3	3	3	4	3	4	3,4	2
15	1	3	3	3	3	5	1,3,5	-
16	3	5	5	3	5	2	2,3,5	-
17	4	4	4	4	4	4	4	1,6
18	4	4	2	2	2	4	2,4	1
19	2	2	4	4	2	2	2,4	6
20	5	5	5	5	1	3	1,3,5	-
21	4	6	4	6	4	1	1,4,6	-
22	3	3	3	3	5	2	2,3,5	-
23	6	6	6	6	3	3	3,6	1
24	4	4	4	4	4	4	4	1,5
25	6	6	6	6	6	6	6	3,4
26	6	6	6	6	6	6	6	2,3
27	4	1	1	4	4	5	1,4,5	-
28	5	5	3	5	5	3	3,5	2
29	3	3	3	3	3	3	3	1,6
30	6	6	6	1	6	5	1,5,6	-

Period 12					
Cell 1	Product			operations performed	operations missed
Operator	X1	X2	X5		
1	3	3	3	3	1,4
2	4	3	4	3,4	2
3	2	2	1	1,2	3
4	6	6	6	6	4,5
5	5	5	5	5	1,2
6	4	4	4	4	6,3
7	5	5	5	5	1,6
8	4	4	3	3,4	1,
9	2	6	2	2,6	5
10	4	4	4	4	3,1
11	1	1	6	1,6	4
12	3	3	2	3,2	5

Period 12									
Cell 2	Product							operations performed	operations missed
Operator	X3	X4	X6	X7	X8	X9	X10		
13	2	2	2	2	2	2	2	2	1,4
14	3	4	3	4	4	3	4	3,4	2
15	3	5	3	5	3	1	3	1,3,5	-
16	3	3	3	3	3	3	3	3	2,5
17	4	6	4	4	4	4	4	4,6	1
18	4	4	4	2	4	4	2	2,4	1
19	2	2	2	2	2	2	4	2,4	6
20	1	1	5	5	5	5	5	1,5	3
21	4	6	1	1	4	4	4	1,4,6	-
22	3	5	3	3	3	3	3	3,5	2
23	3	3	3	6	6	6	6	3,6	1
24	4	4	4	4	4	4	1	4,1	5
25	6	6	3	6	6	6	4	3,4,6	-
26	6	6	6	6	6	6	6	6	2,3
27	5	5	5	5	5	5	5	5	1,4
28	3	3	5	3	3	3	3	3,5	2
29	3	3	3	3	6	3	6	3,6	1
30	6	6	6	5	1	6	6	1,5,6	-

Period 13					
Cell 1	Product			operations performed	operations missed
Operator	X1	X2	X4		
1	3	3	3	3	1,4
2	4	3	2	2,3,4	-
3	2	2	2	,2	1,3
4	6	6	6	6	4,5
5	5	5	5	5	1,2
6	4	4	4	,4	6,3
7	5	5	1	1,5	,6
8	4	4	3	3,4	1,
9	2	6	6	2,6	5
10	4	4	4	4	3,1
11	1	1	6	1,6	4
12	3	3	5	3,5	2

Period 13									
Cell 2	Product							operations performed	operations missed
Operator	X3	X5	X6	X7	X8	X9	X10		
13	2	2	2	2	2	2	2	2	1,4
14	3	4	3	4	4	3	4	3,4	2
15	3	5	3	5	3	1	3	1,3,5	-
16	3	2	3	3	3	3	3	3,2	5
17	4	4	4	4	4	4	4	4	1,6
18	4	4	4	2	4	4	2	2,4	1
19	2	4	2	2	2	2	4	2,4	6
20	1	5	5	5	5	5	5	1,5	3
21	4	1	1	1	4	4	4	1,4	6
22	3	3	3	3	3	3	3	3,5	2
23	3	3	3	6	6	6	6	3,6	1
24	4	4	4	4	4	4	1	1,4	5
25	6	6	3	6	6	6	4	3,4,6	-
26	6	6	6	6	6	6	6	6	2,3
27	5	5	5	5	5	5	5	5	1,4
28	3	2	5	3	3	3	3	2,3,5	-
29	3	3	3	3	6	3	6	3,6	1
30	6	6	6	5	1	6	6	1,5,6	-

Period 14						
Cell 1	Product				operations performed	operations missed
Operator	X1	X3	X4	X6		
1	3	3	3	3	3	1,4
2	4	4	2	3	2,3,4	-
3	2	2	2	2	2	1,3
4	6	6	6	6	6	4,5
5	5	1	1	5	5,1	2
6	4	3	4	4	4,3	6
7	5	5	5	5	5	1,6
8	4	3	3	3	3,4	1
9	2	6	6	6	2,6	5
10	4	4	4	1	4,1	3
11	1	4	6	4	1,6,4	-
12	3	3	5	3	3,5	2

Period 14								
Cell 2	Product						operations performed	operations missed
Operator	X2	X5	X7	X8	X9	X10		
13	4	2	2	2	2	2	2,4	1
14	3	4	4	4	3	4	3,4	2
15	3	5	5	3	1	3	1,3,5	-
16	2	2	3	3	3	3	3,2	5
17	4	1	4	4	4	4	4,1	6
18	2	4	2	4	2	4	2,4	1
19	4	4	2	2	4	2	2,4	6
20	5	5	1	5	5	5	1,5	3
21	4	4	4	1	4	6	1,4,6	-
22	3	3	3	3	3	3	3	2,5
23	6	3	6	6	6	1	1,3,6	-
24	4	4	4	4	4	4	4	5,1
25	6	6	3	4	6	4	3,4,6	-
26	6	6	6	6	6	6	6	2,3
27	1	5	5	5	5	5	5,1	4
28	5	2	5	3	3	3	3,5,2	-
29	3	3	3	6	3	6	3,6	1
30	5	6	6	6	6	6	5,6	1