An operator assignment model in reconfigurable labour-intensive manufacturing cells

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Abstract. This paper aims to propose a new mixed integer programming model to solve simultaneously 2-type cell production systems; divided cells and rotating cells by a reconfigurable labour-intensive manufacturing. In general, the divided cells are included in Cellular Manufacturing (CM) and the rotating cells are in Cell Production Systems (CPS). The advantages of CM and CPS have been widely documented by the large amount of literature. However, almost all manufacturing sites have the traditional assembly lines separately where one or several operators carry out parts/all of the operations in a cell. On the other hand, some advanced manufacturing sites have adopted both CM and CPS in order to absorb variability of demand and operators under the environment of limited multi-skilled operators. Especially, if the operators are replaced by robots, they are called robot cells which are focused as an important component of the cyber-physical system in the real world. Therefore, this paper tackles to propose an operator assignment model in reconfigurable labour-intensive manufacturing cells. Firstly, the traditional model is redefined by new parameters. Secondly, the new proposed model is solved by 2-phase optimization problems. Finally, the new model is compared with the traditional model by using numerical experiments.

Keywords: Operator assignment model, Cellular manufacturing, Cell production systems, Robot cells

1. INTRODUCTION

The advantages of cellular manufacturing (CM) and Cell Production Systems (CPS) have been widely documented by a large amount of literature. The major advantages of CM are reduced lead time and work-in-process (WIP) inventory, improved visibility and quality, simplified scheduling and improved work environment due to team work. In fact, CM and CPS continue to be popular in both the real world and the literature. Generally, the literature has two streams of concepts. One deals with machine-intensive cells and the other with labour-intensive cells.

Machine-intensive cells mean that the operator's role is usually limited to loading and unloading the machines and machining times usually do not vary from one operator to the next. In other words, operator involvement is limited to machine-intensive cells as most of the processing is done by automated machines (Süer and Tummaluri, 2008). Generally, the so-called CM in machine-intensive cells is defined as a component of a cell formation problem (CFP) or a reconfigurable manufacturing system (RMS). Especially CFP is one of the most popular research fields regarding CM in machine-intensive cells. According to Papaioannou and Wilson (2010), CM is an application of Group Technology (GT), and it is common to use mathematical programming models with an objective function to minimize the total number of cellular movements. Other mathematical programming formulations involve cost objective functions. Furthermore, RMS is also a new paradigm, designed specifically for rapid modification in production capacity and functionality through system reconfiguration (Koren et al., 1999; Hoda and ElMaraghy, 2006; Koren and Shpitalni, 2010). This is the reason why RMS has lower reconfiguration costs, more adjustable machine capacity and function than CFP (Ossama et al., 2014). Consequently, in these fields, objective functions focus on more rapid modifications and less cellular movements (i.e. lower cost) based on hardware-centred design.

In labour-intensive cells, on the other hand, the assignment of operators plays a major role for the performance of the cell and directly affects the output of the cell. Generally, labour-intensive manufacturing cells are characterized by the presence of lightweight, small, inexpensive machines and equipment where continuous operator attendance and involvement is required. Consequently, the cell performance is not only affected by how the cells are loaded, but also by the performance of the operators. Thus, issues like operator skill levels, skill-based operation times, cross-training, learning rates, and movement of operators between operations and cells become too important to neglect (Süer and Tummaluri, 2008).

Therefore, focusing on the functions in labour-intensive cells, the so-called CM in labour-intensive cells is defined as a production system where all divided tasks are operated by several semi-skilled workers and a short line staffed with several multi-skilled operators. Many tasks within a cell are divided into different operations. Each operation is operated by one or more workers (Yu et al., 2012; 2013a; 2013b; 2014). Normally, there are no buffers between two operators in a cell (Kasmo et al., 2013). In other words, in the case of no buffers, a cell implies a paced assembly line. On the other hand, Honiden and Hida (2004) offer a comparison of production systems for assembly cells with some buffers. Their models have both unlimited and limited buffers in a cell. For some buffers, a cell implies an un-paced assembly line. Sengupta and Jacobs (2004) compare assembly cells and assembly lines for a variety of operating environments. The model is effective for simulation in serial and parallel cells considering team working environments. However, according to Bidanda et al. (2005) and Süer and Tummaluri (2008), limited research has so far been conducted to investigate the effectiveness of the operator assignment, skill levels, and skill-level based operation times on the performance of CM systems.

Furthermore, focusing on the approaches in labour-intensive cells, there are two streams of concepts. One deals with the large volume production of a narrow variety of products and the other with the low volume production of a wide variety of products. In case of the large volume production of a narrow variety of products, the well-known traditional paced line deals with assembly line balancing problems (e.g. Becker and Scholl, 2006) or sequencing problems (e.g. Boysen et al. 2009) considering cycle time, work elements, and a precedence diagram on production planning. On the other hand, the low volume production of a wide variety of products has been one of the most important production concepts in the recent changeable demand and therefore in the global competition. Most of the research fields deal with paced or un-paced cells in labour-intensive cells where production rate, learning levels and team-work are based on human skill levels and human resource planning. Recent papers are mostly based on mixed integer and integer programming models regarding various divided cells on CM: Süer, 1996; Süer and Bera, 1997, 1998a, 1998b; Süer and Tummmaluri, 2008; McDonalda et al., 2009; Süer and Alhawari, 2012; Süer et al., 2013; Egilmez and Süer, 2011, 2013, 2014.

On the other hand, Kaku et al. (2008, 2009) propose a new theoretical model for line-cell conversion regarding various rotating cells on CPS. The model deals with CPS where a worker does all operational and managerial tasks by her- or himself. Such a Japanese CPS has been called “Seru” in Japan and other Asian countries. Seru, a new production organization, has been adopted by many leading global companies, such as Samsung, Sony, Canon, Panasonic, LG, and Fujitsu (Stecke et al., 2012). Seru overcame a lot of disadvantages inherent in Toyoya Production System (TPS) and brought amazing benefits to Seru users. For example: 1) Seru requires a much smaller workforce, 2) it can greatly reduce space requirements, and 3) it can reduce lead time, setup time, WIP inventories, finished-product inventories, and cost.

In general, almost all manufacturing sites have separately the assembly lines where one or several operators carry out parts/all of the operations in a cell. On the other hand, some advanced manufacturing sites have adopted both of them in order to absorb variability of demand and operators. In particular, the reconfigurable production lines with both of CM and CPS are more effective to absorb unstable demand under the environment of limited multi-skilled operators and has only recently been adopted by some global companies. When the operators are replaced by robots in the real world, they are called robot cells and focused as an important component of the cyber-physical system in the large number of recent reports.

Therefore, the purpose of this paper is to propose a new mixed integer programming model to minimize the number of operators in reconfigurable labour-intensive cells, and to solve not only CM but also CPS simultaneously. Section 2 presents the problem statement of this study. The new model is introduced in Section 3 and Section 4 presents some numerical experiments and results. The results of this paper are summarized in Section 5.

2. PROBLEM STATEMENT

There are n types of products with the demand rate of d_i in a period for product i. All products are produced by conducting s operations in turn, and the unit processing time of product i on operation o is t_{io}. By allocating multiple operators, say M_{iok} with configuration k, to operation o, the production rate of product i on operation o can be represented by M_{iok}/t_{io}. The output rate of product i is given by the minimum value of production rates among all operations, i.e., $\min\{M_{i1k}/t_{i1}, M_{i2k}/t_{i2}, ..., M_{isk}/t_{is}\}$. This means that by allocating more operators to operations, the output rate will be increased, but the rate of increase will be reduced. In addition, there may be a limitation on the maximum number of operators in every operation. Thus, it is generally impossible to process all product types in a single cell under the available production time h in any periods. The present study assumes that the maximum number of cells is m. The b_{jk} denotes the number of operators with configuration k in cell $j = 1,\ldots,m$.

The problem involves the following decision variables; the number of operators allocated to each operation in each cell, and the allocation of products to cells. The total number of operators required is minimized while the demand of all products is satisfied. Some previous papers (e.g. Süer and Tummmaluri, 2008) solve the problem sequentially, i.e., in the first phase, the maximum production rate and operator allocation for each product and the number of available operators are determined as shown in Figure 1. In the second phase, optimal operator levels and loads in each cell are determined as shown in Figure 1.

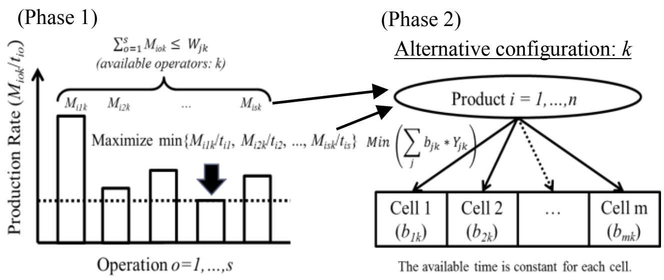

Figure 1: The concept figure of the 2-phase model

3. MODELLING

The object of this paper is to build the deterministic reconfigurable production modeling with both CM and CPS. We assume that the first object is to determine optimal operator levels and loads in each cell. Products are assigned to cells and also the operator level for each cell is determined. These two tasks are also accomplished simultaneously by using a mixed integer programming model based on the previous model (Süer, 1996).

In this study, the following formulation is also added to the objective function to guarantee minimizing not only the total number of operators but also the total time required to produce all products. That is because the combination of optimal operator levels (:integer) might be plural. The Z' (:decimal) is obtained by dividing the total time required to produce all products by the total time available in a period ($h*m$). By this constitution, the optimal solution is determined uniquely.

$$Z' = (\sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{k=1}^{a_j} p_{ijk} * X_{ijk}) / \ (h * m)$$

The p_{ijk} values, i.e. the time required to produce product i in cell j with configuration k, are different between CM model and CPS model as follows.

(CM model)

The p_{ijk} values are obtained by dividing demand (d_i) by the corresponding production rates (R_{ik}) as the following formulation ($p_{ijk} = d_i/R_{ik}$). Consequently, the equation is transformed as follows,

$$\sum_{i=1}^{n} \frac{d_i}{R_{ik}} * X_{ijk} \le h * Y_{jk} \qquad \forall j, k$$

where, X_{ijk} and Y_{jk} are decision variables.

If the production rate (R_{ik}) is also a decision variable, the equation is a non-linier constraint. In this study, the R_{ik} is defined as a parameter in the phase 2 and thus is calculated by using a simple mixed integer programming in the phase 1. We can see it in the end of this section.

(CPS model)

A worker on CPS does all operational and managerial tasks by her- or himself. A rotating cell is often organized in a U-shaped layout with several workers. Each worker assembles an entire product from start to finish without disruption. The assembly tasks are performed on fixed stations, thus workers walk from station to station. Multiple multi-skilled workers are often assigned to rotating cells. It depends on the requirement of production capability of cells, cell size, the complexity of the process, and so on. In the case of multiple workers, cycle time, i.e. the production rate of the lowest multi-skilled worker, is the bottleneck. However, we must note that the output rate for product i in the case of rotating cells on CPS is constant regardless of operator skills in this model. The unit standard time for operation o of product i is t_{io}. Therefore, cycle time is calculated by $\sum_{o=1}^{s} t_{io}$, and thus production rates are $(1/\sum_{o=1}^{s} t_{io})$. Consequently, the production rate for product i assigned to cell j with configuration k on CPS is defined as $((1/\sum_{o=1}^{s} t_{io}) * b_{jk})$, where the b_{jk} is the manpower required for configuration k in cell j.

(Reconfigurable model)

In the reconfigurable model, these two models are integrated as follows. The p_{ijk} values are obtained by the following equation. The m' value is the number of cells on CM. The m value is the total number of CM and CPS.

$$p_{ijk} = \begin{cases} \dfrac{d_i}{R_{ik}}, & j = 1, 2, \dots, m' \\ \dfrac{d_i}{\left(\frac{1}{\sum_{o=1}^{s} t_{io}}\right) * b_{jk}}, & j = m' + 1, \dots, m \end{cases}$$

To consider setup times, a new constraint is added to the reconfigurable model (Süer and Bera, 1998a). The setup time is accounted for as long as an item is produced in that cell. The new decision variable Z_{ijk} takes a value of 1 if any fraction of product i has been assigned to cell j (regardless of configuration k), 0 otherwise. In other words, the Z_{ijk} value is a decision variable to confirm whether an item is produced in CM or not: $Z_{ijk} \geq \sum_{k=1}^{a_j} X_{ijk}$. Generally, the setup time on CPS should be less than that on CM.

Moreover, the q_i value is setup time for product i. The previous equation is modified to the following equation to consider setup time.

$$\sum_{i=1}^{n} (p_{ijk} * X_{ijk} + q_i * Z_{ijk}) \leq h * Y_{jk} \qquad \forall j, k$$

The X_{ijk} is allowed to take real and positive values. This means that lot-splitting is allowed (Süer and Bera, 1998). This variable indicates what fraction of a job has been assigned to cell j with configuration k, i.e. a product can be produced in more than one cell in the same period. As a result, each product might have been assigned to several cells to use cell capacity more efficiently.

Indices:

i	index set of products (i=1,2,…,n)
j	index set of cells (j=1,2,…,m)
k	index set of configurations (k=1,2,…,a_j)
o	index set of operations (o=1,2,….,s)

Variables:

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

Parameters:

n	the number of products
m	the total number of cells
a_j	the number of alternative configurations for cell j
s	the number of operations
u_{io}	the upper limit for operator level for operation o of product i
t_{io}	the unit standard time (standard operation time) for operation o of product i
w_{jk}	the total operators available in the cell j with configuration k
h	the time available in a period
m'	the number of cells on CM
d_i	the demand of product i
b_{jk}	the manpower required for configuration k in cell j
q_i	the setup time for product i

Decision variables:

R_{ik}	the production rate for product i with configuration k
M_{iko}	the operator level for operation o of product i with configuration k
X_{ijk}	the product i assigned to cell j with configuration k
Y_{jk}	the alternative configuration k for cell j
Z_{ijk}	Any fraction of product i assigned to cell j regardless of configuration k

(Phase 1)

The objective is to determine the optimal allocation of operators to operations such that the output rate is maximized for a given operator level based on the previous model (Süer, 1996). The output rate is determined based on the bottleneck operation. Alternative operator levels are generated for each product by using operation standard times. For each operator level, the number of operators needed to perform the operation is determined by using this model.

The objective function maximizes the output rate as given in equation (1). 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 the total number of operators.

Objective function:

$$Z_1 = Max \ \ (R_{ik}) \qquad (1)$$

Subject to:

$$(M_{iko}) * \left(\frac{1}{t_{io}}\right) - R_{ik} \geq 0 \qquad \forall i, k, o \qquad (2)$$

$$M_{iko} \le u_{io} \qquad \forall i,k,o \tag{3}$$

$$\sum_{o=1}^{s} M_{iko} \le w_{jk} \qquad \forall i,j,k \tag{4}$$

$$M_{iko} \qquad integer\ and\ positive \qquad \forall i,k,o$$

$$R_{ik} \qquad real\ and\ positive \qquad \forall i,k$$

(Phase 2)

The objective function minimizes the total number of operators and the total time required to produce all products as given in equation (5). Each product must be assigned to a cell as shown in equation (6). Equation (7) guarantees that each cell will have at most one configuration (i.e., operator level). Equation (8) establishes the upper limit on available capacity in each cell. Finally, equation (9) confirms whether a product is produced in cells or not.

Objective function:

$$Z_2 = Min\{ \sum_{j=1}^{m}\sum_{k=1}^{a_j} b_{jk} * Y_{jk} + (\sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{k=1}^{a_j} p_{ijk} * X_{ijk})/\ (h * m)\ \} \tag{5}$$

Subject to:

$$\sum_{j=1}^{m}\sum_{k=1}^{a_j} X_{ijk} = 1 \qquad \forall i \tag{6}$$

$$\sum_{k=1}^{a_j} Y_{jk} \le 1 \qquad \forall j \tag{7}$$

$$\sum_{i=1}^{n} (p_{ijk} * X_{ijk} + q_i * Z_{ijk}) \le h * Y_{jk} \qquad \forall j,k \tag{8}$$

$$Z_{ijk} \ge \sum_{k=1}^{a_j} X_{ijk} \qquad \forall i,j \tag{9}$$

$$X_{ijk} \qquad real\ and\ positie \qquad \forall i,j,k$$

$$Y_{jk} \ \in\ \{0,1\} \qquad \forall j,k$$

$$Z_{ijk} \ \in\ \{0,1\} \qquad \forall i,j,k$$

4. EXPERIMENTS

In the experiments of this section, the manufacturing process consists of 5 operations and 10 products. The standard times for operations 1, 2, 3, 4 and 5 are randomly generated from uniform distributions in the intervals of [0.04, 0.09], [0.28, 0.45], [0.37, 1.18], [0.47, 0.88] and [0.18, 0.45], respectively as shown in Table 4. 10 alternative operator levels are considered, namely [10…19] on CM and [1…10] on CPS, respectively. Unit transfer size is assumed and the output rate is determined based on the bottleneck operation. By using Table 1, the optimal production rate for product *i* with configuration *k* on CM is shown in Table 2. Furthermore, the output rate $(1/\sum_{o=1}^{s} t_{io})$ for product *i* on CPS in the case of a one-worker rotating cell is constant regardless of operator skills in this section. Consequently, the production rate $((1/\sum_{o=1}^{s} t_{io}) * b_{jk})$ for product *i* with configuration *k* on CPS is calculated as shown in Table 3.

Table 1: Standard unit processing times (Süer and Tummaluri, (2008))

	Operations				
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
3	0.06	0.29	1.18	0.86	0.18
4	0.04	0.31	0.55	0.47	0.40
5	0.08	0.41	0.43	0.74	0.43
6	0.07	0.32	1.18	0.55	0.45
7	0.09	0.37	0.46	0.49	0.26
8	0.08	0.28	0.49	0.61	0.29
9	0.04	0.34	0.81	0.62	0.34
10	0.07	0.43	0.74	0.87	0.43

Table 2: The optimal production rate for product *i* with configuration *k* on CM

	Configurations									
Product	10	11	12	13	14	15	16	17	18	19
1	3.41	4.44	4.55	5.26	5.41	5.68	6.67	6.82	7.89	7.95
2	3.45	4.05	4.84	5.26	5.41	6.45	6.76	6.90	7.89	8.06
3	3.39	3.45	3.49	4.24	4.65	5.08	5.56	5.81	5.93	6.78
4	4.26	5.00	5.45	6.38	6.45	7.27	7.50	8.51	9.09	9.68
5	4.05	4.65	4.65	4.88	5.41	6.76	6.98	6.98	7.32	8.11
6	3.13	3.39	3.64	4.24	4.44	5.08	5.45	5.93	6.25	6.67
7	4.35	5.41	6.12	6.52	7.69	8.11	8.16	8.70	10.20	10.81
8	4.08	4.92	6.12	6.56	6.90	7.14	8.16	8.20	9.84	10.20
9	3.23	3.70	4.84	4.94	5.88	5.88	6.17	6.45	7.41	8.06
10	2.70	3.45	4.05	4.60	4.65	4.65	5.41	5.75	6.76	6.90

Table 3: The production rate for product *i* with configuration *k* on CPS

	Configurations									
Product	1	2	3	4	5	6	7	8	9	10
1	0.47	0.93	1.40	1.86	2.33	2.79	3.26	3.72	4.19	4.65
2	0.48	0.96	1.44	1.92	2.40	2.88	3.37	3.85	4.33	4.81
3	0.39	0.78	1.17	1.56	1.95	2.33	2.72	3.11	3.50	3.89
4	0.56	1.13	1.69	2.26	2.82	3.39	3.95	4.52	5.08	5.65
5	0.48	0.96	1.44	1.91	2.39	2.87	3.35	3.83	4.31	4.78
6	0.39	0.78	1.17	1.56	1.95	2.33	2.72	3.11	3.50	3.89
7	0.60	1.20	1.80	2.40	2.99	3.59	4.19	4.79	5.39	5.99
8	0.57	1.14	1.71	2.29	2.86	3.43	4.00	4.57	5.14	5.71
9	0.47	0.93	1.40	1.86	2.33	2.79	3.26	3.72	4.19	4.65
10	0.39	0.79	1.18	1.57	1.97	2.36	2.76	3.15	3.54	3.94

4.1 The time available (*h*) in single-period

Generally, the value of *h*, i.e. the time available in a period, is set to the constant (e.g. 2,400 minutes (= 5 days * 8 hours *

60 minutes)) during the experiment. However, it might not be the constraint due to official holiday, periodic maintenance, machine failure, and so on. We study cases in which the parameter h ranged from 1,500 to 2,500 to confirm this supposition without setup time in this subsection.

In the experiment, we use the demand of single-period as shown in Table 4. The mean period demand for product i is randomly generated from uniform distribution in the interval of [2200, 7500]. Then, the period demand is summarized for each period. The variation in period demand is (+/-2%-20%) of the mean and in multiples of 50 units (Süer and Tummaluri, 2008). For example, Table 5 represents an example of the optimal solution on the reconfigurable model for period 1 as shown in Table 4. The optimal cell sizes are determined to be 18 and 19 operators for CM 1 and 2, 8 and 5 operators for CPS 1 and 2, respectively. The mathematical model also produces loads on each CM and CPS, and guarantees to minimize not only the total number of operators but also for the total time required to produce all products. However, the sequence of jobs on each cell has been determined randomly.

Table 4: Demand figures for single-period analysis

	Products									
Period	1	2	3	4	5	6	7	8	9	10
1	3,500	7,500	3,400	2,700	2,200	4,000	4,500	2,200	2,300	3,000

Table 5: The optimal solution of the reconfigurable model for period 1 ($h=1,600$)

Cell Type	Operators Range	Optimal Solution	Products / Processing time				Operation Time
CM 1	15-20	18	P1	P2	P8	P10	
			443	489	224	444	1,600
CM 2	15-20	19	P3	P6	P7	P9	
			502	397	416	285	1,600
CPS 1	3-8	8	P2	P4	P5		
			428	597	575		1,600
CPS 2	3-8	5	P2	P6			
			829	695			1,525
Total number of operators:		50			Total operation time:		6,325

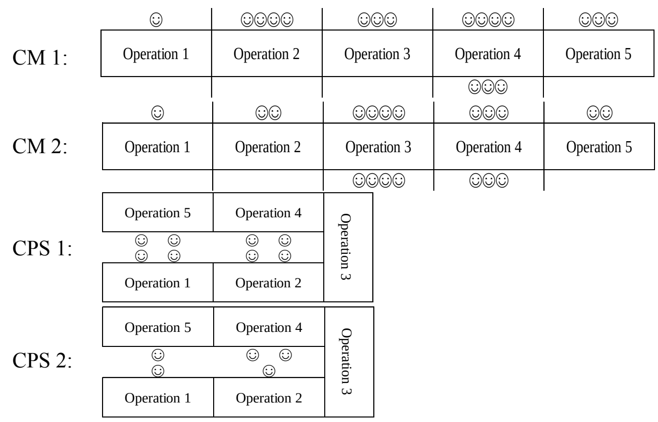

Figure 2: The first reconfigurable configuration of the optimal solution in Table 5

Table 6 shows the optimal solution of both the traditional model and the proposed model for the time available (h) in single-period. Figure 3 shows the number of operators and Figure 4 shows the ratio of the number of operators in reconfigurable model, respectively.

For the total number of operators required, the proposed model has a smaller number of operators than the traditional model in the all cases. The gap between them is almost the constant (i.e. 2 or 3 operators) regardless of the time available (h) in a period as shown in Table 6. This means the proposed model is more effective than the traditional model.

There is a huge configuration gap between 2,000 (h) and 2,100 (h) in the reconfigurable model. As the result of more detailed simulation, it occurs between 2,007 (h) and 2,008 (h), suddenly. This is because it comes up to the upper bound on the total number of operators, i.e. alternative configurations in CM and CPS on the time available of 2,008 (h).

Table 6: The optimal solution of each model on the available time in a period (h)

	Available Time (h)										
Traditional	1,500	1,600	1,700	1,800	1,900	2,000	2,100	2,200	2,300	2,400	2,500
CM 1	18	18	18	18	18	18	18	19	18	19	15
CM 2	19	19	16	19	15	15	13	19	19	16	19
CM 3	18	15	15	10	12	10	10				
Operators	55	52	49	47	45	43	41	38	37	35	34
Av.Op_time	1,489	1,572	1,696	1,738	1,859	1,925	2,061	2,187	2,209	2,378	2,436
Proposed											
CM 1	18	18	18	18	18	18	18	18	18	15	18
CM 2	15	19	15	19	19	19					
CPS 1	10	10	10	8	6	4	10	10	10	10	10
CPS 2	10	3	4				10	8	6	8	4
Operators	53	50	47	45	43	41	38	36	34	33	32
Av.Op_time	1,487	1,569	1,687	1,771	1,842	1,917	2,031	2,174	2,292	2,395	2,364

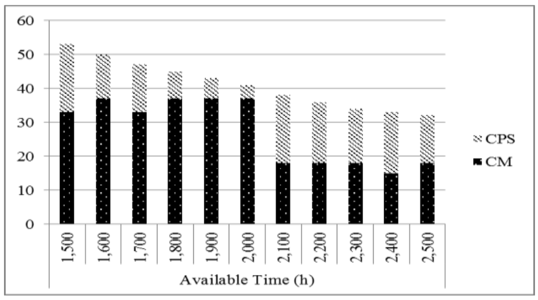

Figure 3: The number of operators in the reconfigurable model

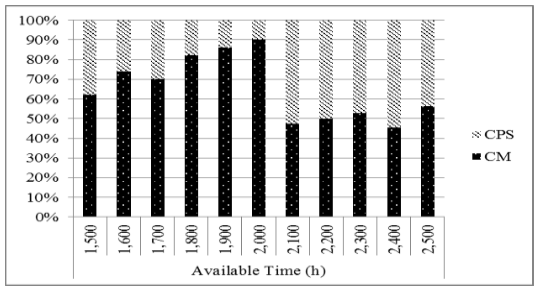

Figure 4: The ratio of the number of operators in reconfigurable model

4.2 The demand and variation in single-period

The demand values are set using a normal distribution with mean values ranging from 2,500 to 4,500, and a standard deviation ranging from 50 to 1,050 as shown in Table 7. The value of h, i.e. the time available in single-period, is set to the constant (1,800) during the experiment.

For the total number of operators required, the proposed model has a smaller number of operators than the traditional model in the all cases. This means the proposed model is more effective than the traditional model. On the other hand, when the deviation is smaller, almost optimal solution is also smaller with respect to the total number of operators in single-period regardless of model types.

Especially, when deviation is smaller, the total number of operators on CPS, i.e., CPS1 and CPS2, is also smaller, i.e. 13, 7, 19 for each demand in the proposed model. This means the proposed model might have the potential to absorb variability of demand and operators by not CM but CPS.

Table 7: The optimal solution of each model for each demand (μ) and deviation (σ) ($N=1$)

	Demand											
	2,500				3,500				4,500			
Traditional	50	350	700	1,050	50	350	700	1,050	50	350	700	1,050
CM 1	18	18	18	19	18	18	19	19	19	18	19	18
CM 2	15	16	16	16	18	18	18	18	18	18	18	18
CM 3					10	10	10	10	12	15	12	15
CM 4									10	10	11	10
Operators	33	34	34	35	46	46	47	47	59	61	60	61
Av.Op_time	1,774	1,769	1,779	1,754	1,772	1,800	1,739	1,758	1,794	1,737	1,787	1,764
Proposed												
CM 1	18	18	18	18	19	19	19	19	19	19	19	19
CM 2					18	18	18	18	18	18	18	19
CPS 1	10	10	10	10	7	8	8	8	10	10	10	10
CPS 2	3	4	4	5					9	10	10	10
Operators	31	32	32	33	44	45	45	45	56	57	57	58
Av.Op_time	1,781	1,733	1,784	1,701	1,798	1,755	1,775	1,794	1,782	1,789	1,779	1,791

5. CONCLUSION

In this paper, a new mixed integer programming model with 2-type cell production systems was proposed to overcome some shortcomings of the traditional model for minimizing the total number of operators in labour-intensive cells. Firstly, the traditional model was redefined by new production rates. Secondly, the new proposed model was solved by 2-phase optimization problems. Furthermore, the new model was compared with the traditional model by using numerical experiments. As a result, this paper showed better cases in which the proposed model could lead to fewer operators and more stable operator assignments than the traditional model. Even if the scale of the problem increases, the proposed model will be able to handle the large-scale problems because 2-phase optimization problems are not complex.

In future, we would like to solve the large-scale problems including robot cells and propose a new mixed integer programming model without phases in reconfigurable production systems. Since the model without phases needs more time to obtain optimal solutions than the 2-phase model, we would like to confirm how it performs if problems get larger, i.e. if there are more cells.

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