

Robust Tabu Search Algorithm for Planning Rail-Truck Intermodal Freight Transport

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Abstract. In this paper a new efficient tabu search algorithm for assigning freight to the intermodal transport connections was developed. There were also formulated properties of the problem that can be used to design robust heuristic algorithms based on the local search methods. The quality of solutions produced by the tabu search algorithm and by often recommended greedy approach were also compared.

Keywords: Intermodal transport · Optimization · Tabu search

1 Introduction

Road transportation is very expensive. Because of that, carrying goods over a long distance is achieved as a combination of different types of transportation (e.g. with the use of rail, ships and trucks). Such means of transportation is called *intermodal freight transport*. The problems related to the intermodal transport are intensely studied by the Operations Research. Thanks to such activities, transport infrastructure can be better designed, vehicle routes and delivery schedules can be planned more consciously which results in savings and consequently may lead to lower prices of transported goods.

A widely used definition of intermodal freight transport was introduced at the European Conference of Ministers of Transport. It was defined as “the movement of goods in one and the same loading unit or vehicle by successive modes of transport without handling of the goods themselves when changing modes”. Second commonly used definition was introduced by Macharis and Bontekoning [18]. They define it as “the combination of at least two modes of transport in a single transport chain, without the change of container for the goods, with most of the route travelled by rail, inland waterway or ocean-going vessel and with the shortest possible initial and final journeys by road”. More definitions of intermodal freight transport can be found in [6].

Problems related to the intermodal transport are much more complex to solve than problems which take into consideration a fixed type of transportation (aka

unimodal problems). Moreover, models used to solve unimodal problems are also applied to intermodal transport problems. For this reason, there is a group of people convinced that intermodal transportation research is emerging as a new transportation research field and it is still in the pre-paradigmatic phase and proper models are not known at the moment (see [6, 18]). Bontekoning, Macharis and Trip [6] described the actual state of intermodal transport research field and marked actions which should be done to make it similar to “normal science”. They proved that the intermodal transport research is in the pre-paradigmatic phase. They found plenty of small research communities that address intermodal transport problems. They proposed transformation of these small communities to one or two large research communities.

Macharis and Bontekoning [18] underlined that the intermodal transport is a very complex process that involves many decision-makers. They distinguished four types of them and emphasized that some decisions can have long-term effects (e.g. planning and building a railway infrastructure) when other can have short-term effects (temporary changes in timetable). Decision-makers should work in a close collaboration to achieve supreme results. Many decisions lead to a variety of areas where optimization can be used, whereas many authors introduced overview of articles and methods used in the intermodal transport research and classified them by the type of decision maker and by the time horizon of operations problem.

Caris, Macharis and Janssens [11] proposed new research fields regarded to decision support in intermodal freight transport. They made an overview of applied applications that support decisions of policy makers, terminal network design, intermodal service network design, intermodal routing, ICT (Information and Communication Technologies) innovations and drayage operations. They pointed out that there is no link between models for terminal network design and intermodal service network design. They recognized the need for solution methods solving intermodal freight transport optimization problems that can accept multiple objective functions, transportation mode schedules, economies of scale and demanded times of delivery.

Intermodal freight transport, due to its big complexity and plenty of constraints imposed on solutions, constitutes a challenge for many types of heuristics and metaheuristics. Caris and Janssens [10] optimized pre- and end-haulage of intermodal container terminals using heuristic approach. They modeled problem as a Full Truckload Pickup and Delivery Problem with Time Windows (FTPDPDPTW) where vehicles carry full truckloads to and from an intermodal terminal. Time windows were used to represent the time interval in which the service at a customer must start. They proposed two-phase insertion heuristic and the improvement heuristic with three types of neighborhood. The solution is obtained by two-phase insertion heuristic and afterwards improved by the improvement heuristic.

There are some articles devoted to commercial decision support systems (DSS). Kelleher, El-Rhalibi and Arshad [16] described features of PISCES, the integrated system for planning intermodal transport. They presented methods used in PISCES for dealing with the triangulation in the pick-up and drop scenario.

Another research on decision support system was published by Rizzoli, Fornara and Gamberdella [21]. They presented the terminal simulator component of the Platform project, funded by the Directorate General VII of the European Community. Presented software can model processes taking place in an intermodal road or rail terminal. It was designed on the basis of discrete-event simulation paradigm. Software user can define the structure of terminal and different input data. It allows us to check how changing terminal structure may have an influence on its performance.

Noteworthy are also researches on systems that support decision-making by more than one policymaker. Febraro, Sacco and Saeednia [12] proposed an agent-based framework for cooperative planning of intermodal freight transport chains. In this system, many actors can work together and negotiate their decisions to achieve a common goal.

Transport companies are not willing to share their tariffs on their websites. This information may be hidden due to many factors, e.g. cost changes. Costs can change overnight because of fluctuations of exchange rates, political situation etc. Moreover, prices vary from one company to another. Researchers need such data to develop better algorithms. Special price models come forward. Hanssen, Mathisen, Jorgensen [15] proposed a generalized transport costs model that can be used to assess mean prices of different types of transport on the given distance. Intermodal transport research field demands knowledge base that will ease scientists to conduct their researches on the real data. Experimental results will be more reliable. It should be in the interest of governments and all shipping companies to support building of such database.

2 Problem Formulation

In a planning phase, transportation management company has to realize a certain number of transport tasks. Transport task is to carry some amount of goods from suppliers to customers. Transport can be organized in two ways: (i) by a single truck, (ii) by the intermodal transport (truck-train-truck). Goods are transported in containers or semitrailers customized to rail transport.

There are known locations of customers, suppliers and intermodal terminals, distances between: (i) intermodal terminals, (ii) intermodal terminals and customers, (iii) suppliers and customers. Of course in the first case this is the length of the rail route and in the other cases it is the length of the road route. Cargo trains implementing intermodal freight transport follow the schedule of courses. Each course specifies initial and final intermodal terminal, time of delivery, unit cost of the course and the amount of free wagons. The number of free wagons is updated online based on reservations of transportation management companies. Attachment of wagons on intermediate stations is forbidden. The objective of optimization is the assignment of task to the train course simultaneously minimizing the overall costs of transport.

Let $J = \{1, \dots, n\}$ be a set consisting of n transport tasks and let $T = \{1, \dots, t\}$ be the set of railway courses. For each task $j \in J$ and each

course $i \in T$ the distance achieved by the traffic transport $d_{j,i}$ is given. Note, that the distance $d_{j,i}$ is the result of summing distances between supplier and the initial intermodal terminal and between final intermodal terminal and the customer. The distance achieved by the traffic transport between supplier and customer for the fixed $j \in J$ is marked as $d_{j,0}$. The railway distance for the course $i \in T$ is r_i . The course $i \in T$ has $l_i \geq 0$ free cargo wagons to load. The overall price for the carriage of freight from the supplier to the customer using cargo train $i \in T$ is $c_{j,i}$. The cost of direct road transport from the supplier to the customer specified in the task j is $c_{j,0}$. Let the assignment of the course to the task j be marked as $a_j, a_j \in \{0\} \cup T$ ($a_j = 0$ if the transport is carried only by the truck). Vector $\alpha = [a_j]$ denotes the assignment of all tasks to the courses. The total cost of transport for assignment α is

$$Cost(\alpha) = \sum_{j=1}^n c_{j,a_j}. \tag{1}$$

We would like to find such assignment α^* that the total cost of transport is as small as possible

$$Cost(\alpha^*) = \min_{\alpha \in A} Cost(\alpha), \tag{2}$$

where A is the set of all possible assignments, $|A| = n^{m+1}$.

2.1 Properties of the Problem

In the current subsection we formulate certain properties of the problem, which can be used in the design of efficient heuristic algorithms based on local search methods. The first one relates to the method that allows us to determine the lower bound of the objective function value for the optimal solution, the second one allows us to reduce the number of solutions in the neighborhood by eliminating the subset with worse solutions.

Proposition 1. *Let $u_i = \min_{k=0,\dots,m} c_{j,k}$, then the lower bound*

$$LB = \sum_{j=1}^n u_j. \tag{3}$$

Proposition 2. *Let α and β be the assignments of tasks to the trains such that $Cost(\beta) < Cost(\alpha)$. Then, at least one task has lower cost of transporting in the assignment β than in the assignment α .*

Proposition 3. *Let β be the assignment of tasks to the trains resulting from α by the assignment of the task j to train i , then*

$$Cost(\beta) = Cost(\alpha) - c_{j,a_j} + c_{j,i}. \tag{4}$$

Proposition 4. *Let β be the assignment of tasks to the trains resulting from α by interchanging assignment of tasks j and k , then*

$$Cost(\beta) = Cost(\alpha) - c_{j,a_j} - c_{k,a_k} + c_{j,a_k} + c_{k,a_j}. \tag{5}$$

Note, if $Cost(\alpha)$ is known, expressions (4) and (5) can be determined in time $O(1)$.

2.2 Example

A certain logistic company has to realize $n = 5$ transportation tasks. Transportation may be achieved with $t = 3$ courses of cargo train. All trains have $l_i = 2$ free cargo wagons to load. The transportation costs (traffic and intermodal) are given in Table 1.

Table 1. Costs of intermodal and traffic transport

	Task 1	Task 2	Task 3	Task 4	Task 5
0-traffic	1962	1863	1879	1947	1972
1-course	1323	1276	1375	1289	1410
2-course	1328	1283	1304	1327	1184
3-course	1057	1156	1140	1072	1047

It is easy to see that the price of road transport is 9623 whereas, the lowest price of transport is $LB = 5472$ (marked with bold). Transport with the lowest price requires use of 5 wagons of the course 3. It is not possible because rail connection 3 has only two free wagons. In Table 1 a feasible connection (that takes into account number of free wagons) with total price 5893 was marked in bold.

Let us consider a greedy strategy that assigns tasks to the cheapest intermodal freight transport connection. In the first row, tasks with the biggest difference in price between road and rail transport will be assigned. Tasks that cannot be achieved by the rail transport with the cheapest cost will be achieved by truck transport. The described strategy is used in many logistic companies, where assignment of transport tasks is realized with the use of forwarding agents. A forwarding agent is concentrated on finding the cheapest solution of transport problem, because his salary depends (directly or indirectly) on the income that is the difference between the price of transport negotiated with a customer and the real price.

Let us assume that road transport prices were negotiated with customers, profits from the intermodal freight transport are formed respectively: 905, 707, 739, 875, 925. Tasks 1 and 5 generate the biggest profits, therefore they will be realized by the intermodal freight transport. The rest of tasks will be realized by trucks.

3 An Approximation Algorithm

In order to solve the stated problem we propose a local search algorithm based on the tabu search (TS) approach [13, 14]. The tabu search is one of the best

methods of constructing heuristic algorithms. This is confirmed for many optimizing problems, as a main method (for scheduling of tasks [3, 4, 8, 19], vehicle routing [9, 20], packing [17], container loading [7]), as well as a key element of higher metaheuristics, e.g. golf method [5]. Neighborhood determination in the tabu search metaheuristics is also frequently parallelized (see [1, 2]).

An algorithm based on this method, in each iteration searches neighborhood of the basic solution for the solution with the best objective function value. In every iteration the best solution replaces the basic solution. To prevent searching loops, the tabu mechanism is used. It is usually implemented as a list with the limited length. In each iteration, selected attributes of subsequently visited solutions are stored. Contents of the list divide the neighborhood into two subsets: a set of forbidden and a set of feasible solutions. Forbidden solutions are not searched except the case when forbidden solution is better than the best solution found so far.

The search stops when the given number of iterations without improving the criterion value has been reached or the algorithm has performed a given number of iterations.

3.1 Moves and Neighborhood

The neighborhood of a solution is generated by moves. In our problem, the solution is represented by a vector of task assignments α . The neighborhood of the solution can be created due to exchanges of assignment of two tasks or change of assignment of a single task.

Let $v = (a, b)$ be a pair of exchanged tasks. We define a new assignment $\alpha^{(v)}$ obtained from $\alpha = (\alpha_1, \dots, \alpha_n)$ by exchanging assignment of tasks a and b as follows:

$$\alpha^{(v)} = (\alpha_1, \dots, \alpha_{a-1}, \alpha_b, \alpha_{a+1}, \dots, \alpha_{b-1}, \alpha_a, \alpha_{b+1}, \dots, \alpha_n) \text{ for } a < b \quad (6)$$

and

$$\alpha^{(v)} = (\alpha_1, \dots, \alpha_{b-1}, \alpha_a, \alpha_{b+1}, \dots, \alpha_{a-1}, \alpha_b, \alpha_{a+1}, \dots, \alpha_n) \text{ for } a > b. \quad (7)$$

Let EX be a set of some such moves and $N(EX, \alpha) = \{\alpha^{(v)} : v \in EX\}$ be a neighborhood of solution α generated by a move set EX . For a feasible solution α every move $v \in EX$ generates a feasible solution.

Let $v = (a, k)$ be the move that changes the assignment of the task a to the course k . We define the new assignment α^v obtained from $\alpha = (\alpha_1, \dots, \alpha_n)$ by execution move v in α as follows:

$$\alpha^{(v)} = (\alpha_1, \dots, \alpha_{a-1}, k, \alpha_{a+1}, \dots, \alpha_n). \quad (8)$$

Let INS be a set of some such moves and $N(INS, \alpha) = \{\alpha^{(v)} : v \in INS\}$ be a neighborhood of solution α generated by a move set INS . For the feasible solution α , there are infeasible moves $v = (a, k) \in INS$ such that $\alpha_a \neq k$ and cargo train $k \in T$ has not free wagons.

Let $U = \{v : \alpha^{(v)} \text{ is feasible} \wedge v \in EX \cup INS\}$ be a set of feasible moves and $N(U, \alpha)$ be a neighborhood of solution α . The neighborhood $N(EX, \alpha)$ has n^2 neighbors, while $N(INS, \alpha)$ has nm neighbors. The determination of the total cost explicitly from the Formula (1) requires $O(n)$ time for each solution, therefore the search of neighborhood can require a great computational effort. The use of expression (4) for moves from INS and expression (5) for moves from EX reduces computation time to $O(1)$ (n times) for each generated solution.

We propose a reduction of the neighborhood size to the set of promising moves. The move v is promising if its execution gives the chance to receive a better solution. From Proposition 2 we have simple conditions for obtaining a better solution:

- $c_{a, \alpha_a} > c_{a, k}$ for move $v = (a, k) \in INS$,
- $c_{a, \alpha_a} > c_{a, \alpha_b}$ for move $v = (a, b) \in EX$,
- $c_{b, \alpha_b} > c_{b, \alpha_a}$ for move $v = (a, b) \in EX$.

We will mark the reduced set of moves as V .

4 Computation Results

The main objective of experimental studies was to evaluate the usefulness of advanced heuristics in assigning transportation tasks to intermodal transport. Experimental test was carried out on the randomly generated data. The set of 120 instances is divided into 12 groups. Each group consists of 10 instances with the same number of tasks n and freight trains t . The study was conducted for groups, where the number of tasks $n \in \{50, 100, 200, 500\}$ and the number of cargo trains $t \in \{10, 20, 30\}$.

Railway distances r_i for course $i \in T$ were generated from the uniform distribution on $[2000, 2500]$, in intermodal transport the distances achieved by traffic transport $d_{j, i}$ were generated from uniform distribution on $[30, 200]$. A traffic transport distance is usually shorter than distance of intermodal transport thus we determine this distance from the expression $d_{j, 0} = \min_{i=1, \dots, t} (r_i - d_{j, i})$.

We assumed unit costs of traffic transport $c_{j, 0} = d_{j, 0}$. The cost of task $j \in J$ carried by freight train $i \in T$ includes the cost of road transport ($d_{j, i}$), the cost of handling in intermodal terminal (h_j), the cost of transporting freight train depending on the distance (r_j) and is expressed by the formula $c_{j, i} = d_{j, i} + h_j + \gamma r_j$, where γ is the factor of the cost of rail transport to the cost of traffic transport. The research was carried out for three values of factor γ (0.8, 0.65, 0.5) and $h_j = 60$. Note that for $\gamma = 0.8$ and transport distance 300 the costs of traffic and intermodal transport are comparable.

The number of free wagons was the same for each cargo train. We considered two levels of wagon availability for loading: (i) a few free wagons: $l_i = \lfloor n/t \rfloor + 1$, (ii) many free wagons: $l_i = 2 \cdot \lfloor n/t \rfloor$.

The algorithm TS was implemented with the reduced neighborhood V , written in C++ and ran on Lenovo T540p personal computer with processor i7-4710 2.5 GHz. Further, we wrote a greedy algorithm G (see Subsect. 2.2 for details)

and an algorithm R which compute the total cost of traffic transportation. The algorithm TS performed 1000 iterations and started from the solution in which all tasks were assigned to road transport.

Since there are no algorithms for solving the considered problem in the literature, we made a comparison of TS, G and R with lower bound LB (3). For each instance, we defined the following values:

$Cost(\alpha^A)$ – the total cost of transportation of tasks forms set J found by the algorithm A , $A \in \{TS, G, R\}$,

$PRD(A)$ – the mean value of the relative cost of solution found by algorithm A with respect to the lower bound LB i.e.

$$PRD(A) = \frac{Cost(\alpha^A) - LB}{LB} \cdot 100[\%], \quad (9)$$

CPU – the mean computation time (in seconds).

The results of computer computations are summarized in Table 2. The first column contains the number of tasks and freight trains in each instance of the group, the second contains the average relative cost of traffic transport, the next three columns refer to instances of the small number of available wagons and include: the average relative cost of the solution generated by greedy algorithm R, the average relative cost of the solution generated by tabu search algorithm TS and the average number of transports carried out exclusively by road in the solution generated by the algorithm TS. The other three columns refer to instances with many free cargo wagons. The table shows the results for different γ values.

At the beginning of the analysis of the results collected in Table 2, it should be noted that the proposed tabu search algorithm successfully finds the task assignments for intermodal transport. The solutions generated by TS algorithm for the intermodal transport with a limited number of free cargo wagons are only a few percent worse than transport with minimum cost i.e. with the unlimited number of free cargo wagons and trucks. It is easy to notice that the algorithm TS finds significantly better solutions for instance with a large number of wagons to be loaded.

According to Table 2, tabu search heuristic performs significantly better than the greedy heuristic. The average relative cost does not exceed 3.2% for instances with large number of free wagons and 8.3% for instances with small number of free wagons. In the case of greedy algorithm this cost varies accordingly from 3.2% to 38.3% and from 6.0% to 52.6%. The superiority of the algorithm TS over the greedy algorithm R increases with decreasing γ (with increasing attractiveness of intermodal transport).

While comparing the cost of road transport and intermodal transport, it can be noted that with decreasing γ values increases the difference between the cost of road transport and the intermodal one. For $\gamma = 0.5$ it is close to 70%. The experiment shows that for the highest γ value, the profit of using intermodal transport is admittedly less (approximately 10%) however, in our opinion, it is

Table 2. Relative cost of traffic and intermodal costs

$n \times t$	G traffic	A few free wagons			Many free wagons		
		Greedy	TS	Use of trucks	Greedy	TS	Use of trucks
$\gamma = 0.80$							
50×10	10.5	6.0	3.7	25.0	3.2	1.5	8.0
50×20	10.5	7.4	5.3	37.0	5.4	2.5	8.8
50×30	10.5	7.7	5.4	32.4	5.8	2.3	2.4
100×10	10.7	6.4	4.3	32.0	3.6	1.3	3.5
100×20	10.5	7.8	5.6	38.8	5.9	3.0	10.4
100×30	10.4	7.7	5.5	37.8	5.9	2.7	7.3
200×10	10.6	6.3	4.4	33.4	3.7	1.4	6.7
200×20	10.7	7.5	5.1	33.7	5.4	2.4	4.7
200×30	10.4	7.9	6.0	45.1	6.1	3.2	12.8
500×10	10.4	6.9	5.2	42.7	4.6	2.5	15.4
500×20	10.6	7.5	5.7	42.4	5.3	2.7	12.5
500×30	10.7	8.1	5.9	41.6	6.2	3.0	7.8
$\gamma = 0.65$							
50×10	34.7	19.5	4.5	0.0	10.4	1.5	0.0
50×20	34.8	24.0	6.7	0.0	17.0	2.4	0.0
50×30	34.9	25.6	6.5	0.0	19.1	2.1	0.0
100×10	35.0	20.5	5.2	0.0	11.6	1.1	0.0
100×20	34.8	25.1	7.2	0.0	18.9	2.8	0.0
100×30	34.8	24.7	6.9	0.0	18.8	2.5	0.0
200×10	34.8	20.5	5.7	0.0	11.3	1.3	0.0
200×20	35.0	24.2	6.1	0.0	17.0	2.1	0.0
200×30	34.8	26.1	8.3	0.0	19.9	3.2	0.0
500×10	34.4	22.9	6.8	0.0	15.5	2.5	0.0
500×20	34.9	24.4	7.6	0.0	16.8	2.7	0.0
500×30	35.1	26.3	8.2	0.0	19.9	2.8	0.0
$\gamma = 0.50$							
50×10	72.4	38.1	3.9	0.0	18.7	1.1	0.0
50×20	72.8	47.5	6.2	0.0	32.4	2.1	0.0
50×30	73.3	51.1	6.0	0.0	36.6	1.8	0.0
100×10	73.0	39.8	4.7	0.0	20.0	0.9	0.0
100×20	72.8	49.2	6.6	0.0	35.4	2.4	0.0
100×30	73.1	49.1	6.4	0.0	35.0	2.2	0.0
200×10	72.8	40.7	5.2	0.0	20.7	1.0	0.0
200×20	73.3	47.7	5.6	0.0	31.8	1.8	0.0
200×30	73.2	53.2	7.8	0.0	38.8	2.9	0.0
500×10	71.9	44.9	6.0	0.0	28.5	1.9	0.0
500×20	73.2	49.0	7.1	0.0	31.7	2.3	0.0
500×30	73.6	52.6	7.7	0.0	38.3	2.5	0.0

Table 3. Computation time in seconds

$n \times t$	A few free wagons		Many free wagons	
	$TS(V)$	$TS(U)$	$TS(V)$	$TS(U)$
100×10	0.1	0.1	0.0	0.1
100×20	0.1	0.2	0.1	0.2
100×30	0.2	0.3	0.1	0.4
200×10	0.3	0.5	0.2	0.5
200×20	0.4	0.8	0.3	1.0
200×30	0.7	1.2	0.4	1.2
500×10	1.9	3.2	1.4	3.2
500×20	3.9	6.2	2.9	6.0
500×30	5.8	9.3	4.6	9.7

important from the standpoint of business activity. In addition, with decreasing γ , the percentage share of road transport in the solutions generated by the algorithm TS is reduced. For $\gamma = 0.8$ it varies from 25% to 45% and from 2.4% to 15.4%, for the remaining values of coefficient γ it equals 0.

Table 3 shows the average computational time for 9 groups of instances (for groups with $n = 50$ the computation time was less than 0.1). The calculations were performed for two versions of the algorithm TS: $TS(V)$ with reduced neighborhood V and $TS(U)$ with the full neighborhood U . It is easy to see that the computation time increases with the increasing number of tasks n and the number of cargo trains t . While comparing computation time $TS(V)$ and $TS(U)$, it should be highlighted that $TS(V)$ runs faster than $TS(U)$ from 30% to 50%. The computation time of algorithm $TS(V)$ does not exceed 6 seconds for instance with the biggest number of tasks and cargo trains.

5 Conclusion

In this paper, we developed the tabu search algorithm to minimize the total cost of transport. We have considered the intermodal transport as an alternative to the most used traffic transport. We have formulated several properties of the problem, which were used not only to increase the efficiency but also to reduce the computation time of TS algorithm. We experimentally proved that the global cost optimization of intermodal transport allows us to achieve significantly higher profits than using in practice of the greedy approach.

The results obtained and our research experience [22] encourage us to extend the ideas proposed to multi-criteria problems generated by intermodal transport.

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