ANT COLONY OPTIMIZATION FOR THE UNEQUAL-AREA FACILITY LAYOUT PROBLEM

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Abstract: In this paper, an ant colony optimization (ACO) approach is proposed to solve the Facility Layout Problem (FLP) with unequal area departments. The flexible bay structure (FBS) is relaxed by allowing empty spaces in bays, which results in more flexibility while assigning departments in bays. The comparative results show that the ACO approach is very promising.

1 INTRODUCTION

The Facility Layout Problem (FLP) is generally defined as locating N departments in an area of size $W \times H$. The inputs of the problem include department area a_i and minimum side length $l_i^{\min}$ requirements for each department i as well as material flow f_{ij} and material handling cost c_{ij} (per unit flow per unit distance travelled) between each department pair i and j. The goal is to minimize the total material handling cost, which is generally expressed as follows:

$$F(s) = \sum_{i=1}^{N} \sum_{j=i+1}^{N} c_{ij} f_{ij} d_{ij}(s) \qquad (1)$$

where $d_{ij}(s)$ is the distance between the centre points of departments i and j for a given layout s. The decision variables of the FLP include determining department centres (x_i, y_i) and department shapes for each department i. Satisfying the area requirements of the departments, the boundaries of the layout and restrictions on the departments' shapes are the problem constraints. The output of the FLP is called block layout, which specifies relative location and shape of each department in the area.

In this paper, an ant colony inspired algorithm is proposed to solve the FLP with unequal area departments in the flexible bay structure (FBS). In the FBS, departments are located only in parallel-bays with varying width, bays are bounded by straight aisles on both sides, and departments are restricted to be located only in one bay. Recently, Komarudin and Wong (2010), Wong and Komarudin (2010), and Kulturel-Konak and Konak (2011a) have proposed ACO approaches to solve the unequal area FLP. In this paper, an ACO approach for the relaxed FBS, called ACO-RFBS, is developed. The relaxed FBS (RFBS) concept was originally proposed by Kulturel-Konak and Konak (2011b) to remedy the drawbacks of the FBS. The RFBS allows empty spaces in bays, which results in more flexibility while assigning departments in bays. Being different from the Particle Swarm Optimization (PSO) by Kulturel-Konak and Konak (2011b), the ACO-RFBS uses a different encoding scheme, a dynamic penalty handling method, and a two-phase diversification scheme. Moreover, in this paper, facility areas are expanded, and the proposed approach is used to solve the problems with expanded areas to demonstrate the advantages of the RFBS.

2 THE ACO-RFBS

2.1 Solution Construction Definition

In the ACO-RFBS, first a *layout sketch* is constructed by filling bays one department at a time, from bottom to top. A layout sketch defines the relative locations of the departments within bays. After creating a layout sketch, the actual locations and shapes of the departments are calculated according to the RFBS as described by Kulturel-Konak and Konak (2011b). Figure 1 demonstrates a

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step-by-step example of constructing a layout sketch with five departments.

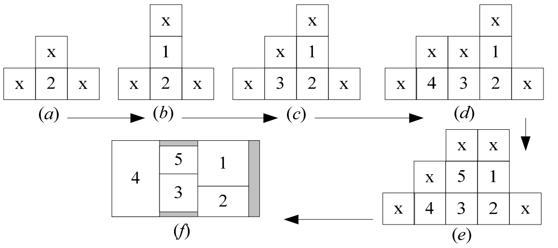

Figure 1: An example of layout construction where (x) represents admissible cells to assign departments.

As demonstrated in the example in Figure 1, three types of department assignments are admissible while adding an unassigned department i to a partial layout sketch as follows:

- $(i, j, 1)$: department j is the first department in the leftmost bay of a partial layout sketch. As a result of this assignment, department i is located immediately to the left of department j.
- $(i, j, 2)$: department j is the last department in a bay. As a result of this assignment, department i is located immediately above department j.
- $(i, j, 3)$: department j is the first department in the rightmost bay of a partial layout sketch. As a result of this assignment, department i is located immediately to the right of department j.

Pheromone $\tau(i, j, k)$ is defined as the favourability of assignment (i, j, k). Let A be the set of all admissible assignments. While constructing a layout sketch, an admissible assignment (i, j, k) is randomly selected from A, and department i is added to the sketch according to the assignment rules defined above. The probability of selecting an admissible assignment (i, j, k) from A is given as follows:

$$p(i,j,k) = \frac{\tau(i,j,k)^{1-\beta}\eta(i,j)^{\beta}}{\sum_{(x,y,z)\in A}\tau(x,y,z)^{1-\beta}\eta(x,y)^{\beta}} \tag{2}$$

where $\eta(i, j)$ is the problem specific heuristic information, which is defined as a function of the normalized flows between departments i and j as follows:

$$\eta(i,j) = 1 + \frac{N \times f_{ij}}{\max_{p,q}\{f_{pq}\}} \tag{3}$$

Unlike the standard ACO (Dorigo et al., 1996; Dorigo and Gambardella, 1997), only a single parameter, $0<\beta<1$, is used in the ACO-RFBS to scale the relative importance of the pheromone and the problem specific heuristic information. To do so, the pheromone and heuristic information values are normalized in the same range. Layout construction initially starts with an empty sketch. While assigning the first department, however, equation (2) cannot be used because A is an empty set. The first department is randomly selected with the following probability,

$$p(j) = \frac{\sum_{i=1,\ldots,N,\, j\neq i}\left(\tau(i,j,1)+\tau(i,j,3)\right)}{\sum_{i=1,\ldots,N}\sum_{l=1,\ldots,N,\, l\neq i}\left(\tau(i,l,1)+\tau(i,l,3)\right)} \tag{4}$$

where $p(j)$ denotes the probability of selecting department j as the first department. In equation (4), only pheromones $\tau(*, j, 1)$ and $\tau(*, j, 3)$ are considered while calculating probability of selecting department j. Therefore, the layout sketch is likely to start with a department that might yield good solutions if it is located as the first department in a bay.

Procedure Solution_Construction()

Step 1. Set $A=\{\}$, $U=\{1,\ldots,N\}$ and calculate $p(i)$ for $i=1,\ldots,N$.

Step 2. Randomly select a department i with probability $p(i)$ to assign to the layout sketch. Let i^+ denote the selected department.

Step 3. Set $U=U\backslash\{i^+\}$ and $A=\{(i, i^+, k): i\in U, k\in\{1, 2, 3\}\}$.

Step 4. Calculate $p(i, j, k)$ for all $(i, j, k)\in A$, and randomly select an assignment. Let (i^+, j^+, k^+) denote the selected assignment.

Step 5. Set $U=U\backslash\{i^+\}$, $A=A\backslash\{(i^+, j, k):(i^+, j, k) \in A\}$, $A=A\backslash\{(i, j^+, k^+):(i, j^+, k^+) \in A\}$, $A=A\cup\{(i, i^+, k): i\in U, k\in\{k^+,2\}\}$.

Step 6. If $U\neq\{\}$, then go to Step 4.

Step 7. Create the actual layout from the sketch.

2.2 Solution Evaluation

Although the FBS representation is relaxed in this paper, some solutions may still have departments with impractical shapes, such as a very narrow/long rectangular department. In addition, the width of the layout may exceed the maximum allowed width of the area because adjusted bay widths are wider than regular bay widths. The ACO-RFBS uses the maximum aspect ratio, which is defined as the ratio of a department's longer side to its shorter side, to quantify the infeasibility of solutions with respect to department shapes. Therefore, a small-sized and a large-sized department can be penalized in the same scale. Let $\alpha_i(s)$ represent the aspect ratio of department i for solution s and let α_i be the given maximum aspect ratio of department i. Let $W(s)$ be the width of the layout for solution s. Solution s is said to be feasible if and only if $\alpha_i(s) \leq \alpha_i$ for each department i and $W(s) \leq W$. Infeasible solutions are dynamically penalized using the near feasibility threshold (*NFT*) concept (Kulturel-Konak et al., 2004).

2.3 Local Search

After evaluating the fitness of the solutions in an iteration, a local search attempts to improve the best solution of the iteration, s^*, where new solutions are created from s^* by swap and insert operators. Operator swap(i, j) swaps the positions of departments i and j. Operator insert(i, b, k) inserts department i into the k^{th} position of bay b. The insert operator changes the relative locations of the bay breaks in a layout. The swap and insert operators are randomly selected in each loop of the local search and performed for all possible combinations. If a better solution is found, s^* is updated, and the local search continues until no improvements possible.

2.4 Pheromone Update, Diversification, and Overall Algorithm Evaluation

In each iteration, μ solutions are generated as described in the previous section, pheromone values are updated based on the best feasible solution s^{**} or the best solution of the iteration s^* as follows:

$$\tau(i,j,k) = \begin{cases} \rho \times \tau(i,j,k) + \omega(i,j,k \mid s^{**}) & s^{**} \text{ is available,} \\ \rho \times \tau(i,j,k) + \omega(i,j,k \mid s^{*}) & \text{otherwise.} \end{cases} \quad (5)$$

where $\rho < 1$ is the evaporation parameter and $\omega(i,j,k|s)$ is a binary function such that $\omega(i, j, k \mid s)=1$ if assignment (i, j, k) is used to construct solution s and $\omega(i, j, k \mid s)=0$, otherwise.

During the search, if s^{**} has not been updated for a certain number of iterations, new solutions cannot be generated. The ACO-RFBS uses a two-phase diversification schema when the search stagnates in such cases as follows:

$$\tau(i,j,k) = \begin{cases} U(1,N) & \text{if } g_s > g^* \text{ and } g_u \leq g^{**}, \\ \max\{0, N - \tau(i,j,k)\} & \text{if } g_s > g^* \text{ and } g_u > g^{**}. \end{cases} \quad (6)$$

where g_u is the number of consecutive iterations such that s^{**} has not been updated, g_s is the number of the consecutive iterations in which the same s^* is obtained, and g^* and g^{**} are diversification parameters. Observing the same s^* in the last g^* iterations indicates stagnation of the search. Therefore, all pheromone values are randomly reset between one and N to restart the search at a different location in the search space. If the search is stagnated without improving s^{**} in the last consecutive g^{**} iterations, the pheromone values are reversed in the second case of equation (6). The search is terminated after performing g_d diversifications.

Procedure ACO-RFBS (μ, ρ, β, g_d, g^*, g^{**})

Step 1. g=0, g_u=0, g_s=0, $s^{**}=\varnothing$, $\tau(i, j, k)=N$ for all i and j, and k=1, 2, 3.

Step 2. Generate μ solutions using Procedure Create_Solution() and calculate the fitness of each solution.

Step 3. Identify s^* and if s^* is different than the best solution of the previous iteration, set g_s=0. Apply the local search on s^* if it is not equal to s^{**} or s^* of the previous iteration. If a better solution is found, replace s^*. Update s^{**} and F^{min} if necessary. Set g_u=0 if s^{**} is updated.

Step 4. Update pheromone values using (5).

Step 5. If one of the conditions in equation (6) is satisfied, apply diversification and set g_s=0.

Step 6. Set $g=g+1$, $g_s= g_s+1$, $g_u= g_u+1$. If g_d number of second phase diversifications have been performed, then stop and return s^{**}; else, go to Step 2.

3 COMPUTATIONAL EXPERIMENTS

To compare the performance of the ACO-RFBS, seven test problems ranging from twelve to 35 departments are used as given in Table 1. All these problems have been previously solved in the literature using the FBS. Additional information about these problems as well as their best RFBS solutions can be found in (Kulturel-Konak and Konak, 2011b). Herein this paper, these problems were first solved with their original dimensions given in the literature, and then, they were solved again with their relaxed dimensions in which the layout widths were increased about 10% allowing empty spaces in bays. In addition, the problems were solved using horizontal and vertical running bays. In problems Tam20, Tam30, SC30, and SC35,

Table 1: Properties of the test problems.

Problem	Relaxed Area	Best Known	Reference	Best Known RFBS
Nug12	5×3	262.00	(Kulturel-Konak and Konak, 2011a)	257.50
Nug15	4×5	524.75		524.75
AB20(4)	35×20	5073.82	(Liu and Meller, 2007)	5336.36
Tam20	44×35	9003.82	(Kulturel-Konak and Konak, 2011a)	8753.57
Tam30	50×40	19667.45		19462.41
SC30	18×12	3679.85	(Wong and Komarudin, 2010)	3443.34
SC35	20×15	3604.00	(Liu and Meller, 2007)	3700.75

Table 2: Solutions found by the ACO-RFBS for the test problems.

	Original Area				Relaxed Area		
Problem	Best	Imp (%) over Best-known	Average	CPU Sec	Best	Imp (%) over Best-known RFBS	CPU Sec
Nug12	257.50	1.75	257.50	57	253.00	1.75	53
Nug15	524.75	0.00	524.75	120	511.50	2.53	121
AB20(4)	5336.36	-5.17	5336.36	1940	5023.23	5.87	288
Tam20	8753.57	2.86	8778.15	311	8727.45	0.30	327
Tam30	19462.41	1.05	19528.96	1881	19462.41	0.00	1669
SC30	3443.34	6.87	3499.20	1655	3259.61	5.34	1797
SC35	3700.75	-2.68	3971.76	2393	3607.60	2.52	3102

Imp (%) =Percent improvement from the previously reported best-solution.

the corresponding areas of the facilities are larger than the total areas of the departments. The ACO-RFBS allows empty spaces in bays by allocating the empty spaces at the top and bottom of the bays. The ACO-RFBS was coded in C and all runs performed on a PC with 3.0 GHz Intel Quad-Core CPU and 32GB memory. The average CPU times in ten replications are given in Table 2. After initial experiments to determine the parameters, the following parameter values were used: μ= 50, ρ= 0.97, β= 0.7, g_d=3, g^*=30, and g^{**}=500.

In Table 2, ACO-RFBS results are compared to their best-known RFBS solutions as well as their best-known solutions. It should be noted that the best-known solutions of several FLP test problems (i.e., Nug12, Tam20, Tam30, and SC30) were improved by the ACO-RFBS in this paper despite the limitations of the FBS as stated in the introduction section. These improvements indicate that the proposed ACO-RFBS is effective. Moreover, when the department widths were relaxed, the proposed ACO-RFBS was able to improve the best solutions for all problems excluding Tam30. Note that such improvements may not be achieved using the original FBS representation. Therefore, these results demonstrate an advantage of the RFBS over the original FBS.

4 CONCLUSIONS

In this paper, an ACO algorithm is proposed to solve FLP with relaxed FBS and compared with the existing methods in the literature with promising results. With the ability of incorporating problem specific heuristic information into the search process, the ACO approach is well suited to effectively solve various facility layout problems. In this paper, it is demonstrated that the relaxed FBS may result in a block layout with a lower material handling cost by expanding the width of a facility.

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