AN APPROACH FOR SOLVING THE INTEGRATIVE FREIGHT MARKET SIMULATION

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ABSTRACT

The Integrative Freight Market Simulation (IFMS) is a new modeling framework for urban goods movements that attempts the development of a comprehensive freight transportation demand model that depicts both commodity flows and vehicle trips (Holguín-Veras, 2000). This model has a two-level solution approach. One level deals with the economic problem of estimating the provision of freight service consistent with market equilibrium and profit maximization, while the other level deals with the network problem of constructing tours which are consistent with the economic solution and other system constraints. The network problem is not strictly a traditional routing problem in that competition is incorporated into the process. To capture the effect of imperfect information and to create an environment of economic competition, a specified number of randomly selected nodes are available to two or more freight companies while the rest are available only to one company. This paper describes a method for solving the IFMS which consists of a "cluster first, route second" approach. The clustering stage consists of a geometric clustering combined with a generalized assignment problem (GAP) to create clusters from which feasible tours can be constructed (Nygard et al. 1988). An initial clustering is performed using a version of the radial sweep method of Gillett and Miller (1974) which provides an estimate of the cost coefficients for the GAP. The GAP is solved to determine a minimum cost clustering with constraints that insure that the resulting node clusters can be turned into feasible routes. The routing is then performed using a tabu search (Glover, 1986). The tours constructed by the tabu search are then scanned to identify feasible node exchanges which can be made between the tours of each company. Any node exchanges which increase the profit of one tour without decreasing the profit of the other are implemented. For comparison purposes, the routing was also done using a mixed integer programming (MIP) formulation.

KEY WORDS: Urban freight transportation modeling, cluster first-route second, tabu search.

1. INTRODUCTION

Freight transportation is essential to the economy, which depends on an efficient freight transportation system for delivery of goods. As a result of the nation's increasing population and income and developments such as just-in-time deliveries and e-commerce, demands on the system are increasing. At the same time, providing more freight infrastructure capacity to meet these demands is becoming more difficult and expensive. Thus, increasing the system's efficiency is essential to the continued economic viability of the nation and the development of better freight transportation models will play a very important part in making the system more efficient (Holguín-Veras and Thorson, 2000, 2003). While freight transportation is extremely important to the nation's economy, it has major negative impacts in terms of congestion, air and noise pollution, and road wear and tear. Better freight transportation models will help transportation planners to develop and implement policies reducing the negative environmental impacts of the freight transportation system (Holguín-Veras and Thorson, 2000, 2003).

Freight transportation phenomena are considerably more difficult to model than passenger transportation (Holguín-Veras and Thorson, 2000, 2003; Cambridge Systematics, 1997; Ogden, 1992). First, in passenger transportation, there is one unit of demand, the passenger, while freight transportation has several units of demand including cargo volume, cargo weight, and vehicle trips. Second, in passenger transportation, there is one decision maker, the passenger, while freight transportation involves complex interactions between different agents including suppliers, carriers, and shippers. Third, information about the freight transportation decision-making process is largely unavailable to researchers due to its commercially sensitive nature. Moreover freight transportation has not received near the attention that passenger transportation has and what little attention that researchers have given to freight transportation has resulted in models which do not adequately describe the complex processes involved in freight transportation.

The main freight transportation units of demand (cargo weight and vehicle trips) have given rise to two types of modeling approaches – commodity-based and trip-based (Holguín-Veras and Thorson, 2000, 2003). Commodity-based models focus on the flow of commodities, while trip-based models focus on vehicle trips. Each of these approaches has both strengths and weaknesses. Commodity-based models are able to describe the economic mechanisms behind freight movements and they are readily applicable to intermodal freight. However, they require data which are very expensive and time-consuming to collect and they are unable to capture empty trips which typically account for 30 to 50% of all truck trips. Trip-based models, on the other hand, require data which are readily available through traditional traffic counts and emerging Intelligent Transportation Systems technologies, and they are able to take empty trips into account. However, these models lack any economic behavioral foundation and they cannot be applied to intermodal freight movements. These limitations are the result of the fact that each type of model focuses on only one side of freight transportation, the demand side in the case of commodity-based models and the supply side in the case of trip-based models. Developing a modeling approach which can take both the demand and the supply side of freight transportation is an important motivation behind the Integrative Freight Transportation Simulation (IFMS).

The main objective of the IFMS is to develop a comprehensive model of urban freight transportation in which both commodity flows and commercial vehicle trips are modeled. There are two parts to the development of the IFMS. The first part involves an application of experimental economics to an urban freight market system. This application consists of a series of experiments in which participants play the role of trucking companies competing for freight within an urban area. The second part is the development of algorithms and heuristics to solve the IFMS. In this phase, the objectives are to develop methods for obtaining solutions which: (1) incorporate competition into the routing process; (2) provide a great level of detail about the resulting commercial vehicle tours so that vehicle trips, commodity flows, and trip chains can be obtained; (3) provide an estimate of the upper bound on the routing problem; and (4) satisfy Cournot-Nash market equilibrium.

As described above, freight transportation involves a complex, multidimensional process involving many different decision-makers. To achieve the objectives outlined above, it is necessary to narrow the scope of the problem and make some simplifying assumptions (Holguín-Veras, 2000). First, it is important to note that the main focus of this paper is on common or for hire carriers, rather than private carriers, that is, trucking companies who pick up freight at the client's location and deliver it elsewhere or pick up freight elsewhere and deliver it to the client. It is assumed that only a single, generic commodity is being transported and that only one type of vehicle with the same capacity is used. Moreover, the location and number of vehicles operated by the different trucking companies are assumed to be known.

In addition, the process in which producers create or transform commodities which shippers arrange for carriers to transport is simplified so that only the behavior of producers, consumers, and carriers is modeled (Holguín-Veras, 2000). Thus, the shipper and carrier are treated as a single, super-decision maker. This appears to be a good approximation because the interactions between shippers and carriers can be characterized as a cooperative game in which both agents make decisions for their common good (Holguín-Veras, 2003).

In another simplification, the IFMS does not explicitly deal with the problem of general spatial price equilibrium. In this case, productions and attractions are decision variables. Rather than dealing with the economics of production, the quantities of goods produced and consumed are assumed to be constant and given. As a result, rather than being described by the production and transportation costs, it deals with only transportation costs.

Another important assumption is that of Cournot-Nash equilibrium. Under this assumption, each company contributes the amount of freight service which maximizes its profits given that the other competitors are also maximizing their profits. This assumption is reasonable for urban freight transportation where there are many competing trucking companies, with no one company dominating the market. Another assumption which is reasonable for urban freight is that competition takes place at the aggregate market level, rather than within specific market segments, since it is likely that trucking companies can compete in all OD markets within the urban area. A final assumption is that travel impedance is constant both temporally and spatially. This assumption is obviously not valid especially for urban areas, however it was deemed necessary to make this assumption in order to help make the problem solvable.

This paper has three chapters in addition to this introduction. *Methodology* describes the solution method and *Results and Discussion* presents results for a sample problem. Finally, *Conclusions* summarizes the conclusions regarding the algorithmic results.

2. METHODOLOGY

The solution method outlined in this paper combined a number of well-established mathematical programming and meta-heuristic techniques to solve the network problem within a cluster first, route second framework. A cluster first, route second approach was chosen because it allows this very difficult problem to be broken down into smaller, more easily solved problems. Dividing the node set into clusters reduces the number of possible routing solutions to be considered. The IFMS problem is considerably more complicated than the typical vehicle routing problem in the following ways: (1) tours consist of both pick-ups and deliveries, (2) any cargo being delivered in a tour was picked up at a previous stop on that tour. As a result of these complications, a simple clustering method is not sufficient to produce subsets of nodes which can be turned into feasible tours. Thus, in addition to a geometrically based clustering, a generalized assignment problem was then solved which incorporated constraints insuring tour feasibility.

Once feasible node clusters were obtained, the routing was performed by tabu search. After an initial tabu search solution was obtained, the tours for each players were examined node by node to see if there were any exchanges of two nodes in different tours of the same player which would increase the profit for at least one tour and not decrease the profit for any tour. Once all possible node exchanges were examined, all nodes which were included in the tour of more than one company were identified. The delivery costs for each player for each contested node were then calculated and these nodes were removed from the node sets of players who did not have the lowest cost and the clustering/routing procedure was repeated with the new node sets. This process was continued until each node was included in exactly one tour. This cluster first, route process is outlined in Figure 1. The details of the clustering and routing procedures are described.

2.1 Radial sweep/GAP clustering

Of the various clustering methods, it was found that a radial sweep method was preferable in that it was easy to control both the number of clusters and the number of nodes in each cluster by adjusting the tour time limit. In the radial sweep method of Gillett and Miller (1974), the polar coordinates of each stop are calculated with the radius defined as the distance between the home base and the stop and the angle defined by two rays – one from the home base to some arbitrary point and the other from the home base through the stop. The stops are sorted according to the size of their polar-coordinate angle, where ties are broken by the distance to the home base. Then a sweep is performed which partitions the stops into routes beginning with the stop that has the smallest angle and adding stops until the estimated total travel time exceeds the tour time duration limit. The violating stop then becomes the first stop in the next route. This process is continued until all stops are assigned to a cluster.

The end result of the radial sweep is a partition of nodes into clusters in which the nodes are relatively close to each other. However, these sets of nodes cannot be turned into feasible routes because the total productions and attractions of the nodes in each cluster do not necessarily balance. Thus, the final clustering is performed using the GAP presented in Nygard et al (1988) with several additional constraints which is as follows:

$$\min \sum_{j\in J}\sum_{k\in K} c_{kj}x_{kj} \qquad (1)$$

subject to:

$$\sum_{k\in K} x_{kj} = 1 \qquad \text{for all } j\in J \qquad (2)$$

$$\sum_{j\in J} p_j x_{kj} - \sum_{j\in J} a_j x_{kj} = 0 \qquad \text{for all } k\in K \qquad (3)$$

$$\sum_{j\in J} p_j x_{kj} \ge \alpha \sum_{j\in J} p_j \qquad \text{for all } k\in K \qquad (4)$$

$$\sum_{j\in J} p_j x_{kj} \le \beta \sum_{j\in J} p_j \qquad \text{for all } k\in K \qquad (5)$$

where K is the set of vehicles, J is the set of stops, c_{kj} is the cost of assigning stop j to vehicle k, x_{kj} is a binary variable equal to one if stop j is assigned to vehicle k, p_j and a_j are the production and attraction of node j respectively, and and are parameters equal to $\alpha < \frac{\sum_j p_j}{|K|}$ and $\beta > \frac{\sum_j p_j}{|K|}$. Constraint 4.4 insures that each node is assigned to exactly one cluster. Constraint 4.5 insures that the total productions and attractions of each cluster are equal. Constraints 4.6 and 4.7 set minimum and maximum cluster capacities so that the amount of freight in each cluster is relatively uniform.

In order for the GAP to produce clusters which can be turned into high quality tours, the cost coefficients in the objective function must accurately reflect the cost of including stop j in route k. Since the actual tours are not known yet, this cost is not known and must be estimated. In Nygard (1988), the cost of adding stop j to vehicle k's tour was estimated as the difference between: (1) the cost of visiting node j, then visiting cluster k (as represented by it centroid), and returning to the home base, and (2) the cost of a round trip from the home base to node j and back to the home base. The cost incurred is then:

c_{kj} = *distance(hb, node j) + distance(node j, centroid k) – distance (centroid k, hb)* (6)

where *hb* is the home base and centroid *k* is the centroid of the *k*th cluster.

This method tended to produce reasonable cost coefficient estimates for nodes which were farther from the home base than the cluster centroid, but not very good values for nodes which were closer in. An alternative method is as follows:

$cost_{kj}$ = *dist(nearest node in k, node j) + dist(node j ,nearest node in k)* (7)

This method appeared to produce more reasonable cost coefficient estimates regardless of where the node was located and, since the nearest node in cluster k is node j itself if it is already in cluster k, there is zero cost for keeping nodes in their current cluster. Once clusters of nodes which can be turned into feasible tours were obtained, the routing was performed with a tabu search which will be described next.

2.2 Tabu search formulation for routing

Tabu search is a local search method for combinatorial optimization problems (Glover, 1986). As described in Glover and Laguna (1993), it explores the solution space by moving from a solution x_i at iteration i to the best solution x_{i+1} in a subset of the neighborhood $N(x_i)$ of x_i. x_{i+1} does not necessarily improve on x_i and a tabu list is maintained to prevent the search from cycling over a sequence of solutions. The tabu list keeps track of some attributes of previous discovered solutions and any new solution with these attributes is considered tabu for t iterations. The neighborhood $N(x_i)$ of x_i is a set of solutions that can be reached from x_i by specified moves. A very common move used in routing problems is called a λ-interchange in which up to λ customers are exchanged between two routes. The attributes of such a move are often the edges which are removed from and added to the routes (Hjorring, 1995). The tabu status of a move can be revoked if it meets an aspiration criterion, for example, the move results in a solution which exceeds any previously discovered solution.

The function to be maximized in the tabu search solution is the following profit function:

$$profit = C_W \sum_{i=1}^{N} (p_i + a_i) - C_T \sum_{(i,j) \in Tour} travel\_time_{i,j} \qquad (8)$$

where N is the number of nodes in the tour, C_W is the benefit of picking up and delivering freight, C_T is the travel time cost, p_i and a_i are the productions and attractions at node i, and $travel\_time_{i,j}$ is the travel time from node i to node j.
In this function, profit is the difference between: (1) the benefit from picking up and delivering freight and (2) the costs incurred in traveling from node to node to pick up and deliver freight.

The following subsections describe important characteristics of the tabu search formulation developed for solving the routing problem of the IFMS, including the tabu search moves, the tabu list, and a general outline of the tabu search algorithm.

2.2.1 Tabu search moves

The tabu search formulation uses four types of moves – adding 2 nodes (one production and one attraction) to the current tour (*add2*), swapping two nodes (one of each) that are in the tour with two that are not (*swap2*), adding one node (*add_node*), and swapping one node (*swap_node*). The decision of which move to make and, for the moves involving one node, which type of node to process, is based on the current tour's production and attraction potential. This quantity is the total difference between the demands of the nodes in the tour and the amount of freight actually picked up/delivered at those nodes:

$$\Delta_{PROD} = \sum_{i} (p_i - u_i) \quad \Delta_{ATT} = \sum_{i:b_i<0} (a_i - d_i) \tag{9}$$

where u_i and d_i are the amounts of freight currently being picked up from or delivered to node i.
If $\Delta_{PROD} = \Delta_{ATT}$, then an *add_2* move is made. If the best possible *add_2* move results in a violation of the tour time constraint, then a *swap_2* move is made. If $\Delta_{PROD} \neq \Delta_{ATT}$, then an *add_node* move is made. If the best possible *add_node* move results in a violation of the tour time constraint, then a *swap_node* move is made.

In the *add_2* and *swap_2* moves, both a production and an attraction node are added/swapped. In the *add_node* and *swap_node* moves, on the other hand, a decision must be made as to whether a production node or an attraction node should be added/swapped. If $\Delta_{PROD} > \Delta_{ATT}$, then the tour has more "unused" production, so an attraction node should be added/swapped. Otherwise, the tour has more "unused" attraction and a production node is added/swapped.

2.2.2 Tabu list

A tabu list keeps track of the arcs that are added to and removed from the tour as a result of these moves. The tabu list is a three dimensional array, $TABU(i, j, k)$ where i and j represent the arc (i,j) and k can have a value of 1 which indicates that the arc is added to the tour or a value of 2 which indicates that the arc is removed from the tour. These arcs remain on the tabu list for p iterations.

For each move, the set of possible moves is identified and the move which results in the highest objective function value is selected. If this move does not involve arcs that are on the tabu list, it is accepted and the tour and tabu list are updated. If the move does involve tabu arcs but the resulting objective function value is greater than any previously attained (the aspiration level, *AL*), it is accepted, the tour and tabu list are updated, and the resulting objective function value becomes the new aspiration level. This process is repeated until a specified number of iterations are performed without any improvement in the best found solution. A flow chart of the tabu search solution process is shown in Figure 2.

After the tabu search procedures outlined in this subsection were applied in the routing phase of the solution process, the resulting tours were examined to see if there were node exchanges that could be made which would increase the profit of at least one tour without decreasing the profit of the other. This node exchange process is described in the following section.

2.4 Intra-player node exchanges

For each node in the tours constructed in the tabu search, the nodes in the other tours for the same player were scanned to identify nodes which had the same production or attraction. Once a pair of nodes in two different tours with the same freight demand was identified, the nodes were exchanged and each was inserted in the new tour in the most profitable location. The new profit for each tour was calculated and, if this new profit was at least equal to the current profit for both tours, then the exchange was accepted. The rationale for this step is that the clustering/GAP/routing solution procedure breaks down the problem so that each tour is constructed independently and this exchange process allows the solution procedure to examine the tours of each player together to see if there is a more profitable set of tours.

Each step in the clustering/GAP/routing procedure has been described. In order to get some idea about the quality of the resulting solutions, the same procedure was undertaken with the routing solved by a mixed integer program which is based on the flow formulation of the traveling salesman problem (Ahuja et al, 1993). For both the tabu search and MIP, the cluster/routing procedure is applied to each company's node set, then the delivery costs for any contested nodes are calculated, and the company with the lowest cost is awarded the node and the node is removed from the node sets of the losing companies. The process is then repeated with the adjusted node sets until all nodes are serviced at the lowest cost. The solution procedure presented in this section is applied to a sample problem next.

3. RESULTS AND DISCUSSION

The sample problem has 4 trucking companies, 150 nodes, and a 50% centroid overlap and is shown in Figure 3. Table 1 compares the profits for the tabu and MIP solutions. This table indicates that the tabu solution is very close to the MIP solution in terms of total profit ($7565.71 for tabu, and $7588.13 for MIP – a difference of only 0.34%). Comparing the profits for each company, the tabu values range from -0.15% less (company 2) to -0.53% less (company 1). A comparison of the profits for individual tours indicates that the tabu search profit values are as high as the corresponding MIP values in over half the cases. In 3 of the 5 tours in which the tabu profit was not as high as the MIP value, the tabu profits were only $3.74 less than the MIP profits (company 2's first tour, company 4's second and third tour). This difference is the result of a total tour travel time which was 0.05 hours longer than in the MIP tour. In the other 2 tours which were not as profitable as the MIP tours, the profits were $7.48 less than the MIP values (company 1's second tour and company 3's second tour). This difference is the result of a total tour travel time which was 0.10 hours longer than in the MIP tour.

The tours in the final tabu search solution are shown in Figure 4. A visual inspection of these tours indicates that they are generally quite good. The two worst tours (the second tours of company 1 and 3) have some segments that appear to be a bit convoluted. In company 1's second tour, it would be better to start with stop 10, then visit stops 11 and 12 before visiting stops 9 through 1 in the reverse order, and ending with stops 13 through 16. In company 3's second tour, stops 3 to 5 could be visited more efficiently, that is, stop 4, 5, and 3. In addition, stops 12 and 13 could be visited after stop 7 and before stop 8, instead of at the end of the tour.

4. CONCLUSION

This paper presented a solution method for the Integrative Freight Market Simulation. This method took a “cluster first, route second” approach in which the first stage consists of a geometric clustering combined with a generalized assignment problem (GAP) to create clusters from which feasible tours can be constructed (Nygard et al. 1988) and the routing stage is performed using a tabu search. For comparison purposes, the routing was also done using a mixed integer programming (MIP) formulation.

Competition among the trucking companies was introduced into the process by the fact that a specified proportion of the nodes were available to more than one company. For these overlapping nodes, the delivery costs for each company servicing the node were then calculated and these nodes were removed from the node sets of players who did not have the lowest cost and the clustering/routing procedure was repeated with the new node sets. This process was continued until each node was included in exactly one tour.

This solution method was applied to a sample problem with four trucking companies, 150 nodes, and a node overlap of 50%. A comparison of the tabu search and MIP solutions indicated that the tabu search solution was only slightly less profitable than the MIP solution. The total profit for all four companies was only 0.34% lower in the tabu search solution than in the MIP solution. An examination of the tours of each company indicated that 6 out of the 11 tabu search tours were as good as the corresponding MIP tours. Three out of the other 5 tours were $3.74 less profitable than the corresponding MIP tour because the total tour time was 0.05 hours longer, while the other 2 tours were $7.48 less profitable because the total tour time was 0.10 hours longer. These very preliminary results indicate that the clustering/GAP/tabu search solution approach presented here appears to be a flexible, efficient method for solving the IFMS which is quite accurate as indicated by the comparison to the MIP solution. The next step is to test the method more extensively by applying it to more problems of varying size and complexity.

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References:

Ahuja, R., T. Magnanti, and J. Orlin (1993) *Network Flows.* Prentice Hall, Upper Saddle River, New Jersey.

Cambridge Systematics Inc. (1997) A Guidebook for Forecasting Freight Transportation Demand, *NCHRP Report* #388, Transportation Research Board, Washington D.C.

Gillett, B. and L. Miller (1974) A heuristic algorithm for the vehicle-dispatch problem, *Operations Research*, Vol. 22, pp. 340-349.

Glover, F. (1986) Future paths for integer programming and links to artificial intelligence, *Computers and Operations Research*, Vol. 5, pp. 533 549.

Glover, F. and M. Laguna (1993) Tabu Search, in: C. Reeves (ed) *Modern Heuristic Techniques for Combinatorial Problems*, Blackwell Scientific Publications, Oxford, pp. 70-150.

Hjorring, C. (1995) The vehicle routing problem and local search metaheuristics, Ph. D thesis, Department of Engineering Science, The University of Auckland, Australia, 1995.

Holguín-Veras, J. (2000) A Framework for an Integrative Freight Market Simulation. IEEE 3rd Annual Intelligent Transportation Systems Conference ITSC-2000, Dearborn Michigan October 2000, pp. 476-481.

Holguín-Veras, J. and E. Thorson (2000) An Investigation of the Relationships between the Trip Length Distributions in Commodity-based and Trip-based Freight Demand Modeling. *Transportation Research Record* #1707 pp. 37-48, September 2000.

Holguín-Veras, J. and E. Thorson (2003) Modeling Commercial Vehicle Empty Trips with a First Order Trip Chain Model, *Transportation Research Part B*, Vol. 37 (2), pp. 129-148.

Nygard K., P. Greenberg, W. Bolkan, and E. Swenson (1988) Generalized assignment methods for the deadline vehicle routing problem in: B. L. Golden and A. A. Assad(eds) *Vehicle routing: Methods and Studies*, North-Holland, Amsterdam, pp. 107-125.

Ogden, K.W. (1992) *Urban Goods Movement*. Ashgate Publishing Limited ISBN 1-85742-029-2, England.

Table 1. Profit for each company in the final tabu search and MIP solutions and the difference in the tabu search results relative to the MIP results expressed as a percentage.

	Tour	Tabu Search	MIP	Rel. Diff. (%)
Company #1	**1**	643.93	643.93	0.00
	2	748.03	755.50	-0.99
	Total	1391.95	1399.43	-0.53
Company #2	**1**	872.26	876.00	-0.43
	2	758.96	758.96	0.00
	3	794.33	794.33	0.00
	Total	2425.55	2429.29	-0.15
Company #3	**1**	557.07	557.07	0.00
	2	499.55	507.03	-1.47
	3	546.14	546.14	0.00
	Total	1602.76	1610.24	-0.46
Company #4	**1**	740.55	740.55	0.00
	2	725.60	729.34	-0.51
	3	679.30	683.03	-0.55
	Total	2145.44	2152.92	-0.35
Total		7565.71	7591.87	-0.34

1. Cluster all nodes available to each player:
    a. perform a radial sweep of the service area to cluster nodes
    b. estimate the cost of including node *i* in cluster *j*
    c. use these costs to solve the GAP to achieve a minimum cost, feasible clustering
2. Use tabu search to route the nodes in each player's clusters
3. Examine all possible intra-player node exchanges to identify and implement any exchanges which increase the profit of at least one tour and decrease the profit of no tour
4. Process contested nodes
    a. identify nodes included in more than one player's routes
    b. calculate the delivery cost for each player
    c. remove the contested node from the node sets of players who do not have the lowest delivery cost with ties remaining in the node sets of the relevant players
5. Return to step 1 with the updated node sets until each node is in exactly one tour

Figure 1. The cluster first, route second procedure.

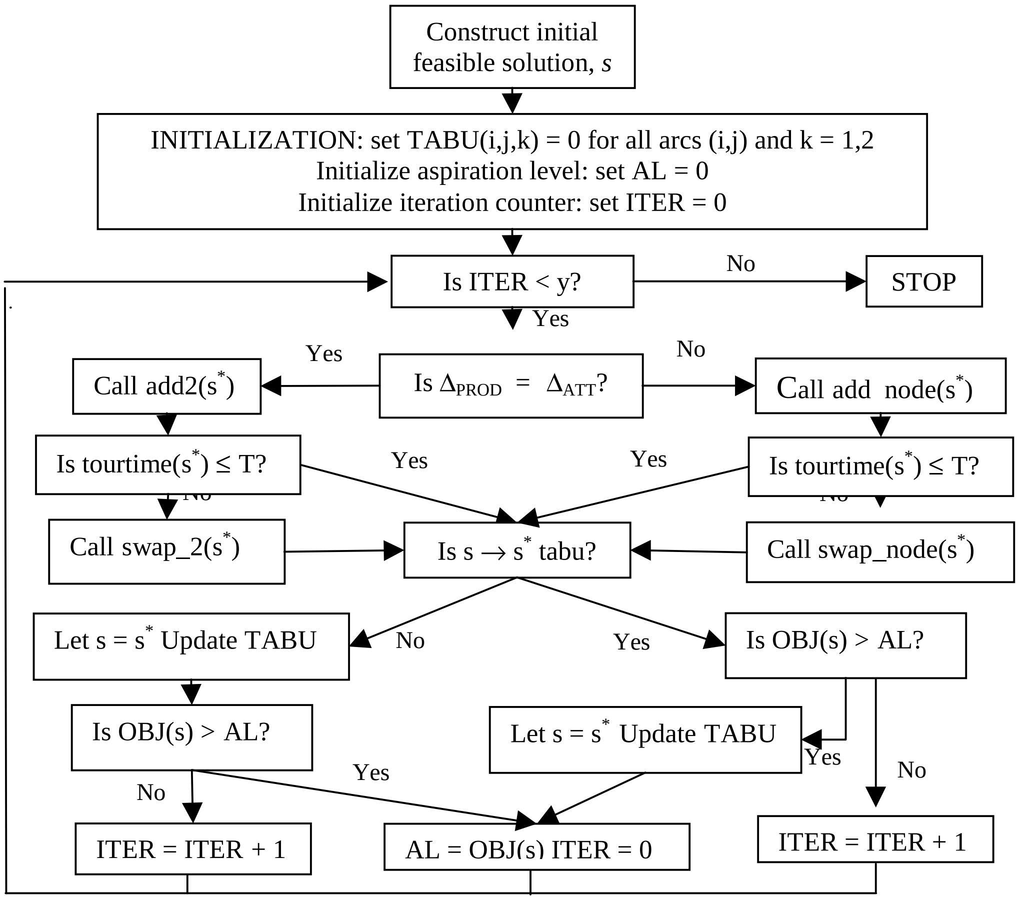
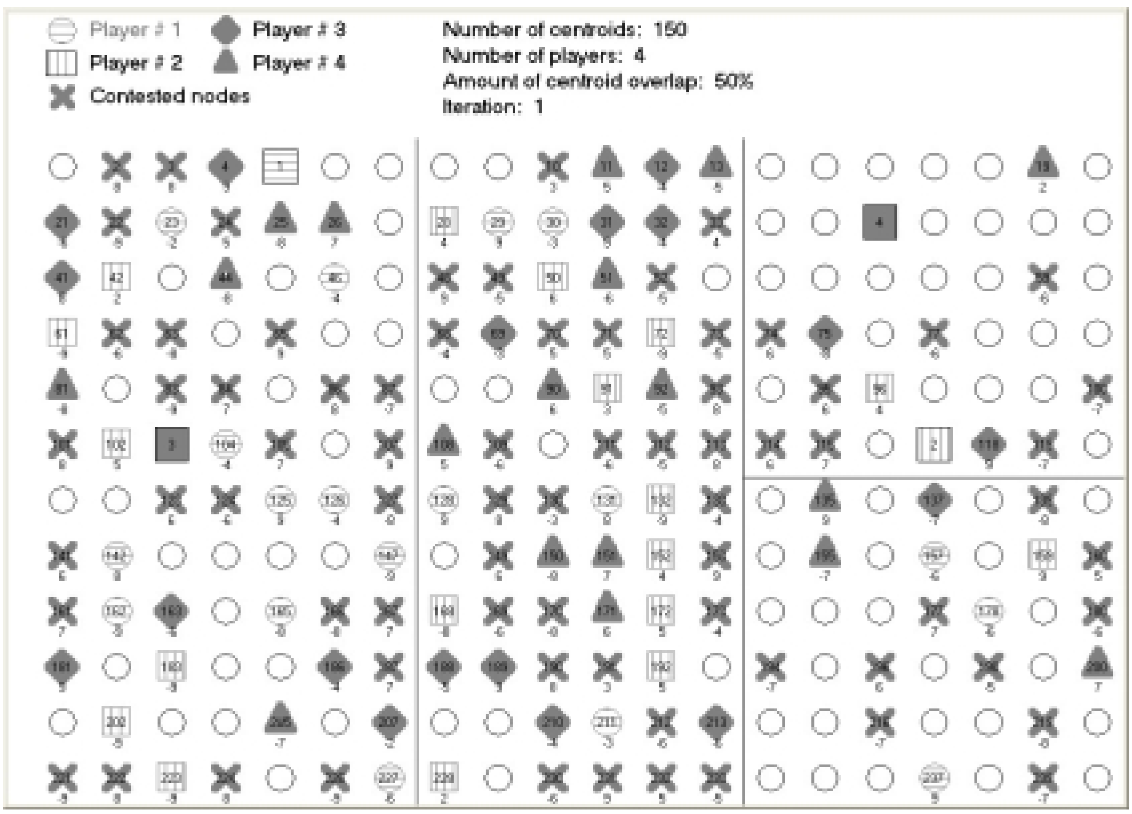


Figure 2. A flow chart of the tabu search.



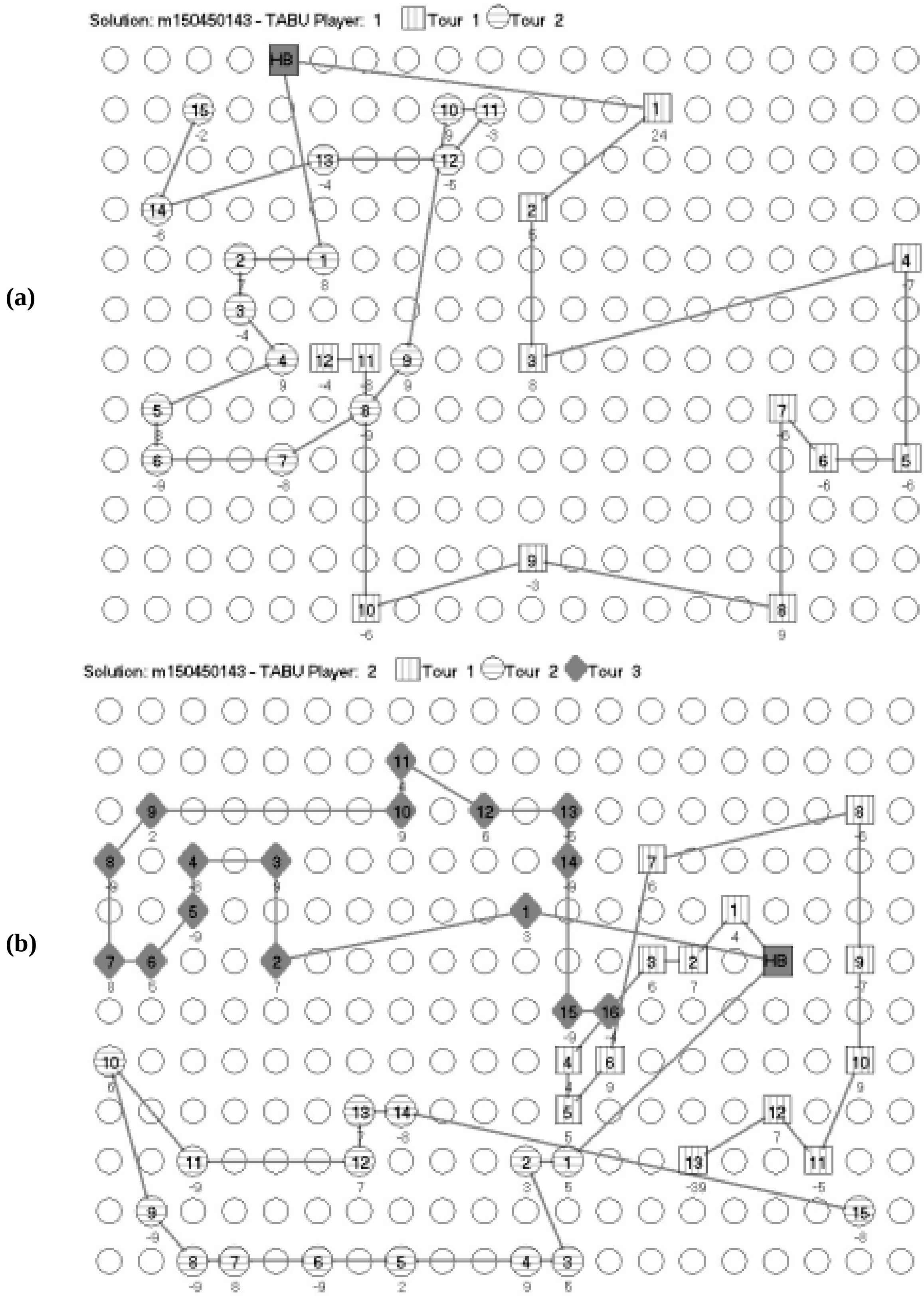
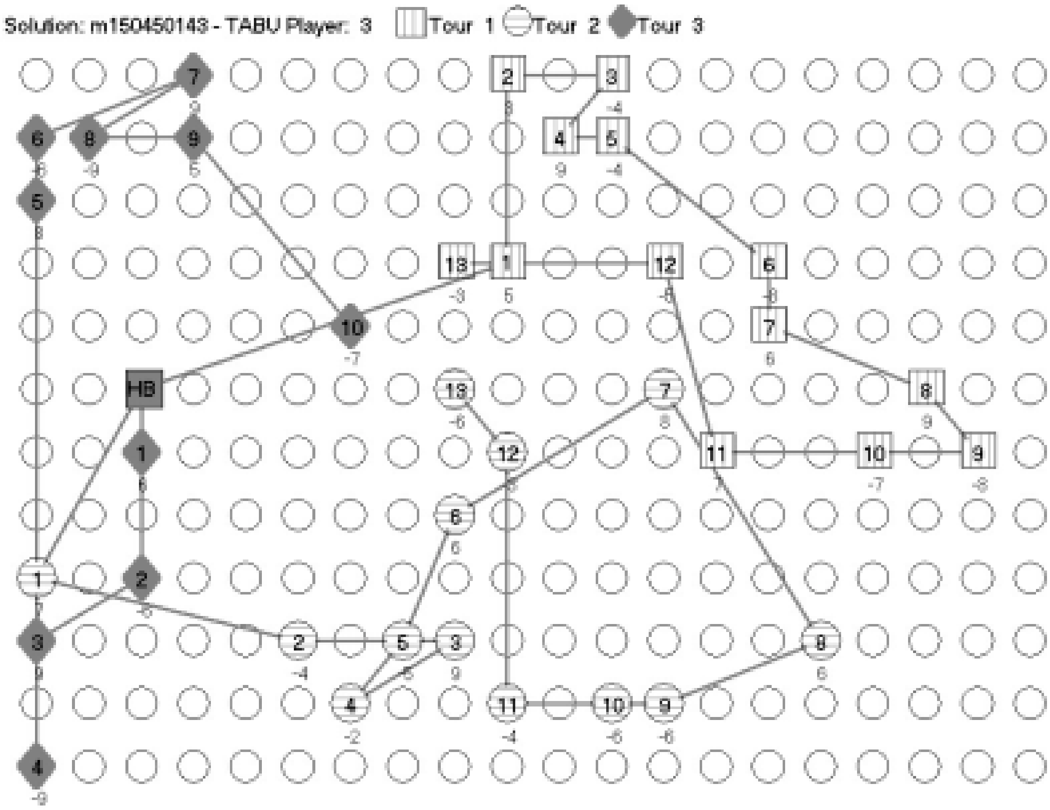


Figure 4. The tours in the tabu search solution for **(a)** company 1 and **(b)** company 2. The stops in each tour are numbered sequentially, HB indicates the company's home base, and the numbers below each stop indicate the node's production (> 0) or the attraction (< 0).

(c)



(d)

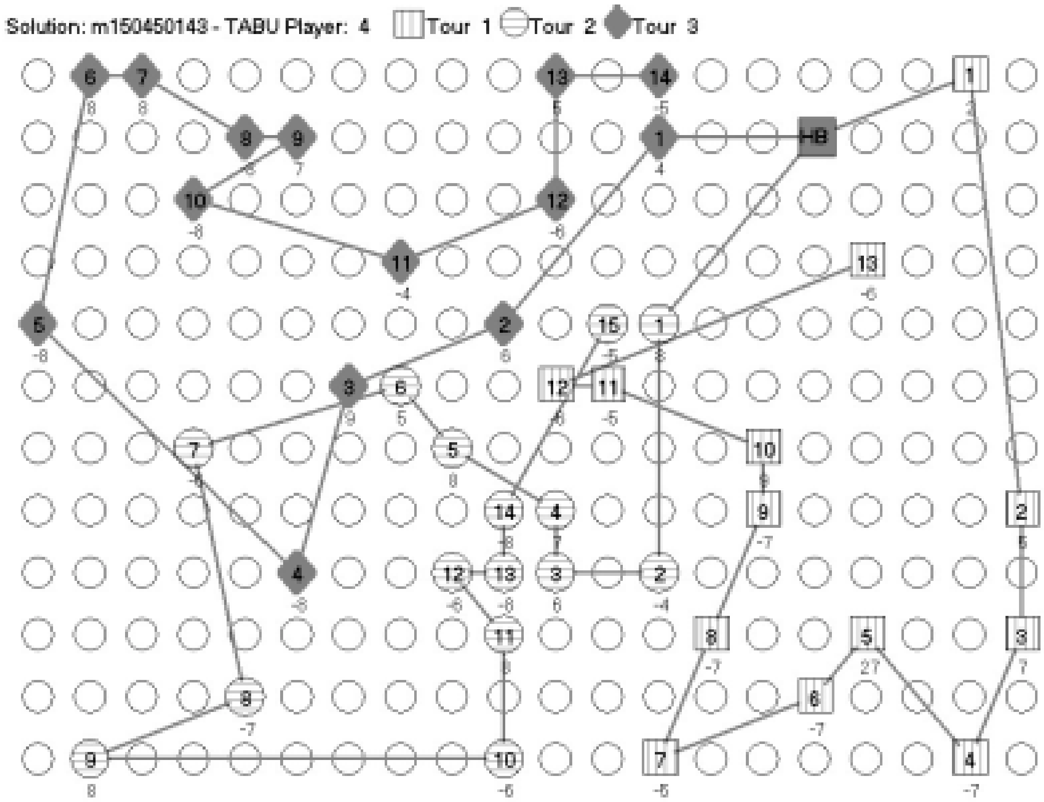


Figure 4 continued. The tours in the tabu search solution for **(c)** company 3 and **(d)** company 4.