Operator assignment in labor intensive cells considering operation time based skill levels, learning and forgetting

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This thesis entitled

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Several solutions to the cell loading problem in labor intensive cells have been reported in the literature. Even though significant research has been done considering the "operator" factor, very little research is done considering operator skills. This thesis makes an effort to assign operators to various operations by considering operator skill levels and operator-operation times as opposed to the classical approach of using standard times. The objective of the thesis is to perform a single - period analysis which includes testing the effect of variability in operator – operation times, impact of more operator skills, comparison of cell loading strategies, and operator assignment approaches and multi – period analysis which includes comparison of operator assignment approaches and impact of operator learning and forgetting rates on operator skills. Results show that the proposed approach in operator assignment outperforms the classical approach of using standard times when both lot splitting and operator sharing are allowed for the problem considered and in the long run Max-Min approach gives better results than the classical approach and Max approach in terms of skill improvement.

Approved:

Gürsel A. Süer

Professor of Industrial and Manufacturing Systems Engineering

Dedication

To

Padma, Shiva, Damu, Usha, and Dr. Süer

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CHAPTER 1 INTRODUCTION

This chapter introduces a typical manufacturing system, different layout types, cellular manufacturing and cellular control issues in labor intensive cells. A brief description of operation times, manpower allocation and mathematical modeling is also given and finally, the objectives, justification and organization of this thesis are presented.

1.1 Manufacturing Systems

Manufacturing is an industrial activity that changes the form of raw materials to create products. To be profitable, an enterprise establishes and nurtures a manufacturing system that facilitates the flow of information to coordinate inputs, processes and outputs [27]. Figure 1.1 shows the diagram of a typical manufacturing system.

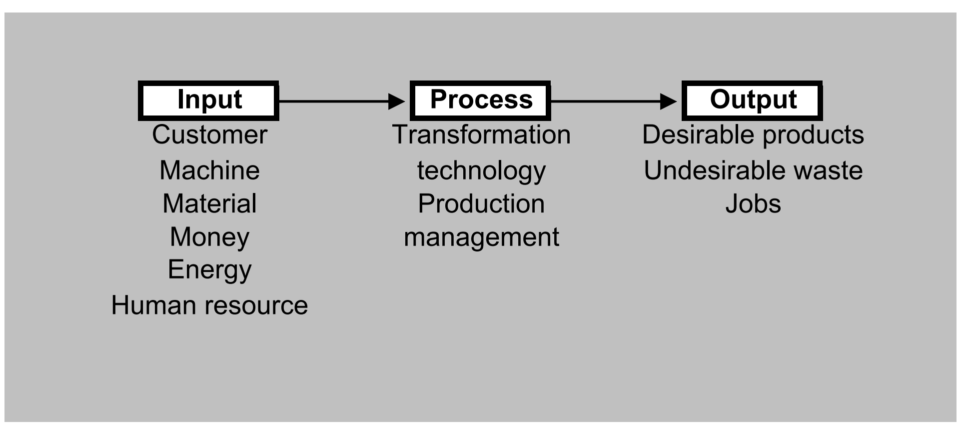
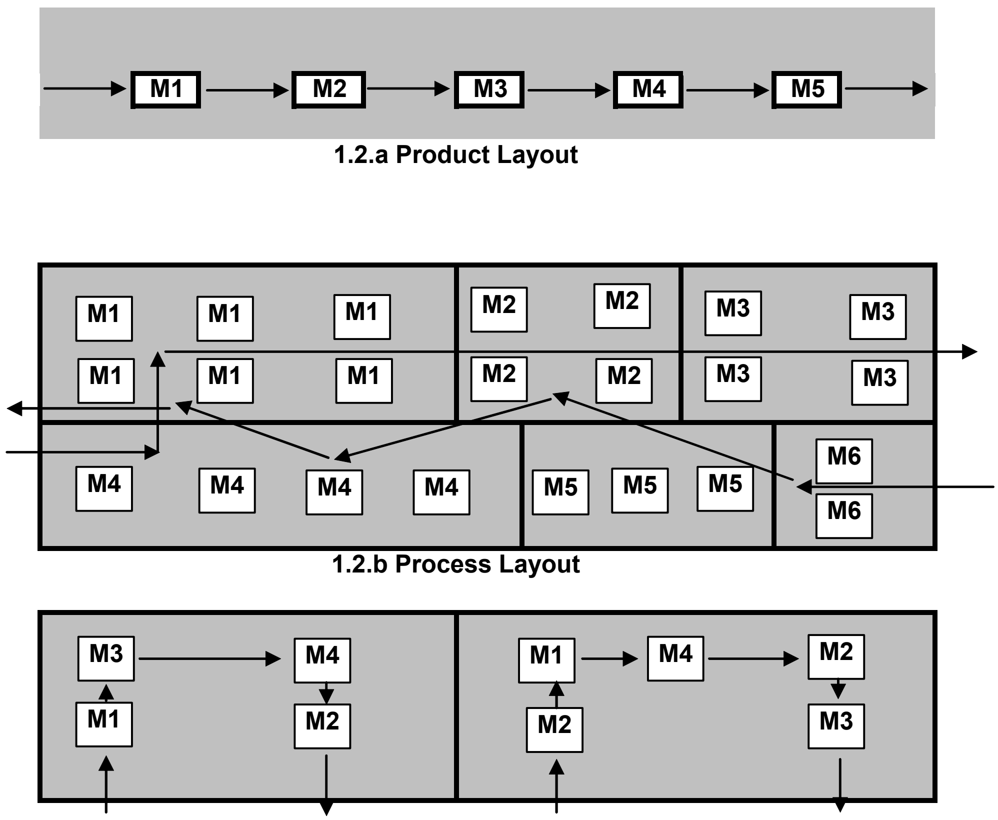


Figure 1.1 Diagram of a typical manufacturing system

Depending upon the inputs, processes and outputs, a manufacturing system can be designed in four different layouts. They are fixed, product, process and cellular layouts. The difference between the four layouts is most easily seen in the material flow system [28]. Figure 1.2 shows the material flow for product, process and cellular layouts.



1.2.c Cellular Layout

Figure 1.2 Material flows for product, process and cellular layouts

Fixed layout is used for large products such as ships, buildings and airplanes, etc. because the size of the product makes it impractical to move the product between processing operations. Product layouts are designed for a single product. Here, machines are arranged based on the sequence of operations required by a product as shown in figure 1.2.a. In process layouts, departments are composed of machines with similar capabilities that perform similar functions as shown in figure 1.2.b. Cellular layouts can be used to convert otherwise process layout system to pseudo product layout environments. Similar parts are grouped together in sufficient quantities to justify their own machines as shown in figure 1.2.c. Table 1.1 points out the strengths and weakness of the layout types [28].

Table 1.1 Characteristics of Layout types

Characteristics	Product Layout	Process Layout	Cellular Layout	Fixed Layout
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	Medim-Low	Medium-High	Medium
Worker utilization	High	High	High	Medium
Unit Product cost	Low	High	Low	High

Each system may be viewed as the best alternative for its appropriate environment. The environment is most easily summarized by the volume – variety combination. Figure 1.3 shows the appropriate layout for combinations of product demand volume and variety of parts or products produced. Process layouts are preferable when product variety is high and production volume is low as it increases flexibility. But efficiency decreases as the material flow is not smooth. Product layout is suitable when production volume is high and product variety is low. Here, flexibility is low as change in product requires the alteration of the present layout leading to higher costs. Cellular layout has advantages of both product and process layouts. It provides increased efficiency and higher flexibility.

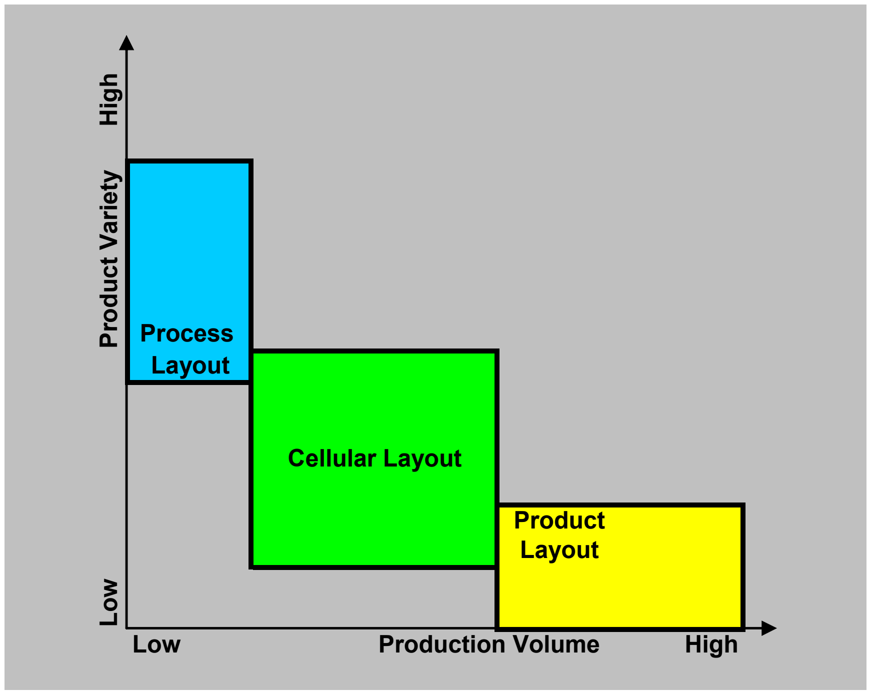


Figure 1.3 Volume vs. Variety for different layouts

1.2 Cellular Manufacturing

Cellular manufacturing is a manufacturing process that produces families of parts within a single line(s) or cell(s) of machines operated by an operator or by robots that operate only within the line(s) or cell(s) [25]. The major benefits of cellular manufacturing are:

- Elimination or reduction of setup times
- Greater manufacturing flexibility
- Reduction of work – in – process inventory
- Less floor space around the high – investment machines
- Fewer costs

To obtain the benefits of cells, planners and managers must overcome the following difficulties:

- Worker rejection or lack of acceptance
- Lack of support or opposition by support staff in production planning, inventory control and/or cost accounting
- Reduced machine utilization
- Need to train or retrain operators
- Wage and performance measurement problems

A manufacturing cell consists of two or more operations, workstations or machines dedicated to processing one or a limited number of parts or products. A cell has a defined working area and is scheduled, managed and measured as a single unit of production facilities. Manufacturing cells are classified into two groups – machine intensive cells and labor intensive cells. Machine intensive cells depend more on machines than labor force. Labor intensive cells depend on the presence of operators most or all of the time. People perform a large variety of tasks in manual as compared to automated cells. Machine intensive cells can be considered as part of a trend towards flexible manufacturing systems and computer integrated manufacturing systems. Most assembly cells are manual due to the difficulties of executing automatic assembly, especially for small products [25] [29]. This thesis focuses on only labor intensive cells.

1.3 Cell Control in Labor Intensive Cells

Three aspects – strategic, tactical and operational must be addressed during various stages of cellular manufacturing [42]. In strategic planning, focusing and designing issues are addressed which include identification of product and part families, establishing machine requirements, number of cells, etc. In tactical planning, cell loading decisions are made. This includes determination of production rates, assignment of products to cells using the production rates, product sequencing, capacity decisions, etc. In operational planning, cell scheduling decisions are made which includes lot sizing, start and completion time on machines/cells, crew size, operator assignment to operations and cells, absenteeism, etc. Cells also require operating procedures for quality, engineering, materials management, maintenance, and accounting and because cells employ personnel in various jobs and capacities, they also require policies and organization structure, leadership and training. Figure 1.4 shows the framework for the decisions to be taken during various stages of cellular manufacturing.

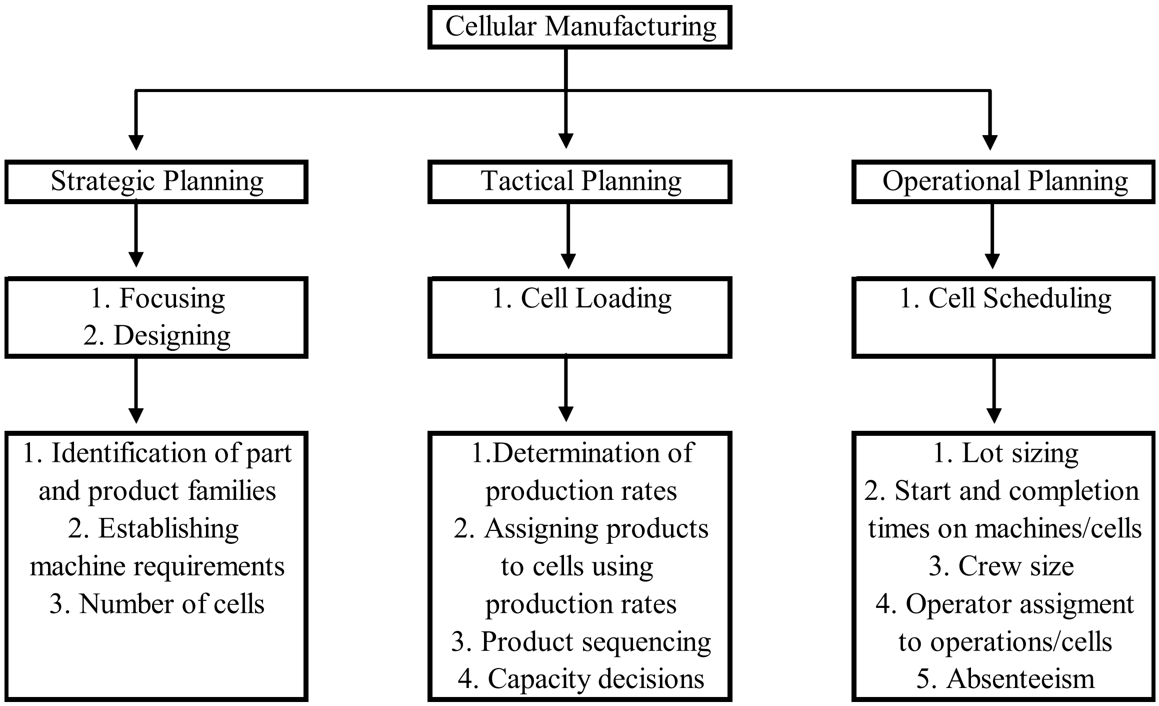


Figure 1.4 Framework for the decisions to be taken during various stages of cellular manufacturing

This thesis focuses on cell loading and operational decision aspects in a manufacturing cell. Deciding on the size and number of cells required is a critical decision. In some cases, putting all of the parts and their required equipment and operators into one cell will make it too large. This can create management and space problems, potential bottlenecks and scheduling difficulties. It may be more practical to couple the products and their processes into two or more cells, even if some equipment has to be duplicated, i.e. assigning certain percent of a product(s) to another cell(s). This is termed as lot splitting in this thesis. In some cases, it becomes necessary to share operators between operations and cells to increase flexibility and solve some management and operational problems. This is termed as operator sharing in this thesis.

Operator related aspects of the cells include – leadership and supervision, job and work assignments, training, cross – training and skill development, performance measurement, recruiting and ongoing staffing. For the greater productivity and maximum throughput, this thesis considers operator skills to assign operators to various operations and cells. Ideally, every cell operator should be able to perform every cell operation with equal ease and effectiveness, but this is not the case in real life labor intensive cells. So, in this thesis operators are assumed to have skills for only some operations. Operators tend to improve their skill levels according to their learning and forgetting rates. This concept is used to analyze the cell performance and operator skill development.

1.4 Operation Times

Time study is performed to develop the standard time to perform operations. Standard time can be defined as the time required by a typical operator, working at a normal pace, to perform a specified task using a prescribed method, with time for personal matters, fatigue and delay allowed [25]. The typical operator is an operator who is representative of the people performing the task. He is not the best nor the worst. He is skilled in the job and can perform it consistently throughout the entire workday.

Selection of the appropriate cell performance measures is an important factor. In this thesis, the major cell performance measures used are makespan, total processing time and idle time. Makespan can be defined as the time to complete the last job. Total processing time can be defined as the total time to complete all the jobs. Idle time can be defined as the time during which the cellular system is not in use but is available.

Performance rating is probably the most important step in the entire time study procedure. It is based entirely on the experience, training, and judgement of the work measurement analyst. It is a technique for equitably determining the time required to perform a task by the normal operator after the observed values of the operation under study have been recorded. A relevant data one may need to analyze the plant's workforce are labor classification system (indicates degree of flexibility) and number of employees per skill level. Just as there is no universal method of performance rating, so there is no universal concept of normal performance. In this thesis, it is assumed that the distribution of the operator skills would approximate the normal curve.

1.5 Manpower Allocation

A cell is a production unit that includes a group of people and equipment. Cell loading is assigning products to cells and manpower allocation is determining the number of operators to be assigned to cells, number of operators per operation and who will be assigned to each operation in each case.

The number of operators assigned to a cell can be changed from one period to the next to adjust to the varying demand. As a result, alternative cell sizes are generated by allocating different number of operators to each cell. However, the total number of operators in the cellular system cannot be exceeded even though the allocation from one cell to the next cell and from one period to the next period can vary. This thesis uses the model proposed by Suer [4] in which manpower allocation and cell loading decisions are made simultaneously.

The traditional concept in manpower allocation is “one worker, one machine”. Here the operator is always assigned to the same machine. In “one worker, multiple machines”, operator moves around in the cell and attends to several processes. This requires proficiency in more than one process. Finally in “multiple workers, multiple operations”, operators are trained in two or more processes. They move to different workstations during a manufacturing cycle. However it also implies that at least some of the operators have overlapping responsibilities, this increases the flexibility to assign cell employees to stations where problems occur and more capacity is needed. The change from one concept to other requires a learning process leading to broadening of operator tasks. In this thesis, the concept of “multiple workers, multiple operations” is used.

The learning process can be different for each operator depending upon his skill level. Learning is a combination of cognitive and skill learning. Learning rate is based on the experience gained in previous time periods by the operator as well as the nature of operation being performed. Similarly forgetting is based on the worker’s learning rate, prior experience, as well as the length of the interruption interval over which the worker experiences forgetting. In this thesis, operator learning and forgetting rate is based on the number of weeks he performs the operation, his present skill level and the probability that he improves or deteriorates his present skill level. Thus, both mental and mechanical skills of the operators are considered while performing the multi – period analysis.

1.6 Mathematical Models

A mathematical model is the use of mathematical language to describe the behavior of a system. It usually describes a system by a set of variables and a set of equations that establish relationships between the variables. The values of the variables can be practically anything; real or integer numbers, Boolean values or strings etc. objectives and constraints of the system can be represented as functions of the output variables or state variables. The objective function depends on the perspective of the model's user. Although there is no limit of objective functions and constraints a model can have, using or optimizing the model becomes more involved. Various models are used and developed for cell loading and operator allocation in this thesis.

ILOG OPL Studio software is used to solve the mathematical models. The solutions obtained by solving these models are optimal, provided they are modeled accurately describing the system. The results obtained by solving the models are used to find the cell sizes and loads, and operator assignment to the operations.

1.7 Objectives of the Thesis

This thesis employs the concept of cell loading and operator assignment introduced by Suer [4] in order to deal with the cell performance and proper allocation of operators in a cellular manufacturing system considering cell loading issues like lot splitting and operator sharing in the context of single period analysis, and operator learning and forgetting for multi – period analysis. The performance measures used are makespan, total processing time and idle time for most of the analysis.

The main objectives of the thesis are:

- To test the effect of variability in operator – operation times in a single – period environment. Mathematical models are used to determine the optimal number of operators to be assigned to each operation for a given operator level, cell sizes and cell loads considering that both operator sharing and lot splitting are not allowed. The proposed max approach (skill maximization) is used to allocate the operators to operations.
- To study the impact of having more operator skills for operations. Cellular performance is compared by allocating 2 and 3 skills to operators. It is assumed that lot splitting and operator sharing is not allowed. Max approach is used to assign the operators to operations.
- To compare the cell performance considering cell loading strategies like lot splitting and operator sharing in a single – period environment using the max approach to assign the operators to operations.
- To compare the cell performance considering the three proposed approaches (max, max – max (skill maximization for bottleneck operations and then skill maximization for non - bottleneck operations) and max – min (skill maximization for bottleneck operations and then skill minimization for non - bottleneck operations)) to assign the operators to operations in a single period environment considering a larger version of the problem and assuming that lot splitting and operator sharing are not allowed.

- To compare the cell performance considering max and max – min approaches in a multi – period environment. It is assumed that lot splitting is allowed and operator sharing is not allowed.
- To test the impact of the proposed operator assignment approaches on the skill improvement of operators considering operator learning and forgetting rates.

1.8 Justification

A lot of research has been done to solve the cell loading problems in labor intensive cells. Even though considerable research has been done considering the "operator" factor, very little research has been done considering operator skills. Various solutions are provided in the literature to determine the optimal number of cells required and what products to be manufactured in which cell.

Usually, manager in the cell allocates the operators to operations and the standard time is developed by performing time study. These standard times are used to forecast the cell performance for varying demands even though after certain time period, operators tend to improve or deteriorate their skills in performing the operations according to their learning and forgetting rates improving/deteriorating the quality of the products and changing their individual operation times. Thus, a difference is created in the actual and forecasted cell performance.

Optimal cell sizes and loads can be found by considering cell loading strategies like lot splitting and operator sharing. Cell performance can also be improved by proper allocation of operators to operations by matching the skills needed with skills available.

By considering issues like variability in operator – operation times, more operator skills and cell loading strategies like lot splitting and operator sharing, single – period analysis of cell performance can be done. By considering the operator learning and forgetting rates, multi - period analysis of cell performance and impact on operator skill levels can be done. This helps the manager to fine tune the cellular system for every period accordingly.

1.9 Organization of the Thesis

The thesis is organized in the following six chapters:

- Chapter 1 briefly explains the manufacturing system, cellular manufacturing and cellular control issues. It also introduces the objectives and justification of the thesis.
- Chapter 2 glances at the previous and current research in cell loading and operator factor in labor intensive cells.
- Chapter 3 describes the issues and problems considered, methodology used and mathematical models for determining cell sizes and loads considering operator sharing and lot splitting.
- Chapter 4 explains the approaches proposed to assign operators to operations considering operator skill levels, operator – operation times and operator learning and forgetting.
- Chapter 5 presents and analyzes the results obtained.
- Chapter 6 concludes the thesis and suggests any future work in the field.

CHAPTER 2 LITERATURE REVIEW

In recent years cellular manufacturing has gained a lot of popularity. The major benefits of cellular manufacturing are reduced lead time and work-in-process inventory, speedy response, higher flexibility, improved visibility and quality, simplified scheduling and improved work environment due to team work. Various production factors have to be considered in order to design manufacturing cells such as stochastic demand, varied product mix, machine capacity and machine overload, alternative process plans, operator allocation, variable operation sequence, setup times and processing times [12]. Manufacturing cells vary from machine intensive cells to labor intensive cells. Operator involvement is limited in machine intensive cells, but in labor intensive cells it plays a major role in the performance of the cell. Thus operator skills, operator-operation times, learning and forgetting rates and the operator assignments to the various operations become important. While the importance of a workforce has been widely recognized, very little research work has been done to investigate the effectiveness of the operator assignment on the performance of cellular manufacturing systems.

In 1970, Nelson [1] developed a simulation model to explore the relationships between the efficiency of labor interchange, the degree of centralized control exercised in labor assignment and queue discipline. The model consists of two work centers and two laborers. The three variables could be controlled to alter the performance of the system. The results focused on labor efficiency, centralized control of labor assignment, queue disciplines and job routings. Wittrock [2] developed a parametric preflow algorithm to solve the problem of assigning human operators to operations in a manufacturing system.

The problem was formulated as a network flow problem with a lexicographic objective. The objective was to maximize the capacity of the system.

Suer et al. [3] discussed cell loading rules and their performance in labor intensive manufacturing cell environment. Ten rules were framed and then were grouped into five categories. These rules could be combined in all possible ways resulting in forty-eight possible rules. Algorithms for both the product and the cell priority searches were discussed and experimentation was carried out in a real cellular manufacturing environment. The results of the experiment were that no single rule performed well with respect to all of the performance measures.

Cesani and Steudal [8] [9] examined the contribution of labor assignment flexibility to cell performance in labor limited cellular manufacturing systems. The concepts of workload balancing, workload sharing and the presence of bottleneck operations were included. Initially the proposed procedure for evaluation of labor assignments is presented and is followed by simulation results. The results showed that the output rate of the system varies significantly with labor strategies employed and the increasing amount of shared workload among operators can significantly increase the performance of the cells. A classification scheme was proposed to categorize labor assignments in cellular manufacturing systems. Two levels- operator level and cell level were considered in this paper to measure the labor flexibility. Jensen [10] examined the performance advantages of machine and labor flexibility over a wide and realistic set of assumptions and shop floor decisions. They tried to prove that promoting labor flexibility to the exclusion of machine flexibility provides excellent performance. Shop floor control was evaluated within three different shop configurations at four different levels of staffing. This investigation was carried out using a computer simulation of a shop with characteristics commonly found in group technology literature.

Today manpower models are required for the effective use of the available manpower for various objectives. Zanakis et al. [13] divided the manpower planning models into two categories – supply models, which analyze current manpower stocks and their projected flows to predict future stocks and demand models, which determine current or future manpower needs for given workload demands. They further viewed this at two levels – macro level, which considers aggregate numbers of people per category, used for annual or long range planning and at micro level, which was mainly used for job type and personnel matching assignments. Vassilou [16], Bratholomew and Forbes [14], and Leeson [15] developed manpower supply models dealing only with the internal flows such as promotions and wastage of the manpower and do not consider demand requirements and or organization structure.

Suer et al. [4] [5] [6] [7] proposed a two-phase hierarchical methodology to find the optimal manpower assignment and cell loads simultaneously. This methodology is valid for most labor-intensive manufacturing cells. Two tasks were focused upon-operator assignment to cells and cell loading. In phase 1, a mixed integer-programming model is used to generate alternative configurations and in phase 2, an integer-programming model is used to find the optimal operator assignment and cell loading. Two alternative approaches were proposed in phase 2 – quadratic assignment and integer programming models. Quadratic assignment model was not solved due to the solution difficulties. The impact of lot splitting was discussed in terms of setup times. It consisted of a similar two-phase approach but the mathematical models proposed were modified to allow for lot splitting and to setup times. The results were that lot splitting is advantageous when setup times are negligible but as the setup times were increased, the advantage of lot splitting diminished. Two mathematical models were proposed to perform cell loading and simultaneously determine the cell size. They tried to maximize the number of products that could be completed with the available capacity in all the periods. The experimentation results showed that the number of tardy jobs decreased as the number of employees in the cell increased. Bokhorst and Slomp [11] formulated an integer programming model to allocate operators to machines in the long term, so that absenteeism of an operator and fluctuation in demand can be effectively dealt with. This model also included the efficiency of operators. An illustrative example involving 6 operators and 9 machines was used. Nicolas et al. [20] focused on real size manpower allocation problems. The problem considered has multiple objectives and is of very large size. The results showed that the modified version of the adopted genetic annealing Meta heuristic gave better results than the conventional integer programming models.

Slomp and Molleman [17] discussed training and cross training policies and problems. A hierarchical approach was described for the assignment of tasks to workers and four heuristics were framed for the selection of a worker to be cross–trained next. An experimental study was done to test the effectiveness of cross-training and the associated policies in various circumstances. The results showed that the worker flexibility policy appears to be only slightly worse than the bottleneck redundancy policy with respect to the load of the bottleneck worker, the utilization of the workers and the standard deviation of the workload among the workers. Stewart et al. [18] developed a mathematical model for optimizing the cost of training the workforce depending on the production demand.

Gass [19] developed a military manpower supply model which used transition rate models to forecast personnel inventory. Though the model considers different grades, skills and experience among the workforce, it deals only with internal flow and wastage of workforce inventory. David [21] discussed the link between various forms of shop floor worker competences and the ability of manufacturing plants to compete on different forms of market attractiveness. Movement along a four level model of competence was showed ranging from operator proficiency to high levels of problem solving ability and how it affects the firm's ability to support improvements in different dimensions of competitiveness. This enabled the firms to consider their worker competence strategies in terms of their specific competitiveness rather than in some general form of abstraction. Cai et al. [22] considered the problem of scheduling staff with mixed skills by proposing a new genetic algorithm to find the desirable solutions. Ying [23] discussed the link between worker skills and wages. It was concluded that better skill allocation would help to narrow gender wage differentials. The overeducated could realize a wage gain by finding the right job, while the undereducated would gain by adjusting their skill level.

The dynamics of workforce skill levels has a considerable effect on cell performance. Workers tend to change their skill levels according to their learning and forgetting rates. Learning and forgetting has been extensively studies by psychologists. But very little research has been done considering them in a manufacturing environment. John et al. [33] discussed the role of three selected workforce management practices – confirmation of work teams, extent of cross training and deployment of workers in developing mix, volume and product flexibility. The effects of these practices are examined at individual operation levels and individual worker. Results indicated that large number of parallel work teams is needed when product variety is high and smaller number when complexity of the tasks is high. It was also observed that as complexity increased the effect of cross training and operator sharing diminishes mainly because of learning and forgetting effects on the workforce.

Nembhard et al. [32] [36] [37] [38] proposed a heuristic approach to assign workers to tasks based on individual learning rates. Two cases were considered – one with longer production run and the other with shorter production run. A simulation study is performed and results indicated that heuristic approach significantly improved the overall productivity. In long product life cycle, workers learned infrequently and in short product life cycle, workers learned frequently. The heuristic performed well in conditions where workers learned more gradually. Various forgetting models to measure the amount of forgetting following a break where both learning and forgetting occur intermittently. The models which performed better in predicting forgetting are identified. These models are important for management in determining labor costs, scheduling and setting time standards. A population based approach is also proposed to measure workforce learning and retention forgetting. Two facilities were considered where workers performed manual tasks and cognitive tasks, respectively. The results showed that workers who learned more gradually reached a higher steady rate of production. This correlation was highest for cognitive tasks. The workers who reached their steady state production rate quickly tend to have lower productivity rates. The correlation between rate of learning and rate of forgetting suggested that workers who learn more rapidly also tend to forget more rapidly during production breaks on the measured task. They also investigated several simulations where patterns of learning and forgetting affected the operating performance in an assembly line. This study did not include the type and range of tasks assigned to workers and it cannot be generalized to situations that are purely work based.

Yohanan et al. [31] compared learning and forgetting of mental and mechanical tasks. Appropriate models were fitted to learning and forgetting processes of the participant subjects performing a simple mechanical and mental task repetitively. After 50% repetition schedules, each participant was given a break of 2 to 6 weeks. The results showed that there is no correlation between the learning process of mechanical and mental tasks. The forgetting effect of the mental task was larger than that of mechanical task and the relearning process is relatively rapid for mechanical tasks.

Amit et al. [30] developed an algorithm to maximize the net present value of the total revenue collected at the delivery of the sub lots based on the learning curve theory. Here learning curve is stated as – when the total quantity of units produced doubles, the number of direct labor hours it takes to produce an individual unit declines by some constant percentage. Two approaches were used to test the algorithm – equal sub lot size and equal time interval considering two cases – no learning curve and the general case. The results showed that when the algorithm was used for the two approaches, it gave optimal results and the revenue became less sensitive to sub lot sizes as the learning effect increased. Mohamad et al. [34] developed a mathematical model and illustrated an example to investigate the effect of learning and forgetting in setups and product quality on the economic lot sizing problem. The results showed that the time to rework a defective piece reduces if production increases, conforming the learning effect and quality deteriorates as forgetting increases due to interruption in the production process.

Jeff et al. [39] presented a discrete event simulation model to understand the dynamics of learning and forgetting to accurately predict the variable manufacturing costs and capacity. The results showed that by increasing the usage of temporary workers, considerable savings can be done. The impact of the mix of permanent and temporary workers on manufacturing performance is studied by varying lot sizes and product complexity. As the product complexity increased, the need of high skilled permanent workers increased to perform the task. The improper usage of temporary workers in other situations increased the mean labor and quality costs because of the hidden costs of learning and forgetting.

Hemanth et al. [40] discussed issues related to modeling worker learning and forgetting effects in dual resource constrained systems. In the DRC system, worker was trained to process in two or three functionally different departments. Learning and relearning effects during the cross training period were captured for the worker by using the LFL (learning-forgetting-learning) model. The performance measures used were job processing time for the tenure of employment for the worker and the final efficiency of the worker. Batch processing times are computed to consider the numerical analysis. The results implicated that when forgetting rate is 85%, the only way to effectively train the worker while reducing the learning and relearning related efficiency losses is through the use of large batch sizes, which in turn reduced available flexibility. Jaber [35] developed a dual phase learning and forgetting model to predict task times. A numerical example was illustrated to examine the model. In the first phase, learning rate is varied according to the experience gained by the operator and the nature of task being performed. In the second case forgetting rate is based on workers learning rate, prior experiencing as well as the length of the interruption interval over which the worker experiences forgetting. The results implied that when a worker learns rapidly, he also tends to forget rapidly and they are less susceptible to forgetting when workers learning tasks are dominated by motor elements (mechanical) than complex tasks (cognitive).

CHAPTER 3. METHODOLOGY - CELL LOADING

This chapter discusses the general methodology used in this thesis. Various issues studied and problems considered in this thesis are explained. Finally, the methodology to generate alternative operator levels and determine the optimal cell sizes and loads by using standard times for all the problems is given.

3.1 General Methodology

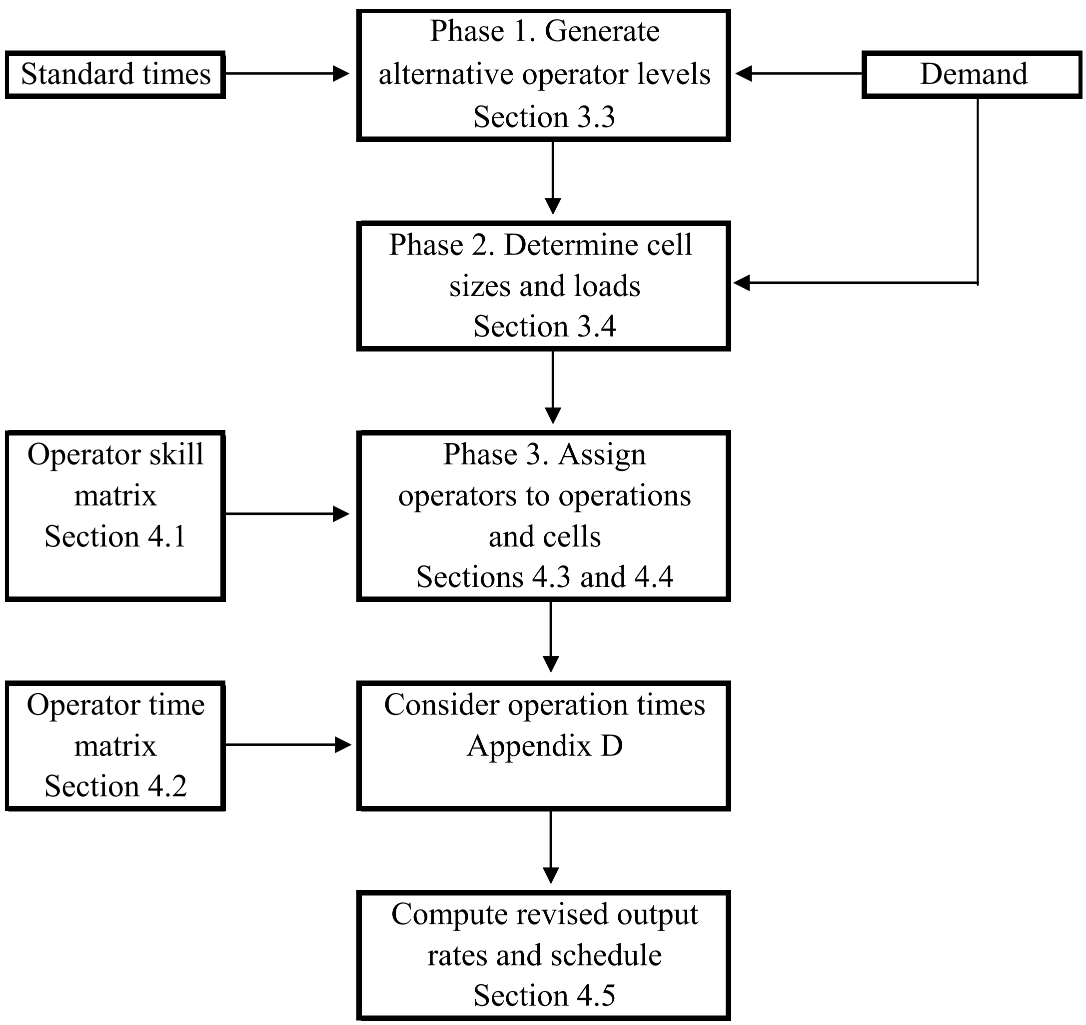
Labor intensive manufacturing cells are characterized by the presence of light weight, small, inexpensive machines and equipment where continuous operator attendance and involvement is required. So, the cell performance is not only affected by how the cells are loaded but is also affected by the performance of the operators. Thus cell loading issues like lot splitting and operator sharing, operator skill levels, operator – operation times, learning and forgetting rates, internal flow of the operators between the operations and cells become too important to avoid and as a result, operator levels in each cell, product assignment to the cells and operator assignment to operations directly affect the output that can be obtained from a cellular manufacturing system. This thesis focuses on three major tasks considering various single period and multi period issues.

- Determining the operator level, that is the total number of operators needed for each cell is affected by a number of factors. Minimum operator level is limited by the number of operations while the maximum operator level is limited to the available space, span of control, availability of machines and equipment or a combination of these factors. In labor intensive manufacturing cells, multiple manning for some operations become necessary when the number of operators assigned is greater than the number of operations, which is some operations will be performed on multiple identical machines by using multiple manning. After determining the operator levels needed, the next step is to determine the optimal number of operators to be assigned to each operation for a given operator level considering whether operator sharing is allowed or not allowed between cells and product operations. Mathematical models are used to determine the optimal number of operators to be assigned to each operation for given operator levels of each product independently for operator sharing not allowed and operator sharing allowed.

- Assigning products to cells is performed to meet the customer demand with minimum number of operators considering whether lot splitting is allowed or not allowed between the cells. Mathematical models are used to determine cell sizes and loads simultaneously for lot splitting not allowed and lot splitting allowed.
- Assigning operators to the operations according to their skill levels in single period analysis and by their learning and forgetting rates in multi period analysis. Three different approaches for these operator allocation decisions are proposed – maximizing the skills for all operations (Max approach), maximizing the skill for bottleneck operations and then maximizing the skill for non – bottleneck operations (Max – Max

approach), and maximizing the skill for bottleneck operations and then minimizing the skills for non – bottleneck operations (Max –Min approach).

Figure 3.1 gives the overview of the general methodology followed in this thesis.



.**Figure 3.1 General Overview of Methodology**

Each phase in the methodology passes through various assumptions considered for the experimentation and has different objectives. Various mathematical models and rules are used and proposed during all the phases in the methodology. Table 3.1 shows the solution techniques and objectives for all the phases in the methodology considering cell loading strategies and operator assignment approach to operations and cells.

Table 3.1 Solution techniques and objectives for all phases

Phase	3.3 Generate alternative operator levels	3.4 Determine cell sizes and loads	4.3 Assign operators to operations	4.4 Assign operators to cells
Solution technique	Mathematical models 3.3.1 Operator sharing not allowed 3.3.2 Operator sharing allowed	Mathematical models 3.4.1 Lotsplitting not allowed and operator sharing not allowed 3.4.2 Lot splitting allowed and operator sharing not allowed 3.4.3 Lot splitting not allowed and operator sharing allowed 3.4.4 Lot splitting allowed and operator sharing allowed	Mathematical models 4.3.1 Max approach 4.3.2 Max - Min approach 4.3.3 Max - Max approach	Rules 4.4.1 Random assignment 4.4.2 According to ratio of op. time to bottleneck time
Objective	Maximize Output rate	Minimize manpower level	Match skills needed with skills available	Match skills needed with skills available

In this thesis, single period analysis is done considering various issues like effect of variability in operator – operation times, impact of more operator skills and cell loading strategies like lot splitting and operator sharing. Multi – period analysis is done considering lot splitting and operator learning and forgetting rates. Three operator assignment approaches are used accordingly to study the issues. Table 3.2 shows the strategies used in various stages for each issue discussed in single and multi – period environment.

Table 3.2 Strategies in various stages for each issue in single and multi – period analysis

	Single - period analysis				Multi - period analysis
	Effect of Variability	Impact of Operator skills	Comparison of Cell loading strategies Strategies	Comparison of operator assignment approches	Comparison of op. assignment approches and effect of op. learning and forgetting rates
Generate alternative operator levels	Operator sharing not allowed	Operator sharing not allowed	Op. sharing not allowed and op. sharing allowed	Op. sharing not allowed	Op. sharing not allowed
Determine cell sizes and loads	Lot splitting not allowed	Lot splitting not allowed	Lot splitting not allowed and Lot splitting allowed	Lot splitting not allowed	Lot splitting allowed
Number of skills per operator	2	2 and 3	2	2	2
Levels of variance	4 (5%, 10%, 15% and 20%)	15%	15%	15%	15%
Operator assignment approach to operations	Max approach	Max approach	Max approach	Max, Max - Max and Max - Min approaches	Max and Max - Min approaches
Operator assignment approach to cells	Ratio of op.time to bottleneck time	Ratio of op.time to bottleneck time	Ratio of op.time to bottleneck time	Random assignment (max) and Ratio of op.time to bottleneck time	Ratio of op.time to bottleneck time
Number of alternative operator levels	2 (15 and 20 Op.)	2 (15 and 20 Op.)	2 (15 and 20 Op.)	3 (15, 20 and 25 Op.)	6 (15, 16, 17, 18, 19 and 20 Op.)
Number of cells	2	2	2	3	2

3.2 Problems Considered

The problems considered in this thesis have been observed in various manufacturing companies such as jewelry, electronic component assembly, electromechanical assembly, medical devices, apparel and sewing industry, etc. The time taken by a machine to complete the specific operation for a product is called operation time. The operation times and weekly demand are generated randomly based on a random uniform distribution. Three problems are considered in this thesis to perform single period analysis and multi period analysis. It is assumed that reasonable alternative operator levels have been determined, capacity analysis has been carried out and the number of cells has been determined. Table 3.3 shows the problems considered to study the various issues in a single and multi – period environment.

Table 3.3 Problems considered for the issues studied

		Problem 1 5 operations 10 products	Problem 2 5 operations 30 products	Problem3 5 operations 10 products
Single - period analysis	Effect of Variability	✓		
	Impact of Operator skills	✓		
	Comparison of cell loading strategies	✓		
	Comparison of operator assignment approches		✓	
Multi - period analysis	Comparison of operator assignment approches			✓
	Impact of opeartor learning and forgetting rates on operator skills			✓

Problem 1 consists of 10 products and 5 operations for each product. For single period analysis, alternative operator levels have been established as 15 and 20 and number of cells needed has been established as 2. Table 3.4 represents the operation times and weekly demand data for problem 1. The processing times of operation 1, operation 2, operation 3, operation 4 and operation 5 for all products are randomly generated from a random uniform distribution in the intervals [.04, .09], [.28, .45], [.37, 1.18], [.47, .88] and [.18, .45], respectively. The weekly demand for all products is randomly generated from a random uniform distribution in the interval [2200, 7500]. Problem 1 is considered to test the effect of variability in operator – operation times, impact of having more operator skills and to compare the performance of the cells considering cell loading strategies like lot splitting and operator sharing using Max Operator assignment approach.

Table 3.4 Operation Times (min) and Demand for Products for Problem 1

	Operations					
Product	**Op. 1**	**Op. 2**	**Op. 3**	**Op. 4**	**Op. 5**	**Weekly Demand (units)**
1	0.07	0.45	0.37	0.88	0.38	3500
2	0.05	0.29	0.62	0.74	0.38	7500
3	0.06	0.29	1.18	0.86	0.18	3400
4	0.04	0.31	0.55	0.47	0.4	2700
5	0.08	0.41	0.43	0.74	0.43	2200
6	0.07	0.32	1.18	0.55	0.45	4000
7	0.09	0.37	0.46	0.49	0.26	4500
8	0.08	0.28	0.49	0.61	0.29	2200
9	0.04	0.34	0.81	0.62	0.34	2300
10	0.07	0.43	0.74	0.87	0.43	3000

Problem 2 consists of 30 products and 5 operations for each product. For single period analysis, alternative operator levels have been established as 15, 20 and 25. Number of cells has been established as 3. Table 3.5 represents the operation times and weekly demand data for the problem. The processing times of operation 1, operation 2, operation 3, operation 4 and operation 5 for all products are randomly generated from a random uniform distribution in the intervals [.04, .11], [.28, .46], [.37, 1.18], [.31, 1.36] and [.18, .45], respectively. The weekly demand for all products is randomly generated from a random uniform distribution in the interval [1200, 3000]. Problem 2 is considered to compare the three proposed operator assignment approaches in the larger version of the problem data.

Table 3.5 Operation Times (min) and Demand for Problem 2

	Operations					
Product	**Op. 1**	**Op. 2**	**Op. 3**	**Op. 4**	**Op. 5**	**Weekly Demand (units)**
1	0.07	0.45	0.37	0.88	0.38	2500
2	0.05	0.29	0.62	0.74	0.38	1800
3	0.06	0.29	1.18	0.86	0.18	3000
4	0.04	0.31	0.55	0.47	0.4	1500
5	0.08	0.41	0.43	0.74	0.43	1200
6	0.07	0.32	1.18	0.55	0.45	2600
7	0.09	0.37	0.46	0.49	0.26	2400
8	0.08	0.28	0.49	0.61	0.29	1900
9	0.04	0.34	0.81	0.62	0.34	1300
10	0.07	0.43	0.74	0.87	0.43	2600
11	0.1	0.29	0.92	0.64	0.19	2800
12	0.12	0.37	0.92	1.29	0.26	1500
13	0.05	0.34	1.05	0.94	0.34	1900
14	0.08	0.39	0.98	1.34	0.35	2200
15	0.06	0.41	0.94	0.94	0.43	2800
16	0.12	0.46	0.39	0.61	0.27	1400
17	0.08	0.37	0.92	0.35	0.23	1600
18	0.04	0.29	0.98	1.18	0.34	2700
19	0.09	0.41	0.61	0.39	0.43	3000
20	0.08	0.38	0.59	0.81	0.21	1600
21	0.07	0.44	0.61	0.91	0.35	2900
22	0.11	0.38	1.15	0.64	0.38	1000
23	0.08	0.31	0.91	0.59	0.43	1400
24	0.09	0.39	0.64	0.31	0.21	1900
25	0.04	0.44	0.96	1.29	0.29	2200
26	0.08	0.29	1.15	0.84	0.39	2800
27	0.06	0.37	0.81	0.64	0.44	1000
28	0.04	0.39	0.76	0.29	0.26	1600
29	0.06	0.44	0.82	1.36	0.35	2400
30	0.09	0.37	0.64	0.94	0.45	3000

Problem 3 consists of 10 products and 5 operations for each product. Operation times remain the same as in problem 1. For multi - period analysis, alternative operator levels have been established as 15, 16, 17, 18, 19 and 20 for each period and number of cells needed has been established as 2. Sixteen periods have been considered to analyze. Table 3.6 represents the product demand and total demand for each period. Each product demand is randomly generated by keeping the demand in the first period as mean and deviation not to exceed more than 1000 units. Problem 3 is considered to test the effect of operator learning and forgetting rates on operator skills and cell performance using two different proposed operator assignment approaches (Max and Max – Min).

Table 3.6 Product Demand and Total Demand for each Period

Period	Product Demand										Total
	1	2	3	4	5	6	7	8	9	10	Demand
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

3.3 Generating Alternative Configurations

In this thesis, it is assumed that the number of alternative operator levels needed for each cell is determined. The next step is to find the optimal number of operators to be assigned to each operation for a given operator level. One major cell loading strategy is operator sharing. The basic advantages of allowing operator sharing between operations and cells are increase in the production rate and decrease in the number of operators needed for the cell. The major disadvantage of allowing operator sharing is it becomes too complex when assigning the operators to the operations. Figure 3.2 explains the concept of operator sharing. This thesis assumes that the operators can be shared between various operations and cells in the following three ways. A) Operator 1 is shared between two different operations (Machine 2 and Machine 3) in the same cell. B) Operator 2 is shared between two cells but performs the same operation (Machine 1). C) Operator 3 is shared between two cells and performs two different operations (Machine 2 and Machine 3).

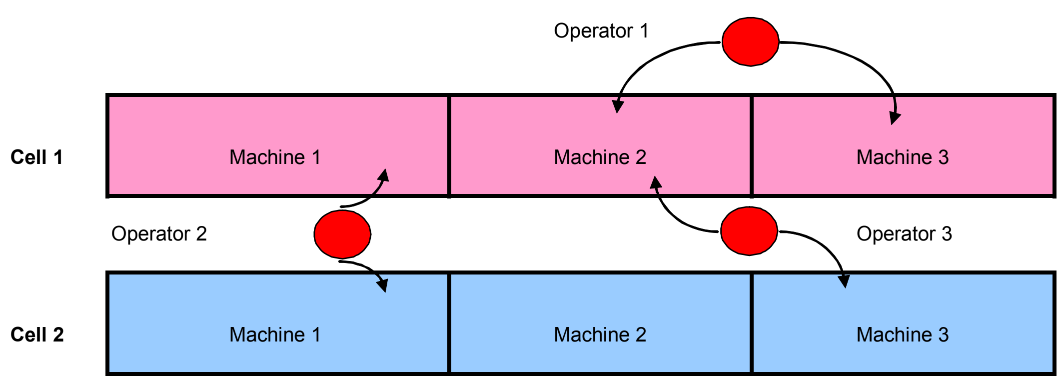


Figure 3.2 Diagrammatic representation of the concept of operator sharing

3.3.1 Operator Sharing Not Allowed

The following mixed integer mathematical model is used [4] to determine the optimal number of operators to be assigned to each operation for a given operator level. The model is applied to each product and alternative operator level combination independently. The objective function maximizes output rate as given in equation 1. The equation 2 guarantees that each operation is assigned enough operators to accomplish the maximum output rate. Equation 3 establishes the upper limit on the number of operators for each operation whereas equation 4 gives the restriction on total number of operators. m_{ij}, integer and positive for all j represents operator sharing not allowed for operator level for operation j of product i.

Objective Function:

$$\text{Max } Z_i = R_i \qquad (1)$$

Subject to:

$$((m_{ij}) * (1/t_{ij}) - R_i \geq 0 \qquad j = 1, 2, 3\ldots s \qquad (2)$$

$$m_{ij} \leq U_{ij} \qquad j = 1, 2, 3\ldots s \qquad (3)$$

$$\sum_{j=1}^{s} m_{ij} \leq W \qquad (4)$$

m_{ij}, integer and positive for all j

R_i, integer and positive

Where,

R_i hourly production rate for all i

m_{ij} operator level for operation j of product i

U_{ij} upper limit for operator level for operation j of product i

t_{ij} unit standard time for operation j of product i

W upper bound on the total number of available operators

s number of operations

The model is then solved in ILOG OPL studio. Figure 3.3 shows the model file and the optimal solution. The number of operators needed for the operations are declared as integer variables because operator sharing is not allowed and the hourly production rate is declared as float variable. The range of each variable along with a Boolean are specified.

```
var float+ R ;
var int+ m1 in 0..maxint;
var int+ m2 in 0..maxint;
var int+ m3 in 0..maxint;
var int+ m4 in 0..maxint;
var int+ m5 in 0..maxint;
var float+ z ;
maximize z
subject to
{
z = R;
(m1/0.07) - R >= 0;
(m2/0.45) - R >= 0;
(m3/0.37) - R >= 0;
(m4/0.88) - R >= 0;
(m5/0.38) - R >= 0;
m1 <= 3;
m2 <= 7;
m3 <= 12;
m4 <= 10;
m5 <= 12;
m1 + m2 + m3 + m4 + m5 <= 25;
};

Optimal Solution with Objective Value: 10.8108
R = 10.8108
m1 = 1
m2 = 5
m3 = 4
m4 = 10
m5 = 5
z = 10.8108
```

Figure 3.3 ILOG OPL model when operator sharing is not allowed

Appendix A1, A2 and A3 represent the results of the application of the model for all products and alternative levels for problem 1, problem 2 and problem 3, respectively. The P_{ijk} values are obtained by dividing demand figures by corresponding production rates.

These values are used as an input to find the cell sizes and loads. Appendix A4 provides the P_{ijk} values for multi - period analysis.

3.3.2 Operator Sharing Allowed

This approach tries to overcome the difficulties associated with not allowing operator sharing between operations and cells. In this model, the objective function (Equation 1) and constraints (Equation 2 and Equation 3) remain the same whereas Equation 4 is modified as

$$\sum_{j=1}^{s} m_{ij} \leq W \tag{5}$$

m_{ij}, real and positive for all j

The model is then solved in ILOG OPL studio. All the variables are declared as float variables. Figure 3.4 shows the sample model file and optimal solution. Problem 1 is considered to compare the effect of operator sharing in cellular manufacturing systems. The range of each variable along with a Boolean are specified. Appendix A5 represents the results of the application of the model for all products and alternative levels for problem 1. The P_{ijk} values are obtained by dividing demand figures by corresponding production rates. These values are used as an input to find the cell sizes and loads.

```
var float+ R ;
var float+ m1 ;
var float+ m2 ;
var float+ m3 ;
var float+ m4 ;
var float+ m5 ;
var float+ z ;
maximize z
subject to
{
z = R;
(m1/0.07) - R >= 0;
(m2/0.45) - R >= 0;
(m3/0.37) - R >= 0;
(m4/0.88) - R >= 0;
(m5/0.38) - R >= 0;
m1 <= 3;
m2 <= 7;
m3 <= 12;
m4 <= 10;
m5 <= 12;
m1 + m2 + m3 + m4 + m5 <= 15;
};

Optimal Solution with Objective Value: 6.9767
R = 6.9767
m1 = 0.4883
m2 = 3.1395
m3 = 2.5814
m4 = 6.1395
m5 = 2.6512
z = 6.9767
```

Figure 3.4 ILOG OPL model when operator sharing is allowed

3.4 Determining Cell Sizes and Loads

Once the optimal production rates, number of operators and P_{ijk} values for the alternative configurations of all products are found, the next step is to determine the cell sizes and cell loads. Cell size means the number of operators to be assigned to each cell and cell loading means product assignment to each cell. This can be done in two ways – allowing lot splitting and not allowing lot splitting between the available cells. The basic advantage of lot splitting is that it breaks orders with high total processing times into smaller lots and offers the ability to move parts more quickly through the production process. Lot splitting is not necessarily always beneficial. One of the major disadvantages is material handling costs could skyrocket and the likelihood of a batch getting misplaced increases dramatically with the number of such batches in the shop. The existence of setup times may counteract the benefits of lot splitting. In this thesis setup times are assumed to be negligible.

3.4.1 Lot Splitting Not Allowed and Operator Sharing Not Allowed

The following integer programming formulation is used [4] to determine cell sizes and loads simultaneously. The objective function minimizes the total number of operators as given in equation 6. Each product must be assigned to a cell as shown in equation 7. Equation 8 guarantees that each cell will have at most one configuration (i.e., operator level). Finally, equation 9 establishes the upper limit on available capacity in each cell.

The available capacity for problem 1 and problem 2 is assumed to be 2200 min, and 2300 min, respectively.

Objective Function:

$$\text{Min } Z = \sum_{j=1}^{m} \sum_{k=1}^{a_j} b_{jk} * Y_{jk} \qquad (6)$$

Subject to:

$$\sum_{j=1}^{m} \sum_{k=1}^{a_j} X_{ijk} = 1 \qquad i = 1, 2, 3 \ldots s \qquad (7)$$

$$\sum_{k=1}^{a_j} Y_{jk} \leq 1 \qquad j = 1, 2, 3 \ldots m \qquad (8)$$

$$\sum_{i=1}^{n} p_{ijk} * X_{ijk} \leq h * Y_{jk} \qquad j = 1, 2, 3 \ldots m;\ k = 1, 2, 3 \ldots a_j \qquad (9)$$

X_{ijk} and Y_{jk} are (0, 1)

Where,

Y_{jk} alternative configuration k for cell j

X_{ijk} product i assigned to cell j with configuration k

p_{ijk} time required to produce product i in cell j with configuration k

b_{jk} manpower required for configuration k in cell j

a_j number of alternative configurations for cell j

m number of cells

n number of products

h time available in a period (week)

The above model is solved in ILOG OPL studio for problem 1 and problem 2. All variables are declared as integer variables. The complete OPL model and the optimal solution for determining cell sizes and cell loads for problem 1 and problem 2 are given in Appendix B1 and B5, respectively.

Figure 3.5 and Figure 3.6 represent the Gantt charts corresponding to the optimal solution to the problem 1 for 2200 minute - weekly work period and problem 2 for 2300 minute - weekly work period, respectively.

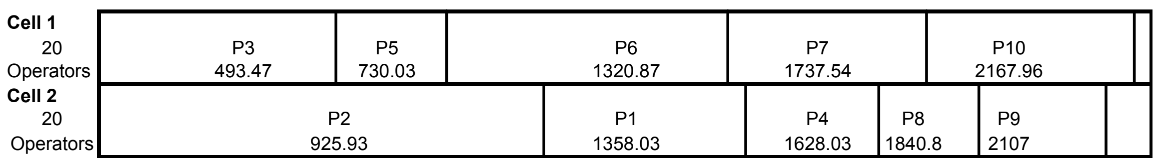


Figure 3.5 Gantt chart for the optimal solution to Problem 1 – Lot splitting not allowed and Operator sharing not allowed

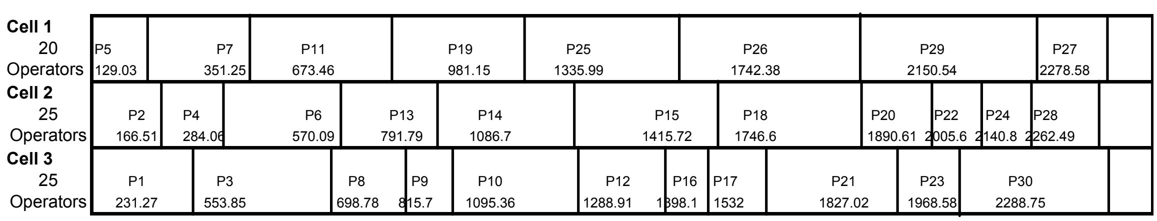


Figure 3.6 Gantt chart for the optimal solution to Problem 2 – Lot splitting not allowed and Operator sharing not allowed

3.4.2 Lot Splitting Allowed and Operator Sharing Not Allowed

This approach tries to overcome the difficulties associated with not allowing lot splitting between operations and cells. In this model, the objective function (Equation 6) and constraints (Equation 8 and Equation 9) remain the same whereas Equation 7 is modified as

$$\sum_{j=1}^{m}\sum_{k=1}^{a_j} X_{ijk} = 1 \qquad I = 1, 2, 3 \ldots s \qquad (10)$$

X_{ijk}, real and positive for each product i assigned to cell j with configuration k

The model is then solved in ILOG OPL studio. X_{ijk} variables are declared as float variables. The range of each variable along with a Boolean are specified. Problem 1 is considered to compare the effect of lot splitting and operator assignment approach (Max approach) in cellular manufacturing systems. Problem 3 is considered to compare the effect of operator learning and forgetting skills using operator assignment approaches (Max and Max – Min) with lot splitting allowed between cells. Figure 3.7 represents the Gantt charts for the optimal solution to problem 1 (Lot splitting allowed) and Figure 3.8 represents the Gantt charts for the optimal solution to problem 3 consisting of 16 periods. The complete ILOG OPL studio sample model and optimal solutions for determining cell sizes and loads simultaneously considering lot splitting is allowed and operator sharing is not allowed for problem 1 is given in Appendix B2 and for problem 3 (16 periods) is provided in Appendix C.

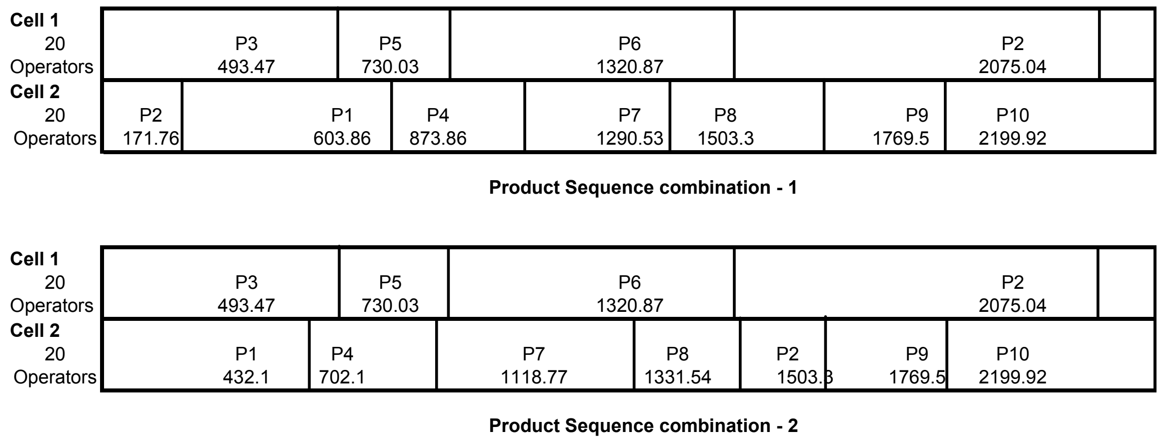
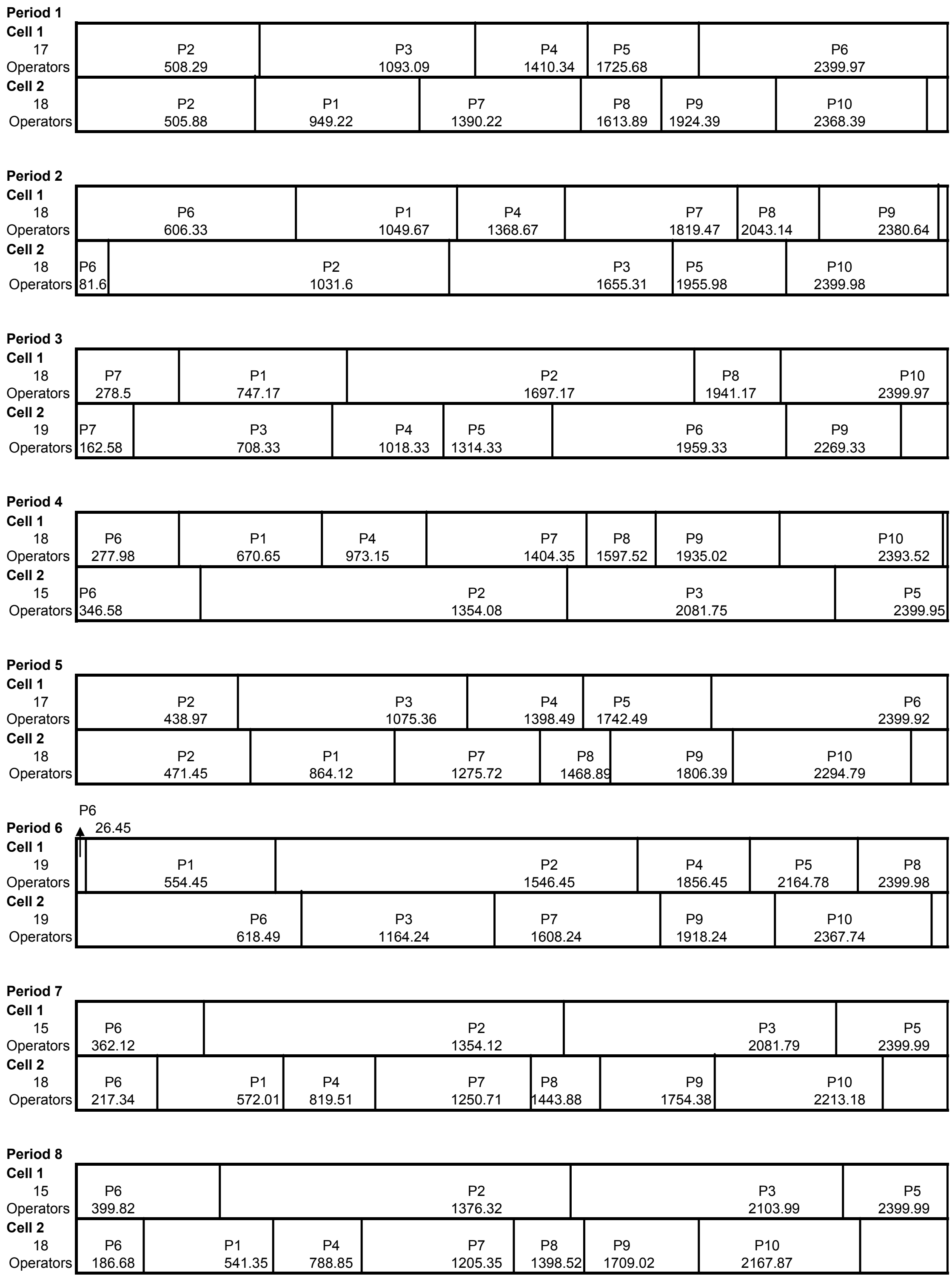


Figure 3.7 Gantt chart for the optimal solution to Problem 1 – Lot splitting allowed and Operator sharing not allowed

Two different product sequences are provided based on the assumption that the production of the product being splitted between the cells can be started at around the same time or at different times. It should be noted that the objective of this model is to minimize the number of operators (not the makespan).



Period 1
Cell 1
17
Operators
P2 508.29
P3 1093.09
P4 1410.34
P5 1725.68
P6 2399.97
Cell 2
18
Operators
P2 505.88
P1 949.22
P7 1390.22
P8 1613.89
P9 1924.39
P10 2368.39
Period 2
Cell 1
18
Operators
P6 606.33
P1 1049.67
P4 1368.67
P7 1819.47
P8 2043.14
P9 2380.64
Cell 2
18
Operators
P6 81.6
P2 1031.6
P3 1655.31
P5 1955.98
P10 2399.98
Period 3
Cell 1
18
Operators
P7 278.5
P1 747.17
P2 1697.17
P8 1941.17
P10 2399.97
Cell 2
19
Operators
P7 162.58
P3 708.33
P4 1018.33
P5 1314.33
P6 1959.33
P9 2269.33
Period 4
Cell 1
18
Operators
P6 277.98
P1 670.65
P4 973.15
P7 1404.35
P8 1597.52
P9 1935.02
P10 2393.52
Cell 2
15
Operators
P6 346.58
P2 1354.08
P3 2081.75
P5 2399.95
Period 5
Cell 1
17
Operators
P2 438.97
P3 1075.36
P4 1398.49
P5 1742.49
P6 2399.92
Cell 2
18
Operators
P2 471.45
P1 864.12
P7 1275.72
P8 1468.89
P9 1806.39
P10 2294.79
P6 26.45
Period 6
Cell 1
19
Operators
P1 554.45
P2 1546.45
P4 1856.45
P5 2164.78
P8 2399.98
Cell 2
19
Operators
P6 618.49
P3 1164.24
P7 1608.24
P9 1918.24
P10 2367.74
Period 7
Cell 1
15
Operators
P6 362.12
P2 1354.12
P3 2081.79
P5 2399.99
Cell 2
18
Operators
P6 217.34
P1 572.01
P4 819.51
P7 1250.71
P8 1443.88
P9 1754.38
P10 2213.18
Period 8
Cell 1
15
Operators
P6 399.82
P2 1376.32
P3 2103.99
P5 2399.99
Cell 2
18
Operators
P6 186.68
P1 541.35
P4 788.85
P7 1205.35
P8 1398.52
P9 1709.02
P10 2167.87

Figure 3.8 Contd.

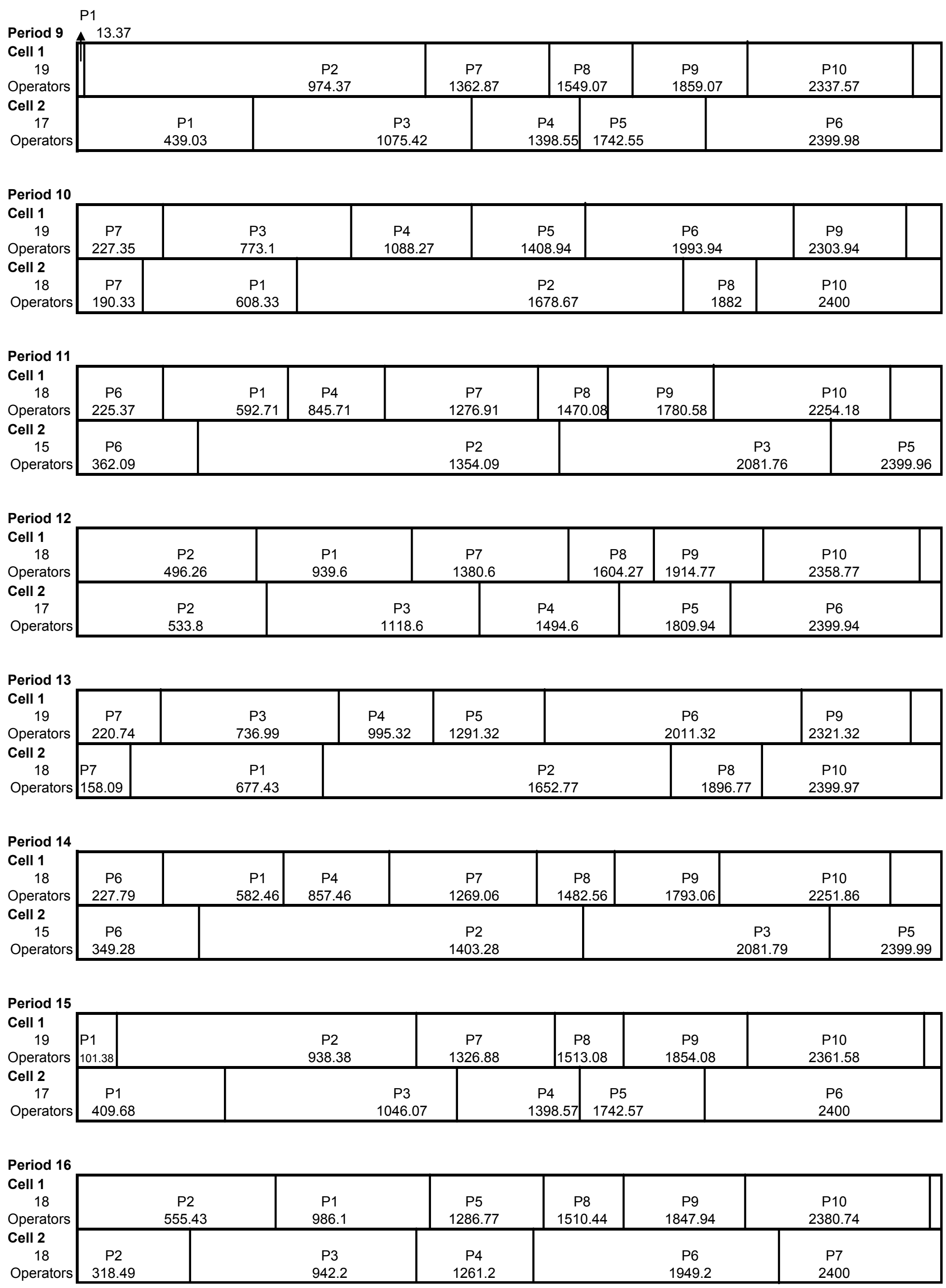


Figure 3.8 Gantt charts for the optimal solution to problem 3 for Multi - Period Analysis

3.4.3 Lot splitting not allowed and Operator sharing allowed

This model tries to overcome the difficulties associated with not allowing operator sharing. In this model, the objective function (Equation 6) and constraints (Equation 7, Equation 8 and Equation 9) remain the same whereas the P_{ijk} values are changed (Appendix A5). The model is then solved in ILOG OPL studio. Problem 1 is considered to test the effect of operator sharing in cell performance. The complete OPL model for this case is given in Appendix B3. Figure 3.9 represents the gantt chart for the optimal solution to problem 1.

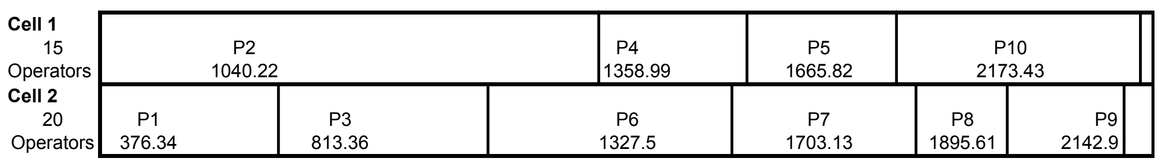


Figure 3.9 Gantt chart for the optimal solution to problem 1 - operator sharing allowed and lot splitting not allowed

It can be seen that the total number of operators needed is less when operator sharing is allowed without compromising the output rate. The total number of operators in the cellular system when operator sharing is not allowed is 40 (20 + 20). The total number of operators in the cellular system when operator sharing is allowed is 35 (15 + 20).

3.4.4 Lot splitting allowed and Operator sharing allowed

This model tries to overcome the difficulties associated with not allowing operator sharing and lot splitting in a cellular manufacturing system. In this model, the objective function (Equation 6) and constraints (Equation 8, Equation 9 and Equation 10) remain the same whereas the P_{ijk} values are changed (Appendix A5). The model is then solved in ILOG OPL studio. The complete OPL model for this case is given in Appendix B4. Problem 1 is considered to test the effect of operator sharing in cell performance. Figure 3.10 represents the gantt chart for the optimal solution to problem 1.

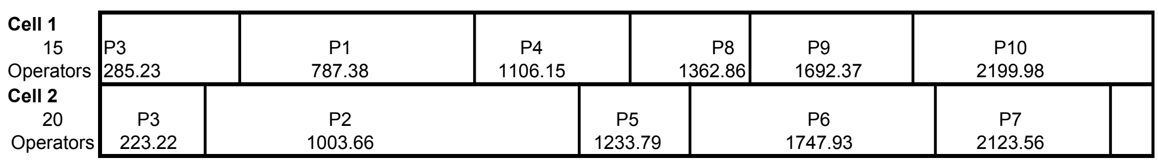


Figure 3.10 Gantt chart for the optimal solution to problem 1 - operator sharing allowed and lot splitting allowed

It should be noted that the objective is to minimize the number of operators (not the makespan) while applying the model for lot splitting and operator sharing.

CHAPTER 4. METHODOLOGY - OPERATOR ASSIGNMENT

In this thesis, various approaches are proposed to assign operators to operations based on their skills and, learning and forgetting rates. This chapter initially provides the framework to allocate skills to operators. Three approaches are proposed to assign the operators to operations. Finally, the procedures to allocate operators to cells and to calculate the revised output rates are provided.

4.1 Operator Skill Levels

After determining the cell sizes and cell loads for all the problems, the operator skills form the basis for operator assignment. Performance rating is probably the most important step in the entire time study procedure. It is a technique for equitably determining the time required to perform a task by the normal operator after the observed values of the operation under study have been recorded. Differences in inherent knowledge, physical capacity, health, trade knowledge, physical dexterity and training cause the operator to outperform another consistently and progressively [24].

The skill levels are grouped into nine categories as shown in Figure 4.1 where level 5 represents the average skill, level 1 represents the best and level 9 is the worst. This is an assumption used in this thesis. No empirical work has been done to verify these results. Some industries use four skill levels. By considering probabilities, five skill groups have more chance which is not significantly different than what has been observed in some industries justifying the assumption the division of operators into nine different skill groups.

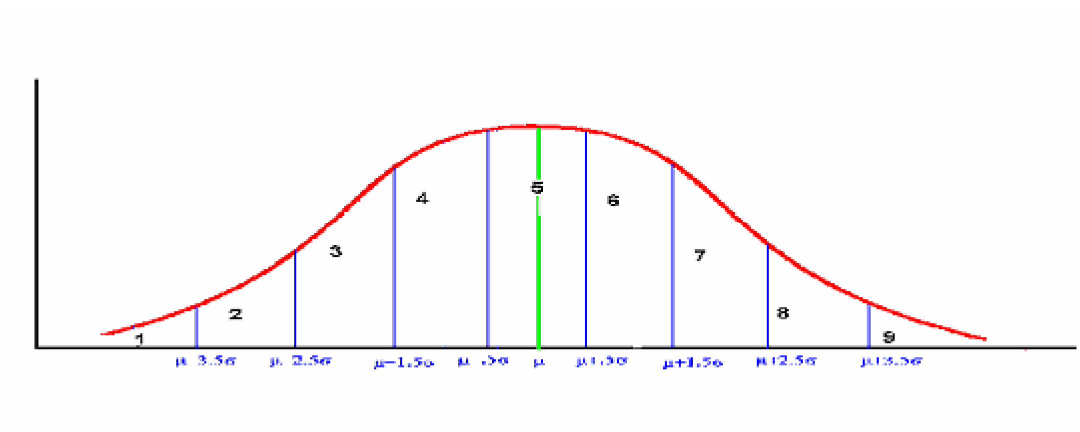


Figure 4.1 Normal Distribution curve for skills

The intervals for these skill levels along with corresponding probabilities are provided in Table 4.1.

Table 4.1 Skill Levels and Probabilities

Skill	Time	Probability
1	$\mu - 4\sigma$	0.0002
2	$\mu - 3\sigma$	0.006
3	$\mu - 2\sigma$	0.0606
4	$\mu - \sigma$	0.2417
5	μ	0.383
6	$\mu + \sigma$	0.2417
7	$\mu + 2\sigma$	0.0606
8	$\mu + 3\sigma$	0.006
9	$\mu + 4\sigma$	0.0002

Problem 1 is considered to compare the performance of the cell when more skills are available and also the cell loading strategies like lot splitting and operator sharing using the operator assignment approach (Max). The total number of operators is assumed to be 40. Two operator skill level matrices are provided. In Table 4.3, initially each operator is randomly assigned uniformly to two operations and then skills are allocated randomly according to the normal distribution and probabilities. Table 4.4 is an extension to Table 4.3 with each operator randomly assigned uniformly to one operation of the three operations left and then allocating the skill according to the normal distribution.

Problem 2 is considered to compare the operator assignment approaches proposed in this thesis to a larger version of the problem. The total number of operators is assumed to be 70. Table 4.5 represents the operator skill levels for problem 2. Assignment of operations and skill levels procedure is similar to the one used for Table 4.3.

Problem 3 is considered to perform a multi - period analysis. The total number of operators is assumed to be 40. It is also assumed that 33 operators work on a permanent basis and the remaining 7 operators work on temporary basis. The operator skill levels for the first period are similar to the skill levels used for problem 1 (Table 4.3). Operator skill level matrix keeps changing for every period according to the operator learning and forgetting rates and the operator assignment approach used (Max and Max – Min). When an operator works on a single operation continuously for a certain amount of time, his skill level improves. Similarly his skill level decreases accordingly. Table 4.2 represents the time taken by an operator to improve or deteriorate his skill level along with a probability. Once the operator reaches the above average skill, he tends to take more time to improve or decrease his skill. The probability of an operator to improve or deteriorate his skill level decreases as the skill level increases. The number of weeks required in the learning process can be related to mechanical learning and the probability to the mental (cognitive) learning.

Table 4.2 Learning and Forgetting Matrix

Learning				Forgetting			
Skill Level		Weeks	Prob.	**Skill Level**		Weeks	Prob.
From	To			From	To		
9	8	4	0.75	8	9	5	0.75
8	7	4	0.7	7	8	5	0.7
7	6	4	0.65	6	7	5	0.65
6	5	4	0.6	5	6	5	0.6
5	4	6	0.5	4	5	7	0.5
4	3	8	0.4	3	4	9	0.4
3	2	10	0.3	2	3	11	0.3
2	1	12	0.25	1	2	13	0.25

Table 4.3 Operator Skill Levels (2 skills – Problem 1)

	Operations				
Operator	**1**	**2**	**3**	**4**	**5**
1				5	5
2		4	5		
3		5	3		
4		5		4	
5			6		7
6		6	6		
7	7		5		
8		7	6		
9		5		4	
10			6		2
11	3			1	
12		5	7		
13				6	6
14		5	4		
15			5	4	
16		9		4	
17		8	7		
18	5		4		
19			6		6
20		4		4	
21			6	8	
22				4	4
23			4	2	
24				5	5
25		6	6		
26		5		5	
27	6			4	
28			5		5
29		3		6	
30			2		3
31			7		5
32				4	4
33	6			3	
34			5	6	
35				5	7
36		1		5	
37			5		5
38			5	4	
39				5	5
40				5	5

Table 4.4 Operator Skill Levels (3 skills – Problem 1)

	Operations				
Operator	**1**	**2**	**3**	**4**	**5**
1			1	5	5
2		4	5	8	
3		5	3	6	
4		5	5	4	
5			6	9	7
6		6	6	2	
7	7		5	8	
8		7	6		4
9		5		4	6
10			6	8	2
11	3	1		1	
12		5	7	6	
13	8			6	6
14		5	4	1	
15		8	5	4	
16	1	9		4	
17		8	7	9	
18	5		4	4	
19			6	9	6
20	5	4		4	
21		8	6	8	
22			6	4	4
23			4	2	7
24			3	5	5
25	4	6	6		
26	6	5		5	
27	6		1	4	
28			5	9	5
29	9	3		6	
30	3		2		3
31		6	7		5
32	5			4	4
33	6		1	3	
34	4		5	6	
35	8			5	7
36		1		5	4
37		6	5		5
38		1	5	4	
39		6		5	5
40			4	5	5

Table 4.5 Operator Skill Levels (Problem 2)

	Operations						Operations				
Operator	**1**	**2**	**3**	**4**	**5**	**Operator**	**1**	**2**	**3**	**4**	**5**
1				5	5	**36**		1		5	
2		4	5			**37**			5		5
3		5	3			**38**			5	4	
4		5		4		**39**				5	5
5			6	7		**40**				5	5
6		6	6			**41**			3		6
7	7		5			**42**				5	1
8		7	6			**43**	5				4
9		5		4		**44**		6		6	
10			6		2	**45**		7	5		
11			3	1		**46**			4		6
12		5	7			**47**				4	5
13			6	6		**48**	4		6		
14		5	4			**49**		5	4		
15			5	4		**50**			9		4
16		9		4		**51**	2			4	
17		8	7			**52**		6	6		
18			4	5		**53**			6	4	
19			6	6		**54**		4	5		
20		4		4		**55**		5	5		
21			6	8		**56**	6		4		
22			4	4		**57**			1	4	
23			4	2		**58**				6	2
24				5	5	**59**			4		5
25		6	6			**60**			6	5	
26		5		5		**61**				5	8
27			6	4		**62**		4		3	
28			5		5	**63**				1	3
29		3		6		**64**			6		5
30			2	3		**65**			5	5	
31			7		5	**66**	4		7		
32				4	4	**67**			5	9	
33	6			3		**68**			4		4
34			5	6		**69**				4	5
35				5	7	**70**			7	5	

4.2 Operator Time Matrix

Operator – Operation time changes based on the operator skill levels. After the assignment of operators using the proposed approaches, operation times are calculated according to the operator skill levels. Table 4.6 provides an example for product 1 with operation times for different skill levels with a standard deviation of 15% of the mean. The σ for operation 1 for product 1 = .07*.15 = .0105. As the skill level increases by 1 level (5 – 4), the operator – operation time = .07 - σ = .0595.

Table 4.6 Operation Times for Different Skill levels with σ = .15 of mean

	Operations				
Product	**1**	**2**	**3**	**4**	**5**
1	0.07	0.45	0.37	0.88	0.38
Std. Dev.	0.0105	0.0675	0.0555	0.132	0.057
Skill Level					
1	0.028	0.18	0.148	0.352	0.152
2	0.0385	0.2475	0.2035	0.484	0.209
3	0.049	0.315	0.259	0.616	0.266
4	0.0595	0.3825	0.3145	0.748	0.323
5	0.07	0.45	0.37	0.88	0.38
6	0.0805	0.5175	0.4255	1.012	0.437
7	0.091	0.585	0.481	1.144	0.494
8	0.1015	0.6525	0.5365	1.276	0.551
9	0.112	0.72	0.592	1.408	0.608

Problem 1 is considered to test the effect of variability in operator – operation times on cell performance. Standard Deviations of 5%, 10%, 15% and 20% of the mean are used. A standard deviation of 15% is used for all other experimentations. Appendix D provides the operation times for different skill levels for all the products.

4.3 Operator Assignment Models

After determining the operator levels and assigning the products to the cells, operators have to be assigned to the possible product combinations among the cells. Appendix E provides all the possible product combinations and number of operators to be assigned to each operation for all the cases. Three different approaches are discussed for operator assignment – Max, Max – Min and Max – Max. Figure 4.2 shows the framework for the different operator assignment approaches and are explained in detail in the following sections.

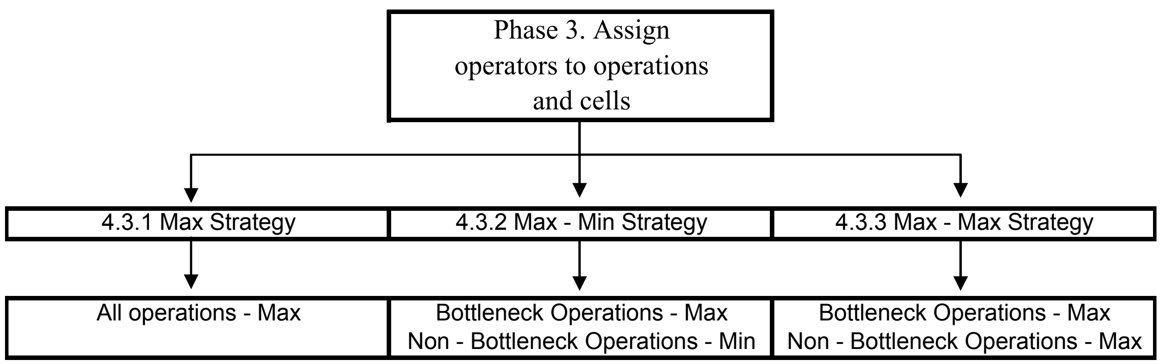


Figure 4.2 Framework for operator assignment approaches

4.3.1 Max Approach

The following classical assignment model is used to perform the task. The objective is to match the skills needed with the skills available at minimum cost (equation 11). The equation 12 guarantees that each operator is assigned to an operation and similarly equation 13 ensures that each operation is assigned required number of operators.

Objective Function

$$\text{Min } Z = \sum_{i=1}^{r} \sum_{j \in f_i} c_{ij} O_{ij} \qquad (11)$$

Subject to

$$\sum_{j \in f_i} O_{ij} = 1 \qquad i = 1, 2, 3 \ldots r \qquad (12)$$

$$\sum_{i \in b_j} O_{ij} = d_j \qquad j = 1, 2, 3 \ldots s \qquad (13)$$

O_{ij} (0, 1)

Where,

O_{ij} operator i assigned to operation j

c_{ij} skill level of operator i for operation j

f_i set of operations that operator i can perform

b_j set of operators who can perform operation j

d_j number of operators needed for operation j

r number of operators

s number of operations

The above model is run in ILOG OPL studio independently for all the possible product combinations in the problems considered. It is possible that the model may be run again for new product combinations while producing the revised gantt charts. This model is run for problem 1 considering cell loading strategies like lot splitting and operator sharing for the following cases -

a) Lot splitting not allowed and Operator sharing not allowed (2 skills and 3 skills)

b) Lot splitting allowed and Operator sharing not allowed (2 product sequence combinations)

c) Lot splitting not allowed and Operator sharing allowed

d) Lot splitting allowed and Operator sharing allowed

The model is also run for problem 2 and for each period in problem 3. When operator sharing is considered in problem 1, the objective function remains the same whereas O_{ij} variables are changed from (0, 1) to real and positive where O_{ij} represents operator i is assigned to operation j. In the OPL model O_{ij} variables are changed from integer variables to float variables to accommodate this change.

Appendix F shows three complete OPL sample models for a product combination for problem 1 (2 skills and 3 skills) and problem 2. Max approach allows the operators to move from one operation to the next in the same cell whenever the current product in the cell is completed (before the next product starts running). Similarly, operators can also move from one cell to the next cell if that gives a better skill match upon completion of a product. For example, an operator assigned to operation 3 for product 4 can be assigned to operation 2 for product 5. Furthermore, an operator assigned to operation 4 for product 4 can be assigned to operation 2 of product 6 once product 4 is completed. In other words, operator assignment decisions are made whenever a product is completed on any of the cells. While this approach is effective to find the best solution for a single period assignment problem, it may present difficulties in the long term. The main disadvantage of this approach is that the operators may be assigned to the operations that they are already good at on a continuous basis. While they sharpen their skills more on these operations, their skills on the remaining operations tend to deteriorate. Eventually, this would lead to highly specialized operators who would not be very effective if they were assigned to other operations.

4.3.2 Max – Min Approach

Max – Min approach tries to overcome the difficulties associated with the max approach without jeopardizing the output rates from the manufacturing cells. The main concept behind this approach is to identify the bottleneck operations and then assign the operators who are very skilled at those operations to them. Once the bottleneck operations and their operators are assigned, the remaining operators and operations are identified. The assignment model is used again this time to assign the remaining operations to the remaining operators with the lowest skills (minimizing the skill match, hence maximizing the cost). The purpose of this strategy is to give operators the chance to perform diverse operations and hence improve their skills in various operations. The main disadvantage of this approach is the output may have to be compromised in the earlier stages.

The bottleneck operation is identified as the slowest operation, i.e. the operation with maximum of $\{t_j/m_j\}$. Table 4.7 shows the bottleneck operations for each product for problem 1 and problem 3 (same products) and Table 4.8 shows the bottleneck operations for problem 2. The bottleneck operations are bolded and underlined.

Table 4.7 Bottleneck Operations for each Product in Problem 1 and Problem 3

			Operations		
Product	**1**	**2**	**3**	**4**	**5**
1	0.07/1= 0.07	0.45/4= 0.112	0.37/3= **0.123**	0.88/8= 0.11	0.38/4= 0.095
2	0.05/1= 0.05	0.29/3= 0.096	0.62/6= 0.103	0.74/6= **0.123**	0.38/4= 0.095
3	0.06/1= 0.06	0.29/2= **0.145**	1.18/9= 0.131	0.86/6= 0.143	0.18/2= 0.09
4	0.04/1= 0.04	0.31/4= 0.077	0.55/6= 0.091	0.47/5= 0.094	0.4/4= **0.1**
5	0.08/1= 0.08	0.41/4= 0.102	0.43/4= **0.107**	0.74/7= 0.105	0.43/4= **0.107**
6	0.07/1= 0.07	0.32/3= 0.106	1.18/8= **0.147**	0.55/4= 0.137	0.45/4= 0.1125
7	0.09/1= 0.09	0.37/5= 0.074	0.46/5= **0.092**	0.49/6= 0.081	0.26/3= 0.086
8	0.08/1= 0.08	0.28/3= 0.093	0.49/6= 0.081	0.61/7= 0.087	0.29/3= **0.096**
9	0.04/1= 0.04	0.34/3= 0.113	0.81/7= **0.115**	0.62/6= 0.103	0.34/3= 0.113
10	0.07/1= 0.07	0.43/3= **0.143**	0.74/6= 0.123	0.87/7= 0.124	0.43/3= **0.143**

Table 4.8 Bottleneck Operations for each Product in Problem 2

		Operations						Operations		
Product	**1**	**2**	**3**	**4**	**5**	**Product**	**1**	**2**	**3**	**4**	**5**
1	0.07/1= 0.07	0.45/5= 0.09	0.37/4= **0.092**	0.88/10= 0.088	0.38/5= 0.076	**16**	0.12/2= 0.06	0.46/6= 0.076	0.39/5= **0.078**	0.61/8= 0.076	0.27/4= 0.067
2	0.05/1= 0.05	0.29/4= 0.072	0.62/7= 0.088	0.74/8= **0.092**	0.38/5= 0.076	**17**	0.08/1= 0.08	0.37/5= 0.074	0.92/11= **0.083**	0.35/5= 0.07	0.23/3= 0.076
3	0.06/1= 0.06	0.29/3= 0.096	1.18/11= 0.107	0.86/8= **0.108**	0.18/2= 0.09	**18**	0.04/1= 0.04	0.29/3= 0.096	0.98/8= **0.122**	1.18/10= 0.118	0.34/3= 0.113
4	0.04/1= 0.04	0.31/4= 0.077	0.55/8= 0.068	0.47/6= **0.078**	0.4/6= 0.066	**19**	0.09/1= 0.09	0.41/4= **0.102**	0.61/6= 0.101	0.39/4= 0.097	0.43/5= 0.086
5	0.08/1= 0.08	0.41/4= 0.102	0.43/4= **0.107**	0.74/7= 0.105	0.43/4= **0.107**	**20**	0.08/1= 0.08	0.38/5= 0.076	0.59/7= 0.084	0.81/9= **0.09**	0.21/3= 0.07
6	0.07/1= 0.07	0.32/3= 0.106	1.18/11= 0.107	0.55/5= **0.11**	0.45/5= 0.09	**21**	0.07/1= 0.07	0.44/5= 0.088	0.61/6= **0.101**	0.91/9= **0.101**	0.35/4= 0.087
7	0.09/1= 0.09	0.37/5= 0.074	0.46/5= **0.092**	0.49/6= 0.081	0.26/3= 0.086	**22**	0.11/1= 0.11	0.38/4= 0.095	1.15/10= **0.115**	0.64/6= 0.106	0.38/4= 0.095
8	0.08/2= 0.04	0.28/4= 0.07	0.49/7= 0.07	0.61/8= **0.076**	0.29/4= 0.072	**23**	0.08/1= 0.08	0.31/4= 0.077	0.91/9= **0.101**	0.59/6= 0.098	0.43/5= 0.086
9	0.04/1= 0.04	0.34/4= 0.085	0.81/9= **0.09**	0.62/7= 0.088	0.34/4= 0.085	**24**	0.09/2= 0.045	0.39/6= 0.065	0.64/9= **0.071**	0.31/5= 0.062	0.21/3= 0.07
10	0.07/1= 0.07	0.43/4= **0.107**	0.74/7= 0.105	0.87/9= 0.096	0.43/4= **0.107**	**25**	0.04/1= 0.04	0.44/3= 0.146	0.96/6= 0.16	1.29/8= **0.161**	0.29/2= 0.145
11	0.1/1= 0.1	0.29/3= 0.096	0.92/8= **0.115**	0.64/6= 0.106	0.19/2= 0.095	**26**	0.08/1= 0.08	0.29/2= **0.145**	1.15/8= 0.143	0.84/6= 0.14	0.39/3= 0.13
12	0.12/1= 0.12	0.37/3= 0.123	0.92/8= 0.115	1.29/10= **0.129**	0.26/3= 0.086	**27**	0.06/1= 0.06	0.37/3= 0.123	0.81/7= 0.115	0.64/5= **0.128**	0.44/4= 0.11
13	0.05/1= 0.025	0.34/3= 0.113	1.05/9= **0.116**	0.94/9= 0.104	0.34/3= 0.113	**28**	0.04/1= 0.04	0.39/6= 0.065	0.76/10= **0.076**	0.29/4= 0.072	0.26/4= 0.065
14	0.08/1= 0.08	0.39/3= 0.13	0.98/8= 0.122	1.34/10= **0.134**	0.35/3= 0.116	**29**	0.06/1= 0.06	0.44/3= 0.146	0.82/5= 0.164	1.36/8= **0.17**	0.35/3= 0.116
15	0.06/1= 0.06	0.41/4= 0.102	0.94/8= **0.117**	0.94/8= **0.117**	0.43/4= 0.107	**30**	0.09/1= 0.09	0.37/4= 0.092	0.64/6= **0.106**	0.94/9= 0.104	0.45/5= 0.09

After finding the bottleneck operations, the assignment model is used only for bottleneck operations with the objective of finding the best match (skill maximization). Objective function (equation 11) and equation 13 remain the same and include only bottleneck operations whereas equation 12 is modified as

$$\sum_{j \in f_i} O_{ij} \leq 1 \qquad i = 1, 2, 3 \ldots r \qquad (14)$$

Once the bottleneck operations are assigned to the highest – skill operators, they are excluded from further consideration. The assignment model is used again this time to assign operations to the operators with the lowest skills (cost maximization). The constraints remain the same where as objective function (equation 11) is modified as

$$\text{Max } Z = \sum_{i=1}^{r} \sum_{j \in f_i} c_{ij} O_{ij} \qquad (15)$$

The motivation behind this approach is that non - bottleneck operations can be assigned to operators with minimum skill to give them the opportunity to perform the operations and improve their skills. It may not be useful in early periods but it is expected that it will provide benefits in the long term. The above models are run in ILOG OPL studio independently for all the possible product combinations in problem 2 and problem 3. It is possible that the model may be run again for new product combinations while producing the revised gantt charts.

4.3.3 Max – Max Approach

This approach is similar to Max – Min approach. The difference being, once the operators are assigned to bottleneck operations and are excluded from further consideration, the remaining operators are assigned to non – bottleneck operations with the best match (skill maximization). The constraints remain the same where as objective function (equation 15) is modified as

$$\text{Min } Z = \sum_{i=1}^{r} \sum_{j \in f_i} c_{ij} O_{ij} \qquad (16)$$

This approach is effective to find the best solution for a single period assignment problem but may present difficulties in the long term. The main disadvantage is similar to that of Max approach – operators may be assigned to the operations that they are already good on a continuous basis and can deteriorate their skill in performing the other operations. The above procedure is applied to all product combinations in problem 2.

4.4 Operator Assignment to Cells

After running the OPL models and determining the operator assignments to the operations, the next step is to determine which operators go to which cell. Two approaches are proposed –

Random assignment of Operators to the cells

After determining the operators to the operations, they can be randomly assigned to the cells according to the requirement. This approach is expected to give simple and fast results in single period assignment problem but in the long term, it may present difficulties like slow learning rate of the operators.

Operator assignment according to skills and bottleneck times (from standard times)

This approach tries to overcome the difficulties associated with the random assignment of the operators. Table 4.9 provides an example for the operator assignment to product combination P3 –P2 for operation 2.

Table 4.9 An example to assign operators to operations for a product combination

Product Combination		**P3-P2**								
Operators allocated to operation 2		2	12	26	29	36				
Skill level - Op.2		4	5	5	3	1				
Product	**Operation times**					**Ratio of Operation time to Bottleneck time**				
2	0.05/1= 0.05	0.29/3= 0.096	0.62/6= 0.103	0.74/6= **<u>0.123</u>**	0.38/4= 0.095	.05/.123= 0.406504	.096/.123= 0.7804878	.103/.123= 0.8373984	.123/.123= 1	.095/.123 0.7723577
3	0.06/1= 0.06	0.29/2= **<u>0.145</u>**	1.18/9= 0.131	0.86/6= 0.143	0.18/2= 0.09	.06/.145= 0.413793	.145/.145= 1	.131/.145= 0.9034483	.143/.145= 0.9862069	.09/.145= 0.6206897

Product 3 is assigned to cell 1 and Product 2 is assigned to cell 2. Two and three operators are required for product 3 and product 2, respectively for operation 2. The ratio of operation time to bottleneck time for operation 2 is greater for product 3 than product

2. So, the better skilled operators (36 and 29) are allocated to product 3 in cell 1 and lesser skilled operators (2, 12 and 26) are allocated to product 2 in cell 2.

Problem 2 is considered to compare the above two approaches. For all other experimentation, the second approach is used to assign operators to operations for all product combinations in all cases considered. In Max – Min approach, the max model is initially run for only bottleneck operations. Then, the min model is run to allocate the remaining operators for non – bottleneck operations and the second approach is used to allocate them to the cells.

4.5 Calculation of the Revised Output Rates

After assigning the operators to the operations in all possible product combinations, the next step is to revise the operation times and hence the output rate by considering the Operator - Time matrix. Assume that SO_j is the set of operators assigned to operation j. The operation time for this group (T_j) is computed by using the following relation.

$$T_j = \left(\sum_{SO_j} T_{ij} * W_{ij} \right) / g \tag{17}$$

Where,

T_{ij} time for operator i for operation j

W_{ij} percentage of output rate for operator i for operation j considering the entire group

g number of operators in the group

Percentage of output rate for operator i assigned to operation j is computed as

$$W_{ij} = (1/T_{ij}) / [\sum_{SO_j} (1/T_{ij})] \quad (18)$$

Table 4.10 shows an example to calculate the operation time for a set of operators for operation 5 of product 2.

Table 4.10 An example to calculate the revised operation times

Operator	Tij	1/Tij	Wij	Tij*Wij
10	0.323	3.095975	0.274765	0.088749
22	0.361	2.770083	0.245842	0.088749
32	0.361	2.770083	0.245842	0.088749
31	0.38	2.631579	0.23355	0.088749
Sum		11.2677		0.354996
Tj				0.088749

T_{ij} values are obtained from operator - time matrix. After calculating the operation times for all product combinations, the bottleneck time determines the output rate and is determined by the relation

$$B = \max \{T_j\} \qquad 1 \leq j \leq g \quad (19)$$

Appendix G shows the operator assignments and operation times for all possible product combinations in the cases considered in problem 1, problem 2 and problem 3.

Once the output rates are determined, product schedules are revised. The following example shows the calculation procedure.

Product Combination	Product	B.times	Demand	Time/Units
P3 – P2	P3	.1382	3400	**469.68**
	P2	.1212	7500	3876
P5 – P2	P5	.1025	2200	222.5+469.88 = **695.38**
	P2	.1182	3624	1907

The bottleneck times for P3 and P2 are .1382 and .1212, respectively. The batch processing time for product 3 is 469.68 minutes (3400*.1382). During this time 3876 units (469.68 / .1212) of product P2 are processed. The next product combination is P5 – P2. The bottleneck times for P5 and P2 are .1025 and .1182, respectively. The batch processing time for product 5 is 225.50. So the completion time for product 5 will be 695.38 (225.50 + 469.88). During this time 1907 units (225.5 / .1182) of product 2 are processed. This analysis is repeated until the entire schedule is completed. It should be noted that the bottleneck times may vary with change in pairing of products in the combination. For example, bottleneck time for product 2 in product combination P3-P2 is .1212 and in P5-P2 is .1182.The revised gantt charts for different cases considered for all the problems are shown in the next chapter.

CHAPTER 5. ANALYSIS OF RESULTS

The experimental study in this thesis attempts to compare the cell performance and effect of lot splitting, operator sharing, operator learning and forgetting when the proposed operator assignment approaches are used to assign operators to operations and cells in a single - period and a multi - period environment. In single – period analysis, effect of variability in operator – operation times, impact of more operator skills and comparison of cell loading strategies and operator assignment approaches are studied. In multi – period analysis, comparison of operator assignment approaches and effect of operator learning and forgetting rates on operator skills is studied. In this chapter, results obtained from the experimental study are provided and analyzed.

5.1 Single Period Analysis

In this thesis, single period analysis of the cell performance is done based on operator skill levels and operator – operation times in labor intensive cells considering issues like lot splitting and operator sharing.

5.1.1 Effect of Variability

Problem 1 is considered to test the effect of variability in operator – operation times on cell performance. Standard deviation of 5%, 10%, 15% and 20% of mean is used. In this case, Max approach is used for the assignment of operators. Max strategy helps improve the results (as opposed to pure random assignment). However, there may be times when these results may not hold. Lot splitting and operator sharing are not allowed in the cellular system. Figure 5.1 shows the revised gantt charts for all the standard deviations. Table 5.1 shows the summary of the gantt charts for all cases considered. It can be clearly seen that Operation time variability impacts the results. Max approach gives better results than the classical approach of using standard times. In this experimentation, standard deviation of 10% of the mean gave the minimum makespan. Standard deviation of 5% of mean gave the minimum total processing time (cell 1 completion time + cell 2 completion time) and maximum idle time ((2200 - cell 1 completion time) + (2200 - cell 2 completion time)). Figure 5.2 shows the graphs plotted between variability and makespan (5.2.a), variability and total processing times (5.2.b) and variability and idle time (5.2.c). It is observed that makespan, total processing times and idle time does not follow any trend to the change in the variability. This can also be concluded from the processing times of operations for every product in the product combinations. The important factor is the operator skill level and operator assignment to operations which in turn affect the processing times.

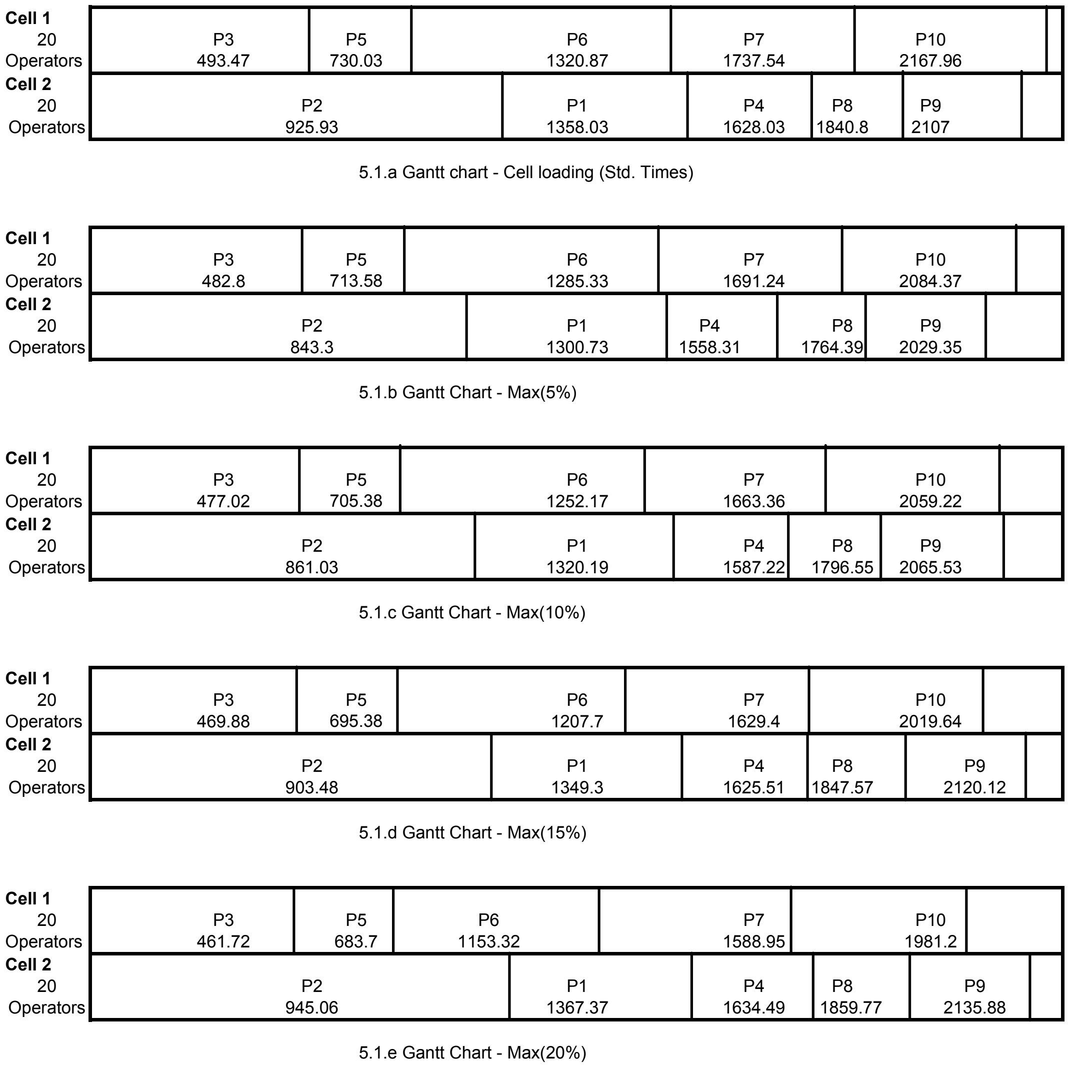
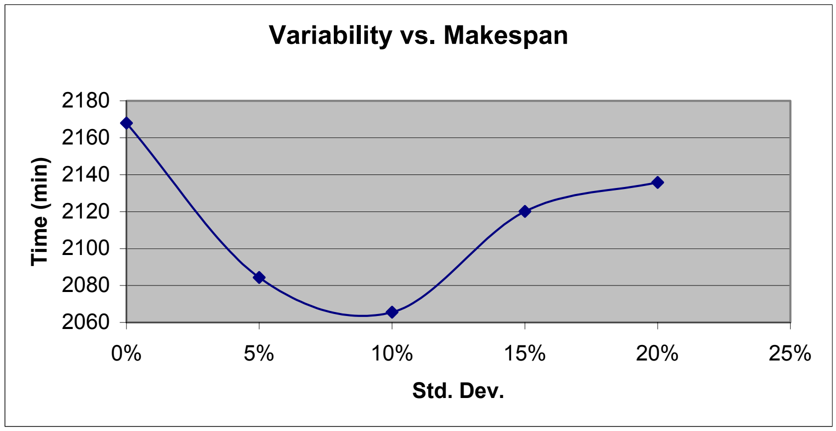


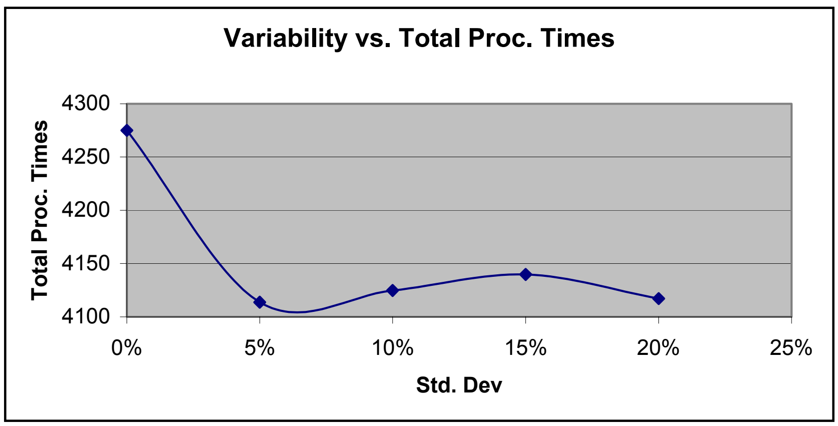
Figure 5.1 Revised Gantt charts for Std. Dev (a) Std. Times, b) 5%, c) 10 %, d) 15% and e) 20%)

Table 5.1 Summary of gantt charts considering variability factor

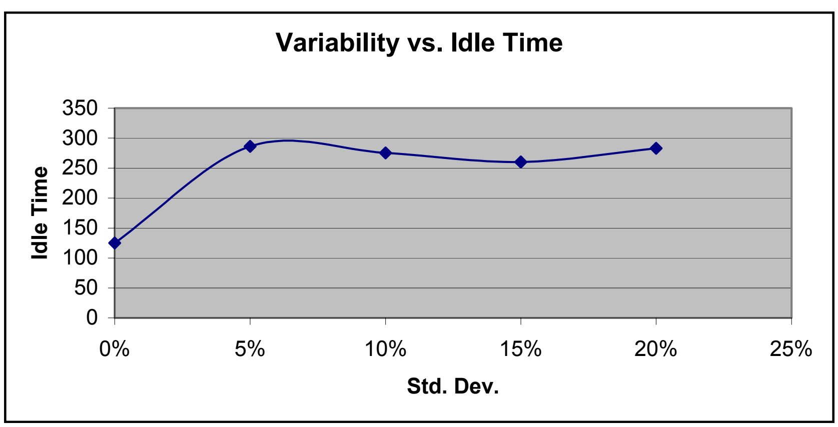
Std Dev.	Makespan	Total Processing Times	Total Idle Time
0%	2167.96	4274.96	125.04
5%	2084.37	4113.72	286.28
10%	2065.53	4124.75	275.25
15%	2120.12	4139.76	260.24
20%	2135.88	4117.08	282.92
Range	102.43	161.24	161.24



5.2.a. Variability vs. Makespan



5.2.b. Variability vs. Total Proc. Times



5.2.c. Variability vs. Idle Time

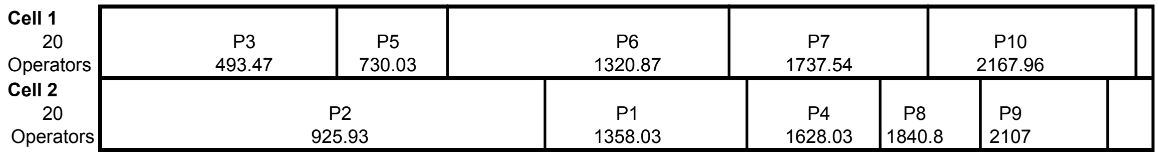
Figure 5.2Variability vs. (a. Makespan, b. Total Proc. Times and c. Idle Time) for Problem 1

5.1.2 Impact of more Operator Skills

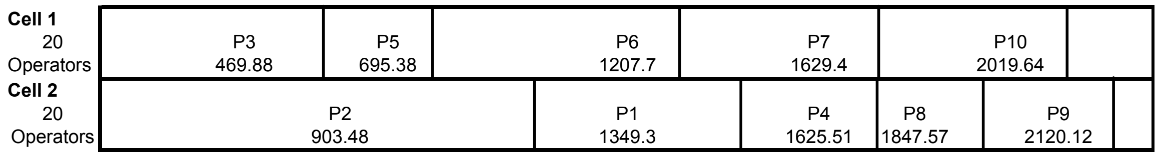
Problem 1 is considered to test the effect of having more operator skills on cell performance. It is assumed that lot splitting and operator sharing is not allowed. Max approach is used to assign the operators. A standard deviation of 15% of mean is used in operator time matrix. In the first case, two skills are allocated to each operator and in the second case three skills are allocated to each operator. Figure 5.3 shows the revised gantt charts for the cases considered. Table 5.2 provides the summary of the gantt charts. Figure 5.4 shows the graphs plotted between number of skills and makespan (5.4.a), number of skills and total processing time (5.4.b) and number of skills and idle time (5.4.c). It can be seen that the makespan for the case, when 2 skills are considered (2120.12 min) is more than the case considered with 3 skills (2027.74) but both the cases gave better results than the classical approach based on standard times (2167.96). The case, when 3 skills are allocated to each operator gave the minimum total processing times and maximum idle time. So it can be concluded that the model gives better results when more operator skills are available to match with the skills needed. Also, cellular flexibility increases when an operator is proficient in more than one process.

Table 5.2 Summary of the gantt charts considering the number of operator skills allocated to each operator

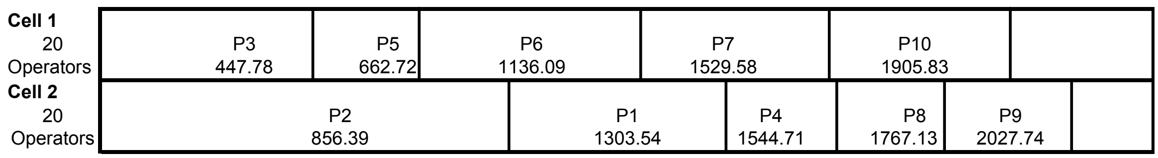
Case	Makespan	Total Proc. Times	Idle Time
Std Times	2167.96	4274.96	125.04
2 Skills	2120.12	4139.76	260.24
3 skills	2027.74	3933.57	466.43



5.3.a Gantt Chart - Cell Loading (Std. Times)

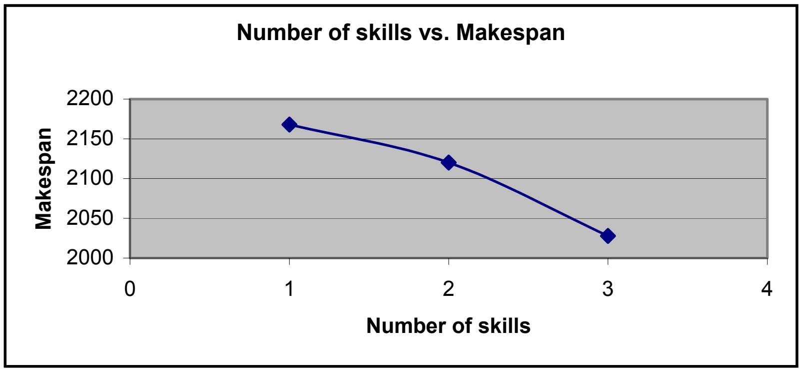


5.3.b Gantt Chart - Max(15%) - 2 Skills

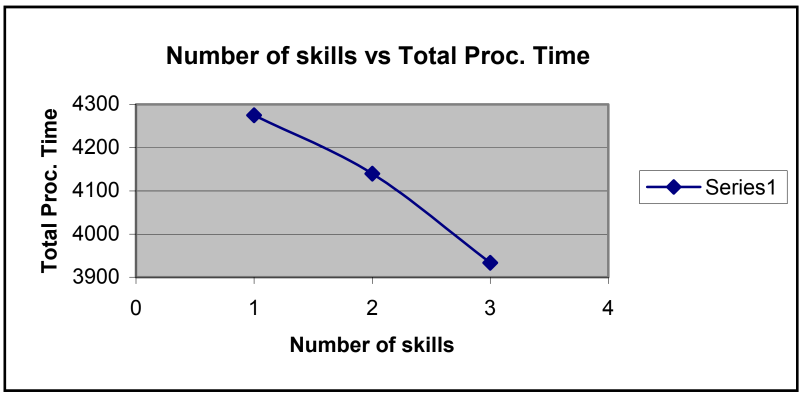


5.3.c Gantt Chart - Max(15%) - 3 Skills

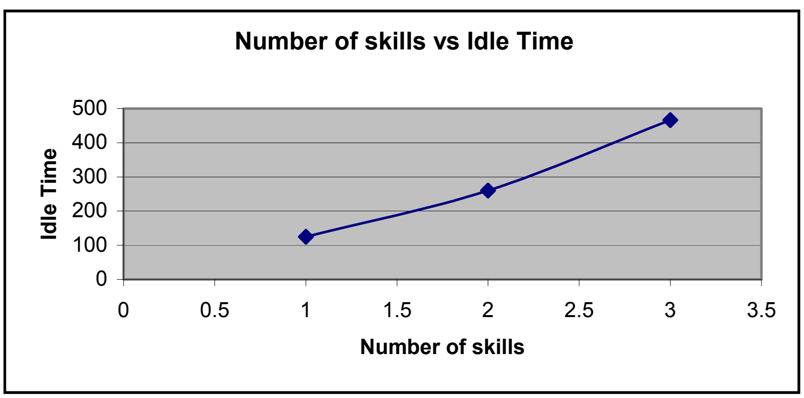
Figure 5.3 Revised Gantt charts (a) Std. Times, b) 2 skills and c) 3 skills)



5.4.a Number of skills vs Makespan



5.4.b Number of skills vs. Total Proc. Time



5.4.c Number of skills vs. Idle Time

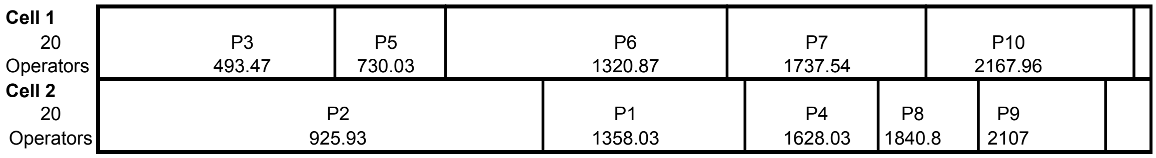
Figure 5.4 Number of skills vs. (a. Makespan, b. Total Proc. Time and c. Idle Time) for problem 1

5.1.3 Comparison of Cell Loading Strategies

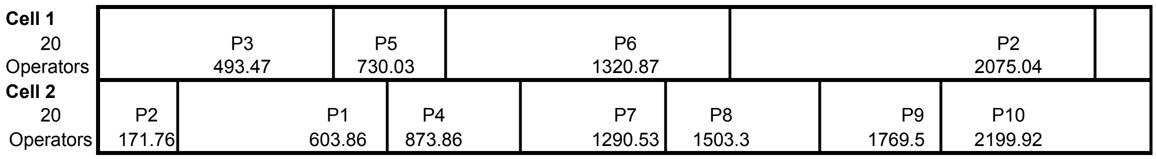
In this thesis, problem 1 is considered to compare the different strategies used in cell loading. Issues like lot splitting and operator sharing are studied. Max approach is used to assign the operators and a standard deviation of 15% of mean is used in operator time matrix. The following cases are studied –

a) Lot splitting not allowed (LSNA) and Operator sharing not allowed (OSNA)
b) Lot splitting allowed – Seq.1(LSA1) and Operator sharing not allowed (OSNA)
c) Lot splitting allowed – Seq.2 (LSA2) and Operator sharing not allowed (OSNA)
d) Lot splitting not allowed (LSNA) and Operator sharing allowed (OSA)
e) Lot splitting allowed (LSA) and Operator sharing allowed (OSA)

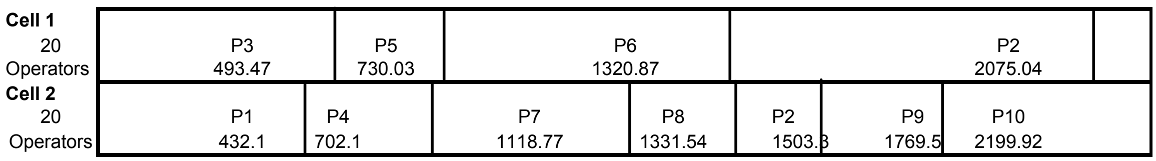
Figure 5.5 shows the cell loading by standard times and max approach for all the cases considered. Table 5.3 represents the summary of the gantt charts considering cell loading strategies.



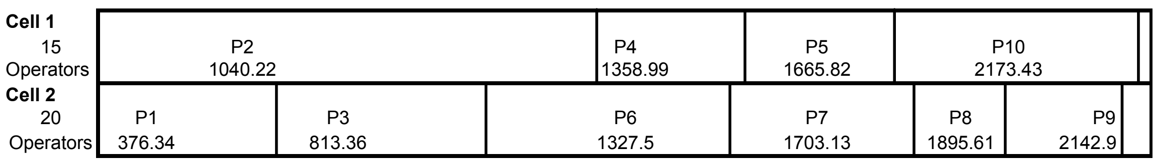
5.4.1 Gantt Chart - LSNA & OSNA - Std. Times



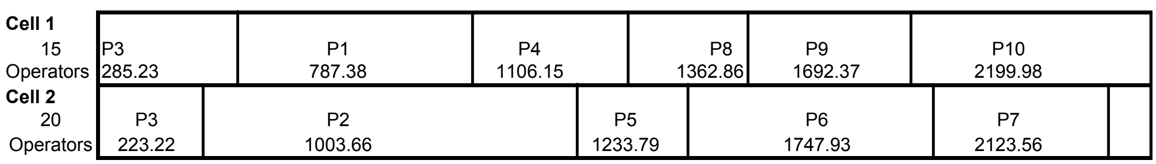
5.4.2 Gantt Chart - LSA1 & OSNA - Std. Times



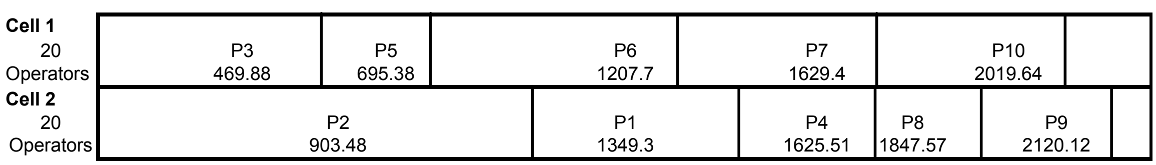
5.4.3 Gantt Chart - LSA2 & OSNA - Std. Times



5.4.4 Gantt Chart - LSNA & OSA - Std. Times

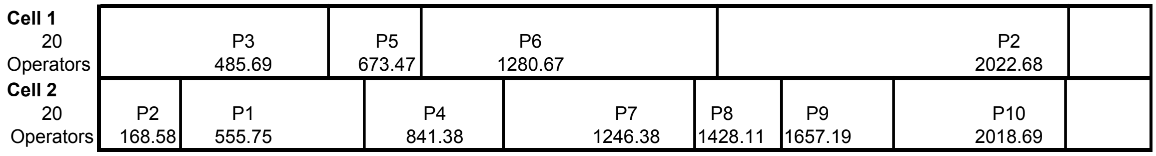


5.4.5 Gantt Chart - LSA & OSA - Std. Times

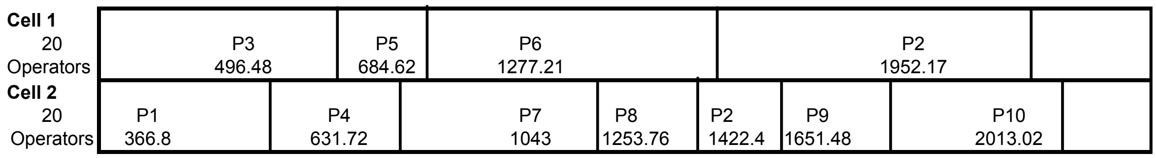


5.4.6 Gantt Chart - LSNA & OSNA - Max(15%)

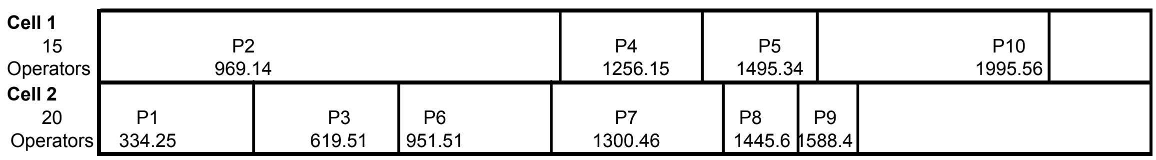
Figure 5.5 Contd.



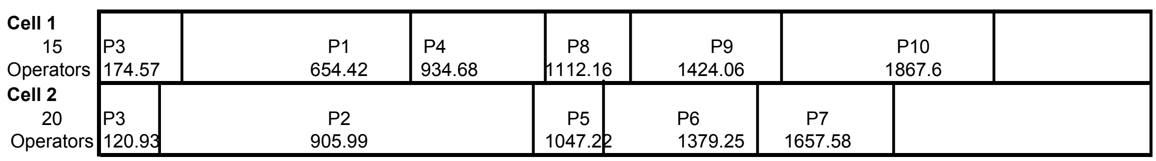
5.4.7 Gantt Chart - LSA1 & OSNA - Max(15%)



5.4.8 Gantt Chart - LSA2 & OSNA - Max(15%)



5.4.9 Gantt Chart - LSNA & OSA - Max(15%)



5.4.10 Gantt Chart - LSA & OSA - Max(15%)

Figure 5.5 Gantt charts for cellular systems considering cell loading strategies

Table 5.3 Summary of the gantt charts considering cell loading strategies

	Cellular system Considered	Cell 1 comp. time(C1C.T)	Cell 2 comp. time(C2C.T)	Makespan	¦C1C.T-C2C.T¦	# of Operators
1	LSNA & OSNA - Std. Times	2167.96	2107	2167.96	60.96	40
2	LSA1 & OSNA - Std. Times	2075.04	2199.92	2199.92	124.88	40
3	LSA2 & OSNA - Std. Times	2075.04	2199.92	2199.92	124.88	40
4	LSNA & OSA - Std. Times	2173.43	2142.9	2173.43	30.53	35
5	LSA & OSA - Std. Times	2199.98	2123.56	2199.98	76.42	35
6	LSNA & OSNA - Max(15%)	2019.64	2120.12	2120.68	100.48	40
7	LSA1 & OSNA - Max(15%)	2022.68	2018.69	2022.68	3.99	40
8	LSA2 & OSNA - Max(15%)	1952.17	2013.02	2013.02	60.85	40
9	LSNA & OSA - Max(15%)	1995.56	1588.4	1995.56	407.16	35
10	LSA & OSA - Max(15%)	1867.6	1657.58	1867.6	210.02	35

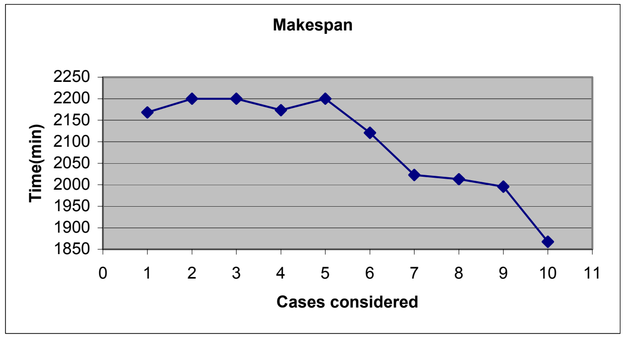
Table 5.3 contd.

	Cellular system Considered	Total Proc. Time	Idle Time
1	LSNA & OSNA - Std. Times	4274.96	125.04
2	LSA1 & OSNA - Std. Times	4274.96	125.04
3	LSA2 & OSNA - Std. Times	4274.96	125.04
4	LSNA & OSA - Std. Times	4316.33	83.67
5	LSA & OSA - Std. Times	4323.54	76.46
6	LSNA & OSNA - Max(15%)	4139.76	260.24
7	LSA1 & OSNA - Max(15%)	4041.37	358.63
8	LSA2 & OSNA - Max(15%)	3965.02	434.98
9	LSNA & OSA - Max(15%)	3583.96	816.04
10	LSA & OSA - Max(15%)	3525.18	874.82

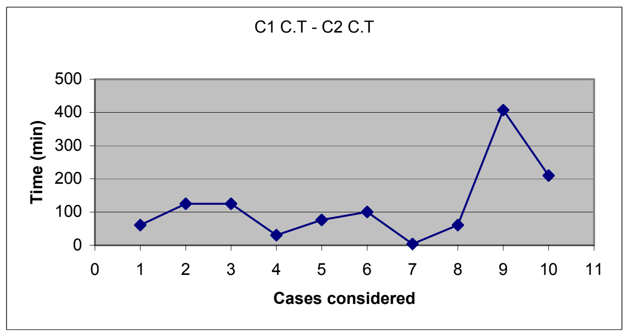
Figure 5.6 shows the graphs plotted for makespan (5.6.a), range (Cell 1 comp. time – Cell 2 comp. time) (5.6.b), total processing time (5.6.c) and idle time (5.6.d) for all the cases considered. It can be observed that the makespan and total processing time for the cases considered using max approach for operator assignment (6, 7, 8, 9 & 10) is less than the cases considered using the classical approach of standard times (1, 2, 3, 4 & 5). The number of operators needed for the cellular system decreased when operator sharing is allowed between operations and cells (40 to 35). It should be noted that models are run to minimize the number of operators, not the makespan during cell loading, considering that lot splitting is allowed. Makespan and range for the cases considered when lot splitting is allowed (7 & 8) is less than the case considered when lot splitting is not allowed (6) but the case considered when both lot splitting and operator sharing are allowed (10) gave the minimum makespan, minimum total processing time and maximum idle time. While lot splitting allowed and operator sharing not allowed model gave the minimum range (7), the model with lot splitting not allowed and operator sharing allowed gave the maximum range (9). It can be concluded that by allowing lot

splitting and operator sharing in the cellular system and using the Max approach for assigning the operators will create more accurate schedules and give a better cell performance especially in labor intensive cells.

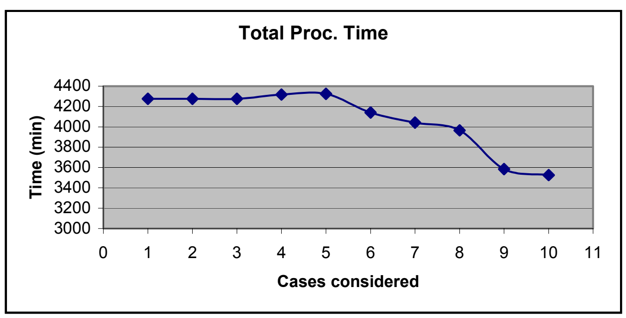
Appendix G5 and G6 show that no more than 7 operators out of 35 operators (20%) were being shared in each product combination between operations and cells when operator sharing was allowed in the cellular system. Out of 20% of the operators who are shared, it is observed that 12% of the operators are shared between the operations in the same cell, 27% of the operators are shared between different cells but perform same operation and 61% of the operators are shared between different operations in different cells. This shows that, by allowing operator sharing and using Max operator assignment approach, most of the operators who are shared are used widely to perform various operations in different cells increasing the flexibility and also improving the cellular performance justifying the better results got from the experimentation.



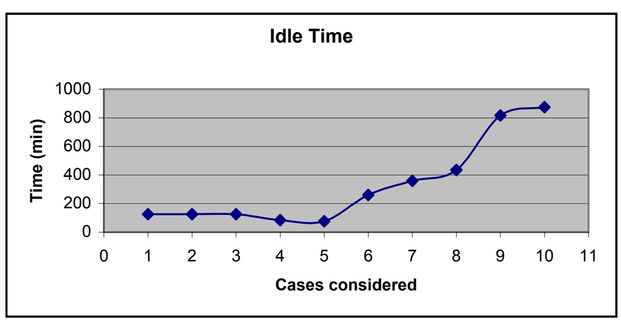
5.6.a Makespan



5.6.b C1 C.T- C2 C.T



5.6.c Total Proc. Time



5.6.d Idle Time

Figure 5.6 Graphs for a. Makespan, b. Range, c. Total Proc. Time and d. Idle Time for all the cases

5.1.4 Comparison of Operator Assignment Models

In this thesis three operator assignment models are discussed. They are

a) Max approach – Match the skills needed with skills available at minimum cost for all operations. Two rules are used to assign the operators to cells.

b) Max – Min approach – Match the skills needed with skills available at minimum cost for bottleneck operations and then to match the skills needed with the skills available at maximum cost for non - bottleneck operations.

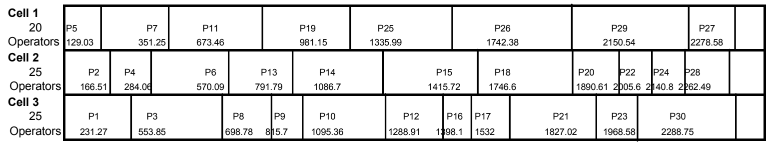
c) Max – Max approach – Match the skills needed with skills available at minimum cost for bottleneck operations and then to match the skills needed with the skills available at minimum cost for non - bottleneck operations.

Problem 2 is considered to compare the three assignment approaches. Each operator is assigned two skills. A standard deviation of 15% of mean is used for operator time matrix. Figure 5.7 shows the revised gantt charts using the three assignment models for a single period assignment problem. Table 5.4 shows the summary of the gantt charts considering operator assignment approaches. Figure 5.8 shows the graphs plotted for makespan, total processing time and idle time for all cases considered. It is observed that the makespan and total processing time is more for max – min approach when compared to the classical approach of using standard times, max approach and max – max approach putting the industrial benefits at risk. Max – Min approach also requires more capacity as the makespan exceeded the normal production time of 2300 minutes. In this case, Max approach gave the minimum total processing time and maximum idle time when the operators are assigned randomly to the cells. For a single period assignment problem, Max and Max – Max approaches are effective in finding the best solution but they may present difficulties in the long term justifying the multi - period analysis done in this thesis.

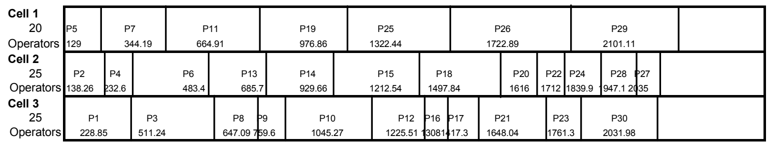
Table 5.4 Summary of gantt charts considering operator assignment approaches

Case	Makespan	Total Proc. Time	Idle Time
5.7.1 Std. Times	2288.75	6829.82	70.18
5.7.2Max approach - Rule 1	2101.11	6168.09	731.91
5.7.3 Max approach - Rule 2	2267.4	6703.72	196.28
5.7.4 Max - Min approach	2629.29	7754.65	-854.65
5.7.5 Max - Max approach	2255.98	6682.9	217.1

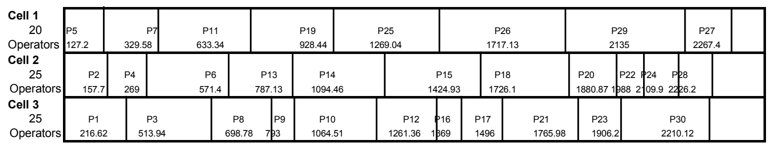
Another issue that can be seen during experimentation is the conversion of non - bottleneck operations into bottleneck operations after the proposed operator assignment approaches are used. For example, after phase 2, the bottleneck operation for product 2 in the product combination P2 – P3 is operation 3. But after max operator assignment approach is used and the revised output rates are calculated, it is seen that the bottleneck operation is operation 2 and the processing time has also increased. From Appendix G, it can be observed that the non - bottleneck operations for more than 70% of the product combinations for all the cases and problems considered have turned into bottleneck operation after the proposed operator assignment approaches are used. Thus, the actual improvement in the production rate is restricted. Even though no effort has been done to restrict this conversion in single – period analysis, proposed assignment approaches (Max and Max –Max) gave better results than the classical approach of using standard times.



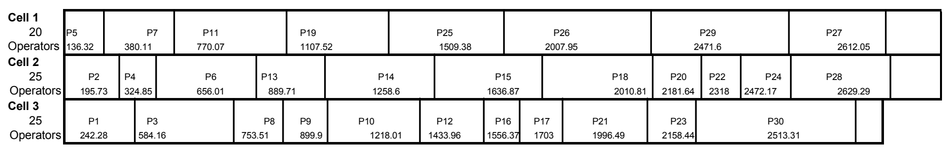
5.7.1 Gantt Chart - Cell Loading



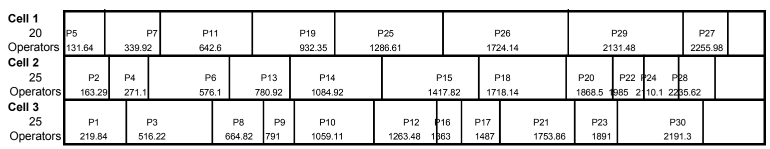
5.7.2 Gantt Chart - Max(15%) - Random Assignment of Operators



5.7.3 Gantt Chart - Max(15%) - according to ratio of operation time to bottleneck time

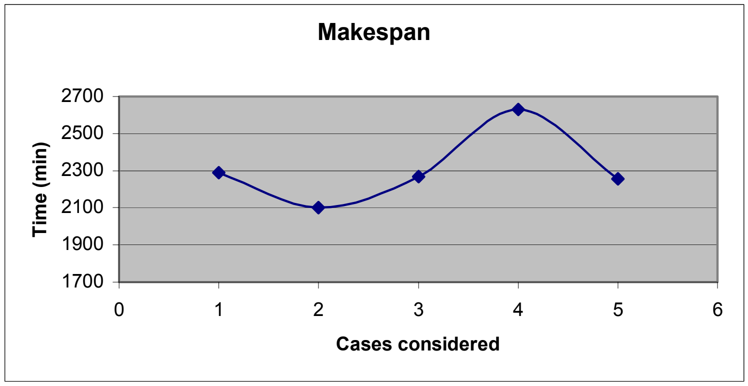


5.7.4 Gantt Chart - Max - Min(15%)

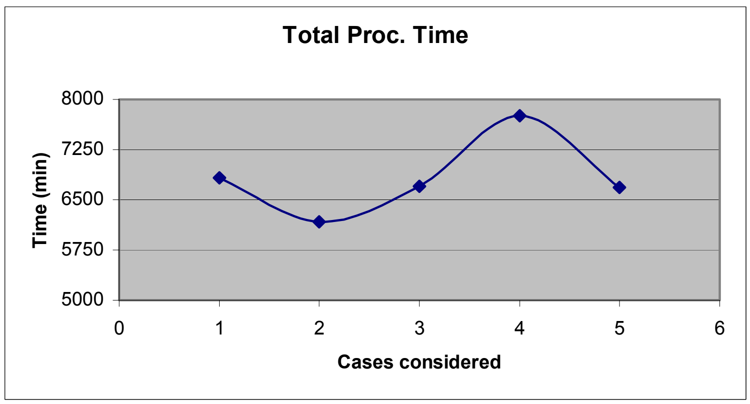


5.7.5 Gantt Chart - Max - Max(15%)

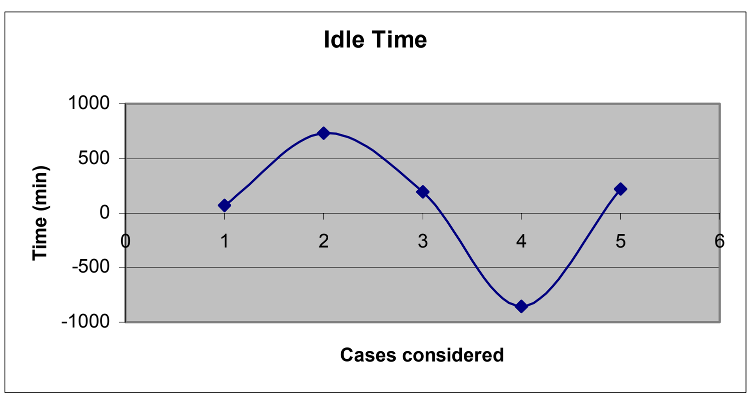
Figure 5.7 Revised Gantt Charts using the Assignment Approaches (Problem 2)



5.8.a Makespan



5.8.b Total Proc. Time



5.8.c Idle Time

Figure 5.8 Graphs for a. Makespan, b. Total Proc. Time and c. Idle Time considering operator assignment approaches

5.2 Multi Period Analysis

When an operator performs an operation for a specific number of periods or time, his skill level tends to improve. Similarly his skill level decreases when he does not perform the operation for a certain period. Problem 3 is considered to compare the cell performances when Max approach and Max – Min approach are used to assign the operators. Simulation study is done for 16 periods (weeks). Operator skill matrix keeps changing for every period according to the operator learning and forgetting rates and assignment model used (Chapter 4). Gantt charts for cell loading using standard times are given in Chapter 3.

5.2.1 Comparison of Assignment Models in a Multi Period Analysis

Figure 5.9 and figure 5.10 show the revised gantt charts when Max approach and Max – Min approach are used to assign the operators to the operations, respectively. A simulation study for 16 periods is done. A standard deviation of 15% of mean is used for operator time matrix. It is assumed that lot splitting is allowed and operator sharing is not allowed. Table 5.5 shows the summary of the gantt charts when standard times, max approach and max – min approach are used for multi – period analysis. It can be observed that the operator level changes from one period to another. Figure 5.11 shows the graphs plotted for makespan, total processing time and idle time considering standard times, Max approach and Max – Min approach. It can be observed that Max approach still gave the minimum makespan, minimum total processing time and maximum idle time at the end of simulation but the rate of improvement in cell performance is more when Max – Min approach is used.

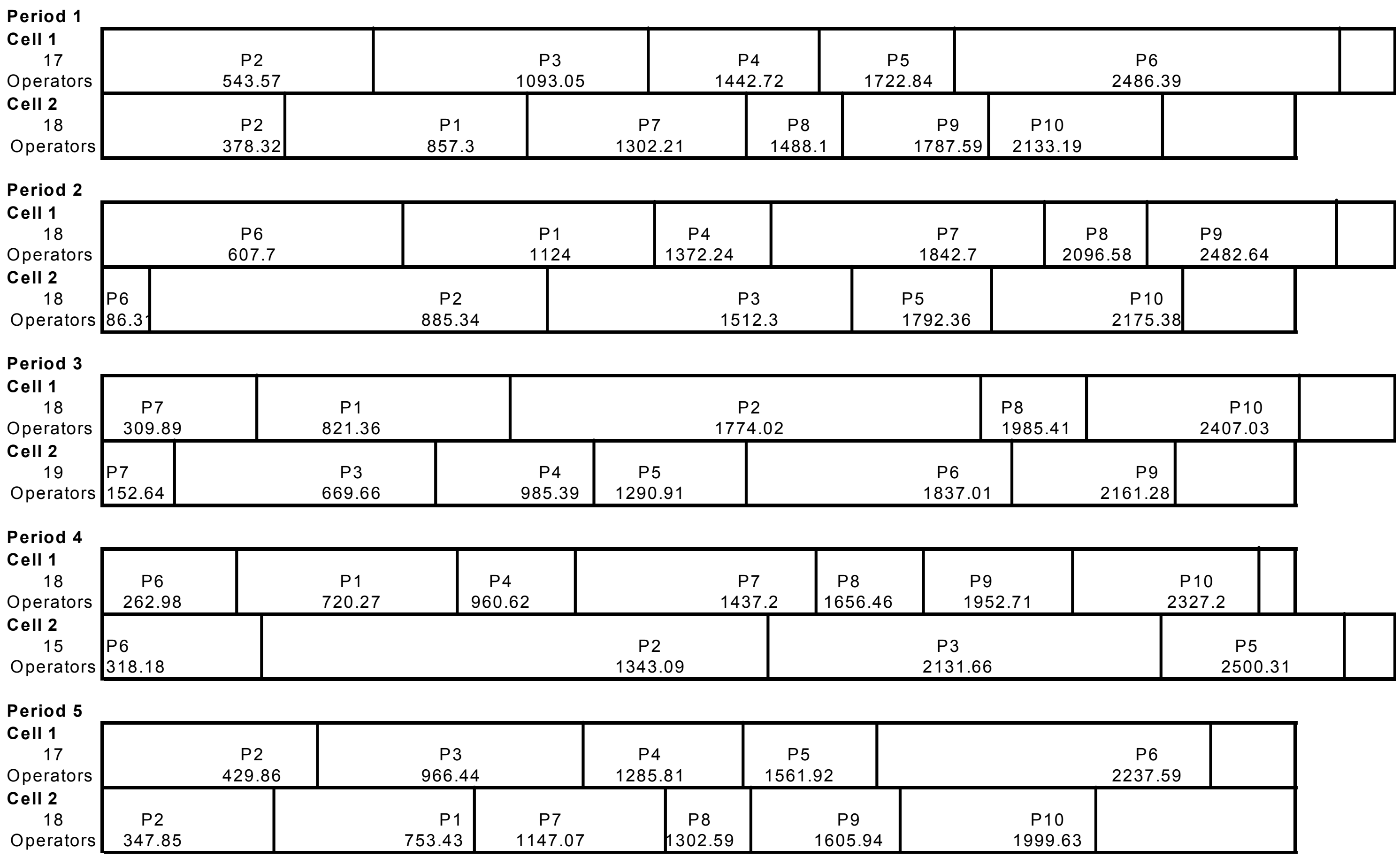

Period 1
Cell 1
17 Operators
P2 543.57
P3 1093.05
P4 1442.72
P5 1722.84
P6 2486.39
Cell 2
18 Operators
P2 378.32
P1 857.3
P7 1302.21
P8 1488.1
P9 1787.59
P10 2133.19
Period 2
Cell 1
18 Operators
P6 607.7
P1 1124
P4 1372.24
P7 1842.7
P8 2096.58
P9 2482.64
Cell 2
18 Operators
P6 86.31
P2 885.34
P3 1512.3
P5 1792.36
P10 2175.38
Period 3
Cell 1
18 Operators
P7 309.89
P1 821.36
P2 1774.02
P8 1985.41
P10 2407.03
Cell 2
19 Operators
P7 152.64
P3 669.66
P4 985.39
P5 1290.91
P6 1837.01
P9 2161.28
Period 4
Cell 1
18 Operators
P6 262.98
P1 720.27
P4 960.62
P7 1437.2
P8 1656.46
P9 1952.71
P10 2327.2
Cell 2
15 Operators
P6 318.18
P2 1343.09
P3 2131.66
P5 2500.31
Period 5
Cell 1
17 Operators
P2 429.86
P3 966.44
P4 1285.81
P5 1561.92
P6 2237.59
Cell 2
18 Operators
P2 347.85
P1 753.43
P7 1147.07
P8 1302.59
P9 1605.94
P10 1999.63

Figure 5.9 Contd.

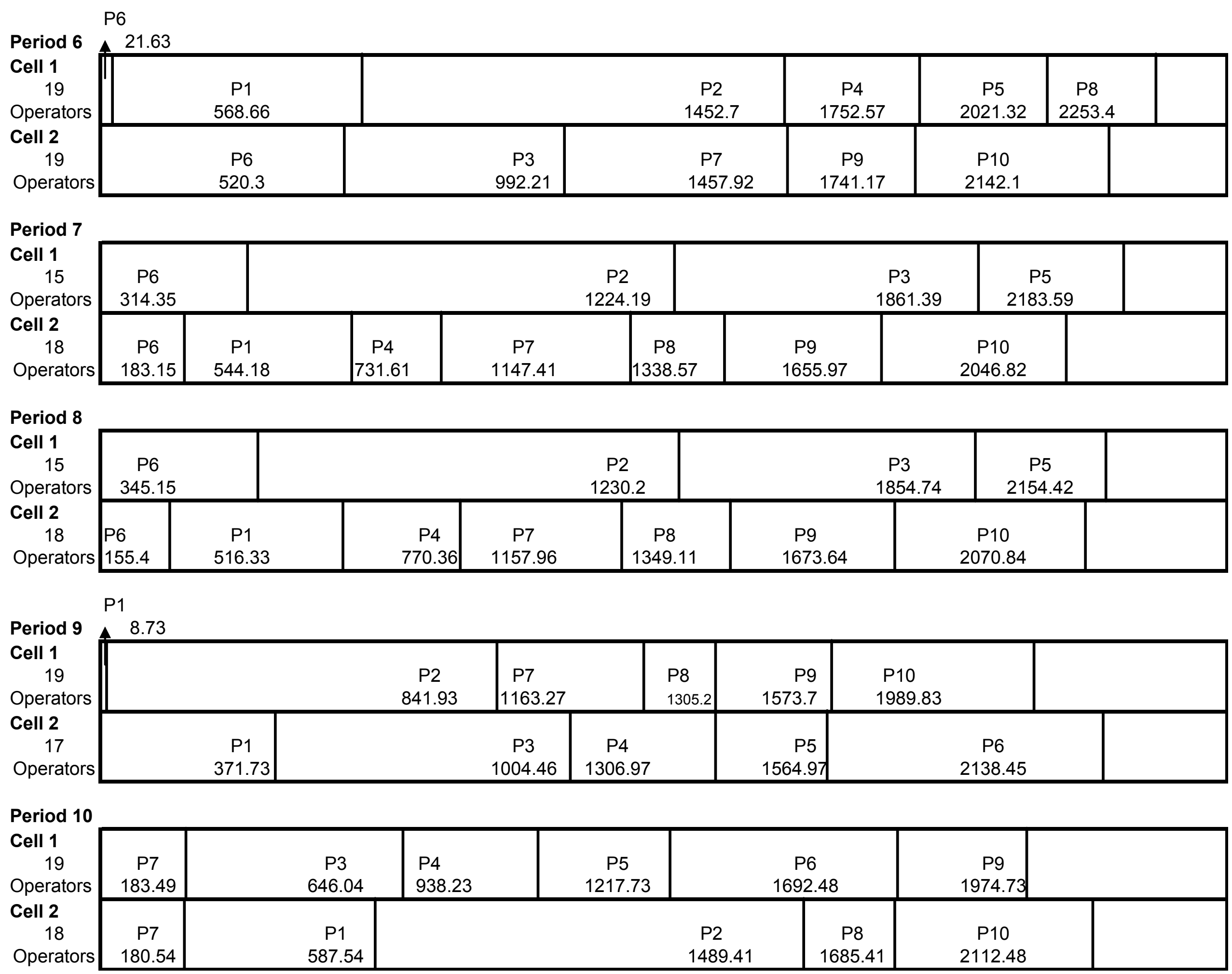


Figure 5.9 Contd.

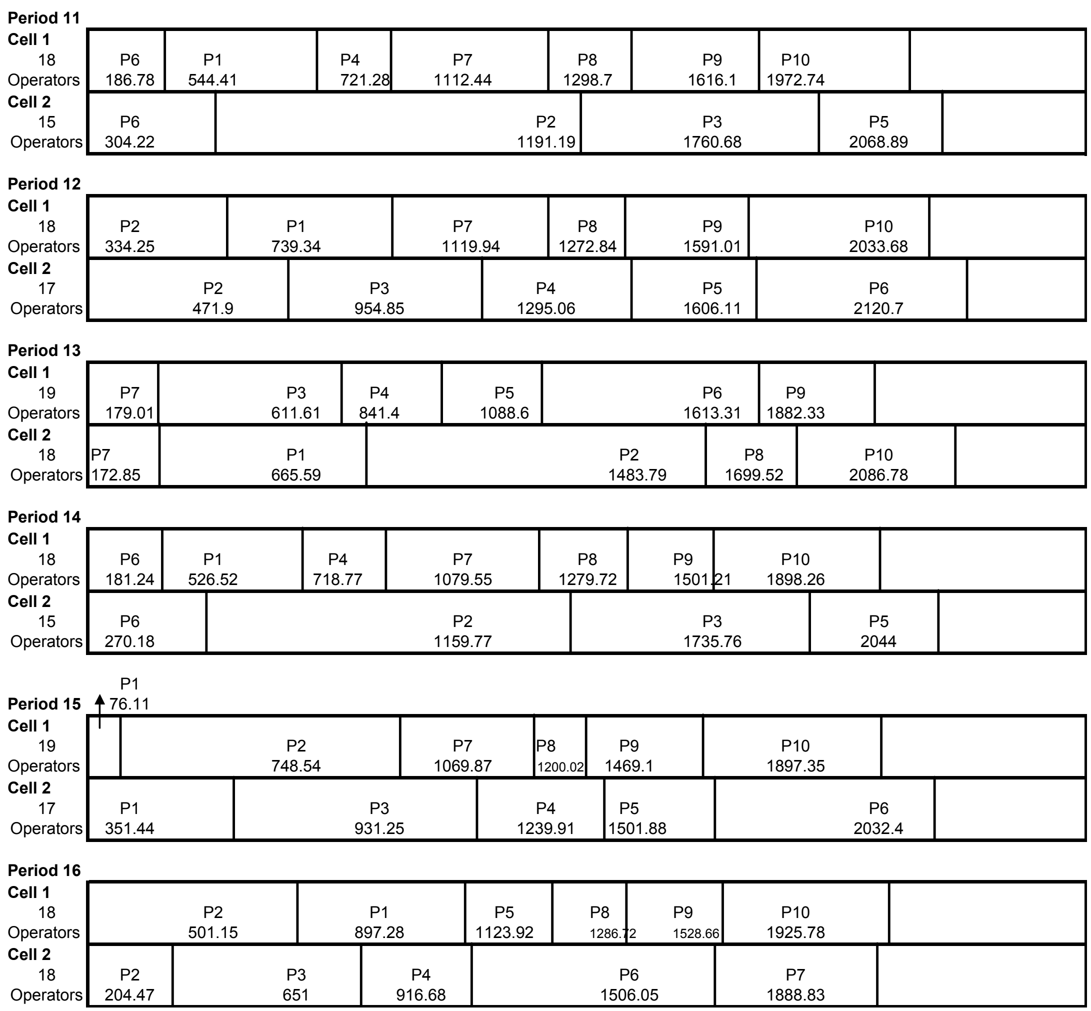


Figure 5.9 Revised Gantt charts using Max approach (problem 3)

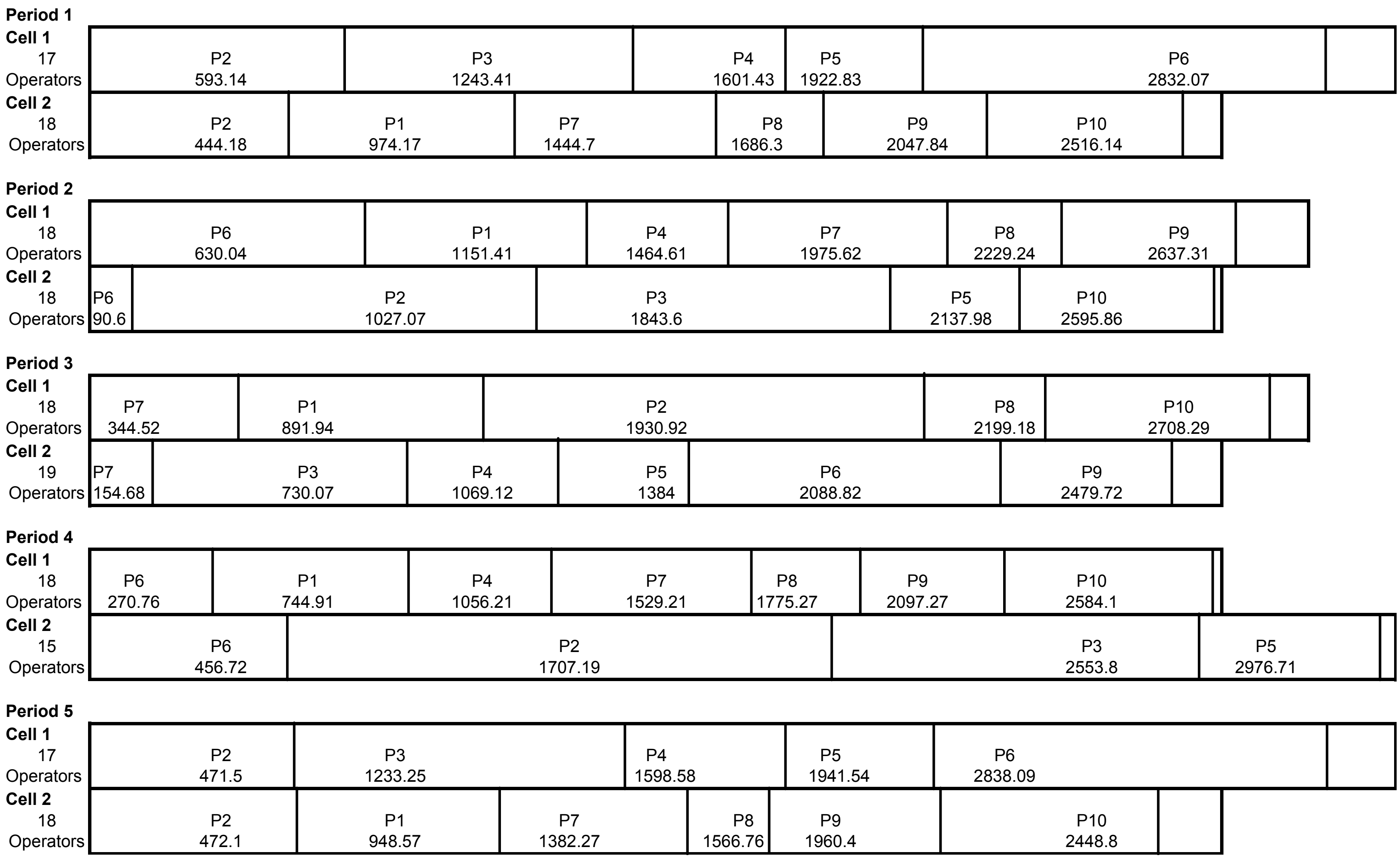

Period 1
Cell 1
17 Operators
P2 593.14
P3 1243.41
P4 1601.43
P5 1922.83
P6 2832.07
Cell 2
18 Operators
P2 444.18
P1 974.17
P7 1444.7
P8 1686.3
P9 2047.84
P10 2516.14
Period 2
Cell 1
18 Operators
P6 630.04
P1 1151.41
P4 1464.61
P7 1975.62
P8 2229.24
P9 2637.31
Cell 2
18 Operators
P6 90.6
P2 1027.07
P3 1843.6
P5 2137.98
P10 2595.86
Period 3
Cell 1
18 Operators
P7 344.52
P1 891.94
P2 1930.92
P8 2199.18
P10 2708.29
Cell 2
19 Operators
P7 154.68
P3 730.07
P4 1069.12
P5 1384
P6 2088.82
P9 2479.72
Period 4
Cell 1
18 Operators
P6 270.76
P1 744.91
P4 1056.21
P7 1529.21
P8 1775.27
P9 2097.27
P10 2584.1
Cell 2
15 Operators
P6 456.72
P2 1707.19
P3 2553.8
P5 2976.71
Period 5
Cell 1
17 Operators
P2 471.5
P3 1233.25
P4 1598.58
P5 1941.54
P6 2838.09
Cell 2
18 Operators
P2 472.1
P1 948.57
P7 1382.27
P8 1566.76
P9 1960.4
P10 2448.8

Figure 5.10 Contd.

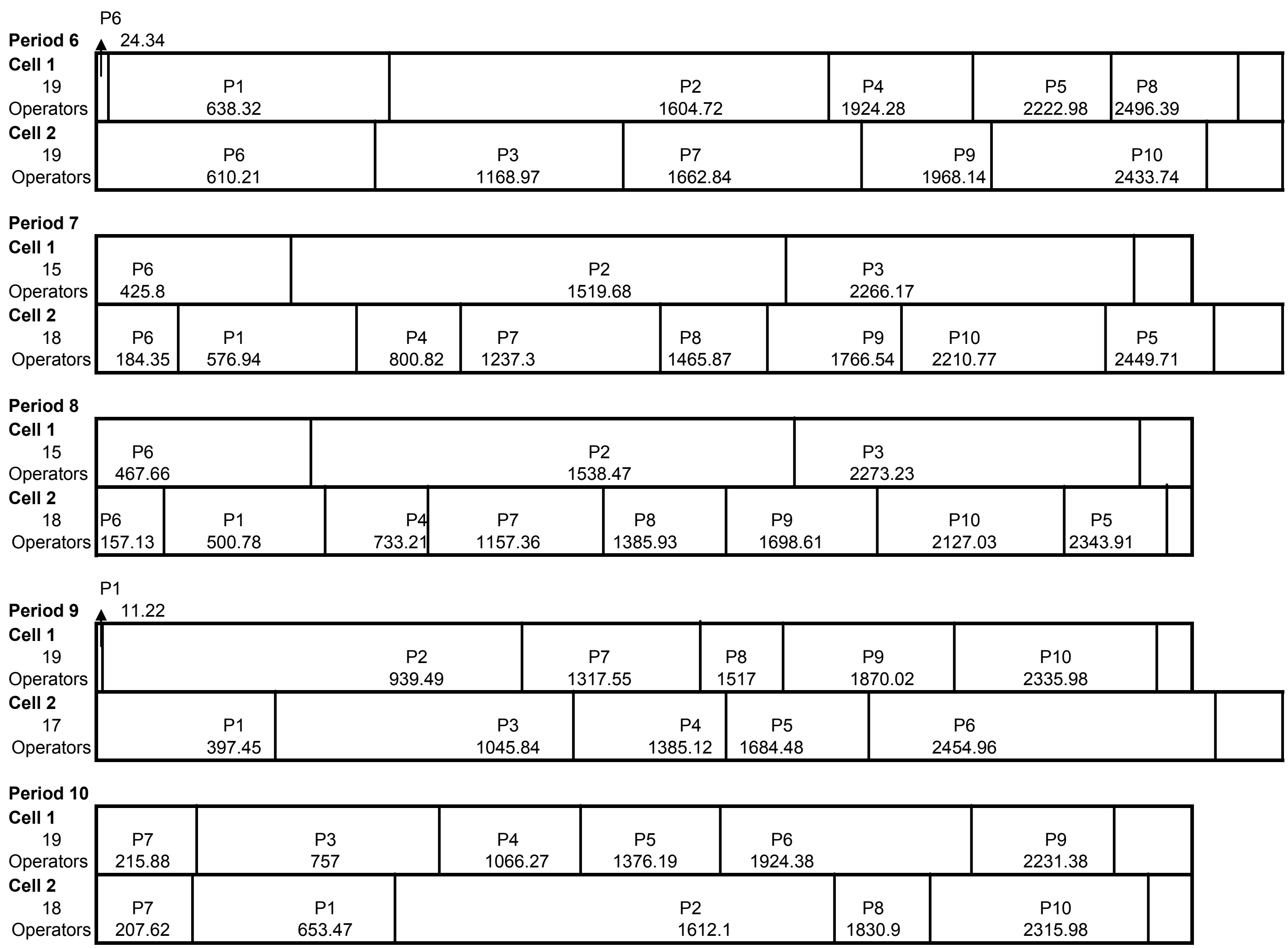


Figure 5.10 Contd.

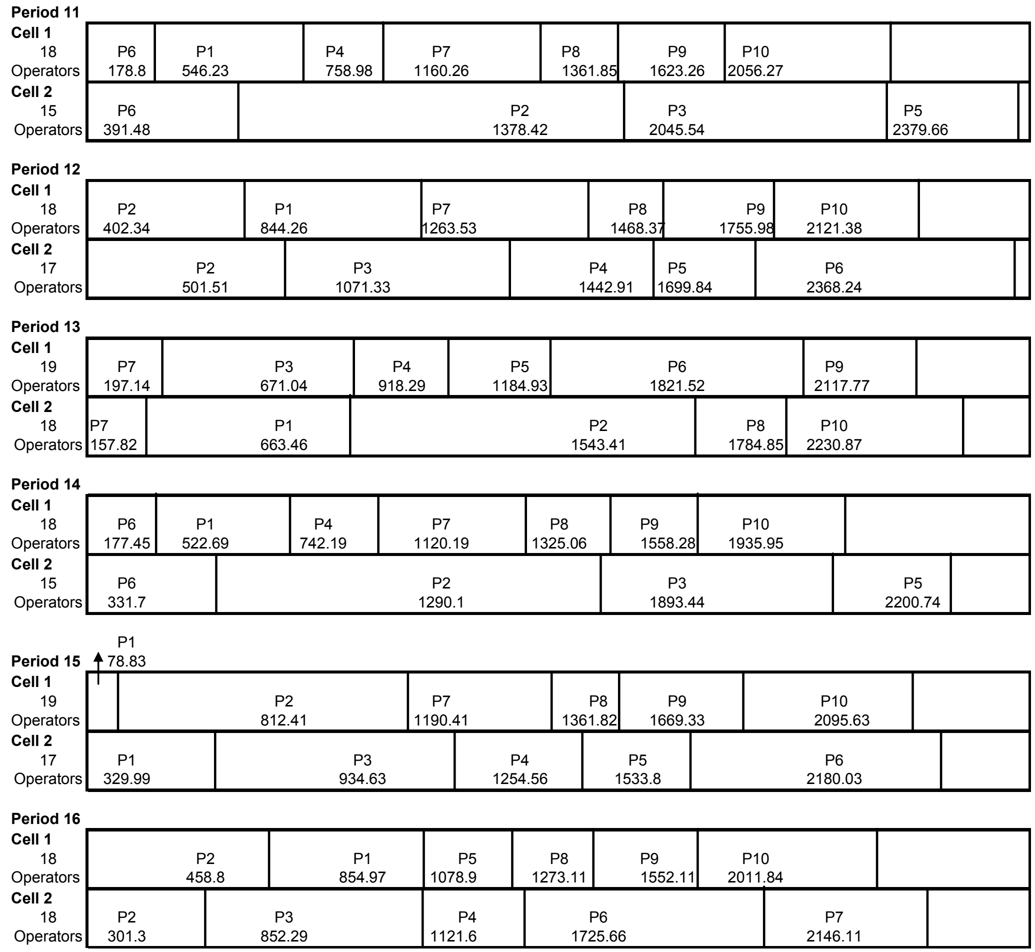
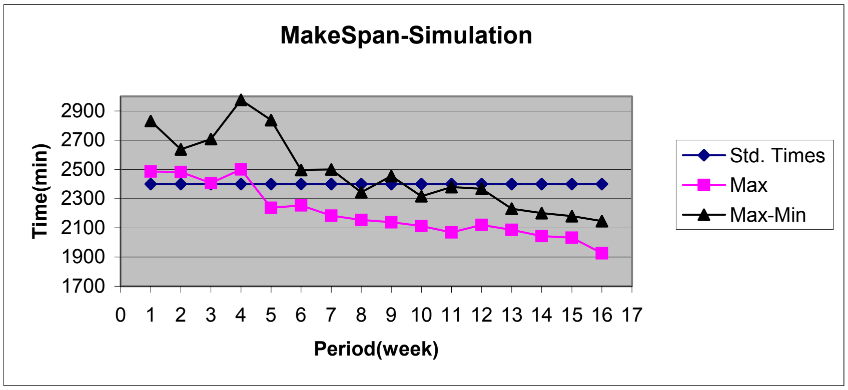


Figure 5.10 Revised Gantt charts using Max – Min approach (problem 3)

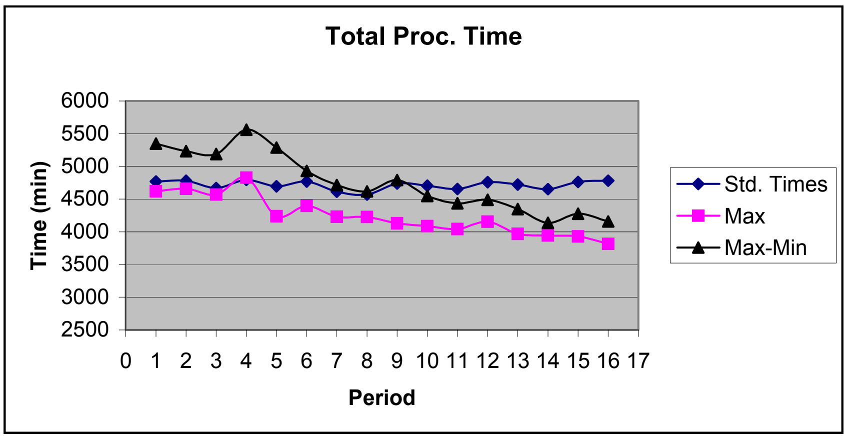
Table 5.5 Summary of gantt charts for multi – period analysis

	Makespan				Total Proc. Time		
Period	**Std. Times**	**Max**	**Max-Min**	**Period**	**Std. Times**	**Max**	**Max-Min**
1	2399.97	2486.39	2832.07	**1**	4768.36	4619.58	5348.21
2	2399.98	2482.64	2637.31	**2**	4780.62	4658.02	5233.17
3	2399.97	2407.03	2708.29	**3**	4669.3	4568.31	5188.01
4	2399.95	2500.31	2976.71	**4**	4793.47	4827.51	5560.81
5	2399.92	2237.59	2838.09	**5**	4694.71	4237.22	5286.89
6	2399.98	2253.4	2496.39	**6**	4767.72	4395.5	4930.13
7	2399.99	2183.59	2499.71	**7**	4613.17	4230.41	4715.88
8	2399.99	2154.42	2343.91	**8**	4567.86	4225.26	4617.14
9	2399.98	2138.45	2454.96	**9**	4737.55	4128.28	4790.94
10	2400	2112.48	2315.98	**10**	4703.94	4087.21	4547.36
11	2399.96	2068.89	2379.66	**11**	4654.14	4041.63	4435.93
12	2399.94	2120.7	2368.24	**12**	4758.71	4154.38	4489.62
13	2399.97	2086.78	2230.87	**13**	4721.29	3969.11	4348.64
14	2399.99	2044	2200.74	**14**	4651.85	3942.26	4136.69
15	2400	2032.4	2180.03	**15**	4761.58	3929.75	4275.66
16	2400	1925.78	2146.11	**16**	4780.74	3814.61	4157.95

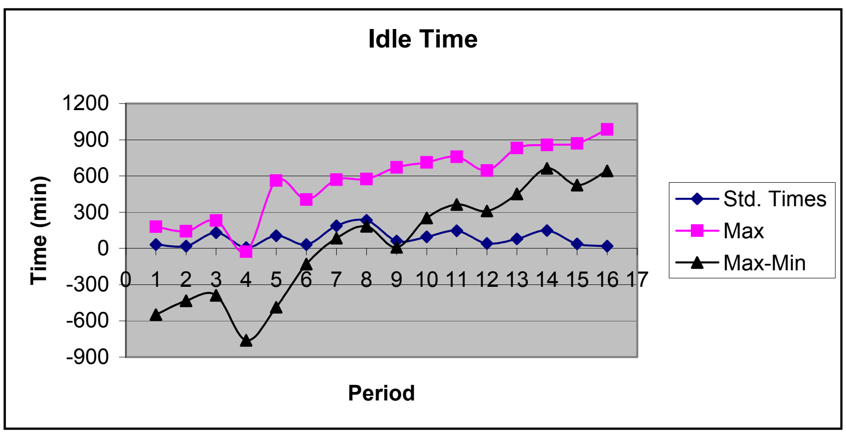
	Idle Time		
Period	**Std. Times**	**Max**	**Max-Min**
1	31.64	180.42	-548.21
2	19.38	141.98	-433.17
3	130.7	231.69	-388.01
4	6.53	-27.51	-760.81
5	105.29	562.78	-486.89
6	32.28	404.5	-130.13
7	186.83	569.59	84.12
8	232.14	574.74	182.86
9	62.45	671.72	9.06
10	96.06	712.79	252.64
11	145.86	758.37	364.07
12	41.29	645.62	310.38
13	78.71	830.89	451.36
14	148.15	857.74	663.31
15	38.42	870.25	524.34
16	19.26	985.39	642.05



5.11.a. Makespan



5.11.b Total Proc. Time



5.11.c Idle Time

Figure 5.11 Graphs for a. Makespan, b. Total Proc. Time and c. Idle Time considering operator assignment approaches

5.2.2 Effect on Operator Skills

Operator skill matrix changes for every period according to the operator learning and forgetting rates and the type of operator assignment approach used. Each operator improves or deteriorates his skill level according to the number of periods he works on an operation and the probability that his skill level is changed (Chapter 4). Table 5.7 and table 5.8 show the operator learning and forgetting matrices when Max approach and Max –Min approach are used to assign the operators to the operations. The bold numbers denote that, at the end of the period the operator changes his skill level. It can be observed that more operators are assigned to multiple operations when Max – Min approach is used. This is an advantage because the operators can maintain or improve their skills as the product mix changes. Table 5.6 shows the number of operators for each skill level at the end of simulation. Figure 5.12 shows the graph plotted for the number of operators at a particular skill at the end of simulation. Figure 5.13 and figure 5.14 show the graphs plotted for the cumulative number of best skills and second best skills for the operators in the simulation period. It can be observed that at the end of simulation, operators with below average skills deteriorated their skills and average and above average skilled operators improved their skills when Max approach is used to assign the operators justifying our assumption that it allows the operators to excel in what they are already good at. But Max – Min approach improved the skills even for below average skilled operators. In fact, there were no operators with skill level less than 7. For this particular problem, both Max and Max – Min approaches produced similar kind of results in the improvement of best skills for operators. But, Max –Min approach gave better performance than Max approach in the improvement of the second best skills for the operators. So, it can be concluded that even though in the earlier periods Max – Min approach does not show great results, in the long term it performs better than the classical approach using standard times and Max approach. Table 5.9 shows the bottleneck operations, times and operator skill levels for product combinations in period 15 when Max and Max – Min approaches are used. Even though, at the end of simulation, Max – Min approach gave better improvement in operator skill levels than Max approach, the idle time for the cellular system was more when Max approach was used. This is happening because there are enough operators with better skill levels (skill level 1 – skill level 6) to perform the operations which can be observed in table 5.9. But, there might be a need for more operator skills when the product mix changes or demand increases. Then Max – Min approach is expected to give better results than Max approach.

Table 5.6 # of operators for each skill level at the end of simulation

	# of operators		
Skill Level	Initial	Max	Max-Min
1	2	3	5
2	3	5	3
3	5	11	21
4	16	22	28
5	28	17	21
6	16	8	2
7	7	6	0
8	2	5	0
9	1	3	0

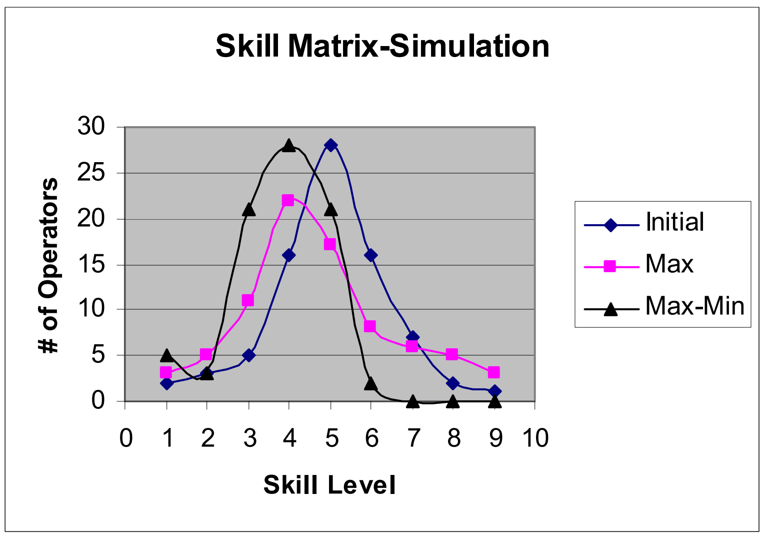


Figure 5.12 Graph for Skill Matrix – Simulation

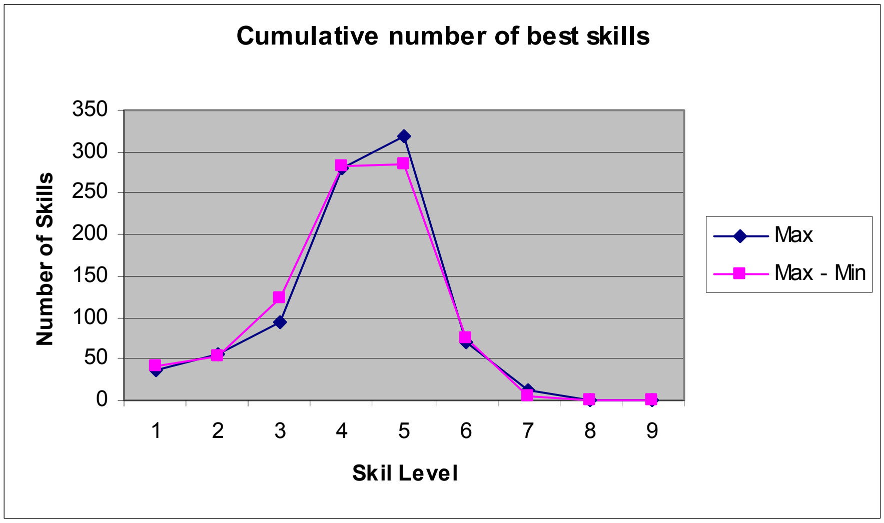


Figure 5.13 Graph for cumulative number of best skills for the operators

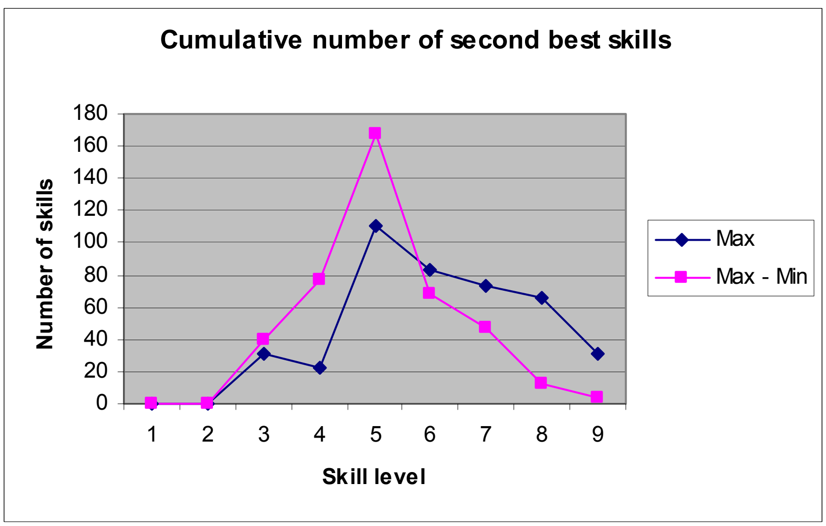


Figure 5.14 Graph for cumulative number of second best skills for the operators

Table 5.7 Operator learning and forgetting matrix – Max approach

Operator	Operation	Period															
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1	4	A/5	A/5	A/5	NA/5	A/5	A/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	A/5	NA/5	NA/5	NA/5
	5	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4	A/4	A/4	A/4	A/4	A/4	A/4	**A/4**	A/3	A/3
2	2	A/4	A/4	A/4	A/4	A/4	A/4	A/4	**A/4**	A/3	A/3	A/3	A/3	A/3	A/3	A/3	A/3
	3	NA/5	A/5	NA/5	NA/5	NA/5	NA/5	A/5	A/5	NA/5	NA/5	NA/5	NA/5	**NA/5**	NA/6	NA/6	NA/6
3	2	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	**NA/5**	NA/6	NA/6	NA/6	NA/6	NA/6	NA/6	NA/6	NA/6
	3	A/3	A/3	A/3	A/3	A/3	A/3	A/3	A/3	A/3	**A/3**	A/2	A/2	A/2	A/2	A/2	A/2
4	2	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	**NA/5**	NA/6	NA/6	NA/6	NA/6	**NA/6**	NA/7	NA/7	NA/7	NA/7
	4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	**A/4**	A/3	A/3	A/3	A/3	A/3	A/3
5	3	A/6	A/6	A/6	**A/6**	A/5	A/5	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4	A/4	A/4	A/4
	5	NA/7	NA/7	NA/7	NA/7	NA/7	NA/7	NA/7	**NA/7**	NA/8	NA/8	NA/8	NA/8	NA/8	NA/8	NA/8	NA/8
6	2	A/6	A/6	A/6	**A/6**	A/5	A/5	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4	A/4	A/4	A/4
	3	A/6	A/6	A/6	A/6	NA/6	NA/6	A/6	A/6	A/6	A/6	A/6	NA/6	NA/6	A/6	A/6	A/6
7	1	A/7	A/7	NA/7	A/7	**A/7**	NA/6	A/6	A/6	A/6	A/6	A/6	A/6	A/6	**A/6**	A/5	A/5
	3	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4
8	2	NA/7	NA/7	NA/7	NA/7	**NA/7**	NA/8	NA/8	NA/8	NA/8	NA/8	NA/8	NA/8	NA/8	NA/8	A/8	NA/8
	3	A/6	A/6	A/6	**A/6**	A/5	A/5	A/5	A/5	A/5	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4
9	2	NA/5	NA/5	NA/5	NA/5	NA/5	**NA/5**	NA/6	NA/6	NA/6	NA/6	**NA/6**	NA/7	NA/7	NA/7	NA/7	NA/7
	4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	**A/4**	A/3	A/3	A/3	A/3	A/3	A/3	A/3	A/3
10	3	NA/6	NA/6	NA/6	NA/6	NA/6	NA/6	NA/6	NA/6	**NA/6**	NA/7	NA/7	NA/7	NA/7	NA/7	NA/7	NA/7
	5	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2
11	1	NA/3	A/3	NA/3	A/3	A/3	A/3	NA/3	NA/3	NA/3	NA/3	A/3	NA/3	NA/3	A/3	NA/3	A/3
	4	A/1	A/1	A/1	A/1	A/1	A/1	A/1	A/1	A/1	A/1	A/1	A/1	A/1	A/1	A/1	A/1
12	2	A/5	A/5	A/5	NA/5	A/5	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4	A/4	A/4	A/4	A/4
	3	NA/7	NA/7	NA/7	NA/7	NA/7	**NA/7**	NA/8	NA/8	NA/8	NA/8	NA/8	**NA/8**	NA/9	NA/9	NA/9	NA/9
13	4	A/6	A/6	A/6	NA/6	NA/6	NA/6	NA/6	NA/6	**NA/6**	NA/7	NA/7	NA/7	NA/7	NA/7	NA/7	NA/7
	5	A/6	A/6	A/6	**A/6**	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4	A/4	A/4	A/4	A/4	A/4
14	2	NA/5	NA/5	NA/5	NA/5	A/5	NA/5	NA/5	NA/5	NA/5	A/5	NA/5	NA/5	**NA/5**	NA/6	NA/6	NA/6
	3	A/4	A/4	A/4	A/4	A/4	A/4	A/4	**A/4**	A/3	A/3	A/3	A/3	A/3	A/3	A/3	A/3
15	3	NA/5	A/5	NA/5	A/5	NA/5	A/5	A/5	A/5	A/5	NA/5	A/5	NA/5	NA/5	A/5	NA/5	NA/5
	4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	**A/4**	A/3	A/3	A/3	A/3
16	2	NA/9	NA/9	NA/9	NA/9	NA/9	NA/9	NA/9	NA/9	NA/9	NA/9	NA/9	NA/9	NA/9	NA/9	NA/9	NA/9
	4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	**A/4**	A/3	A/3	A/3	A/3	A/3	A/3	A/3
17	2	NA/8	NA/8	NA/8	NA/8	NA/8	NA/8	NA/8	NA/8	NA/8	NA/8	NA/8	NA/8	NA/8	NA/8	NA/8	NA/8
	3	A/7	A/7	A/7	**A/7**	A/6	A/6	A/6	**A/6**	A/5	A/5	A/5	A/5	A/5	A/5	A/5	A/5
18	1	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4
	3	NA/4	A/4	NA/4	A/4	A/4	A/4	NA/4	NA/4	NA/4	NA/4	A/4	NA/4	NA/4	A/4	NA/4	A/4
19	3	A/6	A/6	A/6	**A/6**	A/5	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4	A/4	A/4	A/4	A/4
	5	A/6	A/6	A/6	A/6	**A/6**	A/5	A/5	A/5	A/5	A/5	A/5	A/5	A/5	A/5	A/5	A/5
20	2	A/4	NA/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	NA/4	NA/4
	4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	**A/4**	A/3

Table 5.7 Contd.

Operator	Operation	Period															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
21	3	A/6	A/6	A/6	A/6	A/6	**A/6**	A/5	A/5	A/5	A/5	A/5	A/5	A/5	A/5	A/5	A/5
	4	NA/8	NA/8	NA/8	NA/8	**NA/8**	NA/9	NA/9	NA/9	NA/9	NA/9	NA/9	NA/9	NA/9	NA/9	NA/9	NA/9
22	4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	**A/4**	A/3	A/3	A/3	A/3	A/3	A/3	A/3	A/3
	5	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	NA/4	NA/4	NA/4	A/4	NA/4	NA/4	A/4	A/4
23	3	NA/4	NA/4	NA/4	NA/4	NA/4	NA/4	**NA/4**	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	**NA/5**	NA/6	NA/6
	4	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2
24	4	A/5	NA/5	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4
	5	A/5	A/5	A/5	A/5	A/5	A/5	**A/5**	NA/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4
25	2	A/6	A/6	A/6	A/6	**A/6**	A/5	A/5	A/5	A/5	A/5	A/5	A/5	A/5	A/5	A/5	A/5
	3	A/6	A/6	A/6	**A/6**	A/5	A/5	A/5	A/5	A/5	A/5	A/5	A/5	A/5	A/5	A/5	A/5
26	2	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4
	4	NA/5	A/5	A/5	A/5	NA/5	A/5	A/5	NA/5	A/5	NA/5	NA/5	A/5	A/5	A/5	A/5	A/5
27	1	A/6	A/6	A/6	**A/6**	A/5	A/5	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4	A/4	A/4	A/4
	4	A/4	A/4	NA/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4
28	3	A/5	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4
	5	A/5	A/5	A/5	A/5	A/5	NA/5	A/5	A/5	A/5	A/5	NA/5	A/5	A/5	A/5	A/5	A/5
29	2	A/3	A/3	A/3	A/3	A/3	A/3	A/3	A/3	A/3	A/3	A/3	A/3	A/3	A/3	**A/3**	A/2
	4	NA/6	NA/6	NA/6	NA/6	**NA/6**	NA/7	NA/7	NA/7	NA/7	NA/7	NA/7	NA/7	NA/7	NA/7	NA/7	NA/7
30	3	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	**A/2**	A/1	A/1	A/1
	5	NA/3	NA/3	NA/3	NA/3	NA/3	NA/3	NA/3	NA/3	A/3	NA/3	A/3	NA/3	NA/3	NA/3	**NA/3**	NA/4
31	3	NA/7	NA/7	NA/7	NA/7	**NA/7**	NA/8	NA/8	NA/8	NA/8	NA/8	NA/8	NA/8	NA/8	NA/8	NA/8	NA/8
	5	A/5	A/5	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4
32	4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	NA/4	NA/4
	5	A/4	A/4	A/4	NA/4	A/4	A/4	NA/4	A/4	A/4	A/4	A/4	**A/4**	A/3	A/3	A/3	A/3
33	1	NA/6	NA/6	NA/6	NA/6	NA/6	**NA/6**	NA/7	NA/7	NA/7	NA/7	NA/7	NA/7	NA/7	NA/7	NA/7	NA/7
	4	A/3	A/3	A/3	A/3	A/3	A/3	A/3	A/3	A/3	A/3	A/3	A/3	**A/3**	A/2	A/2	A/2
34	3	A/5	A/5	A/5	NA/5	A/5	A/5	NA/5	NA/5	**A/5**	A/4	NA/4	A/4	A/4	NA/4	A/4	A/4
	4	NA/6	NA/6	NA/6	NA/6	A/6	A/6	NA/6	NA/6	A/6	NA/6	NA/6	NA/6	A/6	NA/6	A/6	NA/6
35	4	A/5	A/5	A/5	NA/5	A/5	A/5	NA/5	NA/5	A/5	A/5	NA/5	A/5	A/5	NA/5	A/5	A/5
	5	NA/7	NA/7	NA/7	NA/7	NA/7	NA/7	**NA/7**	NA/8	NA/8	NA/8	NA/8	NA/8	NA/8	NA/8	NA/8	NA/8
36	2	NA/1	A/1	A/1	NA/1	NA/1	A/1	NA/1	NA/1	A/1	A/1	NA/1	NA/1	A/1	NA/1	A/1	A/1
	4	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	**NA/5**	NA/6	NA/6	NA/6	NA/6	NA/6	NA/6	NA/6	NA/6
37	3	NA/5	NA/5	A/5	NA/5	NA/5	A/5	NA/5	NA/5	NA/5	A/5	NA/5	NA/5	A/5	NA/5	NA/5	NA/5
	5	NA/5	NA/5	A/5	NA/5	NA/5	A/5	NA/5	NA/5	NA/5	A/5	NA/5	NA/5	A/5	**NA/5**	NA/6	NA/6
38	3	NA/5	NA/5	NA/5	NA/5	NA/5	A/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5
	4	NA/4	NA/4	NA/4	NA/4	NA/4	A/4	NA/4	NA/4	NA/4	NA/4	NA/4	NA/4	NA/4	NA/4	NA/4	NA/4
39	4	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5
	5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5
40	4	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5
	5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5

Table 5.8 Operator learning and forgetting matrix –Max – Min approach

Operator	Operation	Period															
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1	4	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4	A/4	A/4	A/4	A/4	A/4	A/4	**A/4**	A/3	A/3
	5	A/5	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4
2	2	NA/4	A/4	A/4	NA/4	NA/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	**A/4**	NA/3
	3	A/5	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4
3	2	A/5	A/5	A/5	NA/5	A/5	A/5	NA/5	NA/5	A/5	A/5	NA/5	A/5	**A/5**	NA/4	A/4	A/4
	3	A/3	A/3	A/3	A/3	A/3	A/3	A/3	A/3	A/3	**A/3**	A/2	A/2	A/2	A/2	A/2	A/2
4	2	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4	A/4	NA/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4
	4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	**A/4**	A/3	A/3	A/3	A/3	A/3	A/3	A/3	A/3
5	3	A/6	A/6	A/6	NA/6	A/6	A/6	NA/6	NA/6	A/6	A/6	**A/6**	A/5	A/5	NA/5	A/5	A/5
	5	A/7	A/7	A/7	**A/7**	A/6	A/6	A/6	A/6	**A/6**	NA/5	A/5	A/5	A/5	A/5	A/5	A/5
6	2	A/6	A/6	A/6	**A/6**	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4	NA/4	A/4	A/4	A/4	A/4
	3	A/6	A/6	A/6	A/6	**A/6**	A/5	A/5	A/5	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4	A/4
7	1	A/7	A/7	A/7	**A/7**	A/6	A/6	NA/6	A/6	A/6	**A/6**	A/5	A/5	A/5	A/5	A/5	A/5
	3	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	NA/4	A/4
8	2	A/7	A/7	A/7	A/7	**A/7**	A/6	A/6	A/6	**A/6**	A/5	A/5	A/5	A/5	A/5	A/5	A/5
	3	A/6	A/6	A/6	**A/6**	A/5	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4	A/4	A/4	A/4	A/4
9	2	A/5	A/5	A/5	A/5	A/5	A/5	**A/5**	NA/4	A/4	A/4	NA/4	A/4	A/4	A/4	NA/4	A/4
	4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	**A/4**	A/3	A/3	A/3	A/3	A/3	A/3	A/3
10	3	A/6	A/6	A/6	A/6	A/6	**A/6**	A/5	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4	A/4	A/4
	5	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	**A/2**	A/1	A/1	A/1	A/1
11	1	NA/3	A/3	NA/3	NA/3	NA/3	A/3	A/3	A/3	NA/3	A/3	A/3	NA/3	NA/3	A/3	NA/3	A/3
	4	A/1	A/1	A/1	A/1	A/1	A/1	A/1	A/1	A/1	A/1	A/1	A/1	A/1	A/1	A/1	A/1
12	2	A/5	A/5	NA/5	A/5	A/5	A/5	A/5	**A/5**	A/4	A/4	A/4	A/4	A/4	A/4	NA/4	NA/4
	3	A/7	A/7	A/7	A/7	**A/7**	A/6	A/6	A/6	**A/6**	A/5	A/5	A/5	A/5	A/5	A/5	A/5
13	4	A/6	A/6	A/6	**A/6**	A/5	A/5	A/5	A/5	A/5	A/5	**A/5**	NA/4	A/4	A/4	A/4	A/4
	5	A/6	A/6	A/6	A/6	**A/6**	A/5	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4	A/4	A/4	A/4
14	2	A/5	A/5	A/5	A/5	NA/5	A/5	A/5	**A/5**	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4
	3	A/4	A/4	A/4	A/4	A/4	A/4	A/4	**A/4**	A/3	A/3	A/3	A/3	A/3	A/3	A/3	A/3
15	3	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4
	4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	NA/4	A/4	**A/4**	A/3	A/3	A/3	A/3	A/3	A/3
16	2	A/9	A/9	A/9	**A/9**	A/8	A/8	A/8	**A/8**	A/7	A/7	A/7	**A/7**	A/6	A/6	A/6	A/6
	4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	**A/4**	A/3	A/3	A/3	NA/3	A/3	A/3	A/3
17	2	A/8	A/8	A/8	A/8	**A/8**	A/7	A/7	A/7	**A/7**	A/6	A/6	A/6	**A/6**	A/5	A/5	A/5
	3	A/7	A/7	A/7	**A/7**	NA/6	A/6	A/6	A/6	A/6	**A/6**	A/5	A/5	A/5	A/5	A/5	A/5
18	1	A/5	A/5	A/5	NA/5	A/5	A/5	A/5	A/5	**A/5**	A/4	NA/4	A/4	A/4	NA/4	A/4	A/4
	3	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	**A/4**	A/3	A/3	A/3	A/3	A/3	A/3	A/3
19	3	A/6	A/6	A/6	A/6	A/6	A/6	NA/6	**A/6**	A/5	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4
	5	A/6	A/6	A/6	**A/6**	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4	A/4	NA/4	A/4	A/4	A/4
20	2	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	**A/4**	A/3	A/3	A/3	A/3	A/3
	4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	**A/4**	A/3	A/3	A/3	A/3	A/3	A/3	A/3	A/3

Table 5.8 Contd.

Operator	Operation	Period															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
21	3	A/6	NA/6	A/6	NA/6	A/6	A/6	NA/6	NA/6	A/6	A/6	A/6	A/6	A/6	A/6	**A/6**	NA/5
	4	A/8	A/8	A/8	**A/8**	A/7	A/7	A/7	**A/7**	A/6	A/6	A/6	**A/6**	A/5	A/5	A/5	A/5
22	4	A/4	NA/4	A/4	NA/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	**A/4**	A/3	A/3	A/3
	5	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	**A/4**	A/3	A/3	A/3	A/3	A/3	A/3
23	3	A/4	A/4	A/4	A/4	A/4	A/4	A/4	**A/4**	A/3	A/3	A/3	A/3	A/3	A/3	A/3	A/3
	4	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	**A/2**	A/1
24	4	A/5	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4	A/4	A/4	A/4	A/4	A/4	A/4	**A/4**	A/3
	5	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4	A/4	A/4	A/4	A/4	A/4	A/4	**A/4**	A/3	A/3
25	2	A/6	A/6	A/6	A/6	**A/6**	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4	A/4	A/4	A/4	A/4
	3	A/6	A/6	A/6	**A/6**	A/5	A/5	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4	A/4	A/4	A/4
26	2	A/5	A/5	A/5	A/5	A/5	**A/5**	NA/4	NA/4	A/4	A/4	A/4	A/4	NA/4	NA/4	A/4	NA/4
	4	A/5	A/5	A/5	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4	A/4	A/4	A/4	A/4	A/4	A/4
27	1	A/6	A/6	A/6	A/6	A/6	**A/6**	A/5	A/5	A/5	A/5	NA/5	A/5	A/5	A/5	**A/5**	A/4
	4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	**A/4**	A/3	A/3	A/3	A/3	A/3
28	3	A/5	A/5	A/5	A/5	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4	A/4	A/4	A/4	A/4	A/4
	5	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	**A/4**	A/3
29	2	A/3	A/3	A/3	A/3	A/3	A/3	A/3	A/3	A/3	A/3	A/3	A/3	A/3	**A/3**	A/2	A/2
	4	A/6	A/6	A/6	**A/6**	A/5	A/5	A/5	A/5	A/5	**A/5**	A/4	A/4	A/4	A/4	A/4	A/4
30	3	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	A/2	**A/2**	A/1	A/1	A/1
	5	A/3	A/3	A/3	NA/3	A/3	A/3	NA/3	NA/3	A/3	A/3	NA/3	A/3	A/3	NA/3	A/3	A/3
31	3	A/7	A/7	A/7	A/7	A/7	A/7	**A/7**	A/6	A/6	A/6	A/6	**A/6**	A/5	A/5	A/5	A/5
	5	A/5	A/5	A/5	A/5	A/5	A/5	A/5	A/5	A/5	NA/5	**A/5**	A/4	NA/4	A/4	A/4	A/4
32	4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	A/4	**A/4**	A/3	A/3	A/3	A/3
	5	A/4	A/4	A/4	A/4	A/4	A/4	A/4	**A/4**	A/3	A/3	A/3	A/3	A/3	A/3	A/3	A/3
33	1	A/6	A/6	A/6	A/6	**A/6**	A/5	A/5	A/5	NA/5	A/5	A/5	A/5	**A/5**	A/4	NA/4	A/4
	4	A/3	A/3	A/3	A/3	A/3	A/3	A/3	A/3	A/3	A/3	**A/3**	A/2	A/2	A/2	A/2	A/2
34	3	A/5	A/5	A/5	NA/5	A/5	A/5	NA/5	NA/5	A/5	A/5	NA/5	A/5	A/5	NA/5	A/5	A/5
	4	A/6	A/6	A/6	NA/6	**A/6**	A/5	NA/5	NA/5	A/5	A/5	NA/5	A/5	A/5	NA/5	A/5	A/5
35	4	NA/5	A/5	A/5	NA/5	NA/5	A/5	NA/5	NA/5	NA/5	A/5	NA/5	A/5	A/5	NA/5	A/5	A/5
	5	A/7	A/7	A/7	NA/7	A/7	A/7	NA/7	NA/7	A/7	**A/7**	NA/6	A/6	A/6	NA/6	A/6	A/6
36	2	NA/1	A/1	A/1	NA/1	NA/1	A/1	NA/1	NA/1	A/1	A/1	NA/1	NA/1	A/1	NA/1	A/1	A/1
	4	NA/5	A/5	A/5	NA/5	NA/5	A/5	NA/5	NA/5	A/5	A/5	NA/5	NA/5	A/5	NA/5	A/5	A/5
37	3	NA/5	NA/5	A/5	NA/5	NA/5	A/5	NA/5	NA/5	NA/5	A/5	NA/5	NA/5	A/5	NA/5	NA/5	NA/5
	5	NA/5	NA/5	A/5	NA/5	NA/5	A/5	NA/5	NA/5	NA/5	A/5	NA/5	NA/5	A/5	NA/5	NA/5	NA/5
38	3	NA/5	NA/5	NA/5	NA/5	NA/5	A/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5
	4	NA/4	NA/4	NA/4	NA/4	NA/4	A/4	NA/4	NA/4	NA/4	NA/4	NA/4	NA/4	NA/4	NA/4	NA/4	NA/4
39	4	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5
	5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5
40	4	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5
	5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5	NA/5

Table 5.9 Bottleneck operations, times and operator skill levels for product combinations in Period 15

Period 15/Max				Period 15/Max - Min			
Product Comb.	**Product**	**Bottleneck Op. Time**	**Operator skill Levels**	**Product Comb.**	**Product**	**Bottleneck Op. Time**	**Operator skill Levels**
P1-P1	P1	op4/0.1066	3,3,4,4,4,5,6	**P1-P1**	P1	op3/0.1104	4,4,5
	P1	op3/0.1165	4,5,5		P1	op3/0.1289	5,5,6
P2-P1	P2	op4/0.1002	3,3,4,4,4,5	**P2-P1**	P2	op4/0.1133	4,4,4,5,5,5
	P1	op3/0.1233	5,5,5		P1	op3/0.1104	4,4,5
P2-P3	P2	op4/0.0992	3,3,3,4,5,5	**P2-P3**	P2	op4/0.1064	3,4,4,4,5,5
	P3	op3/0.1567	4,4,4,5,5,5,5		P3	op3/0.1634	4,4,5,5,5,5,6
P7-P3	P7	op1/0.0765	4	**P7-P3**	P7	op1/0.09	5
	P3	op3/0.1567	4,4,4,5,5,5,5		P3	op3/0.1634	4,4,5,5,5,5,6
P7-P4	P7	op1/0.0765	4	**P7-P4**	P7	op1/0.09	5
	P4	op3/0.1027	4,4,5,5,5		P4	op3/0.1063	4,5,5,5,5
P8-P4	P8	op1/0.0685	4	**P8-P4**	P8	op1/0.08	5
	P4	op3/0.1063	4,5,5,5,5		P4	op2/0.108	5,5,6
P9-P4	P9	op3/0.1076	4,4,4,5,5,5,5	**P8-P5**	P8	op2/0.0976	5,5,6
	P4	op4/0.0934	3,3,4,5		P5	op4/0.1165	4,4,5,5,5,5
P9-P5	P9	op2/0.0963	4,4,4	**P9-P5**	P9	op2/0.1116	4,5,6
	P5	op3/0.1075	5,5,5,5		P5	op2/0.1162	4,4,4
P10-P5	P10	op5/0.1218	4,4,4	**P9-P6**	P9	op3/0.1121	4,4,5,5,5,5,6
	P5	op2/0.1223	4,4,5		P6	op5/0.1477	4,5,6
P10-P6	P10	op3/0.1224	4,5,5,5,5,6	**P10-P6**	P10	op2/0.1218	4,4,4
	P6	op2/0.136	4,4		P6	op2/0.1712	5,6

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

This thesis makes an effort to assign operators to operations and cells based on operator skill levels and operator – operation times as opposed to the classical approach of using standard times by considering cell loading strategies like lot splitting and operator sharing, and operator learning and forgetting. Three different approaches (max, max – min and max – max) are proposed to assign the operators to operations. A standard deviation of 15% of mean is used in operator time matrix for all the experimentation. This can be justified from the results obtained by testing the effect of variability. It can be seen that the cell performance does not follow any trend to the change in variability. So, even if the time study follows a different criterion to allocate skill levels to operators, it can be concluded that operator assignment by max approach is expected to give a better cell performance than the classical approach of using standard times.

In real life labor intensive cellular manufacturing environment, cell operator is not proficient in every operation. He has better skills in performing some operations than others. In this thesis, cell performance is compared by assigning 2 skills and 3 skills to each operator. The results showed that when operators have 3 skills, cell performance was better. So, it can be concluded that if every operator has knowledge of every operation or proficient in more than one operation, max approach gives a better cell performance. This can be obtained by cross training the operators, thus increasing the flexibility.

In cellular manufacturing, it is not feasible to keep all the parts and operators in a single cell because of the management and space problems, potential bottlenecks and scheduling difficulties. It will be more practical to divide the cell into two or more cells and allocate products and operators to them. It is also possible to divide the product lot between two cells and allow operators to be shared between the operations and cells. This thesis provides the methodology to find the optimal cell sizes and loads. The results show that for the specific problem considered in the thesis, by allowing lot splitting and operator sharing, and using max approach to assign the operators, cell performance was optimal. This can be generalized for every labor intensive cellular manufacturing system, but the manager can choose the best case of the four cases considered (allowing and not allowing lot splitting and operator sharing) to suit the cell environment depending on the complexity in the various stages of cellular manufacturing.

A single period analysis is done to compare the three proposed approaches (max, max – min and max – max) for assigning the operators considering a larger version of the problem having more products and operators. It is observed that even though max and max – max approaches gave better cell performance when compared to max – min, the main drawback of max and max – max approaches was that operators were assigned to operations that they were already good at, whereas max – min approach assigned operators to multiple operations. To test the cell performance and effect on operator skills in a multi period environment, experimentation was done considering max and max –

min approaches. Results showed that cell performance improved at a faster rate when max – min approach was used and this operator assignment approach has significant and substantial potential for increasing overall operator productivity. The planner can choose between max and max –min approaches depending on whether he wants to improve the cell performance only for that specific period or he wants to improve the operator skill level and cell performance in the long run. These approaches also help in forecasting the cell performance if there is no new hiring and quitting.

6.2 Future Research

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

- Job preferences – Operators tend to have preferences in performing operations. They tend to do better when they are allocated to their choice of operation. Thus, improving their over all productivity. In real life it is not possible to allocate every operator to their choice of operation but using a similar methodology of allocating the operators by maximizing the skills available with the skills needed used in this thesis, we can study job preferences in a manufacturing environment.
- New hiring and quitting – This thesis assumes that there is no new hiring and quitting of operators when performing the multi period analysis. Cell performance can vary depending on this specific issue and is needed to experiment with.
- Product mix variability – In manufacturing industries, product types keep changing from one period to another. In this thesis, product types coming into the system remain the same where as their demands vary through out the time period.

Even though, it is believed that the methodology adopted in this thesis holds good for product mix variability, it should be experimented with.

- It is observed that some non - bottleneck operations after implementing the proposed approaches change in to bottleneck operations. This study can be extended to restrict it.
- A mathematical model was used to allow lot splitting for determining optimal cell sizes and cell loads. But, the objective was only to minimize the number of operators. This study can be further extended by developing a mathematical model to simultaneously minimize the makespan and total number of operators.
- In this thesis, either Max or Max – Min operator assignment approach was used throughout the simulation period. This thesis can be further extended by using both the approaches intermittently.

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APPENDIX A OPTIMAL PRODUCTION RATES AND P_{ijk} VALUES FOR ALL PROBLEMS CONSIDERED

A1.Optimal Production Rates and # Operators for alterative configurations for problem 1 (Operator Sharing not allowed)

		Operations						
Product	**Alternative Operator Level**	**Op 1**	**Op 2**	**Op 3**	**Op 4**	**Op 5**	**Production Rate(per minute)**	**P_{ijk} values**
1	**15**	1	3	3	5	3	5.68	616.20
	20	1	4	3	8	4	8.1	432.10
2	**15**	1	2	4	5	3	6.45	1162.79
	20	1	3	6	6	4	8.1	925.93
3	**15**	1	2	6	5	1	5.08	669.29
	20	1	2	9	6	2	6.89	493.47
4	**15**	1	3	4	4	3	7.27	371.39
	20	1	4	6	5	4	10	270.00
5	**15**	1	3	3	5	3	6.75	325.93
	20	1	4	4	7	4	9.3	236.56
6	**15**	1	2	6	3	3	5.08	787.40
	20	1	3	8	4	4	6.77	590.84
7	**15**	1	3	4	4	3	8.1	555.56
	20	1	5	5	6	3	10.8	416.67
8	**15**	1	2	4	5	3	7.14	308.12
	20	1	3	6	7	3	10.34	212.77
9	**15**	1	3	5	4	2	5.88	391.16
	20	1	3	7	6	3	8.64	266.20
10	**15**	1	2	4	5	3	4.65	645.16
	20	1	3	6	7	3	6.97	430.42

A2. Optimal Production Rates and # Operators for alterative configurations for problem 2

		Operations						
Product	**Alternative Operator Level**	**Op 1**	**Op 2**	**Op 3**	**Op 4**	**Op 5**	**Production Rate(per minute)**	**P_{ijk} values**
1	**15**	1	3	3	5	3	5.68	440.14
	20	1	4	3	8	4	8.1	308.64
	25	1	5	4	10	5	10.81	231.27
2	**15**	1	2	4	5	3	6.45	279.07
	20	1	3	6	6	4	8.1	222.22
	25	1	4	7	8	5	10.81	166.51
3	**15**	1	2	6	5	1	5.08	590.55
	20	1	2	9	6	2	6.89	435.41
	25	1	3	11	8	2	9.3	322.58
4	**15**	1	3	4	4	3	7.27	206.33
	20	1	4	6	5	4	10	150.00
	25	1	4	8	6	6	12.76	117.55
5	**15**	1	3	3	5	3	6.75	177.78
	20	1	4	4	7	4	9.3	129.03
	25	1	5	5	9	5	11.62	103.27
6	**15**	1	2	6	3	3	5.08	511.81
	20	1	3	8	4	4	6.77	384.05
	25	1	3	11	5	5	9.09	286.03
7	**15**	1	3	4	4	3	8.1	296.30
	20	1	5	5	6	3	10.8	222.22
	25	2	5	7	7	4	13.5	177.78
8	**15**	1	2	4	5	3	7.14	266.11
	20	1	3	6	7	3	10.34	183.75
	25	2	4	7	8	4	13.11	144.93
9	**15**	1	3	5	4	2	5.88	221.09
	20	1	3	7	6	3	8.64	150.46
	25	1	4	9	7	4	11.11	117.01
10	**15**	1	2	4	5	3	4.65	559.14
	20	1	3	6	7	3	6.97	373.03
	25	1	4	7	9	4	9.3	279.57
11	**15**	1	2	6	4	2	6.25	448.00
	20	1	3	8	6	2	8.69	322.21
	25	2	4	10	7	2	10.52	266.16
12	**15**	1	2	4	6	2	4.34	345.62
	20	1	3	6	8	2	6.2	241.94
	25	1	3	8	10	3	7.75	193.55
13	**15**	1	2	5	5	2	4.76	399.16
	20	1	3	7	6	3	6.38	297.81
	25	1	3	9	9	3	8.57	221.70
14	**15**	1	2	4	6	2	4.08	539.22
	20	1	3	6	8	2	5.71	385.29
	25	1	3	8	10	3	7.46	294.91
15	**15**	1	2	5	5	2	4.65	602.15
	20	1	3	7	6	3	6.38	438.87
	25	1	4	8	8	4	8.51	329.02

Table A2 Contd.

		Operations						
Product	Alternative Operator Level	Op 1	Op 2	Op 3	Op 4	Op 5	Production Rate(per minute)	P_{ijk} values
	20	1	3	7	6	3	6.38	438.87
	25	1	4	8	8	4	8.51	329.02
16	15	1	4	3	5	2	7.4	189.19
	20	2	5	4	6	3	9.83	142.42
	25	2	6	5	8	4	12.82	109.20
17	15	1	3	6	3	2	6.52	245.40
	20	1	4	9	4	2	8.69	184.12
	25	1	5	11	5	3	11.95	133.89
18	15	1	2	5	5	2	4.23	638.30
	20	1	2	6	8	3	6.12	441.18
	25	1	3	8	10	3	8.16	330.88
19	15	1	3	5	3	3	6.97	430.42
	20	1	4	6	4	5	9.75	307.69
	25	2	5	8	5	5	11.62	258.18
20	15	1	3	4	5	2	6.17	259.32
	20	1	4	6	7	2	8.64	185.19
	25	1	5	7	9	3	11.11	144.01
21	15	1	3	4	5	2	5.49	528.23
	20	1	4	5	7	3	7.69	377.11
	25	1	5	6	9	4	9.83	295.02
22	15	1	2	6	4	2	5.21	191.94
	20	1	3	8	5	3	6.95	143.88
	25	1	4	10	6	4	8.69	115.07
23	15	1	2	5	4	3	5.49	255.01
	20	1	3	7	5	4	7.69	182.05
	25	1	4	9	6	5	9.89	141.56
24	15	1	4	5	3	2	7.81	243.28
	20	1	5	7	4	3	10.93	173.83
	25	2	6	9	5	3	14.06	135.14
25	15	1	2	4	6	2	4.16	528.85
	20	1	3	6	8	2	6.2	354.84
	25	1	4	7	10	3	7.29	301.78
26	15	1	2	6	4	2	4.76	588.24
	20	1	2	8	6	3	6.89	406.39
	25	1	3	10	7	4	8.33	336.13
27	15	1	2	5	4	3	5.4	185.19
	20	1	3	7	5	4	7.81	128.04
	25	1	4	8	7	5	9.87	101.32
28	15	1	3	6	3	2	7.69	208.06
	20	1	5	8	3	3	10.34	154.74
	25	1	6	10	4	4	13.15	121.67
29	15	1	2	4	6	2	4.41	544.22
	20	1	3	5	8	3	5.88	408.16
	25	1	4	7	10	3	7.35	326.53
30	15	1	2	4	5	3	5.31	564.97
	20	1	3	5	7	4	7.44	403.23
	25	1	4	6	9	5	9.37	320.17

A3. Optimal Production Rates and # Operators for multi period analysis

Product	Alternative Operator Level	Operations					Production Rate(per minute)
		Op 1	Op 2	Op 3	Op 4	Op 5	
1	15	1	3	3	5	3	5.6818
	16	1	3	3	6	3	6.6667
	17	1	4	3	6	3	6.8182
	18	1	4	3	7	3	7.8947
	19	1	4	3	7	4	7.9545
	20	1	4	3	8	4	8.1081
2	15	1	2	4	5	3	6.4516
	16	1	2	5	5	3	6.7568
	17	1	2	5	6	3	6.8966
	18	1	3	5	6	3	7.8947
	19	1	3	5	6	4	8.0645
	20	1	3	6	6	4	8.1081
3	15	1	2	6	5	1	5.0847
	16	1	2	7	5	1	5.5556
	17	1	2	7	5	2	5.814
	18	1	2	7	6	2	5.9322
	19	1	2	8	6	2	6.7797
	20	1	2	9	6	2	6.8966
4	15	1	3	4	4	3	7.2727
	16	1	3	5	4	3	7.5
	17	1	3	5	4	4	8.5106
	18	1	3	5	5	4	9.0909
	19	1	3	6	5	4	9.6774
	20	1	4	6	5	4	10
5	15	1	3	3	5	3	6.7568
	16	1	3	3	6	3	6.9767
	17	1	3	4	6	3	6.9767
	18	1	3	4	6	4	7.3171
	19	1	4	4	6	4	8.1081
	20	1	4	4	7	4	9.3023
6	15	1	2	6	3	3	5.0847
	16	1	2	7	3	3	5.4545
	17	1	2	7	4	3	5.9322
	18	1	2	8	4	3	6.25
	19	1	3	8	4	3	6.6667
	20	1	3	8	4	4	6.7797
7	15	1	3	4	4	3	8.1081
	16	1	4	4	4	3	8.1633
	17	1	4	4	5	3	8.6957
	18	1	4	5	5	3	10.2041
	19	1	4	5	6	3	10.8108
	20	1	5	5	6	3	10.8696
8	15	1	2	4	5	3	7.1429
	16	1	3	4	5	3	8.1633
	17	1	3	5	5	3	8.1967
	18	1	3	5	6	3	9.8361
	19	1	3	5	7	3	10.2041
	20	1	3	6	7	3	10.3448
9	15	1	2	5	4	3	5.8824
	16	1	3	5	4	3	6.1728
	17	1	3	6	4	3	6.4516
	18	1	3	6	5	3	7.4074
	19	1	3	7	5	3	8.0645
	20	1	3	7	6	3	8.642
10	15	1	2	4	5	3	4.6512
	16	1	3	4	5	3	5.4054
	17	1	3	5	5	3	5.7471
	18	1	3	5	6	3	6.7568
	19	1	3	6	6	3	6.8966
	20	1	3	6	7	3	6.9767

A4. P_{ijk} Values for multi period analysis

Product	Alternative Operator Level	Production Rate(per minute)	Periods 1		Periods 2		Periods 3		Periods 4		Periods 5	
			Demand	P_{ijk}	Demand	P_{ijk}	Demand	P_{ijk}	Demand	P_{ijk}	Demand	P_{ijk}
1	**15**	5.6818	3500.00	616.00	3500.00	616.00	3700.00	651.20	3100.00	545.60	3100.00	545.60
	16	6.6667		525.00		525.00		555.00		465.00		465.00
	17	6.8182		513.33		513.33		542.67		454.67		454.67
	18	7.8947		443.34		443.34		468.67		392.67		392.67
	19	7.9545		440.00		440.00		465.15		389.72		389.72
	20	8.1081		431.67		431.67		456.33		382.33		382.33
2	**15**	6.4516	7500.00	1162.50	7500.00	1162.50	7500.00	1162.50	6500.00	1007.50	6750.00	1046.25
	16	6.7568		1109.99		1109.99		1109.99		961.99		998.99
	17	6.8966		1087.49		1087.49		1087.49		942.49		978.74
	18	7.8947		950.00		950.00		950.00		823.34		855.00
	19	8.0645		930.00		930.00		930.00		806.00		837.00
	20	8.1081		925.00		925.00		925.00		801.67		832.50
3	**15**	5.0847	3400.00	668.67	3700.00	727.67	3700.00	727.67	3700.00	727.67	3700.00	727.67
	16	5.5556		612.00		665.99		665.99		665.99		665.99
	17	5.814		584.80		636.39		636.39		636.39		636.39
	18	5.9322		573.14		623.71		623.71		623.71		623.71
	19	6.7797		501.50		545.75		545.75		545.75		545.75
	20	6.8966		493.00		536.50		536.50		536.50		536.50
4	**15**	7.2727	2700.00	371.25	2900.00	398.75	3000.00	412.50	2750.00	378.13	2750.00	378.13
	16	7.5		360.00		386.67		400.00		366.67		366.67
	17	8.5106		317.25		340.75		352.50		323.13		323.13
	18	9.0909		297.00		319.00		330.00		302.50		302.50
	19	9.6774		279.00		299.67		310.00		284.17		284.17
	20	10		270.00		290.00		300.00		275.00		275.00
5	**15**	6.7568	2200.00	325.60	2200.00	325.60	2400.00	355.20	2150.00	318.20	2400.00	355.20
	16	6.9767		315.34		315.34		344.00		308.17		344.00
	17	6.9767		315.34		315.34		344.00		308.17		344.00
	18	7.3171		300.67		300.67		328.00		293.83		328.00
	19	8.1081		271.33		271.33		296.00		265.17		296.00
	20	9.3023		236.50		236.50		258.00		231.13		258.00
6	**15**	5.0847	4000.00	786.67	4300.00	845.67	4300.00	845.67	3500.00	688.34	3900.00	767.01
	16	5.4545		733.34		788.34		788.34		641.67		715.01
	17	5.9322		674.29		724.86		724.86		590.00		657.43
	18	6.25		640.00		688.00		688.00		560.00		624.00
	19	6.6667		600.00		645.00		645.00		525.00		585.00
	20	6.7797		590.00		634.25		634.25		516.25		575.25
7	**15**	8.1081	4500.00	555.00	4600.00	567.33	4600.00	567.33	4400.00	542.67	4200.00	518.00
	16	8.1633		551.25		563.50		563.50		539.00		514.50
	17	8.6957		517.50		529.00		529.00		506.00		483.00
	18	10.2041		441.00		450.80		450.80		431.20		411.60
	19	10.8108		416.25		425.50		425.50		407.00		388.50
	20	10.8696		414.00		423.20		423.20		404.80		386.40
8	**15**	7.1429	2200.00	308.00	2200.00	308.00	2400.00	336.00	1900.00	266.00	1900.00	266.00
	16	8.1633		269.50		269.50		294.00		232.75		232.75
	17	8.1967		268.40		268.40		292.80		231.80		231.80
	18	9.8361		223.67		223.67		244.00		193.17		193.17
	19	10.2041		215.60		215.60		235.20		186.20		186.20
	20	10.3448		212.67		212.67		232.00		183.67		183.67
9	**15**	5.8824	2300.00	391.00	2500.00	425.00	2500.00	425.00	2500.00	425.00	2500.00	425.00
	16	6.1728		372.60		405.00		405.00		405.00		405.00
	17	6.4516		356.50		387.50		387.50		387.50		387.50
	18	7.4074		310.50		337.50		337.50		337.50		337.50
	19	8.0645		285.20		310.00		310.00		310.00		310.00
	20	8.642		266.14		289.28		289.28		289.28		289.28
10	**15**	4.6512	3000.00	644.99	3000.00	644.99	3100.00	666.49	3100.00	666.49	3300.00	709.49
	16	5.4054		555.00		555.00		573.50		573.50		610.50
	17	5.7471		522.00		522.00		539.40		539.40		574.20
	18	6.7568		444.00		444.00		458.80		458.80		488.40
	19	6.8966		435.00		435.00		449.50		449.50		478.50
	20	6.9767		430.00		430.00		444.34		444.34		473.00

A4. Contd.

Product	Alternative Operator Level	Production Rate(per minute)	Periods									
			6		7		8		9		10	
			Demand	P_{ijk}	Demand	P_{ijk}	Demand	P_{ijk}	Demand	P_{ijk}	Demand	P_{ijk}
1	15	5.6818	4200.00	739.20	2800.00	492.80	2800.00	492.80	3100.00	545.60	3300.00	580.80
	16	6.6667		630.00		420.00		420.00		465.00		495.00
	17	6.8182		616.00		410.67		410.67		454.67		484.00
	18	7.8947		532.00		354.67		354.67		392.67		418.00
	19	7.9545		528.00		352.00		352.00		389.72		414.86
	20	8.1081		518.00		345.33		345.33		382.33		407.00
2	15	6.4516	8000.00	1240.00	6400.00	992.00	6300.00	976.50	7750.00	1201.25	8450.00	1309.75
	16	6.7568		1183.99		947.19		932.39		1146.99		1250.59
	17	6.8966		1159.99		927.99		913.49		1123.74		1225.24
	18	7.8947		1013.34		810.67		798.00		981.67		1070.34
	19	8.0645		992.00		793.60		781.20		961.00		1047.80
	20	8.1081		986.67		789.33		777.00		955.83		1042.17
3	15	5.0847	3700.00	727.67	3700.00	727.67	3700.00	727.67	3700.00	727.67	3700.00	727.67
	16	5.5556		665.99		665.99		665.99		665.99		665.99
	17	5.814		636.39		636.39		636.39		636.39		636.39
	18	5.9322		623.71		623.71		623.71		623.71		623.71
	19	6.7797		545.75		545.75		545.75		545.75		545.75
	20	6.8966		536.50		536.50		536.50		536.50		536.50
4	15	7.2727	3000.00	412.50	2250.00	309.38	2250.00	309.38	2750.00	378.13	3050.00	419.38
	16	7.5		400.00		300.00		300.00		366.67		406.67
	17	8.5106		352.50		264.38		264.38		323.13		358.38
	18	9.0909		330.00		247.50		247.50		302.50		335.50
	19	9.6774		310.00		232.50		232.50		284.17		315.17
	20	10		300.00		225.00		225.00		275.00		305.00
5	15	6.7568	2500.00	370.00	2150.00	318.20	2000.00	296.00	2400.00	355.20	2600.00	384.80
	16	6.9767		358.34		308.17		286.67		344.00		372.67
	17	6.9767		358.34		308.17		286.67		344.00		372.67
	18	7.3171		341.67		293.83		273.33		328.00		355.33
	19	8.1081		308.33		265.17		246.67		296.00		320.67
	20	9.3023		268.75		231.13		215.00		258.00		279.50
6	15	5.0847	4300.00	845.67	3200.00	629.34	3200.00	629.34	3900.00	767.01	3900.00	767.01
	16	5.4545		788.34		586.67		586.67		715.01		715.01
	17	5.9322		724.86		539.43		539.43		657.43		657.43
	18	6.25		688.00		512.00		512.00		624.00		624.00
	19	6.6667		645.00		480.00		480.00		585.00		585.00
	20	6.7797		634.25		472.00		472.00		575.25		575.25
7	15	8.1081	4800.00	592.00	4400.00	542.67	4250.00	524.17	4200.00	518.00	4400.00	542.67
	16	8.1633		588.00		539.00		520.62		514.50		539.00
	17	8.6957		552.00		506.00		488.75		483.00		506.00
	18	10.2041		470.40		431.20		416.50		411.60		431.20
	19	10.8108		444.00		407.00		393.13		388.50		407.00
	20	10.8696		441.60		404.80		391.00		386.40		404.80
8	15	7.1429	2400.00	336.00	1900.00	266.00	1900.00	266.00	1900.00	266.00	2000.00	280.00
	16	8.1633		294.00		232.75		232.75		232.75		245.00
	17	8.1967		292.80		231.80		231.80		231.80		244.00
	18	9.8361		244.00		193.17		193.17		193.17		203.33
	19	10.2041		235.20		186.20		186.20		186.20		196.00
	20	10.3448		232.00		183.67		183.67		183.67		193.33
9	15	5.8824	2500.00	425.00	2300.00	391.00	2300.00	391.00	2500.00	425.00	2500.00	425.00
	16	6.1728		405.00		372.60		372.60		405.00		405.00
	17	6.4516		387.50		356.50		356.50		387.50		387.50
	18	7.4074		337.50		310.50		310.50		337.50		337.50
	19	8.0645		310.00		285.20		285.20		310.00		310.00
	20	8.642		289.28		266.14		266.14		289.28		289.28
10	15	4.6512	3100.00	666.49	3100.00	666.49	3100.00	666.49	3300.00	709.49	3500.00	752.49
	16	5.4054		573.50		573.50		573.50		610.50		647.50
	17	5.7471		539.40		539.40		539.40		574.20		609.00
	18	6.7568		458.80		458.80		458.80		488.40		518.00
	19	6.8966		449.50		449.50		449.50		478.50		507.50
	20	6.9767		444.34		444.34		444.34		473.00		501.67

A4. Contd.

Product	Alternative Operator Level	Production Rate(per minute)	Periods 11		12		13		14		15		16	
			Demand	P_{ijk}	Demand	P_{ijk}	Demand	P_{ijk}	Demand	P_{ijk}	Demand	P_{ijk}	Demand	P_{ijk}
1	15	5.6818	2900.00	510.40	3500.00	616.00	4100.00	721.60	2800.00	492.80	3600.00	633.60	3400.00	598.40
	16	6.6667		435.00		525.00		615.00		420.00		540.00		510.00
	17	6.8182		425.33		513.33		601.33		410.67		528.00		498.67
	18	7.8947		367.34		443.34		519.34		354.67		456.00		430.67
	19	7.9545		364.57		440.00		515.43		352.00		452.57		427.43
	20	8.1081		357.67		431.67		505.67		345.33		444.00		419.33
2	15	6.4516	6400.00	992.00	7600.00	1178.00	7700.00	1193.50	6800.00	1054.00	6750.00	1046.25	6900.00	1069.50
	16	6.7568		947.19		1124.79		1139.59		1006.39		998.99		1021.19
	17	6.8966		927.99		1101.99		1116.49		985.99		978.74		1000.49
	18	7.8947		810.67		962.67		975.34		861.34		855.00		874.00
	19	8.0645		793.60		942.40		954.80		843.20		837.00		855.60
	20	8.1081		789.33		937.33		949.67		838.67		832.50		851.00
3	15	5.0847	3700.00	727.67	3400.00	668.67	3500.00	688.34	3450.00	678.51	3700.00	727.67	3700.00	727.67
	16	5.5556		665.99		612.00		629.99		621.00		665.99		665.99
	17	5.814		636.39		584.80		602.00		593.40		636.39		636.39
	18	5.9322		623.71		573.14		590.00		581.57		623.71		623.71
	19	6.7797		545.75		501.50		516.25		508.87		545.75		545.75
	20	6.8966		536.50		493.00		507.50		500.25		536.50		536.50
4	15	7.2727	2300.00	316.25	3200.00	440.00	2500.00	343.75	2500.00	343.75	3000.00	412.50	2900.00	398.75
	16	7.5		306.67		426.67		333.33		333.33		400.00		386.67
	17	8.5106		270.25		376.00		293.75		293.75		352.50		340.75
	18	9.0909		253.00		352.00		275.00		275.00		330.00		319.00
	19	9.6774		237.67		330.67		258.33		258.33		310.00		299.67
	20	10		230.00		320.00		250.00		250.00		300.00		290.00
5	15	6.7568	2150.00	318.20	2200.00	325.60	2400.00	355.20	2150.00	318.20	2400.00	355.20	2200.00	325.60
	16	6.9767		308.17		315.34		344.00		308.17		344.00		315.34
	17	6.9767		308.17		315.34		344.00		308.17		344.00		315.34
	18	7.3171		293.83		300.67		328.00		293.83		328.00		300.67
	19	8.1081		265.17		271.33		296.00		265.17		296.00		271.33
	20	9.3023		231.13		236.50		258.00		231.13		258.00		236.50
6	15	5.0847	3250.00	639.17	3500.00	688.34	4800.00	944.01	3200.00	629.34	3900.00	767.01	4300.00	845.67
	16	5.4545		595.84		641.67		880.01		586.67		715.01		788.34
	17	5.9322		547.86		590.00		809.14		539.43		657.43		724.86
	18	6.25		520.00		560.00		768.00		512.00		624.00		688.00
	19	6.6667		487.50		525.00		720.00		480.00		585.00		645.00
	20	6.7797		479.37		516.25		708.00		472.00		575.25		634.25
7	15	8.1081	4400.00	542.67	4500.00	555.00	4000.00	493.33	4200.00	518.00	4200.00	518.00	4600.00	567.33
	16	8.1633		539.00		551.25		490.00		514.50		514.50		563.50
	17	8.6957		506.00		517.50		460.00		483.00		483.00		529.00
	18	10.2041		431.20		441.00		392.00		411.60		411.60		450.80
	19	10.8108		407.00		416.25		370.00		388.50		388.50		425.50
	20	10.8696		404.80		414.00		368.00		386.40		386.40		423.20
8	15	7.1429	1900.00	266.00	2200.00	308.00	2400.00	336.00	2100.00	294.00	1900.00	266.00	2200.00	308.00
	16	8.1633		232.75		269.50		294.00		257.25		232.75		269.50
	17	8.1967		231.80		268.40		292.80		256.20		231.80		268.40
	18	9.8361		193.17		223.67		244.00		213.50		193.17		223.67
	19	10.2041		186.20		215.60		235.20		205.80		186.20		215.60
	20	10.3448		183.67		212.67		232.00		203.00		183.67		212.67
9	15	5.8824	2300.00	391.00	2300.00	391.00	2500.00	425.00	2300.00	391.00	2750.00	467.50	2500.00	425.00
	16	6.1728		372.60		372.60		405.00		372.60		445.50		405.00
	17	6.4516		356.50		356.50		387.50		356.50		426.25		387.50
	18	7.4074		310.50		310.50		337.50		310.50		371.25		337.50
	19	8.0645		285.20		285.20		310.00		285.20		341.00		310.00
	20	8.642		266.14		266.14		289.28		266.14		318.21		289.28
10	15	4.6512	3200.00	687.99	3000.00	644.99	3400.00	730.99	3100.00	666.49	3500.00	752.49	3600.00	773.99
	16	5.4054		592.00		555.00		629.00		573.50		647.50		666.00
	17	5.7471		556.80		522.00		591.60		539.40		609.00		626.40
	18	6.7568		473.60		444.00		503.20		458.80		518.00		532.80
	19	6.8966		464.00		435.00		493.00		449.50		507.50		522.00
	20	6.9767		458.67		430.00		487.34		444.34		501.67		516.00

A5. Optimal Production Rates and # Operators for alterative configurations for problem 1 (Operator Sharing allowed)

		Operations						
Product	**Alternative Operator Level**	**Op 1**	**Op 2**	**Op 3**	**Op 4**	**Op 5**	**Production Rate(per minute)**	**Pijk values**
1	**15**	0.49	3.14	2.58	6.14	2.65	6.97	502.15
	20	0.65	4.19	3.44	8.19	3.53	9.3	376.34
2	**15**	0.36	2.09	4.47	5.34	2.74	7.21	1040.22
	20	0.48	2.79	5.96	7.12	3.65	9.61	780.44
3	**15**	0.35	1.69	6.89	5.02	1.05	5.83	583.19
	20	0.47	2.26	9.18	6.69	1.4	7.78	437.02
4	**15**	0.34	2.63	4.66	3.98	3.39	8.47	318.77
	20	0.45	3.5	6.22	5.31	4.52	11.29	239.15
5	**15**	0.57	2.94	3.09	5.31	3.09	7.17	306.83
	20	0.77	3.92	4.12	7.08	4.11	9.56	230.13
6	**15**	0.41	1.86	6.89	3.21	2.63	5.83	686.11
	20	0.55	2.49	9.18	4.28	3.5	7.78	514.14
7	**15**	0.81	3.32	4.13	4.4	2.34	8.98	501.11
	20	1.08	4.43	5.51	5.87	3.11	11.98	375.63
8	**15**	0.68	2.4	4.2	5.23	2.49	8.57	256.71
	20	0.91	3.2	5.6	6.98	3.31	11.43	192.48
9	**15**	0.28	2.37	5.65	4.33	2.37	6.98	329.51
	20	0.37	3.16	7.54	5.77	3.16	9.3	247.31
10	**15**	0.41	2.54	4.37	5.14	2.54	5.91	507.61
	20	0.55	3.39	5.83	6.85	3.38	7.87	381.19

APPENDIX B OPL MODELS TO DETERMINE CELL SIZES AND LOADS FOR PROBLEM 1

B1. Lot splitting not allowed and operator sharing not allowed

```
var int+ X111 in 0..1;
var int+ X112 in 0..1;
var int+ X121 in 0..1;
var int+ X122 in 0..1;
var int+ X211 in 0..1;
var int+ X212 in 0..1;
var int+ X221 in 0..1;
var int+ X222 in 0..1;
var int+ X311 in 0..1;
var int+ X312 in 0..1;
var int+ X321 in 0..1;
var int+ X322 in 0..1;
var int+ X411 in 0..1;
var int+ X412 in 0..1;
var int+ X421 in 0..1;
var int+ X422 in 0..1;
var int+ X511 in 0..1;
var int+ X512 in 0..1;
var int+ X521 in 0..1;
var int+ X522 in 0..1;
var int+ X611 in 0..1;
var int+ X612 in 0..1;
var int+ X621 in 0..1;
var int+ X622 in 0..1;
var int+ X711 in 0..1;
var int+ X712 in 0..1;
var int+ X721 in 0..1;
var int+ X722 in 0..1;
var int+ X811 in 0..1;
var int+ X812 in 0..1;
var int+ X821 in 0..1;
var int+ X822 in 0..1;
var int+ X911 in 0..1;
var int+ X912 in 0..1;
var int+ X921 in 0..1;
var int+ X922 in 0..1;
var int+ X1011 in 0..1;
var int+ X1012 in 0..1;
var int+ X1021 in 0..1;
var int+ X1022 in 0..1;
var int+ Y11 in 0..1;
var int+ Y12 in 0..1;
var int+ Y21 in 0..1;
var int+ Y22 in 0..1;
var int+ Z in 0..maxint ;
minimize Z
subject to
{
Z= 15*Y11 + 20*Y12 + 15*Y21 + 20*Y22;

X111 + X112 + X121 + X122  = 1;
X211 + X212 + X221 + X222  = 1;
X311 + X312 +  X321 + X322  = 1;
X411 + X412 + X421 + X422  = 1;
X511 + X512 +  X521 + X522  = 1;
X611 + X612  + X621 + X622  = 1;
X711 + X712  + X721 + X722  = 1;
X811 + X812  + X821 + X822  = 1;
X911 + X912  + X921 + X922  = 1;
X1011 + X1012  + X1021 + X1022  = 1;

Y11 + Y12  <= 1;
Y21 + Y22  <= 1;

616.20*X111 + 1162.79*X211 + 669.29*X311 + 371.39*X411 + 325.93*X511 + 787.40*X611 +
555.56*X711 +308.12*X811 + 391.16*X911 + 645.16*X1011 <= 2200*Y11;
432.10*X112 + 925.93*X212 + 493.47*X312 + 270.00*X412 + 236.56*X512 + 590.84*X612 +
416.67*X712 + 212.77*X812 + 266.20*X912 + 430.42*X1012 <= 2200*Y12;
616.20*X121 + 1162.79*X221 + 669.29*X321 + 371.39*X421 + 325.93*X521 + 787.40*X621 +
555.56*X721 +308.12*X821 + 391.16*X921 + 645.16*X1021 <= 2200*Y21;
432.10*X122 + 925.93*X222 + 493.47*X322 + 270.00*X422 + 236.56*X522 + 590.84*X622 +
416.67*X722 + 212.77*X822 + 266.20*X922 + 430.42*X1022 <= 2200*Y22;
};
```

Optimal Solution with Objective Value:

X111 = 0
X112 = 0
X121 = 0
X122 = 1
X211 = 0
X212 = 0
X221 = 0
X222 = 1
X311 = 0
X312 = 1
X321 = 0
X322 = 0
X411 = 0
X412 = 0
X421 = 0
X422 = 1
X511 = 0
X512 = 1
X521 = 0
X522 = 0
X611 = 0
X612 = 1
X621 = 0
X622 = 0
X711 = 0
X712 = 1
X721 = 0
X722 = 0
X811 = 0
X812 = 0
X821 = 0
X822 = 1
X911 = 0
X912 = 0
X921 = 0
X922 = 1
X1011 = 0
X1012 = 1
X1021 = 0
X1022 = 0
Y11 = 0
Y12 = 1
Y21 = 0
Y22 = 1
Z = 40

B2. Lot splitting allowed and operator sharing not allowed

```
var float+ X111 ;
var float+ X112 ;
var float+ X121 ;
var float+ X122 ;
var float+ X211 ;
var float+ X212 ;
var float+ X221 ;
var float+ X222 ;
var float+ X311 ;
var float+ X312 ;
var float+ X321 ;
var float+ X322 ;
var float+ X411 ;
var float+ X412 ;
var float+ X421 ;
var float+ X422 ;
var float+ X511 ;
var float+ X512 ;
var float+ X521 ;
var float+ X522 ;
var float+ X611 ;
var float+ X612 ;
var float+ X621 ;
var float+ X622 ;
var float+ X711 ;
var float+ X712 ;
var float+ X721 ;
var float+ X722 ;
var float+ X811 ;
var float+ X812 ;
var float+ X821 ;
var float+ X822 ;
var float+ X911 ;
var float+ X912 ;
var float+ X921 ;
var float+ X922 ;
var float+ X1011 ;
var float+ X1012 ;
var float+ X1021 ;
var float+ X1022 ;
var int+ Y11 in 0..1;
var int+ Y12 in 0..1;
var int+ Y21 in 0..1;
var int+ Y22 in 0..1;

var int+ Z in 0..maxint ;

minimize Z
subject to
{
Z= 15*Y11 + 20*Y12 + 15*Y21 + 20*Y22;

X111 + X112 + X121 + X122 = 1;
X211 + X212 + X221 + X222 = 1;
X311 + X312 + X321 + X322 = 1;
X411 + X412 + X421 + X422 = 1;
X511 + X512 + X521 + X522 = 1;
X611 + X612 + X621 + X622 = 1;
X711 + X712 + X721 + X722 = 1;
X811 + X812 + X821 + X822 = 1;
X911 + X912 + X921 + X922 = 1;
X1011 + X1012 + X1021 + X1022 = 1;

Y11 + Y12 <= 1;
```

```
Y21 + Y22 <= 1;

616.20*X111 + 1162.79*X211 + 669.29*X311 + 371.39*X411 + 325.93*X511 + 787.40*X611 +
555.56*X711 +308.12*X811 + 391.16*X911 + 645.16*X1011 <= 2200*Y11;
432.10*X112 + 925.93*X212 + 493.47*X312 + 270.00*X412 + 236.56*X512 + 590.84*X612 +
416.67*X712 + 212.77*X812 + 266.20*X912 + 430.42*X1012 <= 2200*Y12;
616.20*X121 + 1162.79*X221 + 669.29*X321 + 371.39*X421 + 325.93*X521 + 787.40*X621 +
555.56*X721 +308.12*X821 + 391.16*X921 + 645.16*X1021 <= 2200*Y21;
432.10*X122 + 925.93*X222 + 493.47*X322 + 270.00*X422 + 236.56*X522 + 590.84*X622 +
416.67*X722 + 212.77*X822 + 266.20*X922 + 430.42*X1022 <= 2200*Y22;
};
```

Optimal Solution with Objective Value: 40

X111 = 0.0000
X112 = 0.0000
X121 = 0.0000
X122 = 1.0000
X211 = 0.0000
X212 = 0.8144
X221 = 0.0000
X222 = 0.1855
X311 = 0.0000
X312 = 1.0000
X321 = 0.0000
X322 = 0.0000
X411 = 0.0000
X412 = 0.0000
X421 = 0.0000
X422 = 1.0000
X511 = 0.0000
X512 = 1.0000
X521 = 0.0000
X522 = 0.0000
X611 = 0.0000
X612 = 1.0000
X621 = 0.0000
X622 = 0.0000
X711 = 0.0000
X712 = 0.0000
X721 = 0.0000
X722 = 1.0000
X811 = 0.0000
X812 = 0.0000
X821 = 0.0000
X822 = 1.0000
X911 = 0.0000
X912 = 0.0000
X921 = 0.0000
X922 = 1.0000
X1011 = 0.0000
X1012 = 0.0000
X1021 = 0.0000
X1022 = 1.0000
Y11 = 0
Y12 = 1
Y21 = 0
Y22 = 1
Z = 40

B3. Lot splitting not allowed and operator sharing allowed

```
var int+ X111 in 0..1;
var int+ X112 in 0..1;
var int+ X121 in 0..1;
var int+ X122 in 0..1;
var int+ X211 in 0..1;
var int+ X212 in 0..1;
var int+ X221 in 0..1;
var int+ X222 in 0..1;
var int+ X311 in 0..1;
var int+ X312 in 0..1;
var int+ X321 in 0..1;
var int+ X322 in 0..1;
var int+ X411 in 0..1;
var int+ X412 in 0..1;
var int+ X421 in 0..1;
var int+ X422 in 0..1;
var int+ X511 in 0..1;
var int+ X512 in 0..1;
var int+ X521 in 0..1;
var int+ X522 in 0..1;
var int+ X611 in 0..1;
var int+ X612 in 0..1;
var int+ X621 in 0..1;
var int+ X622 in 0..1;
var int+ X711 in 0..1;
var int+ X712 in 0..1;
var int+ X721 in 0..1;
var int+ X722 in 0..1;
var int+ X811 in 0..1;
var int+ X812 in 0..1;
var int+ X821 in 0..1;
var int+ X822 in 0..1;
var int+ X911 in 0..1;
var int+ X912 in 0..1;
var int+ X921 in 0..1;
var int+ X922 in 0..1;
var int+ X1011 in 0..1;
var int+ X1012 in 0..1;
var int+ X1021 in 0..1;
var int+ X1022 in 0..1;
var int+ Y11 in 0..1;
var int+ Y12 in 0..1;
var int+ Y21 in 0..1;
var int+ Y22 in 0..1;
var int+ Z in 0..maxint ;

minimize Z
subject to
{
Z= 15*Y11 + 20*Y12 + 15*Y21 + 20*Y22;
```

```
X111 + X112 + X121 + X122 = 1;
X211 + X212 + X221 + X222 = 1;
X311 + X312 + X321 + X322 = 1;
X411 + X412 + X421 + X422 = 1;
X511 + X512 + X521 + X522 = 1;
X611 + X612 + X621 + X622 = 1;
X711 + X712 + X721 + X722 = 1;
X811 + X812 + X821 + X822 = 1;
X911 + X912 + X921 + X922 = 1;
X1011 + X1012 + X1021 + X1022 = 1;

Y11 + Y12 <= 1;
Y21 + Y22 <= 1;

502.15*X111 + 1040.22*X211 + 583.19*X311 + 318.77*X411 + 306.83*X511 + 686.11*X611 +
501.11*X711 +256.71*X811 + 329.51*X911 + 507.61*X1011 <= 2200*Y11;
376.34*X112 + 780.44*X212 + 437.02*X312 + 239.15*X412 + 230.13*X512 + 514.14*X612 +
375.63*X712 + 192.48*X812 + 247.31*X912 + 381.19*X1012 <= 2200*Y12;
502.15*X121 + 1040.22*X221 + 583.19*X321 + 318.77*X421 + 306.83*X521 + 686.11*X621 +
501.11*X721 +256.71*X821 + 329.51*X921 + 507.61*X1021 <= 2200*Y21;
376.34*X122 + 780.44*X222 + 437.02*X322 + 239.15*X422 + 230.13*X522 + 514.14*X622 +
375.63*X722 + 192.48*X822 + 247.31*X922 + 381.19*X1022 <= 2200*Y22;

};
```

Optimal Solution with Objective Value: 35

```
X111 = 0
X112 = 0
X121 = 0
X122 = 1
X211 = 1
X212 = 0
X221 = 0
X222 = 0
X311 = 0
X312 = 0
X321 = 0
X322 = 1
X411 = 1
X412 = 0
X421 = 0
X422 = 0
X511 = 1
X512 = 0
X521 = 0
X522 = 0
X611 = 0
X612 = 0
X621 = 0
X622 = 1
X711 = 0
X712 = 0
X721 = 0
X722 = 1
X811 = 0
X812 = 0
X821 = 0
X822 = 1
X911 = 0
X912 = 0
X921 = 0
X922 = 1
X1011 = 1
X1012 = 0
X1021 = 0
X1022 = 0
Y11 = 1
Y12 = 0
Y21 = 0
Y22 = 1
Z = 35
```

B4. Lot splitting allowed and operator sharing allowed

```
var float+ X111 ;
var float+ X112 ;
var float+ X121 ;
var float+ X122 ;
var float+ X211 ;
var float+ X212 ;
var float+ X221 ;
var float+ X222 ;
var float+ X311 ;
var float+ X312 ;
var float+ X321 ;
var float+ X322 ;
var float+ X411 ;
var float+ X412 ;
var float+ X421 ;
var float+ X422 ;
var float+ X511 ;
var float+ X512 ;
var float+ X521 ;
var float+ X522 ;
var float+ X611 ;
var float+ X612 ;
var float+ X621 ;
var float+ X622 ;
var float+ X711 ;
var float+ X712 ;
var float+ X721 ;
```

```
var float+ X722 ;
var float+ X811 ;
var float+ X812 ;
var float+ X821 ;
var float+ X822 ;
var float+ X911 ;
var float+ Z ;
var float+ X912 ;
var float+ X921 ;
var float+ X922 ;
var float+ X1011 ;
var float+ X1012 ;
var float+ X1021 ;
var float+ X1022 ;
var int+ Y11 in 0..1;
var int+ Y12 in 0..1;
var int+ Y21 in 0..1;
var int+ Y22 in 0..1;

minimize Z
subject to
{
Z= 15*Y11 + 20*Y12 + 15*Y21 + 20*Y22;

X111 + X112 + X121 + X122 = 1;
X211 + X212 + X221 + X222 = 1;
X311 + X312 + X321 + X322 = 1;
X411 + X412 + X421 + X422 = 1;
X511 + X512 + X521 + X522 = 1;
X611 + X612 + X621 + X622 = 1;
X711 + X712 + X721 + X722 = 1;
X811 + X812 + X821 + X822 = 1;
X911 + X912 + X921 + X922 = 1;
X1011 + X1012 + X1021 + X1022 = 1;

Y11 = 1;
Y22 = 1;

502.15*X111 + 1040.22*X211 + 583.19*X311 + 318.77*X411 + 306.83*X511 + 686.11*X611 +
501.11*X711 +256.71*X811 + 329.51*X911 + 507.61*X1011 <= 2200*Y11;
376.34*X112 + 780.44*X212 + 437.02*X312 + 239.15*X412 + 230.13*X512 + 514.14*X612 +
375.63*X712 + 192.48*X812 + 247.31*X912 + 381.19*X1012 <= 2200*Y12;
502.15*X121 + 1040.22*X221 + 583.19*X321 + 318.77*X421 + 306.83*X521 + 686.11*X621 +
501.11*X721 +256.71*X821 + 329.51*X921 + 507.61*X1021 <= 2200*Y21;
376.34*X122 + 780.44*X222 + 437.02*X322 + 239.15*X422 + 230.13*X522 + 514.14*X622 +
375.63*X722 + 192.48*X822 + 247.31*X922 + 381.19*X1022 <= 2200*Y22;

};
```

```
Optimal Solution with Objective Value: 35.0000
X111 = 1.0000
X112 = 0.0000
X121 = 0.0000
X122 = 0.0000
X211 = 0.0000
X212 = 0.0000
X221 = 0.0000
X222 = 1.0000
X311 = 0.4891
X312 = 0.0000
X321 = 0.0000
X322 = 0.5108
X411 = 1.0000
X412 = 0.0000
X421 = 0.0000
X422 = 0.0000
X511 = 0.0000
X512 = 0.0000
X521 = 0.0000
X522 = 1.0000
X611 = 0.0000
X612 = 0.0000
X621 = 0.0000
X622 = 1.0000
X711 = 0.0000
X712 = 0.0000
X721 = 0.0000
X722 = 1.0000
X811 = 1.0000
X812 = 0.0000
X821 = 0.0000
X822 = 0.0000
X911 = 1.0000
X912 = 0.0000
X921 = 0.0000
X922 = 0.0000
X1011 = 1.0000
X1012 = 0.0000
X1021 = 0.0000
X1022 = 0.0000
Y11 = 1
Y12 = 0
Y21 = 0
Y22 = 1
Z = 35.0000
```

B5. OPL MODEL TO DETERMINE CELL SIZES AND LOADS FOR PROBLEM 2

```
var int+ X111 in 0..1;
var int+ X112 in 0..1;
var int+ X113 in 0..1;
var int+ X121 in 0..1;
var int+ X122 in 0..1;
var int+ X123 in 0..1;
var int+ X131 in 0..1;
var int+ X132 in 0..1;
var int+ X133 in 0..1;
var int+ X211 in 0..1;
var int+ X212 in 0..1;
var int+ X213 in 0..1;
var int+ X221 in 0..1;
var int+ X222 in 0..1;
var int+ X223 in 0..1;
var int+ X231 in 0..1;
var int+ X232 in 0..1;
var int+ X233 in 0..1;
var int+ X311 in 0..1;
var int+ X312 in 0..1;
var int+ X313 in 0..1;
var int+ X321 in 0..1;
var int+ X322 in 0..1;
var int+ X323 in 0..1;
var int+ X331 in 0..1;
var int+ X332 in 0..1;
var int+ X333 in 0..1;
var int+ X411 in 0..1;
var int+ X412 in 0..1;
var int+ X413 in 0..1;
var int+ X421 in 0..1;
var int+ X422 in 0..1;
var int+ X423 in 0..1;
var int+ X431 in 0..1;
var int+ X432 in 0..1;
var int+ X433 in 0..1;
var int+ X511 in 0..1;
var int+ X512 in 0..1;
var int+ X513 in 0..1;
var int+ X521 in 0..1;
var int+ X522 in 0..1;
var int+ X523 in 0..1;
var int+ X531 in 0..1;
var int+ X532 in 0..1;
var int+ X533 in 0..1;
var int+ X611 in 0..1;
var int+ X612 in 0..1;
var int+ X613 in 0..1;
var int+ X621 in 0..1;
var int+ X622 in 0..1;
var int+ X623 in 0..1;
var int+ X631 in 0..1;
var int+ X632 in 0..1;
var int+ X633 in 0..1;
var int+ X711 in 0..1;
var int+ X712 in 0..1;
var int+ X713 in 0..1;
var int+ X721 in 0..1;
var int+ X722 in 0..1;
var int+ X723 in 0..1;
var int+ X731 in 0..1;
var int+ X732 in 0..1;
var int+ X733 in 0..1;
var int+ X811 in 0..1;
var int+ X812 in 0..1;
var int+ X813 in 0..1;
var int+ X821 in 0..1;
var int+ X822 in 0..1;
var int+ X823 in 0..1;
var int+ X831 in 0..1;
var int+ X832 in 0..1;
var int+ X833 in 0..1;
var int+ X911 in 0..1;
var int+ X912 in 0..1;
var int+ X913 in 0..1;
var int+ X921 in 0..1;
var int+ X922 in 0..1;
var int+ X923 in 0..1;
var int+ X931 in 0..1;
var int+ X932 in 0..1;
var int+ X933 in 0..1;
var int+ X1011 in 0..1;
var int+ X1012 in 0..1;
var int+ X1013 in 0..1;
var int+ X1021 in 0..1;
var int+ X1022 in 0..1;
var int+ X1023 in 0..1;
var int+ X1031 in 0..1;
var int+ X1032 in 0..1;
var int+ X1033 in 0..1;
var int+ X1111 in 0..1;
var int+ X1112 in 0..1;
var int+ X1113 in 0..1;
var int+ X1121 in 0..1;
var int+ X1122 in 0..1;
var int+ X1123 in 0..1;
var int+ X1131 in 0..1;
var int+ X1132 in 0..1;
var int+ X1133 in 0..1;
var int+ X1211 in 0..1;
var int+ X1212 in 0..1;
var int+ X1213 in 0..1;
var int+ X1221 in 0..1;
var int+ X1222 in 0..1;
var int+ X1223 in 0..1;
var int+ X1231 in 0..1;
var int+ X1232 in 0..1;
var int+ X1233 in 0..1;
var int+ X1311 in 0..1;
var int+ X1312 in 0..1;
var int+ X1313 in 0..1;
var int+ X1321 in 0..1;
var int+ X1322 in 0..1;
var int+ X1323 in 0..1;
var int+ X1331 in 0..1;
var int+ X1332 in 0..1;
var int+ X1333 in 0..1;
var int+ X1411 in 0..1;
var int+ X1412 in 0..1;
var int+ X1413 in 0..1;
var int+ X1421 in 0..1;
var int+ X1422 in 0..1;
var int+ X1423 in 0..1;
var int+ X1431 in 0..1;
var int+ X1432 in 0..1;
var int+ X1433 in 0..1;
var int+ X1511 in 0..1;
var int+ X1512 in 0..1;
var int+ X1513 in 0..1;
var int+ X1521 in 0..1;
var int+ X1522 in 0..1;
var int+ X1523 in 0..1;
var int+ X1531 in 0..1;
var int+ X1532 in 0..1;
var int+ X1533 in 0..1;
var int+ X1611 in 0..1;
var int+ X1612 in 0..1;
var int+ X1613 in 0..1;
var int+ X1621 in 0..1;
var int+ X1622 in 0..1;
var int+ X1623 in 0..1;
```

```
var int+ X1631 in 0..1;
var int+ X1632 in 0..1;
var int+ X1633 in 0..1;
var int+ X1711 in 0..1;
var int+ X1712 in 0..1;
var int+ X1713 in 0..1;
var int+ X1721 in 0..1;
var int+ X1722 in 0..1;
var int+ X1723 in 0..1;
var int+ X1731 in 0..1;
var int+ X1732 in 0..1;
var int+ X1733 in 0..1;
var int+ X1811 in 0..1;
var int+ X1812 in 0..1;
var int+ X1813 in 0..1;
var int+ X1821 in 0..1;
var int+ X1822 in 0..1;
var int+ X1823 in 0..1;
var int+ X1831 in 0..1;
var int+ X1832 in 0..1;
var int+ X1833 in 0..1;
var int+ X1911 in 0..1;
var int+ X1912 in 0..1;
var int+ X1913 in 0..1;
var int+ X1921 in 0..1;
var int+ X1922 in 0..1;
var int+ X1923 in 0..1;
var int+ X1931 in 0..1;
var int+ X1932 in 0..1;
var int+ X1933 in 0..1;
var int+ X2011 in 0..1;
var int+ X2012 in 0..1;
var int+ X2013 in 0..1;
var int+ X2021 in 0..1;
var int+ X2022 in 0..1;
var int+ X2023 in 0..1;
var int+ X2031 in 0..1;
var int+ X2032 in 0..1;
var int+ X2033 in 0..1;
var int+ X2111 in 0..1;
var int+ X2112 in 0..1;
var int+ X2113 in 0..1;
var int+ X2121 in 0..1;
var int+ X2122 in 0..1;
var int+ X2123 in 0..1;
var int+ X2131 in 0..1;
var int+ X2132 in 0..1;
var int+ X2133 in 0..1;
var int+ X2211 in 0..1;
var int+ X2212 in 0..1;
var int+ X2213 in 0..1;
var int+ X2221 in 0..1;
var int+ X2222 in 0..1;
var int+ X2223 in 0..1;
var int+ X2231 in 0..1;
var int+ X2232 in 0..1;
var int+ X2233 in 0..1;
var int+ X2311 in 0..1;
var int+ X2312 in 0..1;
var int+ X2313 in 0..1;
var int+ X2321 in 0..1;
var int+ X2322 in 0..1;
var int+ X2323 in 0..1;
var int+ X2331 in 0..1;
var int+ X2332 in 0..1;
var int+ X2333 in 0..1;
var int+ X2411 in 0..1;
var int+ X2412 in 0..1;
var int+ X2413 in 0..1;
var int+ X2421 in 0..1;
var int+ X2422 in 0..1;
var int+ X2423 in 0..1;
var int+ X2431 in 0..1;
var int+ X2432 in 0..1;
var int+ X2433 in 0..1;
var int+ X2511 in 0..1;
var int+ X2512 in 0..1;
var int+ X2513 in 0..1;
var int+ X2521 in 0..1;
var int+ X2522 in 0..1;
var int+ X2523 in 0..1;
var int+ X2531 in 0..1;
var int+ X2532 in 0..1;
var int+ X2533 in 0..1;
var int+ X2611 in 0..1;
var int+ X2612 in 0..1;
var int+ X2613 in 0..1;
var int+ X2621 in 0..1;
var int+ X2622 in 0..1;
var int+ X2623 in 0..1;
var int+ X2631 in 0..1;
var int+ X2632 in 0..1;
var int+ X2633 in 0..1;
var int+ X2711 in 0..1;
var int+ X2712 in 0..1;
var int+ X2713 in 0..1;
var int+ X2721 in 0..1;
var int+ X2722 in 0..1;
var int+ X2723 in 0..1;
var int+ X2731 in 0..1;
var int+ X2732 in 0..1;
var int+ X2733 in 0..1;
var int+ X2811 in 0..1;
var int+ X2812 in 0..1;
var int+ X2813 in 0..1;
var int+ X2821 in 0..1;
var int+ X2822 in 0..1;
var int+ X2823 in 0..1;
var int+ X2831 in 0..1;
var int+ X2832 in 0..1;
var int+ X2833 in 0..1;
var int+ X2911 in 0..1;
var int+ X2912 in 0..1;
var int+ X2913 in 0..1;
var int+ X2921 in 0..1;
var int+ X2922 in 0..1;
var int+ X2923 in 0..1;
var int+ X2931 in 0..1;
var int+ X2932 in 0..1;
var int+ X2933 in 0..1;
var int+ X3011 in 0..1;
var int+ X3012 in 0..1;
var int+ X3013 in 0..1;
var int+ X3021 in 0..1;
var int+ X3022 in 0..1;
var int+ X3023 in 0..1;
var int+ X3031 in 0..1;
var int+ X3032 in 0..1;
var int+ X3033 in 0..1;
var int+ Y11 in 0..1;
var int+ Y12 in 0..1;
var int+ Y13 in 0..1;
var int+ Y21 in 0..1;
var int+ Y22 in 0..1;
var int+ Y23 in 0..1;
var int+ Y31 in 0..1;
var int+ Y32 in 0..1;
var int+ Y33 in 0..1;
var int+ Z in 0..maxint ;

minimize Z
subject to
{
Z= 15*Y11 + 20*Y12 + 25*Y13 + 15*Y21 + 20*Y22 + 25*Y23 + 15*Y31 + 20*Y32 + 25*Y33;

X111 + X112 + X113 + X121 + X122 + X123 + X131 + X132 + X133 = 1;
X211 + X212 + X213 + X221 + X222 + X223 + X231 + X232 + X233 = 1;
```

X311 + X312 + X313 + X321 + X322 + X323 + X331 + X332 + X333 = 1;
X411 + X412 + X413 + X421 + X422 + X423 + X431 + X432 + X433 = 1;
X511 + X512 + X513 + X521 + X522 + X523 + X531 + X532 + X533 = 1;
X611 + X612 + X613 + X621 + X622 + X623 + X631 + X632 + X633 = 1;
X711 + X712 + X713 + X721 + X722 + X723 + X731 + X732 + X733 = 1;
X811 + X812 + X813 + X821 + X822 + X823 + X831 + X832 + X833 = 1;
X911 + X912 + X913 + X921 + X922 + X923 + X931 + X932 + X933 = 1;
X1011 + X1012 + X1013 + X1021 + X1022 + X1023 + X1031 + X1032 + X1033 = 1;
X1111 + X1112 + X1113 + X1121 + X1122 + X1123 + X1131 + X1132 + X1133 = 1;
X1211 + X1212 + X1213 + X1221 + X1222 + X1223 + X1231 + X1232 + X1233 = 1;
X1311 + X1312 + X1313 + X1321 + X1322 + X1323 + X1331 + X1332 + X1333 = 1;
X1411 + X1412 + X1413 + X1421 + X1422 + X1423 + X1431 + X1432 + X1433 = 1;
X1511 + X1512 + X1513 + X1521 + X1522 + X1523 + X1531 + X1532 + X1533 = 1;
X1611 + X1612 + X1613 + X1621 + X1622 + X1623 + X1631 + X1632 + X1633 = 1;
X1711 + X1712 + X1713 + X1721 + X1722 + X1723 + X1731 + X1732 + X1733 = 1;
X1811 + X1812 + X1813 + X1821 + X1822 + X1823 + X1831 + X1832 + X1833 = 1;
X1911 + X1912 + X1913 + X1921 + X1922 + X1923 + X1931 + X1932 + X1933 = 1;
X2011 + X2012 + X2013 + X2021 + X2022 + X2023 + X2031 + X2032 + X2033 = 1;
X2111 + X2112 + X2113 + X2121 + X2122 + X2123 + X2131 + X2132 + X2133 = 1;
X2211 + X2212 + X2213 + X2221 + X2222 + X2223 + X2231 + X2232 + X2233 = 1;
X2311 + X2312 + X2313 + X2321 + X2322 + X2323 + X2331 + X2332 + X2333 = 1;
X2411 + X2412 + X2413 + X2421 + X2422 + X2423 + X2431 + X2432 + X2433 = 1;
X2511 + X2512 + X2513 + X2521 + X2522 + X2523 + X2531 + X2532 + X2533 = 1;
X2611 + X2612 + X2613 + X2621 + X2622 + X2623 + X2631 + X2632 + X2633 = 1;
X2711 + X2712 + X2713 + X2721 + X2722 + X2723 + X2731 + X2732 + X2733 = 1;
X2811 + X2812 + X2813 + X2821 + X2822 + X2823 + X2831 + X2832 + X2833 = 1;
X2911 + X2912 + X2913 + X2921 + X2922 + X2923 + X2931 + X2932 + X2933 = 1;
X3011 + X3012 + X3013 + X3021 + X3022 + X3023 + X3031 + X3032 + X3033 = 1;

Y11 + Y12 + Y13 <= 1;
Y21 + Y22 + Y23 <= 1;
Y31 + Y32 + Y33 <= 1;

440.14*X111 + 279.07*X211 + 590.55*X311 + 206.33*X411 + 177.78*X511 + 511.81*X611 + 296.30*X711 + 266.11*X811 + 221.09*X911 + 559.14*X1011 + 448.00*X1111 + 345.62*X1211 + 399.16*X1311 + 539.22*X1411 + 602.15*X1511 + 189.19*X1611 + 245.40*X1711 + 638.30*X1811 + 430.42*X1911 + 259.32*X2011 + 528.23*X2111 + 191.94*X2211 + 255.01*X2311 + 243.28*X2411 + 528.85*X2511 + 588.24*X2611 + 185.19*X2711 + 208.06*X2811 + 544.22*X2911 + 564.97*X3011 <= 2300*Y11;
308.64*X112 + 222.22*X212 + 435.41*X312 + 150.00*X412 + 129.03*X512 + 384.05*X612 + 222.22*X712 + 183.75*X812 + 150.46*X912 + 373.03*X1012 + 322.21*X1112 + 241.94*X1212 + 297.81*X1312 + 385.29*X1412 + 438.87*X1512 + 142.42*X1612 + 184.12*X1712 + 441.18*X1812 + 307.69*X1912 + 185.19*X2012 + 377.11*X2112 + 143.88*X2212 + 182.05*X2312 + 173.83*X2412 + 354.84*X2512 + 406.39*X2612 + 128.04*X2712 + 154.74*X2812 + 408.16*X2912 + 403.23*X3012 <= 2300*Y12;
231.27*X113 + 166.51*X213 + 322.58*X313 + 117.55*X413 + 103.27*X513 + 286.03*X613 + 177.78*X713 + 144.93*X813 + 117.01*X913 + 279.57*X1013 + 266.16*X1113 + 193.55*X1213 + 221.70*X1313 + 294.91*X1413 + 329.02*X1513 + 109.20*X1613 + 133.89*X1713 + 330.88*X1813 + 258.18*X1913 + 144.01*X2013 + 295.02*X2113 + 115.07*X2213 + 141.56*X2313 + 135.14*X2413 + 301.78*X2513 + 336.13*X2613 + 101.32*X2713 + 121.67*X2813 + 326.53*X2913 + 320.17*X3013 <= 2300*Y13;
440.14*X121 + 279.07*X221 + 590.55*X321 + 206.33*X421 + 177.78*X521 + 511.81*X621 + 296.30*X721 + 266.11*X821 + 221.09*X921 + 559.14*X1021 + 448.00*X1121 + 345.62*X1221 + 399.16*X1321 + 539.22*X1421 + 602.15*X1521 + 189.19*X1621 + 245.40*X1721 + 638.30*X1821 + 430.42*X1921 + 259.32*X2021 + 528.23*X2121 + 191.94*X2221 + 255.01*X2321 + 243.28*X2421 +

528.85*X2521 + 588.24*X2621 + 185.19*X2721 + 208.06*X2821 + 544.22*X2921 + 564.97*X3021 <= 2300*Y21;
308.64*X122 + 222.22*X222 + 435.41*X322 + 150.00*X422 + 129.03*X522 + 384.05*X622 + 222.22*X722 + 183.75*X822 + 150.46*X922 + 373.03*X1022 + 322.21*X1122 + 241.94*X1222 + 297.81*X1322 + 385.29*X1422 + 438.87*X1522 + 142.42*X1622 + 184.12*X1722 + 441.18*X1822 + 307.69*X1922 + 185.19*X2022 + 377.11*X2122 + 143.88*X2222 + 182.05*X2322 + 173.83*X2422 + 354.84*X2522 + 406.39*X2622 + 128.04*X2722 + 154.74*X2822 + 408.16*X2922 + 403.23*X3022 <= 2300*Y22;
231.27*X123 + 166.51*X223 + 322.58*X323 + 117.55*X423 + 103.27*X523 + 286.03*X623 + 177.78*X723 + 144.93*X823 + 117.01*X923 + 279.57*X1023 + 266.16*X1123 + 193.55*X1223 + 221.70*X1323 + 294.91*X1423 + 329.02*X1523 + 109.20*X1623 + 133.89*X1723 + 330.88*X1823 + 258.18*X1923 + 144.01*X2023 + 295.02*X2123 + 115.07*X2223 + 141.56*X2323 + 135.14*X2423 + 301.78*X2523 + 336.13*X2623 + 101.32*X2723 + 121.67*X2823 + 326.53*X2923 + 320.17*X3023 <= 2300*Y23;
440.14*X131 + 279.07*X231 + 590.55*X331 + 206.33*X431 + 177.78*X531 + 511.81*X631 + 296.30*X731 + 266.11*X831 + 221.09*X931 + 559.14*X1031 + 448.00*X1131 + 345.62*X1231 + 399.16*X1331 + 539.22*X1431 + 602.15*X1531 + 189.19*X1631 + 245.40*X1731 + 638.30*X1831 + 430.42*X1931 + 259.32*X2031 + 528.23*X2131 + 191.94*X2231 + 255.01*X2331 + 243.28*X2431 + 528.85*X2531 + 588.24*X2631 + 185.19*X2731 + 208.06*X2831 + 544.22*X2931 + 564.97*X3031 <= 2300*Y31;
308.64*X132 + 222.22*X232 + 435.41*X332 + 150.00*X432 + 129.03*X532 + 384.05*X632 + 222.22*X732 + 183.75*X832 + 150.46*X932 + 373.03*X1032 + 322.21*X1132 + 241.94*X1232 + 297.81*X1332 + 385.29*X1432 + 438.87*X1532 + 142.42*X1632 + 184.12*X1732 + 441.18*X1832 + 307.69*X1932 + 185.19*X2032 + 377.11*X2132 + 143.88*X2232 + 182.05*X2332 + 173.83*X2432 + 354.84*X2532 + 406.39*X2632 + 128.04*X2732 + 154.74*X2832 + 408.16*X2932 + 403.23*X3032 <= 2300*Y32;
231.27*X133 + 166.51*X233 + 322.58*X333 + 117.55*X433 + 103.27*X533 + 286.03*X633 + 177.78*X733 + 144.93*X833 + 117.01*X933 + 279.57*X1033 + 266.16*X1133 + 193.55*X1233 + 221.70*X1333 + 294.91*X1433 + 329.02*X1533 + 109.20*X1633 + 133.89*X1733 + 330.88*X1833 + 258.18*X1933 + 144.01*X2033 + 295.02*X2133 + 115.07*X2233 + 141.56*X2333 + 135.14*X2433 + 301.78*X2533 + 336.13*X2633 + 101.32*X2733 + 121.67*X2833 + 326.53*X2933 + 320.17*X3033 <= 2300*Y33;

};

Optimal Solution with Objective Value: 70

X111 = 0	X312 = 0	X513 = 0
X112 = 0	X313 = 0	X521 = 0
X113 = 0	X321 = 0	X522 = 0
X121 = 0	X322 = 0	X523 = 0
X122 = 0	X323 = 0	X531 = 0
X123 = 0	X331 = 0	X532 = 0
X131 = 0	X332 = 0	X533 = 0
X132 = 0	X333 = 1	X611 = 0
X133 = 1	X411 = 0	X612 = 0
X211 = 0	X412 = 0	X613 = 0
X212 = 0	X413 = 0	X621 = 0
X213 = 0	X421 = 0	X622 = 0
X221 = 0	X422 = 0	X623 = 1
X222 = 0	X423 = 1	X631 = 0
X223 = 1	X431 = 0	X632 = 0
X231 = 0	X432 = 0	X633 = 0
X232 = 0	X433 = 0	X711 = 0
X233 = 0	X511 = 0	X712 = 1
X311 = 0	X512 = 1	X713 = 0

X721 = 0
X722 = 0
X723 = 0
X731 = 0
X732 = 0
X733 = 0
X811 = 0
X812 = 0
X813 = 0
X821 = 0
X822 = 0
X823 = 0
X831 = 0
X832 = 0
X833 = 1
X911 = 0
X912 = 0
X913 = 0
X921 = 0
X922 = 0
X923 = 0
X931 = 0
X932 = 0
X933 = 1
X1011 = 0
X1012 = 0
X1013 = 0
X1021 = 0
X1022 = 0
X1023 = 0
X1031 = 0
X1032 = 0
X1033 = 1
X1111 = 0
X1112 = 1
X1113 = 0
X1121 = 0
X1122 = 0
X1123 = 0
X1131 = 0
X1132 = 0
X1133 = 0
X1211 = 0
X1212 = 0
X1213 = 0
X1221 = 0
X1222 = 0
X1223 = 0
X1231 = 0
X1232 = 0
X1233 = 1
X1311 = 0
X1312 = 0
X1313 = 0
X1321 = 0
X1322 = 0
X1323 = 1
X1331 = 0
X1332 = 0
X1333 = 0
X1411 = 0
X1412 = 0
X1413 = 0
X1421 = 0
X1422 = 0
X1423 = 1
X1431 = 0
X1432 = 0
X1433 = 0
X1511 = 0
X1512 = 0
X1513 = 0
X1521 = 0
X1522 = 0
X1523 = 1
X1531 = 0
X1532 = 0
X1533 = 0
X1611 = 0
X1612 = 0
X1613 = 0
X1621 = 0
X1622 = 0
X1623 = 0
X1631 = 0
X1632 = 0
X1633 = 1
X1711 = 0
X1712 = 0
X1713 = 0
X1721 = 0
X1722 = 0
X1723 = 0
X1731 = 0
X1732 = 0
X1733 = 1
X1811 = 0
X1812 = 0
X1813 = 0
X1821 = 0
X1822 = 0
X1823 = 1
X1831 = 0
X1832 = 0
X1833 = 0
X1911 = 0
X1912 = 1
X1913 = 0
X1921 = 0
X1922 = 0
X1923 = 0
X1931 = 0
X1932 = 0
X1933 = 0
X2011 = 0
X2012 = 0
X2013 = 0
X2021 = 0
X2022 = 0
X2023 = 1
X2031 = 0
X2032 = 0
X2033 = 0
X2111 = 0
X2112 = 0
X2113 = 0
X2121 = 0
X2122 = 0
X2123 = 0
X2131 = 0
X2132 = 0
X2133 = 1
X2211 = 0
X2212 = 0
X2213 = 0
X2221 = 0
X2222 = 0
X2223 = 1
X2231 = 0
X2232 = 0
X2233 = 0
X2311 = 0
X2312 = 0
X2313 = 0
X2321 = 0
X2322 = 0
X2323 = 0
X2331 = 0
X2332 = 0
X2333 = 1
X2411 = 0
X2412 = 0
X2413 = 0
X2421 = 0
X2422 = 0
X2423 = 1
X2431 = 0
X2432 = 0
X2433 = 0
X2511 = 0
X2512 = 1
X2513 = 0
X2521 = 0
X2522 = 0
X2523 = 0

X2531 = 0
X2532 = 0
X2533 = 0
X2611 = 0
X2612 = 1
X2613 = 0
X2621 = 0
X2622 = 0
X2623 = 0
X2631 = 0
X2632 = 0
X2633 = 0
X2711 = 0
X2712 = 0
X2713 = 0
X2721 = 0
X2722 = 0
X2723 = 1
X2731 = 0
X2732 = 0
X2733 = 0
X2811 = 0
X2812 = 0
X2813 = 0
X2821 = 0
X2822 = 0
X2823 = 1
X2831 = 0
X2832 = 0
X2833 = 0
X2911 = 0
X2912 = 1
X2913 = 0
X2921 = 0
X2922 = 0
X2923 = 0
X2931 = 0
X2932 = 0
X2933 = 0
X3011 = 0
X3012 = 0
X3013 = 0
X3021 = 0
X3022 = 0
X3023 = 0
X3031 = 0
X3032 = 0
X3033 = 1
Y11 = 0
Y12 = 1
Y13 = 0
Y21 = 0
Y22 = 0
Y23 = 1
Y31 = 0
Y32 = 0
Y33 = 1
Z = 70

APPENDIX C OPL MODEL SOLUTIONS TO DETERMINE CELL SIZES AND LOADS FOR PROBLEM 3

Period 1
Optimal Solution with
Objective Value: 35
X111 = 0.0000
X112 = 0.0000
X113 = 0.0000
X114 = 0.0000
X115 = 0.0000
X116 = 0.0000
X121 = 0.0000
X122 = 0.0000
X123 = 0.0000
X124 = 1.0000
X125 = 0.0000
X126 = 0.0000
X211 = 0.0000
X212 = 0.0000
X213 = 0.4674
X214 = 0.0000
X215 = 0.0000
X216 = 0.0000
X221 = 0.0000
X222 = 0.0000
X223 = 0.0000
X224 = 0.5325
X225 = 0.0000
X226 = 0.0000
X311 = 0.0000
X312 = 0.0000
X313 = 1.0000
X314 = 0.0000
X315 = 0.0000
X316 = 0.0000
X321 = 0.0000
X322 = 0.0000
X323 = 0.0000
X324 = 0.0000
X325 = 0.0000
X326 = 0.0000
X411 = 0.0000
X412 = 0.0000
X413 = 1.0000
X414 = 0.0000
X415 = 0.0000
X416 = 0.0000
X421 = 0.0000
X422 = 0.0000
X423 = 0.0000
X424 = 0.0000
X425 = 0.0000
X426 = 0.0000
X511 = 0.0000
X512 = 0.0000
X513 = 1.0000
X514 = 0.0000
X515 = 0.0000
X516 = 0.0000
X521 = 0.0000
X522 = 0.0000
X523 = 0.0000
X524 = 0.0000
X525 = 0.0000
X526 = 0.0000
X611 = 0.0000
X612 = 0.0000
X613 = 1.0000
X614 = 0.0000
X615 = 0.0000
X616 = 0.0000
X621 = 0.0000
X622 = 0.0000
X623 = 0.0000
X624 = 0.0000
X625 = 0.0000
X626 = 0.0000
X711 = 0.0000
X712 = 0.0000
X713 = 0.0000
X714 = 0.0000
X715 = 0.0000
X716 = 0.0000
X721 = 0.0000
X722 = 0.0000
X723 = 0.0000
X724 = 1.0000
X725 = 0.0000
X726 = 0.0000
X811 = 0.0000
X812 = 0.0000
X813 = 0.0000
X814 = 0.0000
X815 = 0.0000
X816 = 0.0000
X821 = 0.0000
X822 = 0.0000
X823 = 0.0000
X824 = 1.00000
X825 = 0.0000
X826 = 0.0000
X911 = 0.0000
X912 = 0.0000
X913 = 0.0000
X914 = 0.0000
X915 = 0.0000
X916 = 0.0000
X921 = 0.0000
X922 = 0.0000
X923 = 0.0000
X924 = 1.0000
X925 = 0.0000
X926 = 0.0000
X1011 = 0.0000
X1012 = 0.0000
X1013 = 0.0000
X1014 = 0.0000
X1015 = 0.0000
X1016 = 0.0000
X1021 = 0.0000
X1022 = 0.0000
X1023 = 0.0000
X1024 = 1.0000
X1025 = 0.0000
X1026 = 0.0000
Y11 = 0
Y12 = 0
Y13 = 1
Y14 = 0
Y15 = 0
Y16 = 0
Y21 = 0
Y22 = 0
Y23 = 0
Y24 = 1
Y25 = 0
Y26 = 0
Z = 35

Period 2
Optimal Solution with
Objective Value: 36
X111 = 0.0000
X112 = 0.0000
X113 = 0.0000
X114 = 1.0000
X115 = 0.0000
X116 = 0.0000
X121 = 0.0000
X122 = 0.0000
X123 = 0.0000

X124 = 0.0000
X125 = 0.0000
X126 = 0.0000
X211 = 0.0000
X212 = 0.0000
X213 = 0.0000
X214 = 0.0000
X215 = 0.0000
X216 = 0.0000
X221 = 0.0000
X222 = 0.0000
X223 = 0.0000
X224 = 1.0000
X225 = 0.0000
X226 = 0.0000
X311 = 0.0000
X312 = 0.0000
X313 = 0.0000
X314 = 0.0000
X315 = 0.0000
X316 = 0.0000
X321 = 0.0000
X322 = 0.0000
X323 = 0.0000
X324 = 1.0000
X325 = 0.0000
X326 = 0.0000
X411 = 0.0000
X412 = 0.0000
X413 = 0.0000
X414 = 1.00000
X415 = 0.0000
X416 = 0.0000
X421 = 0.0000
X422 = 0.0000
X423 = 0.0000
X424 = 0.0000
X425 = 0.0000
X426 = 0.0000
X511 = 0.0000
X512 = 0.0000
X513 = 0.0000
X514 = 0.0000
X515 = 0.0000
X516 = 0.0000
X521 = 0.0000
X522 = 0.0000
X523 = 0.0000
X524 = 1.0000
X525 = 0.0000
X526 = 0.0000
X611 = 0.0000
X612 = 0.0000
X613 = 0.0000
X614 = 0.8813
X615 = 0.0000
X616 = 0.0000
X621 = 0.0000
X622 = 0.0000
X623 = 0.0000
X624 = 0.1186
X625 = 0.0000
X626 = 0.0000
X711 = 0.0000
X712 = 0.0000
X713 = 0.0000
X714 = 1.0000
X715 = 0.0000
X716 = 0.0000
X721 = 0.0000
X722 = 0.0000
X723 = 0.0000
X724 = 0.0000
X725 = 0.0000
X726 = 0.0000
X811 = 0.0000
X812 = 0.0000
X813 = 0.0000
X814 = 1.0000
X815 = 0.0000
X816 = 0.0000
X821 = 0.0000
X822 = 0.0000
X823 = 0.0000
X824 = 0.0000
X825 = 0.0000
X826 = 0.0000
X911 = 0.0000
X912 = 0.0000
X913 = 0.0000
X914 = 1.0000
X915 = 0.0000
X916 = 0.0000
X921 = 0.0000
X922 = 0.0000
X923 = 0.0000
X924 = 0.0000
X925 = 0.0000
X926 = 0.0000
X1011 = 0.0000
X1012 = 0.0000
X1013 = 0.0000
X1014 = 0.0000
X1015 = 0.0000
X1016 = 0.0000
X1021 = 0.0000
X1022 = 0.0000
X1023 = 0.0000
X1024 = 1.0000
X1025 = 0.0000
X1026 = 0.0000
Y11 = 0
Y12 = 0
Y13 = 0
Y14 = 1
Y15 = 0
Y16 = 0
Y21 = 0
Y22 = 0
Y23 = 0
Y24 = 1
Y25 = 0
Y26 = 0
Z = 36

Period3
Optimal Solution with
Objective Value: 37
X111 = 0.0000
X112 = 0.0000
X113 = 0.0000
X114 = 1.0000
X115 = 0.0000
X116 = 0.0000
X121 = 0.0000
X122 = 0.0000
X123 = 0.0000
X124 = 0.0000
X125 = 0.0000
X126 = 0.0000
X211 = 0.0000
X212 = 0.0000
X213 = 0.0000
X214 = 1.0000
X215 = 0.0000
X216 = 0.0000
X221 = 0.0000
X222 = 0.0000
X223 = 0.0000
X224 = 0.0000
X225 = 0.0000
X226 = 0.0000
X311 = 0.0000
X312 = 0.0000
X313 = 0.0000
X314 = 0.0000
X315 = 0.0000
X316 = 0.0000
X321 = 0.0000
X322 = 0.0000
X323 = 0.0000
X324 = 0.0000
X325 = 1.0000
X326 = 0.0000

X411 = 0.0000
X412 = 0.0000
X413 = 0.0000
X414 = 0.0000
X415 = 0.0000
X416 = 0.0000
X421 = 0.0000
X422 = 0.0000
X423 = 0.0000
X424 = 0.0000
X425 = 1.0000
X426 = 0.0000
X511 = 0.0000
X512 = 0.0000
X513 = 0.0000
X514 = 0.0000
X515 = 0.0000
X516 = 0.0000
X521 = 0.0000
X522 = 0.0000
X523 = 0.0000
X524 = 0.0000
X525 = 1.0000
X526 = 0.0000
X611 = 0.0000
X612 = 0.0000
X613 = 0.0000
X614 = 0.0000
X615 = 0.0000
X616 = 0.0000
X621 = 0.0000
X622 = 0.0000
X623 = 0.0000
X624 = 0.0000
X625 = 1.0000
X626 = 0.0000
X711 = 0.0000
X712 = 0.0000
X713 = 0.0000
X714 = 0.6178
X715 = 0.0000
X716 = 0.0000
X721 = 0.0000
X722 = 0.0000
X723 = 0.0000
X724 = 0.0000
X725 = 0.3821
X726 = 0.0000
X811 = 0.0000
X812 = 0.0000
X813 = 0.0000
X814 = 1.0000
X815 = 0.0000
X816 = 0.0000
X821 = 0.0000
X822 = 0.0000
X823 = 0.0000
X824 = 0.0000
X825 = 0.0000
X826 = 0.0000
X911 = 0.0000
X912 = 0.0000
X913 = 0.0000
X914 = 0.0000
X915 = 0.0000
X916 = 0.0000
X921 = 0.0000
X922 = 0.0000
X923 = 0.0000
X924 = 0.0000
X925 = 1.0000
X926 = 0.0000
X1011 = 0.0000
X1012 = 0.0000
X1013 = 0.0000
X1014 = 1.0000
X1015 = 0.0000
X1016 = 0.0000
X1021 = 0.0000
X1022 = 0.0000
X1023 = 0.0000
X1024 = 0.0000
X1025 = 0.0000
X1026 = 0.0000
Y11 = 0
Y12 = 0
Y13 = 0
Y14 = 1
Y15 = 0
Y16 = 0
Y21 = 0
Y22 = 0
Y23 = 0
Y24 = 0
Y25 = 1
Y26 = 0
Z = 37

Period 4
Optimal Solution with
Objective Value: 33
X111 = 0.0000
X112 = 0.0000
X113 = 0.0000
X114 = 1.0000
X115 = 0.0000
X116 = 0.0000
X121 = 0.0000
X122 = 0.0000
X123 = 0.0000
X124 = 0.0000
X125 = 0.0000
X126 = 0.0000
X211 = 0.0000
X212 = 0.0000
X213 = 0.0000
X214 = 0.0000
X215 = 0.0000
X216 = 0.0000
X221 = 1.0000
X222 = 0.0000
X223 = 0.0000
X224 = 0.0000
X225 = 0.0000
X226 = 0.0000
X311 = 0.0000
X312 = 0.0000
X313 = 0.0000
X314 = 0.0000
X315 = 0.0000
X316 = 0.0000
X321 = 1.0000
X322 = 0.0000
X323 = 0.0000
X324 = 0.0000
X325 = 0.0000
X326 = 0.0000
X411 = 0.0000
X412 = 0.0000
X413 = 0.0000
X414 = 1.0000
X415 = 0.0000
X416 = 0.0000
X421 = 0.0000
X422 = 0.0000
X423 = 0.0000
X424 = 0.0000
X425 = 0.0000
X426 = 0.0000
X511 = 0.0000
X512 = 0.0000
X513 = 0.0000
X514 = 0.0000
X515 = 0.0000
X516 = 0.0000
X521 = 1.0000
X522 = 0.0000
X523 = 0.0000
X524 = 0.0000
X525 = 0.0000
X526 = 0.0000
X611 = 0.0000
X612 = 0.0000
X613 = 0.0000

X614 = 0.4964
X615 = 0.0000
X616 = 0.0000
X621 = 0.5035
X622 = 0.0000
X623 = 0.0000
X624 = 0.0000
X625 = 0.0000
X626 = 0.0000
X711 = 0.0000
X712 = 0.0000
X713 = 0.0000
X714 = 1.0000
X715 = 0.0000
X716 = 0.0000
X721 = 0.0000
X722 = 0.0000
X723 = 0.0000
X724 = 0.0000
X725 = 0.0000
X726 = 0.0000
X811 = 0.0000
X812 = 0.0000
X813 = 0.0000
X814 = 1.0000
X815 = 0.0000
X816 = 0.0000
X821 = 0.0000
X822 = 0.0000
X823 = 0.0000
X824 = 0.0000
X825 = 0.0000
X826 = 0.0000
X911 = 0.0000
X912 = 0.0000
X913 = 0.0000
X914 = 1.00000
X915 = 0.0000
X916 = 0.0000
X921 = 0.0000
X922 = 0.0000
X923 = 0.0000
X924 = 0.0000
X925 = 0.0000
X926 = 0.0000
X1011 = 0.0000
X1012 = 0.0000
X1013 = 0.0000
X1014 = 1.0000
X1015 = 0.0000
X1016 = 0.0000
X1021 = 0.0000
X1022 = 0.0000
X1023 = 0.0000
X1024 = 0.0000
X1025 = 0.0000
X1026 = 0.0000
Y11 = 0
Y12 = 0
Y13 = 0
Y14 = 1
Y15 = 0
Y16 = 0
Y21 = 1
Y22 = 0
Y23 = 0
Y24 = 0
Y25 = 0
Y26 = 0
Z = 33

Period 5
Optimal Solution with
Objective Value: 35
X111 = 0.0000
X112 = 0.0000
X113 = 0.0000
X114 = 0.0000
X115 = 0.0000
X116 = 0.0000
X121 = 0.0000
X122 = 0.0000
X123 = 0.0000
X124 = 1.0000
X125 = 0.0000
X126 = 0.0000
X211 = 0.0000
X212 = 0.0000
X213 = 0.4485
X214 = 0.0000
X215 = 0.0000
X216 = 0.0000
X221 = 0.0000
X222 = 0.0000
X223 = 0.0000
X224 = 0.5514
X225 = 0.0000
X226 = 0.0000
X311 = 0.0000
X312 = 0.0000
X313 = 1.0000
X314 = 0.0000
X315 = 0.0000
X316 = 0.0000
X321 = 0.0000
X322 = 0.0000
X323 = 0.0000
X324 = 0.0000
X325 = 0.0000
X326 = 0.0000
X411 = 0.0000
X412 = 0.0000
X413 = 1.0000
X414 = 0.0000
X415 = 0.0000
X416 = 0.0000
X421 = 0.0000
X422 = 0.0000
X423 = 0.0000
X424 = 0.0000
X425 = 0.0000
X426 = 0.0000
X511 = 0.0000
X512 = 0.0000
X513 = 1.0000
X514 = 0.0000
X515 = 0.0000
X516 = 0.0000
X521 = 0.0000
X522 = 0.0000
X523 = 0.0000
X524 = 0.0000
X525 = 0.0000
X526 = 0.0000
X611 = 0.0000
X612 = 0.0000
X613 = 1.0000
X614 = 0.0000
X615 = 0.0000
X616 = 0.0000
X621 = 0.0000
X622 = 0.0000
X623 = 0.0000
X624 = 0.0000
X625 = 0.0000
X626 = 0.0000
X711 = 0.0000
X712 = 0.0000
X713 = 0.0000
X714 = 0.0000
X715 = 0.0000
X716 = 0.0000
X721 = 0.0000
X722 = 0.0000
X723 = 0.0000
X724 = 1.0000
X725 = 0.0000
X726 = 0.0000
X811 = 0.0000
X812 = 0.0000
X813 = 0.0000
X814 = 0.0000
X815 = 0.0000
X816 = 0.0000

X821 = 0.0000
X822 = 0.0000
X823 = 0.0000
X824 = 1.0000
X825 = 0.0000
X826 = 0.0000
X911 = 0.0000
X912 = 0.0000
X913 = 0.0000
X914 = 0.0000
X915 = 0.0000
X916 = 0.0000
X921 = 0.0000
X922 = 0.0000
X923 = 0.0000
X924 = 1.0000
X925 = 0.0000
X926 = 0.0000
X1011 = 0.0000
X1012 = 0.0000
X1013 = 0.0000
X1014 = 0.0000
X1015 = 0.0000
X1016 = 0.0000
X1021 = 0.0000
X1022 = 0.0000
X1023 = 0.0000
X1024 = 1.0000
X1025 = 0.0000
X1026 = 0.0000
Y11 = 0
Y12 = 0
Y13 = 1
Y14 = 0
Y15 = 0
Y16 = 0
Y21 = 0
Y22 = 0
Y23 = 0
Y24 = 1
Y25 = 0
Y26 = 0
Z = 35

Period 6
Optimal Solution with
Objective Value: 38
X111 = 0.0000
X112 = 0.0000
X113 = 0.0000
X114 = 0.0000
X115 = 1.0000
X116 = 0.0000
X121 = 0.0000
X122 = 0.0000
X123 = 0.0000
X124 = 0.0000
X125 = 0.0000
X126 = 0.0000
X211 = 0.0000
X212 = 0.0000
X213 = 0.0000
X214 = 0.0000
X215 = 1.0000
X216 = 0.0000
X221 = 0.0000
X222 = 0.0000
X223 = 0.0000
X224 = 0.0000
X225 = 0.0000
X226 = 0.0000
X311 = 0.0000
X312 = 0.0000
X313 = 0.0000
X314 = 0.0000
X315 = 0.0000
X316 = 0.0000
X321 = 0.0000
X322 = 0.0000
X323 = 0.0000
X324 = 0.0000
X325 = 1.0000
X326 = 0.0000
X411 = 0.0000
X412 = 0.0000
X413 = 0.0000
X414 = 0.0000
X415 = 1.0000
X416 = 0.0000
X421 = 0.0000
X422 = 0.0000
X423 = 0.0000
X424 = 0.0000
X425 = 0.0000
X426 = 0.0000
X511 = 0.0000
X512 = 0.0000
X513 = 0.0000
X514 = 0.0000
X515 = 1.0000
X516 = 0.0000
X521 = 0.0000
X522 = 0.0000
X523 = 0.0000
X524 = 0.0000
X525 = 0.0000
X526 = 0.0000
X611 = 0.0000
X612 = 0.0000
X613 = 0.0000
X614 = 0.0000
X615 = 0.0410
X616 = 0.0000
X621 = 0.0000
X622 = 0.0000
X623 = 0.0000
X624 = 0.0000
X625 = 0.9589
X626 = 0.0000
X711 = 0.0000
X712 = 0.0000
X713 = 0.0000
X714 = 0.0000
X715 = 0.0000
X716 = 0.0000
X721 = 0.0000
X722 = 0.0000
X723 = 0.0000
X724 = 0.0000
X725 = 1.0000
X726 = 0.0000
X811 = 0.0000
X812 = 0.0000
X813 = 0.0000
X814 = 0.0000
X815 = 1.0000
X816 = 0.0000
X821 = 0.0000
X822 = 0.0000
X823 = 0.0000
X824 = 0.0000
X825 = 0.0000
X826 = 0.0000
X911 = 0.0000
X912 = 0.0000
X913 = 0.0000
X914 = 0.0000
X915 = 0.0000
X916 = 0.0000
X921 = 0.0000
X922 = 0.0000
X923 = 0.0000
X924 = 0.0000
X925 = 1.0000
X926 = 0.0000
X1011 = 0.0000
X1012 = 0.0000
X1013 = 0.0000
X1014 = 0.0000
X1015 = 0.0000
X1016 = 0.0000
X1021 = 0.0000
X1022 = 0.0000
X1023 = 0.0000

X1024 = 0.0000
X1025 = 1.0000
X1026 = 0.0000
Y11 = 0
Y12 = 0
Y13 = 0
Y14 = 0
Y15 = 1
Y16 = 0
Y21 = 0
Y22 = 0
Y23 = 0
Y24 = 0
Y25 = 1
Y26 = 0
Z = 38

Period 7
Optimal Solution with
Objective Value: 33
X111 = 0.0000
X112 = 0.0000
X113 = 0.0000
X114 = 0.0000
X115 = 0.0000
X116 = 0.0000
X121 = 0.0000
X122 = 0.0000
X123 = 0.0000
X124 = 1.0000
X125 = 0.0000
X126 = 0.0000
X211 = 1.0000
X212 = 0.0000
X213 = 0.0000
X214 = 0.0000
X215 = 0.0000
X216 = 0.0000
X221 = 0.0000
X222 = 0.0000
X223 = 0.0000
X224 = 0.0000
X225 = 0.0000
X226 = 0.0000
X311 = 1.0000
X312 = 0.0000
X313 = 0.0000
X314 = 0.0000
X315 = 0.0000
X316 = 0.0000
X321 = 0.0000
X322 = 0.0000
X323 = 0.0000
X324 = 0.0000
X325 = 0.0000
X326 = 0.0000
X411 = 0.0000
X412 = 0.0000
X413 = 0.0000
X414 = 0.0000
X415 = 0.0000
X416 = 0.0000
X421 = 0.0000
X422 = 0.0000
X423 = 0.0000
X424 = 1.0000
X425 = 0.0000
X426 = 0.0000
X511 = 1.0000
X512 = 0.0000
X513 = 0.0000
X514 = 0.0000
X515 = 0.0000
X516 = 0.0000
X521 = 0.0000
X522 = 0.0000
X523 = 0.0000
X524 = 0.0000
X525 = 0.0000
X526 = 0.0000
X611 = 0.5754
X612 = 0.0000
X613 = 0.0000
X614 = 0.0000
X615 = 0.0000
X616 = 0.0000
X621 = 0.0000
X622 = 0.0000
X623 = 0.0000
X624 = 0.4245
X625 = 0.0000
X626 = 0.0000
X711 = 0.0000
X712 = 0.0000
X713 = 0.0000
X714 = 0.0000
X715 = 0.0000
X716 = 0.0000
X721 = 0.0000
X722 = 0.0000
X723 = 0.0000
X724 = 1.00000
X725 = 0.0000
X726 = 0.0000
X811 = 0.0000
X812 = 0.0000
X813 = 0.0000
X814 = 0.0000
X815 = 0.0000
X816 = 0.0000
X821 = 0.0000
X822 = 0.0000
X823 = 0.0000
X824 = 1.0000
X825 = 0.0000
X826 = 0.0000
X911 = 0.0000
X912 = 0.0000
X913 = 0.0000
X914 = 0.0000
X915 = 0.0000
X916 = 0.0000
X921 = 0.0000
X922 = 0.0000
X923 = 0.0000
X924 = 1.0000
X925 = 0.0000
X926 = 0.0000
X1011 = 0.0000
X1012 = 0.0000
X1013 = 0.0000
X1014 = 0.0000
X1015 = 0.0000
X1016 = 0.0000
X1021 = 0.0000
X1022 = 0.0000
X1023 = 0.0000
X1024 = 1.0000
X1025 = 0.0000
X1026 = 0.0000
Y11 = 1
Y12 = 0
Y13 = 0
Y14 = 0
Y15 = 0
Y16 = 0
Y21 = 0
Y22 = 0
Y23 = 0
Y24 = 1
Y25 = 0
Y26 = 0
Z = 33

Period 8
Optimal Solution with
Objective Value: 33
X111 = 0.0000
X112 = 0.0000
X113 = 0.0000
X114 = 0.0000
X115 = 0.0000
X116 = 0.0000

X121 = 0.0000
X122 = 0.0000
X123 = 0.0000
X124 = 1.0000
X125 = 0.0000
X126 = 0.0000
X211 = 1.0000
X212 = 0.0000
X213 = 0.0000
X214 = 0.0000
X215 = 0.0000
X216 = 0.0000
X221 = 0.0000
X222 = 0.0000
X223 = 0.0000
X224 = 0.0000
X225 = 0.0000
X226 = 0.0000
X311 = 1.0000
X312 = 0.0000
X313 = 0.0000
X314 = 0.0000
X315 = 0.0000
X316 = 0.0000
X321 = 0.0000
X322 = 0.0000
X323 = 0.0000
X324 = 0.0000
X325 = 0.0000
X326 = 0.0000
X411 = 0.0000
X412 = 0.0000
X413 = 0.0000
X414 = 0.0000
X415 = 0.0000
X416 = 0.0000
X421 = 0.0000
X422 = 0.0000
X423 = 0.0000
X424 = 1.0000
X425 = 0.0000
X426 = 0.0000
X511 = 1.0000
X512 = 0.0000
X513 = 0.0000
X514 = 0.0000
X515 = 0.0000
X516 = 0.0000
X521 = 0.0000
X522 = 0.0000
X523 = 0.0000
X524 = 0.0000
X525 = 0.0000
X526 = 0.0000
X611 = 0.6353
X612 = 0.0000
X613 = 0.0000
X614 = 0.0000
X615 = 0.0000
X616 = 0.0000
X621 = 0.0000
X622 = 0.0000
X623 = 0.0000
X624 = 0.3646
X625 = 0.0000
X626 = 0.0000
X711 = 0.0000
X712 = 0.0000
X713 = 0.0000
X714 = 0.0000
X715 = 0.0000
X716 = 0.0000
X721 = 0.0000
X722 = 0.0000
X723 = 0.0000
X724 = 1.0000
X725 = 0.0000
X726 = 0.0000
X811 = 0.0000
X812 = 0.0000
X813 = 0.0000
X814 = 0.0000
X815 = 0.0000
X816 = 0.0000
X821 = 0.0000
X822 = 0.0000
X823 = 0.0000
X824 = 1.0000
X825 = 0.0000
X826 = 0.0000
X911 = 0.0000
X912 = 0.0000
X913 = 0.0000
X914 = 0.0000
X915 = 0.0000
X916 = 0.0000
X921 = 0.0000
X922 = 0.0000
X923 = 0.0000
X924 = 1.0000
X925 = 0.0000
X926 = 0.0000
X1011 = 0.0000
X1012 = 0.0000
X1013 = 0.0000
X1014 = 0.0000
X1015 = 0.0000
X1016 = 0.0000
X1021 = 0.0000
X1022 = 0.0000
X1023 = 0.0000
X1024 = 1.0000
X1025 = 0.0000
X1026 = 0.0000
Y11 = 1
Y12 = 0
Y13 = 0
Y14 = 0
Y15 = 0
Y16 = 0
Y21 = 0
Y22 = 0
Y23 = 0
Y24 = 1
Y25 = 0
Y26 = 0
Z = 33

Period 9
Optimal Solution with Objective Value: 36
X111 = 0.0000
X112 = 0.0000
X113 = 0.0000
X114 = 0.0000
X115 = 0.0343
X116 = 0.0000
X121 = 0.0000
X122 = 0.0000
X123 = 0.9656
X124 = 0.0000
X125 = 0.0000
X126 = 0.0000
X211 = 0.0000
X212 = 0.0000
X213 = 0.0000
X214 = 0.0000
X215 = 1.0000
X216 = 0.0000
X221 = 0.0000
X222 = 0.0000
X223 = 0.0000
X224 = 0.0000
X225 = 0.0000
X226 = 0.0000
X311 = 0.0000
X312 = 0.0000
X313 = 0.0000
X314 = 0.0000
X315 = 0.0000
X316 = 0.0000
X321 = 0.0000
X322 = 0.0000
X323 = 1.0000

X324 = 0.0000
X325 = 0.0000
X326 = 0.0000
X411 = 0.0000
X412 = 0.0000
X413 = 0.0000
X414 = 0.0000
X415 = 0.0000
X416 = 0.0000
X421 = 0.0000
X422 = 0.0000
X423 = 1.0000
X424 = 0.0000
X425 = 0.0000
X426 = 0.0000
X511 = 0.0000
X512 = 0.0000
X513 = 0.0000
X514 = 0.0000
X515 = 0.0000
X516 = 0.0000
X521 = 0.0000
X522 = 0.0000
X523 = 1.0000
X524 = 0.0000
X525 = 0.0000
X526 = 0.0000
X611 = 0.0000
X612 = 0.0000
X613 = 0.0000
X614 = 0.0000
X615 = 0.0000
X616 = 0.0000
X621 = 0.0000
X622 = 0.0000
X623 = 1.0000
X624 = 0.0000
X625 = 0.0000
X626 = 0.0000
X711 = 0.0000
X712 = 0.0000
X713 = 0.0000
X714 = 0.0000
X715 = 1.0000
X716 = 0.0000
X721 = 0.0000
X722 = 0.0000
X723 = 0.0000
X724 = 0.0000
X725 = 0.0000
X726 = 0.0000
X811 = 0.0000
X812 = 0.0000
X813 = 0.0000
X814 = 0.0000
X815 = 1.0000
X816 = 0.0000
X821 = 0.0000
X822 = 0.0000
X823 = 0.0000
X824 = 0.0000
X825 = 0.0000
X826 = 0.0000
X911 = 0.0000
X912 = 0.0000
X913 = 0.0000
X914 = 0.0000
X915 = 1.0000
X916 = 0.0000
X921 = 0.0000
X922 = 0.0000
X923 = 0.0000
X924 = 0.0000
X925 = 0.0000
X926 = 0.0000
X1011 = 0.0000
X1012 = 0.0000
X1013 = 0.0000
X1014 = 0.0000
X1015 = 1.0000
X1016 = 0.0000
X1021 = 0.0000
X1022 = 0.0000
X1023 = 0.0000
X1024 = 0.0000
X1025 = 0.0000
X1026 = 0.0000
Y11 = 0
Y12 = 0
Y13 = 0
Y14 = 0
Y15 = 1
Y16 = 0
Y21 = 0
Y22 = 0
Y23 = 1
Y24 = 0
Y25 = 0
Y26 = 0
Z = 36

Period 10
Optimal Solution with
Objective Value: 37
X111 = 0.0000
X112 = 0.0000
X113 = 0.0000
X114 = 0.0000
X115 = 0.0000
X116 = 0.0000
X121 = 0.0000
X122 = 0.0000
X123 = 0.0000
X124 = 1.0000
X125 = 0.0000
X126 = 0.0000
X211 = 0.0000
X212 = 0.0000
X213 = 0.0000
X214 = 0.0000
X215 = 0.0000
X216 = 0.0000
X221 = 0.0000
X222 = 0.0000
X223 = 0.0000
X224 = 1.0000
X225 = 0.0000
X226 = 0.0000
X311 = 0.0000
X312 = 0.0000
X313 = 0.0000
X314 = 0.0000
X315 = 1.0000
X316 = 0.0000
X321 = 0.0000
X322 = 0.0000
X323 = 0.0000
X324 = 0.0000
X325 = 0.0000
X326 = 0.0000
X411 = 0.0000
X412 = 0.0000
X413 = 0.0000
X414 = 0.0000
X415 = 1.0000
X416 = 0.0000
X421 = 0.0000
X422 = 0.0000
X423 = 0.0000
X424 = 0.0000
X425 = 0.0000
X426 = 0.0000
X511 = 0.0000
X512 = 0.0000
X513 = 0.0000
X514 = 0.0000
X515 = 1.00000
X516 = 0.0000
X521 = 0.0000
X522 = 0.0000
X523 = 0.0000
X524 = 0.0000
X525 = 0.0000
X526 = 0.0000

X611 = 0.0000
X612 = 0.0000
X613 = 0.0000
X614 = 0.0000
X615 = 1.0000
X616 = 0.0000
X621 = 0.0000
X622 = 0.0000
X623 = 0.0000
X624 = 0.0000
X625 = 0.0000
X626 = 0.0000
X711 = 0.0000
X712 = 0.0000
X713 = 0.0000
X714 = 0.0000
X715 = 0.5586
X716 = 0.0000
X721 = 0.0000
X722 = 0.0000
X723 = 0.0000
X724 = 0.4414
X725 = 0.0000
X726 = 0.0000
X811 = 0.0000
X812 = 0.0000
X813 = 0.0000
X814 = 0.0000
X815 = 0.0000
X816 = 0.0000
X821 = 0.0000
X822 = 0.0000
X823 = 0.0000
X824 = 1.0000
X825 = 0.0000
X826 = 0.0000
X911 = 0.0000
X912 = 0.0000
X913 = 0.0000
X914 = 0.0000
X915 = 1.0000
X916 = 0.0000
X921 = 0.0000
X922 = 0.0000
X923 = 0.0000
X924 = 0.0000
X925 = 0.0000
X926 = 0.0000
X1011 = 0.0000
X1012 = 0.0000
X1013 = 0.0000
X1014 = 0.0000
X1015 = 0.0000
X1016 = 0.0000
X1021 = 0.0000
X1022 = 0.0000
X1023 = 0.0000
X1024 = 1.0000
X1025 = 0.0000
X1026 = 0.0000
Y11 = 0
Y12 = 0
Y13 = 0
Y14 = 0
Y15 = 1
Y16 = 0
Y21 = 0
Y22 = 0
Y23 = 0
Y24 = 1
Y25 = 0
Y26 = 0
Z = 37

Period 11

Optimal Solution with
Objective Value: 33
X111 = 0.0000
X112 = 0.0000
X113 = 0.0000
X114 = 1.0000
X115 = 0.0000
X116 = 0.0000
X121 = 0.0000
X122 = 0.0000
X123 = 0.0000
X124 = 0.0000
X125 = 0.0000
X126 = 0.0000
X211 = 0.0000
X212 = 0.0000
X213 = 0.0000
X214 = 0.0000
X215 = 0.0000
X216 = 0.0000
X221 = 1.0000
X222 = 0.0000
X223 = 0.0000
X224 = 0.0000
X225 = 0.0000
X226 = 0.0000
X311 = 0.0000
X312 = 0.0000
X313 = 0.0000
X314 = 0.0000
X315 = 0.0000
X316 = 0.0000
X321 = 1.0000
X322 = 0.0000
X323 = 0.0000
X324 = 0.0000
X325 = 0.0000
X326 = 0.0000
X411 = 0.0000
X412 = 0.0000
X413 = 0.0000
X414 = 1.0000
X415 = 0.0000
X416 = 0.0000
X421 = 0.0000
X422 = 0.0000
X423 = 0.0000
X424 = 0.0000
X425 = 0.0000
X426 = 0.0000
X511 = 0.0000
X512 = 0.0000
X513 = 0.0000
X514 = 0.0000
X515 = 0.0000
X516 = 0.0000
X521 = 1.0000
X522 = 0.0000
X523 = 0.0000
X524 = 0.0000
X525 = 0.0000
X526 = 0.0000
X611 = 0.0000
X612 = 0.0000
X613 = 0.0000
X614 = 0.4334
X615 = 0.0000
X616 = 0.0000
X621 = 0.5665
X622 = 0.0000
X623 = 0.0000
X624 = 0.0000
X625 = 0.0000
X626 = 0.0000
X711 = 0.0000
X712 = 0.0000
X713 = 0.0000
X714 = 1.0000
X715 = 0.0000
X716 = 0.0000
X721 = 0.0000
X722 = 0.0000
X723 = 0.0000
X724 = 0.0000
X725 = 0.0000
X726 = 0.0000
X811 = 0.0000
X812 = 0.0000
X813 = 0.0000

X814 = 1.0000
X815 = 0.0000
X816 = 0.0000
X821 = 0.0000
X822 = 0.0000
X823 = 0.0000
X824 = 0.0000
X825 = 0.0000
X826 = 0.0000
X911 = 0.0000
X912 = 0.0000
X913 = 0.0000
X914 = 1.00000
X915 = 0.0000
X916 = 0.0000
X921 = 0.0000
X922 = 0.0000
X923 = 0.0000
X924 = 0.0000
X925 = 0.0000
X926 = 0.0000
X1011 = 0.0000
X1012 = 0.0000
X1013 = 0.0000
X1014 = 1.0000
X1015 = 0.0000
X1016 = 0.0000
X1021 = 0.0000
X1022 = 0.0000
X1023 = 0.0000
X1024 = 0.0000
X1025 = 0.0000
X1026 = 0.0000
Y11 = 0
Y12 = 0
Y13 = 0
Y14 = 1
Y15 = 0
Y16 = 0
Y21 = 1
Y22 = 0
Y23 = 0
Y24 = 0
Y25 = 0
Y26 = 0
Z = 33

Period 12
Optimal Solution with
Objective Value: 35
X111 = 0.0000
X112 = 0.0000
X113 = 0.0000
X114 = 1.0000
X115 = 0.0000
X116 = 0.0000
X121 = 0.0000
X122 = 0.0000
X123 = 0.0000
X124 = 0.0000
X125 = 0.0000
X126 = 0.0000
X211 = 0.0000
X212 = 0.0000
X213 = 0.0000
X214 = 0.5155
X215 = 0.0000
X216 = 0.0000
X221 = 0.0000
X222 = 0.0000
X223 = 0.4844
X224 = 0.0000
X225 = 0.0000
X226 = 0.0000
X311 = 0.0000
X312 = 0.0000
X313 = 0.0000
X314 = 0.0000
X315 = 0.0000
X316 = 0.0000
X321 = 0.0000
X322 = 0.0000
X323 = 1.0000
X324 = 0.0000
X325 = 0.0000
X326 = 0.0000
X411 = 0.0000
X412 = 0.0000
X413 = 0.0000
X414 = 0.0000
X415 = 0.0000
X416 = 0.0000
X421 = 0.0000
X422 = 0.0000
X423 = 1.0000
X424 = 0.0000
X425 = 0.0000
X426 = 0.0000
X511 = 0.0000
X512 = 0.0000
X513 = 0.0000
X514 = 0.0000
X515 = 0.0000
X516 = 0.0000
X521 = 0.0000
X522 = 0.0000
X523 = 1.0000
X524 = 0.0000
X525 = 0.0000
X526 = 0.0000
X611 = 0.0000
X612 = 0.0000
X613 = 0.0000
X614 = 0.0000
X615 = 0.0000
X616 = 0.0000
X621 = 0.0000
X622 = 0.0000
X623 = 1.0000
X624 = 0.0000
X625 = 0.0000
X626 = 0.0000
X711 = 0.0000
X712 = 0.0000
X713 = 0.0000
X714 = 1.0000
X715 = 0.0000
X716 = 0.0000
X721 = 0.0000
X722 = 0.0000
X723 = 0.0000
X724 = 0.0000
X725 = 0.0000
X726 = 0.0000
X811 = 0.0000
X812 = 0.0000
X813 = 0.0000
X814 = 1.00000
X815 = 0.0000
X816 = 0.0000
X821 = 0.0000
X822 = 0.0000
X823 = 0.0000
X824 = 0.0000
X825 = 0.0000
X826 = 0.0000
X911 = 0.0000
X912 = 0.0000
X913 = 0.0000
X914 = 1.0000
X915 = 0.0000
X916 = 0.0000
X921 = 0.0000
X922 = 0.0000
X923 = 0.0000
X924 = 0.0000
X925 = 0.0000
X926 = 0.0000
X1011 = 0.0000
X1012 = 0.0000
X1013 = 0.0000
X1014 = 1.0000
X1015 = 0.0000
X1016 = 0.0000

X1021 = 0.0000
X1022 = 0.0000
X1023 = 0.0000
X1024 = 0.0000
X1025 = 0.0000
X1026 = 0.0000
Y11 = 0
Y12 = 0
Y13 = 0
Y14 = 1
Y15 = 0
Y16 = 0
Y21 = 0
Y22 = 0
Y23 = 1
Y24 = 0
Y25 = 0
Y26 = 0
Z = 35

Period 13
Optimal Solution with
Objective Value: 37
X111 = 0.0000
X112 = 0.0000
X113 = 0.0000
X114 = 0.0000
X115 = 0.0000
X116 = 0.0000
X121 = 0.0000
X122 = 0.0000
X123 = 0.0000
X124 = 1.0000
X125 = 0.0000
X126 = 0.0000
X211 = 0.0000
X212 = 0.0000
X213 = 0.0000
X214 = 0.0000
X215 = 0.0000
X216 = 0.0000
X221 = 0.0000
X222 = 0.0000
X223 = 0.0000
X224 = 1.0000
X225 = 0.0000
X226 = 0.0000
X311 = 0.0000
X312 = 0.0000
X313 = 0.0000
X314 = 0.0000
X315 = 1.0000
X316 = 0.0000
X321 = 0.0000
X322 = 0.0000
X323 = 0.0000
X324 = 0.0000
X325 = 0.0000
X326 = 0.0000
X411 = 0.0000
X412 = 0.0000
X413 = 0.0000
X414 = 0.0000
X415 = 1.0000
X416 = 0.0000
X421 = 0.0000
X422 = 0.0000
X423 = 0.0000
X424 = 0.0000
X425 = 0.0000
X426 = 0.0000
X511 = 0.0000
X512 = 0.0000
X513 = 0.0000
X514 = 0.0000
X515 = 1.0000
X516 = 0.0000
X521 = 0.0000
X522 = 0.0000
X523 = 0.0000
X524 = 0.0000
X525 = 0.0000
X526 = 0.0000
X611 = 0.0000
X612 = 0.0000
X613 = 0.0000
X614 = 0.0000
X615 = 1.0000
X616 = 0.0000
X621 = 0.0000
X622 = 0.0000
X623 = 0.0000
X624 = 0.0000
X625 = 0.0000
X626 = 0.0000
X711 = 0.0000
X712 = 0.0000
X713 = 0.0000
X714 = 0.0000
X715 = 0.5966
X716 = 0.0000
X721 = 0.0000
X722 = 0.0000
X723 = 0.0000
X724 = 0.4033
X725 = 0.0000
X726 = 0.0000
X811 = 0.0000
X812 = 0.0000
X813 = 0.0000
X814 = 0.0000
X815 = 0.0000
X816 = 0.0000
X821 = 0.0000
X822 = 0.0000
X823 = 0.0000
X824 = 1.0000
X825 = 0.0000
X826 = 0.0000
X911 = 0.0000
X912 = 0.0000
X913 = 0.0000
X914 = 0.0000
X915 = 1.0000
X916 = 0.0000
X921 = 0.0000
X922 = 0.0000
X923 = 0.0000
X924 = 0.0000
X925 = 0.0000
X926 = 0.0000
X1011 = 0.0000
X1012 = 0.0000
X1013 = 0.0000
X1014 = 0.0000
X1015 = 0.0000
X1016 = 0.0000
X1021 = 0.0000
X1022 = 0.0000
X1023 = 0.0000
X1024 = 1.0000
X1025 = 0.0000
X1026 = 0.0000
Y11 = 0
Y12 = 0
Y13 = 0
Y14 = 0
Y15 = 1
Y16 = 0
Y21 = 0
Y22 = 0
Y23 = 0
Y24 = 1
Y25 = 0
Y26 = 0
Z = 37

Period 14
Optimal Solution with
Objective Value: 33
X111 = 0.0000
X112 = 0.0000
X113 = 0.0000

X114 = 1.0000
X115 = 0.0000
X116 = 0.0000
X121 = 0.0000
X122 = 0.0000
X123 = 0.0000
X124 = 0.0000
X125 = 0.0000
X126 = 0.0000
X211 = 0.0000
X212 = 0.0000
X213 = 0.0000
X214 = 0.0000
X215 = 0.0000
X216 = 0.0000
X221 = 1.0000
X222 = 0.0000
X223 = 0.0000
X224 = 0.0000
X225 = 0.0000
X226 = 0.0000
X311 = 0.0000
X312 = 0.0000
X313 = 0.0000
X314 = 0.0000
X315 = 0.0000
X316 = 0.0000
X321 = 1.0000
X322 = 0.0000
X323 = 0.0000
X324 = 0.0000
X325 = 0.0000
X326 = 0.0000
X411 = 0.0000
X412 = 0.0000
X413 = 0.0000
X414 = 1.0000
X415 = 0.0000
X416 = 0.0000
X421 = 0.0000
X422 = 0.0000
X423 = 0.0000
X424 = 0.0000
X425 = 0.0000
X426 = 0.0000
X511 = 0.0000
X512 = 0.0000
X513 = 0.0000
X514 = 0.0000
X515 = 0.0000
X516 = 0.0000
X521 = 1.0000
X522 = 0.0000
X523 = 0.0000
X524 = 0.0000
X525 = 0.0000
X526 = 0.0000
X611 = 0.0000
X612 = 0.0000
X613 = 0.0000
X614 = 0.4449
X615 = 0.0000
X616 = 0.0000
X621 = 0.5550
X622 = 0.0000
X623 = 0.0000
X624 = 0.0000
X625 = 0.0000
X626 = 0.0000
X711 = 0.0000
X712 = 0.0000
X713 = 0.0000
X714 = 1.0000
X715 = 0.0000
X716 = 0.0000
X721 = 0.0000
X722 = 0.0000
X723 = 0.0000
X724 = 0.0000
X725 = 0.0000
X726 = 0.0000
X811 = 0.0000
X812 = 0.0000
X813 = 0.0000
X814 = 1.0000
X815 = 0.0000
X816 = 0.0000
X821 = 0.0000
X822 = 0.0000
X823 = 0.0000
X824 = 0.0000
X825 = 0.0000
X826 = 0.0000
X911 = 0.0000
X912 = 0.0000
X913 = 0.0000
X914 = 1.0000
X915 = 0.0000
X916 = 0.0000
X921 = 0.0000
X922 = 0.0000
X923 = 0.0000
X924 = 0.0000
X925 = 0.0000
X926 = 0.0000
X1011 = 0.0000
X1012 = 0.0000
X1013 = 0.0000
X1014 = 1.0000
X1015 = 0.0000
X1016 = 0.0000
X1021 = 0.0000
X1022 = 0.0000
X1023 = 0.0000
X1024 = 0.0000
X1025 = 0.0000
X1026 = 0.0000
Y11 = 0
Y12 = 0
Y13 = 0
Y14 = 1
Y15 = 0
Y16 = 0
Y21 = 1
Y22 = 0
Y23 = 0
Y24 = 0
Y25 = 0
Y26 = 0
Z = 33

Period 15
Optimal Solution with Objective Value: 36
X111 = 0.0000
X112 = 0.0000
X113 = 0.0000
X114 = 0.0000
X115 = 0.2240
X116 = 0.0000
X121 = 0.0000
X122 = 0.0000
X123 = 0.7759
X124 = 0.0000
X125 = 0.0000
X126 = 0.0000
X211 = 0.0000
X212 = 0.0000
X213 = 0.0000
X214 = 0.0000
X215 = 1.0000
X216 = 0.0000
X221 = 0.0000
X222 = 0.0000
X223 = 0.0000
X224 = 0.0000
X225 = 0.0000
X226 = 0.0000
X311 = 0.0000
X312 = 0.0000
X313 = 0.0000
X314 = 0.0000
X315 = 0.0000
X316 = 0.0000

X321 = 0.0000
X322 = 0.0000
X323 = 1.0000
X324 = 0.0000
X325 = 0.0000
X326 = 0.0000
X411 = 0.0000
X412 = 0.0000
X413 = 0.0000
X414 = 0.0000
X415 = 0.0000
X416 = 0.0000
X421 = 0.0000
X422 = 0.0000
X423 = 1.0000
X424 = 0.0000
X425 = 0.0000
X426 = 0.0000
X511 = 0.0000
X512 = 0.0000
X513 = 0.0000
X514 = 0.0000
X515 = 0.0000
X516 = 0.0000
X521 = 0.0000
X522 = 0.0000
X523 = 1.0000
X524 = 0.0000
X525 = 0.0000
X526 = 0.0000
X611 = 0.0000
X612 = 0.0000
X613 = 0.0000
X614 = 0.0000
X615 = 0.0000
X616 = 0.0000
X621 = 0.0000
X622 = 0.0000
X623 = 1.0000
X624 = 0.0000
X625 = 0.0000
X626 = 0.0000
X711 = 0.0000
X712 = 0.0000
X713 = 0.0000
X714 = 0.0000
X715 = 1.0000
X716 = 0.0000
X721 = 0.0000
X722 = 0.0000
X723 = 0.0000
X724 = 0.0000
X725 = 0.0000
X726 = 0.0000
X811 = 0.0000
X812 = 0.0000
X813 = 0.0000
X814 = 0.0000
X815 = 1.0000
X816 = 0.0000
X821 = 0.0000
X822 = 0.0000
X823 = 0.0000
X824 = 0.0000
X825 = 0.0000
X826 = 0.0000
X911 = 0.0000
X912 = 0.0000
X913 = 0.0000
X914 = 0.0000
X915 = 1.0000
X916 = 0.0000
X921 = 0.0000
X922 = 0.0000
X923 = 0.0000
X924 = 0.0000
X925 = 0.0000
X926 = 0.0000
X1011 = 0.0000
X1012 = 0.0000
X1013 = 0.0000
X1014 = 0.0000
X1015 = 1.0000
X1016 = 0.0000
X1021 = 0.0000
X1022 = 0.0000
X1023 = 0.0000
X1024 = 0.0000
X1025 = 0.0000
X1026 = 0.0000
Y11 = 0
Y12 = 0
Y13 = 0
Y14 = 0
Y15 = 1
Y16 = 0
Y21 = 0
Y22 = 0
Y23 = 1
Y24 = 0
Y25 = 0
Y26 = 0
Z = 36

Period 16
Optimal Solution with
Objective Value: 36
X111 = 0.0000
X112 = 0.0000
X113 = 0.0000
X114 = 1.0000
X115 = 0.0000
X116 = 0.0000
X121 = 0.0000
X122 = 0.0000
X123 = 0.0000
X124 = 0.0000
X125 = 0.0000
X126 = 0.0000
X211 = 0.0000
X212 = 0.0000
X213 = 0.0000
X214 = 0.6355
X215 = 0.0000
X216 = 0.0000
X221 = 0.0000
X222 = 0.0000
X223 = 0.0000
X224 = 0.3644
X225 = 0.0000
X226 = 0.0000
X311 = 0.0000
X312 = 0.0000
X313 = 0.0000
X314 = 0.0000
X315 = 0.0000
X316 = 0.0000
X321 = 0.0000
X322 = 0.0000
X323 = 0.0000
X324 = 1.0000
X325 = 0.0000
X326 = 0.0000
X411 = 0.0000
X412 = 0.0000
X413 = 0.0000
X414 = 0.0000
X415 = 0.0000
X416 = 0.0000
X421 = 0.0000
X422 = 0.0000
X423 = 0.0000
X424 = 1.0000
X425 = 0.0000
X426 = 0.0000
X511 = 0.0000
X512 = 0.0000
X513 = 0.0000
X514 = 1.0000
X515 = 0.0000
X516 = 0.0000
X521 = 0.0000
X522 = 0.0000
X523 = 0.0000
X524 = 0.0000

X525 = 0.0000
X526 = 0.0000
X611 = 0.0000
X612 = 0.0000
X613 = 0.0000
X614 = 0.0000
X615 = 0.0000
X616 = 0.0000
X621 = 0.0000
X622 = 0.0000
X623 = 0.0000
X624 = 1.0000
X625 = 0.0000
X626 = 0.0000
X711 = 0.0000
X712 = 0.0000
X713 = 0.0000
X714 = 0.0000
X715 = 0.0000
X716 = 0.0000
X721 = 0.0000
X722 = 0.0000
X723 = 0.0000
X724 = 1.0000
X725 = 0.0000
X726 = 0.0000
X811 = 0.0000
X812 = 0.0000
X813 = 0.0000
X814 = 1.0000
X815 = 0.0000
X816 = 0.0000
X821 = 0.0000
X822 = 0.0000
X823 = 0.0000
X824 = 0.0000
X825 = 0.0000
X826 = 0.0000
X911 = 0.0000
X912 = 0.0000
X913 = 0.0000
X914 = 1.0000
X915 = 0.0000
X916 = 0.0000
X921 = 0.0000
X922 = 0.0000
X923 = 0.0000
X924 = 0.0000
X925 = 0.0000
X926 = 0.0000
X1011 = 0.0000
X1012 = 0.0000
X1013 = 0.0000
X1014 = 1.0000
X1015 = 0.0000
X1016 = 0.0000
X1021 = 0.0000
X1022 = 0.0000
X1023 = 0.0000
X1024 = 0.0000
X1025 = 0.0000
X1026 = 0.0000
Y11 = 0
Y12 = 0
Y13 = 0
Y14 = 1
Y15 = 0
Y16 = 0
Y21 = 0
Y22 = 0
Y23 = 0
Y24 = 1
Y25 = 0
Y26 = 0
Z = 36

APPENDIX D OPERATION TIMES FOR DIFFERENT SKILL LEVELS

Operation times for different skill levels with std. dev of 5%

	Operations				
Product	**1**	**2**	**3**	**4**	**5**
1	0.07	0.45	0.37	0.88	0.38
Std. Dev.	0.0035	0.0225	0.0185	0.044	0.019
Skill Level					
1	0.056	0.36	0.296	0.704	0.304
2	0.0595	0.3825	0.3145	0.748	0.323
3	0.063	0.405	0.333	0.792	0.342
4	0.0665	0.4275	0.3515	0.836	0.361
5	0.07	0.45	0.37	0.88	0.38
6	0.0735	0.4725	0.3885	0.924	0.399
7	0.077	0.495	0.407	0.968	0.418
8	0.0805	0.5175	0.4255	1.012	0.437
9	0.084	0.54	0.444	1.056	0.456

	Operations				
Product	**1**	**2**	**3**	**4**	**5**
2	0.05	0.29	0.62	0.74	0.38
Std. Dev.	0.0025	0.0145	0.031	0.037	0.019
Skill Level					
1	0.04	0.232	0.496	0.592	0.304
2	0.0425	0.2465	0.527	0.629	0.323
3	0.045	0.261	0.558	0.666	0.342
4	0.0475	0.2755	0.589	0.703	0.361
5	0.05	0.29	0.62	0.74	0.38
6	0.0525	0.3045	0.651	0.777	0.399
7	0.055	0.319	0.682	0.814	0.418
8	0.0575	0.3335	0.713	0.851	0.437
9	0.06	0.348	0.744	0.888	0.456

	Operations				
Product	**1**	**2**	**3**	**4**	**5**
3	0.06	0.29	1.18	0.86	0.18
Std. Dev.	0.003	0.0145	0.059	0.043	0.009
Skill Level					
1	0.048	0.232	0.944	0.688	0.144
2	0.051	0.2465	1.003	0.731	0.153
3	0.054	0.261	1.062	0.774	0.162
4	0.057	0.2755	1.121	0.817	0.171
5	0.06	0.29	1.18	0.86	0.18
6	0.063	0.3045	1.239	0.903	0.189
7	0.066	0.319	1.298	0.946	0.198
8	0.069	0.3335	1.357	0.989	0.207
9	0.072	0.348	1.416	1.032	0.216

	Operations				
Product	**1**	**2**	**3**	**4**	**5**
4	0.04	0.31	0.55	0.47	0.4
Std. Dev.	0.002	0.0155	0.0275	0.0235	0.02
Skill Level					
1	0.032	0.248	0.44	0.376	0.32
2	0.034	0.2635	0.4675	0.3995	0.34
3	0.036	0.279	0.495	0.423	0.36
4	0.038	0.2945	0.5225	0.4465	0.38
5	0.04	0.31	0.55	0.47	0.4
6	0.042	0.3255	0.5775	0.4935	0.42
7	0.044	0.341	0.605	0.517	0.44
8	0.046	0.3565	0.6325	0.5405	0.46
9	0.048	0.372	0.66	0.564	0.48

	Operations				
Product	**1**	**2**	**3**	**4**	**5**
5	0.08	0.41	0.43	0.74	0.43
Std. Dev.	0.004	0.0205	0.0215	0.037	0.0215
Skill Level					
1	0.064	0.328	0.344	0.592	0.344
2	0.068	0.3485	0.3655	0.629	0.3655
3	0.072	0.369	0.387	0.666	0.387
4	0.076	0.3895	0.4085	0.703	0.4085
5	0.08	0.41	0.43	0.74	0.43
6	0.084	0.4305	0.4515	0.777	0.4515
7	0.088	0.451	0.473	0.814	0.473
8	0.092	0.4715	0.4945	0.851	0.4945
9	0.096	0.492	0.516	0.888	0.516

	Operations				
Product	**1**	**2**	**3**	**4**	**5**
6	0.07	0.32	1.18	0.55	0.45
Std. Dev.	0.0035	0.016	0.059	0.0275	0.0225
Skill Level					
1	0.056	0.256	0.944	0.44	0.36
2	0.0595	0.272	1.003	0.4675	0.3825
3	0.063	0.288	1.062	0.495	0.405
4	0.0665	0.304	1.121	0.5225	0.4275
5	0.07	0.32	1.18	0.55	0.45
6	0.0735	0.336	1.239	0.5775	0.4725
7	0.077	0.352	1.298	0.605	0.495
8	0.0805	0.368	1.357	0.6325	0.5175
9	0.084	0.384	1.416	0.66	0.54

	Operations				
Product	**1**	**2**	**3**	**4**	**5**
7	0.09	0.37	0.46	0.49	0.26
Std. Dev.	0.0045	0.0185	0.023	0.0245	0.013
Skill Level					
1	0.072	0.296	0.368	0.392	0.208
2	0.0765	0.3145	0.391	0.4165	0.221
3	0.081	0.333	0.414	0.441	0.234
4	0.0855	0.3515	0.437	0.4655	0.247
5	0.09	0.37	0.46	0.49	0.26
6	0.0945	0.3885	0.483	0.5145	0.273
7	0.099	0.407	0.506	0.539	0.286
8	0.1035	0.4255	0.529	0.5635	0.299
9	0.108	0.444	0.552	0.588	0.312

	Operations				
Product	**1**	**2**	**3**	**4**	**5**
8	0.08	0.28	0.49	0.61	0.29
Std. Dev.	0.004	0.014	0.0245	0.0305	0.0145
Skill Level					
1	0.064	0.224	0.392	0.488	0.232
2	0.068	0.238	0.4165	0.5185	0.2465
3	0.072	0.252	0.441	0.549	0.261
4	0.076	0.266	0.4655	0.5795	0.2755
5	0.08	0.28	0.49	0.61	0.29
6	0.084	0.294	0.5145	0.6405	0.3045
7	0.088	0.308	0.539	0.671	0.319
8	0.092	0.322	0.5635	0.7015	0.3335
9	0.096	0.336	0.588	0.732	0.348

			Operations						Operations		
Product	**1**	**2**	**3**	**4**	**5**	**Product**	**1**	**2**	**3**	**4**	**5**
9	0.04	0.34	0.81	0.62	0.34	**10**	0.07	0.43	0.74	0.87	0.43
Std. Dev.	0.002	0.017	0.0405	0.031	0.017	**Std. Dev.**	0.0035	0.0215	0.037	0.0435	0.0215
Skill Level						Skill Level					
1	0.032	0.272	0.648	0.496	0.272	1	0.056	0.344	0.592	0.696	0.344
2	0.034	0.289	0.6885	0.527	0.289	2	0.0595	0.3655	0.629	0.7395	0.3655
3	0.036	0.306	0.729	0.558	0.306	3	0.063	0.387	0.666	0.783	0.387
4	0.038	0.323	0.7695	0.589	0.323	4	0.0665	0.4085	0.703	0.8265	0.4085
5	0.04	0.34	0.81	0.62	0.34	5	0.07	0.43	0.74	0.87	0.43
6	0.042	0.357	0.8505	0.651	0.357	6	0.0735	0.4515	0.777	0.9135	0.4515
7	0.044	0.374	0.891	0.682	0.374	7	0.077	0.473	0.814	0.957	0.473
8	0.046	0.391	0.9315	0.713	0.391	8	0.0805	0.4945	0.851	1.0005	0.4945
9	0.048	0.408	0.972	0.744	0.408	9	0.084	0.516	0.888	1.044	0.516

Operation times for different skill levels with std. dev of 10%

			Operations						Operations		
Product	**1**	**2**	**3**	**4**	**5**	**Product**	**1**	**2**	**3**	**4**	**5**
1	0.07	0.45	0.37	0.88	0.38	**2**	0.05	0.29	0.62	0.74	0.38
Std. Dev.	0.007	0.045	0.037	0.088	0.038	**Std. Dev.**	0.005	0.029	0.062	0.074	0.038
Skill Level						Skill Level					
1	0.042	0.27	0.222	0.528	0.228	1	0.03	0.174	0.372	0.444	0.228
2	0.049	0.315	0.259	0.616	0.266	2	0.035	0.203	0.434	0.518	0.266
3	0.056	0.36	0.296	0.704	0.304	3	0.04	0.232	0.496	0.592	0.304
4	0.063	0.405	0.333	0.792	0.342	4	0.045	0.261	0.558	0.666	0.342
5	0.07	0.45	0.37	0.88	0.38	5	0.05	0.29	0.62	0.74	0.38
6	0.077	0.495	0.407	0.968	0.418	6	0.055	0.319	0.682	0.814	0.418
7	0.084	0.54	0.444	1.056	0.456	7	0.06	0.348	0.744	0.888	0.456
8	0.091	0.585	0.481	1.144	0.494	8	0.065	0.377	0.806	0.962	0.494
9	0.098	0.63	0.518	1.232	0.532	9	0.07	0.406	0.868	1.036	0.532

			Operations						Operations		
Product	**1**	**2**	**3**	**4**	**5**	**Product**	**1**	**2**	**3**	**4**	**5**
3	0.06	0.29	1.18	0.86	0.18	**4**	0.04	0.31	0.55	0.47	0.4
Std. Dev.	0.006	0.029	0.118	0.086	0.018	**Std. Dev.**	0.004	0.031	0.055	0.047	0.04
Skill Level						Skill Level					
1	0.036	0.174	0.708	0.516	0.108	1	0.024	0.186	0.33	0.282	0.24
2	0.042	0.203	0.826	0.602	0.126	2	0.028	0.217	0.385	0.329	0.28
3	0.048	0.232	0.944	0.688	0.144	3	0.032	0.248	0.44	0.376	0.32
4	0.054	0.261	1.062	0.774	0.162	4	0.036	0.279	0.495	0.423	0.36
5	0.06	0.29	1.18	0.86	0.18	5	0.04	0.31	0.55	0.47	0.4
6	0.066	0.319	1.298	0.946	0.198	6	0.044	0.341	0.605	0.517	0.44
7	0.072	0.348	1.416	1.032	0.216	7	0.048	0.372	0.66	0.564	0.48
8	0.078	0.377	1.534	1.118	0.234	8	0.052	0.403	0.715	0.611	0.52
9	0.084	0.406	1.652	1.204	0.252	9	0.056	0.434	0.77	0.658	0.56

			Operations						Operations		
Product	**1**	**2**	**3**	**4**	**5**	**Product**	**1**	**2**	**3**	**4**	**5**
5	0.08	0.41	0.43	0.74	0.43	**6**	0.07	0.32	1.18	0.55	0.45
Std. Dev.	0.008	0.041	0.043	0.074	0.043	**Std. Dev.**	0.007	0.032	0.118	0.055	0.045
Skill Level						Skill Level					
1	0.048	0.246	0.258	0.444	0.258	1	0.042	0.192	0.708	0.33	0.27
2	0.056	0.287	0.301	0.518	0.301	2	0.049	0.224	0.826	0.385	0.315
3	0.064	0.328	0.344	0.592	0.344	3	0.056	0.256	0.944	0.44	0.36
4	0.072	0.369	0.387	0.666	0.387	4	0.063	0.288	1.062	0.495	0.405
5	0.08	0.41	0.43	0.74	0.43	5	0.07	0.32	1.18	0.55	0.45
6	0.088	0.451	0.473	0.814	0.473	6	0.077	0.352	1.298	0.605	0.495
7	0.096	0.492	0.516	0.888	0.516	7	0.084	0.384	1.416	0.66	0.54
8	0.104	0.533	0.559	0.962	0.559	8	0.091	0.416	1.534	0.715	0.585
9	0.112	0.574	0.602	1.036	0.602	9	0.098	0.448	1.652	0.77	0.63

	Operations						Operations				
Product	**1**	**2**	**3**	**4**	**5**	**Product**	**1**	**2**	**3**	**4**	**5**
7	0.09	0.37	0.46	0.49	0.26	**8**	0.08	0.28	0.49	0.61	0.29
Std. Dev.	0.009	0.037	0.046	0.049	0.026	**Std. Dev.**	0.008	0.028	0.049	0.061	0.029
Skill Level						Skill Level					
1	0.054	0.222	0.276	0.294	0.156	1	0.048	0.168	0.294	0.366	0.174
2	0.063	0.259	0.322	0.343	0.182	2	0.056	0.196	0.343	0.427	0.203
3	0.072	0.296	0.368	0.392	0.208	3	0.064	0.224	0.392	0.488	0.232
4	0.081	0.333	0.414	0.441	0.234	4	0.072	0.252	0.441	0.549	0.261
5	0.09	0.37	0.46	0.49	0.26	5	0.08	0.28	0.49	0.61	0.29
6	0.099	0.407	0.506	0.539	0.286	6	0.088	0.308	0.539	0.671	0.319
7	0.108	0.444	0.552	0.588	0.312	7	0.096	0.336	0.588	0.732	0.348
8	0.117	0.481	0.598	0.637	0.338	8	0.104	0.364	0.637	0.793	0.377
9	0.126	0.518	0.644	0.686	0.364	9	0.112	0.392	0.686	0.854	0.406

	Operations						Operations				
Product	**1**	**2**	**3**	**4**	**5**	**Product**	**1**	**2**	**3**	**4**	**5**
9	0.04	0.34	0.81	0.62	0.34	**10**	0.07	0.43	0.74	0.87	0.43
Std. Dev.	0.004	0.034	0.081	0.062	0.034	**Std. Dev.**	0.007	0.043	0.074	0.087	0.043
Skill Level						Skill Level					
1	0.024	0.204	0.486	0.372	0.204	1	0.042	0.258	0.444	0.522	0.258
2	0.028	0.238	0.567	0.434	0.238	2	0.049	0.301	0.518	0.609	0.301
3	0.032	0.272	0.648	0.496	0.272	3	0.056	0.344	0.592	0.696	0.344
4	0.036	0.306	0.729	0.558	0.306	4	0.063	0.387	0.666	0.783	0.387
5	0.04	0.34	0.81	0.62	0.34	5	0.07	0.43	0.74	0.87	0.43
6	0.044	0.374	0.891	0.682	0.374	6	0.077	0.473	0.814	0.957	0.473
7	0.048	0.408	0.972	0.744	0.408	7	0.084	0.516	0.888	1.044	0.516
8	0.052	0.442	1.053	0.806	0.442	8	0.091	0.559	0.962	1.131	0.559
9	0.056	0.476	1.134	0.868	0.476	9	0.098	0.602	1.036	1.218	0.602

Operation times for different skill levels with std. dev of 15%

	Operations						Operations				
Product	**1**	**2**	**3**	**4**	**5**	**Product**	**1**	**2**	**3**	**4**	**5**
1	0.07	0.45	0.37	0.88	0.38	**2**	0.05	0.29	0.62	0.74	0.38
Std. Dev.	0.0105	0.0675	0.0555	0.132	0.057	**Std. Dev.**	0.0075	0.0435	0.093	0.111	0.057
Skill Level						Skill Level					
1	0.028	0.18	0.148	0.352	0.152	1	0.02	0.116	0.248	0.296	0.152
2	0.0385	0.2475	0.2035	0.484	0.209	2	0.0275	0.1595	0.341	0.407	0.209
3	0.049	0.315	0.259	0.616	0.266	3	0.035	0.203	0.434	0.518	0.266
4	0.0595	0.3825	0.3145	0.748	0.323	4	0.0425	0.2465	0.527	0.629	0.323
5	0.07	0.45	0.37	0.88	0.38	5	0.05	0.29	0.62	0.74	0.38
6	0.0805	0.5175	0.4255	1.012	0.437	6	0.0575	0.3335	0.713	0.851	0.437
7	0.091	0.585	0.481	1.144	0.494	7	0.065	0.377	0.806	0.962	0.494
8	0.1015	0.6525	0.5365	1.276	0.551	8	0.0725	0.4205	0.899	1.073	0.551
9	0.112	0.72	0.592	1.408	0.608	9	0.08	0.464	0.992	1.184	0.608

	Operations						Operations				
Product	**1**	**2**	**3**	**4**	**5**	**Product**	**1**	**2**	**3**	**4**	**5**
3	0.06	0.29	1.18	0.86	0.18	**4**	0.04	0.31	0.55	0.47	0.4
Std. Dev.	0.009	0.0435	0.177	0.129	0.027	**Std. Dev.**	0.006	0.0465	0.0825	0.0705	0.06
Skill Level						Skill Level					
1	0.024	0.116	0.472	0.344	0.072	1	0.016	0.124	0.22	0.188	0.16
2	0.033	0.1595	0.649	0.473	0.099	2	0.022	0.1705	0.3025	0.2585	0.22
3	0.042	0.203	0.826	0.602	0.126	3	0.028	0.217	0.385	0.329	0.28
4	0.051	0.2465	1.003	0.731	0.153	4	0.034	0.2635	0.4675	0.3995	0.34
5	0.06	0.29	1.18	0.86	0.18	5	0.04	0.31	0.55	0.47	0.4
6	0.069	0.3335	1.357	0.989	0.207	6	0.046	0.3565	0.6325	0.5405	0.46
7	0.078	0.377	1.534	1.118	0.234	7	0.052	0.403	0.715	0.611	0.52
8	0.087	0.4205	1.711	1.247	0.261	8	0.058	0.4495	0.7975	0.6815	0.58
9	0.096	0.464	1.888	1.376	0.288	9	0.064	0.496	0.88	0.752	0.64

	Operations						Operations				
Product	**1**	**2**	**3**	**4**	**5**	**Product**	**1**	**2**	**3**	**4**	**5**
5	0.08	0.41	0.43	0.74	0.43	**6**	0.07	0.32	1.18	0.55	0.45
Std. Dev.	0.012	0.0615	0.0645	0.111	0.0645	**Std. Dev.**	0.0105	0.048	0.177	0.0825	0.0675
Skill Level						Skill Level					
1	0.032	0.164	0.172	0.296	0.172	1	0.028	0.128	0.472	0.22	0.18
2	0.044	0.2255	0.2365	0.407	0.2365	2	0.0385	0.176	0.649	0.3025	0.2475
3	0.056	0.287	0.301	0.518	0.301	3	0.049	0.224	0.826	0.385	0.315
4	0.068	0.3485	0.3655	0.629	0.3655	4	0.0595	0.272	1.003	0.4675	0.3825
5	0.08	0.41	0.43	0.74	0.43	5	0.07	0.32	1.18	0.55	0.45
6	0.092	0.4715	0.4945	0.851	0.4945	6	0.0805	0.368	1.357	0.6325	0.5175
7	0.104	0.533	0.559	0.962	0.559	7	0.091	0.416	1.534	0.715	0.585
8	0.116	0.5945	0.6235	1.073	0.6235	8	0.1015	0.464	1.711	0.7975	0.6525
9	0.128	0.656	0.688	1.184	0.688	9	0.112	0.512	1.888	0.88	0.72

	Operations						Operations				
Product	**1**	**2**	**3**	**4**	**5**	**Product**	**1**	**2**	**3**	**4**	**5**
7	0.09	0.37	0.46	0.49	0.26	**8**	0.08	0.28	0.49	0.61	0.29
Std. Dev.	0.0135	0.0555	0.069	0.0735	0.039	**Std. Dev.**	0.012	0.042	0.0735	0.0915	0.0435
Skill Level						Skill Level					
1	0.036	0.148	0.184	0.196	0.104	1	0.032	0.112	0.196	0.244	0.116
2	0.0495	0.2035	0.253	0.2695	0.143	2	0.044	0.154	0.2695	0.3355	0.1595
3	0.063	0.259	0.322	0.343	0.182	3	0.056	0.196	0.343	0.427	0.203
4	0.0765	0.3145	0.391	0.4165	0.221	4	0.068	0.238	0.4165	0.5185	0.2465
5	0.09	0.37	0.46	0.49	0.26	5	0.08	0.28	0.49	0.61	0.29
6	0.1035	0.4255	0.529	0.5635	0.299	6	0.092	0.322	0.5635	0.7015	0.3335
7	0.117	0.481	0.598	0.637	0.338	7	0.104	0.364	0.637	0.793	0.377
8	0.1305	0.5365	0.667	0.7105	0.377	8	0.116	0.406	0.7105	0.8845	0.4205
9	0.144	0.592	0.736	0.784	0.416	9	0.128	0.448	0.784	0.976	0.464

	Operations						Operations				
Product	**1**	**2**	**3**	**4**	**5**	**Product**	**1**	**2**	**3**	**4**	**5**
9	0.04	0.34	0.81	0.62	0.34	**10**	0.07	0.43	0.74	0.87	0.43
Std. Dev.	0.006	0.051	0.1215	0.093	0.051	**Std. Dev.**	0.0105	0.0645	0.111	0.1305	0.0645
Skill Level						Skill Level					
1	0.016	0.136	0.324	0.248	0.136	1	0.028	0.172	0.296	0.348	0.172
2	0.022	0.187	0.4455	0.341	0.187	2	0.0385	0.2365	0.407	0.4785	0.2365
3	0.028	0.238	0.567	0.434	0.238	3	0.049	0.301	0.518	0.609	0.301
4	0.034	0.289	0.6885	0.527	0.289	4	0.0595	0.3655	0.629	0.7395	0.3655
5	0.04	0.34	0.81	0.62	0.34	5	0.07	0.43	0.74	0.87	0.43
6	0.046	0.391	0.9315	0.713	0.391	6	0.0805	0.4945	0.851	1.0005	0.4945
7	0.052	0.442	1.053	0.806	0.442	7	0.091	0.559	0.962	1.131	0.559
8	0.058	0.493	1.1745	0.899	0.493	8	0.1015	0.6235	1.073	1.2615	0.6235
9	0.064	0.544	1.296	0.992	0.544	9	0.112	0.688	1.184	1.392	0.688

	Operations						Operations				
Product	**1**	**2**	**3**	**4**	**5**	**Product**	**1**	**2**	**3**	**4**	**5**
11	0.1	0.29	0.92	0.64	0.19	**12**	0.12	0.37	0.92	1.29	0.26
Std. Dev.	0.015	0.0435	0.138	0.096	0.0285	**Std. Dev.**	0.018	0.0555	0.138	0.1935	0.039
Skill Level						Skill Level					
1	0.04	0.116	0.368	0.256	0.076	1	0.048	0.148	0.368	0.516	0.104
2	0.055	0.1595	0.506	0.352	0.1045	2	0.066	0.2035	0.506	0.7095	0.143
3	0.07	0.203	0.644	0.448	0.133	3	0.084	0.259	0.644	0.903	0.182
4	0.085	0.2465	0.782	0.544	0.1615	4	0.102	0.3145	0.782	1.0965	0.221
5	0.1	0.29	0.92	0.64	0.19	5	0.12	0.37	0.92	1.29	0.26
6	0.115	0.3335	1.058	0.736	0.2185	6	0.138	0.4255	1.058	1.4835	0.299
7	0.13	0.377	1.196	0.832	0.247	7	0.156	0.481	1.196	1.677	0.338
8	0.145	0.4205	1.334	0.928	0.2755	8	0.174	0.5365	1.334	1.8705	0.377
9	0.16	0.464	1.472	1.024	0.304	9	0.192	0.592	1.472	2.064	0.416

	Operations						Operations				
Product	**1**	**2**	**3**	**4**	**5**	**Product**	**1**	**2**	**3**	**4**	**5**
13	0.05	0.34	1.05	0.94	0.34	**14**	0.08	0.39	0.98	1.34	0.35
Std. Dev.	0.0075	0.051	0.1575	0.141	0.051	**Std. Dev.**	0.012	0.0585	0.147	0.201	0.0525
Skill Level						Skill Level					
1	0.02	0.136	0.42	0.376	0.136	1	0.032	0.156	0.392	0.536	0.14
2	0.0275	0.187	0.5775	0.517	0.187	2	0.044	0.2145	0.539	0.737	0.1925
3	0.035	0.238	0.735	0.658	0.238	3	0.056	0.273	0.686	0.938	0.245
4	0.0425	0.289	0.8925	0.799	0.289	4	0.068	0.3315	0.833	1.139	0.2975
5	0.05	0.34	1.05	0.94	0.34	5	0.08	0.39	0.98	1.34	0.35
6	0.0575	0.391	1.2075	1.081	0.391	6	0.092	0.4485	1.127	1.541	0.4025
7	0.065	0.442	1.365	1.222	0.442	7	0.104	0.507	1.274	1.742	0.455
8	0.0725	0.493	1.5225	1.363	0.493	8	0.116	0.5655	1.421	1.943	0.5075
9	0.08	0.544	1.68	1.504	0.544	9	0.128	0.624	1.568	2.144	0.56

	Operations						Operations				
Product	**1**	**2**	**3**	**4**	**5**	**Product**	**1**	**2**	**3**	**4**	**5**
15	0.06	0.41	0.94	0.94	0.43	**16**	0.12	0.46	0.39	0.61	0.27
Std. Dev.	0.009	0.0615	0.141	0.141	0.0645	**Std. Dev.**	0.018	0.069	0.0585	0.0915	0.0405
Skill Level						Skill Level					
1	0.024	0.164	0.376	0.376	0.172	1	0.048	0.184	0.156	0.244	0.108
2	0.033	0.2255	0.517	0.517	0.2365	2	0.066	0.253	0.2145	0.3355	0.1485
3	0.042	0.287	0.658	0.658	0.301	3	0.084	0.322	0.273	0.427	0.189
4	0.051	0.3485	0.799	0.799	0.3655	4	0.102	0.391	0.3315	0.5185	0.2295
5	0.06	0.41	0.94	0.94	0.43	5	0.12	0.46	0.39	0.61	0.27
6	0.069	0.4715	1.081	1.081	0.4945	6	0.138	0.529	0.4485	0.7015	0.3105
7	0.078	0.533	1.222	1.222	0.559	7	0.156	0.598	0.507	0.793	0.351
8	0.087	0.5945	1.363	1.363	0.6235	8	0.174	0.667	0.5655	0.8845	0.3915
9	0.096	0.656	1.504	1.504	0.688	9	0.192	0.736	0.624	0.976	0.432

	Operations						Operations				
Product	**1**	**2**	**3**	**4**	**5**	**Product**	**1**	**2**	**3**	**4**	**5**
17	0.08	0.37	0.92	0.35	0.23	**18**	0.04	0.29	0.98	1.18	0.34
Std. Dev.	0.012	0.0555	0.138	0.0525	0.0345	**Std. Dev.**	0.006	0.0435	0.147	0.177	0.051
Skill Level						Skill Level					
1	0.032	0.148	0.368	0.14	0.092	1	0.016	0.116	0.392	0.472	0.136
2	0.044	0.2035	0.506	0.1925	0.1265	2	0.022	0.1595	0.539	0.649	0.187
3	0.056	0.259	0.644	0.245	0.161	3	0.028	0.203	0.686	0.826	0.238
4	0.068	0.3145	0.782	0.2975	0.1955	4	0.034	0.2465	0.833	1.003	0.289
5	0.08	0.37	0.92	0.35	0.23	5	0.04	0.29	0.98	1.18	0.34
6	0.092	0.4255	1.058	0.4025	0.2645	6	0.046	0.3335	1.127	1.357	0.391
7	0.104	0.481	1.196	0.455	0.299	7	0.052	0.377	1.274	1.534	0.442
8	0.116	0.5365	1.334	0.5075	0.3335	8	0.058	0.4205	1.421	1.711	0.493
9	0.128	0.592	1.472	0.56	0.368	9	0.064	0.464	1.568	1.888	0.544

	Operations						Operations				
Product	**1**	**2**	**3**	**4**	**5**	**Product**	**1**	**2**	**3**	**4**	**5**
19	0.09	0.41	0.61	0.39	0.43	**20**	0.08	0.38	0.59	0.81	0.21
Std. Dev.	0.0135	0.0615	0.0915	0.0585	0.0645	**Std. Dev.**	0.012	0.057	0.0885	0.1215	0.0315
Skill Level						Skill Level					
1	0.036	0.164	0.244	0.156	0.172	1	0.032	0.152	0.236	0.324	0.084
2	0.0495	0.2255	0.3355	0.2145	0.2365	2	0.044	0.209	0.3245	0.4455	0.1155
3	0.063	0.287	0.427	0.273	0.301	3	0.056	0.266	0.413	0.567	0.147
4	0.0765	0.3485	0.5185	0.3315	0.3655	4	0.068	0.323	0.5015	0.6885	0.1785
5	0.09	0.41	0.61	0.39	0.43	5	0.08	0.38	0.59	0.81	0.21
6	0.1035	0.4715	0.7015	0.4485	0.4945	6	0.092	0.437	0.6785	0.9315	0.2415
7	0.117	0.533	0.793	0.507	0.559	7	0.104	0.494	0.767	1.053	0.273
8	0.1305	0.5945	0.8845	0.5655	0.6235	8	0.116	0.551	0.8555	1.1745	0.3045
9	0.144	0.656	0.976	0.624	0.688	9	0.128	0.608	0.944	1.296	0.336

	Operations						Operations				
Product	**1**	**2**	**3**	**4**	**5**	**Product**	**1**	**2**	**3**	**4**	**5**
21	0.07	0.44	0.61	0.91	0.35	**22**	0.11	0.38	1.15	0.64	0.38
Std. Dev.	0.0105	0.066	0.0915	0.1365	0.0525	**Std. Dev.**	0.0165	0.057	0.1725	0.096	0.057
Skill Level						Skill Level					
1	0.028	0.176	0.244	0.364	0.14	1	0.044	0.152	0.46	0.256	0.152
2	0.0385	0.242	0.3355	0.5005	0.1925	2	0.0605	0.209	0.6325	0.352	0.209
3	0.049	0.308	0.427	0.637	0.245	3	0.077	0.266	0.805	0.448	0.266
4	0.0595	0.374	0.5185	0.7735	0.2975	4	0.0935	0.323	0.9775	0.544	0.323
5	0.07	0.44	0.61	0.91	0.35	5	0.11	0.38	1.15	0.64	0.38
6	0.0805	0.506	0.7015	1.0465	0.4025	6	0.1265	0.437	1.3225	0.736	0.437
7	0.091	0.572	0.793	1.183	0.455	7	0.143	0.494	1.495	0.832	0.494
8	0.1015	0.638	0.8845	1.3195	0.5075	8	0.1595	0.551	1.6675	0.928	0.551
9	0.112	0.704	0.976	1.456	0.56	9	0.176	0.608	1.84	1.024	0.608

	Operations						Operations				
Product	**1**	**2**	**3**	**4**	**5**	**Product**	**1**	**2**	**3**	**4**	**5**
23	0.08	0.31	0.91	0.59	0.43	**24**	0.09	0.39	0.64	0.31	0.21
Std. Dev.	0.012	0.0465	0.1365	0.0885	0.0645	**Std. Dev.**	0.0135	0.0585	0.096	0.0465	0.0315
Skill Level						Skill Level					
1	0.032	0.124	0.364	0.236	0.172	1	0.036	0.156	0.256	0.124	0.084
2	0.044	0.1705	0.5005	0.3245	0.2365	2	0.0495	0.2145	0.352	0.1705	0.1155
3	0.056	0.217	0.637	0.413	0.301	3	0.063	0.273	0.448	0.217	0.147
4	0.068	0.2635	0.7735	0.5015	0.3655	4	0.0765	0.3315	0.544	0.2635	0.1785
5	0.08	0.31	0.91	0.59	0.43	5	0.09	0.39	0.64	0.31	0.21
6	0.092	0.3565	1.0465	0.6785	0.4945	6	0.1035	0.4485	0.736	0.3565	0.2415
7	0.104	0.403	1.183	0.767	0.559	7	0.117	0.507	0.832	0.403	0.273
8	0.116	0.4495	1.3195	0.8555	0.6235	8	0.1305	0.5655	0.928	0.4495	0.3045
9	0.128	0.496	1.456	0.944	0.688	9	0.144	0.624	1.024	0.496	0.336

	Operations						Operations				
Product	**1**	**2**	**3**	**4**	**5**	**Product**	**1**	**2**	**3**	**4**	**5**
25	0.04	0.44	0.96	1.29	0.29	**26**	0.08	0.29	1.15	0.84	0.39
Std. Dev.	0.006	0.066	0.144	0.1935	0.0435	**Std. Dev.**	0.012	0.0435	0.1725	0.126	0.0585
Skill Level						Skill Level					
1	0.016	0.176	0.384	0.516	0.116	1	0.032	0.116	0.46	0.336	0.156
2	0.022	0.242	0.528	0.7095	0.1595	2	0.044	0.1595	0.6325	0.462	0.2145
3	0.028	0.308	0.672	0.903	0.203	3	0.056	0.203	0.805	0.588	0.273
4	0.034	0.374	0.816	1.0965	0.2465	4	0.068	0.2465	0.9775	0.714	0.3315
5	0.04	0.44	0.96	1.29	0.29	5	0.08	0.29	1.15	0.84	0.39
6	0.046	0.506	1.104	1.4835	0.3335	6	0.092	0.3335	1.3225	0.966	0.4485
7	0.052	0.572	1.248	1.677	0.377	7	0.104	0.377	1.495	1.092	0.507
8	0.058	0.638	1.392	1.8705	0.4205	8	0.116	0.4205	1.6675	1.218	0.5655
9	0.064	0.704	1.536	2.064	0.464	9	0.128	0.464	1.84	1.344	0.624

	Operations						Operations				
Product	**1**	**2**	**3**	**4**	**5**	**Product**	**1**	**2**	**3**	**4**	**5**
27	0.06	0.37	0.81	0.64	0.44	**28**	0.04	0.39	0.76	0.29	0.26
Std. Dev.	0.009	0.0555	0.1215	0.096	0.066	**Std. Dev.**	0.006	0.0585	0.114	0.0435	0.039
Skill Level						Skill Level					
1	0.024	0.148	0.324	0.256	0.176	1	0.016	0.156	0.304	0.116	0.104
2	0.033	0.2035	0.4455	0.352	0.242	2	0.022	0.2145	0.418	0.1595	0.143
3	0.042	0.259	0.567	0.448	0.308	3	0.028	0.273	0.532	0.203	0.182
4	0.051	0.3145	0.6885	0.544	0.374	4	0.034	0.3315	0.646	0.2465	0.221
5	0.06	0.37	0.81	0.64	0.44	5	0.04	0.39	0.76	0.29	0.26
6	0.069	0.4255	0.9315	0.736	0.506	6	0.046	0.4485	0.874	0.3335	0.299
7	0.078	0.481	1.053	0.832	0.572	7	0.052	0.507	0.988	0.377	0.338
8	0.087	0.5365	1.1745	0.928	0.638	8	0.058	0.5655	1.102	0.4205	0.377
9	0.096	0.592	1.296	1.024	0.704	9	0.064	0.624	1.216	0.464	0.416

	Operations						Operations				
Product	**1**	**2**	**3**	**4**	**5**	**Product**	**1**	**2**	**3**	**4**	**5**
29	0.06	0.44	0.82	1.36	0.35	**30**	0.09	0.37	0.64	0.94	0.45
Std. Dev.	0.009	0.066	0.123	0.204	0.0525	**Std. Dev.**	0.0135	0.0555	0.096	0.141	0.0675
Skill Level						Skill Level					
1	0.024	0.176	0.328	0.544	0.14	1	0.036	0.148	0.256	0.376	0.18
2	0.033	0.242	0.451	0.748	0.1925	2	0.0495	0.2035	0.352	0.517	0.2475
3	0.042	0.308	0.574	0.952	0.245	3	0.063	0.259	0.448	0.658	0.315
4	0.051	0.374	0.697	1.156	0.2975	4	0.0765	0.3145	0.544	0.799	0.3825
5	0.06	0.44	0.82	1.36	0.35	5	0.09	0.37	0.64	0.94	0.45
6	0.069	0.506	0.943	1.564	0.4025	6	0.1035	0.4255	0.736	1.081	0.5175
7	0.078	0.572	1.066	1.768	0.455	7	0.117	0.481	0.832	1.222	0.585
8	0.087	0.638	1.189	1.972	0.5075	8	0.1305	0.5365	0.928	1.363	0.6525
9	0.096	0.704	1.312	2.176	0.56	9	0.144	0.592	1.024	1.504	0.72

Table 15d. Operation times for different skill levels with std. dev of 20%

	Operations						Operations				
Product	**1**	**2**	**3**	**4**	**5**	**Product**	**1**	**2**	**3**	**4**	**5**
1	0.07	0.45	0.37	0.88	0.38	**2**	0.05	0.29	0.62	0.74	0.38
Std. Dev.	0.014	0.09	0.074	0.176	0.076	**Std. Dev.**	0.01	0.058	0.124	0.148	0.076
Skill Level						Skill Level					
1	0.014	0.09	0.074	0.176	0.076	1	0.01	0.058	0.124	0.148	0.076
2	0.028	0.18	0.148	0.352	0.152	2	0.02	0.116	0.248	0.296	0.152
3	0.042	0.27	0.222	0.528	0.228	3	0.03	0.174	0.372	0.444	0.228
4	0.056	0.36	0.296	0.704	0.304	4	0.04	0.232	0.496	0.592	0.304
5	0.07	0.45	0.37	0.88	0.38	5	0.05	0.29	0.62	0.74	0.38
6	0.084	0.54	0.444	1.056	0.456	6	0.06	0.348	0.744	0.888	0.456
7	0.098	0.63	0.518	1.232	0.532	7	0.07	0.406	0.868	1.036	0.532
8	0.112	0.72	0.592	1.408	0.608	8	0.08	0.464	0.992	1.184	0.608
9	0.126	0.81	0.666	1.584	0.684	9	0.09	0.522	1.116	1.332	0.684

	Operations						Operations				
Product	**1**	**2**	**3**	**4**	**5**	**Product**	**1**	**2**	**3**	**4**	**5**
3	0.06	0.29	1.18	0.86	0.18	**4**	0.04	0.31	0.55	0.47	0.4
Std. Dev.	0.012	0.058	0.236	0.172	0.036	**Std. Dev.**	0.008	0.062	0.11	0.094	0.08
Skill Level						Skill Level					
1	0.012	0.058	0.236	0.172	0.036	1	0.008	0.062	0.11	0.094	0.08
2	0.024	0.116	0.472	0.344	0.072	2	0.016	0.124	0.22	0.188	0.16
3	0.036	0.174	0.708	0.516	0.108	3	0.024	0.186	0.33	0.282	0.24
4	0.048	0.232	0.944	0.688	0.144	4	0.032	0.248	0.44	0.376	0.32
5	0.06	0.29	1.18	0.86	0.18	5	0.04	0.31	0.55	0.47	0.4
6	0.072	0.348	1.416	1.032	0.216	6	0.048	0.372	0.66	0.564	0.48
7	0.084	0.406	1.652	1.204	0.252	7	0.056	0.434	0.77	0.658	0.56
8	0.096	0.464	1.888	1.376	0.288	8	0.064	0.496	0.88	0.752	0.64
9	0.108	0.522	2.124	1.548	0.324	9	0.072	0.558	0.99	0.846	0.72

	Operations						Operations				
Product	**1**	**2**	**3**	**4**	**5**	**Product**	**1**	**2**	**3**	**4**	**5**
5	0.08	0.41	0.43	0.74	0.43	**6**	0.07	0.32	1.18	0.55	0.45
Std. Dev.	0.016	0.082	0.086	0.148	0.086	**Std. Dev.**	0.014	0.064	0.236	0.11	0.09
Skill Level						Skill Level					
1	0.016	0.082	0.086	0.148	0.086	1	0.014	0.064	0.236	0.11	0.09
2	0.032	0.164	0.172	0.296	0.172	2	0.028	0.128	0.472	0.22	0.18
3	0.048	0.246	0.258	0.444	0.258	3	0.042	0.192	0.708	0.33	0.27
4	0.064	0.328	0.344	0.592	0.344	4	0.056	0.256	0.944	0.44	0.36
5	0.08	0.41	0.43	0.74	0.43	5	0.07	0.32	1.18	0.55	0.45
6	0.096	0.492	0.516	0.888	0.516	6	0.084	0.384	1.416	0.66	0.54
7	0.112	0.574	0.602	1.036	0.602	7	0.098	0.448	1.652	0.77	0.63
8	0.128	0.656	0.688	1.184	0.688	8	0.112	0.512	1.888	0.88	0.72
9	0.144	0.738	0.774	1.332	0.774	9	0.126	0.576	2.124	0.99	0.81

Operations						Operations					
Product	**1**	**2**	**3**	**4**	**5**	**Product**	**1**	**2**	**3**	**4**	**5**
7	0.09	0.37	0.46	0.49	0.26	**8**	0.08	0.28	0.49	0.61	0.29
Std. Dev.	0.018	0.074	0.092	0.098	0.052	**Std. Dev.**	0.016	0.056	0.098	0.122	0.058
Skill Level						Skill Level					
1	0.018	0.074	0.092	0.098	0.052	1	0.016	0.056	0.098	0.122	0.058
2	0.036	0.148	0.184	0.196	0.104	2	0.032	0.112	0.196	0.244	0.116
3	0.054	0.222	0.276	0.294	0.156	3	0.048	0.168	0.294	0.366	0.174
4	0.072	0.296	0.368	0.392	0.208	4	0.064	0.224	0.392	0.488	0.232
5	0.09	0.37	0.46	0.49	0.26	5	0.08	0.28	0.49	0.61	0.29
6	0.108	0.444	0.552	0.588	0.312	6	0.096	0.336	0.588	0.732	0.348
7	0.126	0.518	0.644	0.686	0.364	7	0.112	0.392	0.686	0.854	0.406
8	0.144	0.592	0.736	0.784	0.416	8	0.128	0.448	0.784	0.976	0.464
9	0.162	0.666	0.828	0.882	0.468	9	0.144	0.504	0.882	1.098	0.522

Operations						Operations					
Product	**1**	**2**	**3**	**4**	**5**	**Product**	**1**	**2**	**3**	**4**	**5**
9	0.04	0.34	0.81	0.62	0.34	**10**	0.07	0.43	0.74	0.87	0.43
Std. Dev.	0.008	0.068	0.162	0.124	0.068	**Std. Dev.**	0.014	0.086	0.148	0.174	0.086
Skill Level						Skill Level					
1	0.008	0.068	0.162	0.124	0.068	1	0.014	0.086	0.148	0.174	0.086
2	0.016	0.136	0.324	0.248	0.136	2	0.028	0.172	0.296	0.348	0.172
3	0.024	0.204	0.486	0.372	0.204	3	0.042	0.258	0.444	0.522	0.258
4	0.032	0.272	0.648	0.496	0.272	4	0.056	0.344	0.592	0.696	0.344
5	0.04	0.34	0.81	0.62	0.34	5	0.07	0.43	0.74	0.87	0.43
6	0.048	0.408	0.972	0.744	0.408	6	0.084	0.516	0.888	1.044	0.516
7	0.056	0.476	1.134	0.868	0.476	7	0.098	0.602	1.036	1.218	0.602
8	0.064	0.544	1.296	0.992	0.544	8	0.112	0.688	1.184	1.392	0.688
9	0.072	0.612	1.458	1.116	0.612	9	0.126	0.774	1.332	1.566	0.774

APPENDIX E PRODUCT COMBINATIONS AND NUMBER OF OPERATORS FOR EACH OPERATION

E1. Lot splitting not allowed and operator sharing not allowed – problem 1

	Operations				
Product Combinations	1	2	3	4	5
P3-P2	1+1=2	2+3=5	9+6=15	6+6=12	2+4=6
P5-P2	1+1=2	4+3=7	4+6=10	7+6=13	4+4=8
P6-P2	1+1=2	3+3=6	8+6=14	4+6=10	4+4=8
P6-P1	1+1=2	3+4=7	8+3=11	4+8=12	4+4=8
P7-P1	1+1=2	5+4=9	5+3=8	6+8=14	3+4=7
P7-P4	1+1=2	5+4=9	5+6=11	6+5=11	3+4=7
P7-P8	1+1=2	5+3=8	5+6=11	6+7=13	3+3=6
P10-P8	1+1=2	3+3=6	6+6=12	7+7=14	3+3=6
P10-P9	1+1=2	3+3=6	6+7=13	7+6=13	3+3=6
P10-P4	1+1=2	3+4=7	6+6=12	7+5=12	3+4=7

E2. Lot splitting allowed (sequence 1) and operator sharing not allowed – problem 1

	Operations				
Product Combinations	1	2	3	4	5
P3-P2	1+1=2	2+3=5	9+6=15	6+6=12	2+4=6
P3-P1	1+1=2	2+4=6	9+3=12	6+8=14	2+4=6
P5-P1	1+1=2	4+4=8	4+3=7	7+8=15	4+4=8
P5-P4	1+1=2	4+4=8	4+6=10	7+5=12	4+4=8
P6-P4	1+1=2	3+4=7	8+6=14	4+5=9	4+4=8
P6-P7	1+1=2	3+5=8	8+5=13	4+6=10	4+3=7
P6-P8	1+1=2	3+3=6	8+6=14	4+7=11	4+3=7
P2-P8	1+1=2	3+3=6	6+6=12	6+7=13	4+3=7
P2-P9	1+1=2	3+3=6	6+7=13	6+6=12	4+3=7
P2-P10	1+1=2	3+3=6	6+6=12	6+7=13	4+3=7

E3. Lot splitting allowed (sequence 2) and operator sharing not allowed – problem 1

	Operations				
Product Combinations	1	2	3	4	5
P3-P1	1+1=2	2+4=6	9+3=12	6+8=14	2+4=6
P3-P4	1+1=2	2+4=6	9+6=15	6+5=11	2+4=6
P5-P4	1+1=2	4+4=8	4+6=10	7+5=12	4+4=8
P5-P7	1+1=2	4+5=9	4+5=9	7+6=13	4+3=7
P6-P7	1+1=2	3+5=8	8+5=13	4+6=10	4+3=7
P6-P8	1+1=2	3+3=6	8+6=14	4+7=11	4+3=7
P2-P8	1+1=2	3+3=6	6+6=12	6+7=13	4+3=7
P2-P2	1+1=2	3+3=6	6+6=12	6+6=12	4+4=8
P2-P9	1+1=2	3+3=6	6+7=13	6+6=12	4+3=7
P2-P10	1+1=2	3+3=6	6+6=12	6+7=13	4+3=7
P6-P2	1+1=2	3+3=6	8+6=14	4+6=10	4+4=8

E4. Lot splitting not allowed and operator sharing allowed – problem 1

	Operations				
Product Combinations	1	2	3	4	5
P2-P1	.36+.65=1.01	2.09+4.19=6.28	4.47+3.44=7.91	5.34+8.19=13.53	2.74+3.53=6.27
P2-P3	.36+.47=.83	2.09+2.26=4.35	4.47+9.18=13.65	5.34+6.69=12.03	2.74+1.40=4.14
P2-P6	.36+.55=.91	2.09+2.49=4.58	4.47+9.18=13.65	5.34+4.28=9.62	2.74+3.50=6.24
P4-P6	.34+.55=.89	2.63+2.49=5.12	4.66+9.18=13.84	3.98+4.28=8.26	3.39+3.50=6.89
P4-P7	.34+1.08=1.42	2.63+4.43=7.06	4.66+5.51=10.17	3.98+5.87=9.85	3.39+3.11=6.5
P5-P7	.57+1.08=1.65	2.94+4.43=7.37	3.09+5.51=8.6	5.31+5.87=11.18	3.09+3.11=6.2
P10-P7	.41+1.08=1.49	2.54+4.43=6.97	4.37+5.51=9.88	5.14+5.87=11.01	2.54+3.11=5.65
P10-P8	.41+.91=1.32	2.54+3.20=5.74	4.37+5.60=9.97	5.14+6.98=12.12	2.54+3.31=5.85
P10-P9	.41+.37=.78	2.54+3.16=5.70	4.37+7.54=11.91	5.14+5.77=10.91	2.54+3.16=5.70
P2-P7	.36+1.08=1.44	2.09+4.43=6.52	4.47+5.51=9.98	5.34+5.87=11.21	2.74+3.11=5.85
P5-P8	.57+.91=1.48	2.94+3.20=6.14	3.09+5.6=8.69	5.31+6.98=12.29	3.09+3.31=6.4
P5-P9	.57+.37=.94	2.94+3.16=6.1	3.09+7.54=10.63	5.31+5.77=11.08	3.09+3.16=6.25

E5. Lot splitting allowed and operator sharing allowed – problem 1

	Operations				
Product Combinations	1	2	3	4	5
P3-P3	.35+.47=.82	1.69+2.26=3.95	6.89+9.18=16.07	5.02+6.69=11.71	1.05+1.4=2.45
P3-P2	.35+.48=.83	1.69+2.79=4.48	6.89+5.96=12.85	5.02+7.12=12.14	1.05+3.65=4.7
P1-P2	.49+.48=.97	3.14+2.79=5.93	2.58+5.96=8.54	6.14+7.12=13.26	2.65+3.65=6.3
P4-P2	.34+.48=.82	2.63+2.79=5.42	4.66+5.96=10.62	3.98+7.12=11.1	3.39+3.65=7.04
P4-P5	.34+.77=1.11	2.63+3.92=6.55	4.66+4.12=8.78	3.98+7.08=11.06	3.39+4.11=7.5
P8-P5	.68+.77=1.45	2.4+3.92=6.32	4.2+4.12=8.32	5.23+7.08=12.31	2.49+4.11=6.6
P8-P6	.68+.55=1.23	2.4+2.49=4.89	4.2+9.18=13.38	5.23+4.28=9.51	2.49+3.5=5.99
P9-P6	.28+.55=.83	2.37+2.49=4.86	5.65+9.18=14.83	4.33+4.28=8.61	2.37+3.5=5.87
P10-P6	.41+.55=.96	2.54+2.49=5.03	4.37+9.18=13.55	5.14+4.28=9.42	2.54+3.5=6.04
P10-P7	.41+1.08=1.49	2.54+4.43=6.97	4.37+5.51=9.88	5.14+5.87=11.01	2.54+3.11=5.65
P9-P7	.28+1.08=1.36	2.37+4.43=6.8	5.65+5.51=11.16	4.33+5.87=10.2	2.37+3.11=5.48

E6. Lot splitting not allowed and operator sharing not allowed - problem 2

	Operations				
Product Combinations	1	2	3	4	5
P5-P2-P1	1+1+1=3	4+4+5=13	4+7+4=15	7+8+10=25	4+5+5=14
P7-P2-P1	1+1+1=3	5+4+5=14	5+7+4=16	6+8+10=24	3+5+5=13
P7-P4-P1	1+1+1=3	5+4+5=14	5+8+4=17	6+6+10=22	3+6+5=14
P7-P4-P3	1+1+1=3	5+4+3=12	5+8+11=24	6+6+8=20	3+6+2=11
P7-P6-P3	1+1+1=3	5+3+3=11	5+11+11=27	6+5+8=19	3+5+2=10
P7-P6-P8	1+1+2=4	5+3+4=12	5+11+7=23	6+5+8=19	3+5+4=12
P11-P6-P3	1+1+1=3	3+3+3=9	8+11+11=30	6+5+8=19	2+5+2=9
P11-P6-P8	1+1+2=4	3+3+4=10	8+11+7=26	6+5+8=19	2+5+4=11
P11-P13-P8	1+1+2=4	3+3+4=10	8+9+7=24	6+9+8=23	2+3+4=9
P11-P13-P9	1+1+1=3	3+3+4=10	8+9+9=26	6+9+7=22	2+3+4=9
P19-P13-P8	1+1+2=4	4+3+4=11	6+9+7=22	4+9+8=21	5+3+4=12
P19-P13-P9	1+1+1=3	4+3+4=11	6+9+9=24	4+9+7=20	5+3+4=12
P19-P14-P9	1+1+1=3	4+3+4=11	6+8+9=23	4+10+7=21	5+3+4=12
P19-P14-P10	1+1+1=3	4+3+4=11	6+8+7=21	4+10+9=23	5+3+4=12
P25-P14-P9	1+1+1=3	3+3+4=10	6+8+9=23	8+10+7=25	2+3+4=9
P25-P14-P10	1+1+1=3	3+3+4=10	6+8+7=21	8+10+9=27	2+3+4=9
P25-P15-P10	1+1+1=3	3+4+4=11	6+8+7=21	8+8+9=25	2+4+4=10
P25-P15-P12	1+1+1=3	3+4+3=10	6+8+8=22	8+8+10=26	2+4+3=9
P25-P15-P16	1+1+2=4	3+4+6=13	6+8+5=19	8+8+8=24	2+4+4=10
P25-P15-P17	1+1+1=3	3+4+5=12	6+8+11=25	8+8+5=21	2+4+3=9
P26-P15-P10	1+1+1=3	2+4+4=10	8+8+7=23	6+8+9=23	3+4+4=11
P26-P15-P12	1+1+1=3	2+4+3=9	8+8+8=24	6+8+10=24	3+4+3=10
P26-P15-P16	1+1+2=4	2+4+6=12	8+8+5=21	6+8+8+=22	3+4+4=11
P26-P15-P17	1+1+1=3	2+4+5=11	8+8+11=27	6+8+5=19	3+4+3=10
P26-P18-P17	1+1+1=3	2+3+5=10	8+8+11=27	6+10+5=21	3+3+3=9
P26-P18-P21	1+1+1=3	2+3+5=10	8+8+6=22	6+10+9=25	3+3+4=10
P29-P20-P21	1+1+1=3	3+5+5=13	5+7+6=18	8+9+9=26	3+3+4=10
P29-P20-P23	1+1+1=3	3+5+4=12	5+7+9=21	8+9+6=23	3+3+5=11
P29-P22-P23	1+1+1=3	3+4+4=11	5+10+9=24	8+6+6=20	3+4+5=12
P29-P22-P30	1+1+1=3	3+4+4=11	5+10+6=21	8+6+9=23	3+4+5=12
P29-P24-P30	1+2+1=4	3+6+4=13	5+9+6=20	8+5+9=22	3+3+5=11
P27-P24-P30	1+2+1=4	3+6+4=13	7+9+6=22	5+5+9=19	4+3+5=12
P27-P28-P30	1+1+1=3	3+6+4=13	7+10+6=23	5+4+9=18	4+4+5=13
P11-P13-P3	1+1+1=3	3+3+3=9	8+9+11=28	6+9+8=23	2+3+2=7
P19-P15-P10	1+1+1=3	4+4+4=12	6+8+7=21	4+8+9=21	5+4+4=13
P25-P18-P12	1+1+1=3	3+3+3=9	6+8+8=22	8+10+10=28	2+3+3=8
P25-P18-P16	1+1+2=4	3+3+6=12	6+8+5=19	8+10+8=26	2+3+4=9
P25-P18-P17	1+1+1=3	3+3+5=11	6+8+11=25	8+10+5=23	2+3+3=8
P26-P20-P21	1+1+1=3	2+5+5=12	8+7+6=21	6+9+9=24	3+3+4=10
P26-P22-P21	1+1+1=3	2+4+5=11	8+10+6=24	6+6+9=21	3+4+4=11
P26-P22-P23	1+1+1=3	2+4+4=10	8+10+9=27	6+6+6=18	3+4+5=12
P26-P24-P23	1+2+1=4	2+6+4=12	8+9+9=26	6+5+6=17	3+3+5=11
P29-P24-P23	1+2+1=4	3+6+4=13	5+9+9=23	8+5+6=19	3+3+5=11
P29-P28-P30	1+1+1=3	3+6+4=13	5+10+6=21	8+4+9=21	3+4+5=12
P29-P27-P30	1+1+1=3	3+4+4=11	5+8+6=19	8+7+9=24	3+5+5=13
P25-P14-P12	1+1+1=3	3+3+3=9	6+8+8=22	8+10+10=28	2+3+3=8
P29-P18-P21	1+1+1=3	3+3+5=11	5+8+6=19	8+10+9=27	3+3+4=10
P26-P18-P23	1+1+1=3	2+3+4=9	8+8+9=25	6+10+6=22	3+3+5=11
P29-P18-P23	1+1+1=3	3+3+4=10	5+8+9=22	8+10+6=24	3+3+5=11
P29-P20-P30	1+1+1=3	3+5+4=12	5+7+6=19	8+9+9=22	3+3+5=11

E7. Lot splitting allowed and operator sharing not allowed – problem 3

Period 1							**Period 2**						
Product	Configuration	Operation					Product	Configuration	Operation				
Combination	level	1	2	3	4	5	Combination	level	1	2	3	4	5
P2	17	1	2	5	6	3	P6	18	1	2	8	4	3
P2	18	1	3	5	6	3	P6	18	1	2	8	4	3
		2	5	10	12	6			2	4	16	8	6
P2	17	1	2	5	6	3	P6	18	1	2	8	4	3
P1	18	1	4	3	7	3	P2	18	1	3	5	6	3
		2	6	8	13	6			2	5	13	10	6
P3	17	1	2	7	5	2	P1	18	1	4	3	7	3
P1	18	1	4	3	7	3	P2	18	1	3	5	6	3
		2	6	10	12	5			2	7	8	13	6
P3	17	1	2	7	5	2	P1	18	1	4	3	7	3
P7	18	1	4	5	5	3	P3	18	1	2	7	6	2
		2	6	12	10	5			2	6	10	13	5
P4	17	1	3	5	4	4	P4	18	1	3	5	5	4
P7	18	1	4	5	5	3	P3	18	1	2	7	6	2
		2	7	10	9	7			2	5	12	11	6
P4	17	1	3	5	4	4	P7	18	1	4	5	5	3
P8	18	1	3	5	6	3	P3	18	1	2	7	6	2
		2	6	10	10	7			2	6	12	11	5
P5	17	1	3	4	6	3	P7	18	1	4	5	5	3
P8	18	1	3	5	6	3	P5	18	1	3	4	6	4
		2	6	9	12	6			2	7	9	11	7
P5	17	1	3	4	6	3	P8	18	1	3	5	6	3
P9	18	1	3	6	5	3	P5	18	1	3	4	6	4
		2	6	10	11	6			2	6	9	12	7
P6	17	1	2	7	4	3	P8	18	1	3	5	6	3
P9	18	1	3	6	5	3	P10	18	1	3	5	6	3
		2	5	13	9	6			2	6	10	12	6
P6	17	1	2	7	4	3	P9	18	1	3	6	5	3
P10	18	1	3	5	6	3	P10	18	1	3	5	6	3
		2	5	12	10	6			2	6	11	11	6
							P7	18	1	4	5	5	3
							P10	18	1	3	5	6	3
									2	7	10	11	6
Period 3							**Period 4**						
Product	Configuration	Operation					Product	Configuration	Operation				
Combination	level	1	2	3	4	5	Combination	level	1	2	3	4	5
P7	18	1	4	5	5	3	P6	18	1	2	8	4	3
P7	19	1	4	5	6	3	P6	15	1	2	6	3	3
		2	8	10	11	6			2	4	14	7	6
P7	18	1	4	5	5	3	P1	18	1	4	3	7	3
P3	19	1	2	8	6	2	P6	15	1	2	6	3	3
		2	6	13	11	5			2	6	9	10	6
P1	18	1	4	3	7	3	P1	18	1	4	3	7	3
P3	19	1	2	8	6	2	P2	15	1	2	4	5	3
		2	6	11	13	5			2	6	7	12	6
P1	18	1	4	3	7	3	P4	18	1	3	5	5	4
P4	19	1	3	6	5	4	P2	15	1	2	4	5	3
		2	7	9	12	7			2	5	9	10	7
P2	18	1	3	5	6	3	P7	18	1	4	5	5	3
P4	19	1	3	6	5	4	P2	15	1	2	4	5	3
		2	6	11	11	7			2	6	9	10	6
P2	18	1	3	5	6	3	P7	18	1	4	5	5	3
P5	19	1	4	4	6	4	P3	15	1	2	6	5	1
		2	7	9	12	7			2	6	11	10	4
P2	18	1	3	5	6	3	P8	18	1	3	5	6	3
P6	19	1	3	8	4	3	P3	15	1	2	6	5	1
		2	6	13	10	6			2	5	11	11	4
P8	18	1	3	5	6	3	P9	18	1	3	6	5	3
P6	19	1	3	8	4	3	P3	15	1	2	6	5	1
		2	6	13	10	6			2	5	12	10	4
P10	18	1	3	5	6	3	P10	18	1	3	5	6	3
P6	19	1	3	8	4	3	P3	15	1	2	6	5	1
		2	6	13	10	6			2	5	11	11	4
P10	18	1	3	5	6	3	P10	18	1	3	5	6	3
P9	19	1	3	7	5	3	P5	15	1	3	3	5	3
		2	6	12	11	6			2	6	8	11	6
P8	18	1	3	5	6	3	P8	18	1	3	5	6	3
P9	19	1	3	7	5	3	P2	15	1	2	4	5	3
		2	6	12	11	6			2	5	9	11	6

Period 5							**Period 6**						
Product	Configuration	Operation					Product	Configuration	Operation				
Combination	level	1	2	3	4	5	Combination	level	1	2	3	4	5
P2	17	1	2	5	6	3	P6	19	1	3	8	4	3
P2	18	1	3	5	6	3	P6	19	1	3	8	4	3
		2	5	10	12	6			2	6	16	8	6
P3	17	1	2	7	5	2	P1	19	1	4	3	7	4
P2	18	1	3	5	6	3	P6	19	1	3	8	4	3
		2	5	12	11	5			2	7	11	11	7
P3	17	1	2	7	5	2	P2	19	1	3	5	6	4
P1	18	1	4	3	7	3	P6	19	1	3	8	4	3
		2	6	10	12	5			2	6	13	10	7
P3	17	1	2	7	5	2	P2	19	1	3	5	6	4
P7	18	1	4	5	5	3	P3	19	1	2	8	6	2
		2	6	12	10	5			2	5	13	12	6
P4	17	1	3	5	4	4	P2	19	1	3	5	6	4
P7	18	1	4	5	5	3	P7	19	1	4	5	6	3
		2	7	10	9	7			2	7	10	12	7
P4	17	1	3	5	4	4	P4	19	1	3	6	5	4
P8	18	1	3	5	6	3	P7	19	1	4	5	6	3
		2	6	10	10	7			2	7	11	11	7
P5	17	1	3	4	6	3	P4	19	1	3	6	5	4
P8	18	1	3	5	6	3	P9	19	1	3	7	5	3
		2	6	9	12	6			2	6	13	10	7
P5	17	1	3	4	6	3	P5	19	1	4	4	6	4
P9	18	1	3	6	5	3	P9	19	1	3	7	5	3
		2	6	10	11	6			2	7	11	11	7
P6	17	1	2	7	4	3	P5	19	1	4	4	6	4
P9	18	1	3	6	5	3	P10	19	1	3	6	6	3
		2	5	13	9	6			2	7	10	12	7
P6	17	1	2	7	4	3	P8	19	1	3	5	7	3
P10	18	1	3	5	6	3	P10	19	1	3	6	6	3
		2	5	12	10	6			2	6	11	13	6
P2	17	1	2	5	6	3	P1	19	1	4	3	7	4
P1	18	1	4	3	7	3	P3	19	1	2	8	6	2
		2	6	8	13	6			2	6	11	13	6
P4	17	1	3	5	4	4	P4	19	1	3	6	5	4
P9	18	1	3	6	5	3	P10	19	1	3	6	6	3
		2	6	11	9	7			2	6	12	11	7
Period 7							**Period 8**						
Product	Configuration	Operation					Product	Configuration	Operation				
Combination	level	1	2	3	4	5	Combination	level	1	2	3	4	5
P6	15	1	2	6	3	3	P6	15	1	2	6	3	3
P6	18	1	2	8	4	3	P6	18	1	2	8	4	3
		2	4	14	7	6			2	4	14	7	6
P6	15	1	2	6	3	3	P6	15	1	2	6	3	3
P1	18	1	4	3	7	3	P1	18	1	4	3	7	3
		2	6	9	10	6			2	6	9	10	6
P2	15	1	2	4	5	3	P2	15	1	2	4	5	3
P1	18	1	4	3	7	3	P1	18	1	4	3	7	3
		2	6	7	12	6			2	6	7	12	6
P2	15	1	2	4	5	3	P2	15	1	2	4	5	3
P4	18	1	3	5	5	4	P4	18	1	3	5	5	4
		2	5	9	10	7			2	5	9	10	7
P2	15	1	2	4	5	3	P2	15	1	2	4	5	3
P7	18	1	4	5	5	3	P7	18	1	4	5	5	3
		2	6	9	10	6			2	6	9	10	6
P2	15	1	2	4	5	3	P2	15	1	2	4	5	3
P8	18	1	3	5	6	3	P8	18	1	3	5	6	3
		2	5	9	11	6			2	5	9	11	6
P3	15	1	2	6	5	1	P3	15	1	2	6	5	1
P8	18	1	3	5	6	3	P8	18	1	3	5	6	3
		2	5	11	11	4			2	5	11	11	4
P3	15	1	2	6	5	1	P3	15	1	2	6	5	1
P9	18	1	3	6	5	3	P9	18	1	3	6	5	3
		2	5	12	10	4			2	5	12	10	4
P3	15	1	2	6	5	1	P3	15	1	2	6	5	1
P10	18	1	3	5	6	3	P10	18	1	3	5	6	3
		2	5	11	11	4			2	5	11	11	4
P5	15	1	3	3	5	3	P5	15	1	3	3	5	3
P10	18	1	3	5	6	3	P10	18	1	3	5	6	3
		2	6	8	11	6			2	6	8	11	6
P2	15	1	2	4	5	3	P2	15	1	2	4	5	3
P9	18	1	3	6	5	3	P9	18	1	3	6	5	3

Period 9							**Period 10**						
Product	Configuration	Operation					Product	Configuration	Operation				
Combination	level	1	2	3	4	5	Combination	level	1	2	3	4	5
P1	19	1	4	3	7	4	P7	19	1	4	5	6	3
P1	17	1	4	3	6	3	P7	18	1	4	5	5	3
		2	8	6	13	7			2	8	10	11	6
P2	19	1	3	5	6	4	P7	19	1	4	5	6	3
P1	17	1	4	3	6	3	P1	18	1	4	3	7	3
		2	7	8	12	7			2	8	8	13	6
P2	19	1	3	5	6	4	P3	19	1	2	8	6	2
P3	17	1	2	7	5	2	P1	18	1	4	3	7	3
		2	5	12	11	6			2	6	11	13	5
P7	19	1	4	5	6	3	P3	19	1	2	8	6	2
P3	17	1	2	7	5	2	P2	18	1	3	5	6	3
		2	6	12	11	5			2	5	13	12	5
P7	19	1	4	5	6	3	P4	19	1	3	6	5	4
P4	17	1	3	5	4	4	P2	18	1	3	5	6	3
		2	7	10	10	7			2	6	11	11	7
P8	19	1	3	5	7	3	P5	19	1	4	4	6	4
P4	17	1	3	5	4	4	P2	18	1	3	5	6	3
		2	6	10	11	7			2	7	9	12	7
P8	19	1	3	5	7	3	P6	19	1	3	8	4	3
P5	17	1	3	4	6	3	P2	18	1	3	5	6	3
		2	6	9	13	6			2	6	13	10	6
P9	19	1	3	7	5	3	P6	19	1	3	8	4	3
P5	17	1	3	4	6	3	P8	18	1	3	5	6	3
		2	6	11	11	6			2	6	13	10	6
P9	19	1	3	7	5	3	P6	19	1	3	8	4	3
P6	17	1	2	7	4	3	P10	18	1	3	5	6	3
		2	5	14	9	6			2	6	13	10	6
P10	19	1	3	6	6	3	P9	19	1	3	7	5	3
P6	17	1	2	7	4	3	P10	18	1	3	5	6	3
		2	5	13	10	6			2	6	12	11	6
P9	19	1	3	7	5	3							
P4	17	1	3	5	4	4							
		2	6	12	9	7							
Period 11							**Period 12**						
Product	Configuration	Operation					Product	Configuration	Operation				
Combination	level	1	2	3	4	5	Combination	level	1	2	3	4	5
P6	18	1	2	8	4	3	P2	18	1	3	5	6	3
P6	15	1	2	6	3	3	P2	17	1	2	5	6	3
		2	4	14	7	6			2	5	10	12	6
P1	18	1	4	3	7	3	P1	18	1	4	3	7	3
P6	15	1	2	6	3	3	P2	17	1	2	5	6	3
		2	6	9	10	6			2	6	8	13	6
P1	18	1	4	3	7	3	P1	18	1	4	3	7	3
P2	15	1	2	4	5	3	P3	17	1	2	7	5	2
		2	6	7	12	6			2	6	10	12	5
P4	18	1	3	5	5	4	P7	18	1	4	5	5	3
P2	15	1	2	4	5	3	P3	17	1	2	7	5	2
		2	5	9	10	7			2	6	12	10	5
P7	18	1	4	5	5	3	P7	18	1	4	5	5	3
P2	15	1	2	4	5	3	P4	17	1	3	5	4	4
		2	6	9	10	6			2	7	10	9	7
P8	18	1	3	5	6	3	P8	18	1	3	5	6	3
P2	15	1	2	4	5	3	P4	17	1	3	5	4	4
		2	5	9	11	6			2	6	10	10	7
P8	18	1	3	5	6	3	P8	18	1	3	5	6	3
P3	15	1	2	6	5	1	P5	17	1	3	4	6	3
		2	5	11	11	4			2	6	9	12	6
P9	18	1	3	6	5	3	P9	18	1	3	6	5	3
P3	15	1	2	6	5	1	P5	17	1	3	4	6	3
		2	5	12	10	4			2	6	10	11	6
P10	18	1	3	5	6	3	P9	18	1	3	6	5	3
P3	15	1	2	6	5	1	P6	17	1	2	7	4	3
		2	5	11	11	4			2	5	13	9	6
P10	18	1	3	5	6	3	P10	18	1	3	5	6	3
P5	15	1	3	3	5	3	P6	17	1	2	7	4	3
		2	6	8	11	6			2	5	12	10	6
P9	18	1	3	6	5	3	P9	18	1	3	6	5	3
P2	15	1	2	4	5	3	P4	17	1	3	5	4	4
		2	5	10	10	6			2	6	11	9	7
							P10	18	1	3	5	6	3
							P5	17	1	3	4	6	3

Period 13							**Period 14**						
Product	Configuration	Operation					Product	Configuration	Operation				
Combination	level	1	2	3	4	5	Combination	level	1	2	3	4	5
P7	19	1	4	5	6	3	P6	18	1	2	8	4	3
P7	18	1	4	5	5	3	P6	15	1	2	6	3	3
		2	8	10	11	6			2	4	14	7	6
P7	19	1	4	5	6	3	P1	18	1	4	3	7	3
P1	18	1	4	3	7	3	P6	15	1	2	6	3	3
		2	8	8	13	6			2	6	9	10	6
P3	19	1	2	8	6	2	P1	18	1	4	3	7	3
P1	18	1	4	3	7	3	P2	15	1	2	4	5	3
		2	6	11	13	5			2	6	7	12	6
P3	19	1	2	8	6	2	P4	18	1	3	5	5	4
P2	18	1	3	5	6	3	P2	15	1	2	4	5	3
		2	5	13	12	5			2	5	9	10	7
P4	19	1	3	6	5	4	P7	18	1	4	5	5	3
P2	18	1	3	5	6	3	P2	15	1	2	4	5	3
		2	6	11	11	7			2	6	9	10	6
P5	19	1	4	4	6	4	P8	18	1	3	5	6	3
P2	18	1	3	5	6	3	P2	15	1	2	4	5	3
		2	7	9	12	7			2	5	9	11	6
P6	19	1	3	8	4	3	P8	18	1	3	5	6	3
P2	18	1	3	5	6	3	P3	15	1	2	6	5	1
		2	6	13	10	6			2	5	11	11	4
P6	19	1	3	8	4	3	P9	18	1	3	6	5	3
P8	18	1	3	5	6	3	P3	15	1	2	6	5	1
		2	6	13	10	6			2	5	12	10	4
P6	19	1	3	8	4	3	P10	18	1	3	5	6	3
P10	18	1	3	5	6	3	P3	15	1	2	6	5	1
		2	6	13	10	6			2	5	11	11	4
P9	19	1	3	7	5	3	P10	18	1	3	5	6	3
P10	18	1	3	5	6	3	P5	15	1	3	3	5	3
		2	6	12	11	6			2	6	8	11	6
P4	19	1	3	6	5	4							
P1	18	1	4	3	7	3							
		2	7	9	12	7							
P9	19	1	3	7	5	3							
P8	18	1	3	5	6	3							
		2	6	12	11	6							

Period 15							**Period 16**						
Product	Configuration	Operation					Product	Configuration	Operation				
Combination	level	1	2	3	4	5	Combination	level	1	2	3	4	5
P1	19	1	4	3	7	4	P2	18	1	3	5	6	3
P1	17	1	4	3	6	3	P2	18	1	3	5	6	3
		2	8	6	13	7			2	6	10	12	6
P2	19	1	3	5	6	4	P2	18	1	3	5	6	3
P1	17	1	4	3	6	3	P3	18	1	2	7	6	2
		2	7	8	12	7			2	5	12	12	5
P2	19	1	3	5	6	4	P1	18	1	4	3	7	3
P3	17	1	2	7	5	2	P3	18	1	2	7	6	2
		2	5	12	11	6			2	6	10	13	5
P7	19	1	4	5	6	3	P1	18	1	4	3	7	3
P3	17	1	2	7	5	2	P4	18	1	3	5	5	4
		2	6	12	11	5			2	7	8	12	7
P7	19	1	4	5	6	3	P5	18	1	3	4	6	4
P4	17	1	3	5	4	4	P4	18	1	3	5	5	4
		2	7	10	10	7			2	6	9	11	8
P8	19	1	3	5	7	3	P5	18	1	3	4	6	4
P4	17	1	3	5	4	4	P6	18	1	2	8	4	3
		2	6	10	11	7			2	5	12	10	7
P8	19	1	3	5	7	3	P8	18	1	3	5	6	3
P5	17	1	3	4	6	3	P6	18	1	2	8	4	3
		2	6	9	13	6			2	5	13	10	6
P9	19	1	3	7	5	3	P9	18	1	3	6	5	3
P5	17	1	3	4	6	3	P6	18	1	2	8	4	3
		2	6	11	11	6			2	5	14	9	6
P9	19	1	3	7	5	3	P10	18	1	3	5	6	3
P6	17	1	2	7	4	3	P6	18	1	2	8	4	3
		2	5	14	9	6			2	5	13	10	6
P10	19	1	3	6	6	3	P10	18	1	3	5	6	3
P6	17	1	2	7	4	3	P7	18	1	4	5	5	3
		2	5	13	10	6			2	7	10	11	6
P9	19	1	3	7	5	3	P9	18	1	3	6	5	3
P4	17	1	3	5	4	4	P7	18	1	4	5	5	3

APPENDIX F SAMPLE OPL MODEL FOR MAX APPROACH

Product combination (P3-P2) and 2 Skills

```
var int+ O0104 in 0..1;
var int+ O0105 in 0..1;
var int+ O0202 in 0..1;
var int+ O0203 in 0..1;
var int+ O0302 in 0..1;
var int+ O0303 in 0..1;
var int+ O0402 in 0..1;
var int+ O0404 in 0..1;
var int+ O0503 in 0..1;
var int+ O0505 in 0..1;
var int+ O0602 in 0..1;
var int+ O0603 in 0..1;
var int+ O0701 in 0..1;
var int+ O0703 in 0..1;
var int+ O0802 in 0..1;
var int+ O0803 in 0..1;
var int+ O0902 in 0..1;
var int+ O0904 in 0..1;
var int+ O1003 in 0..1;
var int+ O1005 in 0..1;
var int+ O1101 in 0..1;
var int+ O1104 in 0..1;
var int+ O1202 in 0..1;
var int+ O1203 in 0..1;
var int+ O1304 in 0..1;
var int+ O1305 in 0..1;
var int+ O1402 in 0..1;
var int+ O1403 in 0..1;
var int+ O1503 in 0..1;
var int+ O1504 in 0..1;
var int+ O1602 in 0..1;
var int+ O1604 in 0..1;
var int+ O1702 in 0..1;
var int+ O1703 in 0..1;
var int+ O1801 in 0..1;
var int+ O1803 in 0..1;
var int+ O1903 in 0..1;
var int+ O1905 in 0..1;
var int+ O2002 in 0..1;
var int+ O2004 in 0..1;
var int+ O2103 in 0..1;
var int+ O2104 in 0..1;
var int+ O2204 in 0..1;
var int+ O2205 in 0..1;
var int+ O2303 in 0..1;
var int+ O2304 in 0..1;
var int+ O2404 in 0..1;
var int+ O2405 in 0..1;
var int+ O2502 in 0..1;
var int+ O2503 in 0..1;
var int+ O2602 in 0..1;
var int+ O2604 in 0..1;
var int+ O2701 in 0..1;
var int+ O2704 in 0..1;
var int+ O2803 in 0..1;
var int+ O2805 in 0..1;
var int+ O2902 in 0..1;
var int+ O2904 in 0..1;
var int+ O3003 in 0..1;
var int+ O3005 in 0..1;
var int+ O3103 in 0..1;
var int+ O3105 in 0..1;
var int+ O3204 in 0..1;
var int+ O3205 in 0..1;
var int+ O3301 in 0..1;
var int+ O3304 in 0..1;
var int+ O3403 in 0..1;
var int+ O3404 in 0..1;
var int+ O3504 in 0..1;
var int+ O3505 in 0..1;
var int+ O3602 in 0..1;
var int+ O3604 in 0..1;
var int+ O3703 in 0..1;
var int+ O3705 in 0..1;
var int+ O3803 in 0..1;
var int+ O3804 in 0..1;
var int+ O3904 in 0..1;
var int+ O3905 in 0..1;
var int+ O4004 in 0..1;
var int+ O4005 in 0..1;
var int+ z in 0..maxint;
minimize z
subject to
{
z = 5*O0104 + 5*O0105 + 4*O0202 + 5*O0203 + 5*O0302 + 3*O0303 + 5*O0402 + 4*O0404 +
6*O0503 + 7*O0505 + 6*O0602 + 6*O0603 + 7*O0701 + 5*O0703 + 7*O0802 + 6*O0803 +
5*O0902 + 4*O0904 + 6*O1003 + 2*O1005 + 3*O1101 + 1*O1104 + 5*O1202 + 7*O1203 +
6*O1305 + 6*O1304 + 5*O1402 + 4*O1403 + 5*O1503 + 4*O1504 + 9*O1602 + 4*O1604 +
8*O1702 + 7*O1703 + 4*O1803 + 5*O1801 + 6*O1903 + 6*O1905 + 4*O2002 + 4*O2004 +
6*O2103 + 8*O2104 + 4*O2205 + 4*O2204 + 4*O2303 + 2*O2304 + 5*O2404 + 5*O2405 +
6*O2502 + 6*O2503 + 5*O2602 + 5*O2604 + 6*O2701 + 4*O2704 + 5*O2803 + 5*O2805 +
3*O2902 + 6*O2904 + 2*O3003 + 3*O3005 + 7*O3103 + 5*O3105 + 4*O3204 + 4*O3205 +
6*O3301 + 3*O3304 + 5*O3403 + 6*O3404 + 5*O3504 + 7*O3505 + 1*O3602 + 5*O3604 +
5*O3703 + 5*O3705 + 5*O3803 + 4*O3804 + 5*O3904 + 5*O3905 + 5*O4004+ 5*O4005;

    O0104 + O0105 = 1;
    O0202 + O0203 = 1;
    O0302 + O0303 = 1;
    O0402 + O0404 = 1;
    O0503 + O0505 = 1;
    O0602 + O0603 = 1;
    O0701 + O0703 = 1;
    O0802 + O0803 = 1;
    O0902 + O0904 = 1;
    O1003 + O1005 = 1;
    O1101 + O1104 = 1;
    O1202 + O1203 = 1;
    O1305 + O1304 = 1;
    O1402 + O1403 = 1;
    O1503 + O1504 = 1;
    O1602 + O1604 = 1;
    O1702 + O1703 = 1;
    O1803 + O1801 = 1;
    O1903 + O1905 = 1;
    O2002 + O2004 = 1;
    O2103 + O2104 = 1;
```

O2205 + O2204 = 1;
O2303 + O2304 = 1;
O2404 + O2405 = 1;
O2502 + O2503 = 1;
O2602 + O2604 = 1;
O2701 + O2704 = 1;
O2803 + O2805 = 1;
O2902 + O2904 = 1;
O3003 + O3005 = 1;
O3103 + O3105 = 1;
O3204 + O3205 = 1;
O3301 + O3304 = 1;
O3403 + O3404 = 1;
O3504 + O3505 = 1;
O3602 + O3604 = 1;
O3703 + O3705 = 1;
O3803 + O3804 = 1;
O3904 + O3905 = 1;
O4004 + O4005 = 1;

O0701+ O1101 + O1801 + O2701 + O3301 = 2;

O0202 + O0302 + O0402 + O0602 + O0802 + O0902 + O1202 + O1402 + O1602 + O1702 + O2002 + O2502 + O2602 + O2902 + O3602 = 5;

O0203 + O0303 + O0503 + O0603 + O0703 + O0803 + O1003 + O1203 + O1403 + O1503 + O1703 + O1803 + O1903 + O2103 + O2303 + O2503 + O2803 + O3003 + O3103 + O3403 + O3703 + O3803 = 15;

O0104 + O0404 + O0904 + O1104 + O1304 + O1504 + O1604 + O2004 + O2104 + O2204 + O2304 + O2404 + O2604 + O2704 + O2904 + O3204 + O3304 + O3404 + O3504 + O3604 + O3804 + O3904 + O4004 = 12;

O0105 + O0505 + O1005+ O1305 + O1905+ O2205+ O2405 + O2805 + O3005+ O3105 + O3205 + O3505 + O3705 + O3905 + O4005 = 6;
};

Optimal Solution with Objective Value: 178

O0104 = 1
O0105 = 0
O0202 = 1
O0203 = 0
O0302 = 0
O0303 = 1
O0402 = 0
O0404 = 1
O0503 = 1
O0505 = 0
O0602 = 0
O0603 = 1
O0701 = 0
O0703 = 1
O0802 = 0
O0803 = 1
O0902 = 0
O0904 = 1
O1003 = 0
O1005 = 1
O1101 = 1
O1104 = 0
O1202 = 1
O1203 = 0
O1304 = 1
O1305 = 0
O1402 = 0
O1403 = 1
O1503 = 0
O1504 = 1
O1602 = 0
O1604 = 1
O1702 = 0
O1703 = 1
O1801 = 0
O1803 = 1
O1903 = 1
O1905 = 0
O2002 = 0
O2004 = 1
O2103 = 1
O2104 = 0
O2204 = 0
O2205 = 1
O2303 = 0
O2304 = 1
O2404 = 1
O2405 = 0
O2502 = 0
O2503 = 1
O2602 = 1
O2604 = 0
O2701 = 1
O2704 = 0
O2803 = 1
O2805 = 0
O2902 = 1
O2904 = 0
O3003 = 1
O3005 = 0
O3103 = 0
O3105 = 1
O3204 = 0
O3205 = 1
O3301 = 0
O3304 = 1
O3403 = 1
O3404 = 0
O3504 = 1
O3505 = 0
O3602 = 1
O3604 = 0
O3703 = 1
O3705 = 0
O3803 = 0
O3804 = 1
O3904 = 0
O3905 = 1
O4004 = 0
O4005 = 1
z = 178

Product combination (P3-P2) and 3 skills

```
var int+ O0103 in 0..1;
var int+ O0104 in 0..1;
var int+ O0105 in 0..1;
var int+ O0202 in 0..1;
var int+ O0203 in 0..1;
var int+ O0204 in 0..1;
var int+ O0302 in 0..1;
var int+ O0303 in 0..1;
var int+ O0304 in 0..1;
var int+ O0402 in 0..1;
var int+ O0403 in 0..1;
var int+ O0404 in 0..1;
var int+ O0503 in 0..1;
var int+ O0504 in 0..1;
var int+ O0505 in 0..1;
var int+ O0602 in 0..1;
var int+ O0603 in 0..1;
var int+ O0604 in 0..1;
var int+ O0701 in 0..1;
var int+ O0703 in 0..1;
var int+ O0704 in 0..1;
var int+ O0802 in 0..1;
var int+ O0803 in 0..1;
var int+ O0805 in 0..1;
var int+ O0902 in 0..1;
var int+ O0904 in 0..1;
var int+ O0905 in 0..1;
var int+ O1003 in 0..1;
var int+ O1004 in 0..1;
var int+ O1005 in 0..1;
var int+ O1101 in 0..1;
var int+ O1102 in 0..1;
var int+ O1104 in 0..1;
var int+ O1202 in 0..1;
var int+ O1203 in 0..1;
var int+ O1204 in 0..1;
var int+ O1301 in 0..1;
var int+ O1304 in 0..1;
var int+ O1305 in 0..1;
var int+ O1402 in 0..1;
var int+ O1403 in 0..1;
var int+ O1404 in 0..1;
var int+ O1502 in 0..1;
var int+ O1503 in 0..1;
var int+ O1504 in 0..1;
var int+ O1601 in 0..1;
var int+ O1602 in 0..1;
var int+ O1604 in 0..1;
var int+ O1702 in 0..1;
var int+ O1703 in 0..1;
var int+ O1704 in 0..1;
var int+ O1801 in 0..1;
var int+ O1803 in 0..1;
var int+ O1804 in 0..1;
var int+ O1903 in 0..1;
var int+ O1905 in 0..1;
var int+ O1904 in 0..1;
var int+ O2001 in 0..1;
var int+ O2002 in 0..1;
var int+ O2004 in 0..1;
var int+ O2102 in 0..1;
var int+ O2103 in 0..1;
var int+ O2104 in 0..1;
var int+ O2203 in 0..1;
var int+ O2204 in 0..1;
var int+ O2205 in 0..1;
var int+ O2305 in 0..1;
var int+ O2303 in 0..1;
var int+ O2304 in 0..1;
var int+ O2403 in 0..1;
var int+ O2404 in 0..1;
var int+ O2405 in 0..1;
var int+ O2501 in 0..1;
var int+ O2502 in 0..1;
var int+ O2503 in 0..1;
var int+ O2601 in 0..1;
var int+ O2602 in 0..1;
var int+ O2604 in 0..1;
var int+ O2701 in 0..1;
var int+ O2703 in 0..1;
var int+ O2704 in 0..1;
var int+ O2803 in 0..1;
var int+ O2804 in 0..1;
var int+ O2805 in 0..1;
var int+ O2901 in 0..1;
var int+ O2902 in 0..1;
var int+ O2904 in 0..1;
var int+ O3001 in 0..1;
var int+ O3003 in 0..1;
var int+ O3005 in 0..1;
var int+ O3102 in 0..1;
var int+ O3103 in 0..1;
var int+ O3105 in 0..1;
var int+ O3201 in 0..1;
var int+ O3204 in 0..1;
var int+ O3205 in 0..1;
var int+ O3301 in 0..1;
var int+ O3303 in 0..1;
var int+ O3304 in 0..1;
var int+ O3401 in 0..1;
var int+ O3403 in 0..1;
var int+ O3404 in 0..1;
var int+ O3501 in 0..1;
var int+ O3504 in 0..1;
var int+ O3505 in 0..1;
var int+ O3602 in 0..1;
var int+ O3604 in 0..1;
var int+ O3605 in 0..1;
var int+ O3702 in 0..1;
var int+ O3703 in 0..1;
var int+ O3705 in 0..1;
var int+ O3802 in 0..1;
var int+ O3803 in 0..1;
var int+ O3804 in 0..1;
var int+ O3902 in 0..1;
var int+ O3904 in 0..1;
var int+ O3905 in 0..1;
var int+ O4003 in 0..1;
var int+ O4004 in 0..1;
var int+ O4005 in 0..1;
var int+ z in 0..maxint;

minimize z
subject to
{
z = 1*O0103 + 5*O0104 + 5*O0105 + 4*O0202 + 5*O0203 +8*O0204 +  5*O0302 + 3*O0303
+6*O0304 +  5*O0402 +  5*O0403 + 4*O0404 + 6*O0503 + 9*O0504 + 7*O0505 + 6*O0602 +
6*O0603 +4*O0604 +  7*O0701 + 5*O0703 +8*O0704 +  7*O0802 + 6*O0803 + 4*O0805 +
5*O0902 + 4*O0904 +6*O0905 +  6*O1003 + 8*O1004 + 2*O1005 + 3*O1101 + 1*O1102 +
```

1*O1104 + 5*O1202 + 7*O1203 + 6*O1204 + 8*O1301 + 6*O1305 + 6*O1304 + 5*O1402 + 4*O1403 + 1*O1404 + 8*O1502 + 5*O1503 + 4*O1504 + 1*O1601 + 9*O1602 + 4*O1604 + 8*O1702 + 7*O1703 + 9*O1704 + 4*O1803 + 5*O1801 + 4*O1804 + 6*O1903 + 9*O1904 + 6*O1905 + 5*O2001 + 4*O2002 + 4*O2004 + 8*O2102 + 6*O2103 + 8*O2104 + 4*O2205 + 6*O2203 + 4*O2204 + 4*O2303 + 2*O2304 + 7*O2305 + 3*O2403 + 5*O2404 + 5*O2405 + 4*O2501 + 6*O2502 + 6*O2503 + 6*O2601 + 5*O2602 + 5*O2604 + 6*O2701 + 1*O2703 + 4*O2704 + 5*O2803 + 9*O2804 + 5*O2805 + 9*O2901 + 3*O2902 + 6*O2904 + 3*O3001 + 2*O3003 + 3*O3005 + 6*O3102 + 7*O3103 + 5*O3105 + 5*O3201 + 4*O3204 + 4*O3205 + 6*O3301 + 1*O3303 + 3*O3304 + 4*O3401 + 5*O3403 + 6*O3404 + 8*O3501 + 5*O3504 + 7*O3505 +
1*O3602 + 5*O3604 + 4*O3605 + 6*O3702 + 5*O3703 + 5*O3705 + 1*O3802 + 5*O3803 + 4*O3804 + 6*O3902 + 5*O3904 + 5*O3905 + 4*O4003 + 5*O4004+ 5*O4005;

O0103 +O0104 + O0105 = 1;
O0202 + O0203+ O0204 = 1;
O0302 + O0303+ O0304 = 1;
O0402 + O0403 + O0404 = 1;
O0503 + O0504 + O0505 = 1;
O0602 + O0603+ O0604 = 1;
O0701 + O0703 + O0704= 1;
O0802 + O0803+ O0805 = 1;
O0902 + O0904+ O0905 = 1;
O1003 + O1004 + O1005 = 1;
O1101 + O1102 + O1104 = 1;
O1202 + O1203+ O1204 = 1;
O1301 + O1305 + O1304 = 1;
O1402 + O1403+ O1404 = 1;
O1502 + O1503 + O1504 = 1;
O1601 +O1602 + O1604 = 1;
O1702 + O1703+ O1704 = 1;
O1803 + O1801 + O1804= 1;
O1903 + O1904 + O1905 = 1;
O2001 +O2002 + O2004 = 1;
O2102 + O2103 + O2104 = 1;
O2203 +O2205 + O2204 = 1;
O2303 + O2304 + O2305= 1;
O2403 + O2404 + O2405 = 1;
O2501 +O2502 + O2503 = 1;
O2601 +O2602 + O2604 = 1;
O2701+ O2703 + O2704 = 1;
O2803 + O2804 + O2805 = 1;
O2901 +O2902 + O2904 = 1;
O3001 +O3003 + O3005 = 1;
O3102 +O3103 + O3105 = 1;
O3201 + O3204 + O3205 = 1;
O3301 + O3303 + O3304 = 1;
O3401 +O3403 + O3404 = 1;
O3501 + O3504 + O3505 = 1;
O3602 + O3604+ O3605 = 1;
O3702 + O3703 + O3705 = 1;
O3802 +O3803 + O3804 = 1;
O3902 + O3904 + O3905 = 1;
O4003 + O4004 + O4005 = 1;

O0701+ O1101+ O1301 + O1601 + O1801+ O2001 + O2501 + O2601 + O2701+ O2901+ O3001+ O3201 + O3301+ O3401+ O3501 = 2;

O0202 + O0302 + O0402 + O0602 + O0802 + O0902+ O1102 + O1202 + O1402 + O1502 + O1602 + O1702 + O2002+ O2102 + O2502 + O2602 + O2902+ O3102 + O3602 + O3702+ O3802+ O3902 = 5;

O0103 +O0203 + O0303 + O0403 +O0503 + O0603 + O0703 + O0803 + O1003 + O1203 + O1403 + O1503 + O1703 + O1803 + O1903 + O2103 + O2203 + O2303 + O2403 +O2503 + O2703 + O2803 + O3003 + O3103 + O3303 + O3403 + O3703 + O3803 +O4003 = 15;

O0104 + O0204 + O0304 + O0404 + O0504 + O0604 + O0704 +O0904 + O1004 + O1104 + O1204 +O1304 + O1404 + O1504 + O1604 + O1704 + O1804 + O1904 + O2004 + O2104 + O2204 + O2304 + O2404 + O2604 + O2704 + O2804 +O2904 + O3204 + O3304 + O3404 + O3504 + O3604 + O3804 + O3904 = 12;

O0105 + O0505 + O0805 + O0905 +O1005+ O1305 + O1905+ O2205+ O2305 + O2405 + O2805 + O3005+ O3105 + O3205 + O3505 + O3605 + O3705 + O3905 + O4005 = 6;
};

Optimal Solution with Objective Value: 147

O0103 = 1
O0104 = 0
O0105 = 0
O0202 = 1
O0203 = 0
O0602 = 0
O0603 = 0
O0604 = 1
O0701 = 0
O0703 = 1
O0704 = 0
O0802 = 0
O0803 = 0
O0805 = 1
O0902 = 0
O0904 = 1
O0905 = 0
O1003 = 0
O1004 = 0
O1005 = 1
O1101 = 0
O1102 = 0
O1104 = 1
O1202 = 1
O1203 = 0
O1204 = 0
O1301 = 0
O1304 = 0
O1305 = 1
O1402 = 0
O1403 = 0
O1404 = 1
O1502 = 0
O1503 = 0
O1504 = 1
O1601 = 1
O1602 = 0
O1604 = 0
O1702 = 0
O1703 = 1
O1704 = 0
O1801 = 0
O1803 = 1
O1804 = 0
O1903 = 1
O1905 = 0
O1904 = 0
O2001 = 0
O2002 = 0
O2004 = 1
O2102 = 0
O2103 = 1
O2104 = 0
O2203 = 0
O0204 = 0
O0302 = 0
O0303 = 1
O0304 = 0
O0402 = 0
O2204 = 0
O2205 = 1
O2305 = 0
O2303 = 0
O2304 = 1
O2403 = 1
O2404 = 0
O2405 = 0
O2501 = 1
O2502 = 0
O2503 = 0
O2601 = 0
O2602 = 0
O2604 = 1
O2701 = 0
O2703 = 1
O2704 = 0
O2803 = 0
O2804 = 0
O2805 = 1
O2901 = 0
O2902 = 1
O2904 = 0
O3001 = 0
O3003 = 1
O3005 = 0
O3102 = 0
O3103 = 0
O3105 = 1
O3201 = 0
O3204 = 1
O3205 = 0
O3301 = 0
O3303 = 1
O3304 = 0
O3401 = 0
O3403 = 1
O3404 = 0
O3501 = 0
O3504 = 1
O3505 = 0
O3602 = 1
O3604 = 0
O3605 = 0
O3702 = 0
O3703 = 1
O3705 = 0
O3802 = 1
O3803 = 0
O0403 = 0
O0404 = 1
O0503 = 1
O0504 = 0
O0505 = 0
O3804 = 0
O3902 = 0
O3904 = 1
O3905 = 0
O4003 = 1
O4004 = 0
O4005 = 0
z = 147

Product combination (P5-P2-P1)

```
var int+ O0104 in 0..1;
var int+ O0105 in 0..1;
var int+ O0202 in 0..1;
var int+ O0203 in 0..1;
var int+ O0302 in 0..1;
var int+ O0303 in 0..1;
var int+ O0402 in 0..1;
var int+ O0404 in 0..1;
var int+ O0503 in 0..1;
var int+ O0504 in 0..1;
var int+ O0602 in 0..1;
var int+ O0603 in 0..1;
var int+ O0701 in 0..1;
var int+ O0703 in 0..1;
var int+ O0802 in 0..1;
var int+ O0803 in 0..1;
var int+ O0902 in 0..1;
var int+ O0904 in 0..1;
var int+ O1003 in 0..1;
var int+ O1005 in 0..1;
var int+ O1103 in 0..1;
var int+ O1104 in 0..1;
var int+ O1202 in 0..1;
var int+ O1203 in 0..1;
var int+ O1303 in 0..1;
var int+ O1304 in 0..1;
var int+ O1402 in 0..1;
var int+ O1403 in 0..1;
var int+ O1503 in 0..1;
var int+ O1504 in 0..1;
var int+ O1602 in 0..1;
var int+ O1604 in 0..1;
var int+ O1702 in 0..1;
var int+ O1703 in 0..1;
var int+ O1803 in 0..1;
var int+ O1804 in 0..1;
var int+ O1903 in 0..1;
var int+ O1904 in 0..1;
var int+ O2002 in 0..1;
var int+ O2004 in 0..1;
var int+ O2103 in 0..1;
var int+ O2104 in 0..1;
var int+ O2203 in 0..1;
var int+ O2204 in 0..1;
var int+ O2303 in 0..1;
var int+ O2304 in 0..1;
var int+ O2404 in 0..1;
var int+ O2405 in 0..1;
var int+ O2502 in 0..1;
var int+ O2503 in 0..1;
var int+ O2602 in 0..1;
var int+ O2604 in 0..1;
var int+ O2703 in 0..1;
var int+ O2704 in 0..1;
var int+ O2803 in 0..1;
var int+ O2805 in 0..1;
var int+ O2902 in 0..1;
var int+ O2904 in 0..1;
var int+ O3003 in 0..1;
var int+ O3004 in 0..1;
var int+ O3103 in 0..1;
var int+ O3105 in 0..1;
var int+ O3204 in 0..1;
var int+ O3205 in 0..1;
var int+ O3301 in 0..1;
var int+ O3304 in 0..1;
var int+ O3403 in 0..1;
var int+ O3404 in 0..1;
var int+ O3504 in 0..1;
var int+ O3505 in 0..1;
var int+ O3602 in 0..1;
var int+ O3604 in 0..1;
var int+ O3703 in 0..1;
var int+ O3705 in 0..1;
var int+ O3803 in 0..1;
var int+ O3804 in 0..1;
var int+ O3904 in 0..1;
var int+ O3905 in 0..1;
var int+ O4004 in 0..1;
var int+ O4005 in 0..1;
var int+ O4103 in 0..1;
var int+ O4105 in 0..1;
var int+ O4204 in 0..1;
var int+ O4205 in 0..1;
var int+ O4301 in 0..1;
var int+ O4305 in 0..1;
var int+ O4402 in 0..1;
var int+ O4404 in 0..1;
var int+ O4502 in 0..1;
var int+ O4503 in 0..1;
var int+ O4603 in 0..1;
var int+ O4605 in 0..1;
var int+ O4704 in 0..1;
var int+ O4705 in 0..1;
var int+ O4801 in 0..1;
var int+ O4803 in 0..1;
var int+ O4902 in 0..1;
var int+ O4903 in 0..1;
var int+ O5003 in 0..1;
var int+ O5005 in 0..1;
var int+ O5101 in 0..1;
var int+ O5104 in 0..1;
var int+ O5202 in 0..1;
var int+ O5203 in 0..1;
var int+ O5303 in 0..1;
var int+ O5304 in 0..1;
var int+ O5402 in 0..1;
var int+ O5403 in 0..1;
var int+ O5502 in 0..1;
var int+ O5503 in 0..1;
var int+ O5601 in 0..1;
var int+ O5603 in 0..1;
var int+ O5703 in 0..1;
var int+ O5704 in 0..1;
var int+ O5804 in 0..1;
var int+ O5805 in 0..1;
var int+ O5903 in 0..1;
var int+ O5905 in 0..1;
var int+ O6003 in 0..1;
var int+ O6004 in 0..1;
var int+ O6104 in 0..1;
var int+ O6105 in 0..1;
var int+ O6202 in 0..1;
var int+ O6204 in 0..1;
var int+ O6304 in 0..1;
var int+ O6305 in 0..1;
var int+ O6403 in 0..1;
var int+ O6405 in 0..1;
var int+ O6503 in 0..1;
var int+ O6504 in 0..1;
var int+ O6601 in 0..1;
var int+ O6603 in 0..1;
var int+ O6703 in 0..1;
var int+ O6704 in 0..1;
var int+ O6803 in 0..1;
var int+ O6805 in 0..1;
var int+ O6904 in 0..1;
var int+ O6905 in 0..1;
var int+ O7003 in 0..1;
var int+ O7004 in 0..1;
```

```
var int+ z in 0..maxint;


minimize z
subject to
{
z = 5*O0104 + 5*O0105 + 4*O0202 + 5*O0203 + 5*O0302 + 3*O0303 + 5*O0402 + 4*O0404 +
6*O0503 + 7*O0504 + 6*O0602 + 6*O0603 + 7*O0701 + 5*O0703 + 7*O0802 + 6*O0803 +
5*O0902 + 4*O0904 + 6*O1003 + 2*O1005 + 3*O1103 + 1*O1104 + 5*O1202 + 7*O1203 +
6*O1303 + 6*O1304 + 5*O1402 + 4*O1403 + 5*O1503 + 4*O1504 + 9*O1602 + 4*O1604 +
8*O1702 + 7*O1703 + 4*O1803 + 5*O1804 + 6*O1903 + 6*O1904 + 4*O2002 + 4*O2004 +
6*O2103 + 8*O2104 + 4*O2203 + 4*O2204 + 4*O2303 + 2*O2304 + 5*O2404 + 5*O2405 +
6*O2502 + 6*O2503 + 5*O2602 + 5*O2604 + 6*O2703 + 4*O2704 + 5*O2803 + 5*O2805 +
3*O2902 + 6*O2904 + 2*O3003 + 3*O3004 + 7*O3103 + 5*O3105 + 4*O3204 + 4*O3205 +
6*O3301 + 3*O3304 + 5*O3403 + 6*O3404 + 5*O3504 + 7*O3505 +
1*O3602 + 5*O3604 + 5*O3703 + 5*O3705 + 5*O3803 + 4*O3804 + 5*O3904 +  5*O3905 +
5*O4004 + 5*O4005 + 3*O4103 + 6*O4105 + 5*O4204 + 1*O4205 + 5*O4301 + 4*O4305 +
6*O4402 + 6*O4404 + 7*O4502 + 5*O4503 + 4*O4603 + 6*O4605 + 4*O4704 + 5*O4705 +
4*O4801 + 6*O4803 + 5*O4902 + 4*O4903 + 9*O5003 + 4*O5005 + 2*O5101 + 4*O5104 +
6*O5202 + 6*O5203 + 6*O5303 + 4*O5304 + 4*O5402 + 5*O5403 + 5*O5502 + 5*O5503 +
6*O5601 + 4*O5603 + 1*O5703 + 4*O5704 + 6*O5804 + 2*O5805 + 4*O5903 + 5*O5905 +
6*O6003 + 5*O6004 + 5*O6104 + 8*O6105 + 4*O6202 + 3*O6204 + 1*O6304 + 3*O6305 +
6*O6403 + 5*O6405 + 5*O6503 + 5*O6504 + 4*O6601 + 7*O6603 + 5*O6703 + 9*O6704 +
4*O6803 + 4*O6805 + 4*O6904 + 5*O6905 + 7*O7003 + 5*O7004 ;

    O0104 + O0105 = 1;
    O0202 + O0203 = 1;
    O0302 + O0303 = 1;
    O0402 + O0404 = 1;
    O0503 + O0504 = 1;
    O0602 + O0603 = 1;
    O0701 + O0703 = 1;
    O0802 + O0803 = 1;
    O0902 + O0904 = 1;
    O1003 + O1005 = 1;
    O1103 + O1104 = 1;
    O1202 + O1203 = 1;
    O1303 + O1304 = 1;
    O1402 + O1403 = 1;
    O1503 + O1504 = 1;
    O1602 + O1604 = 1;
    O1702 + O1703 = 1;
    O1803 + O1804 = 1;
    O1903 + O1904 = 1;
    O2002 + O2004 = 1;
    O2103 + O2104 = 1;
    O2203 + O2204 = 1;
    O2303 + O2304 = 1;
    O2404 + O2405 = 1;
    O2502 + O2503 = 1;
    O2602 + O2604 = 1;
    O2703 + O2704 = 1;
    O2803 + O2805 = 1;
    O2902 + O2904 = 1;
    O3003 + O3004 = 1;
    O3103 + O3105 = 1;
    O3204 + O3205 = 1;
    O3301 + O3304 = 1;
    O3403 + O3404 = 1;
    O3504 + O3505 = 1;
    O3602 + O3604 = 1;
    O3703 + O3705 = 1;
    O3803 + O3804 = 1;
    O3904 + O3905 = 1;
    O4004 + O4005 = 1;
    O4103 + O4105 = 1;
    O4204 + O4205 = 1;
    O4301 + O4305 = 1;
    O4402 + O4404 = 1;
    O4502 + O4503 = 1;
    O4603 + O4605 = 1;
    O4704 + O4705 = 1;
    O4801 + O4803 = 1;
    O4902 + O4903 = 1;
    O5003 + O5005 = 1;
    O5101 + O5104 = 1;
    O5202 + O5203 = 1;
    O5303 + O5304 = 1;
    O5402 + O5403 = 1;
    O5502 + O5503 = 1;
    O5601 + O5603 = 1;
    O5703 + O5704 = 1;
    O5804 + O5805 = 1;
    O5903 + O5905 = 1;
    O6003 + O6004 = 1;
    O6104 + O6105 = 1;
    O6202 + O6204 = 1;
    O6304 + O6305 = 1;
    O6403 + O6405 = 1;
    O6503 + O6504 = 1;
    O6601 + O6603 = 1;
    O6703 + O6704 = 1;
    O6803 + O6805 = 1;
    O6904 + O6905 = 1;
    O7003 + O7004 = 1;
```

O0701 + O3301 + O4301 + O4801 + O5101 + O5601 + O6601 = 3;

O0202 + O0302 + O0402 + O0602 + O0802 + O0902 + O1202 + O1402 + O1602 + O1702 + O2002 + O2502 + O2602 + O2902 + O3602 + O4402 + O4502 + O4902 + O5202 + O5402 + O5502 + O6202 = 13;

O0203 + O0303 + O0503 + O0603 + O0703 + O0803 + O1003 + O1103 + O1203 + O1303 + O1403 + O1503 + O1703 + O1803 + O1903 + O2103 + O2203 + O2303 + O2503 + O2703 + O2803 + O3003 + O3103 + O3403 + O3703 + O3803 + O4103 + O4503 + O4603 + O4803 + O4903 + O5003 + O5203 + O5303 + O5403 + O5503 + O5603 + O5703 + O5903 + O6003 + O6403 + O6503 + O6603 + O6703 + O6803 + O7003 = 15;

O0104 + O0404 + O0504 + O0904 + O1104 + O1304 + O1504 + O1604 + O1804 + O1904 + O2004 + O2104 + O2204 + O2304 + O2404 + O2604 + O2704 + O2904 + O3004 + O3204 + O3304 + O3404 + O3504 + O3604 + O3804 + O3904 + O4004 + O4204 + O4404 + O4704 + O5104 + O5304 + O5704 + O5804 + O6004 + O6104 + O6204 + O6304 + O6504 + O6704 + O6904 + O7004 = 25;

O0105 + O1005 + O2405 + O2805 + O3105 + O3205 + O3505 + O3705 + O3905 + O4005 + O4105 + O4205 + O4305 + O4605 + O4705 + O5005 + O5805 + O5905 + O6105 + O6305 + O6405 + O6805 + O6905 = 14;
};

P5-P2-P1

Optimal Solution with Objective Value: 294

O0104 = 1	O1403 = 1	O2803 = 0
O0105 = 0	O1503 = 0	O2805 = 1
O0202 = 1	O1504 = 1	O2902 = 1
O0203 = 0	O1602 = 0	O2904 = 0
O0302 = 0	O1604 = 1	O3003 = 1
O0303 = 1	O1702 = 0	O3004 = 0
O0402 = 0	O1703 = 1	O3103 = 0
O0404 = 1	O1803 = 1	O3105 = 1
O0503 = 1	O1804 = 0	O3204 = 0
O0504 = 0	O1903 = 0	O3205 = 1
O0602 = 1	O1904 = 1	O3301 = 0
O0603 = 0	O2002 = 0	O3304 = 1
O0701 = 0	O2004 = 1	O3403 = 1
O0703 = 1	O2103 = 1	O3404 = 0
O0802 = 1	O2104 = 0	O3504 = 1
O0803 = 0	O2203 = 0	O3505 = 0
O0902 = 0	O2204 = 1	O3602 = 1
O0904 = 1	O2303 = 0	O3604 = 0
O1003 = 0	O2304 = 1	O3703 = 0
O1005 = 1	O2404 = 0	O3705 = 1
O1103 = 0	O2405 = 1	O3803 = 0
O1104 = 1	O2502 = 1	O3804 = 1
O1202 = 1	O2503 = 0	O3904 = 1
O1203 = 0	O2602 = 1	O3905 = 0
O1303 = 0	O2604 = 0	O4004 = 0
O1304 = 1	O2703 = 0	O4005 = 1
O1402 = 0	O2704 = 1	O4103 = 1

O4105 = 0
O4204 = 0
O4205 = 1
O4301 = 0
O4305 = 1
O4402 = 1
O4404 = 0
O4502 = 0
O4503 = 1
O4603 = 1
O4605 = 0
O4704 = 1
O4705 = 0
O4801 = 1
O4803 = 0
O4902 = 1
O4903 = 0
O5003 = 0
O5005 = 1
O5101 = 1
O5104 = 0
O5202 = 1
O5203 = 0
O5303 = 0
O5304 = 1
O5402 = 1
O5403 = 0
O5502 = 1
O5503 = 0
O5601 = 0
O5603 = 1
O5703 = 1
O5704 = 0
O5804 = 0
O5805 = 1
O5903 = 0
O5905 = 1
O6003 = 0
O6004 = 1
O6104 = 1
O6105 = 0
O6202 = 0
O6204 = 1
O6304 = 1
O6305 = 0
O6403 = 0
O6405 = 1
O6503 = 0
O6504 = 1
O6601 = 1
O6603 = 0
O6703 = 1
O6704 = 0
O6803 = 0
O6805 = 1
O6904 = 1
O6905 = 0
O7003 = 0
O7004 = 1
z = 294

APPENDIX G OPERATOR ASSIGNMENTS AND OPERATION TIMES

G1. Lot splitting not allowed and operator sharing not allowed – Problem 1

Operator assignment to product combinations

Product Comb.	Product	Operations 1	2	3	4	5
P3-P2	P3	11	36,29	30,3,14,18,7,28,34,37,5	20,38,1,24,35,13	39,40
	P2	27	2,12,26	6,8,19,21,25,17	23,33,4,9,15,16	10,22,32,31
P5-P2	P5	18	36,29,2,20	30,3,14,7	16,38,1,24,35,39,13	10,22,32,28
	P2	27	12,26,25	34,5,6,8,21,17	11,23,33,4,9,15	31,37,40,19
P6-P2	P6	18	20,12,26	30,3,14,7,28,34,37,5	16,32,38,35	31,39,40,13
	P2	27	36,29,2	6,8,19,21,25,17	11,23,33,4,9,15	10,22,1,24
P6-P1	P6	27	12,26,25	30,3,14,7,28,34,5,6	11,23,33,4	37,39,40,19
	P1	18	36,29,2,20	8,21,17	9,15,16,38,1,24,35,13	10,22,32,31
P7-P1	P7	18	12,26,6,25,8	28,34,5,21,17	27,32,38,24,35,13	10,1,31
	P1	7	36,29,2,20	30,3,14	11,23,33,4,9,15,16,22	37,39,40,19
P7-P4	P7	18	36,29,2,20,12	30,3,14,7,28	15,16,38,24,35,13	31,39,40
	P4	27	26,6,25,8	34,37,5,19,21,17	11,23,33,4,9	10,22,32,31
P7-P8	P7	18	20,12,26,6,25	30,3,14,7,28	22,32,38,24,35,13	39,40,19
	P8	27	36,29,2	34,37,5,8,21,17	11,23,33,4,9,15,16	10,1,31
P10-P8	P10	7	36,29,2	30,3,14,28,34,37	27,38,1,24,35,39,13	10,22,32
	P8	18	20,12,26	5,6,8,21,25,17	11,23,33,4,9,15,16	31,40,19
P10-P9	P10	18	36,29,2	5,6,8,21,25,17	16,38,1,24,35,39,13	10,22,32
	P9	27	20,12,26	30,3,14,7,28,34,37	11,23,33,4,9,15	31,40,19
P10-P4	P10	18	36,29,2	5,8,19,21,25,17	15,16,27,38,35,39,13	24,31,40
	P4	7	20,12,26,6	30,3,14,28,34,37	11,23,33,4,9	10,22,32,1

Revised Operation times

Std. Dev- 5%

Product Comb.	Product	Operations 1	2	3	4	5
P3-P2	P3	0.054	0.1228	0.1263	**0.1420**	0.0900
	P2	0.0525	0.0950	0.1093	**0.1139**	0.0887
P5-P2	P5	0.08	0.0918	0.0991	**0.1049**	0.1004
	P2	0.0525	0.0982	0.1084	**0.1105**	0.0961
P6-P2	P6	0.07	0.1048	**0.1423**	0.1323	0.1139
	P2	0.0525	0.0850	0.1093	**0.1105**	0.0899
P6-P1	P6	0.0735	0.1084	**0.1431**	0.1198	0.1139
	P1	0.0700	0.1008	**0.1315**	0.1078	0.0887
P7-P1	P7	0.09	0.0769	**0.0956**	0.0802	0.0819
	P1	0.0770	0.1008	**0.1108**	0.1000	0.0961
P7-P4	P7	**0.09**	0.0677	0.0861	0.0802	0.0867
	P4	0.0420	0.0813	**0.0954**	0.0832	0.0934
P7-P8	P7	**0.09**	0.0746	0.0861	0.0802	0.0881
	P8	0.0840	0.0820	0.0850	0.0787	**0.0913**
P10-P8	P10	0.077	0.1260	0.1167	0.1233	**0.1310**
	P8	0.0800	0.0917	0.0864	0.0787	**0.0982**
P10-P9	P10	0.07	0.1260	0.1305	0.1233	**0.1310**
	P9	0.0420	0.1114	0.1104	0.0926	**0.1152**

Std. Dev- 10%

Product Comb.	Product	Operations 1	2	3	4	5
P3-P2	**P3**	0.048	0.0994	0.1203	**0.1403**	0.0900
	P2	0.0550	0.0932	**0.1153**	0.1039	0.0817
P5-P2	**P5**	0.08	0.0798	0.0898	**0.1038**	0.0925
	P2	0.0550	0.0997	**0.1134**	0.0964	0.0972
P6-P2	**P6**	0.07	0.1029	**0.1357**	0.1269	0.1151
	P2	0.0550	0.0720	**0.1153**	0.0964	0.0837
P6-P1	**P6**	0.077	0.1100	**0.1371**	0.1008	0.1151
	P1	0.0700	0.0876	**0.1395**	0.1053	0.0817
P7-P1	**P7**	0.09	0.0795	**0.0989**	0.0785	0.0758
	P1	0.0840	0.0876	**0.0976**	0.0889	0.0972
P7-P4	**P7**	**0.09**	0.0603	0.0795	0.0785	0.0867
	P4	0.0440	0.0849	**0.0989**	0.0716	0.0860
P7-P8	**P7**	**0.09**	0.0751	0.0795	0.0785	0.0894
	P8	0.0880	0.0695	**0.0881**	0.0694	0.0846
P10-P8	**P10**	0.084	0.1068	0.1090	**0.1220**	0.1178
	P8	0.0800	0.0900	0.0911	0.0694	**0.0997**
P10-P9	**P10**	0.07	0.1068	**0.1376**	0.1220	0.1178
	P9	0.0440	0.1093	0.1040	0.0807	**0.1169**

Std. Dev- 15%

Product Comb.	Product	Operations 1	2	3	4	5
P3-P2	**P3**	0.042	0.0738	0.1127	**0.1382**	0.0900
	P2	0.0575	0.0913	**0.1212**	0.0931	0.0735
P5-P2	**P5**	0.08	0.0653	0.0793	**0.1025**	0.0832
	P2	0.0575	0.1011	**0.1182**	0.0798	0.0982
P6-P2	**P6**	0.07	0.1007	**0.1270**	0.1214	0.1163
	P2	0.0575	0.0568	**0.1212**	0.0798	0.0761
P6-P1	**P6**	0.0805	0.1115	**0.1288**	0.0794	0.1163
	P1	0.0700	0.0716	**0.1475**	0.1026	0.0735
P7-P1	**P7**	0.09	0.0821	**0.1020**	0.0766	0.0681
	P1	0.0910	0.0716	0.0836	0.0757	**0.0982**
P7-P4	**P7**	**0.09**	0.0508	0.0716	0.0766	0.0867
	P4	0.0460	0.0884	**0.1023**	0.0580	0.0774
P7-P8	**P7**	0.09	0.0753	0.0716	0.0766	**0.0906**
	P8	**0.0920**	0.0548	0.0911	0.0584	0.0760
P10-P8	**P10**	0.091	0.0842	0.0997	**0.1205**	0.1031
	P8	0.0800	0.0881	0.0958	0.0584	**0.1011**
P10-P9	**P10**	0.07	0.0842	**0.1446**	0.1205	0.1031
	P9	0.0460	0.1070	0.0962	0.0668	**0.1185**

Std. Dev- 20%

Product Comb.	Product	Operations 1	2	3	4	5
P3-P2	**P3**	0.036	0.0435	0.1026	**0.1358**	0.0900
	P2	0.0600	0.0892	**0.1270**	0.0807	0.0633
P5-P2	**P5**	0.08	0.0447	0.0670	**0.1009**	0.0717
	P2	0.0600	0.1024	**0.1228**	0.0573	0.0991
P6-P2	**P6**	0.07	0.0985	0.1151	0.1158	**0.1174**
	P2	0.0600	0.0366	**0.1270**	0.0573	0.0661
P6-P1	**P6**	0.084	0.1129	0.1170	0.0528	**0.1174**
	P1	0.0700	0.0491	**0.1554**	0.0996	0.0633
P7-P1	**P7**	0.09	0.0845	**0.1050**	0.0744	0.0578
	P1	0.0980	0.0491	0.0683	0.0571	**0.0991**
P7-P4	**P7**	**0.09**	0.0364	0.0620	0.0744	0.0867
	P4	0.0480	0.0917	**0.1055**	0.0403	0.0667
P7-P8	**P7**	0.09	0.0753	0.0620	0.0744	**0.0918**
	P8	**0.0960**	0.0354	0.0940	0.0431	0.0644
P10-P8	**P10**	0.098	0.0543	0.0879	**0.1186**	0.0860
	P8	0.0800	0.0862	0.1004	0.0431	**0.1024**
P10-P9	**P10**	0.07	0.0543	**0.1516**	0.1186	0.0860
	P9	0.0480	0.1046	0.0860	0.0480	**0.1200**
P10-P4	**P10**	0.07	0.0543	**0.1516**	0.1111	0.1433
	P4	0.0560	**0.0759**	0.0653	0.0403	0.0667

G2. Lot splitting not allowed and operator sharing not allowed (3 skills) –

Problem 1

Operator assignment and operation times to product combinations

Product Comb.	Product	Operations				
		1	2	3	4	5
P3-P2	P3	16	36,38	1,27,33,30,3,24,18,40,7	15,20,32,26,35,39	31,13
	Op. time	0.024	0.0580	0.0760	**0.1317**	0.0963
	P2	25	29,2,12	34,37,5,19,21,17	11,14,6,23,4,9	10,8,22,28
	Op. time	0.0425	0.0804	**0.1153**	0.0673	0.0735
P5-P2	P5	16	36,38,29,2	1,27,33,30	15,18,20,32,26,35,13	10,8,22,28
	Op. time	0.032	0.0539	0.0461	**0.0977**	0.0832
	P2	34	12,25,17	3,24,40,7,5,21	11,14,6,23,4,9	31,37,39,19
	Op. time	0.0425	**0.1133**	0.0915	0.0673	0.0982
P6-P2	P6	16	2,12,26	1,27,33,30,3,24,18,40	15,20,32,35	31,39,13,19
	Op. time	0.028	0.1007	0.0812	**0.1214**	0.1203
	P2	25	36,38,29	7,34,37,5,21,17	11,14,6,23,4,9	10,8,22,28
	Op. time	0.0425	0.0451	**0.1126**	0.0673	0.0735
P6-P1	P6	25	2,12,26	1,27,33,30,3,24,40,7	14,6,23,4	31,37,39,19
	Op. time	0.0595	0.1007	0.0822	0.0752	**0.1163**
	P1	16	11,36,38,29	5,21,17	9,15,18,20,32,35,13,34	10,8,22,28
	Op. time	0.0280	0.0504	**0.1475**	0.1021	0.0735
P7-P1	P7	16	12,26,25,31,17	3,24,40,7,21	20,22,32,35,39,13	10,30,8
	Op. time	0.036	**0.0835**	0.0779	0.0766	0.0588
	P1	34	36,38,29,2	1,27,33	11,14,6,23,4,9,15,18	28,37,19,5
	Op. time	0.0595	0.0592	0.0493	0.0660	**0.1044**
P7-P4	P7	16	11,36,38,29,2	1,27,33,30,3	15,18,32,35,39,13	31,37,19
	Op. time	0.036	0.0366	0.0428	0.0766	**0.0906**
	P4	34	20,12,26,25	24,40,7,5,21,17	14,6,23,4,9	10,8,22,28
	Op. time	0.0340	0.0766	**0.0900**	0.0554	0.0774
P7-P8	P7	16	29,2,20,12,25	1,27,33,30,3	22,32,26,35,39,13	31,37,17
	Op. time	0.036	0.0655	0.0428	0.0787	**0.0906**
	P8	34	11,36,38	24,40,7,5,21,17	14,6,23,4,9,15,18	10,8,28
	Op. time	0.0680	0.0373	**0.0802**	0.0563	0.0726
P10-P8	P10	25	11,36,38	1,27,33,30,3,24	20,22,32,26,35,39,13	10,8,28
	Op. time	0.0595	0.0573	0.0608	**0.1176**	0.1076
	P8	16	29,2,12	40,7,34,5,21,17	14,6,23,4,9,15,18	31,37,19
	Op. time	0.0320	0.0777	0.0862	0.0563	**0.1011**
P10-P9	P10	16	11,36,38	7,34,5,19,21,17	18,20,32,26,35,39,13	10,8,22
	Op. time	0.028	0.0573	**0.1376**	0.1176	0.1031
	P9	25	29,2,12	1,27,33,30,3,24,40	14,6,23,4,9,15	28,31,37
	Op. time	0.0340	0.0943	0.0607	0.0641	**0.1133**
P10-P4	P10	16	11,36,38	40,7,34,5,21,17	15,18,20,22,32,35,13	37,39,19
	Op. time	0.028	0.0573	0.1302	0.1122	**0.1498**
	P4	25	29,2,12,26	1,27,33,30,3,24	14,6,23,4,9	10,8,28,31
	Op. time	0.0340	0.0673	0.0452	0.0554	**0.0801**

G3. Lot splitting allowed (sequence 1) and operator sharing not allowed – Problem 1

Operator assignment and operation times to product combinations

Product Comb.	Product	Operations				
		1	2	3	4	5
P3-P2	P3	11	36,29	30,3,14,18,7,28,34,37,5	20,38,1,24,35,13	39,40
	Op. time	0.042	0.0738	0.1127	**0.1382**	0.0900
	P2	27	2,12,26	6,8,19,21,25,17	23,33,4,9,15,16	10,22,32,31
	Op. time	0.0575	0.0913	**0.1212**	0.0931	0.0735
P3-P1	P3	7	36,29	28,34,37,5,6,8,21,25,17	11,23,33,4,9,15	40,19
	Op. time	0.078	0.0738	**0.1454**	0.0927	0.0963
	P1	18	2,20,12,26	30,3,14	16,27,38,1,24,35,39,13	10,22,32,31
	Op. time	0.0700	0.1034	0.0934	**0.1048**	0.0735
P5-P1	P5	18	36,29,2,20	30,3,14,34	11,23,33,4,9,15,16	10,1,28,31
	Op. time	0.08	0.0653	0.0793	0.0708	**0.0892**
	P1	7	12,6,25,8	5,21,17	22,27,32,38,24,26,35,13	37,39,40,19
	Op. time	0.0910	0.1283	**0.1475**	0.1026	0.0982
P5-P4	P5	18	36,29,2,20	30,3,14,7	11,23,33,4,9,15,16	10,22,32,31
	Op. time	0.08	0.0653	0.0793	0.0708	**0.0832**
	P4	27	12,26,6,25	28,34,5,8,21,17	38,1,24,35,13	37,39,40,19
	Op. time	0.0460	0.0829	0.1023	0.0931	**0.1034**
P6-P4	P6	18	12,26,25	30,3,14,7,15,28,34,37	16,38,35,13	24,31,39,40
	Op. time	0.07	0.1115	0.1252	**0.1303**	0.1125
	P4	27	36,29,2,20	5,6,8,19,21,17	11,23,33,4,9	10,22,32,1
	Op. time	0.0460	0.0494	**0.1075**	0.0580	0.0774
P6-P7	P6	27	12,26,25	34,37,5,6,8,19,21,17	11,23,33,4	1,31,39,40
	Op. time	0.0805	0.1115	**0.1658**	0.0794	0.1125
	P7	18	36,29,2,20,9	30,3,14,7,28	15,16,38,24,35,13	10,22,32
	Op. time	**0.0900**	0.0508	0.0716	0.0766	0.0623
P6-P8	P6	27	20,12,26	30,3,14,7,28,34,37,5	11,23,33,4	1,31,39,40
	Op. time	0.0805	0.1007	**0.1270**	0.0794	0.1125
	P8	18	36,29,2	6,8,19,21,25,17	9,15,16,38,24,35,13	10,22,32
	Op. time	0.0800	0.0548	**0.0958**	0.0805	0.0695
P2-P8	P2	27	20,12,26	5,6,8,21,25,17	38,1,24,35,39,13	31,37,40,19
	Op. time	0.0575	0.0913	0.1212	**0.1224**	0.0982
	P8	18	36,29,2	30,3,14,7,28,34	11,23,33,4,9,15,16	10,22,32
	Op. time	**0.0800**	0.0548	0.0675	0.0584	0.0693
P2-P9	P2	18	20,12,26	5,6,8,21,25,17	11,23,33,4,9,15	31,39,40,19
	Op. time	0.05	0.0913	**0.1212**	0.0798	0.0982
	P9	27	36,29,2	30,3,14,7,28,34,37	16,38,1,24,35,13	10,22,32
	Op. time	0.0460	0.0666	0.0962	**0.0996**	0.0815
P2-P10	P2	27	20,12,26	5,6,8,21,25,17	11,23,33,4,9,15	31,37,40,19
	Op. time	0.0575	0.0913	**0.1212**	0.0798	0.0982
	P10	18	36,29,2	30,3,14,7,28,34	16,38,1,24,35,39,13	10,22,32
	Op. time	0.0700	0.0842	0.0997	**0.1205**	0.1031

G4. Lot splitting allowed (sequence 2) and operator sharing not allowed – Problem 1

Operator assignment and operation times to product combinations

Product Comb.	Product	Operations				
		1	2	3	4	5
P3-P1	P3	7	36,29	28,34,37,5,6,8,21,25,17	11,23,33,4,9,15	40,19
	Op. time	0.078	0.0738	**0.1454**	0.0927	0.0963
	P1	18	2,20,12,26	30,3,14	16,27,38,1,24,35,39,13	10,22,32,31
	Op. time	0.0700	0.1034	0.0934	**0.1048**	0.0735
P3-P4	P3	18	36,29	34,37,5,6,8,19,21,25,17	11,23,33,4,9,16	39,40
	Op. time	0.06	0.0738	**0.1477**	0.0927	0.0900
	P4	27	2,20,12,26	30,3,14,7,15,28	38,1,24,35,13	10,22,32,31
	Op. time	0.0460	0.0712	0.0741	**0.0931**	0.0774
P5-P4	P5	18	36,29,2,20	30,3,14,7	11,23,33,4,9,15,16	10,22,32,31
	Op. time	0.08	0.0653	0.0793	0.0708	**0.0832**
	P4	27	12,26,6,25	28,34,5,8,21,17	38,1,24,35,13	37,39,40,19
	Op. time	0.0460	0.0829	0.1023	0.0931	**0.1034**
P5-P7	P5	27	36,29,2,20	30,3,14,7	11,23,33,4,9,15,16	10,1,31,37
	Op. time	**0.092**	0.0653	0.0793	0.0708	0.0892
	P7	18	12,26,6,25,8	28,34,5,21,17	22,32,38,24,35,13	39,40,19
	Op. time	0.0900	0.0821	**0.1020**	0.0759	0.0906
P6-P7	P6	27	12,26,25	34,37,5,6,8,19,21,17	11,23,33,4	1,31,39,40
	Op. time	0.0805	0.1115	**0.1658**	0.0794	0.1125
	P7	18	36,29,2,20,9	30,3,14,7,28	15,16,38,24,35,13	10,22,32
	Op. time	**0.0900**	0.0508	0.0716	0.0766	0.0623
P6-P8	P6	27	20,12,26	30,3,14,7,28,34,37,5	11,23,33,4	1,31,39,40
	Op. time	0.0805	0.1007	**0.1270**	0.0794	0.1125
	P8	18	36,29,2	6,8,19,21,25,17	9,15,16,38,24,35,13	10,22,32
	Op. time	0.0800	0.0548	**0.0958**	0.0805	0.0695
P2-P8	P2	27	20,12,26	5,6,8,21,25,17	38,1,24,35,39,13	31,37,40,19
	Op. time	0.0575	0.0913	0.1212	**0.1224**	0.0982
	P8	18	36,29,2	30,3,14,7,28,34	11,23,33,4,9,15,16	10,22,32
	Op. time	**0.0800**	0.0548	0.0675	0.0584	0.0693
P2-P2	P2	18	36,29,2	30,3,14,7,28,34	11,23,33,4,9,15	10,22,32,31
	Op. time	0.05	0.0568	**0.0835**	0.0798	0.0735
	P2	27	20,12,26	5,6,8,21,25,17	16,38,1,24,35,13	37,39,40,19
	Op. time	0.0575	0.0913	**0.1212**	0.1189	0.0982
P2-P9	P2	18	20,12,26	5,6,8,21,25,17	11,23,33,4,9,15	31,39,40,19
	Op. time	0.05	0.0913	**0.1212**	0.0798	0.0982
	P9	27	36,29,2	30,3,14,7,28,34,37	16,38,1,24,35,13	10,22,32
	Op. time	0.0460	0.0666	0.0962	**0.0996**	0.0815
P2-P10	P2	27	20,12,26	5,6,8,21,25,17	11,23,33,4,9,15	31,37,40,19
	Op. time	0.0575	0.0913	**0.1212**	0.0798	0.0982
	P10	18	36,29,2	30,3,14,7,28,34	16,38,1,24,35,39,13	10,22,32
	Op. time	0.0700	0.0842	0.0997	**0.1205**	0.1031
P6-P2	P6	18	20,12,26	30,3,14,7,28,34,37,5	16,38,35,13	24,31,39,40
	Op. time	0.07	0.1007	0.1270	**0.1303**	0.1125
	P2	27	36,29,2	6,8,19,21,25,17	11,23,33,4,9,15	10,22,32,1
	Op. time	0.0575	0.0568	**0.1212**	0.0798	0.0735

G5. Lot splitting not allowed and operator sharing allowed – Problem 1

Operator assignment and operation times to product combinations

Product Comb.	Product	Operations 1	2	3	4	5
P2-P1	**P2**	**7(.01),18(.35)**	29,2,**20(.09)**	30,3,**7(.47)**,34,5	**20(.61)**,32,1,**24(.73)**, 26,35	**31(.74)**,13,19
	Op. time	0.0035	0.0266	0.0957	0.1112	**0.1346**
	P1	**18(.65)**	**20(.11)**,12,14,6, 25,**8(.08)**	**7(.52)**,**8(.92)**,21,17	11,23,33,4,9,15,16, **20(.19)**,27	10,22,**24(.27)**, 28,**31(.26)**
	Op. time	0.0700	0.0268	**0.0955**	0.0543	0.0466
P2-P3	**P2**	**18(.36)**	29,**2(.09)**,20	19,21,25,17,**2(.47)**	16,27,32,1,**24(.17)**, **26(.17)**,35	**24(.14)**,31,13,**22(.60)**
	Op. time	0.0500	0.0266	**0.1260**	0.0561	0.0506
	P3	**18(.47)**	12,**26(.83)**,**2(.43)**	30,3,14,**18(.17)**, **2(.01)**,7,28,34,5,6,8	11,23,33,4,9,15, **24(.69)**	10,**22(.40)**
	Op. time	0.0600	0.0779	0.0121	**0.0839**	0.0540
P2-P6	**P2**	**11(.36)**	20,12,**26(.09)**	19,21,25,17,**18(.47)**	15,16,27,**1(.76)**, **26(.42)**,35,**11(.16)**	31,13,**24(.74)**
	Op. time	0.0035	0.0313	0.1179	0.0407	**0.1292**
	P6	**11(.20)**,**18(.35)**	29,2,**26(.49)**	30,3,14,**18(.18)**,7, 28,34,5,6,8	**11(.28)**,23,33,4,9	10,22,32,**1(.24)**, **24(.26)**
	Op. time	0.0255	**0.0830**	0.0776	0.0442	0.0528
P4-P7	**P4**	**27(.34)**	6,25,**26(.63)**	30,3,14,7,**28(.17)**, **34(.49)**	11,23,33,**4(.94)**, **27(.04)**	**28(.83)**,31,13,**32(.56)**
	Op. time	0.0460	**0.1063**	0.0531	0.0162	0.0912
	P7	18,**27(.08)**	29,2,20,**4(.06)**,12, **26(.37)**	5,8,19,21,17,**34(.51)**	9,15,16,**27(.54)**, **32(.33)**,1,35	10,22,**32(.11)**,24
	Op. time	0.0126	0.0207	**0.0807**	0.0518	0.0228
P5-P7	**P5**	**7(.40)**,**27(.17)**	6,25,**26(.94)**	8,21,17,**7(.09)**	16,**27(.51)**,32,1, **24(.80)**,35	31,13,19,**24(.09)**
	Op. time	0.0399	**0.1493**	0.0409	0.1057	0.0402
	P7	**27(.08)**,18	29,2,20,**4(.37)**, 12,**26(.06)**	30,3,14,**7(.51)**,34,5	11,23,33,**4(.63)**,9, 15,**27(.24)**	10,22,**24(.11)**,28
	Op. time	0.0140	0.0207	**0.0607**	0.0393	0.0256
P10-P8	**P10**	**18(.41)**	6,25,**20(.54)**	5,8,**19(.37)**,21,17	32,1,**24(.14)**,26, 35,16	31,13,**19(.03)**,**24(.51)**
	Op. time	0.0700	0.1296	**0.1478**	0.0813	0.0206
	P8	**18(.59)**,**27(.32)**	29,2,**20(.20)**,12	30,3,14,7,34,**19(.60)**	11,23,33,4,9,15, **20(.26)**,**27(.68)**,**24(.04**	10,22,**24(.31)**,28
	Op. time	0.0398	0.0369	**0.0667**	0.0194	0.0485
P10-P9	**P10**	**18(.41)**	12,**26(.23)**,6,**25(.31)**	8,19,21,**25(.37)**,17	15,16,27,**32(.14)**, 1,35	31,13,**32(.54)**
	Op. time	0.0700	0.0751	0.1478	0.0729	**0.1667**
	P9	**18(.37)**	29,2,20,**26(.16)**	30,3,14,**18(.22)**,7, 28,34,5,**25(.32)**	11,23,33,4,9, **26(.61)**,**32(.16)**	10,22,**32(.16)**,24
	Op. time	0.0400	0.0429	**0.0591**	0.0440	0.0379
P2-P7	**P2**	**18(.36)**	29,2,**26(.09)**	30,3,14,7,**19(.47)**	15,16,32,1,**24(.17)**, **26(.17)**,35	31,13,**19(.02)**,**24(.72)**
	Op. time	0.0500	0.0303	**0.0953**	0.0561	0.0119
	P7	**27(.44)**,**18(.64)**	20,12,**26(.43)**,6,25	34,5,8,**19(.51)**,21,17	11,23,33,4,9,**27(.56)**, **26(.31)**	10,22,**24(.11)**,28
	Op. time	0.0471	0.0669	**0.0823**	0.0435	0.0256
P5-P8	**P5**	**18(.57)**	6,25,**12(.80)**,**26(.14)**	8,21,17,**7(.09)**	32,1,**24(.60)**,**26(.86)**, **16(.85)**,35	31,13,19,**24(.09)**
	Op. time	0.0800	0.0551	0.0409	**0.1131**	0.0398
	P8	**27(.17)**,**7(.31)**, **18(.43)**	29,2,20,**12(.20)**	30,3,14,34,5,**7(.60)**	11,23,33,4,9,15, **16(.15)**,**27(.83)**	10,22,28,**24(.31)**
	Op. time	0.0266	0.0399	**0.0660**	0.0377	0.0485
P5-P9	**P5**	**18(.57)**	6,25,**12(.84)**,**26(.10)**	19,21,17,**28(.09)**	15,16,27,1,35, **32(.18)**,**26(.13)**	24,31,13,**28(.09)**
	Op. time	**0.0800**	0.0431	0.0409	0.0494	0.0398
	P9	**18(.37)**	29,2,20,**12(.16)**	30,3,14,**18(.06)**,7, 5,8,**28(.48)**	11,23,33,4,9, **26(.77)**	10,22,**32(.82)**,**28(.34)**
	Op. time	0.0400	0.0429	0.0324	**0.0686**	0.0584

G6. Lot splitting allowed and operator sharing allowed – Problem 1

Operator assignment and operation times to product combinations

Product Comb.	Product	Operations				
		1	2	3	4	5
P3-P3	**P3**	**11(.35)**	29,**12(.69)**	30,3,14,18,**23(.02)**, 2,7,**15(.87)**	**11(.04)**,**23(.98)**,33, 4,9,16	10,**13(.05)**
	Op. time	0.0420	**0.1193**	0.0203	0.0148	0.0178
	P3	**11(.47)**	20,**12(.26)**,26	28,34,5,6,8,19,21, 25,**12(.05)**,17,**15(.13)**	22,27,32,1,24,35, **13(.55)**,**11(.14)**	31,**13(.40)**
	Op. time	0.0420	0.0639	0.0454	0.0396	**0.0810**
P3-P2	**P3**	**18(.35)**	12,**26(.48)**,**20(.21)**	30,3,14,**18(.17)**,7, **28(.68)**,34,5,**6(.04)**	11,23,33,4,9,**24(.02)**	10,**24(.05)**
	Op. time	**0.0600**	0.0593	0.0412	0.0177	0.0157
	P2	**18(.48)**	29,2,**20(.79)**	8,19,21,25,17, **6(.96)**	15,16,27,32,1, **24(.60)**,**26(.52)**,35	22,**24(.33)**,**28(.32)**, 31,13
	Op. time	0.0500	0.0762	**0.1211**	0.0808	0.0566
P1-P2	**P1**	**18(.49)**	12,**14(.14)**,6,25	21,17,**8(.58)**	11,23,33,4,9,15, **20(.14)**	10,22,**24(.30)**, **28(.35)**
	Op. time	0.0700	0.0580	**0.1371**	0.0567	0.0624
	P2	**18(.48)**	29,2,**20(.44)**,**14(.35)**	30,3,**14(.51)**,**18(.03)**, 7,34,5,**8(.42)**	16,**20(.42)**,27,32,1, **24(.70)**,26,35	31,13,19,**28(.65)**
	Op. time	0.0500	0.0511	0.0167	0.0773	**0.0974**
P4-P2	**P4**	**18(.34)**	6,25,**12(.63)**	30,3,14,**18(.18)**,7, **28(.44)**,**34(.04)**	11,23,33,**4(.98)**	10,22,32,**1(.39)**
	Op. time	0.0400	**0.1063**	0.0211	0.0680	0.0701
	P2	**18(.48)**	29,2,**20(.42)**, **12(.37)**	5,8,19,21,17, **34(.96)**	9,15,16,**20(.58)**,27, **1(.52)**,26,35,**4(.02)**	24,**28(.56)**,31,13, **1(.09)**
	Op. time	0.0500	0.0513	**0.1180**	0.0135	0.0330
P4-P5	**P4**	**7(.11)**,**18(.23)**	29,2,**20(.63)**	30,3,**14(.89)**,**7(.77)**, 34	11,23,33,**32(.50)**, **26(.48)**	10,22,**32(.39)**,24
	Op. time	0.0207	0.0791	**0.0859**	0.0580	0.0673
	P5	**18(.77)**	12,**14(.11)**,**26(.44)**, 6,25,**20(.37)**	5,8,21,17,**7(.12)**	4,9,15,16,27,1, **26(.08)**,35	28,31,13,19, **32(.11)**
	Op. time	**0.0800**	0.0363	0.0446	0.0408	0.0362
P8-P5	**P8**	**18(.68)**	29,2,**20(.40)**	30,3,**14(.77)**,**7(.43)**, 34	11,23,33,4,9, **24(.23)**	10,22,**24(.49)**
	Op. time	**0.0800**	0.0631	0.0720	0.0562	0.0694
	P5	**7(.45)**,**18(.32)**	12,**14(.23)**,**26(.09)**, 6,25,**20(.60)**	5,8,21,17,**7(.12)**	15,16,27,32,1, **24(.17)**,**26(.91)**,35	28,31,13,19,**24(.11)**
	Op. time	0.0430	0.0311	0.0446	**0.0611**	0.0408
P8-P6	**P8**	**18(.68)**	20,12,**26(.40)**	19,21,25,17,**15(.20)**	9,**15(.34)**,16,**27(.77)**, **32(.01)**,1,**26(.11)**,35	31,13,**32(.49)**
	Op. time	0.0800	0.0748	0.0696	0.0069	**0.0818**
	P6	**27(.23)**,**18(.32)**	29,2,**26(.49)**	30,3,14,7,**15(.18)**, 28,34,5,6,8	11,23,33,4,**15(.28)**	10,22,**32(.50)**,24
	Op. time	0.0369	**0.0830**	0.0825	0.0578	0.0810
P9-P6	**P9**	**11(.28)**	20,12,**26(.37)**	8,19,21,25,17, **18(.65)**	16,27,**32(.13)**,1, **26(.14)**,35,**11(.06)**	31,13,**32(.37)**
	Op. time	0.0280	0.0882	**0.1420**	0.0161	0.0852
	P6	**18(.17)**,**11(.38)**	29,2,**26(.49)**	30,3,14,**18(.18)**,7,15, 28,34,5,6	**11(.28)**,23,33,4,9	10,22,**32(.50)**,24
	Op. time	0.0264	**0.0830**	0.0770	0.0442	0.0810
P10-P7	**P10**	**18(.41)**	6,25,**26(.54)**	5,8,**19(.37)**,21,17	15,16,32,1,**24(.11)**, **26(.03)**,35	31,13,**19(.12)**,**24(.42)**
	Op. time	0.0700	0.1414	**0.1478**	0.0247	0.0589
	P7	**27(.49)**,**18(.59)**	29,2,20,12,**26(.43)**	30,3,14,7,34, **19(.51)**	11,23,33,4,9, **27(.51)**,**24(.36)**	10,22,**24(.11)**,28
	Op. time	0.0480	0.0588	**0.0616**	0.0443	0.0256
P9-P7	**P9**	**18(.28)**	6,**25(.41)**,**26(.96)**	34,5,8,19,21, **25(.16)**,**17(.49)**	15,16,1,35, **32(.29)**,**26(.04)**	31,13,**32(.37)**
	Op. time	0.0400	**0.1067**	0.0874	0.0257	0.0852
	P7	**27(.36)**,**18(.72)**	29,2,20,12,**25(.43)**	30,3,14,7,34, **17(.51)**	11,23,33,4,9, **27(.64)**,**32(.23)**	10,22,24,**32(.11)**
	Op. time	0.0438	0.0614	**0.0632**	0.0388	0.0228

G7. Operation times to product combinations (random assignment) – Problem 2 (Max)

Product Comb.	Product	Operations				
		1	2	3	4	5
P5-P2-P1	P5	0.068	**0.1075**	0.0961	0.0815	0.0892
	P2	0.0275	0.0500	**0.0769**	0.0753	0.0555
	P1	0.0595	**0.0915**	0.0632	0.0706	0.0616
P7-P2-P1	P7	0.0765	0.0741	**0.0877**	0.0620	0.0681
	P2	0.0275	0.0500	0.0732	**0.0753**	0.0569
	P1	0.0595	**0.0915**	0.0632	0.0706	0.0599
P7-P4-P1	P7	0.0765	0.0741	**0.0877**	0.0620	0.0681
	P4	0.0220	0.0535	0.0570	**0.0629**	0.0521
	P1	0.0595	**0.0915**	0.0632	0.0697	0.0599
P7-P4-P3	P7	0.0765	0.0727	**0.0913**	0.0597	0.0681
	P4	0.0220	0.0535	**0.0621**	0.0618	0.0498
	P3	0.0510	**0.0952**	0.0854	0.0822	0.0639
P7-P6-P3	P7	0.0765	0.0727	**0.0913**	0.0597	0.0681
	P6	0.0385	0.0649	**0.0961**	0.0833	0.0640
	P3	0.0510	**0.0995**	0.0890	0.0822	0.0639
P7-P6-P8	P7	0.0900	0.0727	**0.0913**	0.0597	0.0681
	P6	0.0595	0.0649	**0.0947**	0.0833	0.0869
	P8	0.0267	**0.0715**	0.0532	0.0583	0.0447
P11-P6-P3	P11	0.0850	0.0913	**0.1172**	0.0723	0.0674
	P6	0.0385	0.0888	**0.0967**	0.0951	0.0640
	P3	0.0510	0.0320	**0.0899**	0.0822	0.0639
P11-P13-P3	P11	0.0850	0.0865	**0.1110**	0.0780	0.0674
	P13	0.0275	0.0690	**0.1074**	0.0872	0.0701
	P3	0.0510	**0.0952**	0.0808	0.0822	0.0639
P11-P13-P8	P11	0.1000	0.0952	**0.1128**	0.0780	0.0674
	P13	0.0425	0.0709	0.1016	0.0872	**0.1070**
	P8	0.0267	**0.0715**	0.0532	0.0583	0.0447
P11-P13-P9	P11	0.0850	0.0865	**0.1128**	0.0810	0.0674
	P13	0.0275	0.1031	**0.1033**	0.0858	0.0727
	P9	0.0340	0.0628	**0.0712**	0.0668	0.0657
P19-P13-P8	P19	0.0900	**0.1047**	0.0998	0.0666	0.0717
	P13	0.0425	0.0690	0.0999	0.0855	**0.1133**
	P8	0.0267	**0.0715**	0.0532	0.0583	0.0447
P19-P13-P9	P19	0.0765	**0.1047**	0.0982	0.0666	0.0717
	P13	0.0275	0.0690	**0.1039**	0.0831	0.0756
	P9	0.0340	**0.1047**	0.0712	0.0668	0.0657
P19-P14-P9	P19	0.0765	**0.1047**	0.0982	0.0666	0.0717
	P14	0.0440	0.0791	0.1076	**0.1089**	0.0778
	P9	0.0340	**0.0868**	0.0712	0.0668	0.0657
P19-P14-P10	P19	0.0765	**0.1047**	0.0998	0.0666	0.0717
	P14	0.0440	0.0791	0.1049	**0.1117**	0.0748
	P10	0.0595	**0.1098**	0.0804	0.0759	0.0832
P19-P15-P10	P19	0.0765	0.0971	**0.0998**	0.0928	0.0739
	P15	0.0330	0.0707	**0.1026**	0.0962	0.0758
	P10	0.0595	**0.1098**	0.0804	0.0748	0.0832
P25-P14-P10	P25	0.0340	0.1445	**0.1570**	0.1258	0.1029
	P14	0.0440	0.0813	0.1049	**0.1138**	0.0748
	P10	0.0595	**0.1098**	0.0804	0.0759	0.0832
P25-P15-P10	P25	0.0340	0.1445	**0.1570**	0.1258	0.1029
	P15	0.0330	0.0707	**0.1007**	0.0962	0.0758
	P10	0.0595	**0.1098**	0.0804	0.0759	0.0832
P25-P15-P12	P25	0.0340	0.1445	**0.1570**	0.1258	0.1029
	P15	0.0330	0.0723	**0.1007**	0.0979	0.0735
	P12	0.1020	**0.1215**	0.0886	0.1035	0.0651
P25-P18-P12	P25	0.0340	0.1445	**0.1570**	0.1297	0.1029
	P18	0.0220	0.0835	**0.1055**	0.0987	0.0727
	P12	0.1020	0.0791	0.0913	**0.1046**	0.0651

Product Comb.	Product	Operations				
		1	2	3	4	5
P25-P18-P16	P25	0.0340	0.1445	0.1545	0.1170	0.1029
	P18	0.0220	0.0952	0.1129	0.1010	0.0727
	P16	0.0401	0.0586	0.0555	**0.0593**	0.0522
P25-P18-P17	P25	0.0340	0.1445	**0.1545**	0.1170	0.1029
	P18	0.0340	0.0952	**0.1049**	0.0987	0.0756
	P17	**0.0680**	0.0530	0.0666	0.0493	0.0576
P26-P15-P12	P26	0.0680	**0.1417**	0.1409	0.1024	0.1021
	P15	0.0330	0.0707	**0.1026**	0.0925	0.0735
	P12	0.1020	**0.1215**	0.0886	0.1046	0.0651
P26-P15-P16	P26	0.0800	**0.1417**	0.1409	0.1063	0.1021
	P15	0.0510	0.1013	0.0975	0.0944	**0.1030**
	P16	0.0401	0.0586	0.0555	**0.0593**	0.0416
P26-P15-P17	P26	0.0680	**0.1417**	0.1409	0.1024	0.1021
	P15	0.0330	0.1013	**0.1026**	0.0944	0.0735
	P17	**0.0680**	0.0336	0.0530	0.0493	0.0576
P26-P18-P17	P26	0.0680	0.1332	**0.1464**	0.1024	0.1021
	P18	0.0220	0.0952	**0.1100**	0.0987	0.0701
	P17	**0.0680**	0.0541	0.0666	0.0493	0.0576
P26-P18-P21	P26	0.0680	**0.1417**	0.1409	0.1063	0.1021
	P18	0.0220	0.0835	**0.1016**	0.0987	0.0727
	P21	0.0595	0.0686	0.0760	**0.0794**	0.0677
P26-P20-P21	P26	0.0680	**0.1417**	0.1409	0.1024	0.1021
	P20	0.0440	0.0694	0.0723	**0.0740**	0.0449
	P21	0.0595	0.0686	0.0760	**0.0794**	0.0677
P26-P22-P21	P26	0.0680	**0.1417**	0.1409	0.1024	0.1021
	P22	0.0605	0.0939	**0.0999**	0.0823	0.0691
	P21	0.0595	0.0631	0.0760	**0.0803**	0.0677
P26-P22-P23	P26	0.0680	**0.1417**	0.1409	0.0931	0.1021
	P22	0.0605	**0.0939**	0.0899	0.0897	0.0910
	P23	0.0680	0.0519	**0.0822**	0.0728	0.0561
P26-P24-P23	P26	0.0800	0.1417	**0.1441**	0.0931	0.1021
	P24	0.0301	0.0489	0.0619	0.0520	**0.0661**
	P23	0.0680	0.0792	**0.0799**	0.0728	0.0574
P29-P24-P30	P29	0.0600	0.1563	**0.1564**	0.1248	0.0917
	P24	0.0301	0.0489	0.0609	0.0536	**0.0661**
	P30	0.0765	**0.0945**	0.0797	0.0820	0.0587
P27-P24-P30	P27	0.0600	**0.1314**	0.1111	0.0910	0.0913
	P24	0.0301	0.0489	0.0609	0.0470	**0.0661**
	P30	0.0765	**0.0945**	0.0797	0.0808	0.0600
P27-P28-P30	P27	0.0510	**0.1215**	0.1160	0.0910	0.0913
	P28	0.0220	0.0489	**0.0650**	0.0535	0.0623
	P30	0.0765	**0.0945**	0.0797	0.0808	0.0587
P29-P24-P23	P29	0.0600	0.1445	**0.1534**	0.1201	0.0917
	P24	0.0301	0.0489	0.0661	0.0520	**0.0700**
	P23	0.0680	**0.0792**	0.0782	0.0728	0.0561
P29-P28-P30	P29	0.0510	0.1445	**0.1661**	0.1201	0.0917
	P28	0.0220	0.0489	**0.0670**	0.0607	0.0473
	P30	0.0765	**0.0945**	0.0797	0.0808	0.0709
P29-P27-P30	P29	0.0510	0.1445	**0.1534**	0.1311	0.0917
	P27	0.0510	0.0827	0.0877	0.0740	**0.0880**
	P30	0.0765	0.0667	0.0780	**0.0820**	0.0587

G8. Operation times to product combinations (acc. to bottleneck ratio) – Problem 2 (Max)

Product Comb.	Product	Operations				
		1	2	3	4	5
P5-P2-P1	P5	0.068	**0.1060**	0.0599	0.0899	0.0588
	P2	0.0425	**0.0859**	0.0732	0.0560	0.0687
	P1	0.0385	0.0640	0.0786	**0.0887**	0.0760
P7-P2-P1	P7	0.0495	0.0760	0.0551	**0.0854**	0.0561
	P2	0.0425	0.0859	**0.0953**	0.0560	0.0666
	P1	0.0595	0.0624	**0.0786**	0.0783	0.0760
P7-P4-P1	P7	0.0495	**0.0871**	0.0551	0.0854	0.0424
	P4	0.0340	0.0494	**0.0716**	0.0433	0.0596
	P1	0.0595	**0.0869**	0.0786	0.0771	0.0760
P7-P4-P3	P7	0.0495	**0.0826**	0.0558	0.0817	0.0424
	P4	0.0340	0.0494	**0.0773**	0.0433	0.0613
	P3	0.0510	0.0913	**0.0964**	0.0914	0.0900
P7-P6-P3	P7	0.0495	**0.0826**	0.0542	0.0793	0.0424
	P6	0.0595	0.0627	**0.1137**	0.0568	0.0869
	P3	0.0510	0.0865	**0.0964**	0.0914	0.0765
P7-P6-P8	P7	0.0495	**0.0826**	0.0551	0.0742	0.0819
	P6	0.0595	0.0627	**0.0937**	0.0568	0.0900
	P8	0.0368	0.0643	**0.0801**	0.0648	0.0397
P11-P6-P3	P11	0.0550	0.1011	0.0803	**0.1067**	0.0634
	P6	0.0595	0.0627	**0.1230**	0.0568	0.0841
	P3	0.0510	0.0369	**0.1008**	0.0931	0.0417
P11-P6-P8	P11	0.0550	**0.1112**	0.0774	0.1059	0.0873
	P6	0.0595	0.0627	**0.1008**	0.0568	0.0900
	P8	0.0368	0.0643	**0.0801**	0.0648	0.0397
P11-P13-P8	P11	0.0550	**0.1112**	0.0774	0.0907	0.0950
	P13	0.0500	0.0666	**0.1139**	0.1024	0.0554
	P8	0.0340	0.0692	**0.0801**	0.0462	0.0666
P11-P13-P9	P11	0.0550	**0.1112**	0.0774	0.0907	0.0950
	P13	0.0425	0.0666	**0.1082**	0.1039	0.0554
	P9	0.0340	0.0781	**0.0998**	0.0515	0.0751
P19-P13-P8	P19	0.0495	0.0653	**0.0934**	0.0829	0.0860
	P13	0.0500	**0.1133**	0.0804	0.1000	0.0554
	P8	0.0340	**0.0805**	0.0784	0.0462	0.0666
P19-P13-P9	P19	0.0495	0.0653	**0.1192**	0.0829	0.0860
	P13	0.0425	**0.1133**	0.0804	0.0968	0.0554
	P9	0.0340	**0.0978**	0.0850	0.0515	0.0751
P19-P14-P9	P19	0.0495	0.0653	0.0910	**0.0975**	0.0860
	P14	0.0680	0.1300	**0.1377**	0.0861	0.1044
	P9	0.0340	**0.0978**	0.0620	0.0787	0.0465
P19-P14-P10	P19	0.0495	0.0653	0.0640	0.0829	**0.0860**
	P14	0.0680	**0.1495**	0.1352	0.0861	0.0992
	P10	0.0595	**0.1111**	0.0939	0.0918	0.0588
P25-P14-P9	P25	0.0340	**0.1687**	0.1470	0.0977	0.1233
	P14	0.0440	0.0764	**0.1352**	0.1193	0.1167
	P9	0.0340	0.0840	0.0620	**0.0903**	0.0465
P25-P14-P10	P25	0.0340	**0.1687**	0.1008	0.0977	0.1233
	P14	0.0680	**0.1359**	0.1352	0.1193	0.1167
	P10	0.0385	0.0685	0.0939	**0.0981**	0.0588
P25-P14-P12	P25	0.0340	**0.1606**	0.1008	0.0977	0.0672
	P14	0.0680	0.0764	0.1103	**0.1193**	0.0839
	P12	0.0660	0.1104	0.1269	**0.1343**	0.0867
P25-P15-P12	P25	0.0340	0.1385	**0.1432**	0.0977	0.1233
	P15	0.0510	**0.1179**	0.0791	0.1018	0.0588
	P12	0.0660	0.0725	0.1269	**0.1307**	0.0867
P25-P15-P16	P25	0.0400	0.1533	**0.1785**	0.0977	0.1233
	P15	0.0510	**0.1214**	0.0791	0.1038	0.0588
	P16	0.0401	0.0544	0.0655	**0.0775**	0.0675

Product Comb.	Product	Operations				
		1	2	3	4	5
P25-P15-P17	P25	0.0340	0.0862	**0.1876**	0.0977	0.1450
	P15	0.0510	**0.1179**	0.0791	0.1038	0.0949
	P17	0.0440	0.0691	**0.0786**	0.0700	0.0223
P26-P15-P10	P26	0.0680	0.0738	0.0727	0.1190	**0.1300**
	P15	0.0510	**0.1142**	0.0791	0.0712	0.0681
	P10	0.0385	0.0988	**0.1210**	0.0948	0.0588
P26-P15-P12	P26	0.0680	0.0738	0.1321	**0.1431**	0.1163
	P15	0.0510	**0.1136**	0.0791	0.0691	0.0588
	P12	0.1020	0.1104	**0.1293**	0.1113	0.1148
P26-P15-P16	P26	0.0680	0.0738	**0.1587**	0.1431	0.1228
	P15	0.0600	**0.1179**	0.0791	0.0712	0.0588
	P16	0.0401	0.0705	0.0684	**0.0775**	0.0673
P26-P15-P17	P26	0.0680	0.0738	**0.1616**	0.1190	0.1300
	P15	0.0510	**0.1179**	0.0786	0.0712	0.0949
	P17	0.0440	0.0669	**0.0798**	0.0700	0.0375
P26-P18-P17	P26	0.0680	0.0738	**0.1646**	0.1253	0.1300
	P18	0.0340	**0.1112**	0.0825	0.0758	0.0554
	P17	0.0440	0.0669	**0.0786**	0.0700	0.0652
P26-P18-P21	P26	0.0680	0.0861	**0.1587**	0.1431	0.1105
	P18	0.0340	**0.1112**	0.0825	0.1067	0.0554
	P21	0.0385	0.0815	**0.0910**	0.0633	0.0875
P29-P20-P21	P29	0.0510	**0.1467**	0.1394	0.1030	0.1167
	P20	0.0440	0.0895	**0.0907**	0.0791	0.0626
	P21	0.0596	0.0590	0.0640	**0.1041**	0.0479
P29-P20-P23	P29	0.0510	0.0862	**0.1532**	0.1030	0.1167
	P20	0.0440	0.0710	**0.0944**	0.0805	0.0526
	P23	0.0680	0.0891	0.0703	**0.1005**	0.0507
P29-P22-P23	P29	0.0510	0.0862	**0.1931**	0.1030	0.1167
	P22	0.0605	0.0910	0.0822	**0.1036**	0.0910
	P23	0.0680	0.0891	**0.0987**	0.0836	0.0507
P29-P22-P30	P29	0.0510	0.1467	**0.1931**	0.1030	0.1167
	P22	0.0605	**0.1093**	0.0808	0.1090	0.0873
	P30	0.0765	0.0589	**0.1036**	0.0918	0.0530
P29-P24-P30	P29	0.0600	0.1754	**0.1873**	0.1030	0.1167
	P24	0.0383	0.0461	0.0490	**0.0637**	0.0342
	P30	0.0495	**0.0990**	0.0944	0.0935	0.0814
P27-P24-P30	P27	0.0600	0.0725	**0.1297**	0.0662	0.1011
	P24	0.0383	**0.0627**	0.0490	0.0620	0.0342
	P30	0.0495	**0.1095**	0.0980	0.0888	0.0900
P27-P28-P30	P27	0.0510	0.0725	**0.1324**	0.0661	0.0602
	P28	0.0340	0.0712	0.0534	**0.0725**	0.0597
	P30	0.0495	0.0850	**0.1007**	0.0918	0.0900
P29-P18-P21	P29	0.0510	0.1467	**0.1931**	0.1030	0.1167
	P18	0.0340	0.1112	0.0825	**0.1212**	0.0554
	P21	0.0385	0.0590	**0.0960**	0.0874	0.0773
P29-P28-P30	P29	0.0510	0.1385	**0.1931**	0.1030	0.1167
	P28	0.0340	0.0712	0.0541	**0.0749**	0.0356
	P30	0.0495	0.0589	**0.1067**	0.0903	0.0900

G9. Operation times to product combinations – Problem 2 (Max - Min)

Product Comb.	Product	Operations				
		1	2	3	4	5
P5-P2-P1	P5	0.068	**0.1136**	0.0599	0.0983	0.0588
	P2	0.0650	0.0936	**0.1074**	0.0560	0.0734
	P1	0.0595	0.0814	0.0786	**0.1028**	0.0878
P7-P2-P1	P7	0.0900	0.0826	0.0825	**0.1044**	0.0867
	P2	0.0650	0.1016	**0.1119**	0.0560	0.0760
	P1	0.0805	0.0814	0.0516	0.0843	**0.0852**
P7-P4-P1	P7	0.0765	0.0994	0.0551	**0.1044**	0.0819
	P4	0.0520	0.0684	**0.0841**	0.0433	0.0667
	P1	0.0805	**0.0976**	0.0786	0.0857	0.0852
P7-P4-P3	P7	0.0900	**0.0994**	0.0558	0.0970	0.0819
	P4	0.0520	0.0742	**0.0872**	0.0433	0.221
	P3	0.0690	0.1112	0.1103	0.0914	**0.1234**
P7-P6-P3	P7	0.0900	**0.0994**	0.0542	0.0884	0.0819
	P6	0.0805	0.1067	**0.1323**	0.0568	0.1040
	P3	0.0780	**0.1112**	0.1076	0.0914	0.0900
P7-P6-P8	P7	0.0495	**0.0994**	0.0551	0.0970	0.0867
	P6	0.0700	0.1007	**0.1103**	0.0568	0.1040
	P8	0.0488	0.0776	**0.0901**	0.0648	0.0694
P11-P6-P3	P11	0.1000	**0.1392**	0.0774	0.1155	0.0950
	P6	0.0805	0.1115	**0.1323**	0.0568	0.1016
	P3	0.0780	**0.1112**	0.1107	0.0914	0.0900
P11-P6-P8	P11	0.0550	**0.1392**	0.0774	0.1266	0.0950
	P6	0.0700	0.1115	**0.1121**	0.0568	0.1040
	P8	0.0488	0.0829	**0.0901**	0.0648	0.0725
P11-P13-P8	P11	0.0850	**0.1392**	0.0774	0.0954	0.1302
	P13	0.0650	0.1133	0.1082	**0.1225**	0.1133
	P8	0.0368	0.0829	**0.0884**	0.0462	0.0725
P11-P13-P9	P11	0.0850	**0.1392**	0.0774	0.1067	0.1302
	P13	0.0575	0.1070	0.1044	**0.1204**	0.0769
	P9	0.0340	**0.0942**	0.0900	0.0769	0.0814
P19-P13-P8	P19	0.0765	0.0653	**0.1088**	0.0934	0.0964
	P13	0.0650	0.1133	0.0804	**0.1181**	0.1070
	P8	0.0368	**0.0981**	0.0869	0.0462	0.0725
P19-P13-P9	P19	0.0765	0.0653	**0.1334**	0.0975	0.0964
	P13	0.0575	0.1116	0.0789	**0.1236**	0.0943
	P9	0.0400	**0.1151**	0.0820	0.0753	0.0850
P19-P14-P9	P19	0.0765	0.0653	0.1039	**0.1320**	0.0964
	P14	0.0680	0.1300	**0.1505**	0.0861	0.1167
	P9	0.0520	**0.1192**	0.0620	0.0957	0.0814
P19-P14-P10	P19	0.0900	0.0653	0.0960	0.0861	**0.1024**
	P14	0.1040	**0.1803**	0.1505	0.0861	0.1167
	P10	0.0805	0.0988	**0.1216**	0.1112	0.0588
P25-P14-P9	P25	0.0520	**0.1965**	0.1712	0.0977	0.1450
	P14	0.0800	0.1228	**0.1505**	0.1139	0.1423
	P9	0.0460	0.0978	0.0620	**0.1065**	0.0850
P25-P14-P10	P25	0.0520	**0.1965**	0.1554	0.0959	0.1551
	P14	0.0920	0.1300	**0.1553**	0.1139	0.1503
	P10	0.0700	0.0685	**0.1236**	0.1063	0.0588
P25-P14-P12	P25	0.0520	**0.1965**	0.1600	0.0959	0.0672
	P14	0.0920	0.1138	0.1383	0.1139	**0.1503**
	P12	0.1200	0.1351	**0.1458**	0.1246	0.1070
P25-P15-P12	P25	0.0520	**0.1687**	0.1673	0.0977	0.1450
	P15	0.0690	**0.1324**	0.0791	0.0999	0.0861
	P12	0.1020	0.1026	**0.1435**	0.1246	0.0949
P25-P15-P16	P25	0.0520	0.1687	**0.1919**	0.0977	0.1450
	P15	0.0600	**0.1324**	0.0791	0.0999	0.1075
	P16	0.0510	0.0577	0.0684	**0.0911**	0.0781

Product Comb.	Product	Operations				
		1	2	3	4	5
P25-P15-P17	**P25**	0.0520	0.0893	**0.2012**	0.0977	0.1988
	P15	0.0600	**0.1324**	0.0791	0.0999	0.1075
	P17	0.0680	0.0803	0.0786	**0.0834**	0.0767
P26-P15-P10	**P26**	0.0680	0.0738	**0.1511**	0.1286	0.1480
	P15	0.0780	**0.1437**	0.0791	0.0712	0.1030
	P10	0.0595	0.0949	**0.1335**	0.1150	0.0588
P26-P15-P12	**P26**	0.0800	0.0738	0.1539	**0.1662**	0.1300
	P15	0.0780	**0.1324**	0.0791	0.0712	0.1075
	P12	0.1020	0.1233	**0.1435**	0.1097	0.1123
P26-P15-P16	**P26**	0.0800	0.0738	0.1666	**0.1795**	0.1300
	P15	0.0780	**0.1437**	0.0791	0.0712	0.0892
	P16	0.0510	**0.0820**	0.0684	0.0754	0.0781
P26-P15-P17	**P26**	0.0680	0.0738	**0.1698**	0.1420	0.1586
	P15	0.0600	**0.1388**	0.0791	0.0712	0.1075
	P17	0.0680	0.0781	0.0786	**0.0916**	0.0602
P26-P18-P17	**P26**	0.0800	0.0738	**0.1823**	0.1498	0.1586
	P18	0.0460	**0.1392**	0.0808	0.1084	0.0943
	P17	0.0680	0.0746	0.0763	**0.0916**	0.0767
P26-P18-P21	**P26**	0.0680	0.0861	0.1698	**0.1790**	0.1300
	P18	0.0520	**0.1392**	0.0825	0.1130	0.1070
	P21	0.0595	0.1005	0.0910	0.0633	**0.1012**
P29-P20-P21	**P29**	0.0780	0.1606	**0.1625**	0.1030	0.1220
	P20	0.0680	0.0958	**0.1046**	0.0900	0.0700
	P21	0.0805	0.0604	0.0662	**0.1011**	0.0584
P29-P20-P23	**P29**	0.0780	0.1164	**0.1800**	0.1030	0.1423
	P20	0.0800	0.0825	**0.1065**	0.0765	0.0700
	P23	0.0920	0.1001	0.0703	**0.1167**	0.0860
P29-P22-P23	**P29**	0.0780	0.1467	**0.2101**	0.1030	0.1423
	P22	0.0935	0.1093	0.0808	**0.1296**	0.0950
	P23	0.0680	**0.1050**	0.0973	0.0904	0.0831
P29-P22-P30	**P29**	0.0780	0.1687	**0.2101**	0.1030	0.1423
	P22	0.0935	0.1332	0.0808	**0.1364**	0.0950
	P30	0.0765	0.0956	**0.1007**	0.0995	0.0869
P29-P24-P30	**P29**	0.0780	0.1687	**0.1984**	0.1030	0.1423
	P24	0.0414	0.0645	0.0490	**0.0811**	0.0700
	P30	0.0765	**0.1422**	0.0980	0.1049	0.0900
P27-P24-P30	**P27**	0.0780	0.1165	**0.1436**	0.0662	0.1100
	P24	0.0414	0.0743	0.0490	**0.0811**	0.0661
	P30	0.0495	**0.1200**	0.0980	0.1049	0.1009
P27-P28-P30	**P27**	0.0780	0.1165	**0.1403**	0.0661	0.1011
	P28	0.0340	0.0826	0.0534	**0.0982**	0.0650
	P30	0.0495	0.0990	0.1007	**0.1103**	0.0944
P26-P18-P23	**P26**	0.0800	0.0738	0.1758	**0.1790**	0.1300
	P18	0.0460	0.0995	0.0808	**0.1190**	0.0943
	P23	0.0680	**0.1050**	0.0905	0.0807	0.0964
P29-P18-P23	**P29**	0.0600	0.1385	**0.2101**	0.1030	0.1423
	P18	0.0520	0.1112	0.0825	**0.1360**	0.1133
	P23	0.0680	**0.1087**	0.0938	0.0904	0.0860
P29-P20-P30	**P29**	0.0780	0.1606	**0.1610**	0.1030	0.1503
	P20	0.0800	0.0958	**0.1084**	0.0765	0.0700
	P30	0.1035	0.0774	0.0672	**0.1180**	0.0751

G10. Operation times to product combinations – Problem 2 (Max - Max)

Product Comb.	Product	Operations				
		1	2	3	4	5
P5-P2-P1	P5	0.068	**0.1097**	0.0599	0.0899	0.0588
	P2	0.0425	**0.0907**	0.0897	0.0560	0.0710
	P1	0.0385	0.0603	0.0786	**0.0904**	0.0760
P7-P2-P1	P7	0.0495	0.0781	0.0825	**0.0854**	0.0424
	P2	0.0425	**0.0907**	0.0897	0.0560	0.0710
	P1	0.0595	0.0603	0.0516	**0.0771**	0.0760
P7-P4-P1	P7	0.0495	**0.0910**	0.0551	0.0854	0.0424
	P4	0.0340	0.0494	**0.0695**	0.0433	0.0630
	P1	0.0595	**0.0892**	0.0786	0.0748	0.0760
P7-P4-P3	P7	0.0765	**0.0888**	0.0558	0.0750	0.0424
	P4	0.0400	0.0494	**0.0762**	0.0433	0.0648
	P3	0.0510	**0.0967**	0.0964	0.0914	0.0900
P7-P6-P3	P7	0.0495	**0.0826**	0.0542	0.0771	0.0424
	P6	0.0595	0.0627	**0.1182**	0.0568	0.0900
	P3	0.0510	0.0913	**0.0964**	0.0914	0.0765
P7-P6-P8	P7	0.0495	**0.0888**	0.0551	0.0771	0.0867
	P6	0.0595	0.0627	**0.0964**	0.0568	0.0900
	P8	0.0368	0.0670	**0.0772**	0.0648	0.0397
P11-P6-P3	P11	0.0550	**0.1059**	0.0774	0.1036	0.0634
	P6	0.0595	0.0627	**0.1230**	0.0568	0.0869
	P3	0.0510	0.0913	**0.1008**	0.0914	0.0417
P11-P6-P8	P11	0.0550	**0.1112**	0.0774	0.1007	0.0950
	P6	0.0595	0.0627	**0.1008**	0.0568	0.0900
	P8	0.0368	0.0670	**0.0788**	0.0648	0.0397
P11-P13-P8	P11	0.0550	**0.1112**	0.0774	0.0907	0.0950
	P13	0.0500	0.0666	**0.1082**	0.1054	0.0554
	P8	0.0340	0.0724	**0.0768**	0.0462	0.0694
P11-P13-P9	P11	0.0550	**0.1245**	0.0758	0.0980	0.0950
	P13	0.0425	0.0666	0.1044	**0.1147**	0.0554
	P9	0.0340	**0.0942**	0.0900	0.0616	0.0751
P19-P13-P8	P19	0.0765	0.0653	**0.0960**	0.0829	0.0860
	P13	0.0650	**0.1070**	0.0804	0.1000	0.0554
	P8	0.0368	**0.0805**	0.0784	0.0462	0.0666
P19-P13-P9	P19	0.0495	0.0653	**0.1134**	0.0829	0.0860
	P13	0.0425	0.1070	0.0789	**0.1076**	0.0554
	P9	0.0340	**0.0978**	0.0820	0.0632	0.0751
P19-P14-P9	P19	0.0765	0.0653	0.0960	**0.0975**	0.0860
	P14	0.0680	0.1228	**0.1403**	0.0861	0.1167
	P9	0.0400	**0.0942**	0.0620	0.0753	0.0465
P19-P14-P10	P19	0.0495	0.0653	0.0834	0.0829	**0.0860**
	P14	0.0680	0.1359	**0.1429**	0.0861	0.1044
	P10	0.0595	0.0988	**0.1050**	0.0930	0.0588
P25-P14-P9	P25	0.0400	**0.1687**	0.1511	0.0977	0.1450
	P14	0.0680	0.0764	**0.1377**	0.1139	0.1167
	P9	0.0340	0.0840	0.0620	**0.0886**	0.0465
P25-P14-P10	P25	0.0400	**0.1687**	0.1269	0.0959	0.1332
	P14	0.0680	0.1228	**0.1377**	0.1157	0.1167
	P10	0.0595	0.0685	**0.1006**	0.0962	0.0588
P25-P14-P12	P25	0.0400	**0.1533**	0.1269	0.0959	0.0672
	P14	0.0680	0.1031	**0.1173**	0.1139	0.0876
	P12	0.1200	0.1289	**0.1362**	0.1246	0.0967
P25-P15-P12	P25	0.0460	0.1385	**0.1554**	0.0977	0.1450
	P15	0.0510	**0.1179**	0.0791	0.0999	0.0718
	P12	0.1020	0.0725	**0.1362**	0.1246	0.0867
P25-P15-P16	P25	0.0520	0.1687	**0.1752**	0.0977	0.1450
	P15	0.0600	**0.1324**	0.0791	0.0999	0.0588
	P16	0.0510	0.0568	0.0684	**0.0746**	0.0675

Product Comb.	Product	Operations				
		1	2	3	4	5
P25-P15-P17	**P25**	0.0400	0.0862	**0.1752**	0.0977	0.1450
	P15	0.0510	**0.1324**	0.0791	0.0999	0.1030
	P17	0.0680	**0.0803**	0.0786	0.0700	0.0375
P26-P15-P10	**P26**	0.0680	0.0738	**0.1377**	0.1190	0.1300
	P15	0.0780	**0.1136**	0.0791	0.0712	0.0988
	P10	0.0595	0.0949	**0.1236**	0.0930	0.0588
P26-P15-P12	**P26**	0.0680	0.0738	0.1348	**0.1400**	0.1300
	P15	0.0600	**0.1097**	0.0791	0.0691	0.0588
	P12	0.1020	0.1104	**0.1342**	0.1097	0.1148
P26-P15-P16	**P26**	0.0800	0.0738	**0.1559**	0.1464	0.1300
	P15	0.0780	**0.1179**	0.0791	0.0712	0.0588
	P16	0.0510	**0.0705**	0.0684	0.0648	0.0673
P26-P15-P17	**P26**	0.0680	0.0738	**0.1587**	0.1190	0.1300
	P15	0.0600	**0.1179**	0.0791	0.0712	0.1030
	P17	0.0680	0.0691	**0.0786**	0.0676	0.0375
P26-P18-P17	**P26**	0.0800	0.0738	**0.1559**	0.1322	0.1300
	P18	0.0340	**0.1112**	0.0808	0.0868	0.0554
	P17	0.0440	0.0708	**0.0763**	0.0739	0.0686
P26-P18-P21	**P26**	0.0680	0.0738	**0.1559**	0.1464	0.1228
	P18	0.0400	**0.1112**	0.0825	0.1050	0.1070
	P21	0.0595	0.0843	**0.0910**	0.0633	0.0875
P29-P20-P21	**P29**	0.0690	**0.1606**	0.1532	0.1030	0.1167
	P20	0.0680	**0.0983**	0.0965	0.0765	0.0661
	P21	0.0595	0.0604	0.0640	**0.1011**	0.0584
P29-P20-P23	**P29**	0.0600	0.0862	**0.1483**	0.1030	0.1167
	P20	0.0680	0.0753	**0.0929**	0.0765	0.0700
	P23	0.0680	0.0959	0.0711	**0.0983**	0.0517
P29-P22-P23	**P29**	0.0510	0.0862	**0.1819**	0.1030	0.1167
	P22	0.0605	0.0982	0.0808	**0.1115**	0.0950
	P23	0.0680	0.0918	**0.0973**	0.0836	0.0507
P29-P22-P30	**P29**	0.0510	0.1606	**0.1684**	0.1030	0.1167
	P22	0.0605	**0.1188**	0.0808	0.1162	0.0950
	P30	0.0765	0.0624	**0.1007**	0.0903	0.0530
P29-P24-P30	**P29**	0.0600	**0.1975**	0.1730	0.1030	0.1167
	P24	0.0383	0.0481	0.0490	**0.0654**	0.0342
	P30	0.0495	**0.0990**	0.0980	0.0918	0.0869
P27-P24-P30	**P27**	0.0600	0.0725	**0.1226**	0.0662	0.1011
	P24	0.0383	**0.0680**	0.0490	0.0637	0.0342
	P30	0.0495	0.1157	**0.0980**	0.0903	0.0900
P27-P28-P30	**P27**	0.0510	0.0725	**0.1245**	0.0661	0.0602
	P28	0.0340	0.0765	0.0534	**0.0776**	0.0597
	P30	0.0495	0.0925	**0.1007**	0.0935	0.0900
P26-P20-P21	**P26**	0.0800	0.0738	0.1295	**0.1464**	0.0636
	P20	0.0680	0.0849	**0.0925**	0.0563	0.0661
	P21	0.0595	0.0796	0.0640	0.0874	**0.0875**
P29-P28-P30	**P29**	0.0510	0.1467	**0.1684**	0.1030	0.1167
	P28	0.0340	0.0801	0.0534	**0.0827**	0.0356
	P30	0.0495	0.0606	**0.1007**	0.0935	0.0869

G11. Bottleneck times to product combinations – Problem 3 (Max)

Period 1			Period 2			Period 3		
Product Comb.	**Product**	**Bottleneck Op. Time**	**Product Comb.**	**Product**	**Bottleneck Op. Time**	**Product Comb.**	**Product**	**Bottleneck Op. Time**
P2-P2	P2	0.146	**P6-P6**	P6	0.1229	**P7-P7**	P7	0.1051
	P2	0.1011		P6	0.1689		P7	0.09
P2-P1	P2	0.1416	**P6-P2**	P6	0.1689	**P7-P3**	P7	0.1083
	P1	0.1203		P2	0.0965		P3	0.1344
P3-P1	P3	0.1668	**P1-P2**	P1	0.1475	**P1-P3**	P1	0.1475
	P1	0.1475		P2	0.1324		P3	0.1422
P3-P7	P3	0.1551	**P1-P3**	P1	0.1475	**P1-P4**	P1	0.1203
	P7	0.1083		P3	0.1551		P4	0.1034
P4-P7	P4	0.1295	**P4-P3**	P4	0.0856	**P2-P4**	P2	0.1011
	P7	0.09		P3	0.1971		P4	0.107
P4-P8	P4	0.1295	**P7-P3**	P7	0.1083	**P2-P5**	P2	0.1189
	P8	0.08		P3	0.1551		P5	0.1273
P5-P8	P5	0.1273	**P7-P5**	P7	0.099	**P2-P6**	P2	0.146
	P8	0.1022		P5	0.1273		P6	0.127
P5-P9	P5	0.1273	**P7-P10**	P7	0.1051	**P8-P6**	P8	0.1154
	P9	0.1241		P10	0.1264		P6	0.127
P6-P9	P6	0.1423	**P8-P10**	P8	0.1154	**P8-P9**	P8	0.08
	P9	0.1583		P10	0.1323		P9	0.1297
P6-P10	P6	0.1971	**P9-P10**	P9	0.1544	**P10-P9**	P10	0.136
	P10	0.1152		P10	0.1152		P9	0.1297

Period 4			Period 5			Period 6		
Product Comb.	**Product**	**Bottleneck Op. Time**	**Product Comb.**	**Product**	**Bottleneck Op. Time**	**Product Comb.**	**Product**	**Bottleneck Op. Time**
P6-P6	P6	0.1689	**P2-P2**	P2	0.1324	**P6-P6**	P6	0.1229
	P6	0.16		P2	0.0995		P6	0.1525
P1-P6	P1	0.1475	**P2-P1**	P2	0.1308	**P1-P6**	P1	0.1351
	P6	0.184		P1	0.1163		P6	0.1252
P1-P2	P1	0.1475	**P3-P1**	P3	0.145	**P1-P3**	P1	0.095
	P2	0.1387		P1	0.1351		P3	0.1525
P4-P2	P4	0.0874	**P3-P7**	P3	0.145	**P2-P3**	P2	0.1308
	P2	0.1835		P7	0.0971		P3	0.1252
P7-P2	P7	0.1083	**P4-P7**	P4	0.1161	**P2-P7**	P2	0.0967
	P2	0.1668		P7	0.09		P7	0.0971
P7-P3	P7	0.1083	**P4-P8**	P4	0.1161	**P4-P7**	P4	0.0958
	P3	0.1618		P8	0.08		P7	0.09
P8-P3	P8	0.1154	**P5-P8**	P5	0.115	**P4-P9**	P4	0.1
	P3	0.207		P8	0.1011		P9	0.1133
P9-P3	P9	0.1185	**P5-P9**	P5	0.115	**P4-P10**	P4	0.1
	P3	0.2306		P9	0.1185		P10	0.1433
P10-P3	P10	0.1152	**P6-P9**	P6	0.15	**P5-P10**	P5	0.1075
	P3	0.2306		P9	0.1411		P10	0.1289
P10-P5	P10	0.1264	**P6-P10**	P6	0.1751	**P8-P10**	P8	0.0967
	P5	0.1714		P10	0.1193		P10	0.1289

Period 7			Period 8			Period 9		
Product Comb.	**Product**	**Bottleneck Op. Time**	**Product Comb.**	**Product**	**Bottleneck Op. Time**	**Product Comb.**	**Product**	**Bottleneck Op. Time**
P6-P6	P6	0.1553	**P6-P6**	P6	0.1517	**P1-P1**	P1	0.0959
	P6	0.1525		P6	0.1525		P1	0.1338
P6-P1	P6	0.16	**P6-P1**	P6	0.164	**P2-P1**	P2	0.1075
	P1	0.1289		P1	0.1289		P1	0.1233
P2-P1	P2	0.1297	**P2-P1**	P2	0.1297	**P2-P3**	P2	0.1075
	P1	0.1289		P1	0.1289		P3	0.1718
P2-P4	P2	0.1602	**P2-P4**	P2	0.145	**P7-P3**	P7	0.0765
	P4	0.0833		P4	0.1129		P3	0.1686
P2-P7	P2	0.145	**P2-P7**	P2	0.145	**P7-P4**	P7	0.0765
	P7	0.0945		P7	0.0912		P4	0.11
P2-P8	P2	0.1297	**P2-P8**	P2	0.1297	**P8-P4**	P8	0.0747
	P8	0.1006		P8	0.1006		P4	0.11
P3-P8	P3	0.18	**P3-P8**	P3	0.18	**P9-P4**	P9	0.1179
	P8	0.1006		P8	0.1006		P4	0.1038
P3-P9	P3	0.1553	**P3-P9**	P3	0.1517	**P9-P5**	P9	0.107
	P9	0.138		P9	0.1411		P5	0.1075
P3-P10	P3	0.201	**P3-P10**	P3	0.201	**P9-P6**	P9	0.1179
	P10	0.1137		P10	0.1137		P6	0.147
P5-P10	P5	0.1498	**P5-P10**	P5	0.1498	**P10-P6**	P10	0.1261
	P10	0.1433		P10	0.1433		P6	0.147
Period 10			**Period 11**			**Period 12**		
Product Comb.	**Product**	**Bottleneck Op. Time**	**Product Comb.**	**Product**	**Bottleneck Op. Time**	**Product Comb.**	**Product**	**Bottleneck Op. Time**
P7-P7	P7	0.0765	**P6-P6**	P6	0.1499	**P2-P2**	P2	0.0913
	P7	0.09		P6	0.147		P2	0.1198
P7-P1	P7	0.0867	**P1-P6**	P1	0.1233	**P1-P2**	P1	0.1034
	P1	0.1233		P6	0.16		P2	0.1198
P3-P1	P3	0.125	**P1-P2**	P1	0.1233	**P1-P3**	P1	0.1233
	P1	0.1233		P2	0.1258		P3	0.145
P3-P2	P3	0.125	**P4-P2**	P4	0.0769	**P7-P3**	P7	0.092
	P2	0.1273		P2	0.155		P3	0.1385
P4-P2	P4	0.0958	**P7-P2**	P7	0.0889	**P7-P4**	P7	0.0765
	P2	0.0913		P2	0.145		P4	0.1063
P5-P2	P5	0.1075	**P8-P2**	P8	0.098	**P8-P4**	P8	0.0695
	P2	0.1075		P2	0.1206		P4	0.1063
P6-P2	P6	0.1214	**P8-P3**	P8	0.098	**P9-P4**	P9	0.107
	P2	0.124		P3	0.153		P4	0.1063
P6-P8	P6	0.1214	**P9-P3**	P9	0.138	**P9-P5**	P9	0.107
	P8	0.098		P3	0.1402		P5	0.1075
P6-P10	P6	0.1443	**P10-P3**	P10	0.1066	**P10-P5**	P10	0.1354
	P10	0.1282		P3	0.1967		P5	0.1291
P9-P10	P9	0.1129	**P10-P5**	P10	0.115	**P10-P6**	P10	0.148
	P10	0.1219		P5	0.1433		P6	0.147

Period 13			Period 14		
Product Comb.	**Product**	**Bottleneck Op. Time**	**Product Comb.**	**Product**	**Bottleneck Op. Time**
P7-P7	P7	0.0765	**P6-P6**	P6	0.1435
	P7	0.1035		P6	0.136
P7-P1	P7	0.0867	**P1-P6**	P1	0.1233
	P1	0.1233		P6	0.147
P3-P1	P3	0.1236	**P1-P2**	P1	0.1233
	P1	0.1233		P2	0.1206
P4-P1	P4	0.0919	**P4-P2**	P4	0.0769
	P1	0.0994		P2	0.1485
P4-P2	P4	0.0919	**P7-P2**	P7	0.0859
	P2	0.0859		P2	0.1332
P5-P2	P5	0.103	**P8-P2**	P8	0.0915
	P2	0.1002		P2	0.1192
P6-P2	P6	0.1093	**P8-P3**	P8	0.098
	P2	0.124		P3	0.153
P6-P8	P6	0.1093	**P9-P3**	P9	0.0963
	P8	0.098		P3	0.1952
P9-P8	P9	0.1076	**P10-P3**	P10	0.143
	P8	0.0799		P3	0.153
P9-P10	P9	0.1076	**P10-P5**	P10	0.1113
	P10	0.1139		P5	0.1433

Period 15			Period 16		
Product Comb.	**Product**	**Bottleneck Op. Time**	**Product Comb.**	**Product**	**Bottleneck Op. Time**
P1-P1	P1	0.1066	**P2-P2**	P2	0.1121
	P1	0.1165		P2	0.0813
P2-P1	P2	0.1002	**P2-P3**	P2	0.1158
	P1	0.1233		P3	0.1152
P2-P3	P2	0.0992	**P1-P3**	P1	0.1165
	P3	0.1567		P3	0.1332
P7-P3	P7	0.0765	**P1-P4**	P1	0.1165
	P3	0.1567		P4	0.0919
P7-P4	P7	0.0765	**P5-P4**	P5	0.103
	P4	0.1027		P4	0.0878
P8-P4	P8	0.0685	**P5-P6**	P5	0.103
	P4	0.1063		P6	0.136
P9-P4	P9	0.1076	**P8-P6**	P8	0.074
	P4	0.0934		P6	0.1376
P9-P5	P9	0.0963	**P9-P6**	P9	0.0963
	P5	0.1075		P6	0.1376
P10-P5	P10	0.1218	**P9-P7**	P9	0.1014
	P5	0.1223		P7	0.0832
P10-P6	P10	0.1224	**P10-P7**	P10	0.1103
	P6	0.136		P7	0.0832

G12. Bottleneck times to product combinations – Problem 3 (Max - Min)

Period 1			**Period 2**			**Period 3**		
Product Comb.	**Product**	**Bottleneck Op. Time**	**Product Comb.**	**Product**	**Bottleneck Op. Time**	**Product Comb.**	**Product**	**Bottleneck Op. Time**
P2-P2	P2	0.1578	**P6-P6**	P6	0.1317	**P7-P7**	P7	0.117
	P2	0.1187		P6	0.1773		P7	0.0912
P2-P1	P2	0.1578	**P6-P2**	P6	0.1739	**P7-P3**	P7	0.12
	P1	0.1326		P2	0.1158		P3	0.1499
P3-P1	P3	0.208	**P1-P2**	P1	0.1475	**P1-P3**	P1	0.1537
	P1	0.1603		P2	0.1397		P3	0.1584
P3-P7	P3	0.1716	**P1-P3**	P1	0.1537	**P1-P4**	P1	0.1358
	P7	0.1109		P3	0.2206		P4	0.113
P4-P7	P4	0.1326	**P4-P3**	P4	0.108	**P2-P4**	P2	0.1187
	P7	0.0971		P3	0.2206		P4	0.113
P4-P8	P4	0.1326	**P7-P3**	P7	0.1109	**P2-P5**	P2	0.1392
	P8	0.1063		P3	0.2206		P5	0.1312
P5-P8	P5	0.1367	**P7-P5**	P7	0.1116	**P2-P6**	P2	0.146
	P8	0.1169		P5	0.132		P6	0.1668
P5-P9	P5	0.1497	**P8-P5**	P8	0.1067	**P8-P6**	P8	0.1211
	P9	0.1632		P5	0.1353		P6	0.1545
P6-P9	P6	0.1604	**P8-P10**	P8	0.1344	**P8-P9**	P8	0.1006
	P9	0.1469		P10	0.1552		P9	0.1412
P6-P10	P6	0.2434	**P9-P10**	P9	0.1632	**P10-P9**	P10	0.1642
	P10	0.1561		P10	0.152		P9	0.1632
Period 4			**Period 5**			**Period 6**		
Product Comb.	**Product**	**Bottleneck Op. Time**	**Product Comb.**	**Product**	**Bottleneck Op. Time**	**Product Comb.**	**Product**	**Bottleneck Op. Time**
P6-P6	P6	0.1739	**P2-P2**	P2	0.1449	**P6-P6**	P6	0.1383
	P6	0.2295		P2	0.135		P6	0.1599
P1-P6	P1	0.1537	**P3-P2**	P3	0.1675	**P1-P6**	P1	0.1475
	P6	0.2434		P2	0.1495		P6	0.1475
P1-P2	P1	0.1524	**P3-P1**	P3	0.2103	**P1-P3**	P1	0.1233
	P2	0.1671		P1	0.1537		P3	0.1988
P4-P2	P4	0.1132	**P3-P7**	P3	0.1988	**P2-P3**	P2	0.1179
	P2	0.1988		P7	0.1109		P3	0.1491
P7-P2	P7	0.1075	**P4-P7**	P4	0.1331	**P2-P7**	P2	0.1245
	P2	0.2206		P7	0.0912		P7	0.1035
P8-P2	P8	0.1344	**P4-P8**	P4	0.1326	**P4-P7**	P4	0.1023
	P2	0.1668		P8	0.0971		P7	0.0985
P8-P3	P8	0.1182	**P4-P9**	P4	0.1326	**P4-P9**	P4	0.1075
	P3	0.234		P9	0.1582		P9	0.1228
P9-P3	P9	0.1288	**P5-P9**	P5	0.1429	**P5-P9**	P5	0.1273
	P3	0.2206		P9	0.1582		P9	0.1179
P10-P3	P10	0.157	**P6-P9**	P6	0.16	**P5-P10**	P5	0.1182
	P3	0.234		P9	0.1429		P10	0.141
P10-P5	P10	0.157	**P6-P10**	P6	0.232	**P8-P10**	P8	0.1139
	P5	0.1967		P10	0.148		P10	0.163

Period 7			Period 8			Period 9		
Product Comb.	**Product**	**Bottleneck Op. Time**	**Product Comb.**	**Product**	**Bottleneck Op. Time**	**Product Comb.**	**Product**	**Bottleneck Op. Time**
P6-P6	P6	0.2052	**P6-P6**	P6	0.2052	**P1-P1**	P1	0.1233
	P6	0.1535		P6	0.1542		P1	0.1351
P6-P1	P6	0.2193	**P6-P1**	P6	0.2193	**P2-P1**	P2	0.1189
	P1	0.1402		P1	0.1215		P1	0.132
P2-P1	P2	0.1496	**P2-P1**	P2	0.1496	**P2-P3**	P2	0.1204
	P1	0.1402		P1	0.1352		P3	0.1739
P2-P4	P2	0.177	**P2-P4**	P2	0.177	**P7-P3**	P7	0.09
	P4	0.0995		P4	0.1033		P3	0.1821
P2-P7	P2	0.1988	**P2-P7**	P2	0.1988	**P7-P4**	P7	0.09
	P7	0.0992		P7	0.0998		P4	0.1221
P2-P8	P2	0.1496	**P2-P8**	P2	0.1445	**P8-P4**	P8	0.0881
	P8	0.1203		P8	0.1203		P4	0.1287
P2-P9	P2	0.1332	**P2-P9**	P2	0.145	**P8-P5**	P8	0.1163
	P9	0.1288		P9	0.146		P5	0.1261
P3-P9	P3	0.1988	**P3-P9**	P3	0.1988	**P9-P5**	P9	0.1412
	P9	0.1311		P9	0.1275		P5	0.1236
P3-P10	P3	0.207	**P3-P10**	P3	0.207	**P9-P6**	P9	0.1412
	P10	0.1433		P10	0.1382		P6	0.1705
P3-P5	P3	0.177	**P3-P5**	P3	0.177	**P10-P6**	P10	0.1412
	P5	0.1111		P5	0.1084		P6	0.208
Period 10			**Period 11**			**Period 12**		
Product Comb.	**Product**	**Bottleneck Op. Time**	**Product Comb.**	**Product**	**Bottleneck Op. Time**	**Product Comb.**	**Product**	**Bottleneck Op. Time**
P7-P7	P7	0.09	**P6-P6**	P6	0.1435	**P2-P2**	P2	0.1099
	P7	0.1035		P6	0.1953		P2	0.1273
P7-P1	P7	0.0939	**P1-P6**	P1	0.1289	**P1-P2**	P1	0.1179
	P1	0.1351		P6	0.1953		P2	0.1273
P3-P1	P3	0.1465	**P1-P2**	P1	0.1237	**P1-P3**	P1	0.1289
	P1	0.1351		P2	0.1371		P3	0.177
P3-P2	P3	0.145	**P4-P2**	P4	0.0925	**P7-P3**	P7	0.0971
	P2	0.1308		P2	0.1551		P3	0.1551
P4-P2	P4	0.1014	**P7-P2**	P7	0.0912	**P7-P4**	P7	0.0889
	P2	0.0998		P2	0.177		P4	0.1161
P5-P2	P5	0.1192	**P8-P2**	P8	0.1061	**P8-P4**	P8	0.0915
	P2	0.1104		P2	0.1332		P4	0.1161
P6-P2	P6	0.1421	**P9-P2**	P9	0.1185	**P8-P5**	P8	0.1061
	P2	0.1345		P2	0.1369		P5	0.1223
P6-P8	P6	0.1344	**P9-P3**	P9	0.1133	**P9-P5**	P9	0.1288
	P8	0.1094		P3	0.1807		P5	0.1162
P6-P10	P6	0.1525	**P10-P3**	P10	0.1354	**P9-P6**	P9	0.1116
	P10	0.146		P3	0.18		P6	0.1531
P9-P10	P9	0.1228	**P10-P5**	P10	0.1308	**P10-P6**	P10	0.1218
	P10	0.1369		P5	0.1554		P6	0.1953

Period 13			Period 14		
Product Comb.	**Product**	**Bottleneck Op. Time**	**Product Comb.**	**Product**	**Bottleneck Op. Time**
P7-P7	P7	0.0832	**P6-P6**	P6	0.1405
	P7	0.0945		P6	0.1712
P7-P1	P7	0.0906	**P1-P6**	P1	0.1233
	P1	0.1233		P6	0.1712
P3-P1	P3	0.1354	**P1-P2**	P1	0.1233
	P1	0.1233		P2	0.1297
P3-P2	P3	0.1354	**P4-P2**	P4	0.0878
	P2	0.1198		P2	0.145
P4-P2	P4	0.0989	**P7-P2**	P7	0.09
	P2	0.1059		P2	0.1551
P5-P2	P5	0.1111	**P8-P2**	P8	0.0976
	P2	0.1072		P2	0.1233
P6-P2	P6	0.1317	**P8-P3**	P8	0.0971
	P2	0.1273		P3	0.18
P6-P8	P6	0.1328	**P9-P3**	P9	0.1014
	P8	0.1006		P3	0.1672
P6-P10	P6	0.1405	**P10-P3**	P10	0.1218
	P10	0.1498		P3	0.18
P9-P10	P9	0.1185	**P10-P5**	P10	0.1218
	P10	0.1297		P5	0.1429
Period 15			**Period 16**		
Product Comb.	**Product**	**Bottleneck Op. Time**	**Product Comb.**	**Product**	**Bottleneck Op. Time**
P1-P1	P1	0.1104	**P2-P2**	P2	0.1011
	P1	0.1289		P2	0.1198
P2-P1	P2	0.1133	**P2-P3**	P2	0.1121
	P1	0.1104		P3	0.1354
P2-P3	P2	0.1064	**P1-P3**	P1	0.1165
	P3	0.1634		P3	0.1551
P7-P3	P7	0.09	**P1-P4**	P1	0.1165
	P3	0.1634		P4	0.0947
P7-P4	P7	0.09	**P5-P4**	P5	0.1018
	P4	0.1063		P4	0.0925
P8-P4	P8	0.08	**P8-P4**	P8	0.0933
	P4	0.108		P4	0.0947
P8-P5	P8	0.0976	**P8-P6**	P8	0.0869
	P5	0.1165		P6	0.1477
P9-P5	P9	0.1116	**P9-P6**	P9	0.1116
	P5	0.1162		P6	0.1328
P9-P6	P9	0.1121	**P10-P6**	P10	0.1412
	P6	0.1477		P6	0.1477
P10-P6	P10	0.1218	**P10-P7**	P10	0.1207
	P6	0.1712		P7	0.0914