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Optimal Operator Assignment and Cell Loading in Labor-Intensive Manufacturing Systems with Inter-Cell Operator Sharing

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Abstract
This research deals with an operator assignment and cell loading problem in multi-cell production systems with inter-cell operator sharing. A two-phase methodology is proposed to minimize the total manpower requirement. In the first phase, manpower configurations for all products with all levels of manpower available will be generated taking inter-cell operator sharing into consideration. The second phase optimizes the cell loading and selects the manpower configuration for all cells when given a product mix. In order to further reduce manpower requirements, lot-splitting is considered. For both phases, the corresponding mathematical models, which can be optimized by commercial software, LINGO 17, are developed. A case study of a jewelry manufacturing company proposed taken from the literature is adopted to test the proposed methodology. The results show the strategy of inter-cell operator sharing can save 11.56% manpower at most. Moreover, if lot-splitting is considered, at most 14.66% of manpower can be saved.

Keywords
Cellular Production, Operator assignment, Mathematical Programming, Cell Loading, Operator sharing.

Introduction

Operator assignment is important for labor-intensive production systems. Due to the various demands from customers, the product mix changes constantly. For multi-cell production systems, it would be helpful if the arrangement of operators and loading of cells could be optimized with a minimal manpower level. This research deals with multi-cell production systems in which all product types are produced by the same operating procedure, but the operation times are different. Each operator can only be assigned to perform one operation. In order to balance the utility of operators, more than one operator can be assigned to perform the same operation. The more operators assigned to a cell, the higher the production rate will be. When more than one product type is to be produced in the same cell, setup time is required.

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This research takes the strategy of "operator sharing" into consideration. Operator sharing allows one operator to be assigned to perform the operations of two adjacent cells. For example, in Figure 1, there are two identical production cells with three operations. The corresponding operation times for both cells are 0.25, 0.65, and 0.80 minutes, respectively. If 10 operators are available, both cells select the manpower configuration with 5 operators in which 1, 2, and 2 operators are assigned to perform operations 1, 2, and 3. It is found that all operators are assigned to perform the corresponding operation in a single cell. Thus, the production rates for the two cells are 1.25/minute, and the productivity is 0.25/minute/operator.

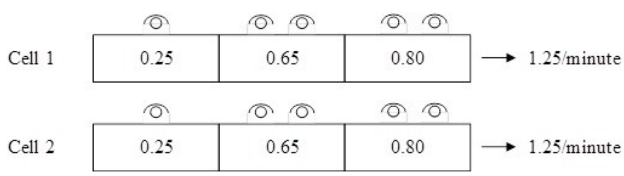

Fig. 1. An example of no operator sharing

Figure 2 shows a manpower configuration with 10 operators in two cells and it exemplifies the advantage of operator sharing. In Figure 2, if the first operation of both cells can share one operator, that means the operator performs the first operation of both cells. The overall manpower needed is reduced to 9 operators in total. Although the production rates for the two cells are also 1.25/minute, the productivity increases to 0.28/minute/operator.

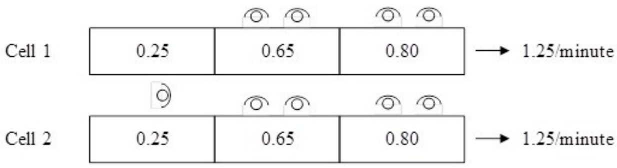

Fig. 2. An example of inter-cell operator sharing

According to the examples in Figures 1 and 2, the strategy of operator sharing provides the opportunity to produce products at the same production rates with fewer operators, thus increasing the productivity of operators.

For a given product mix, all products have to be assigned to cells, according to their product types and volumes. This decision is called cell loading (Kuo et al., 2018). The decisions of operator assignment and cell loading always affect each other. When a larger number of products are assigned to a cell, more manpower is required, and vice versa. However, when taking the manpower sharing strategy into consideration, the same problem becomes more complicated. Both decisions must be considered together with the adjacent cells. Since the inter-cell operator sharing strategy provides the opportunity to improve the performance of the production cell, this study should be able to make contributions to both academic and practical aspects.

This research aims to minimize the manpower level required when given a product mix by optimizing the operator assignment and cell loading. A two-phase methodology is proposed. The remainder of this paper is organized as follows. Section Two reviews the relevant literature. Section Three describes the assumptions underpinning the proposed problem, and Section Four presents the methodology for the proposed problem. It consists of four parts. The first two parts aim to generate the optimal manpower configuration "without operator sharing" and "with operator sharing" respectively. The third and fourth parts optimize the cell loading and manpower configuration selection for each cell with "no lot splitting" and "lot splitting" respectively. Details of the empirical illustration are discussed in Section Five. Conclusions and future research opportunities are addressed in the final section.

Literature review

Many factors have been considered in the research on operator assignment. Kuo and Yang (2007) assumed that one operator can be assigned to execute the operations for which they are qualified, in the sense that they have the appropriate skills, and that operators have different skill sets. A mixed integer programming formulation is proposed to optimize operator assignment. Azadeh et al. (2011) used simulation to evaluate the performances of different operator assignments in a cellular manufacturing system. A fuzzy multi-criteria decision making method was proposed that took into account average lead time, average operator utilization, number of operators, transfer batch size, and demand level. Zhang et al. (2020) extended a restarted iterated Pareto greedy algorithm to minimize both ergonomic risk and cycle time simultaneously in the U-shaped assembly line balancing problem. Koltai et al. (2021) considered robots with different technological capabilities to perform a predetermined set of tasks. Mathematical programming models were proposed to determine the optimal number of workstations and cycle time.

Research dealing with both operator assignment and cell loading is rare in the literature. Süer (1996) proposed a two-phase methodology to optimize the operator assignment and cell loading problem in a multi-cell production system for a jewelry manufacturing company located in Puerto Rico. In both phases, simple and effective mathematical programming were proposed. The first phase aimed to optimize the number of operators assigned to each operation in one single cell for all product types with several manpower levels available. The assignment of operators for one manpower level is called the manpower configuration. Based on all manpower configurations for all product types, the second phase aimed to select the manpower configuration and product types for all cells to minimize the total manpower required when given a product mix. Based on the structure of the two-phase methodology proposed by Süer (1996), other studies have identified some issues related to operator assignment and cell loading. They are summarized in the literature that follows.

Süer and Bera (1998) revised the mathematical programming of the second phase proposed by Süer (1996) to take lot-splitting into consideration. That means one product type could be arranged to be produced by more than one cell. Then Kuo and Yang (2006) adopted the methodology proposed by Süer and Bera (1998) to optimize the operator assignment and cell loading in a TFT-LCD (thin film transistor liquid crystal display) inspection and packing process.

In Suer (1996), Suer and Bera (1998), and Kuo and Yang (2006), one manpower configuration indicates one manpower level available for a cell, and only one manpower configuration can be selected for a cell. That means the number of operators assigned to each cell will not change during the plan period. The operation times are different for different product types. When a cell completes a product type, some operators should transfer to perform different operations when the cell starts to produce another product type. The more transfers, the higher the setup cost. Süer and Dagli (2005) first optimize the sequence of all product types to minimize the total number of transfers and then arrange all product types into cells. To address the issue of transfers, as proposed by Süer and Dagli (2005), Süer et al. (2009) proposed a methodology to optimize the arrangement of product types to cells first and then optimize the production sequence for each cell. Besides makespan and number of transfers, machine requirements were also included as performance measures.

Süer and Tummaluri (2008) extended the problem proposed by Süer and Bera (1998) to take the skill, learning, and forgetting of operators into consideration. When an operator performs a single operation continuously for a certain amount of time, his skill level improves. Similarly, the skill level decreases when he does not perform the corresponding operation for a period. Therefore, all operators have different skill levels for all operations. Süer and Tummaluri (2008) proposed a three-phase methodology in which the first and second phases are similar to the methodology proposed by Süer and Bera (1998). In the third phase, two heuristics were developed to decide which operator should be assigned to which operation.

Süer et al. (2013) dealt with a multi-cell environment. They assumed that operators can be assigned to perform different operations in a cell at the same time, and this strategy is called “intra-cell operator sharing.” A two-phase methodology was proposed. In the first phase, three different levels of intra-cell operator sharing were designed to generate the manpower configuration. Then, the second phase optimized the schedule to minimize the total tardiness. Yu et al. (2013) assume that all operators have to perform all operations in the cells to which they are assigned. Moreover, if an operator is assigned to a cell and the corresponding number of operations is more than his normal loading, extra operation time is required. Egilmez et al. (2014) dealt with the stochastic skill-based manpower allocation problem in which operation times and customer demand are uncertain. A four-phase methodology was developed to optimize the manpower level, product-cell formations, and individual operator assignment, hierarchically with respect to a specified risk level.

Bagheri and Bashiri (2014) dealt with multi-period and multi-cell manufacturing systems. The location of each cell, the assignment of machines to cells, and the assignment of operators to machines can be different in different periods. By taking inter-intra-cell part trips, machine relocation cost, and operator cost into consideration, a mathematical model was proposed to optimize the cell formation, operator assignment, and inter-cell layout problems simultaneously. Mehdizadeh and Rahimi (2016) dealt with a similar problem to that proposed by Bagheri and Bashiri (2014) but took machine operating and purchasing costs into consideration. The objectives were minimizing inter/intra cell part movements and machine relocation, minimizing machine and operator-related costs, and maximizing the consecutive forward flow ratio.

Kuo and Liu (2017) dealt with two consecutive cell environments in a bicycle assembly company. There were four working periods that were divided by three rest times in a day. Operators could transfer to another cell during the rest times. The number of operations was more than the number of operators. Thus, one operator could be assigned to perform more than one operation at the same time. The objective was to minimize the total manpower required. Kuo et al. (2018) dealt with the same bicycle assembly company as described by Kuo and Liu (2017). They focused on the first cell and assumed that one new cell was added, making an assembly system consisting of two identical cells. When a cell just completes a product type, some operations should be transferred to be performed by other operators when the cell starts to produce another product type. A four-phase methodology was proposed to minimize the total manpower required and operation transfers at the same time. The four phases are manpower configuration design, calculating the number of task transfers, minimizing the manpower requirement, and cell loading and product sequencing optimization.

According to the literature surveyed above, some research deals with the issue of operator sharing. For example, Süer and Dagli (2005), Süer et al. (2009), and Kuo et al. (2018) aimed to minimize the total “transfer” in which operators are arranged to perform different operations when producing different product types. Bagheri and Bashiri (2014), Mehdizadeh and Rahimi (2016), and Kuo and Liu (2017) allowed different numbers of operators to be assigned to each cell in different time periods. Süer et al. (2013) dealt with intra-cell operator sharing, which allows more than one operation at a time to be assigned to an operator in a cell. However, no research was found that deals with inter-cell operator sharing.

In the current research, the strategy of inter-cell operator sharing, whereby the same operation in two adjacent cells can be assigned to one operator, is considered. The objective is to minimize the total manpower required. To the best of the author's knowledge, no research has been conducted that addresses these conditions. Since labor-intensive production systems are still prevalent in industry, the present study may not only contribute to the academic literature, but also have practical implications.

Problem description

This research aims to minimize the total number of operators required by optimizing operator assignment and cell loading with intra-cell operator sharing. The following features and assumptions are considered:

1. The operations of all product types are the same.
2. The production times of the same operation for different product types are different.
3. All operators can perform all operations for all product types.
4. The performance of all operators is the same; production times depend only on product types and operations.
5. Merging different operations for a product type to create a new operation is not allowed.
6. Operations cannot be split into multiple operations.
7. Manpower configurations are categorized by the number of operators required. When given a number of operators available, the number of operators assigned to perform each operation for each product type may be different, but they are viewed as the same manpower configuration.
8. All cells are arranged in the same direction and adjacent to each other.
9. One operator can be assigned to a "shared operator", to perform the operation in two adjacent cells, only if the two cells produce the same product type.
10. Only the same operation performed in adjacent cells can share the same operator.
11. For any operation performed in two adjacent cells, the strategy of inter-cell operator sharing should be adopted, but only one operator can be shared.
12. When the strategy of inter-cell operator sharing is adopted, the corresponding manpower configuration occupied two cells' space.
13. Because the shared operators have to move between the two adjacent cells, a certain level of efficiency is always lost when sharing operators.
14. Setup time is required before producing each product type.

Solution methodology

A two-phase methodology is proposed to minimize the total number of operators required by optimizing operator assignment and cell loading with intra-cell operator sharing. In the first phase, manpower configurations for all products with all levels of manpower availability are generated with both "no operator sharing" and "operator sharing". Then, based on the manpower configurations generated in the first phase, the second phase optimizes the cell loading and manpower configurations for all cells for the given product mix. For each issue, a corresponding mathematical model is developed and introduced as described below.

Phase I: manpower configuration with no operator sharing

When no operator sharing is allowed, only one single cell is considered. In this section, an integer-programming model is proposed to maximize the production rate and determine the optimal manpower levels for each operation, also called the manpower configuration. The proposed integer-programming model is based on Süer (1996). For the development of the model, the required notation and variables are defined as follows:

Notation:

- i index of product types
- j index of operations
- o_j the upper limit that the number of operators can be assigned to operation i
- M total manpower available
- p_{ij} operation time of operation j of product type i
- r_{ij} the production rate of operation j when producing product type i
- R_i the production rate when producing product type i

Decision Variables:

W_{ij} number of operators assigned to operation j

The formulation of the first phase with no operator sharing is shown as equations (1)–(5).

$$\text{Max} R_i \tag{1}$$

$$\sum_{j=1}^{J} W_{ij} \leq M \tag{2}$$

$$W_{ij} \leq o_j \qquad \forall j \tag{3}$$

$$\frac{W_{ij}}{p_{ij}} = r_{ij} \qquad \forall j \tag{4}$$

$$R_i \leq r_{ij} \qquad \forall j \tag{5}$$

Equation (1) is the objective function that maximizes the production rate of the whole cell. The total number of operators available must be less than or equal to its upper limit, as shown in Equation (2). Each cell has an upper limit for the number of operators assigned to it, as shown in Equation (3). Equation (4) is used to calculate the production rate of each cell. The production rate of the whole cell must not be higher than the production rate of all operations, as shown in Equation (5).

Phase I: manpower configuration with operator sharing

When inter-cell operator sharing is considered, two cells are involved in the manpower configurations. In this section, another integer-programming model is proposed to maximize the production rate and determine the optimal manpower levels for each operation. Unlike the method adopted in Section 4-1, two cells are considered together in terms of production rate and manpower levels. For the development of the model, the additional notation and variables are defined as follows:

Notation:

- α extra operation time required for shared operators

Decision variables:

- U_{ij} the number of non-sharing operators for operation j when producing product type i
- Z_{ij} 1, if an operator shared for operation j when producingproduct type i; 0, otherwise

The formulation of the first phase with operator sharing is shown as equations (6)–(11).

$$\mathrm{Max} R_i \tag{6}$$

$$\sum_{j=1}^{J} W_{ij} \leq M \tag{7}$$

$$W_{ij} \leq 2o_j \qquad \forall j \tag{8}$$

$$W_{ij} - 2U_{ij} = Z_{ij} \qquad \forall j \tag{9}$$

$$\frac{W_{ij}}{p_{ij} + \alpha \times Z_{ij}} = r_{ij} \qquad \forall j \tag{10}$$

$$R_i \leq r_{ij} \qquad \forall j \tag{11}$$

Equation (6) is the objective function that maximizes the production rate of the two cells. The total number of operators available must be less or equal to its upper limit, as shown in Equation (7). Each cell has an upper limit for the number of operators assigned to it, as shown in Equation (8). Because two cells are considered together, the upper limits are twice as much as o_j, as shown in Equation (8). Equation (9) is adopted to judge if any operator is shared for each operation. If the number of operators assigned to the operation, W_{ij}, is odd, then one operator is shared ($Z_{ij} = 1$), otherwise no operator is shared ($Z_{ij} = 0$). Once an operator is shared, moving back and forth between the two cells is required. Thus, the operation time of the shared operator is longer by α, and then the production rate of the cell is reduced, as shown in Equation (10). The whole production rate of the two cells cannot be higher than the production rate of any operation, as shown in Equation (11).

Phase II: cell loading and manpower configuration selecting

Based on all manpower configurations, including conditions with and without operator sharing, generated by the first phase, an integer-programming model is proposed in the second phase to optimize the cell loading and select the manpower configuration for all cells for the given product mixes. The additional notation and decision variables needed for the development of the model are defined as follows:

Notation:

- c index of manpower configurations
- k index of cells
- R_{ic} the production rate of product i with manpower configuration c
- q_c cell space occupied by manpower configuration c (0, 1, or 2)
- e_c 1, if any cell space occupied by manpower configuration c ($q_c = 1 \text{and} 2$); 0, otherwise ($q_c = 0$)
- b_c the number of operators required for manpower configuration c
- d_i demand for product type i
- t_{ic} the time required to produce product type i with manpower configuration c
- S setup time
- h planning horizon

Decision variables:

- X_{kc} 1, if manpower configuration c is selected by cell k; 0, otherwise
- F_{ik} product type i is arranged to be produced in cell k; 0, otherwise

The formulation of the second phase with operator sharing is shown as equations (12)–(18).

$$\mathrm{Min} \sum\nolimits_{k=1}^{K} \sum\nolimits_{c=1}^{C} X_{kc} b_c \tag{12}$$

$$\sum\nolimits_{c=0}^{C} X_{kc} = 1 \qquad \forall k \tag{13}$$

$$\sum\nolimits_{k=1}^{k} \sum\nolimits_{c=0}^{C} X_{kc} q_c \leq K \tag{14}$$

$$\sum_{k=1}^{K} F_{ik} = 1 \qquad \forall i \tag{15}$$

$$F_{ik} \le \sum_{c=0}^{C} X_{kc} e_c \qquad \forall ik \tag{16}$$

$$t_{ic} = \frac{d_i}{R_{ic}} \qquad \forall ic = 1, 2, \ldots, C \tag{17}$$

$$\sum_{i=1}^{I} \sum_{c=1}^{C} t_{ic} F_{ik} X_{kc} + S \sum_{i=1}^{I} F_{ik} \le h \qquad \forall k \tag{18}$$

Equation (12) is the objective function that aims to minimize the total number of operators required. Only one manpower configuration can be selected for each cell, as shown in Equation (13). In Equation (13), $c = 0$ indicates no manpower configuration is selected. That means the corresponding cell is "closed," and thus $q_0 = 0$ and $e_0 = 0$. Otherwise, if any configuration is selected for a cell, it indicates the cell is "open," and at least one cell space is occupied. In this research, the total number of cell spaces that can be occupied is limited by the number of cells available, as shown in Equation (14). All product types must be arranged to be produced, as shown in Equation (15). However, no product type can be assigned to a "closed cell", as shown in Equation (16). Equation (17) is adopted to calculate the time required for producing each product type with the corresponding selected manpower configuration. All product types must be produced within the planning horizon, including setup time, as shown in Equation (18).

Phase II: cell loading and manpower configuration selection with lot splitting

The mathematical model proposed in Section 4-3 assumes that the entire batch of a product type must be assigned to only one cell. In order to allow the splitting of a batch of product type so that it can be assigned to different cells, this research adds a decision variable, V_{ik}, and modifies the model proposed in Section 4-3. V_{ik} indicates the fractions of demand for product type i assigned to be produced in cell k. Therefore, Equation (19) is added to the model.

$$V_{ik} \le F_{ik} \quad \forall ik \tag{19}$$

Then Equations (15) and (18) are modified as Equations (20) and (21)

$$\sum_{k=1}^{K} V_{ik} = 1 \qquad \forall i \tag{20}$$

$$\sum_{i=1}^{I} \sum_{c=1}^{C} t_{ic} V_{ik} X_{kc} + S \sum_{i=1}^{I} F_{ik} \le h \qquad \forall k \tag{21}$$

Equation (20) indicates that the whole demand for all product types must be produced. All product types must be produced within the planning horizon, including setup time, as shown in Equation (21).

Empirical illustrations

The case introduced by Süer (1996) is adopted to test the proposed methodology. It is a jewelry production system. There are 6 product types with 5 operations which are casting, deburring, linking, stone set and enameling, and carding and packing. The processing times for each operation for different product types are different. Readers can refer to Süer (1996) for detailed information about the processing times and demands. The structure of the experiment is illustrated in Figure 3. Firstly, in Phase I, manpower configurations with and without operator sharing are generated by the integer-programming models introduced in Sections and . Based on the generated manpower configurations, operator assignment and cell loading for different strategies are optimized in Phase II. In Phase II, the results of three strategies are generated for comparison. The first result is for the case where there is no operator sharing (No-OS). The second result is for operator sharing (OS). And the third the result takes both operator sharing and lot-splitting (OS&LS) into consideration.

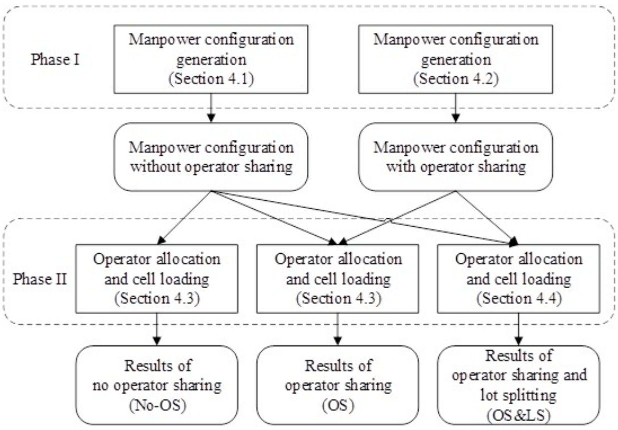

Fig. 3. The structure of the experiment

Using the proposed integer-programming model in Phase I (Section 4-1), the manpower configurations for 15–20 operators are illustrated in Table 1. The manpower configurations are shown in columns 3 to 7, which indicate the number of operators assigned to operations in a single cell. The corresponding production rates are shown in the last column.

Table 1
Results of Phase I with no operator sharing

Product type	# operators available	# operators assigned to operations					Production rate
		1	2	3	4	5	
1	15	1	3	3	5	3	5.68
	16	1	3	3	6	3	6.67
	17	1	4	3	6	3	6.82
	18	1	4	3	7	3	7.89
	19	1	4	3	7	4	7.95
	20	1	4	3	8	4	8.11
2	15	1	3	5	3	3	7.89
	16	1	3	5	3	4	8.06
	17	1	3	6	3	4	9.68
	18	1	3	7	3	4	10.34
	19	1	4	7	3	4	10.34
	20	1	4	7	4	4	10.53
3	15	1	2	6	5	1	5.08
	16	1	2	7	5	1	5.56
	17	1	2	7	5	2	5.81
	18	1	2	7	6	2	5.93
	19	1	2	8	6	2	6.78
	20	1	2	9	6	2	6.90
4	15	1	3	4	4	3	7.27
	16	1	3	5	4	3	7.50
	17	1	3	5	4	4	8.51
	18	1	3	5	5	4	9.09
	19	1	3	6	5	4	9.68
	20	1	4	6	5	4	10.00
5	15	1	2	3	7	2	4.65
	16	1	2	3	7	3	4.88
	17	1	3	3	7	3	5.07
	18	1	3	3	8	3	5.80
	19	1	3	3	9	3	6.52
	20	1	3	3	10	3	6.98
6	15	1	2	6	3	3	5.08
	16	1	2	7	3	3	5.45
	17	1	2	7	4	3	5.93
	18	1	2	8	4	3	6.25
	19	1	3	8	4	3	6.67
	20	1	3	8	4	4	6.78

For the case of operator sharing, $\alpha = 0.02$ is first tested. This means that, where an operator is shared by two cells, the processing time will increase by 0.02 minutes. By using the proposed mathematical model in Phase I (described in Section 4-2), the manpower configurations for 30-35 operators are illustrated in Table 2. The manpower configurations are shown in columns 3 to 7, which indicate the number of operators assigned to operations for two cells. If the number of operators assigned to one production is an odd number, it indicates that one operator is shared by the two cells. On the other hand, if the number of operators assigned to one production is an even number, it indicates that all operators are divided into two groups, and perform the operation in only one cell that they are assigned. The asterisks in the second column indicate that at least one operation adopts the strategy of operator sharing. The results show that the operator sharing strategy is adopted in 33 out of 36 cases, and the productivity is higher when the operator sharing strategy is adopted. For example, in Table 1, if there are 15 operators available without operator sharing, the production rate is 5.68 per minute, so the productivity for all operators in the cell is 0.379/minute. However, in Table 2, when 30 operators are available with operator sharing, the production rate is 12.50 per minute, and the productivity for all operators in the two cells increases to 0.42/minute.

Based on the manpower configurations shown in Table 1 and the product mix provided by Süer (1996), the results of operator assignment and cell loading derived from the Phase II mathematical model (described in Section 4-3) with zero setup time are illustrated in Figure 4. Product types 1, 3, and 4 are assigned to be produced in Cell 1 with 16 operators, and Product types 2, 5, and 6 are assigned to be produced in Cell 2 with 17 operators. In all, 33 operators are required.

Table 2
Results of Phase I with operator sharing($\alpha = 0.02$)

Product type	# operators available	# operators assigned to operations					Production rate
		1	2	3	4	5	
1	*30	2	6	5	12	5	12.50
	*31	2	6	5	12	6	12.82
	32	2	6	6	12	6	13.33
	*33	2	7	6	12	6	13.64
	*34	2	7	6	13	6	14.44
	*35	2	7	6	14	6	14.89
2	*30	2	5	11	5	7	16.13
	*31	2	5	11	6	7	16.13
	*32	2	6	11	6	7	17.19
	*33	2	6	12	6	7	17.50
	34	2	6	12	6	8	19.35
	*35	2	6	13	6	8	20.31
3	*30	1	4	13	10	2	10.83
	*31	1	4	14	10	2	11.11
	*32	1	4	14	10	3	11.63
	*33	1	4	14	11	3	11.86
	*34	1	4	15	11	3	12.50
	*35	1	4	16	11	3	12.50
4	*30	1	5	8	8	8	14.55
	*31	1	5	9	8	8	15.15
	*32	1	6	9	8	8	15.79
	*33	1	6	10	8	8	16.67
	34	2	6	10	8	8	17.02
	*35	2	6	10	9	8	18.18
5	*30	1	5	5	14	5	10.00
	*31	2	5	5	14	5	10.14
	*32	2	5	5	15	5	10.71
	*33	2	5	5	16	5	11.11
	*34	2	5	5	16	5	11.11
	*35	2	5	6	16	6	11.59
6	*30	1	4	13	6	6	10.83
	*31	1	4	14	6	6	10.91
	*32	1	4	14	7	6	11.11
	*33	2	4	14	7	6	11.86
	*34	2	4	15	7	6	12.28
	*35	2	4	15	8	6	12.50

*operator sharing by two cells

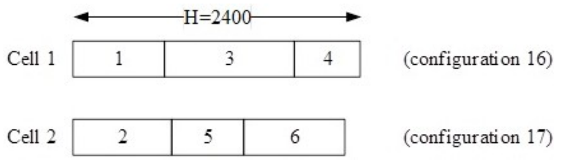

Fig. 4. An example result without operator sharing (No-OS)

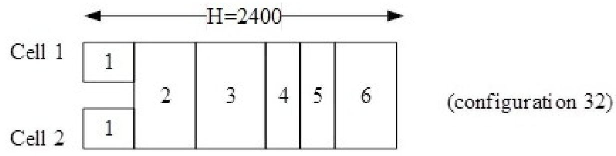

Fig. 5. An example result with operator sharing (OS)

The results from the Phase II mathematical model (described in Section 4-4) take the manpower configurations from both Tables 1 and 2 into consideration, and are illustrated in Figure 5. A manpower configuration with 32 operators is selected. That means the two cells employ the manpower configuration with 32 operators between them. There is no operator sharing for Product type 1 with 32 operators allocated, as shown in Table 2. Therefore, the two cells produce Product type 1 individually and produce the remaining product type with operator sharing. One less operator is needed for the case where the strategy of operator sharing is adopted.

Based on the data provided by Süer (1996), this research increases the demand for all product types from 0% to 100% and takes setup times from 0 to 90 minutes into consideration. The demand for Product types 1 to 6 provided by Süer (1996) are 5000, 8000, 6000, 4000, 3000, and 5000. In Table 3, DL indicates the proportion of the demand suggested by Süer (1996). For example, the demand for Product type 1 when DL=0.6 is 8000 (5000×(1+0.6)). Assuming that the planning horizon is 2400 minutes (5 days×480 minutes), the results are shown in Table 3.

Table 3 shows, in columns 4, 5, and 6, that 21 cases adopt the strategy of operator sharing. Of these 21 cases, 20 cases can reduce the manpower requirement, and the greatest saving in manpower is 11.56%. When lot-splitting is considered, as shown by the results in columns 7, 8, and 9, the number of cases where operator sharing is advantageous

Table 3
The experimental results

DL	No-OS		OS			OS&LS		
	#OR	OA	#OR	OA	IP	#OR	OA	IP
	Setup time=0							
0.0	33	16, 17	*32	32	3.03%	32	15, 17	3.03%
0.2	38	19, 19	38	19, 19	0.00%	37	18, 19	2.63%
0.4	47	15, 16, 16	*46	16, 30	2.13%	*45	15, 30	4.26%
0.6	53	17, 18, 18	*50	18, 32	5.66%	50	15, 17, 18	5.66%
0.8	64	15, 15, 17, 17	*60	30, 30	6.25%	55	18, 18, 19	14.66%
1.0	67	15, 15, 18, 19	*63	30, 33	5.97%	*62	30, 32	7.45%
	Setup time=10 minutes							
0.0	33	16, 17	*32	32	3.30%	*32	32	3.03%
0.2	38	19, 19	38	19, 19	0.00%	38	19, 19	0.00%
0.4	47	15, 16, 16	*46	16, 30	2.13%	*45	15, 30	4.26%
0.6	53	17, 18, 18	*51	18, 33	3.77%	*50	18, 32	5.66%
0.8	64	15, 15, 16, 18	*60	30, 30	6.25%	56	18, 19, 19	12.50%
1.0	67	15, 15, 18, 19	*64	31, 33	4.48%	*63	30, 33	5.97%
	Setup time=30 minutes							
0.0	34	15, 19	34	15, 19	0.00%	33	16, 17	2.94%
0.2	40	20, 20	40	20, 20	0.00%	40	20, 20	0.00%
0.4	48	15, 15, 18	*47	17, 30	2.08%	*46	16, 30	4.17%
0.6	53	17, 18, 18	*52	18, 34	1.89%	*51	18, 33	3.77%
0.8	64	15, 15, 16, 18	*60	30, 30	6.25%	57	20, 18, 19	10.94%
1.0	67	15, 15, 18, 19	*65	32, 33	2.99%	*64	30, 34	4.48%

Table 3 continued on the next page

Table 3 continued from the previous page

DL	No-OS		OS			OS&LS		
	#OR	OA	#OR	OA	IP	#OR	OA	IP
	Setup time=60 minutes							
0.0 0.2 0.4 0.6 0.8 1.0	35 45 49 54 66 70	17, 18 15, 15, 15 16, 16, 17 17, 18, 19 15, 15, 17, 19 15, 16, 19, 20	35 45 *49 54 *61 *67	17, 18 15, 15, 15 19, 30 17, 18, 19 30, 31 32, 35	0.00% 0.00% 0.00% 0.00% 7.58% 4.29%	35 45 48 53 *61 66	15, 20 15, 15, 15 15, 16, 17 15, 18, 20 30, 31 15, 16, 17, 18	0.00% 0.00% 2.04% 1.85% 7.58% 5.71%
	Setup time=90 minutes							
0.0 0.2 0.4 0.6 0.8 1.0	36 46 50 55 66 78	18, 18 16, 15, 15 16, 17, 17 17, 19, 19 15, 15, 18, 18 15, 15, 15, 16, 17	36 *45 *49 55 *64 *69	17, 19 15, 30 19, 30 17, 19, 19 16, 18, 30 16, 19, 34	0.00% 2.17% 2.00% 0.00% 3.03% 11.56%	36 45 49 55 63 *68	18, 18 15, 15, 15 15, 17, 17 18, 18, 19 15, 15, 16, 17 18, 20, 30	0.00% 2.17% 2.00% 0.00% 4.55% 12.82%

DL: Demand level # OR: number of operators required OA: operator allocation for cells
IP: improvement *: operator sharing adopted

drops to 11. However, the number of cases where less manpower is required rises to 24, and in the best case the manpower saving is 14.66%. Therefore, both strategies of operator sharing and lot-splitting can provide the opportunity to save manpower.

Furthermore, Table 3 also shows that when the setup time is 60 minutes and 90 minutes, only one case of the operator sharing strategy is adopted. This is because when the operator sharing strategy is adopted, the same product is produced in both cells and a larger number of operators are assigned. Therefore, when the production cell has to stop in order to set up for the production of different products, more operators are stopped from producing, and this results in a more significant loss of manpower.

This research further tests the Phase I mathematical model for $\alpha = 0.1$. This indicates that an additional 0.1 minutes of operation time are required if an operator is shared to perform an operation in two adjacent cells. Table 4 shows the manpower configurations generated for the strategy of operator sharing (the mathematical model described in Section 4-2).

Table 4
Results of Phase I with operator sharing($\alpha = 0.1$)

Product type	# operators available	# operators assigned to operations					Production rate
		1	2	3	4	5	
1	30	2	6	6	10	6	11.36
	31	2	6	6	10	6	11.36
	32	2	6	6	12	6	#13.33
	33	2	6	6	12	6	13.33
	34	2	8	6	12	6	13.64
	35	2	8	6	12	6	13.64
2	30	2	6	10	4	8	15.79
	31	2	6	10	6	6	15.79
	32	2	6	10	6	8	16.13
	33	2	6	10	6	8	16.13
	34	2	6	12	6	8	#19.35
	35	2	6	12	6	8	19.35

Table 4 continued on the next page

Table 4 continued from the previous page

Product type	# operators available	# operators assigned to operations					Production rate
		1	2	3	4	5	
3	30	2	4	12	10	2	10.17
	31	2	4	12	10	2	10.17
	32	2	4	14	10	2	11.11
	33	2	4	14	10	2	11.11
	34	2	4	14	10	4	11.63
	35	2	4	14	10	5	11.63
4	30	2	6	8	8	6	#14.55
	31	2	6	8	8	6	14.55
	32	2	6	10	8	6	15.00
	33	2	6	10	8	6	15.00
	34	2	6	10	8	8	#17.02
	35	2	6	10	8	8	17.02
5	*30	2	4	5	14	5	9.43
	*31	2	4	6	14	5	9.43
	32	2	4	6	15	6	9.76
	*33	2	5	6	14	6	9.81
	34	2	6	6	14	6	10.14
	35	2	6	6	14	6	10.14
6	30	2	4	12	6	6	10.17
	31	2	4	12	6	6	10.17
	32	2	4	14	6	6	10.91
	33	2	4	14	6	6	10.91
	34	2	4	14	8	6	11.86
	35	2	4	14	8	6	11.86

*operator sharing by two cells
the throughput rate is the same as when $\alpha = 0.02$

Table 4 shows that only 3 cases adopted the strategy of operator sharing. Compared with the production rates shown in Table 1, the production rates shown in Table 4 are lower in most cases, and are the same in only 4 cases. This indicates that when α is higher, the benefit of operator sharing will be less.

Conclusions and future research opportunities

This research deals with operator assignment and cell loading in multiple cell production systems in which operator sharing and lot-splitting are considered. A two-phase methodology is proposed to minimize the total manpower required. In the first phase, one single cell with no operator sharing and two cells with operator sharing are considered for generating the manpower configurations. Two corresponding integer programming models are proposed to maximize the production rates by optimizing the manpower configurations for all available manpower levels. The manpower configurations then become input data for Phase 2. In the second phase, a mixed-integer programming is developed to minimize the total manpower required by optimizing the operator assignment and cell loading for a given product mix. The experimental results show that both strategies of operator sharing and lot-splitting can provide the opportunity to reduce manpower.

However, the experiment found that extra operation time required for shared operators and set up time for product change affect the advantages of the labor-sharing strategy. If these two types of time can be shortened in some way, such as reducing the distance between cells, introducing automation equipment or robotics, the application value of this research result will be enhanced.

This research optimizes all mathematical programming using the commercial software LINGO 17. Since MIP formulation is an NP-hard problem, it may be computationally prohibitive for a larger problem. The application case in this study is a labor-intensive industry, but when the production unit is further supplied with robots to improve efficiency, it will help to move further towards Industry 4.0 that is more flexible, efficient, and capable of adapting quickly to changing market conditions (Goli, 2024). In that case, an efficient solution heuristic will be needed and the search for that heuristic is an opportunity for future research. In addition, this research assumes that the skill level of all operators is the same, and the operation time will be increased for shared operators. However, the skill levels of operators may be different. If an operator can have higher priority to be assigned to perform the operation in two adjacent cells if their skill level is higher in the corresponding operation, then the performance levels found in this study could be further improved. This can also be a future research opportunity for further investigation. In addition, the introduction of automatic or robotic resources may improve the efficiency of the operation, but when these resources are limited, the question of how to allocate resources to multiple units to support different operations of production cells so that the manpower requirement can be further reduced may also be a topic for future research.

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References

Azadeh, A., Nazari-Shirkouhi, S., Hatami-Shirkouhi, L. and Ansarinejad, A., (2011). A unique fuzzy multi-criteria decision making: computer simulation approach for productive operators' assignment in cellular manufacturing systems with uncertainty and vagueness. *The International Journal of Advanced Manufacturing Technology*, *56*, 329–343.

Bagheri, M. and Bashiri, M., (2014). A new mathematical model towards the integration of cell formation with operator assignment and inter-cell layout problems in a dynamic environment. *Applied Mathematical Modelling, 38*, 1237–1254.

Egilmez, G., Erenay, B. and Süer, G.A., (2014). Stochastic skill-based manpower allocation in a cellular manufacturing system. *Journal of Manufacturing Systems*, *33*, 578–588.

Goli, A., (2024). Efficient optimization of robust project scheduling for industry 4.0: A hybrid approach based on machine learning and meta-heuristic algorithms. *International Journal of Production Economics, 278*, 109427.

Koltai, T., Dimeny, I., Gallina, V., Gaal, A. and Sepe, C., (2021). An analysis of task assignment and cycle times when robots are added to human-operated assembly lines, using mathematical programming models. *International Journal of Production Economics*, *242*, 108292.

Kuo, Y., Chen, Y.P. and Wang, Y.C., (2018). Operator assignment with cell loading and product sequencing in labour-intensive assembly cells – a case study of a bicycle assembly company. *International Journal of Production Research*, *56*(13). 5495–5510.

Kuo, Y. and Liu, C.C., (2017). Operator assignment in a labor-intensive manufacturing cell considering inter-cell manpower transfer. *Computers and Industrial Engineering, 110*, 83–91.

Kuo, Y. and Yang, T., (2007). Optimization of mixed-skill multi-line operator allocation problem. *Computers and Industrial Engineering*, *53*(5). 386–393.

Kuo, Y. and Yang, T., (2006). A case study on the operator allocation decision for TFT-LCD inspection and packaging process. *Journal of Manufacturing Technology Management*, *17*(2). 363–375.

Mehdizadeh, E. and Rahimi, E., (2016). An integrated mathematical model for solving dynamic cell formation problem considering operator assignment and inter/intra cell layouts. *Applied Soft Computing, 42*, 325–341.

Süer, G.A., (1996). Optimal operator assignment and cell loading in labor intensive manufacturing cells. *Computers and Industrial Engineering, 31*(1/2). 155–158.

Süer, G.A. and Bera, I.S., (1998). Optimal operator assignment and cell loading when lot splitting is allowed. *Computers and Industrial Engineering*, *35*(3–4). 431–434.

Süer, G.A. and Cosner, J. and Patten, A., (2009). Models for cell loading and product sequencing in labor-intensive cells. *Computers and Industrial Engineering*, *56*, 97–105.

Süer, G.A. and Dagli, C., (2005). Intra-cell manpower transfers and cell loading in labor-intensive manufacturing cells. *Computers and Industrial Engineering*, *48*, 643–655.

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

Süer, G.A. and Tummaluri, R.R., (2008). Multi-period operator assignment considering skills, learning and forgetting in labour-intensive cells. *International Journal of Production Research, 46*(1). 469–493.

Yu, Y., Tang, J., Sun, W., Ying, Y. and Kaku, I, (2013). Reducing worker(s) by converting assembly line into a pure cell system. *International Journal of Production Economics, 145*, 799–806.

Zhang, Z. Tang, Q.H., Ruiz, R. and Zhang, L.P., (2020). Ergonomic risk and cycle time minimization for the U-shaped worker assignment assembly line balancing problem: A multi-objective approach. *Computers and Operations Research*, *118*, 104905.