Freight Service Design for an Italian Railways Company

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Abstract. In this paper, we present a mathematical model to design the service network, that is the set of origin-destination connections. The resulting model considers both full and empty freight car movements, and takes into account handling costs. More specifically, the model suggests the services to provide, as well as the number of trains and the number and type of cars traveling on each connection. Quality of service, which is measured as total travel time, is established by minimizing the waiting time of cars at intermediate stations.

Our approach yields a multi-commodity network design problem with concave arc cost functions. To solve this problem, we implement a tabu search procedure which adopts "perturbing" mechanisms to force the algorithm to explore a larger portion of the feasible region. Computational results on realistic instances show a significant improvement over current practice.

Keywords. railways transportation, service network design, tabu search

1 Introduction

Railways freight transportation is a relevant activity in many economies. It supports and makes possible most other economic activities and exchanges. In the last twenty years, the privatization and reorganization of most of the national railways companies, combined with the removal of many entrance barriers and national protectionism to markets and the consequent increase of competition have boosted the development of Operations Research methods applied to railways transportation.

ATMOS 2006
6th Workshop on Algorithmic Methods and Models for Optimization of Railways
http://drops.dagstuhl.de/opus/volltexte/2006/685

For comprehensive reviews on planning models for freight transportation, the reader may refer to the surveys by Crainic and Laporte [1] and by Cordeau, Toth and Vigo [2]. The former describes the main issues in freight transportation planning and operations and presents OR models, methods and tools to be used in this field of application. The latter is specifically focused on railways transportation. The authors provide a complete list of routing and fleet management models for freight transportation, of scheduling models for train dispatching and of assignment models to assign locomotives and cars.

The two cited surveys also give a broad overview on several types of problems and issues arising within the freight transportation arena. Obviously, most of railways transportation models available in the literature belong to the class of network flow models [3], since this is the topological structure of the problem. However, the general network flow model is often customized to take into account specific aspects of the problem. We here consider the freight service design problem, i.e. the problem of deciding the set of origin-destination connections. The reader may refer to [1] for a survey of the topic. This problem is a typical tactical planning problem, since the effects of decisions span a mid-term planning horizon.

A first example of a tactical planning model applied to rail freight transportation can be found in [4]. In this paper the authors examined traffic routing, train scheduling and allocation of work between yards. They also presented an optimization model intended to compute efficient solutions, allowing a reduction of costs, and to provide good quality of services in terms of transportation delays and reliability, over a medium term planning horizon. A nonlinear mixed-integer multi-commodity formulation is given and a heuristic algorithm is tested on instances arising from the Canadian National Railroads. Kwon et al. [5] presented a network flow model on a time-space network to model the problem of dynamic freight car routing and scheduling, which is solved with the column generation technique. Holmberg and Hellstrand [6] proposed a Lagrangean heuristic within a Branch & Bound framework to solve the uncapacitated network design problem with single origins and destinations for each commodity, which can be used to model the rail freight transportation. Fukasawa et al. [7] presented a network flow model to maximize the total profits, while satisfying the demands within a certain period of time, given the schedules and the capacities of the trains.

In railways freight transportation the movement of empty cars represents an important source of costs. Dejax and Crainic [8] provided a complete review of models for empty cars movement in freight transportation. Moreover we can mention some recently published papers in this specific area of research. Holmberg et al. [9] faced the problem of identifying distribution plans for the movement of empty cars by solving an integer multi-commodity network flow model on a time-expanded network. Sherali and Suharco [10] proposed a tactical model for the distribution and repositioning of empty railcars for shipping automobiles. Jaborn et al. [11] analyzed the cost structure for the repositioning of empty cars, and showed that such costs often depend on the number of car groups handled at yards. In the cost structure they also compounded costs due to car classification at intermediate yards. They observed the economy-of-scale behavior of total distribution costs, which can be reasonably decreased by building fewer but larger car groups. The authors modeled the empty freight car distribution problem as a capacitated network design on a time-dependent network and solved it with a tabu search meta-heuristic.

The application of railways transportation models to real operations generally requires the solution of large size instances, thus calling for a compromise between solution quality and computational time. On this subject, meta-heuristic algorithms have been widely implemented. For instance, we can mention Marín and Salmerón [12], [13] and Gorman [14] among others. Marín and Salmerón [12], [13] compared the application of three different local search meta-heuristics to the tactical planning of rail freight networks. Gorman [14] discussed both genetic and tabu search meta-heuristics to solve the weekly routing and scheduling problem of a major US freight railroad.

Herein, we present a case study on the Italian freight railways transportation, whose features make it rather different from other systems and in particular from the North American reality. In Italy, freight trains run according to a fixed schedule, and they cannot exceed 20 cars, due to length and weight limits. Moreover, cars are generally managed individually and *blocks* (groups) of cars are not composed. The problem of identifying a blocking plan in order to minimize handling costs, known as *Railroad Blocking Problem*, has been recently faced by several papers. For instance, Newton et al. [15] and Barnhart et al. [16] presented two network design formulations and solved real instances by a column-generation algorithm and a heuristic Lagrangean approach, respectively. Ahuja et al. [17] developed a Very Large-Scale Neighborhood Search for the blocking problem and tested it on data provided by three major US railroad companies. All these papers showed that relevant savings can be obtained by establishing "good" blocking plans. Moreover, composing blocks of cars permits large economies of scale in North American systems, as pointed out in [11]. This is true for the American reality. On the contrary, in Italy blocks are not formed. At any classification yard, cars are uncoupled from the incoming train, reclassified and coupled again to a new outgoing train, if they have not reached their final destination. Therefore, at any intermediate yard, car handling implies a coupling and an uncoupling manoeuvre, with relevant impacts on the total transportation costs and delivery times. Blocks are not formed mainly for organizational reasons: at the moment, it is not possible to organize blocks of cars directed to the same destination and the automatism to hook cars, enabling engine-drivers to easily handling groups of cars, is not available on the Italian cars. Moreover, American blocks may easily exceed 20 cars, which is the standard size of an Italian train. Therefore, no economies of scale can be achieved in the Italian reality.

In every rail transportation system, to satisfy the transportation demand, empty car repositioning has to be handled. The movement of empty cars is quite relevant in Italy and it reflects the economy of the country, characterized by production districts concentrated mainly in the northern part. The movement of empty cars is about 36% of the total. Besides the movement of empty cars, there is another relevant source of cost: the car handling process at intermediate yards. More than one third of the cars are coupled to at least three trains before arriving at their final destinations. Handling costs at intermediate yards represent a large percentage of total transportation costs: on average they contribute for one third to the total transportation cost borne to move a car from its origin to its final destination. Furthermore, handling a car at intermediate yards has also consequences on delivery time of goods. Taking into account such costs also guarantees a good level of service to customers by reducing delivery time.

In the sequel, we present a service network design model (refer to [18] for more details on the problem) for the Italian rail transportation, which is devoted to define the set of direct train connections between yards. The mathematical model we propose is tailored to the Italian system. We focus our attention on movements of both full and empty cars, taking into account the specific cost structure of the Italian freight railways transportation. We formalize a mathematical model classified as a Concave-cost Multi-commodity Network Design Problem which takes into account both the specific cost structure and the movements of both full and empty cars. In the proposed model, we also indirectly guarantee the quality of service, by minimizing the waiting time of cars at intermediate yards.

This problem is $\mathcal{NP}$-hard (see [19]). To solve real instances of the model, we propose a tabu search algorithm. We furnish the algorithm with additional mechanisms adopted to perturb the current solution with the scope of exploring a larger portion of the feasible region. The tabu search procedure takes advantage of the particular structure of the network, thus resulting an efficient algorithm as opposed to previous experience with similar problems.

The paper is organized as follows. In Section 2, we propose a mathematical formulation for the tactical problem of designing the network of services to move cars in order to satisfy transportation demand at minimum cost. Section 3 is dedicated to the description of the meta-heuristic algorithm designed in order to solve real instances of the problem. Section 4 reports some results of computational tests, and Section 5 concludes.

2 A mathematical model for tactical planning

Railways freight transportation problems are generally large-size and high level of difficulty problems. Operations Research-based methods can be useful in providing valid decision support systems to decision makers. We here propose a model to design the set of services of the Italian rail network in order to satisfy the whole transportation demand at minimum cost.

To formulate our model, we make use of the network of possible services, which is represented by a directed graph $D = (\mathcal{N}, \mathcal{A})$, where $\mathcal{N}$ denotes the set of yards and $\mathcal{A}$ the set of all the possible direct services. Since it is always possible to have a direct train between any pair of yards, we can reasonably assume that the following hypothesis holds true.

Hypothesis 1 *The graph representing the network of* possible *services is complete:* $\mathcal{A} \equiv \mathcal{N} \times \mathcal{N}$.

The purpose of the model that we propose is to design the network of activated services, namely $D' = (\mathcal{N}, \mathcal{S})$, which is a subgraph of $D = (\mathcal{N}, \mathcal{N} \times \mathcal{N})$, the complete (directed) graph defined on $n = |\mathcal{N}|$ vertices. More precisely, if $(i, j) \in \mathcal{S}$, then yard $i \in \mathcal{N}$ is directly connected to yard $j \in \mathcal{N}$ by a *service*, that is, at least one direct train connects i to j.

Cars move from their origins to their destinations using either a direct service, if one exists, or a sequence of trains with intermediate stops. In the Italian railways transportation operations blocks of cars are not allowed or at least they are extremely rare, see Section 1. Therefore, we can assume, without incurring in poor approximations, the following hypothesis.

Hypothesis 2 *If a train stops at an intermediate classification yard, all its cars are reclassified.*

In view of Hypothesis 2, we can directly associate handling costs to arcs $(i, j) \in (\mathcal{N} \times \mathcal{N})$ representing direct connections between pairs of yards $i, j \in \mathcal{N}$.

Finally, according to the experience of the Italian railways operator, capacity constraints are not restrictive at a tactical decision level, since enough cars to satisfy all the demands can be routed on each railroad; therefore, we are allowed to assume what follows.

Hypothesis 3 *The network of services is uncapacitated.*

The scope of the model we here propose is twofold. First, define the number of direct trains connecting origin-destination pairs. Second, route cars on the network in order to satisfy all the transportation demands. We consider both the full and the empty cars, and all the decisions are taken in order to minimize the total costs.

The notation of the model is in the sequel:

- $\mathcal{N} = 1, 2, \ldots, n$: set of yards;
- $\mathcal{K} = 1, 2, \ldots, k$: set of types of cars;
- f_{ij}: unit cost associated with the planning of a train on the direct service (i, j);
- c_{ij}: unit cost associated to link (i, j). This cost compounds the movement of a car on the link and the handling costs at yard i (coupling manoeuvre) and at yard j (uncoupling manoeuvre);
- b_i^p: supply (if positive) or demand (if negative) of cars of type p at yard i;
- α: maximum number of cars that can be assigned to a train.

The decision variables of the model are:

- x_{ij}^p: number of cars of type $p \in \mathcal{K}$ assigned to a service (i, j);

– y_{ij}: frequency of the service (i, j), i.e., number of trains traveling on the direct service (i, j).

The non-linear integer programming formulation is the following:

$$Min \sum_{(i,j)\in\mathcal{A}} f_{ij} \cdot h(y_{ij}) \cdot y_{ij} + \sum_{(i,j)\in\mathcal{A},p\in\mathcal{K}} c_{ij} \cdot x^p_{ij}$$

$$s.t.$$

$$\sum_{j\in\mathcal{N}} x^p_{ji} - \sum_{j\in\mathcal{N}} x^p_{ij} = b^p_i \qquad \forall i \in \mathcal{N},\ \ \forall p \in \mathcal{K}. \tag{1}$$

$$\sum_{p\in\mathcal{K}} x^p_{ij} \le \alpha \cdot y_{ij} \qquad \forall i, j \in \mathcal{N} : i \neq j. \tag{2}$$

$$x^p_{ij} \ge 0 \text{ integer} \qquad \forall i, j \in \mathcal{N} : i \neq j,\ \ \forall p \in \mathcal{K}. \tag{3}$$

$$y_{ij} \ge 0 \text{ integer} \qquad \forall i, j \in \mathcal{N} : i \neq j. \tag{4}$$

$$\tag{5}$$

where $h(y_{ij}) = \left(a + \frac{b}{y_{ij}+1}\right)$, with $a, b \in IR^+$.

This is a multi-commodity network design problem with a concave cost function. The cost function is composed by two terms: a train cost, which takes into account the planning of direct trains between origin-destination pairs, and a car cost.

The train cost is computed by multiplying the number y_{ij} of trains planned on a link (i, j) by a locomotive cost f_{ij} (computed as $f_{ij} = f \cdot d_{ij}$, where d_{ij} is the length of the link (i, j) and f is a train cost per kilometer, which accounts depreciation, maintenance, power, toll and engine drivers) and by a factor $h(y_{ij})$, which depends on the number of trains planned on the direct service (i, j). This last factor, which makes the objective function *concave*, is introduced in order to take into account a "quality" cost, which depends on the frequency of a service, i.e. on the number of available trains. In fact, an increase in the frequency of a service implies a decrease in the waiting times of cars at intermediate yards and therefore an increase in the quality of the service provided to the customers.

The car cost is computed by multiplying the total number of trains traveling on link (i, j) by a car unit cost c_{ij} that is computed as $c_{ij} = c \cdot d_{ij} + m_i + m_j$, where c is a car cost per kilometer which accounts both car depreciation and maintenance, and m_i, m_j are car handling costs at yards i and j, respectively.

It is worth noticing that all cost parameters are chosen according to the cost structure of the accounting system of the Italian railways company, and that we deliberately do not consider in the model the possibility to form blocks of cars, since at the moment this opportunity cannot be implemented in the Italian transportation reality.

Minimum concave-cost network flow problems are known to be $\mathcal{NP}$-hard (refer to [20] for a survey on algorithms and applications). Several solution techniques have been developed, both exact and approximate. The first ones explicitly or implicitly enumerate the vertices of the polyhedron defined by the network constraints, and are based on branch & bound, extreme point ranking methods or dynamic programming [20]. The second ones can be subdivided into two classes: heuristic and approximate algorithms. Heuristics find local optima using standard convex programming techniques; approximate algorithms underestimate the concave objective functions with piecewise linear functions (for instance, see [21] for a recent result).

We here propose a heuristic algorithm based on a tabu search, which computes good solutions in reasonable CPU time.

3 A heuristic algorithm

The size of any realistic instance of the service network design model presented in Section 2 is extremely large. Even instances which consider only classification yards lead to formulations with a number of constraints and variables of order of several hundreds of thousands. Given the computational complexity of the problem ($\mathcal{NP}$-hard), to solve the formulation and compute a good solution in reasonable time, we propose a heuristic algorithm based on a tabu search. The algorithm is furnished with a perturbing mechanism which alters the current solution in order to explore a larger portion of the solution space.

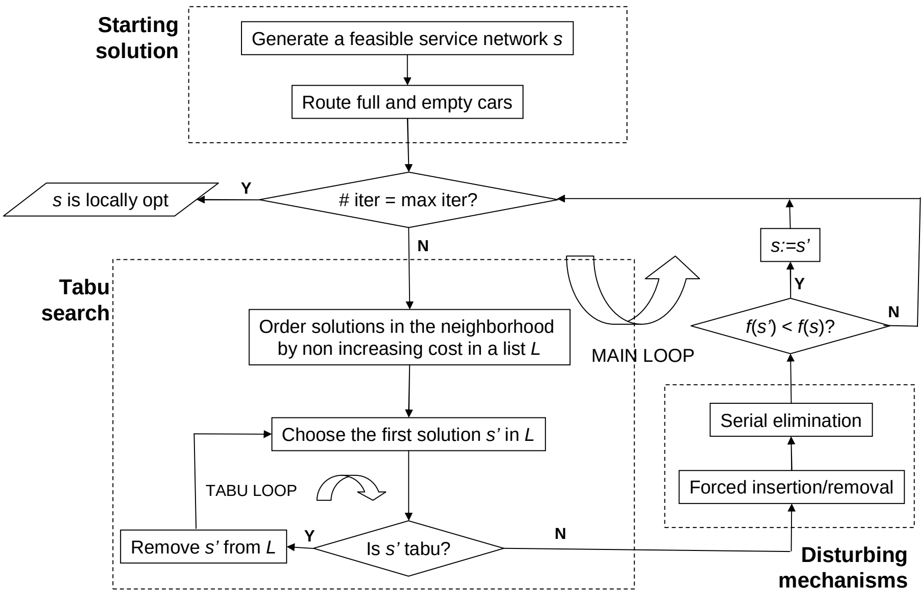

Fig. 1. Flow chart of the heuristic algorithm.

In our model, decisions can be classified into service decisions - deciding whether to activate or not a direct connection between a pair of yards of the network - and routing decisions. In the proposed heuristic we treat the two types of decisions in a hierarchical manner, i.e., we first fix the value of service decision variables and then we decide how to route cars using the activated services.

Finding a starting feasible solution. Our heuristic procedure is initialized with initial feasible solutions computed with the procedures reported in the sequel.

Minimum spanning tree: The initial solution is given by a minimum spanning tree (MST) found on a complete graph, whose arc costs r_{ij} are computed as follows:

$$r_{ij} = \frac{d_{ij}}{f_{ij}}, \quad \forall (i,j) \in \mathcal{N} \times \mathcal{N}$$

where f_{ij} represents the total demand for full cars from origin i to destination j, and d_{ij} is the length of the link (i,j). Observe that the MST minimizes the number of services, i.e. direct links between specified origins and destinations.

Currently used logistic network: We use the solution currently implemented, which is computed on practitioners' experience.

"Complete" graph: We compute a solution which satisfies all the demands with a direct service. This solution clearly minimizes the car handling costs.

Minimum distance sub-graph: We compute a feasible solution selecting arcs in a minimum length order until a connected sub-graph is obtained.

In the computational analysis we verified that the algorithm shows better performances when the minimum spanning tree or the currently used logistic network are chosen as initial feasible solutions.

Once the initial feasible service network is determined, we route the cars minimizing the overall cost. Observe that we deal with full and empty cars separately, since they have a different feature. Full cars are characterized by a fixed O/D pair, while empties have to satisfy only constraints on the type: any demand for empties can be satisfied with cars located at any origin. As observed in Section 2, the service network is uncapacitated and we can schedule as many trains as needed on any service. Therefore, the flow of full cars can be computed using a shortest path algorithm for each commodity. In particular, we implement a Floyd-Warshall algorithm. As regards the routing of empty cars, we solve an uncapacitated minimum cost flow problem. In particular, we solve a minimum cost flow for each commodity.

Tabu search procedure. As we have already mention, the core routine of our heuristic is a tabu search procedure, see [22] and [23] for details on tabu search. We implement as notion of neighborhood of the current solution within search for a better solution, the set of all the networks that can be obtained from the current service network adding or deleting an arc. Adding an arc corresponds to opening a new service, while deleting an arc corresponds to closing the corresponding service.

For each possible “move” from the current solution to a new one in the neighborhood we have to evaluate the cost of such solution. This requires solving the routing sub-problem of cars, both empties and fulls. This procedure can be very time consuming and it may lead to high computational time. To overcome this drawback, we use estimates of such costs which are easily computed. Let us evaluate the cost of a solution obtained by opening a new direct service (arc) between nodes i and j. In this case all the flow going from i to j will be re-routed on the directed arc (i, j). Given the new flow vector, the new cost of the objective function is obtained simply adding up the new total transport and the new car handling costs. In closing a service, we first have to guarantee that the deletion of the arc leaves the graph connected. Therefore we only consider among all the arc deletions those which maintain graph connectivity. When the arc is removed, all the flow which previously used arc (i, j), is re-routed on the shortest path connecting i to j.

These procedures are fast and easy to implement; in fact, they do not compute the vector of flows (routing of cars) *from scratch*, but they focus their attention on the O/D pair $i-j$ whose connection status has changed. However, these estimates may clearly be non-exact. It is worth noticing that, once the most convenient move is determined based on the cost estimates, the new service network (new solution) is considered, and full and empty cars are routed optimally according to the procedures discussed above, thus computing the *optimal* vector of flows and the *exact* cost value.

Two different data structures are used in order to keep memory of the more recently visited solutions: a tabu list $TL1$ and a tabu list $TL2$. $TL1$ is a l-dimensional list which is filled with the last l solutions visited by the algorithm, while $TL2$ is an h-dimensional list which contains the last h moves performed by the procedure. The dimensions of the lists are read as input parameters at the beginning of the procedure. Once the number of solutions belonging to $TL1$ (respectively, $TL2$) is equal to its dimension l (respectively h) and it becomes necessary to add a new solution to the list, the maximum cost solution in the list is deleted. The algorithm ends when a maximum number of iterations is achieved.

Perturbing mechanisms. To visit a larger portion of the feasible region, we furnish our tabu search algorithm with a perturbing mechanism in the search procedure. Whenever the current optimal solution is not updated within a certain (fixed) number of iterations, the algorithm is forced to perform a move. The move consists in adding (*forced insertion*) or deleting (*forced removal*) an arc. The arc added or removed is the one that gives the highest improvement (or the lowest worsening) in the objective function, among a set of candidate arcs. The set of candidate arcs is composed by a certain (fixed) number of less recently selected arcs. Again, if a removal is performed, network connectivity has to be verified.

We also introduce another perturbing mechanism, referred to as *serial elimination* whose scope is to let the algorithm to "re-start from zero". Whenever the current optimal solution is not updated within a certain (fixed) number of iterations, the serial elimination forces the algorithm to re-start the local search from a service network which is composed by a "small" number of direct arcs. The procedure forces the algorithm to remove arcs until the solution becomes composed by a small fixed number of arcs. Again, removed arcs are those preserving network connectivity and providing the highest improvement (or the lowest worsening) in the objective function.

4 Computational experience on a real instance

The proposed heuristic algorithm has been tested on both a set of random generated instances and on a real instance relative to the Italian case. In particular, we considered a set of 25 random generated "small" instances, which we solved using a mixed-integer programming solver based on the Branch & Bound algorithm, called MINLP-B&B. All random generated instances have been solved to optimality by the Branch & Bound procedure quickly. We compared these optimal solution with the solutions proposed by our tabu search heuristic, and we verified that in most cases our algorithm finds the optimum and that the deviation from the optimal solution is rather low (1.78 %, on average).

The real-world instance has been obtained by an elaboration of the data contained into the historical databases, and into the accounting systems of our industrial partner. The maximum number of cars which can be assigned to a train has been set to 20. The parameters defining the multiplicative factor which gives the non-linearity of the objective function are fixed according to cost criteria which are currently used in the accounting systems. We restrict our analysis to a network composed by a set of 39 nodes, which correspond to the set of all the major classification yards and frontier passes. The number of commodities is 375. The main characteristics of the considered instance are reported in Table 1.

Table 1. Characteristics of a real instance of the problem.

	Real instance
Number of instances	1
Number of yards (n)	39
Number of commodities (p)	375
Distances (Km)	0 to 2000
Demands (number of cars)	-2000 to 2000
Car handling cost (euro)	0 to 50

In Table 2 we compare the solution proposed by our algorithm with the solution currently implemented by the Italian railways company. In particular, we consider the following technical and economical statistics.

1. C: it is the objective function value and represents a measure of the total cost.
2. S: number of directed services between yards.
3. T: number of trains necessary to deliver all the cars on the service network in order to satisfy all the transportation demands.
4. TK: total amount of kilometers covered by all the trains traveling on the network.
5. CK: total amount of kilometers covered by all the cars traveling on the network.
6. M: number of manoeuvres.

Table 2. Comparison between the currently used logistic network and the network proposed by the heuristic algorithm.

Statistic	Current network	Algorithm solution	% Comparison
C	11767851	11318144	-3.82%
S	144	158	+9.72%
T	4258	3851	-9.56%
TK	1060889	1027310	-3.17%
CK	21217665	20546329	-3.16%
M	170390	154014	-9.61%

It can be observed that total costs decrease of 3.82%, as well as the number of trains (−9.56%), car manoeuvres (−9.61%), and the total amount of kilometers covered by all the trains (cars, respectively) traveling on the service network (−3.17 and −3.16%, respectively). On the other hand, we have an increase in the number of directed services which are activated in the solution proposed by the algorithm (+9.72%).

5 Conclusions

The purpose of this paper is two-fold. First, we focus on the current Italian rail transportation reality. Several different features identify the Italian system with respect to others, especially the Northern American ones. Relevant differences arise with respect to the planning process, the structure of railroads, the limits in terms of maximum weight and length of a train and finally in the policies adopted to compose trains. Furthermore, in Italy both empty cars distribution and cars handling at intermediate yards have a relevant impact on total transportation costs.

Second, we proposed a mathematical model intended to design the set of direct connections between yards, and to route cars on it. The model combines both the full and empty freight cars management and takes into account the handling costs, suggesting the services to provide and the number of trains and the number and type of cars traveling on each service. In order to ensure a certain level of quality of the service which is offered to the customers, a concave cost objective function is introduced. The resulting model, which can be classified within the class of minimum concave-cost network design problems, is solved with a tabu search meta-heuristic which adopts some perturbing mechanisms in order to force the search process to explore a larger portion of the feasible region.

The computational results showed a good behavior of the algorithm on realistic instances of the problem, thus proving the viability for an integration in a decision support system.

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