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APPLICATION OF OPTIMIZATION TECHNIQUES TO THE RAILROAD EMPTY CAR DISTRIBUTION PROCESS: A SURVEY

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Abstract: Recently, in the area of freight transport, the railroads of almost all countries, have faced strong competition and a prominent trend of market reduction. It has become imperative for rail systems to develop better planned instruments for more rational and efficient utilization of freight cars that represent 40% of total investments, according to the data of many Railway Boards. This active preciousness today spends more than half of its available time empty. Better utilization of this resource reduces operational expenses and enlarges carriage capacities. The considerations in this work are examining the nature of the problem and the interrelationship between problem solving algorithm techniques and the development of practical application systems. This paper gives an epitomized presentation of successfully applied optimal techniques for railroad empty car distribution and describes the main research directions and perspectives.

Keywords: Rail freight cars, empty car allocation, fleet size.

1. INTRODUCTION

The primary purpose of this paper is to highlight the fleet management problem from different modeling and solving perspectives. The distribution of empty and loaded freight cars is considered to be a practical decision making problem. The transportation of merchandise, as a response to the function of demand for a transportation service, represents the primary economic activity of railroad companies. This problem is solved by the fleet which, in an economic sense, represents a large investment. Analyses made in the USA show that there are 1.5 million freight cars (valued at 25 billion USD), and that they spend as much as half the time empty [14] [48]. Asymmetric demand between pairs of stations on some network results in the formation of flows of different intensity, according to the directions. An unstable equilibrium must be followed by sending empty cars to other stations.

The fast growth of ownership expenses (high interest rates) and operational expenses (growth in the price of fuel and manpower), in recent years on almost all railroads in the world has made the possibility of the investment returns more difficult.

There are two main research directions in this area. The first focuses on the allocation of available car capacity to various destinations. This problem involves the calculation of empty car movements. The basic assumption of the second direction is the treatment of fleet size as an unknown parameter that is determined as a function of the demand for transportation.

The aim of this paper is to present the optimization methods for empty car allocation and fleet management in freight transportation, versus the simulation methods, and to reconsider the application of other approaches.

The paper is organised as follows: Section 2 gives the formulation of the allocation problem through linear programming and describes its influence on research trends. Section 3 is devoted to the introduction of a dynamic aspect through the time dimension, and to the application of Ford-Fulkerson's algorithm. Section 4 describes a combined and stochastic approach. A review of several attempts to develop integral models is given in Section 5, and Section 6 presents the concluding remarks.

2. LINEAR PROGRAMMING AND EMPTY CAR ALLOCATION

In the historical sense, the first perception of the importance of knowing the condition and location of cars is related to the railroad. Decisions regarding empty car allocation were made mostly by a train dispatcher and based on the average rate of empty car exploitation. This way of making decisions gave good results until they had, day by day, important exceptions occurred regarding the average number of available empty cars at the stations. Decisions made by a dispatcher's experience started to be uncertain and created dissatisfied customers. The first registered attempt to model this problem was made 40 years ago [17]. A formal basis for modelling the movement of empty cars from the unloading point to the next shipper can be made using standard mathematical programming techniques. A commonly used formulation is the most direct extension of linear programming. The mathematical formulation can be stated as follows [37]:

$$\text{minimize} \quad \left[\sum_{j=1}^{N} \sum_{i=1}^{N} e_{ij} E_{ij} + \sum_{j=1}^{N} r_j \left(D_j - \sum_{i=1}^{N} E_{ij} \right) \right] \tag{2.1}$$

subject to

$$\sum_{j=1}^{N} E_{ij} \le S_i, \quad i = 1,2,\ldots,N \tag{2.2}$$

$$\sum_{i=1}^{N} E_{ij} \le D_j, \quad j = 1,2,\ldots, N \tag{2.3}$$

$$E_{ij} \ge 0, \quad i = 1,2,\ldots, N, \; j = 1,2,\ldots, N \tag{2.4}$$

The decision variable is given by

E_{ij} - number of empty cars dispatched from station i to station j

The parameters are defined as:

e_{ij} - unit transportation cost of moving an empty car from station i to station j

r_j - revenue per carload at station j

S_i - supply of empty cars at station i

D_j - demand for empty cars at station j

N - number of stations in the network

The objective function given in (2.1) aims at minimizing the total cost of moving empty cars between supply and demand stations and the shortage cost. Constraints (2.2) and (2.3) model the supply and demand limitation.

Deterministic demand and loaded flows, and ignorance of their time dimension, were the basic premises of this model. The requirements concerning the necessary parameters are the principal reason for its unsuccessful application. For the needs of the Louisville and Nashville railroad [35], the technique of linear programming was developed and successfully applied to the model of empty car allocation. The minimization of empty car movements and of corresponding expenses, taking into account demand and supply constraints, appeared as an answer to the better fulfillment of demand. The forecast of demand and supply values was considered every two days. The final results were the flows of cars between demand and supply stations with a minimum of travel time. A software package of the simplex method was applied, and the results for a fleet of 1500 cars were 90% of fulfilled demands, instead of 60-70% before.

Clearinghouse railroads applied linear programming for the calculation of weekly movements between four regional areas [42]. Necessary details to determine the minimal number of miles of empty cars are the mutual distances of the regions and flows of loaded cars on a weekly basis.

For the needs of Indian railroads, a static model (without a time dimension, with deterministic supply and demand) of the optimization of car utilisation on the network was developed [39]. The author analyses the transportation and simplex method. The transportation method is efficient as a solution for three types of problems: putting empty cars at the sender, disposal of the choice of traffic routes, and the definition of new locations (a storehouse for locomotives and fuel, places of distribution). Moving cars towards desired locations is the solution to a classical transportation problem and is demonstrated on the example of four stations and twenty possible transportation routes. The problem of saturation and transportation capacity, which is important for the choice of car flows, cannot be solved without the simplex method. The transportation method has constraints $E_{ij} < C$ (E_{ij} is the flow from station i to station j, C is the capacity), while the simplex method has the form $\Sigma E_{ij} < C$. This procedure allows the definition of a feasible course and the reduction of the needed number of empty cars, with the possibility of calculating saved travel hours. For this type of calculation it is necessary to have a precise schedule.

The main shortcoming of the mentioned models lies in their static formulation. The status and location of cars in a system continuously change, and shipper's day to day variation in car orders is also great. In previous models it was assumed that supplies and demands of empty cars are deterministic. This is an unrealistic assumption and is a crucial reason for unsuccessful model implementations.

3. FORMULATION OF "TRANSSHIPMENT"

3.1. Rail carrier

The static formulation of the problem of empty car allocation is based on average time data, so it has many deficiencies. From the practical point of view, the dynamic presentation of this problem, shaped as a deterministic network transshipment is more interesting. White and Bomberault [51] developed a model which could be interpreted as a multi-period transportation problem. They introduced a space-time diagram which allows explicit consideration of the time dimension, and construction of the corresponding network. An important attribute of these networks is their acyclic structure. It is not possible to move on the network in the signed direction and come to a station already crossed with empty cars. They completely ignored the ownership costs of a car. This problem is in the category of linear programs, known as the transshipment problem and can be solved using minimum cost-feasible flow network techniques. A modified version of the out-of-kilter algorithm was applied to solve this problem. The fleet is homogeneous with known supply and demand. The final results are given in the number of cars which have to be moved from the stations, as well as in the trains needed to acquire the optimal empty car allocation. Although the implementation of this model is faciliated in this way there has been no practical confirmation about its use.

Cuimet [10] is the first who tried to compare two forms of organization structure of directions for empty car allocation: decentralized with five regions (every region has six units) and centralized with 30 service units. In centralized organizations the fulfillment is made step by step, according to the available supply. In the decentralized organization structure the local agent orders from the local dispatcher. If the number of cars is insufficient, the demand is distributed further, to the regional units. The simulation made in the case of car insufficiency at the local agent's (demand 15, supply 10 cars/per day) favors the centralized organization structure. For this form the author suggests a deterministic dynamic model for empty car allocation. It is supposed that the values of the future supply and demand (for the next 5 days), as well as the transportation time of empty cars, are known. This model was solved as a minimum cost flow problem on the space – time graph. The arcs connecting demand nodes with zero cost, the arcs with decision variables, and the arcs connecting supply nodes with zero cost were defined; then Ford-Fulkerson's out-of-kilter algorithm was successfully applied. The model was successfully verified using real historical data for a part of the Canadian Pacific Railroad.

With the aim of improving the distribution of empty cars, the Swiss Federal Railroads developed a mathematical optimization model for calculating the movement of empty cars [28]. The supposition takes into consideration different car types and the possibility of their substitution, while the time needed for the calculation makes daily application in a real situation possible. On this relatively small network, 12,000 freight cars – 70 different types, are distributed every day between 850 stations [29]. Before they introduced this system, decisions had been made manually, and the whole region had been divided into 5 areas. This was a big load for the manpower. During a phone call, lasting approximately 20 minutes, they made an equilibrium between these areas about demand distribution and new orders. The new system made possible the minimization of the movement of empty cars, the disburdening of centers, the fulfillment of demand, the substitution of car types, management from one central place, better time usage, and better and early distribution of orders. This model is based on graph theory and solved using Ford-Fulkerson's out-of-kilter algorithm. Compared with manual and analytical methods, it could bring savings of 2%, which is a good result considering the dimensions of the network, the fleet size and difficulties made by the human factor. The dimensions of German railways (DB) and the fleet size are limiting factors for the practical application of the Swiss railway model. As a solution for a heterogeneous fleet, Hein [25][26] transformed a theoretical model on the graph into a classical transportation problem in two parts. The first is based on the out-of kilter algorithm, the second on the necessary transformation of only one graph part. The structure of the cost matrix makes possible the application of a heuristic procedure of the north-west angle. The matrix used is big in size and sparsely occupied, and does not permit the application of approximate calculation methods. The author suggests a new procedure which gives a transportation problem with a relatively small but well occupied matrix. This task can be solved very fast and precisely for practical application purposes.

3.2. Rail – multicarrier

An association of a few rails, or with big shippers, gives members the opportunity to hire cars at very low rates. This system is very common in the USA, and the first initiator of this concept was the automobile industry. Avi-Itzak, Benn and

Powell [4] propose a model for describing the behavior of car-pool systems. They have shown that mathematical models, based on inventory control theory, are applicable to other modes of transportation.

Glickman and Sherali [21] considered the distribution problem of empty cars, regarding the mentioned concept of railway pooling, and developed three models. Additional problems compared with the rail-carrier case were: a larger number of supply and demand stations, increased percentage of possibilities to substitute different car types, and an equal benefit distribution for all stations.

The first model is based on the minimization of the total cost (transportation, storage and substitution of car types) of empty cars. All origin and destination stations, as well as car types, shortage cars including all costs, are presented by geometrical arcs. The mathematical formulation is as follows:

$$\text{minimize} \quad Z_0 = \sum_i \sum_j e_{ij} E_{ij} \tag{3.1}$$

$$\sum_j E_{ij} \le S_i \text{, for a supply station} \tag{3.2}$$

$$\sum_i E_{ij} = D_j \text{, for a demand station} \tag{3.3}$$

$$E_{ij} \ge 0 \tag{3.4}$$

A modified version of the NETFLO algorithm, specialized for transportation problems presented on the space-time network, was used efficiently.

The second model strives to obtain the optimal level of the entire cost of empty cars and make a balance of individual relative railroad enterprise savings. These savings represent the difference between the amount which every individual railroad will spend for the transportation of empty cars, if they are not in a pool system, and real carriage cost. Two main criteria are given: to maximize the minimum relative savings of all the railroads, and to minimize the mean absolute deviation of the sum of the relative savings.

The third model is presented from the aspect of the participants individually where they define in advance the lower limits of all relative savings. It is very similar to the first model with an additional constraint for every railroad.

These models have been solved successfully using the decomposition method of Dantzig and Wolfe with a certain heuristic procedure to obtain a feasible integer solution.

The reported numerical experiments on real data for the first and second models confirm their practical applicability. For a network with 155 origin and 41 destination points, four car types, 15 pooled railroad managements and a fleet of 68,772 cars, the obtained results show savings of 28.7 million dollars. This represents an improvement of 31.5%. In spite of the negative relative savings for three railroad managements, obtained by using the first model, solving the second one gave an inconsiderable reduction of all savings of 2.1%, and positive relative savings for all railroads.

Kikuchi [34] emphasizes the necessity of having a permanent control system of the car positions, a system of data transmission between different railroad managements, and a distribution procedure to minimize the time of car empty state. Using the "transshipment" approach and daily data about supplies and demands provides the option of keeping cars. No implementation is mentioned.

4. COMBINED AND STOCHASTIC MODELS

During the last decade, besides all the enumerated and most used techniques, many successful attempts have been made to model the allocation of empty freight cars by using an apparatus out of standard. This is so-called combined approach.

Mendiratta [37] observes this problem through the decentralized structure of decision making. He develops two interactive submodels: a centralized network model and a decentralized terminal model. The mechanism of coordination between these models is established through transfer or shadow prices. These shadow prices are basic information about the supply of cars and demand for cars at a given location on that day. Minimization of the sum of transportation, holding and shortage costs is the objective of the master problem. The network model has the form of a classical transportation problem. The terminal model takes into consideration the stochastic nature of the lead time, represented by the Erlang probability, and stochastic characteristics of demand. The model makes certain analogy with optimal inventory control theory. A difference equation of the state vector has been defined:

$$X(t+1) = PX(t) + Q_u U(t) + Q_\beta \beta(t) \tag{4.1}$$

This relation represents a discrete form of the stochastic linear inventory model. The problem is to find a vector $U(t)$ (the number of cars ordered or dispatched in period t) such that the total expected costs are minimized over the planning period.

$$J = E\{\sum_t f_0[X(t+1), U(t)]\} \tag{4.2}$$

The main shortcoming of this model is the application of irreversible aggregative processes in modeling the movement of empty cars. This representation does not account for the fact that a dispatched car may have a different delay from cars that are ordered, and for this reason it is inadequate for describing car arrivals at the station. In the implementation phase the author suggests very complex and pretty inefficient managerial control. Conducted numerical experiments using data of the Missouri Pacific railroad for an aggregated network of 19 stations and 32 links, show the model's superiority concerning the minimization of empty car miles, empty trips and empty car days.

Ratcliffe, Vinod and Sparrow [44] suggest a combined simulation-optimization methodology to resolve the problem of empty car allocation. The algorithm used is based on linear programming (when freight car orders are known) and stochastic linear programming (to preposition empty freight cars toward stations where the orders are expected). The objective function of this problem is minimization of the total transit time of empty cars for a network with N stations. The mathematical programming problem is [44]

$$\min Z = \sum_{i=1}^{N} \sum_{j=1}^{N} COST_{ij} E_{ij} \tag{4.3}$$

subject to

$$\sum_{i=1}^{N} E_{ij} = D_j, \quad \text{for} \quad j = 1,2,\ldots, N \tag{4.4}$$

$$\sum_{j=1}^{N} E_{ij} = S_i, \quad \text{for} \quad i = 1,2,\ldots, N \tag{4.5}$$

E_{ij} is the decision variable that denotes the final car movement from station i to station j. The parameters are defined as:

S_i - net car supply at i

D_j - demand at j, and

$COST_{ij}$ - car movement time between i and j.

The stochastic linear model uses the states of nature, which actually present the vector of demand at a station with a corresponding probability. Knowing the supply and demand of cars from railroad enterprise statistics, in the simulation experiments they are obtained from the known distributions. The language used in the simulation is SLAM. Its network possibilities as well as simple interaction with other optimization packages were the most important criteria for its selection. The obtained results based on intervals of 36 and 48 hours between the realization of the algorithm for the network of Frisco railroads (9 geographic areas) show the important savings of the total transit time (14-15%).

Jordan [32], Jordan and Turnquist [33], in their research, start from the stochastic nature of supply and demand, noting that they are assumed to be normally distributed. The travel time between stations is of a stochastic character and is described with a negative binomial distribution. The necessary initial information for the model includes a physical layout of the rail network, costs and revenues, the moments of new orders by station and time, the moments of the number of cars entering the system by station and time, and the moments of travel time between all station pairs. The demands not fulfilled in one period are carried over to the next. The stochastic nature of demand has a bigger impact than is the case with supply. An explanation could be given through the flexibility of supply, while demand is joined with the stations. The objective function is nonlinear and since it is impossible to prove its concavity, the Frank-Wolfe's algorithm (constraints are linear) appeared as a good heuristic procedure. Experiments made on a nineteen-station network, with a 10-day planning horizon, show convergence after six iterations. The authors especially accentuate the importance of car value at the end of the horizon and its sensitivity toward optimal problem solution.

5. FLEET SIZING AND CAR ALLOCATION

In all the mentioned studies the size of the fleet in operation was treated as input data, although academic discussions directed attention to the potential benefit from the investments in this capital resource. For clarity in discussing the common research factors, we have classified them into three categories according to: form of the traffic pattern (movement from a single origin to a single destination, from one origin to many destinations, and from many origins to many destinations), the size of the parcel (loaded and partially loaded cars) and deterministic vs. stochastic analysis [48]. The aim of these studies is the minimization of capital fixed and variable operating costs [13]. For stations with defined times of departure and arrival (a deterministic variant), a model has been developed which helps to define the optimal fleet [20]. It is based on the application of the deficit function and the obtained result is general for periodic schedules.

Sim and Templeton [46] developed an efficient recursive algorithm for car behavior analysis from one departure point to one arrival point. The travel time was treated following the exponential distribution, while the arrivals at the departure point were individual in accordance with a Poisson process. For the defined cost functions and the rules of dispatching cars, based on the queue theory, an optimal fleet was determined.

Etezadi and Beasley [16] considered simultaneously the problem of the definition of the optimal fleet structure and its optimal size. Decision making in this type of problem usually covers a longer time horizon and it is important to show that the model presents the problem of mixed integer linear programming. The authors suggest the application of simulation to resolve the problem precisely.

Turnquist and Jordan [50] primarily consider the impact of the stochastic nature of travel time on fleet size. The problem addressed in their paper concerns a parcel of freighted cars using the pattern from one origin to more destinations. The conducted experiments show the necessity of researching the parcel system from many origins to many destinations.

Beaujon and Turnquist [5] discern the importance of the mutual dependence of the problems of the use and the size of rail freight car fleets. They define the net number of cars per each station (represented using a normal distribution) and the associated holding or penalty costs. Travel times are assumed to be deterministic. The problem of fleet sizing could be expressed as a network problem, with nonlinear costs on some arcs. The allocation of loaded and empty cars is defined simultaneously on a network of relatively small dimensions. The network approximation is good enough to obtain a solution regarding car allocation and car fleet size. The initial solution was obtained using a deterministic variant of the problem (all variances of cars per station are set to zero). This solution will certainly be below the optimal fleet value, but offers a sufficiently exact set of car movements required for calculating the variance. Frank Wolfe's algorithm was used for the estimated values of the variances. The iteration is continued until the change in the variance from one iteration to the next is sufficiently small. Using a hypothetical network of five stations and six days, the authors compare static deterministic, dynamic deterministic and dynamic stochastic variants. The obtained results show a very important interaction between decisions concerning the fleet size and the allocation of freight cars, and the applied model could be evaluated as a promising one.

6. CONCLUDING REMARKS

This paper presented several major areas as focal points for research in fleet management and railroad empty car distribution. Different methodological approaches were systematically analyzed and potentially operative strategies were evaluated. In this paper we described several algorithms based upon different criteria and evaluated from a practical point of view. Successfully applied models were reviewed. We also emphasized that models developed to support car distribution decision making have not found real application in the railroads. The unadapted organisation structure for new sets of criteria could be one of the key elements for unsuccessful model implementation.

Important areas for future research efforts may be grouped along two guidelines: a) inclusion of as many realistic assumptions into the problem statement as possible, and b) selection of appropriate modelling approaches. Problem statements should incorporate stochastic treatment of transport supply and demand and travel times. Special attention should be devoted to the selection of appropriate algorithms for solving the models proposed. An imperative for all researches is the use of artificial intelligence techniques for the simultaneous determination of loaded and empty trips.

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