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Cell Loading and Scheduling in Synchronized Manufacturing Cells

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Abstract

This study has been conducted based on a case observed in a jewelry manufacturing company where the company has converted a process layout into cellular layout. This conversion created the need for cell loading and cell scheduling process. Cell loading assigns the products to the cells and then the cell scheduling isperformed to determine product sequence and manpower allocation decisions in each cell. In this paper, a synchronized manufacturing environment is considered. The products move from one manufacturing stage to the next at the end of each time period also known a stime bucket. The number of operators needed in a time bucket may be different based on the manpower requirement for each process. This study examines the mathematical model for cell loading and cell sequencing in multiple cells. Several experiments have been conducted that shows that multiple cell sequencing outperform the single cell sequencing.

Keywords
Cell loading, synchronized manufacturing cell, manpower allocation, product sequence, multiple cell loading

1. Introduction
Based on the plant layout, manufacturing systems can be categorized into four groups: product layout, process layout, fixed layout and cellular layout (Yarimoglu 2009). According to Askin and Standridge (1993), plant layout determination is affected by product volume and product variety. In cellular layout, products are grouped based on similar process and then assigned to a cell. In this layout, distance is insignificant due to the proximity of machines. Cellular design leads to lower work-in-process inventory, setup times, flow times and lead times.

In cellular manufacturing
a product is to be completed in a single unit instead moving the product to different departments to be finished. Similar products are grouped together into product families and manufactured in their assigned cells. Each cell consists of required machines to finish production of each product assigned to the family. Kay and Suresh (1998) summarized the benefits of cellular manufacturing as follows:

- Less work-in-process (WIP) inventory and thus less space
- Smaller and predictable lead times
- Smaller setup times because of similarities of products in families
- Smaller lot production
- Simpler work flow
- Simpler and better control since there is no operation-wise division in responsibilities as in process layout

However, there are several related issues related to cellular manufacturing including family sequencing, family scheduling, cell loading, product sequencing, cell scheduling, crew size determination, and manpower allocation to operations (Yarimoglu 2009). In their work, Suer and Yarimoglu (2013, p 2) summarized each issue as follows:

1. The sequence of the products will be determined in the *family sequencing phase*.
2. The start and completion times of families in each cell are assigned in the *family scheduling phase*.
3. *Cell loading phase* determines product assignment to cells and followed by *product sequencing* to determine the order of products in a cell.
4. *Cell scheduling* determines the start and completion times of products on machines in cell in addition to the product sequence.
5. *Crew size* calculates the numbers of workers needed to be assigned to each cell.
6. *Manpower allocation* determines the assignments of workers for each operation/machine in each cell.

Süer and Gonzalez (1993) implemented synchronous manufacturing in a labor-intensive cell of a jewelry manufacturing plant. According to them, synchronous manufacturing is defined as follows:

> "A systematic way that provides a perfect flow of material through the production system by making it available for the right resource at the right time using a periodic approach with the objective of simplifying the scheduling task and minimizing the work-in-process inventory and the flow time"

The synchronization was needed due to different daily schedules that depended heavily on the planners, schedulers, supervisors and employees. For the synchronization, they implemented uniform time bucket approach leading to easier scheduling by converting the dynamic and stochastic scheduling problem into a static deterministic problem.

Yarimoglu and Süer (2009) managed to sequence products in a synchronized flow environment where the number of time periods exceeding available manpower is minimized. The product sequencing and manpower allocation were performed after the family sequencing and scheduling. The objective of this paper is to explore the possibility of performing cell loading, product sequencing and cell scheduling simultaneously. By eliminating the family sequencing and family scheduling, the flexibility of product assignments in available cells without exceeding available manpower is increased. The problem is solved by modifying the previous mathematical model.

2. Background

The problem observed in the jewelry manufacturing company is labor intensive where continuous operator attendance is necessary. Machines and equipment are considered inexpensive and lighter, hence it is possible to move the machines around. The number of operators available in a cell are more than the number of operations resulting in machines duplication to maximize production rates by utilizing all of the available operators. However, the number of workers needed in a cell is determined based on the products assigned to the cells. Therefore, product sequencing is critical to determine the performance of the cells by assigning products in appropriate cells based on the total available numbers of workers in each cell. This paper proposes math model for product sequencing in multiple cells.

Previous studies have been conducted in cell loading and product sequencing based on the result of manpower allocation in cellular manufacturing. Greene and Sadowski (1984) and Greene and Cleary (1985) have developed and compared some cell loading rules based on their benefits and disadvantages. Süer, Saiz, Dagli and Gonzalez (1995) developed some cell loading rules for connected cells based on a real manufacturing environment. Later, they extended their work to independent cells (Süer, Saiz and Gonzalez 1999). In 1997, Süer developed and compared mathematical formulations for different approaches to minimize number of tardy jobs in a multi-period environment. Then, Süer and Bera (1998) discussed cell loading and cell size determination for multiple periods. In this study, they identified a significant characteristic of the problem—a product will be assigned to the same cell once it was initially assigned to a cell throughout the periods due to the setup time, learning curves, etc. The result of their study was a two phase methodology to maximize the number of products in all periods using available capacity.

Later in 2008, Süer, Arikan, and Babayigit proposed a fuzzy bi-objective mathematical model in order to minimize the total number of operators and number of tardy jobs simultaneously. The mathematical model developed performed several tasks at the same time, such as deciding number of cells to open, deciding cell sizes, assigning products to cells, determining the sequence of products in each cell. Fuzzy model was utilized to deal with the conflicts inherent in the problem. The results showed that fuzzy gave a chance to acquire solutions according to preferences. In the same year, Süer and Tummaluri (2008) discussed operator assignments in multi-period environment and learning and forgetting in labor-intensive cells. Furthermore, in order to minimize makespan, machine requirements and intra-cell manpower transfers, Süer, Cosner and Patten (2009) developed mathematical models for cell loading and product sequencing. Later, Süer, Kamat, Mese, and Huang (2013) proposed math models for manpower allocation and cell loading to minimize total tardiness in the presence of multiple cells.

There have been several studies conducted specializing on scheduling in a synchronized environment. Burdbidge (1975) proposed a simplified means in controlling manufacturing process resulting in a Period Batch Control (PBC). This approach allowed different activities being grouped into stages where product mix moved from one to stage to the next at the end of time period. In 1984, Whybark reported that Kumero Oy implemented another approach of product grouping into five families resulting in the division of manufacturing process into five stages. A repetitive cycle of five weeks was conducted consisting of a new product family was released to the first stage each week leading this product family moved from one stage to the next at the end of every week.

Uniform Time Bucket was suggested by Süer in 1989 and various heuristics and mathematical model were developed to determine product grouping for each time bucket. In this approach, planning periods are divided into time buckets and manufacturing processes are clustered into stages. The products moves from one stage to the subsequent stage at the end of each time bucket. To illustrate the problem, consider a 5-stage production system. If a job (S_t) is scheduled to be completed at the end of time bucket (t), then it should be processed at stage 4 in period (t-1), at stage 3 in period (t-2) and so on as shown in Table 1.

Table 1: Uniform time bucket approach (Suer and Yarimoglu 2013)

	TIME BUCKETS							
STAGE	…	t-5	t-4	t-3	t-2	t-1	t	…
1		S_{t-1}	S_t					
2			S_{t-1}	S_t				
3				S_{t-1}	S_t			
4					S_{t-1}	S_t		
5						S_{t-1}	S_t	

.

The objective of this paper is to sequence products with multiple cells in synchronized flow environment by minimizing number of time buckets where available manpower is exceeded. Mathematical modeling approach is employed to solve this problem. To the best knowledge of authors, this is the first attempt to solve product scheduling decisions with multiple cells assignments in a synchronized flow environment where number of periods with insufficient capacity is minimized.

3. Problem Statement

The synchronous manufacturing approach proposed here was implemented in a jewelry company (see Suer 1993). This paper is using 12 products as an example and manufacturing processes were grouped into four stages. The number of time buckets is uniform and determined based on the number of products, number of cells and number of stages. For example purpose, the number of cells used is two. The 12 products are assigned into two uniform cells with the same number of operators, therefore a maximum of 6 time buckets (=12/2) is available.

In the previous study, Yarimoglu and Suer (2009) used the couple of steps to determine the number of time buckets where available manpower is exceeded is minimized. The first step was allocating the number of operators to stages. They have developed a mathematical model to perform operator allocation to stages in order to maximize production rate. The next step is to determine the required number of time buckets for each product based on their production rate and demand. The final task is to put these products in order so that the number of time buckets where available manpower is exceeded is minimized. However, in this study, the mathematical model is modified to minimize the number of time buckets where available manpower is exceeded with multiple cells.

In the example provided in Table 2, there are twelve products considered with their optimal manpower levels for each stage based on a crew size of 20 workers for each cell. Assuming the first phase of manpower allocation has been conducted, the optimal allocation of workers for product 1 is 4, 6, 5, and 5, workers for stages 1, 2, 3, and 4, respectively. Products 1-6 are assigned to cell 1 and products 7-12 are assigned to cell 2 to illustrate the problem as given in Table 3. Even though 12 products are sequenced in 6 time buckets, a planning horizon of 9 [=12/(number of cells)+(number of stages-1)] buckets are considered in the planning horizon due to the effect of synchronization.

Table 2: Manpower levels for 12 Products

	Products											
Stages	1	2	3	4	5	6	7	8	9	10	11	12
1	4	5	6	6	5	7	3	5	5	3	6	3
2	6	5	6	4	3	6	5	7	5	5	7	4
3	5	5	3	6	5	5	6	5	7	10	4	8
4	5	5	5	4	7	2	6	3	3	2	3	5
Total manpower	20	20	20	20	20	20	20	20	20	20	20	20

Table 3: Initial random sequence of products from 1 to 12 in 2 cells

Cell 1	Period /Bucket								
	1	2	3	4	5	6	7	8	9
Product	1	2	3	4	5	6			
Stage 1	4	5	6	6	5	7	5.5	5.5	5.5
Stage 2	4	6	5	6	4	3	6	5.0	5.0
Stage 3	5	5	5	5	3	6	5	5	4.8
Stage 4	3	4	2	5	5	5	4	7	2
Manpower needed	16	20	18	22	17	21	20.5	22.5	17.3
Remaining manpower	4	0	2	-2	3	-1	-0.5	-2.5	2.67
Cell 2	**Period /Bucket**								
	1	2	3	4	5	6	7	8	9
Product	7	8	9	10	11	12			
Stage 1	3	5	5	3	6	3	4.2	4.2	4.2
Stage 2	5	5	7	5	5	7	4	5.5	5.5
Stage 3	2	3	6	5	7	10	4	8	6.7
Stage 4	7	6	4	6	3	3	2	3	5
Total manpower	17.0	19.0	22.0	19.0	21.0	23.0	14.2	20.7	21.3
Remaining manpower	3	1	-2	1	-1	-3	5.83	-0.67	-1.33

A product that enters the cell in time bucket 1 in stage 1 moves to stage 2 in time bucket 2; moves to stage 3 in time bucket 3 and so on. Finally, it leaves the system at the end of time bucket 4 after stage 4 operation(s) is completed. Grey cells that are at the left bottom show the manpower levels based on the scheduling decisions made in previous periods. The black cells on the right hand of the table are the average of corresponding manpower levels at that stage as manpower levels estimation for the next three periods. For example the estimate for stage 1 cell 2 is calculated as (3+5+5+3+6+3)/6 = 4.2. The integer number means that there is a floating manpower ready to be shared in each needed time bucket.

It is not desirable to exceed the available manpower capacity in any of the time buckets. The remaining manpower row shows the extra manpower left after allocation is made and is calculated as (20 – total manpower assigned in that bucket). For instance, for time bucket 1 cell 1 (t = 1), the remaining manpower is 2 [20 – (4 + 4 + 5 + 3)]. The negative numbers show that there is a shortage in the manpower allocation. In Table 3, there are four time buckets in cell 1 and five time buckets in cell 2 with manpower shortages. In cell 1 the shortages are in time bucket 4 (-2), in time bucket 6 and 7 (-1) and in period 8 (-3). In cell 2, the shortages are in time bucket 3 (-2), in time bucket 5 (-1), in time bucket 6 (-3) and in time bucket 8 and 9 (-1). Total shortages are 6 workers for cell one and 8 for cell two.

If this problem is solved with single cell sequencing approach, each cell will be treated individually. Using math model that Yarimoglu (2009) developed, the result of product sequence are 6-1-3-2-4-5 in cell one and 12-9-7-10-11-8 with 2.3 manpower shortage in cell one and 8 manpower shortage in cell two. So in total there are 10.3 manpower shortages for two cells. The result is illustrated in the table 4 below.

Table 4: Sequence of products from 1 to 12 in 2 cells

Cell 1	Period /Bucket								
	1	2	3	4	5	6	7	8	9
Product	6	1	3	2	4	5			
Stage 1	7	4	6	5	6	5	5.5	5.5	5.5
Stage 2	4	6	6	6	5	4	3	5.0	5.0
Stage 3	5	5	5	5	3	5	6	5	4.8
Stage 4	3	4	2	2	5	5	5	4	7
Manpower needed	19.0	19.0	19.0	18.0	19.0	19.0	19.5	19.5	22.3
Remaining manpower	1	1	1	2	1	1	0.5	0.5	-2.3
Cell 2	Period /Bucket								
	1	2	3	4	5	6	7	8	9
Product	12	9	7	10	11	8			
Stage 1	3	5	3	3	6	5	4.2	4.2	4.2
Stage 2	5	4	5	5	5	7	7	5.5	5.5
Stage 3	2	3	8	7	6	10	4	5	6.7
Stage 4	7	6	4	5	3	6	2	3	3
Total manpower	17.0	18.0	20.0	20.0	20.0	28.0	17.2	17.7	19.3
Remaining manpower	3	2	0	0	0	-8	2.83	2.33	0.67

In general, manpower shortage can be handled either by reducing quantity to be produced for those particular products or by bringing additional workers from other cells or production departments, if they are available. However, this manpower allocation shortage for each time bucket could be anticipated if the time bucket of each cell is calculated as a synchronized system. This will allow manpower transfer from cells as needed. In this example, manpower shortage of time bucket 6 could be reduced to 7 by allocating the extra manpower of the same bucket in cell one to cell two.

4. Methodology

The objective is to determine the sequence for *n* products in *k* cells such that the number of time buckets in which available capacity is exceeded is minimized. The mathematical model to solve the problem is given below with indices, parameters and decision variables (The model has been given for the example problem to reduce the complexity of the notation).

<u>*Indices:*</u>

i	*product index*
j	*bucket index*
k	*cell index*
l	*total period index*
s	*stage index*

<u>*Parameters:*</u>

M_{si}	*manpower level for stage s of product i*
E_j	*total manpower level already committed in bucket j in all cell (based on decisions made in previous periods or anticipated in future periods)* (Values of this parameter for this example problem, $E_1=(4+5+3)+(5+2+7)=26$; $E_2=(5+4)+(3+6)=18$; $E_3=4+2=6$; $E_4=E_5=E_6=0$; $E_7=5.5+4.2=9.7$; $E_8=(5.5+5)(4.2+5.5)=20.2$; $E_9=(5.5+5+4.8)+(4.2+5.5+6.7=31.7)$
T	*total manpower available in the cell in every bucket*
n	*number of products to be sequenced (assumed to be 12 products)*(i = 1, 2, 3 … 12)
L	*total number of buckets included in the planning horizon* $((n/2)+(s-1))$

<u>*Decision Variables:*</u>

X_{ijk}	*1 if product i is assigned to bucket j, cell k, 0 otherwise*
t_j	*total load in period j*
S_j	*1 if manpower shortage occurs in bucket j, 0 otherwise*

Objective Function:

$$Minimize\ z = \sum_{l=1}^{L} S_l \tag{1}$$

Subject to:

$$\sum_{j=1}^{J}\sum_{k=1}^{K} x_{ijk} = 1 \qquad for\ \ j = 1, \ldots, J \qquad for\ \ k = 1, \ldots, K \tag{2}$$

$$\sum_{i=1}^{n} x_{ijk} = 1 \qquad for\ \ i = 1, \ldots, n \tag{3}$$

$$1000 * S_j \geq t_j - T \qquad for\ j = 1, \ldots, J \tag{4}$$

$$\sum_{i=1}^{n}\sum_{k=1}^{K} m_{1i} * x_{i1\mathrm{k}} + E_1 = t_1 \tag{5}$$

$$\sum_{i=1}^{n}\sum_{k=1}^{K} m_{2i} * x_{i1\mathrm{k}} + \sum_{i=1}^{n}\sum_{k=1}^{K} m_{1i} * x_{i2\mathrm{k}} + E_2 = t_2$$

$$\sum_{i=1}^{n}\sum_{k=1}^{K} m_{3i} * x_{i1\mathrm{k}} + \sum_{i=1}^{n}\sum_{k=1}^{K} m_{2i} * x_{i2\mathrm{k}} + \sum_{i=1}^{n}\sum_{k=1}^{K} m_{1i} * x_{i3\mathrm{k}} + E_3 = t_3$$

$$\sum_{i=1}^{n}\sum_{k=1}^{K} m_{4i} * x_{ij\mathrm{k}} + \sum_{i=1}^{n}\sum_{k=1}^{K} m_{3i} * x_{i(j+1)\mathrm{k}} + \sum_{i=1}^{n}\sum_{k=1}^{K} m_{2i} * x_{i(j+2)\mathrm{k}} + \sum_{i=1}^{n}\sum_{k=1}^{K} m_{1i} * x_{i(j+3)\mathrm{k}} + E_{(\mathrm{j}+3)} = t_{(j+3)} \qquad for\ all\ j{=}1{,}2{,}3$$

$$\sum_{i=1}^{n}\sum_{k=1}^{K} m_{4i} * x_{i4\mathrm{k}} + \sum_{i=1}^{n}\sum_{k=1}^{K} m_{3i} * x_{i5\mathrm{k}} + \sum_{i=1}^{n}\sum_{k=1}^{K} m_{2i} * x_{i6\mathrm{k}} + E_7 = t_7$$

$$\sum_{i=1}^{n}\sum_{k=1}^{K} m_{4i} * x_{i5} + \sum_{i=1}^{n}\sum_{k=1}^{K} m_{3i} * x_{i6\mathrm{k}} + E_8 = t_8$$

$$\sum_{i=1}^{n}\sum_{k=1}^{K} m_{4i} * x_{i6\mathrm{k}} + E_9 = t_9$$

The objective function minimizes the number of time buckets where available manpower is not sufficient (Eq.1). Equation (2) assures that every product is assigned to a bucket. Equation (3) guarantees that each bucket in each cell has a product assigned to it. According to Equation (4), if the total load of bucket j exceeds T, y_j takes a value of 1. All of the equations starting with (5) are used to calculate the total load in each bucket.

The following optimal solution is obtained for the example problem when mathematical model is solved: 12-5-4-11-2-9 in cell one and 7-6-10-1-8-3 in cell two with only one time bucket (time bucket 5) with total 8 manpower shortages. This result is illustrated in Table 5 below. Compared to the previous example that utilizes single cell sequencing approach, the manpower shortage is reduced to 2.3 and the number of time buckets with shortages is reduced from two time buckets to one bucket. In this example, it is proven that the multiple cell loading approach is better in reducing the the number of time buckets that have shortages (considering all cells simultaneously).

A couple of experiments is conducted to prove the validity of the developed mathematical model. The first experiment is carried out with 10 products, 20 total of manpower needed, 5 stages and two cells. Then, total manpower allocation needed is altered into different numbers with the same number of products, cells and stages. The alternative total manpower levels allocated are 18, 19, 21 and 22. Later, 21 products with 20 total manpower allocations with 5 stages are implemented into 3 cells. The results are discussed in section 5.

Table 5: Sequence of products from 1 to 12 in 2 cells with multiple cells loading approach

Cell 1									
Period	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Product	**12**	**5**	**4**	**11**	**2**	**9**			
Stage 1	3	5	6	6	5	5	5.0	5.0	5.0
Stage 2	4	4	3	4	7	5	5	4.7	4.7
Stage 3	5	5	8	5	6	4	5	7	5.8
Stage 4	3	4	2	5	7	4	3	5	3
Manpower needed	15	18	19	20	25	18	18	22	19
Remaining manpower	5	2	1	0	-5	2	2	-1.7	1.5

Cell 2									
Period	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Product	**7**	**6**	**10**	**1**	**8**	**3**			
Stage 1	3	7	3	4	5	6	4.7	4.7	4.7
Stage 2	5	5	6	5	6	7	6	5.8	5.8
Stage 3	2	3	6	5	10	5	5	3	5.7
Stage 4	7	6	4	6	2	2	5	3	5
Total manpower	17	21	19	20	23	20	21	17	21
Remaining manpower	3	-1	1	0	-3	0	-1	3.5	-1.2
Total manpower for 2 cells	32.0	39.0	38.0	40.0	48.0	38.0	38.7	38.2	39.7

5. Experiments and Results

5.1 Experiment 1(10 products, 20 manpower level, 5 stages, 2 cells)

The initial manpower allocation needed for each of 5 stages and each product are shown in Table 6. The next step is to assign products into two cells (Table 7). In this section, it has been done randomly. In the initial random sequence, there are total 6 time buckets with manpower shortages. In cell one, time buckets 2, 3, 6 and 9 have total of 5 manpower shortages. In cell two, time buckets 4, 5 and 6 have total 10 manpower shortages.

Table 6: Manpower levels for 10 Products of total 20 manpower

	Products									
Stages	1	2	3	4	5	6	7	8	9	10
1	3	5	3	2	2	3	2	4	3	8
2	5	3	2	6	2	2	2	4	3	3
3	4	4	2	6	5	2	5	4	5	3
4	6	4	8	3	5	8	5	4	5	3
5	2	4	5	2	5	5	5	4	3	3
Total manpower	20	20	20	19	19	20	19	20	19	20
Cell capacity	20	20	20	20	20	20	20	20	20	20

Table 7: Initial random sequence of products from 1 to 10 in 2 cells

Cell 1	Period /Bucket								
	1	2	3	4	5	6	7	8	9
Product	1	2	3	4	5				
Stage 1	3	5	3	2	2	3	3	3	3
Stage 2	4	5	3	2	6	2	3.6	3.6	3.6
Stage 3	6	4	4	4	2	6	5	4.2	4.2
Stage 4	3	4	5	6	4	8	3.0	5.0	5.2
Stage 5	2	3	2	4	2	4	5	2.0	5.0
Manpower needed	18	21	17	18	16	23	19.6	17.8	21
Remaining manpower	2	-1	3	2	4	-3	0.4	2.2	-1

Cell 2	Period /Bucket								
	1	2	3	4	5	6	7	8	9
Product	6	7	8	9	10				
Stage 1	3	2	4	3	8	4	4	4	4
Stage 2	4	2	2	4	3	3	2.8	2.8	2.8
Stage 3	6	4	2	5	4	5	3	3.8	3.8
Stage 4	3	4	5	8	5	4.0	5	3.0	5
Stage 5	2	3	2	4	5	5	4	3	3.0
Total manpower	18	15	15	24	25	21	18.8	16.6	18.6
Remaining manpower	2	5	5	-4	-5	-1	1.2	3.4	1.4

The solved problem results in following product sequences: 7-2-9-1-6 in cell one and 3-10-8-5-4 in cell two. This result has eliminated the manpower shortage into 0 manpower shortage. The result is illustrated in Table 8 below.

Table 8: Sequence of products from 1 to 10 in 2 cells with multiple cells loading approach

Cell 1	Period /Bucket								
	1	2	3	4	5	6	7	8	9
Product	7	2	9	1	6				
Stage 1	2	5	3	3	3	3.2	3.2	3.2	3.2
Stage 2	4	2	3	3	5	2	3	3	3
Stage 3	6	4	5	4	5	4	2	4	4
Stage 4	3	4	5	5	4	5	6.0	8.0	5.6
Stage 5	2	3	2	4	5	4	3	2.0	5.0
Manpower needed	17	18	18	19	22	18.2	17.2	20.2	20.8
Remaining manpower	3	2	2	1	-2	1.8	2.8	-0.2	-0.8

Cell 2	Period /Bucket								
	1	2	3	4	5	6	7	8	9
Product	3	10	8	5	4				
Stage 1	3	8	4	2	2	3.8	3.8	3.8	3.8
Stage 2	4	2	3	4	2	6	3.4	3.4	3.4
Stage 3	6	4	2	3	4	5	6	4	4
Stage 4	3	4	5	8	3	4.0	5	3.0	4.6
Stage 5	2	3	2	4	5	3	4	5	2.0
Total manpower	18	21	16	21	16	21.8	22.2	19.2	17.8
Remaining manpower	2	-1	4	-1	4	-1.8	-2.2	0.8	2.2
Total manpower for 2 cells	35	39	34	40	38	40	39.4	39.4	38.6

5.2 Experiment 2 (10 products various manpower levels, 5 stages, 2 cells)

In the experiment with various manpower levels, the same steps were taken. Only the manpower allocation levels for each stage are adjusted according to the number of manpower allocation. The example of the adjusted manpower is illustrated in Table 9. The results of the multiple cell scheduling with different manpower allocation are summarized in Table 10.

Table 9: Sequence of products from 1 to 10 in 2 cells with multiple cells loading approach

Stages	1	2	3	4	5	6	7	8	9	10
1	3	4	3	2	2	3	2	4	3	6
2	4	3	2	5	2	2	2	4	3	3
3	4	3	2	5	4	2	4	3	4	3
4	5	4	6	3	4	6	4	3	4	3
5	2	4	5	2	5	5	5	4	3	3
Total manpower	18	18	18	17	17	18	17	18	17	18
Cell capacity	18	18	18	18	18	18	18	18	18	18

Table 10: Summary of results of multiple cell loading with different manpower allocation

Number of Manpower	Product Sequence Cell 1	Product Sequence Cell 2
18	1-2-3-8-6	5-4-7-9-10
19	3-9-2-4-1	8-5-10-6-7
21	8-10-5-2-3	6-1-7-4-9
22	1-6-8-2-10	9-4-3-5-7

5.3 Experiment 3 (21 products, 20 manpower level, 4 stages, 3 cells)

For 21 products, the initial manpower allocation needed for each of 4 stages and each product are shown in Table 11. The next step is to sequence products (randomly) into three cells (Table 12). In the initial random sequence, there are total 13 time buckets with manpower shortages. With 21 products and 4 stages, there are 10 time buckets with 20 manpower allocation for each cell. In cell one, time buckets 4, 6, 8 and 10 have total of 6.2 manpower shortages. In cell two, time buckets 2, 4, 5 and 7 have total 7 manpower shortages. Total of 5.4 manpower shortages are observed within cell three in time buckets 2, 4, 6, 9 and 10.

Table 11: Manpower levels for 21 Products of total 20 manpower

	Products																				
Stages	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	4	5	6	6	5	7	3	5	5	3	6	3	4	5	6	6	5	7	3	5	3
2	6	5	6	4	3	6	5	7	5	5	7	4	6	5	6	4	3	6	5	7	4
3	5	5	3	6	5	5	6	5	7	10	4	8	5	5	3	6	5	5	6	5	8
4	5	5	5	4	7	2	6	3	3	2	3	5	5	5	5	4	7	2	6	3	5
Total manpower	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
Cell Capacity	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20

Table 12: Initial random sequence of products from 1 to 21 in 3 cells

Cell 1	Period /Bucket									
	1	2	3	4	5	6	7	8	9	10
Product	1	2	3	4	5	6	7			
Stage 1	4	5	6	6	5	7	3	5.1	5.1	5.1
Stage 2	4	6	5	6	4	3	6	5	5.0	5.0
Stage 3	5	5	5	5	3	6	5	5	6	5.0
Stage 4	3	4	2	5	5	5	4	7	2	6
Manpower needed	16	20	18	22	17	21	18	22.1	18.1	21.1
Remaining manpower	4	0	2	-2	3	-1	2	-2.1	1.86	-1.1

Cell 2	Period /Bucket									
	1	2	3	4	5	6	7	8	9	10
Product	8	9	10	11	12	13	14			
Stage 1	5	5	3	6	3	4	5	4.4	4.4	4.4
Stage 2	4	7	5	5	7	4	6	5	5.6	5.6
Stage 3	5	4	5	7	10	4	8	5	5	6.3
Stage 4	3	5	3	3	3	2	3	5	5	5
Manpower needed	17	21	16	21	23	14	22	19.4	20	21.3
Remaining manpower	3	-1	4	-1	-3	6	-2	0.57	0	-1.3

Cell 3	Period /Bucket									
	1	2	3	4	5	6	7	8	9	10
Product	15	16	17	18	19	20	21			
Stage 1	6	6	5	7	3	5	3	5.0	5.0	5.0
Stage 2	5	6	4	3	6	5	7	4	5.0	5.0
Stage 3	2	3	3	6	5	5	6	5	8	5.4
Stage 4	7	6	4	5	4	7	2	6	3	5
Total manpower	20.0	21.0	16.0	21.0	18.0	22.0	18.0	20	21	20.4
Remaining manpower	0.0	-1.0	4.0	-1.0	2.0	-2.0	2.0	0.0	-1.0	-0.4

The solved problem results in following product sequences: 4-20-16-17-15-14 in cell one, 9-7-8-18-1-2-19 in cell two and 8-17-11-13-10-21-3 in cell three. This result has eliminated the manpower shortage into 1 manpower shortage in bucket 10 within cell 3. The result is illustrated in table 13 below.

Table 13: Sequence of products from 1 to 21 in 3 cells with multiple cells loading approach

Cell 1	Period /Bucket									
	1	2	3	4	5	6	7	8	9	10
Product	4	20	16	12	15	14	5			
Stage 1	6	5	6	3	6	5	5	5.1	5.1	5.1
Stage 2	4	4	7	4	4	6	5	3	4.7	4.7
Stage 3	5	5	6	5	6	8	3	5	5	5.4
Stage 4	3	4	2	4	3	4	5	3	5	7
Manpower needed	18	18	21	16	19	23	18	16.1	19.9	22.3
Remaining manpower	2	2	-1	4	1	-3	2	3.86	0.14	-2.29

Cell 2	Period /Bucket									
	1	2	3	4	5	6	7	8	9	10
Product	9	7	8	18	1	2	19			
Stage 1	5	3	5	7	4	5	3	4.6	4.6	4.6
Stage 2	4	5	5	7	6	6	5	5	5.6	5.6
Stage 3	5	4	7	6	5	5	5	5	6	5.6
Stage 4	3	5	3	3	6	3	2	5	5	6
Manpower needed	17	17	20	23	21	19	15	19.6	21.1	21.7
Remaining manpower	3	3	0	-3	-1	1	5	0.43	-1.14	-1.71

Cell 3	Period /Bucket									
	1	2	3	4	5	6	7	8	9	10
Product	6	17	11	13	10	21	3			
Stage 1	7	5	6	4	3	3	6	4.9	4.9	4.9
Stage 2	5	6	3	7	6	5	4	6	5.3	5.3
Stage 3	2	3	5	5	4	5	10	8	3	5.7
Stage 4	7	6	4	2	7	3	5	2	5	5
Total manpower	21.0	20.0	18.0	18.0	20.0	16.0	25.0	20.9	18.1	20.9
Remaining manpower	-1	0	2	2	0	4	-5	-0.86	1.86	-0.86
Total Manpower	56.0	55.0	59.0	57.0	60.0	58.0	58.0	56.6	59.1	64.9

6. Conclusion and Future Research

Based on the results, it can be concluded that the mathematical model developed for multiple cell loading approach is able to solve problems with different number of products, stages and cells. However, the mathematical model only focuses on minimizing the number time buckets with manpower shortages for all cells. It does not address minimization of the maximum manpower shortage in the time bucket nor total manpower shortage..

For future research, it is recommended to expand the mathematical model and include multiple objectives in minimizing the total manpower shortages simultaneously with the minimum of time bucket with manpower allocation shortage. And genetic algorithm approach could also be utilized to solve multiple cell loading approach.

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