

CELLULAR LAYOUT DESIGN USING TABU SEARCH, A CASE STUDY

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Abstract. This paper presents a facility layout design for a cellular manufacturing system (CMS), with the automated guided vehicles (AGVs) as the transportation device, to minimize the total material handling costs. A new concept of assigning the workstations to the non-overlapping closed zones, by which independent AGVs are allocated for internal transfer of materials/parts in each zone, is proposed. To handle this problem, a mathematical programming model is developed. The problem has been shown to be NP-hard. This computational difficulty has led us to consider suboptimal solutions generated by a Tabu search with three algorithmic variants. To evaluate the efficiencies of these algorithms, an ANOVA statistical test is performed and the best algorithm is designated. The solution of the new algorithms is then compared with the solution obtained by the CPLEX software. The result indicates that the designated algorithm can provide an average solution with a small deviation of only 0.01% from the optimal solution. This algorithm is also applied to a real-world case problem. The use of this algorithm for re-designing of the layout for the real-world case problem shows considerable cost saving comparing to its existing layout design.

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1. INTRODUCTION

Increasing growth of competition has forced the manufacturing firms to improve their manufacturing productivity. Utilizing a more advanced manufacturing technology such as the cellular manufacturing system (CMS) is one of the approaches for lowering the manufacturing costs and enhancing the production productivity. CMS is a manufacturing arrangement which is a division of just-in-time manufacturing and lean manufacturing including group technology. In CMS, similar machines such as lathes, mills, drills, and grindings are located close together. CMS is a production process in which a collection of parts with similar manufacturing process or geometric shape/size are grouped to form a product family. The product group is processed in a center, composed of one or multiple different machines, called a machining cell. Each machining cell consists of several functionally dissimilar machines with the capability of processing a specific product family. In terms of the facility layout planning, the utilization of the CMS provides the obvious benefits of less travel distance for parts, less required machines space, fewer needed machines, efficient flow and high production rate, and reduction of the setup time.

Keywords. Facility layout, cellular manufacturing system, automated guided vehicles (AGV), Tabu search, real-world case problem, power train manufacturing.

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In the literature, the basic types of layouts are classified as: “product layout”, “process layout”, and “fixed position layout”. Fixed position layout is apt where products are heavy so movement of machineries and equipment are less costly compared to movement of products. Product oriented layout is suitable for high volume, low variety products. Process oriented layout is appropriated for low volume, high variety products. Process layout is a design for the floor plan of a shop which aims to improve efficiency by arranging equipment according to its function [14]. In this type of layout, departments are placed with large interdepartmental flow of parts next to one another [28]. Process layout design is more complex than other two types [17]. In a type process layout, the shops can be divided into small groups or cells of machines. This type of configuration is called cellular manufacturing layout. Cellular manufacturing is a type of layout where machines are grouped according to the process requirements for a set of similar items. These groups are called cells. Therefore, a cellular layout is an equipment layout configured to support cellular manufacturing. This type of layout provides several advantages. In that; material flow is significantly improved, the distance traveled by materials is considerably reduced, parts inventory is decreased, and overall productivity is improved. In this paper, the general problem of cellular manufacturing layout design, with the automated guided vehicles (AGVs) as the transportation device, to minimize the total material handling costs is considered. A new concept of assigning the workstations to the non-overlapping closed zones, by which independent AGVs are allocated for internal transfer of materials/parts in each zone, is proposed. The flow of the material among the zones is handled by the lift truck.

This paper also proposes to use the above mentioned problem to solve a layout design problem of a real-world manufacturing firm named “MM Power train Manufacturing Inc. (MMPM²)”. Due to high variety of products, the layout of MMPM plants is a process layout. The core components are manufactured in plants of MMPM and additionally there are 346 contractors which supply a vast verity of the other parts and components to MMPM. All these parts and components are assembled in MMPM to make the final products. The new management board decided to improve the plant efficiency through redesign of the current layout. Although this study is an attempt for proposing a solution for the MMPM problem, however, we considered a general layout design of cellular manufacturing system (CMS) and proposed a cost-efficient solution approach which can be adapted to the manufacturer with the similar problems. Therefore, this paper can be regarded as two distinct subjects. In the first subject, the facility layout planning problems for a CMS is considered in which the automated guided vehicles (AGVs) are employed as the transportation systems. The result of this research is then applied for solving the MMPM problem.

A mathematical programming model in the form of a nonlinear mixed integer program (NMIP) is developed to minimize the total facility layout costs. A Tabu search with three algorithmic variants is developed for solving the proposed problem. The efficiencies of these algorithms are then evaluated by an ANOVA statistical test [33], and the best algorithm is designated. The designated algorithm is used for solving the MMPM problem.

The remainder of this manuscript is organized as follows: In Section 2 we present a review of the previous research studies on the related area. The developed mathematical model is presented in Section 3. Section 4 describes the development of three algorithms. In Section 5 we demonstrate the computational experiments and a brief discussion on the results of the randomly generated test problems. The case problem is described in Section 6. Finally, Section 7 concludes this research study.

2. LITERATURE REVIEW

Well-designed facility layout proved to be efficacious by contributing many benefits, such as: reduction in material handling cost and work in process; and increase of the adjacencies score between department pairs and safety through better equipment arrangements [13, 27]. Layout problems are found in several types of manufacturing systems. Layout design of CMSs is one of interesting types.

² www.megamotor.ir

Design of CMSs can be categorized into: part selection and/or formation; machines configuration: and, and design of the facilities and facilities layout [5]. Although extensive research efforts are dedicated to the field of CMSs design, however most of them are focused on the cell formation problem. Very few researches are concurrently considering all three phases of the CMS design.

Among the works devoting the problems of cell formation, is the study conducted by Sankaran and Kasilingam [32]. The machine-cell formation problem and the within-cell layout problem are concurrently considered in [30]. A mathematical programming model for the cell formation problems is proposed in [31]. A study considering changing part routings, adding a new machine, duplicating an existing machine, removing an existing machine and transferring a machine to another cell is presented in [37].

One of the early research efforts considering the simultaneous solution of the machine grouping and layout problems of the CMS is the work of Alfa *et al.* [1]. A coincident problem of cell formation and cell layout design in CMS is studied in [7]. The joint problem of the cell formation problem and the machine layout are proposed by Mahdavi *et al.* [25]. Ariaifar *et al.* [3] presented an algorithm for solving the cellular layout design for arranging the machines within machine cells, and cells in the shop-floor. In an extension, a mathematical model for layout problems in a hybrid CMS that minimizes both inter-cell and intra-cell material handling cost proposed in [4]. An attempt to concurrently design the Inter-cell layout and the material handling system is a study conducted by Leno *et al.* [23]. A new mathematical model for inter- and intra-cell layout problem in CMS is the work of Jolai *et al.* [19]. Kia *et al.* [20] presented a mixed-integer non-linear mathematical model for designing group layout of a CMS in a dynamic environment. Other studies dealing with the layout problems of CMSs refer to [11, 21]. A mathematical programming to solve the cell formation, operator assignment and inter-cell layout problems, simultaneously is proposed in [6]. Development of an algorithm to solve a classical cell formation problem can be found in [34]. This algorithm has been claimed to outperform current available heuristics in the literature. Mohammadi and Forghani [26] proposed a new layout framework for the layout of CMSs. A study investigating reconfigurable CMSs and hybrid manufacturing-remanufacturing systems has been conducted by Aljuneidi and Bulgak [2]. Golmohammadi *et al.* [16] considered a lean technique of producing similar parts using cells or groups of team members, workstations, or equipment to facilitate operations by removing setup and unnecessary cost components among various operations. The cell formation problem determining decomposition of the manufacturing cells of a production system is the work of Noktehdan *et al.* [29]. A mathematical programming incorporating cell formation and cell layout with the alternative process is introduced in [12]. A two-phase heuristic approach to solve the dynamic cellular FLP is proposed in [22]. Other research studies focused on dynamic cellular FLPs are found in [15, 18, 24].

The problem of cell formation by employing AGVs for transferring parts through cells is addressed in [9]. The only research study considering the use of AGVs for designing of the layout problem in CMSs is the work of Xing *et al.* [36]. The intra-cell machine re-layout problem of CMSs is considered in which the AGVs were used for transporting the materials between manufacturing cells. An efficient utilization of the AGV is considered in [35]. A two-stage model called Spine Bay Layout is developed to allocate the workstations into several inter-bay systems to minimize the material handling cost. For a review of material transferring methods, related techniques, and their effects on CMSs refer to [10, 39, 40].

Thorough review of the related literature reveals that, no work is dedicated to the facility layout of CMSs with the objective minimizing the transportation cost between cells, investment cost for procuring the AGVs, and the cost for loading and unloading of the lift trucks. Also, the problem of cell formation to the non-overlapping closed zones in which the material flow between cells is eliminated is not overlooked. Also, the reviewed works have shown that the Tabu search outperforms other algorithms in terms of the objective function value and average execution time for adapting the similar optimization problem. But, none has considered the use of Tabu search algorithm for the facility layout of the CMS problems with the AGV as the transportation vehicle. These observations motivated us to adapt the Tabu search technique as the solution approach for the problem under consideration.

3. MATHEMATICAL PROGRAMMING MODEL

Before presenting the mathematical programming model, the parameters and the decision variables are defined as follow:

- C Per unit AGV transportation cost per unit distance.
- V The load capacity of an AGV.
- d_{jl} Distance between cell location j and l , where $j, l \in N$
- φ_{ik} Transportation load between cell i and k , where $i, k \in M$
- R Purchasing cost of an AGV.
- P Penalty cost for per unit loading and/or unloading of lift truck between two zones.
- T_h Total number of AGVs required for zone h , where $h \in H$
- Z_h A set containing of the location numbers in the h th zone.
- N Total number of locations.
- H Total number of zones.
- M Total number of cells.
- X_0 Total cost.
- x_{ij} A zero-one variable taking 1, if cell i is assigned to location j and takes the value of zero otherwise

$$X_0 = \sum_{i=1}^M \sum_{j=1}^N \sum_{k=1}^M \sum_{l=1}^N C\varphi_{ik}d_{jl}x_{ij}x_{kl} + \sum_{h=1}^H \sum_{\substack{t=1 \\ t \neq h}}^H \sum_{i=1}^M \sum_{j \in Z_h} \sum_{k=1}^M \sum_{l \in Z_t} P\varphi_{ik}x_{ij}x_{kl} + \sum_{h=1}^H RT_h \quad (3.1)$$

Subject to:

$$\sum_{j=1}^M x_{ij} = 1 \quad \forall i = 1, 2, \dots, N \quad (3.2)$$

$$\sum_{i=1}^N x_{ij} \leq 1 \quad \forall j = 1, 2, \dots, M \quad (3.3)$$

$$\sum_{i=1}^M \sum_{j \in Z_h} \sum_{k=1}^M \sum_{l \in Z_h} \varphi_{ik}x_{ij}x_{kl} \leq V * T_h \quad \forall h = 1, 2, \dots, H \quad (3.4)$$

$$x_{ij} = 0 \text{ or } 1 \quad \forall i = 1, 2, \dots, N, \& j = 1, 2, \dots, M \quad (3.5)$$

$$T_h = 0, 1, 2, \dots \quad \forall h = 1, 2, \dots, H \quad (3.6)$$

The first term of equation (3.1) indicates the total AGVs transportation cost among cells within and between the zones. The second term presents the cost of loading and unloading of material between the zones. And the last term is dedicated for the purchasing costs of the AGVs. By constraint (3.2) it is secured that a cell is allocated to the only one of the location. Constraint (3.3) is presented to enforce that at most one cell is assigned to each location. Constraint (3.4) is presented for imposing the AGV load capacity limitation in each zone. Finally, constraints (3.5) and (3.6) each defines the characteristic of the variables.

4. DEVELOPMENT OF THE ALGORITHM

The proposed mathematical programming is an NP-hard model and it cannot provide the optimal solution of the real sized problems [8, 38]. Therefore, a heuristic approach has to be employed for finding a good solution for the proposed problem.

There are several heuristic and Meta heuristic approaches for solving the layout problems of the CMSs. Among them the Tabu search (TS) approach has not been considered as much as the other metaheuristic approaches. A

preliminary investigation, conducted prior to this study, comparing a genetic algorithm with TS revealed that for a given computational time the TS provide a better solution. Therefore, we are motivated to explore the use of this method for solving the layout problems of the CMSs. To conduct this, some preliminary concepts and procedures are presented as follows:

Solution space: The solution space is defined by Matrix SP with N rows and M columns in which its ij element represents the allocation of the i th cell to the j th location. This element takes one if the i th cell is assigned to the j th location, and has the zero value otherwise.

Determining the initial feasible solution: Given the flow matrix denoted by φ and the distance matrix denoted by D , the initial feasible solution is constructed by the following steps:

- Step 1. Among the un-flagged elements of Matrix φ , designate the element with the maximum value.
- Step 2. Among the un-flagged elements of Matrix D take the element with the minimum value.
- Step 3. Assign the selected cell to the selected location of Matrix SP .
- Step 4. Flagged the selected elements of Matrix φ and Matrix D . If all elements of Matrix φ are flagged, go to step 5. Otherwise go to step 1.
- Step 5. Stop, and take Matrix SP as the initial feasible solution.

Generating a neighboring feasible solution: The neighboring feasible solutions are generated using the pseudo random generation number. By the use of this random number, a uniform density function with range of 1 to M and a uniform density function with range of 1 to N are employed to generate a cell number and a location number respectively. The generated cell is then assigned to the generated location. This routine is repeated until a neighboring feasible solution is completed.

Determining the Tabu List: Three different methods are evaluated for determining the Tabu list. Based on this evaluation three variant of the Tabu search algorithms are proposed as follows:

- TSC algorithm– The move of a specific cell is prohibited for the pre-specified number of iterations (the Tabu size).
- TSL algorithm– Any assignment to a specified location is prohibited.
- TSCL algorithm– The assignment of a specified cell to a specified location is prohibited.

Tabu size: A preliminary computational experiment is conducted for determining the best value of the Tabu size. As the result, the best Tabu size is determined as 1, 3, and 5 for the small, the medium, and the large group respectively. This experiment will be illustrated in the next section of this paper.

Aspiration criteria: Using the objective function value, two aspiration criteria are defined as follows:

Aspiration criterion 1: Tabu is designated as overridden if a Tabu move has a solution better than any obtained so far.

Aspiration criterion 2: If there is no available move, then a solution is removed from Tabu list based on the FIFO discipline.

Stopping rule: A specific number of iterations and/or the computational time are defined as the stopping rule.

Searching procedure: Ten of the generated neighboring feasible solutions, with the lowest objective function values, are selected as the search base. Then algorithm is moved to the new solution with the best objective function value, even if the objective function value is not better than the current solution.

Based on the above-mentioned procedures, the steps of main algorithm will be presented as follows:

Initialization steps:

- Step 1: Choose the type of the Tabu list (TSC, TSL, or TSCL), and input the SI (the limit on the number of algorithm iteration).

- Step 2: Designate the problem group PG . *i.e.* $PG=1$ for the small group, $PG=2$ for the medium group, $PG=3$ for the large group. Assign the Tabu size of $T^*=1$ for $PG=1$, the Tabu size of $T^*=3$ for $PG=2$, the Tabu size of $T^*=5$ for $PG=3$.
- Step 2.1. Let $PG=1$, and $IT=1$.
- Step 2.2. Generate 10 test problems of group PG , using the random number generation mechanism.
- Step 2.3. Let $k=1$.
- Step 2.4. Solve test problem k using the Tabu size T^* , and designate its objective as $O(T)_k$.
- Step 2.5. If $T=SI$, go to Step 2.6, otherwise let $IT=IT+1$, and go to Step 2.4.
- Step 2.6. Let $O^*(k)=\text{Max}\{O(T)_k\}$, and let frequency $F(k)=IT$ for obtaining O^* . If $k=10$, go to Step 2.7, otherwise let $k=k+1$ and $IT=1$, then go to Step 2.4.
- Step 2.7. Assign the most frequent $T, F(k)=T$, to the Tabu size T^* (PG), and designate this Tabu size for the test problems in group PG .
- Step 2.8. If $PG<3$, let $PG=PG+1$ and go to Step 2.2, otherwise go to Step 3.
- Step 3: Generate the flow between cells and locations, and construct flow Matrix $\varphi_{M \times M}$ and $D_{N \times N}$. Construct the solution space, Matrix $SP_{M \times N}$, and assign zero to all elements of the solution space matrix.
- Step 4: Select two cells having the largest flow from Matrix $\varphi_{M \times M}$ and two locations having smallest value distance from $D_{N \times N}$. Allocate the two selected cells to the two selected locations by assigning 1 to their associated elements in Matrix $SP_{M \times N}$.
- Step 5: If all the rows of the $SP_{M \times N}$ have one element with value 1, let the iteration number, $IT=1$, and the Tabu size, $TS=0$, and go to Step 6, otherwise eliminate the selected cells and the selected locations and go to Step 4.

Iterative steps:

- Step 6: By selecting the Tabu list type (Step 1) and having the Tabu size determined for the problem group (Step 2.8), construct the Tabu list using the random number generation mechanism.
- Step 7: Generate ten neighboring feasible solutions using random number generation mechanism, and find the solution with the lowest value of the objective function.
- Step 8: If this solution is not restricted by the Tabu list or if this solution has the best solutions found so far, move from initial solution to this solution and designate this solution as the initial solution. Let the best solution becomes the solution with the lowest objective function value and go to Step 10. In case that the selected neighboring solution is in the Tabu list, update the Tabu list using the random number generation and go to Step 10. Otherwise find the next lowest objective function from the neighboring feasible solution which is not restricted by the Tabu list, then move from initial solution to this solution and designate this solution as the initial solution, and go to Step 10.
- Step 9: If $TS=T^*$, update the Tabu list using random generation mechanism, and let $TS=0$, and go to Step 7, otherwise go to Step 10.
- Step 10: If $IT=SI$, stop and designate the best solution as the final solution, otherwise let $TS=TS+1$, and $IT=IT+1$, then go to Step 7.

5. COMPUTATIONAL EXPERIMENTS

Two distinct computational experiments are performed for evaluating the efficiency of the proposed algorithm and its variations. A statistical test is conducted for comparing the performance of the three Tabu algorithms. Then the closeness of the objective function values obtained by the proposed algorithms and the optimal solution is determined.

Before conducting these experiments, a preliminary analysis is performed to determine the best value for the Tabu size. In this analysis, 30 distinct test problems are generated and classified per their sizes as; small; medium; and large instances. For each individual problem in each class, the Tabu size is varied from 1 to 20 and 20, and the test problems are randomly generated and solved. The best objective function frequency and

its associated Tabu size are recorded for each group. Based on the result of this experiment, the best Tabu size is determined as 1, 3, and 5 for the small, the medium, and the large group respectively.

5.1. Statistical experiment

A paired one-tailed, sample t-tests is performed to evaluate the equality of the average objective function values of every pair of the propose algorithms. Note that by conducting this type of test, there would be no need to perform a statistical test for the equality of their variances.

In this experiment, 30 test problems are randomly generated and grouped in three classes of the small, the medium and the large size. The data for quantity of flow between two cells, and distance between two locations, are generated by employing two uniform density functions with the ranges of [50, 150] and [1, 15] respectively. Four constant values of, 10, 1000, 100, and 20 are assigned to the unit transportation cost, the AGV price, the AGV capacity, and the loading unloading cost, respectively.

The Tabu size of 1, 3 and 5 are assigned for the small, the medium and the large size problems. The generated test problems are solved by the three-proposed algorithms and the objective function values are attained as presented in Table 1. Referring to this table, it can be realized that the deviation of the objective function values for some of the three-proposed algorithms are so small and could be due to the random variations. However, as it can be realized, TSC is more frequently appeared to be the best algorithms. This is also acknowledged by the results of the second experiment. Therefore, a one tailed test can be performed for statistically verification of the equality of the average objective function values.

The powerful program of R, version 2.8.1, is employed for this test. Three ANOVA statistical tests are performed to evaluate the equality of the average objective function values of the three-proposed algorithms as follows:

Case I.

$$\begin{aligned} H_0 &: \text{Average}_{\text{TSC}} > \text{Average}_{\text{TSC}} \\ H_0 &: \text{Average}_{\text{TSC}} \leq \text{Average}_{\text{TSC}} \end{aligned}$$

Case II.

$$\begin{aligned} H_0 &: \text{Average}_{\text{TSL}} > \text{Average}_{\text{TSC}} \\ H_0 &: \text{Average}_{\text{TSL}} \leq \text{Average}_{\text{TSC}} \end{aligned}$$

Case III.

$$\begin{aligned} H_0 &: \text{Average}_{\text{TSL}} > \text{Average}_{\text{TSC}} \\ H_0 &: \text{Average}_{\text{TSL}} \leq \text{Average}_{\text{TSC}} \end{aligned}$$

The result of the hypothesis for *Case I* reveals that the p -value is greater than α . Therefore, there would be no justification for the rejection of the null hypothesis. This indicates that Algorithm TSC on average provides a better solution comparing to Algorithm TSCL.

The result of the hypothesis for *Case II* shows that the p -value is greater than α . Therefore, the null hypothesis cannot be rejected. It indicts that Algorithm TSC on average provides a better solution comparing to Algorithm TSL.

Heretofore, it is concluded that Algorithm TSC performs better than Algorithm TSCL as well as Algorithm TSL, in terms of the average objective function value. It is worthy to compare the same measure for the two later algorithms. Case III presents the hypothesis testing for average objective function values of these two algorithms. The result of the hypothesis for *Case III* concludes that Algorithm TSCL on average provides a better solution comparing to Algorithm TSL.

The results of the three-hypothesis testing for the three cases reveal that Algorithm TSC performs better than Algorithm TSCL and consecutively Algorithm TSCL performs better than Algorithm TSL.

TABLE 1. Comparing the objective function values of the proposed algorithms.

	Number of locations	Number of zones	Number of cells	TSL	TSC	TSCL	Best OF	The best algorithm(s)	
Small	8	2	5	24644.61	24644.61	24644.61	24644.61	TSL, TSC, TSCL	
	10	2	6	32292.22	32292.22	32292.22	32292.22	TSL, TSC, TSCL	
	12	3	7	47395.18	47395.18	47395.18	47395.18	TSL, TSC, TSCL	
	12	3	8	60502.52	60372.52	60392.52	60372.52	TSC	
	15	3	10	100419.70	99933.95	92797.47	92797.47	TSCL	
	15	5	10	95301.83	96422.26	95367.44	95301.83	TSL	
	15	5	12	159917.95	158752.60	159718.90	158752.60	TSC	
	15	3	13	188191.04	187108.75	187594.95	187108.75	TSC	
	20	5	14	207447.90	209599.02	208411.50	207447.90	TSL	
	20	4	15	236817.33	233764.80	236070.14	233764.80	TSC	
	Medium	16	4	15	250923.80	250143.98	250230.91	250143.98	TSC
		20	4	17	323765.70	325500.52	324299.40	323765.70	TSL
		25	5	21	483286.43	484199.13	482293.78	482293.78	TSCL
		30	5	24	633926.61	632167.69	631792.97	631792.97	TSCL
		30	5	25	680299.47	676029.26	679703.55	676029.26	TSC
35		7	26	716316.51	716841.26	721239.69	716316.51	TSL	
40		5	28	856650.62	854877.49	859698.22	854877.49	TSC	
40		8	28	832017.67	831055.31	834210.49	831055.31	TSC	
40		4	30	1027398.59	1029697.13	1019534.44	1019534.44	TSCL	
45		9	30	948192.84	947817.79	945053.35	945053.35	TSCL	
Large		40	8	31	1034450.78	1033543.95	1032577.20	1032577.20	TSCL
		50	10	32	1069939.40	1073553.36	1072108.41	1069939.40	TSL
		45	9	35	1294978.54	1295967.47	1294375.77	1294375.77	TSCL
		45	5	37	1563752.78	1551340.08	1568783.13	1551340.08	TSC
		50	5	39	1720924.84	1718284.87	1716376.40	1716376.40	TSCL
	55	11	41	1766402.98	1767346.67	1759456.11	1759456.11	TSCL	
	44	11	42	1829935.38	1831675.83	1830576.82	1829935.38	TSL	
	60	6	44	2170166.41	2173741.75	2174386.94	2170166.41	TSL	
	60	6	45	2256107.06	2235893.74	2245105.59	2235893.74	TSC	
	63	9	45	2160466.84	2155181.77	2163690.64	2155181.77	TSC	

5.2. Comparing the solution of the proposed algorithm with the optimal solution

In this experiment, a set of 15 small size test problems is generated using the density functions described in Section 5.1. For each test problem, the number of zones, the number of cells, and the number of locations as well as the constant values of, 10, 1000, 100, and 20 for the unit transportation cost, the AGV price, the AGV capacity, and the loading unloading cost respectively, are assigned. The quantity of flow between every two cells, and distance between every two locations, are generated by employing two uniform density functions with the ranges of [50, 150] and [1, 15] respectively. Using the generated data the test problems are solved by the proposed algorithms and the CPLEX software. To obtain the solutions of the CPLEX software, the test problems are converted to a linear form, as below:

Let a zero-one variable Y_{ijkl} is defined as: $Y_{ijkl} = x_{ij} * x_{kl}$. Then the convert model will be as follow:

$$X_0 = \sum_{i=1}^M \sum_{j=1}^N \sum_{k=1}^M \sum_{l=1}^N \sum_{l=1}^{N_h} C\varphi_{ik}d_{jl}y_{ijkl} + \sum_{h=1}^H \sum_{\substack{t=1 \\ t \neq h}}^H \sum_{i=1}^M \sum_{j \in Z_h} \sum_{k=1}^M \sum_{l \in Z_t} P\varphi_{ik}y_{ijkl} + \sum_{h=1}^H RT_h \tag{5.1}$$

$$\sum_{j=1}^M x_{ij} = 1 \quad \forall i = 1, 2, \dots, N \tag{5.2}$$

$$\sum_{i=1}^N x_{ij} \leq 1 \quad \forall j = 1, 2, \dots, M \tag{5.3}$$

$$\sum_{i=1}^M \sum_{j \in Z_h} \sum_{k=1}^M \sum_{l \in Z_h} C\varphi_{ik}y_{ijkl} \leq VT_h \quad \forall h = 1, 2, \dots, H \tag{5.4}$$

$$x_{ij} + x_{kl} - y_{ijkl} \leq 1 \quad \forall \text{ all values of } i, j, k, l', s, i \neq k, j \neq l \tag{5.5}$$

$$\frac{1}{2}x_{ij} + \frac{1}{2}x_{kl} - y_{ijkl} \geq 0 \quad \forall \text{ all values of } i, j, k, l', s, i \neq k, j \neq l \tag{5.6}$$

$$x_{ij}, y_{ijkl} = 0 \text{ or } 1 \quad \forall \text{ all values of } i, j, k, l', s, i \neq k, j \neq l \tag{5.7}$$

$$T_h = 0, 1, 2, \dots \quad \forall h = 1, 2, \dots, H \tag{5.8}$$

In this model Y_{ijkl} , a zero-one variable to substitute $x_{ij} * x_{kl}$. To support this substitution, constraints (5.5) and (5.6) are presented. Constraint (5.6) forces Y_{ijkl} becomes zero if either $x_{ij} = 0$ or $x_{kl} = 0$, or both simultaneously take zero value. While constraint (5.5) insures that if $x_{ij} = 1$ and $x_{kl} = 1$, then $Y_{ijkl} = 1$.

The percent deviation of the objective function obtained by the proposed algorithms from the optimal solution is calculated for each problem using the following relation:

$$\text{Deviation}\% = \frac{\text{Objective function of algorithm} - \text{Optimal objective function}}{\text{Optimal objective function}} \times 100. \tag{5.9}$$

The result of this experiment is presented in Table 2. As it is realized the average deviations of the best solution obtained by the proposed algorithm from the optimal solution is 0.01% with the standard deviation of 0.92. Referring to this table, it can also be realized that the best solution is more frequently obtained by Algorithm TSC. To reveal this fact the best solution is bolded in this table. These numbers indicate that the proposed algorithms can provide a solution very closed to the optimal solution. Specially, Algorithm TSC can obtain an astonishing solution.

6. A CASE PROBLEM

In the previous sections of this paper, we considered a general version of cellular manufacturing system with the AGV as its transportation vehicle and we developed a Tabu search algorithm for solving the layout design

TABLE 2. The % deviation of solutions of the proposed algorithms comparing to the CPLEX software solutions.

Problem no.	Number of zones	Number of cells	Number of locations	O. F. value of the proposed algorithms			Objective function of CPLEX	% Deviations from the optimal solution		
				TSL	TSC	TSCL		TSL	TSC	TSCL
1	2	5	8	*24644.61	24644.61	24644.61	24644.61	0.00	0.00	0.00
2	2	6	10	34262.32	34262.32	34262.32	34262.32	0.00	0.00	0.00
3	3	7	12	45146.01	44985.41	46281.09	44715.36	0.95	0.60	3.38
4	3	8	12	60129.37	60024.31	60183.04	60024.31	0.17	0.00	0.26
5	3	10	15	101964.09	101777.45	101877.62	101774.45	0.19	0.00	0.10
6	5	11	15	129514.15	129399.26	129793.55	127907.72	1.24	1.15	1.45
7	5	12	15	148787.18	148002.47	149000.07	147421.25	0.92	0.39	1.06
8	3	13	15	189900.98	189893.05	189893.05	188350.51	0.82	0.81	0.81
9	5	14	20	202002.33	200463.38	201173.62	200462.97	0.76	0.00	0.35
10	4	15	20	237591.82	237591.28	237882.31	235015.25	1.08	1.08	1.21
11	4	9	12	79908.47	78948.41	79347.71	77377.74	3.17	1.99	2.48
12	5	9	15	73734.76	73636.68	73701.32	72141.48	2.16	2.03	2.12
13	3	11	12	144012.12	143141.07	142882.30	139364.80	3.23	2.64	2.46
14	5	11	20	118521.13	117593.17	117908.86	114875.77	3.08	2.31	2.57
15	3	12	18	137997.39	138014.72	138007.17	135477.48	1.83	1.84	1.83
				Average				1.31	0.99	1.34

*The minimum values are designated with the bold and italic numbers.

of the proposed problem. The proposed algorithm is constructed in such way to handle the general version of a cellular manufacturing plant layout design. However, the main objective was to use the proposed algorithm for solving the layout design problem of MMPM firm. This section provides an overview of the layout design of the case study company.

6.1. Overview of the MMPM company

The case study plant is a power train manufacturer for different types of vehicles which provides design, manufacture, testing, distribute, return/repair services and assembly of vehicle part components. The MMPM is a manufacturing firm, affiliates directly as a subsidiary of a vehicle industrial group in a developing country. This vehicle industrial group is a public corporation producing various types of vehicles with more than 80 subsidiaries. The MMPM is established to manufacture all the power trains (engine, gearbox, and axle) for different types of the vehicles which are produced in the industrial group. MMPM has two manufacturing sites located in two different cities. The main site is located in the same city of the industrial group and supplies most of the required power trains of the industrial group. The other site is a relatively small plant which manufactures the power trains of the only two types of the vehicle. The layout design proposal however faces by the both sites. Currently the layout of MMPM in the both plants is a process layout. The major manufacturing operations of MMPM are parts machining. That is the raw parts either casted or forged cut into a desired final shape and sized by a controlled material-removal process. The core components are manufactured in plants and additionally there are 346 contractors supply a vast verity of the other parts and components to MMPM. All these parts and components are assembled in MMPM to make the final products.

6.2. Data gathering and analysis and modeling

Essential data of the plant such as product data, manufacturing process data, flow process (routing), the available spaces, the space requirements, the existing layout pattern, manufacturing facilities and relationship between each process are collected. The general information of the company such as company mission, business groups, strategy, history, products, factory size, and so on are also gathered. As mentioned before the current plant layout is a process layout. In order to design a cellular layout, the products are grouped by their weights. The products of this plant are grouped into the heavy products, medium weight products, and low weight products. The engine's housing, engine's cylinder head, axle's housing, and gearbox housing are some example of the heavy weight products. Axle shaft crankshafts, camshafts, flywheels, and clutch housing are some examples of the medium weight products. Different types of pulleys, flanges, and piston rods of different kinds of engines are some example of the low weight products. Then cells are created by consolidating the processes required to create parts.

6.3. Alternative layout improvement and selection

Layout improvement alternatives have been developed using the proposed Tabu search algorithm. A set of 24 alternative layouts is generated by manipulating different combination of the algorithm parameters, such as the Tabu size, the Tabu list, the *Aspiration criteria*, etc. Among them, five layout designs having the five lowest objective function value are designated for the final selection. A committee consisting of the representatives from five departments; process engineering, supply chain, planning, plant engineering, and a top manager representative is held to review and evaluate the practical consideration of the designated five layouts. As the result a layout design is selected to be implemented.

6.4. Findings

The AGV's purchasing investment cost and material handling costs are considered as the measure of effectiveness for the re-layout of MMPM plants. The suggested cellular layout, with AGV as the material handling device, to substitute the current process layout requires an extra initial the AGV purchasing investment. Moreover the new concept of non-overlapping zones has a higher initial investment for purchasing some extra AGVs.

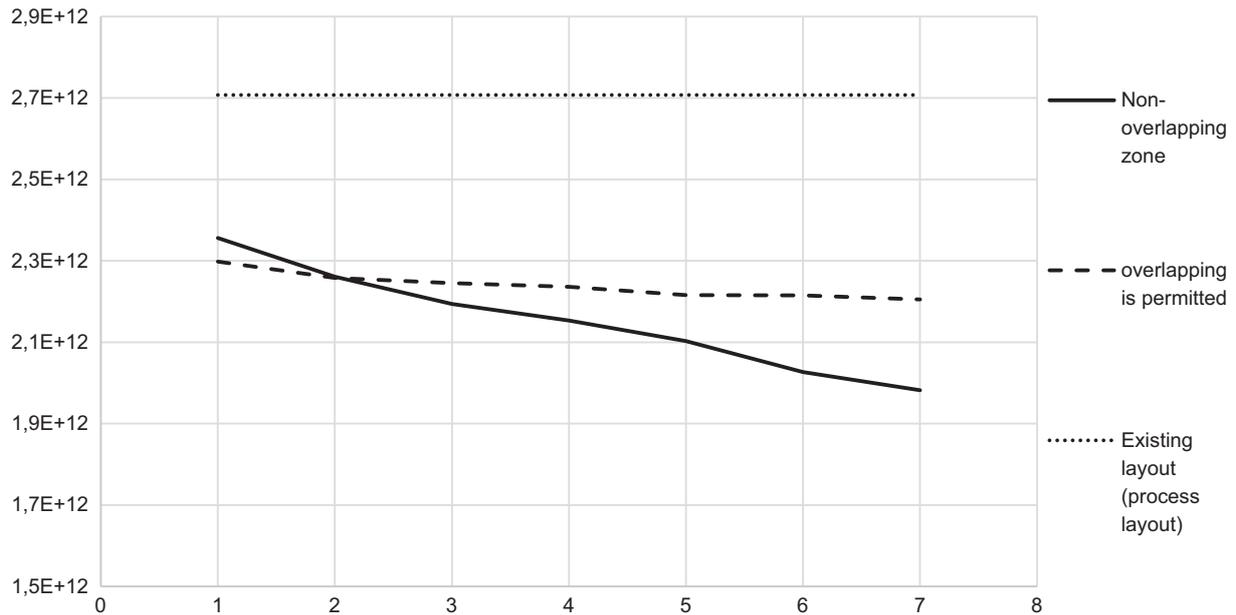


FIGURE 1. Comparison of the objective function value (material handling costs + AGV investment annual cost).

Therefore, for justification of the proposed layout solution, we must show that these initial investments can be compensated by the reduction in material handling costs. To disclose this a period of 7 years (as a period for depreciation of the AGVs) is considered to evaluate the total cost of these three plans. Figure 1 depicts the trend of the objective function values of these three plans. In this figure the objective function values of the current layout is depicted by a dotted line. This line remains flat since there is no initial investment in this case. The cellular layout without overlapping zones and the cellular layout considering non-overlapping zones are depicted by a dashed line and a solid line respectively. Referring to this figure it is realized that although the line showing the non-overlapping zone layout costs has higher cost initially, but it is declined more rapidly comparing to the overlapping zone layout costs after the first year. As it reveals, the cellular layout, in both cases, provides considerable saving over the current layout. Additionally it reveals that although the layout without non-overlapping due to the initial investment has a smaller objective function, however the reduction in the material handling costs reimburses this initial cost over the future periods.

7. CONCLUSIONS

In this paper, a facility layout planning problem for a CMS in which AGVs are employed as the transportation systems is considered. A new concept of assigning the workstations to the non-overlapping closed zones, in which independent AGVs are used for internal transfer of materials/parts in each zone, is proposed. It is assumed that AGVs have limited capacity for transporting material/parts. All the transportation of the material/parts is carried exclusively by AGVs and the lift trucks are only used for delivering loads between zones (loading and unloading). It is assumed that the facility layout costs comprise three types of costs; the transportation cost between cells, investment cost for procuring the AGVs, and the cost for loading and unloading of the lift trucks.

A nonlinear mixed integer mathematical program is developed to model the proposed problem. The proposed mathematical programming model is a NP-hard model. Therefore, a Tabu search algorithm with three variants is developed. The developed variants are named as TSC algorithm, TSCL algorithm, and TSL algorithm based on

the distinct Tabu list for prohibiting some of the solutions. The efficiencies of these variants are then evaluated through a statistical test. To perform this evaluation a set of test problems are generated using the pseudo random number generation mechanism. Through this analysis one of the variants of the three algorithms which demonstrated to have significantly better result is distinguished.

To evaluate quality of the solution of the proposed algorithms, 15 test problems are randomly generated, and solved by the proposed algorithms and CPLEX.V12.1. To conduct the later computational experiment, the developed NMIP model is converted to a linear form to become suitable for solving by CPLEX software. The result indicates that one of the proposed algorithms can provide the average solution with a small deviation of only 0.99% from the optimal solution, while in 5 out of 15 instances it is reached to the optimal solution. This algorithm is designated for designing of the layout problem in a real-world case problem.

The AGV's investment cost and material handling costs are considered as the measure of effectiveness for the re-layout of case problem. The measure of effectiveness of the proposed layout design is compared with the existing layout. The result indicates a considerable saving on the material handling costs. Since in the proposed layout design a concept of non-overlapping zones is considered for the AGV paths, it is also compared to the case where the non-overlapping paths are not considered. The result reveals that although the layout without non-overlapping initially has a smaller objective function value, however the reduction in the material handling costs in every other years reimburses this over initial cost.

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REFERENCES

- [1] A.S. Alfa, M. Chen and S.S. Heragu, Integrating the grouping and layout problems in cellular manufacturing systems. *Comput. Ind. Eng.* **23** (1992) 55–58.
- [2] T. Aljuneidi and A.A. Bulgak, A mathematical model for designing reconfigurable cellular hybrid manufacturing-remanufacturing systems. *Int. J. Adv. Manuf. Technol.* **87** (2016) 1585–1596.
- [3] S. Ariafar, N. Ismail, S.H. Tang, M.K.A.M. Ariffin and Z. Firoozi, Inter-cell and intra-cell layout design in a cellular manufacturing system. *IEEE Symp. Bus. Eng. Ind. Appl.* **25–28** (2011) 28–33.
- [4] S. Ariafar, N. Ismail, S.H. Tang, M.K.A.M. Ariffin and Z. Firoozi, Facility layout design for hybrid cellular manufacturing systems. *Int. J. Phys. Sci.* **6** (2011) 3551–3556.
- [5] J. Arkat, M.H. Farahani and L. Hosseini, Integrating cell formation with cellular layout and operations scheduling. *Int. J. Adv. Manuf. Technol.* **61** (2012) 637–647.
- [6] M. Bagheri and M. Bashiri, A new mathematical model towards the integration of cell formation with operator assignment and inter-cell layout problems in a dynamic environment. *Appl. Math. Model.* **38** (2014) 1237–1254.
- [7] C.C. Chang, T.H. Wu and S.H. Chung, A novel approach for cell formation and cell layout design in cellular manufacturing system. In: *2009 International Conference on Management and Service Science, Wuhan, China*. IEEE Publ. (2019) 10953739.
- [8] W. Chmiel, P. Kadłuczka, J. Kwiecień, B. Filipowicz, A comparison of nature inspired algorithms for the quadratic assignment problem. *J. Pol. Acad. Sci.* **65** (2017) 513–522.
- [9] S. Dehnavi-Arani and M.S. Mehrabad, A two stage model for Cell Formation Problem (CFP) considering the inter-cellular movements by AGVs. *Int. J. Ind. Syst. Eng.* **7** (2014) 43–55.
- [10] A. Delgoshaei, K.A.M.A. Mohd, Z. Leman and G. Chandima, Review of evolution of cellular manufacturing system's approaches: Material transferring models. *Int. J. Precis. Eng. Manuf.* **17** (2016) 131–149.
- [11] K. Forghani, M.A. Sobhanallahi, A. Mirzazadeh and M. Mohammadi, A mathematical model in cellular manufacturing system considering subcontracting approach under constraints. *Manag. Sci. Lett.* **2** (2012) 2393–2408.
- [12] M.A. Gargari, R. Tavakoli-Moghadam and A. Hafezalkotob, Bertrand competition for a cellular manufacturing system. *Int. J. Comput. Integr. Manuf.* **30** (2017) 1–15.
- [13] F. Ghassemi-Tari and H. Neghabi, A new linear adjacency approach for facility layout problem with unequal-area departments. *J. Manuf. Syst.* **37** (2015) 93–103.
- [14] F. Ghassemi Tari and H. Neghabi, Constructing an optimal facility layout to maximize adjacency as a function of common boundary length. *Eng. Optim.* **50** (2018) 499–515.
- [15] T. Ghosh, B. Doloi and P.K. Dan, Applying soft-computing techniques in solving dynamic multi-objective layout problems in cellular manufacturing system. *Int. J. Adv. Manuf. Technol.* **86** (2016) 237–257.
- [16] A. Golmohammadi, H. Bani-Asadi, H. Esmaeeli, H. Hadian and F. Bagheri, Facility layout for cellular manufacturing system under dynamic conditions. *Decis. Sci. Lett.* **5** (2016) 407–416.

- [17] S.S. Heragu, Facilities Design, 4th edition. CRC Press (2016).
- [18] S.S. Hosseini and M. Seifbarghy, A novel meta-heuristic algorithm for multi-objective dynamic facility layout problem. *RAIRO: OR* **50** (2016) 869–890.
- [19] F. Jolai, M. Taghipour and B. Javadi, A variable neighborhood binary particle swarm algorithm for cell layout problem. *Int. J. Adv. Manuf. Technol.* **55** (2011) 327–339.
- [20] R. Kia, N. Javadian, R. Tavakkoli-Moghaddam and A. Aghajani, A mathematical model for designing group layout of a dynamic cellular manufacturing system with variable number of cells. In: *CIE42 Proceedings* (2012) 264.1–264.12.
- [21] R. Kia, A. Baboli, N. Javadian, R. Tavakoli-Moghaddam, M. Kazemi and J. Khorrami, Solving a group layout design model of a dynamic cellular manufacturing system with alternative process routings, lot splitting and flexible reconfiguration by simulated annealing. *Comput. Oper. Res.* **39** (2012) 2642–2658.
- [22] R. Kumar and S.P. Singh, A similarity score-based two-phase heuristic approach to solve the dynamic cellular facility layout for manufacturing systems. *Eng. Optim.* **49** (2017) 1848–1867.
- [23] J. Leno, S.S. Sankar and S.G. Ponnambalam, Integrated layout design approach for cellular manufacturing system. *Trends Intell. Robot. Autom. Manuf.* **330** (2012) 426–435.
- [24] L. Li, C. Li, H. Ma and Y. Tang, An optimization method for the remanufacturing dynamic facility layout problem with uncertainties. *Discret. Dyn. Nat. Soc.* **2015** (2015) 11.
- [25] M.M. Mahdavi, M. Paydar, M. Solimanpur and M. Saidi-Mehrabad, A mathematical model for integrating cell formation problem with machine layout. *Int. J. Ind. Eng. Prod. Res.* **21** (2010) 61–70.
- [26] M. Mohammadi and K. Forghani, Designing cellular manufacturing systems considering S-shaped layout. *Comput. Ind. Eng.* **98** (2016) 221–236.
- [27] H. Neghabi and F. Ghassemi-Tari, A new concept of adjacency for concurrent consideration of economic and safety aspects in design of facility layout problems. *J. Loss Prev. Process Ind.* **40** (2016) 603–614.
- [28] H. Neghabi and F. Ghassemi Tari, An optimal approach for maximizing the number of adjacencies in multi floor layout problem. *Int. J. Prod. Res.* **53** (2015) 3462–3474.
- [29] A. Noktehdan, S. Seyedhosseini and M. Saidi-Mehrabad, A metaheuristic algorithm for the manufacturing cell formation problem based on grouping efficacy. *Int. J. Adv. Manuf. Technol.* **82** (2016) 25–37.
- [30] M.M. Paydar, I. Mahdavi, I. Sharafuddin and M. Solimanpur, Applying simulated annealing for designing cellular manufacturing systems using MDm TSP. *Comput. Ind. Eng.* **59** (2010) 929–936.
- [31] S. Saeedi, M. Solimanpur, I. Mahdavi and N. Javadian, Heuristic approaches for cell formation in cellular manufacturing. *J. Softw. Eng. Appl.* **3** (2010) 674–682.
- [32] S. Sankaran and R.G. Kasilingam, An integrated approach to cell formation and part routing in group technology manufacturing systems. *Eng. Optim.* **16** (1990) 235–245.
- [33] J.R. Tuner and J.F. Thayer, Introduction to Analysis of Variance: Design, Analysis & Interpretation. Sage Publication Inc. (2001).
- [34] B. Ulutas, Assessing the number of cells for a cell formation problem. *IFAC-Paper Online* **48** (2015) 1122–1127.
- [35] H.F. Wang and C.M. Chang, Facility layout for an automated guided vehicle system. *Proc. Comput. Sci.* **55** (2015) 52–61.
- [36] B. Xing, W.J. Gao, F.V. Nelwamondo, K. Battle and T. Marwala, Swarm Intelligence in Cellular Manufacturing: Application of Hybrid Ant System to Manufacturing Cell Machine Layout Problem. World Automation Congress (2010) 1–6.
- [37] E. Yilmaz and R. Erol, A mathematical programming model for reconfiguration of flexible manufacturing cells. *Eng. Optim.* **47** (2015) 184–203.
- [38] A.N.H. Zaied and L.A. El-Fatah, A Survey of the quadratic assignment problem. *Int. J. Comput. Appl.* **101** (2014) 28–36.
- [39] R. Zanjirani-Farahani and F. Ghassemi-Tari, Optimal flow path design of unidirectional AGV systems. *Int. J. Eng. Sci.* **21** (2001) 31–44.
- [40] R. Zanjirani-Farahani and F. Ghassemi-Tari, A branch-and-bound method for finding flowpath designing of AGV systems. *Int. J. Eng. Trans. A* **15** (2002) 81–89.