Museum Visitor Routing Problem with the Balancing of Concurrent Visitors

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Abstract. In the museum visitor routing problem, each visitor has some exhibits of interest. The visiting route requires going through all the locations of the exhibits that he/she wants to visit. Routes need to be scheduled based on certain criteria to avoid congestion and/or prolonged touring time. In this study, museum visitor routing problems (MVRPs) are formulated by mixed integer programming and can be solved as open shop scheduling (OSS) problems. While visitors can be viewed as jobs, exhibits are like machines. Each visitor would view an exhibit for a certain amount of time, which is analogous to the processing time required for each job at a particular machine. The traveling distance from one exhibit to another can be modeled as the setup time at a machine. It is clear that such setup time is sequence dependent which are not considered in OSS problems. Therefore, this kind of routing problem is an extension of OSS problems. Due to the intrinsic complexity of this kind of problems, that is NP-hard, a simulated annealing approach is proposed to solve MVRPs. The computational results show that the proposed approach solves the MVRPS with a reasonable amount of computational time.

Keywords. Museum Visitor Routing Problem, Open Shop Scheduling, Simulated Annealing, Sequence-dependence Setup Times

1 Introduction

Museums provide people a physical environment for leisure sight-seeing and knowledge acquisition. By enhancing museum collection and services, countries all over the world are able to use museums as a core facility to facilitate the elevation of culture, art and tourism industry. Due to the advent of IT and networking technologies, museum services can be strengthened by providing context-aware guidance systems for visitors with different background, interests and/or time constraints.

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In order to establish a prototype tour guild system for the National Palace Museum of Taiwan, a context-aware framework where visitors in different contexts can obtain information customized to their needs is established. Visitors provide their personal data, special needs and constraints to the guidance system. The system in turn extracts suitable information from the structured museum contents for the visitors to utilize during the visit. Such context data are classified by demographic data, preferences and interests such as ages, genders, education, professions, languages, media type preferred, time available, special subject of interest, specific assignment, device used, and the location.

This research implements a route guidance function to automatically provide real-time information to visitors. Routes need to be scheduled based on certain criteria to avoid congestion and/or prolonged touring time. In a museum visitor routing problem, each visitor has some locations to visit; the visiting sequence is not restricted as long as visitors trip all the stations that they want to visit. Visitors are like jobs, display locations are like machines. Each visitor stays at a display in a certain amount of time, which is analogous to the processing time required for each job being processed at a particular machine. This routing problem can therefore be solved as an open shop scheduling (OSS) problem. In an OSS, the processing jobs follow no definite sequence of operations. As long as all the operations needed for a job are done, the processing for the job is considered done. The open shop formulation allows much flexibility in scheduling, but is more difficult to develop rules that give an optimum sequence for the problem.

The objective of the museum visitor routing problem can therefore be modeled as (1) minimizing the makespan, that is minimizing the visiting completion time of the last visitor; (2) minimizing the variation of flow time, that is, each visitor is required to spend as close amount of time in visiting as possible; and (3) minimizing the maximum lateness, that is, if an expected visiting time is pre-determined, the visiting completion time of each visitor is scheduled as close to the expected visiting time as possible. In this study, the objective is to minimize the makespan.

Yet, the visitor's travelling distance between two display locations depends the physical distance between them, indicating that there exists a sequence-dependent setup time in OSS. In addition, each display has a maximal space where visitors can stay and browse. The museum visitor routing problem is therefore more complicated than the OSS. This study applied the simulated annealing (SA) approach for solving the museum visitor routing problem to find a solution which is a (near) global optimization based on the objective function of the problem.

The prototype system is tested in a small exhibition area in the National Palace Museum. As this research is a continuing work, the functionalities and stability of the system will be enhanced and tested in various sites in Taiwan to increase its applicability.

2 Problem Formulation and Literature Review

The museum visitor routing problems (MVRPs) are similar to the open shop scheduling problems in industrial engineering. Open job scheduling problems can be defined as follows. There are *m* machines and *n* job to be scheduled. Each job has to be processed again on each one of the m machines. However, some of these processing times may be zero. There are no restrictions with regard to the routing of each job through the machine environment. The scheduler is allowed to determine the route for each job, and different jobs may have different routes. The museum visitor routing problems can be stated as follows. There are m exhibits to be visited and there are n visitors in the museum. Each visitor needs to visit each exhibit once. There are no restrictions with regard to the routing of each visitor through the museum environment. The main difference between museum visitor routing problems and open shop scheduling problem is that the sequence dependent setup time will be incurred because visitor are required to walk some distance between exhibits in museum visitor routing problems. Thus, the different routing has different travelling time (distance). This requirement is not imposed in open shop scheduling problems when job is moved from one machine to another machine. That is, the MVRPs are the extension of open shop scheduling problems.

Supposed the objective function of the museum visitor routing problem is to minimize the makespan which is the time from beginning of the leaving of indoor until the end of last visitor arrive at the outdoor. Let t_{ij} denote the visiting time of visitor *i* on exhibition j. It is easy to establish a lower bound for the makespan with m exhibitions when non-preemptions are allowed:

$$c_{\max} \geq \max\left(\max_{j\in\{1,\ldots,m\}} \sum_{i=1}^{n} t_{ij}, \max_{i\in\{1,\ldots,n\}} \sum_{j=1}^{m} t_{ij} \right)$$

That is, the makespan is at least as large as the maximum visiting time of each of the m exhibitions and at least as large as the total amount of visiting to be done on each of the n visitors. Because the sequence dependent setup times are not included in the above lower bound for the makespan, the results obtained can not be better than the lower bound.

As usual, let c_{ik} denote the completion time of any visitor on exhibition *k*. In order to simplify the mathematical model, we assume the travelling speed is the same for all visitors. Let s_{hk} denote the travelling time from for exhibition *h* to exhibition k of all visitors, and denote s_{0k} the travelling time of any visitor which is travels to exhibition k from the indoor directly. Let s_{k0} denote the travelling time of visitor who travels to outdoor from the exhibition *k* directly. For a visitor *i*, if the visit on exhibition *h* precedes that on exhibition *k*, we need the following constraint: $c_{ik} - t_{ik} - s_{hk} \geq c_{ih}$. If, on the other hand, the visit on exhibition *k* comes first, then we need the following constraint: $c_{ih} - t_{ih} - s_{hk} \geq c_{ik}$. It is useful to define an indicator variable a_{ihk} as follows:

$$a_{ihk} = \begin{cases} 1, & \text{visit on exhibition } h \text{ precedes that on exhibition } k \text{ for visitor } i \\ 0, & \text{otherwise} \end{cases}$$

Then we can rewrite the above constraints as follows:

$$c_{ik} - t_{ik} - s_{hk} + M(1 - a_{ihk}) \geq c_{ih},\ i = 1,2,\ldots,n,\ h,k = 1,2,\ldots,m$$

where *M* is a large positive number. Note that the inequalities very cleverly capture the precedents. If visit on exhibition h comes first, $M(1-a_{ihk})$ is zero, giving the inequality as desired. On the other hand, $M(1-a_{ihk})$ becomes very large, making the

inequality true also. Now we consider the visit un-overlapping constraint for a given exhibition. For two visitors *i* and *j*, both need to visit exhibition *k*. If visitor *i* comes before visitor *j*, we need the following constraint: $c_{jk} - c_{ik} \geq t_{jk}$. If, on the other hand, job *j* comes first, then we need the following constraint: $c_{ik} - c_{jk} \geq t_{ik}$.
We define an indicator variable x_{ijk} as follows:

$$x_{ijk} = \begin{cases} 1, & \text{if visitor } i \text{ precedes visitor } j \text{ on exhibition } k \\ 0, & \text{otherwise} \end{cases}$$

Then we can rewrite the above constraints as follows:

$$c_{jk} - c_{ik} + M(1 - x_{ijk}) \geq t_{jk},\ i, j = 1,2,\ldots,n,\ k = 1,2,\ldots,m$$

The MVRPs with a makespan objective can be formulated as follows:

$$\min \max_{i \leq i \leq n} \{c_{i0}\}$$

$$c_{ik} - t_{ik} - s_{hk} + M(1 - a_{ihk}) \geq c_{ih},\ i = 1,2,\ldots,n,\ h,k = 1,2,\ldots,m \tag{1}$$

$$c_{jk} - c_{ik} + M(1 - x_{ijk}) \geq t_{jk},\ i, j = 1,2,\ldots,n,\ k = 1,2,\ldots,m \tag{2}$$

$$c_{ik} \geq s_{0k} + t_{ik}, i, h = 1,2,\ldots..,n,\ k = 1,2,\ldots,m \tag{3}$$

$$c_{i0} \geq c_{ik} + s_{k0}, i, h = 1,2,\ldots..,n,\ k = 1,2,\ldots,m \tag{4}$$

$$a_{ihk} = 0 \text{ or } 1, i, h = 1,2,\ldots,n, k = 1,2,\ldots,m \tag{5}$$

$$x_{ihk} = 0 \text{ or } 1, i, h = 1,2,\ldots,n, k = 1,2,\ldots,m \tag{6}$$

The objective is to minimize the makespan, constraint (1) ensure each visit can visit on only exhibition at a time. Constraint (2) ensures that exhibition can be visited only one visitor at a time. Constraint (3) ensures that the traveling distance from indoor any exhibition is included in the model. Constraint (4) ensures that the traveling distance from any exhibition to the outdoor in computed in the model.

Notably, the scale of the problem is primarily determined by the number of constraints. Owing to the complexity of the problem, global optimal solutions are difficult to obtain when the problem size is large. Optimization algorithm such as branch bound algorithm [5][6] reported good quality solutions, but with high cost in time and are limited to smaller-sized problems. Therefore researchers apply polynomially or pseudo-polynomially solvable algorithms for solving for special cases on open shop scheduling without considering the sequence-dependent costs.

For the case where m=2, Gonzalez and Sahni [9] proposed a polynomial time algorithm to solve this problem. A simple rule called "the Longest Alternate Processing Time first" (LAPT) has proven to give optimal schedules [11], also solves this problem in polynomial time. Even though it is shown that for $m \geqq 3$, the open shop scheduling problem is NP-complete [9], some open shop problems with special structures are polynomially solvable. For example, Fiala [8] proposed a polynomial time algorithm which solves the problem for arbitrary m, whenever the sum of processing times for one machine is large enough with respect to the maximal processing time. Adiri and Aizikowitz [1] developed a linear time algorithm for the three-machine open shop scheduling problems, provided that there is a machine dominating one of the other two. Algorithms for arbitrary m-machine problems with one or two dominating machines are proposed by Strusevich and summarized in Tanaev et al. [18].

As far as heuristics are concerned, there are only few heuristic procedures for the general m-machine open shop problem published in the literature. Rock and Schmidt [16] introduced a machine aggregation algorithm based on the result that the two-machine cases are polynomially solvable. Gueret and Prins [10] proposed a simple list scheduling heuristics based on priority dispatching rules. The shifting bottleneck procedure, originally designed for the JSP, has been adapted by Ramudhin and Marier [15] to the OSP. Bräsel et al. [4] proposed efficient constructive insertion algorithms based on an analysis of the structure of a feasible combination of job and machine orders.

Recently, meta-heuristic approaches have been developed to solve the open shop problem, including tabu search (TS) [2][12], genetic algorithm (GA) [7] and simulated annealing [13]. Liao [14] developed a powerful hybrid genetic algorithm (HGA) that incorporates TS as a local improvement procedure into a basic GA. Furthermore, Blum [3] proposed a hybrid ant colony optimization with bean search to open shop scheduling, and obtain better solution in existing benchmark instances. Meta-heuristic approach can obtain (near) optimal solution at the expense of large computing resource. To the best we know, there are seldom literature to deal with museum visitor routing problems which is the extension of OSS with sequence-dependence setup times.

3 The Proposed Approach

Annealing is the process through which slow cooling of metal produces good and low energy state crystallization, whereas fast cooling produces poor crystallization. The optimization procedure of simulated annealing reaching a (near) global minimum mimics the crystallization cooling procedure. For the application of the SA approach to the MVRPs, the solution representation, the neighbourhood, procedure and the parameters used are discussed as follows.

Solution representation: For an *n*-visitors *m*-exhibitions problem, a solution can be represented as a string of $n*m$ entry (p_1, p_2, …, p_{nm}). An entry p_i represents one visit and the value of p_i ranges from 1 to $n*m$. Thus, the solution representation is the permutation of $n*m$ number. The lookup table can be constructed to identify which visit is taken into consideration decoded from the solution representation. For example, if there is a 3-visitor and 4-exhibition museum visitor routing problem, each visit can be coded by a unique index value as shown in Table 1. Given a solution representation, the routes are derived by the following way. The value of entry p_i is used to determine the i^{th} visit. Suppose that the value of entry p_3 is 6, it means that the third visit to be considered is the one that visitor 2 visits the exhibition 2. The value of entry p_7 is 9, it means that the 7^{th} visit to be considered is the one that visitor 3 visits the exhibition 1.

Table 1. Visit encoding example of 3-visitors and 4-exhibitions.

	Exhibition 1	Exhibition 2	Exhibition 3	Exhibition 4
Visitor 1	1	2	3	4
Visitor 2	5	6	7	8
Visitor 3	9	10	11	12

Consider the 3-visitors and 4-exhibitions problem given in Tables 2, 3 and 4. Suppose a solution representation is given as [2 5 11 12 1 4 6 10 8 3 7 9]. Generate the schedule by a one-pass heuristic based on the list. The resulting active visitor routing schedule is shown in Figure 1.

Table 2. Example of 3-visitor and 4-exhibit museum visitor routing problem.

Visiting time	Exhibition 1	Exhibition 2	Exhibition 3	Exhibition 4
Visitor 1	4	5	5	4
Visitor 2	4	5	5	4
Visitor 3	4	5	5	4

Table 3. Travelling time (setup time) required from exhibition *i* to exhibition *j*.

Travelling time	Exhibition 1	Exhibition 2	Exhibition 3	Exhibition 4
Exhibition 1	—	2	1	2
Exhibition 2	—	—	2	2
Exhibition 3	—	—	—	2
Exhibition 4	—	—	—	—

Table 4. The travelling time required from indoor to exhibition and the exhibition to outdoor.

Travelling time (setup time)	Exhibition 1	Exhibition 2	Exhibition 3	Exhibition 4
Travelling time from indoor to exhibition	2	2	1	2
Travelling time from exhibition to outdoor	2	2	1	2

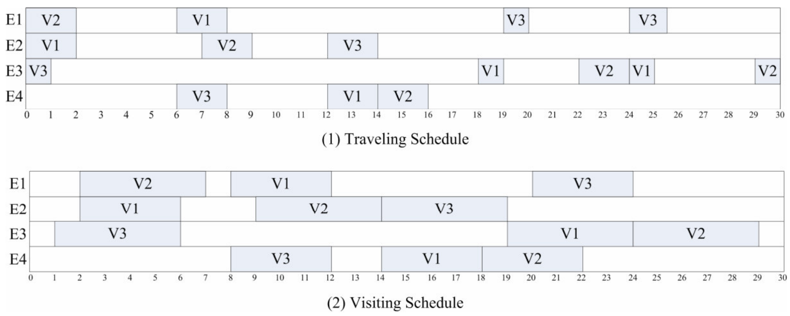

Figure 1. Decode active visitor routing schedule.

Neighbourhood: Neighborhood is sampled either by insertion or swap at random. The insertion is carried out by randomly selecting the i^{th} number of X and inserting it into the position immediately preceding the randomly selected j^{th} number of X. The swap is performed by randomly selecting both the i^{th} and j^{th} number of X, and then swapping the values of these two numbers directly. A 50 percent probability exists of carrying out an insertion, and there is a 50 percent probability exists of carrying out a swap in obtaining the neighbourhood solution of X.

SA procedure and parameter used: In the beginning the current temperature T is set to be the same as T_0. Next, an initial solution X is randomly generated. The current best solution X_{best} is set to be equal to X, the current objective function value F_{cur} is set to be equal to the objective function value of X, F_X, and the best objective function value obtained so far F_{best} is set to be equal to F_{cur}. For each iteration, the next solution Y is generated from $N(X)$ and its objective function values are evaluated. T is decreased after running I_{iter} iterations from the previous decrease, according to a formula $T \leftarrow \alpha T$, where $0 < \alpha < 1$. Let obj(X) denote the calculation of the objective function value of X, and Δ denote the difference between obj(X) and obj(Y); that is $\Delta = \text{obj}(Y)\text{-obj}(X)$. The probability of replacing X with Y, where X is the current solution and Y is the next solution, given that $\Delta > 0$, is $\exp(-\Delta / T)$, is accomplished by generating a random number $r \in [0,\ 1]$ and replacing the solution X with Y if $r < \exp(-\Delta / T)$. Meanwhile, if $\Delta \leq 0$, the probability of replacing X with Y is 1. If the solution X is replaced by Y. If T is lower than T_F, the algorithm is terminated. The X_{best} records the best solution as the algorithm progresses.

4 Computation results

The problem set from Taillard [17] is used to verify the developed approach. This set consists of six different problem types and 10 instances of each problem type, for a total of 60 different problems. However, only 3 instances of each problem type are tested. These problems are all square problem, i.e., n=m, and range form small ones with 16 visits to problem with 400 visits (Taillard observed that open shop problems with n=m are harder to solve than those with n>>m). The problem set from Taillard is originally used in open shop scheduling; therefore, we add the sequence-dependence setup times in problems. The sequence-dependent setup times for problems are generated by the similar way of Taillard's problems set. The setup times are generated uniformly distributed over the interval [1, 5], with $\bar{s} = 3$. The proposed SA approach is implemented in C and run on a Pentium-IV 2.6GHz PC with 512 MB Memory. After running a few problems with several combinations of parameters, the parameter values for SA were I_{iter}=m*n*500, T_0=100, T_F=1, α=0.965 where n is the number of visitors and m is the number of exhibitions to be visited. Each problem is solved 5 times. The worst, average, and best objective function among 5 runs are shown in Table 5. It can be found in Table 5, the range of the solution obtained among 5 times for each problem is smaller, which means the proposed SA approach is stable to the MVRPs.

Table 5. Results for benchmarks.

Problem	Time seed	n	m	Worst objective function value	Average objective function value	Best objective function value	Average running time (s)
4×4_1	1166510396	4	4	285	285.0	285	1.144
4×4_2	1624514147	4	4	358	358.0	358	1.144
4×4_3	1116611914	4	4	381	381.0	381	1.134
5×5_1	527556884	5	5	483	469.4	463	2.725
5×5_2	1046824493	5	5	367	362.2	361	2.716
5×5_3	1165033492	5	5	553	547.6	541	2.722
7×7_1	1840686215	7	7	649	643.8	640	10.978
7×7_2	1026771938	7	7	677	665.8	659	10.978
7×7_3	609471574	7	7	755	745.2	732	10.994
10×10_1	1344106948	10	10	1036	1021.2	1002	52.703
10×10_2	425990073	10	10	858	845.0	830	52.622
10×10_3	666128954	10	10	893	882.2	874	52.831
15×15_1	1561423441	15	15	1379	1371.0	1365	332.609
15×15_2	204120997	15	15	1390	1378.8	1372	332.753
15×15_3	801158374	15	15	1308	1293.0	1278	332.641
20×20_1	957638	20	20	1809	1772.4	1746	1257.323
20×20_2	162587311	20	20	1971	1965.8	1943	1257.475
20×20_3	965299017	20	20	1990	1950.6	1915	1257.089

5. Conclusions

In this study, museum visitor routing problems (MVRPs) is formulated as a mixed integer programming**.** While the problem can be formulated as a mixed integer programming problem, solving this problem using mathematical methods is not feasible when problem scale is large. A simulated annealing approach is proposed to solve the MVRPs. The effectiveness of the proposed SA approach is demonstrated in experiments with encouraging results. The SA approach presented in this paper provides an effective method to generate very good solutions to this problem with computer technology that is well within the reach of museum.

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