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A TWO-LEVEL APPROACH TO THE PROBLEM OF RAIL FREIGHT CAR FLEET COMPOSITION

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Abstract. One of the main objectives for a rail company is to minimize the size of rail freight car fleet in order to reduce operating costs. The problem of rail freight car fleet composition is aimed at determining an optimal structure and size of freight car fleet in order to respond to actual transport demand. A rail company must have capabilities to respond to actual transport demand in case it wants to increase the level of competitiveness on the transport market. Therefore, it is necessary that the structure and size of rail freight car fleet correspond to the structure and size of rail transport demand. In this paper, we developed a two-level approach to determining an optimal rail freight car fleet composition. This approach has been tested for the case of the Public Enterprise 'Serbian Railways' and the obtained results show the potential for a practical application of the proposed approach.

Keywords: rail freight car, AHP, fuzzy, multi-objective optimization.

1. Introduction

The problem of rail freight car fleet management belongs to a class of the most important railway optimization problems that are very complex due to the presence of various types and subtypes of freight cars, the size and value of rail freight car fleet as well as because of its significant role in rail transport operations.

The problem of the optimal composition of freight car fleet also has a great impact on the profit of a rail company. On the one hand, there are customers with very specific and different requirements. Each of them wants a certain type and number of a rail freight car and usually prefers using a special one for every specific kind of commodity. On the other hand, the presence of different types of rail cars implies an increase in the costs of a rail company. Having rolling stock consisting of only one type of a rail car that can be used for transporting any kind of commodity is the most suitable choice made by a rail company. These conflicting requests must be solved by searching for an optimal composition of rail freight car fleet satisfying demand and reducing costs (Bojovic 2002).

In the past, the development of rail rolling stock was mainly based on empiric models considering intuitive predictions for the rate of transport growth. The consequences of this approach for rail freight car fleet planning are inconsistency between the structure and size of actual demand on the one hand and the structure and size of freight car fleet on the other. This implies unnecessary costs that decrease the total profit of a rail company.

It is necessary that the structure of rail rolling stock completely corresponds to the structure of rail transport demand defined through:

- the types of commodities in respect to main physical-chemical features and other techno-economic transport requests;
- the state and manifestation form of commodity (solid, fluid and gaseous state, sprinkled and fragmented commodity, pallets and containers);
- the low of request evolution (deterministic or stochastic nature of request evolution process);
- service level (time of request execution, waiting interval for accepting commodity, reliability).

The most suitable way to deal with rail car fleet composition is to decompose this problem into two related sub-problems:

- the best rail fleet mix problem considering the selection of types and subtypes of rail freight cars;
- the best rail fleet size problem considering the

determination of the necessary number of rail freight cars.

We are using the fuzzy analytic hierarchy process for developing the most suitable rail freight car fleet mix. The solution obtained at the first level consists of a set of the most suitable types of rail freight cars that can be used for transporting commodities. On the basis of the defined structure from the aspect of the type and subtype of freight cars, at the second level, the optimal size of rail freight car fleet is determined using the fuzzy multi-objective linear programming approach.

This paper is organized in six sections including Section 1 introducing the problem. Section 2 gives a brief summary of work in the past aimed at fleet composition problems. Section 3 considers the best rail fleet mix problem and proposes an approach to solving this problem. In Section 4, the second phase is treated and a suitable problem-solution approach is developed. Section 5 suggests a model applied for determining the optimal rail freight car fleet composition for the case of Serbian railways and the obtained results are given. Finally, Section 6 concludes this paper.

2. Literature Review

Papers appearing in literature dealing with the problem of vehicle fleet composition can be classified into those discussing the problems of vehicle fleet size where the type of vehicles are given and papers debating the problems of vehicle fleet composition where decisions to be made relate to both the type of vehicles and the number of each type.

Salzborn (1970) developed a mathematical method for minimizing the number of railcars needed for a suburban railway system. Two objectives are considered within this approach making an optimum plan of rail car movement along the lines and the minimization of the total driver plan. The formulation of this problem is defined as a set of linear binary integer programs.

Levy *et al.* (1980) presented an integer programming formulation for the vehicle fleet composition problem and developed several heuristics that are mainly based upon the concept of a 'giant tour' (a single tour linking the depot and all customers together). The computational results of these heuristics indicate the effectiveness of the developed heuristics.

Etezadi and Beasley (1983) investigated a problem of determining the optimal fleet composition for a central depot supplying a number of customers. They developed a mixed-integer programming model that addresses long-term decisions concerning the number and type of vehicles that the company should operate.

Sherali and Maguire (2000) designed a model for the optimization of rail fleet sizes for shipping automobiles. For each carious rail car type model, we can determine the minimum number of railcars needed to conduct the anticipated business. This model and methodology have proven to be very beneficial to the automobile and railroad industries in terms of determining appropriate rail fleet sizes and structures.

Bojovic and Milenkovic (2008) considered an application of the Analytic Hierarchy Process (AHP) on the best rail fleet mix problem. For a given set of rail car types and a given set of criteria, an optimal rail freight car mix is defined.

Sayarshad and Ghoseiri (2009) proposed a formulation and a solution procedure for optimizing fleet size and freight car allocation wherein car demands and travel times are assumed to be deterministic and unmet demands are backordered. Interactions between decisions on sizing rail car fleet and utilizing that fleet are considered. The optimum use of rail-cars for demands response in the length of time periods is one of the main advantages of the proposed model. The model also provides rail network information such as yard capacity, unmet demands and the number of loaded and empty rail-cars at any given time and location. Computational tests showed that small-size instances could be solved by the exact approach; however, it is not feasible for medium and large-size instances. To tackle, the Simulated Annealing algorithm (SA) is proposed to solve the model.

3. The Best Rail Fleet Mix Problem

As mentioned above, the best rail fleet mix problem represents the first level within the process of rail freight car fleet composition. From the strategic point of view, it is very important for the rail fleet planning of a rail operating company to determine the most suitable type of a freight car for each of homogenous commodity groups. Otherwise, there is freight car fleet though composed of cars but not corresponding to the structure of rail transport demand.

3.1. Rail Freight Car Fleet

According to the regulations of the International Union of Railways, there is a unique system of rail freight car marking. According to this system, all freight cars fall in four main groups and can be subdivided into thirteen types:

- covered rail cars including G, H, I and T car series;
- open rail cars containing E and F car series;
- flat rail cars consisting of K, L, O, R and S car series;
- other cars including U and Z car series.

Within each car type, there are cars of a standard and special type where the first one have broader use, whereas the second type of cars serve for carrying specific commodities. Each of these groups has its main common technical-exploitation features from which their purpose depends.

3.2. Proposed Commodity Classification

For the sake of solving the best rail fleet mix problem, we proposed suitable commodity classification based on strong techno-economic relationships between the type of commodity and the type, series and sub series of rail freight cars. A variety of commodity classifications, as for example classification grouping all commodities in 659 positions, are not applicable in this case (Gever 1989).

Considering the fact that all commodities according to their manifestation form can be classified in several groups (bulk cargo, general cargo, vehicles, pallets or containers, commodity in fluid or gaseous condition etc.), the difference between the basic features of the rail cars of certain types and practice by which the construction concept of rail cars relied on the physical-chemical features of particular commodities and its manifestation form, we applied suitable commodity classification (Table 1).

Table 1. New commodity classification

No.	Characteristics of homogeneous groups	Rail freight car type
I	Mass products in bulk condition, resistant to atmospheric influences	E, F
II	Powdery and grained products in bulk, non resistant to atmospheric influences, not requiring ventilation	G, T, U
III	Packaged products on pallets or without pallets, non resistant to atmospheric influences	G, H, T
IV	Packed products that need ventilation and temperature controlled conditions	G, I
V	Metal and timber products.	R, S, E
VI	Containers, road vehicles, mechanization	K, R, S
VII	Long objects, automobiles, containers of medium size	L
VIII	Live stock	G

This eight-group classification shows the fundamental techno-economic correspondence between the types of commodities and the types and series of rail freight cars. As we can see, at least one, two or three types of rail cars correspond to the certain groups of commodities. The presence of more types of cars for a certain cargo group indicates, in some way, the evolution of design solutions to the individual types of rail freight cars.

3.3. The Proposed Solution to the Best Rail Fleet Mix Problem

The best fleet mix problem belongs to a class of multicriteria decision making problems with respect to the following features:

- the presence of a number of criteria from the aspect of rail, customers and society;
- the presence of conflicts between criteria;
- the presence of non comparable scales between criteria;
- a finite number of alternative solutions for selection.

A decision model corresponding to a specific problem can be presented in a form of a matrix of $m \times n$ size:

$$D = \begin{array}{c} c_1 \\ c_2 \\ \cdot \\ \cdot \\ \cdot \\ c_m \end{array} \begin{bmatrix} \alpha_{11}\alpha_{12}\dots\alpha_{1n_1} & \beta_{11}\beta_{12}\dots\beta_{1n_2} & \gamma_{11}\gamma_{12}\dots\gamma_{1n_3} \\ \alpha_{21}\alpha_{22}\dots\alpha_{2n_1} & \beta_{21}\beta_{22}\dots\beta_{2n_2} & \gamma_{21}\gamma_{22}\dots\gamma_{2n_3} \\ \dots & \dots & \dots \\ \dots & \dots & \dots \\ \dots & \dots & \dots \\ \alpha_{m_1}\alpha_{m_2}\dots\alpha_{mn_1} & \beta_{m_1}\beta_{m_2}\dots\beta_{mn_2} & \gamma_{m_1}\gamma_{m_2}\dots\gamma_{mn_3} \end{bmatrix}, \quad (1)$$

where: $i = 1,..,m$; $j=1,..,n_1$; $k=1,..,n_2$; $l=1,..,n_3$; D – decision matrix for the problem; $c_1, c_2, ..., c_m$ – possible combinations of subseries for a certain freight car series as alternatives; $\alpha_{11}, \alpha_{12}, ..., \alpha_{m_1}, \alpha_{m_2}, ..., \alpha_{mn_1}$ – values for a group of criteria preferred by the rail company for each of the alternatives; $\beta_{11}, \beta_{12}, ..., \beta_{m_1}, \beta_{m_2}, ..., \beta_{mn_2}$ – values for a group of criteria preferred by the rail customers for each of the alternatives; $\gamma_{11}, \gamma_{12}, ..., \gamma_{m_1}, \gamma_{m_2}, ..., \gamma_{mn_3}$ – values for a group of criteria preferred by the society for each of the alternatives.

A difficult task is determining several independent criteria sets completely reflecting interests of a rail company, customers and society because there is a number of sub types for each freight car type as well as correspondence between commodities and rail freight cars (up to three car series belong to a homogenous commodity group). Comprehensive analysis has shown that the set of criteria preferred from a rail company point of view includes the interest of customers and society.

These criteria cover:

- carrying capacity;
- capacity;
- tare weight rate;
- rail freight car buying price;
- suitability of a particular car from the aspect of commodity type;
- suitability of a particular car from the aspect of commodity manifestation form;
- suitability of a particular car from the aspect of loading and downloading;
- the number of apertures;
- protection during the transportation process.

Considering the nature of the problem, a strategic impact of making a proper decision and the need for including opinions of experts from various fields, fuzzy AHP (Analytic Hierarchy Process) (Saaty 1980; Brauers *et al.* 2008; Collette and Siarry 2003; Kauko 2007; Ginevičius and Podvezko 2008a, 2008b, 2009; Ginevicius *et al.* 2008a, 2008b; Kahraman 2008; Kaplinski 2008; Šarka *et al.* 2008; Dytczak and Ginda 2009; Podvezko 2009; Ulubeyli and Kazaz 2009; Podvezko *et al.* 2010; Tupenaitė *et al.* 2010) is chosen as a tool for determining the most appropriate type and subtype of freight cars for each of eight homogenous commodity groups.

Within the given set of criteria, there are some for which a precise assessment of alternatives can be made. Thus, we extended analysis including the fuzzy environment of decision making process.

An alternative assessment of some criteria

$$\mu_R(A) = \max[\min(\mu_A(x), \mu_{\max(x)})]; \quad (2)$$

$$\mu_L(A) = \max[\min(\mu_A(x), \mu_{\max(x)})]; \quad (3)$$

$$\mu_T(A) = \frac{\mu_R(A) + 1 - \mu_L(A)}{2}; \quad (4)$$

where: $\mu_R(A)$ – left spread of fuzzy number *A*; $\mu_L(A)$ – right spread of fuzzy number *A*; $\mu_T(A)$ – the final value after transforming the fuzzy number.

After obtaining the numerical values of alternatives for some criteria sets, the classic AHP methodology is performed for determining the most appropriate freight car series and subseries for each of these eight groups of commodities.

4. The Best Rail Fleet Size Problem

Rail operators, customers and society have no common economic and technologic interests within the area of freight transport. Each of them has a particular set of requests that have to be fulfilled. Therefore, the problem of rail freight car fleet sizing can be treated as a multi-criteria problem which calls for defining a set of criteria and constraints as well as the selection of the solving approach.

4.1. Objective Functions and Constraints

In this case, the criteria represent objective functions comprising the interests of all parties. There are a great number of objective functions that can be generated, and therefore the choice of the most appropriate set of objective functions is a very complex task. Following the types of the objective, the following functions can be analyzed:

- a function of rail freight car supplying;
- a function of freight car fleet immobilization;
- a function of freight car fleet scrapping;
- a function of freight car fleet productivity;
- a function of the size of active freight car fleet;
- a function of customer's profit decrease due to a lack of freight cars.

The existing constraints dealing with this problem are as follows:

- the number of the cars of a certain type can be only the positive integer number;
- the available capacity of freight car fleet must be greater or equal than the freight transport volume;
- the productivity of freight car fleet by types of cars has to be greater than the total transport output on the network;
- the total number of immobilized freight cars by types must be lower or equal than the total number of freight cars that can be immobilized;
- the total number of active freight car fleet by types of cars must be greater than or equal to the product of freight car turnover and the number of cars on loading.

4.2. The Proposed Solution for the Best Rail Fleet Size Problem

The problem of fleet sizing formulated so that minimizing (maximizing) a certain number of linear objective functions subject to given constraints is necessary which represents a multi-objective linear programming problem.

In general, the multi-objective linear programming problem can be presented in a matrix form like:

$$\max(\min) Cx; \quad (5)$$

$$Ax \le b; \quad (6)$$

$$x \ge 0; \quad (7)$$

where: x represents the vector of variables while c and b are the vectors of known coefficients and A is a matrix of coefficients.

The values of objective functions are obtained by searching for minimum value for each of the functions subject to the common set of constraints. These values represent optimal values for each of these objectives because there is no conflict between them and they are known as marginal solutions.

In this approach, we allowed certain variations in values for objective functions defined in consultation with experts in this field. These variations are defined so that we can get the most efficient solution approved in a real situation because objective functions have different importance. This way defined fuzzy multi-objective linear programming model gives a satisfying degree of freedom for a decision maker.

On the base of the fuzzy set theory, we can now define membership functions for a given set of objective functions as follows:

$$\mu(c_i x) = \begin{Bmatrix} 0, c_i x \ge z_i^0 \\ \dfrac{c_i x - z_i^0}{z_i^1 - z_i^0}, z_i^1 \le c_i x \le z_i^0 \\ 1, c_i x \le z_i^1 \end{Bmatrix}, \quad (8)$$

where: z_i^0 and z_i^1 represent the values of objective functions for which membership functions have values between 0 and 1. Therefore, value z_i^1 represents the minimum of objective function while value z_i^0 – the value of minimum increased for the allowed variation.

After defining all membership functions for a set of objective functions where the criteria of all decision makers are satisfied, it is possible to determine the aggregate function as follows:

$$\mu = \mu(\mu_1(c_1 x), \ldots, \mu_k(c_k x)). \quad (9)$$

If adopting Belman's minimum operator as an aggregate function, fuzzy multi-objective linear programming can be presented as:

$$\max[\min\{\mu_i(c_i x)\}],\ i = 1, \ldots, k; \quad (10)$$

$$Ax \le b; \quad (11)$$

$$x \ge 0. \quad (12)$$

5. Numerical Example

Considering the selected set of criteria, the characteristics of freight cars as well as the performances of commodities applying the proposed approach lead to an optimal solution for the first level of the best rail fleet composition problem. The selection of an optimal series and subseries of rail freight cars with main characteristics for each of eight homogenous commodity groups is shown in Table 2.

Table 2. The optimal type, series and subseries of a freight car

Commodity groups	Car type	Car volume (m^3)	Axles	Apertures
I	Eas1	74	4	6
II	Gas-z	92	4	6
III	Habis	150	4	4
IV	Ibbiis	57	2	–
V	Eas2	70	4	6
VI	Smmp-tz	–	4	–
VII	Laekks	–	3	–
VIII	Gkks	57.8	2	4

On the second level, it is necessary to define the objective function and constraints. After selecting the model, testing real data is performed. Data is provided from the Public Enterprise 'Serbian Railways'.

During 2008, 6608462 million tons of freight was transported. It should be noticed that this loading was performed also including freight cars from foreign rail companies. But for the sake of simplicity, it is assumed that the number of empty cars used by Serbian railways is the same as the number of domestic cars used in other rail networks, i.e. the exchange rate is equal to zero. The average daily number of cars on current and investment maintenance is between 500 and 800 cars. In 2008, 42323 million net ton-kilometres were realized. The average turn around cycle is 6.4 days which is different for various car types and series. Daily productivities of freight cars are calculated due to the realized net ton-kilometres and the necessary number of freight cars in an active fleet. A productivity figure by the series of freight cars is obtained on the base of the structure of the transported freight and used cars. The overall synthesis of the problem is as follows:

$$\min[F_1(x) = 0.06x_1 + 0.05x_2 + 0.05x_3 + 0.04x_4 + 0.06x_5 + 0.011x_6 + 0.027x_7 + 0.05x_8]; \quad (13)$$

$$\min[F_2(x) = 0.02x_1 + 0.015x_2 + 0.015x_3 + 0.01x_4 + 0.02x_5 + 0.02x_6 + 0.015x_7 + 0.015x_8]; \quad (14)$$

$$\min[F_3(x) = 7.5x_1 + 6.8x_2 + 6.8x_3 + 6.3x_4 + 7.4x_5 + 6.5x_6 + 5.1x_7 + 6.8x_8], \quad (15)$$

subject to:

$$44.66x_1 + 44.28x_2 + 44.12x_3 + 19.25x_4 + 44.97x_5 + 45.82x_6 + 15.4x_7 + 18.5x_8 \geq 32994; \quad (16)$$

$$1591x_1 + 313x_2 + 147x_3 + 113x_4 + 362x_5 + 405x_6 + 86x_7 + 49x_8 \geq 15526164; \quad (17)$$

$$x_1 \geq 3083; \quad (18)$$

$$x_2 \geq 550; \quad (19)$$

$$x_3 \geq 258; \quad (20)$$

$$x_4 \geq 158; \quad (21)$$

$$x_5 \geq 633; \quad (22)$$

$$x_6 \geq 679; \quad (23)$$

$$x_7 \geq 130; \quad (24)$$

$$x_8 \geq 86. \quad (25)$$

All variables $x_1, x_2, .., x_8$ are integers and represent the number of cars by series. As objective functions (13)–(15), the function of freight car fleet immobilization $F_1(x)$, the function of freight car fleet scrapping $F_2(x)$ and the function of the size of active freight car fleet $F_3(x)$ are applied. Within the functions of immobilization and car scrapping, the coefficients represent a percentage of immobilized cars and cars for scrapping by series, respectively. Within the formulation of the third objective function, the coefficients represent turn around cycles by car series.

Constraint (16) represents the daily level of transport satisfaction for a given freight transport volume. The coefficients in this constraint are carrying capacities by car series. The second constraint (17) is concerned with a condition that the total productivity of rail car fleet must be greater than the total transport output on the rail network. The coefficients in this constraint represent daily productivity by a series of freight cars. Constraints (18)–(25) refer to the necessary number of rail freight cars by series.

The first step when solving this problem is to find the minimum of each function separately subject to the given constraints. With respect to these solutions, in consultation with experts in this field, we defined the allowable variations in objective function values and developed a model of fuzzy multi-objective linear programming. The initial solutions and allowable variations are given in the Table 3.

Following the fourth iteration in which we made a change of allowable variation in the functions of freight car scraping and active fleet size, we got the optimal solution given in the number of rail cars for each type and series and subseries of freight cars chosen as the most suitable in the first phase of the best rail fleet composition problem (Table 4). *Matlab* 7 software package was used for all computations.

Table 3. Values and allowable variations in objective functions

Objective function	Value	Allowable variations
Function of immobilization	655	50
Function of car scrapping	229	20
Functions of active fleet size	86700	3000

Table 4. Optimal rail freight car fleet composition

Type, series and subseries	Variable name	Optimal number of cars
Eas1	x_1	6342
Gas-z	x_2	550
Habis	x_3	258
Ibbiis	x_4	185
Eas2	x_5	633
Smmp-tz	x_6	729
Laekks	x_7	130
Gkks	x_8	86

6. Conclusions

The problem of rail fleet composition represents a very complex problem having strategic importance to a rail company. The existence of a great number of rail freight car types, series and subseries as well as conflicting demands from the side of customers and society gives more complexity to the encountered problem.

Socio-economic factors vary with time and railway as a transport mode having a significant share in freight transport is very dependent on these changes having the strongest influence on the necessary number of freight cars. Beside external factors on the size of rail freight car fleet, the technical-exploitation characteristics of rail cars, locomotives, rail lines and yards also have a great impact.

A two-level approach for solving this problem was developed in this paper. This approach is based on a real situation in decision making within the process of planning rail freight car fleet. The numerical example is solved to check for the consistency of the proposed approach. We conclude that this method is useful for identifying good strategies for the problem of rail freight car fleet composition.

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