A Fuzzy Green Mathematical Model for Hazmat and Freight Transportation in a Railway Network

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ABSTRACT

Nowadays, transportation is a very important issue to be considered for the development of transportation in various areas. Transportation of materials and final products is carried out by various vehicles. However, rail transport is known as green and safe transportation due to safety and environmental sustainability. Regarding the world industrialization, transportation of hazmat materials is as an inseparable component of the transportation directory. In the real world, the combined daily transportation of hazmat and non-hazmat materials occurs because of lower transportation costs. Thus, because of the safety and the long distances between origins and destinations, the rail network is used. Thus, in this paper, we develop a freight transportation model for a railway network considering a hazmat and green transportation issue. In the considered transportation system, different customers can request for carrying hazmat and non- hazmat boxes. It is assumed that the sequence of the trains in the network is known. The objective is to assign the non-hazmat and hazmat boxes to the wagons of the trains such that transportation becomes safer. A zero-one integer programming model is developed that minimizes the cost of safe transportation and consumed fuel. To make the model closer to the real world, we consider a fuzziness concept in the presented model. This fuzzy model is solved by using a new fuzzy approach, named TH method. A numerical example is considered and the related results are compared with the optimal solution. Finally, the conclusion is provided.

1. Introduction

In response to the increasing demand, manufacturers have doubled their production efforts since the beginning of the last century. As far as total cost of production is concerned, transportation sector has a great impact on economic growth. Transportation is separated in to several sections (e.g., urban transportation and freight transportation). It can be noted that the industry is dependent on transportation and vice versa. Therefore, by expanding industries, transport should also be expanded. As a result of development of the hazmat producing industries, such as nuclear power plants, the requirement for hazmat transportation is increasing. Thus, considering the safety factor in modeling the transportation systems is of importance to the environment and society.

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Transportation of hazmat materials for various intervals in order to different targets happens. The researchers have offered several ways to achieve safe transportation of hazardous materials. One of the main related studies is to use of the rail network for long distances. This network is recognized as safe and green transport. Anghinolfi et al. [1] presented a mathematical model and MIP heuristic approaches for freight transportation in railway networks with automated terminals.

In this paper, we develop a model in the field of rail transport in accordance with the transporting of hazardous materials and safe and green transport. We extend the model [1] by considering hazmat and non-hazmat material boxes that should be moved between origins and destinations by trains in the network with a predetermined sequence. In fact, these boxes are similar to passengers of a subway in a specific sequence that move from an origin to a destination. The most important issue is that both types of these boxes should not be assigned to the same wagon in one train, because this can lead to an explosion and its aftermath. The routes in a network are connected to each other by terminals. In these terminals, there are Metrocargo, which is a fast system that can move the boxes in a terminal, and special tools for moving hazmat boxes. So, the goal is to assign the boxes to wagons that they can be delivered safely in deadline time with the minimum cost. To consider the compatibility of transportation to with the environment and eco-system, minimizing fuel consumption has been also proposed in the model. Additionally, we consider fuzziness for uncertainty parameters because of being closer to the real world.

The remainder of the paper is organized as follows. In the next section, a brief literature review is presented. Section 3 introduces the problem formulation and notations. The solution methodology is described in Section 4. Finally, the last section concludes the paper.

2. Literature Review

Based on characteristics of the problem explained previously, we review the relevant and recent literature in three subsections, namely freight, hazmat, and green transportation.

2-1. Freight Transportation

Jiang-Ping and Shuai [2] reviewed on the model of freight transportation on the level of urban and metropolitan. They classified these models to five groups: (1) growth-factor and origin/destination (O/D) combination, (2) commodity-based, (3) vehicle-based or trip-based, (4) tour-based, and (5) logistics or supply-chain based; then the models were evaluated using ten criteria. López et al. [3] suggested a methodology for measuring environmental impacts of railway transportation that is based on estimating dissimilar contributions to railway utilization by factors such as mobility and operation. The process also

allows applying this methodology for analyzing and designing transportation policies in detail like improving traffic control and so on. Perego et al. [4] surveyed 44 articles on freight transportation and logistics. They analyzed these studies from two aspects; namely, research method and contents. The contribution of this work is in the classification of research issues for future research.

Crainic et al. [5] considered an application of this issue in the technology section. The purpose of their study is to evaluate intelligent transportation system's achievements with respect to the transportation of freight and to identify opportunities. One main sub-problem of the freight railroad management problem is train scheduling and dispatching because railway transportation plays an effective role in transportation. Nosoohi and Shetab-Boushehri [6] presented a framework for ranking of transportation projects by considering fuzzy logic and multi criteria (e.g., the effect of transportation project on the traffic flow, economical growth and environment beside budget constraint).

They also used a fuzzy inference system (FIS) that with respect to criteria estimates the value of each project. So, their study can be a good guide line for managers in selection of transportation project plans. Mu and Dessouky [7] introduced two mathematical formulations for the scheduling problem, and then proposed an exact method for solving the given problem. They presented a new heuristic method for solving formulation that can extensively reduce the solution time is equal to the exact methods time and obtain solutions with the minimum delay in the network.

Cacchiani et al. [8] presented an integer linear programming by means of a space–time graph for scheduling extra freight trains on a railway network, when passengers or goods have a prescribed timetable that cannot be changed. They solved the model using a heuristic algorithm based on Lagrangian relaxation. Investigating under the mixed uncertain environment of randomness and fuzziness is strategic planning level in a railway freight transportation planning problem. Yang et al. [9] proposed a model for determining the optimal path by means of chance measure and critical values of the random fuzzy variable.

They used hybrid algorithm to solve the problem and presented few examples to show the application of their algorithm.

The network design problem is very important in optimization problems, in which the multi commodity network design problem has many applications in different fields. The excellent and complete review paper in this issue is given by Yaghini and Akhavan [10]. For a comprehensive review of design of a service network for freight transportation, see Wieberneit [11].

2-2. Hazmat Transportation

Verma and Verter [12] focused on the incident of railroad transport of hazmat materials that are airborne. They offered a risk assessment methodology that provides valuable insights of railroad transport risk. To adapt the parameters of their methodology, they considered a worse-case approach. Shariat Mohaymany and Khodadadiyan [13] presented a tool in order to reduce risk in the hazmat transportation road network. This tool reduces risk by identifying safe and economic routes. For decreasing damage to people and environment, they also proposed hazmat transportation system management that associated a distinct rout between all origin and destination pairs for different hazmat materials.

They solved their model by a branch-and-bound method. Their case studies were several cities in Iran. Bianco et al. [14] proposed a bi-level model for hazardous transportation by considering local and regional government authorities in a form of mixed-integer programming. For the overall view of the hazmat transportation literature, the reader can see Erkut and Alp [15].

Many researchers have focused on the risk of hazmat transportation. Kawprasert and Barkan [16] described a basic model with an optimization technique to evaluate rationalization routes considering risk reduction and presented a risk analysis model for rail transport of hazmat materials. They used the risk model combined with the application of a linear programming model that allows several elements to be integrated and simultaneously measured. Saat and Barkan [17] presented a generalized safety design optimization model that allows estimation of the effect on safety and transport efficiency and cost-effectively railroad hazmat materials transportation risk. This model provides a quantitative structure for a rational decision making process too.

In fact the main task of this model is the trade-off between safety and efficiency on hazmat transportation. Dadkar et al. [18] enhanced a game-theoretic model for the analysis of between government agencies and terrorists; this model is non-liner so they solved it with the tabu search method. Bonvicini and Spadoni [19] believed that routing can reduce the risk of hazmat transportation. Then, they presented a new model (OPTI PATH) for solving of routing problem for multi-commodity in hazmat transportation that satisfies risk.

2-3. Green Transportation

Hoo Baeet al. [20] focused green transportation fleets especially trucks and automobiles and because of competitive and increase cost pressures developed a two-stage game theoretic model. Zahabi et al. [21] surveyed the effect of green technology, urban form and transit accessibility alone and the relation of them and other issues like employment status or income and their time work on greenhouse gas (GHG) in Montreal.

Finally they had several suggests policy for reduce GHG, like increase transit accessibility instance replacing this with hybrid bus or other vehicles. The survey of the relation between efficient transportation and CO_2 was done by Leonardi and Baumgartner [22]. Trappey et al. [23] proposed a model for reducing carbon and saving energy (or cost) regard to the proposal by Taiwan government (zero carbon) for green transportation and they used system dynamics for this aim.

One the other branch of green transportation is a green vehicle routing problem (G-VRP) considered by Erdog'an and Miller-Hooks [24].

In this paper, we present a model for hazmat and freight transportation in a railway network. This model considers to the environmental issue that makes the model closer to the real world by considering fuzziness for uncertainty parameters. Thus, the model presented in this paper is a fuzzy green hazmat and freight transportation model. This model is solved by Lingo software and then performed the TH method [25].

3. Model Description

In this section, a mathematical formulation is developed by considering hazmat boxes. In fact, the goal of this model is to determine the route of each hazmat box and each non-hazmat box and the wagon used in the train for moving it between the origin and destination and the sequence of the trains along the routes. For the sequence, we use pre-analysis of Anghinolfi et al. [1]. Now, we introduce the indices, variables and parameters used in the model:

M Set of materials (m=1 for non-hazmat and m=2 for hazmat)

N Railway terminal's set

R Train's set

TR_n Set of trains passing in terminal n; $TR_n \subseteq R$

$fcb_{m,n}$ Fixed cost per unit for m material's boxes handling at terminal n

$qb_{m,n}$ Hourly cost per unit for m material's boxes storing at terminal n

h_n Maximum number of handling actions(loading and unloading) allowed at terminal n for each train

L Set of railway links, $L=\{(i,j): i,j \in N, i \neq j\}$; a railway link are denoted as $l = (i, j)$, where j is the head of l and i is its end

nl_r Number of railway links that train r cover

T_r Timetable for train r, identifying the nl_r links covered by r and the coming and times at the visited terminals

CT_r Cost for using of train r

$\bar{G}_r$ Maximum tolerable weight for train r

W_r Set of wagons of train r

$\bar{D}_{r,w}$ Length of wagon w of train r

$\bar{g}_{r,w}$ The maximum tolerable weight for wagon w of train r

O Set of orders

TR_o^s Release time at the origin terminal for order o

TD_o^d Deadline at the destination terminal for order o

$\widetilde{\tau_{p,o_{b_m}}}$ Cost of route p for order o of m material box b that is weighted according to the route priority

B_m Set of m material boxes

o_{b_m} Order including m material box $o_{b_m} \in O$

d_{b_m} Length of m material box b

g_{b_m} Weight of m material box b

C Cost of safety handling tool for hazmat boxes per unit

$\overline{E_r}$ Fuel consumption of train r for each kilometer

dl_r Length of each railway link that train r cover

The pre-analysis data:

$S_{o_{b_m}}$ Set of train sequences that are founded for order o of m material boxes b

$R_{s,o_{b_m}}$ Set of trains in sequence s for order o of m material boxes b

$S^U_{o_{b_m},n,r}$ Set of indices of sequences that involve the unloading of m material boxes b for order o at terminal n from train r

$S^L_{o_{b_m},n,r}$ Set of indices of sequences that involve the loading of m material boxes b for order o at terminal n from train r

$S^T_{o_{b_m},n,r}$ Set of indices of sequences that involve the a transfer action of m material boxes b for order o at terminal n with train r

$P_{s,o_{b_m}}$ Path associated with train sequence s of order o of m material boxes b

$c_{s,o_{b_m}}$ Cost of serving sequence s of order o of m material boxes b

In addition, two amounts should be computed that are showed in the following:

$\rho^n_{o_{b_m},s} \in \{0, 1\}$ Indicating if the m material boxes b of order o in sequence s involve a train change at terminal $n \in N$

and

$Q^n_{o_{b_m},s}$ Storage time (in hours) required for m material boxes b of order o in sequence s at terminal $n \in N$

where $c_{s,o_{b_m}}$ is computed by following formulation:

The priority cost $(\widetilde{\tau_{p,o_{b_m}}})$ multiplied by the sum of unloading and storage costs for all the in use terminals.

$$\widetilde{c_{s,o_{b_m}}} = \widetilde{\tau_{p,o_{b_m}}} \sum_{n \in N}(\rho^n_{o_{b_m},s} \cdot fcb_{m,n} + Q^n_{o_{b_m},s} \cdot qb_{m,n})$$

This formulation with $fcb_{1,n}$ and $qb_{1,n}$ equal with $c_{s,o_{b_1}}$ and with $fcb_{2,n}$ and $qb_{2,n}$ equal with $c_{s,o_{b_2}}$. Since of safety for hazmat material transportation these value have different amounts.

$$y_{s,o_{b_m}} = \begin{cases} 1 & \text{if } m \text{ material box } b \text{ is assigned to sequence } s \\ 0 & \text{otherwise} \end{cases} \quad b_m \in B_m, s \in S_{o_{b_m}}$$

$$x_{o_{b_m},s,r,w} = \begin{cases} 1 & \text{if } m \text{ material box } b \text{ is assigned to wagon } w \text{ of train } r \text{ in sequence } s \\ 0 & \text{otherwise} \end{cases} \quad b_m \in B_m, s \in S_{o_{b_m}}, w \in W, r \in R_{s,o_{b_m}}$$

$$v_{o_{b_m}} = \begin{cases} 1 & \text{if } m \text{ material box } b \text{ is } not\ served \\ 0 & \text{otherwise} \end{cases} \quad b_m \in B_m$$

$$z_r = \begin{cases} 1 & \text{if train } r \text{ is used} \\ 0 & \text{otherwise} \end{cases} \quad r \in R$$

We consider the following points in our presented model.

- Before presentation of the model this worthy say that the $\widetilde{c_{s,o_{b_m}}}$ must be computed from term (I) and then use in the model.

- The pre-analysis is performed like Anghinolfi et al. [1].

The developed mathematical model for transportation of hazmat and non-hazmat boxes is as follows:

$$\text{Min } Z_1 = \sum_{b_m \in B_m} \sum_{s \in S_{o_{b_m}}} \widetilde{c_{s,o_{b_m}}} \cdot y_{s,o_{b_m}} + \sum_{r \in R} k_r \cdot z_r + MM \cdot \sum_{b_m \in B_m} v_{o_{b_m}} + C \cdot \sum_{b_2 \in B_2} \sum_{s \in S_{o_{b_2}}} \sum_{r \in R_{s,o_{b_2}}} \sum_{w \in W} x_{o_{b_2},s,r,w}$$

$$\text{Min } Z_2 = \sum_{r \in R_{s,o_{b_m}}} \overline{E_r} \cdot dl_r \cdot nl_r$$

s.t.

$$\sum_{s \in S_{o_{b_m}}} y_{s,o_{b_m}} + v_{o_{b_m}} = 1 \quad b_m \in B_m \tag{1}$$

$$\sum_{w \in W_r} x_{o_{b_m},s,r,w} = y_{s,o_{b_m}} \quad b_m \in B_m, s \in S_{o_{b_m}}, r \in R_{s,o_{b_m}} \tag{2}$$

$$\sum_{s \in (S^L_{o_{b_m},n,r} \cup S^T_{o_{b_m},n,r})} \sum_{w \in W_r} \sum_{b_m \in B_m} x_{o_{b_m},s,r,w} \cdot g_{b_m} \leq \overline{G_r} \cdot z_r \quad n \in N, r \in TR_n \tag{3}$$

$$\sum_{b_m \in B_m} \sum_{s \in (S^L_{b_m,n,r} \cup S^T_{b_m,n,r})} x_{o_{b_m},s,r,w} \cdot g_{b_m} \leq \bar{g}_{r,w} \quad n \in N,\ r \in TR_n,\ w \in W_r \tag{4}$$

$$\sum_{b_m \in B_m} \sum_{s \in (S^L_{b_m,n,r} \cup S^T_{b_m,n,r})} x_{o_{b_m},s,r,w} \cdot d_{b_m} \leq \bar{D}_{r,w} \quad n \in N,\ r \in TR_n,\ w \in W_r \tag{5}$$

$$\sum_{s \in (S^L_{b_m,n,r} \cup S^T_{b_m,n,r})} \sum_{w \in W_r} \sum_{b_m \in B_m} x_{o_{b_m},s,r,w} \leq h_n \quad n \in N,\ r \in TR_n \tag{6}$$

$$x_{o_{b_1},s,r,w} + x_{o_{b_2},s,r,w} = 1 \quad b_m \in B_m,\ n \in N,\ w \in W_r,\ r \in TR_n \tag{7}$$

$$y_{s,o_{b_m}} \in \{0,1\} \quad b_m \in B_m,\ s \in S_{o_{b_m}} \tag{8}$$

$$x_{o_{b_m},s,r,w} \in \{0,1\} \quad b_m \in B_m,\ s \in S_{o_{b_m}},\ r \in R_{s,o_{b_m}},\ w \in W_r \tag{9}$$

$$v_{o_{b_m}} \in \{0,1\} \quad b_m \in B_m \tag{10}$$

$$z_r \in \{0,1\} \quad r \in R \tag{11}$$

The first objective function (Z_1) minimizes the total cost that respectively consists of cost of assigning a sequence computed in a pre-analysis step, cost of using the train, the penalty of not serving orders that are for both materials (where MM is a very large positive quantity) and the cost of a safety tool for safer handling of hazmat boxes.

The second objective function (Z_2) minimizes the consumed fuel of trains used for service.

Eq. (1) ensures that each service box (non-hazmat or hazmat) is assigned to one and only one train sequence. Eq. (2) assures that after a box is assigned to a train sequence, then it must be assigned to one wagon of each train of sequence. Ensuring that sum weights of boxes do not exceed form the maximum tolerable weight of train is in Eq. (3). Equally, constraints (4) and (5) show the assurance about balance of the wagon length and weight limitations and the boxes assigned to wagons. Eq. (6) guarantees that at a specified terminal, the maximum number of handling actions to be done for each train is not exceeded from limitation. The assurance for safety that non-hazmat material box and hazmat material box don't assign to same wagon of train indicated in Eq. (7). Constraints from (8) to (11) denote the binary variables.

4. Solution Methodology

4-1. Result

In this section, we verify the model by solving a small-sized problem by Lingo 11.0, whose results are shown in Table 1. The number in parenthesis of column "Order" shows the order quantity of hazmat material boxes and by subtracting the number in parenthesis, and out of parenthesis the order quantity of non-hazmat material boxes is found.

Tab. 1. Results of small-sized problems

No. of nodes	No. of arcs	No. of trains	Order (hazmat)	Obj. (Z_1)	Obj. (Z_2)	CUP time (s)
5	9	10	20(9)	20756	352	6259
5	9	10	30(9)	26895	500	6520
5	9	10	20(12)	30561	420	6865
5	9	10	20(20)	35742	351	6925

Considering a small rail network of the problem, we can mention that the objective function value increases by considering hazmat material transportation. When the order increases, the objective function value increases as well. While hazmat materials increase, the objective function value increases more; however, we can make certain that this transportation is safe. The reason is that hazmat and non-hazmat material boxes are not assigned to the same wagon of the train assigned to the sequence.

We also observe that the transportation cost of hazmat materials is a little more than the combination transportation cost, so combination transportation has less cost. However, this model is suitable for hazmat railway transportation because it also considers the safety issue and in overall, the model is efficient. It is worthy to say that in a shipment the idea of the decision maker for suitable transportation of each type material is important. Therefore, in the following section, we determine the weights of transportation of each material in the objective function.

4-2. A New Fuzzy Approach

Torabi and Hassini [25] proposed a novel interactive fuzzy approach and established a compromise solution for a mixed-integer liner programming (MILP) model of a supply chain that includes multiple suppliers, one manufacturer and multiple distribution centers. They proposed a method, which is very promising for any multi-objective linear model and for the mixed-integer

type because they tested this method for numerical examples and observed good results.

Triangular possibility distribution is the base of this method. In fact, this method by computing a coefficient according to a degree of satisfaction can help the decision maker for making the final decision. This method has six steps. The first step is to determine a suitable triangular possibility distribution for fuzzy parameters.

The second step is to convert fuzzy objectives to crisp objectives. The third step is converting fuzzy constraints to crisp constraints. The forth step is to solve the model and compute the positive and negative ideal solutions. The fifth step is to compute a linear membership function. We consider the same small problem considered in the previous subsection. The results of the TH method for this example are illustrated in Table 2.

Tab. 2. Results of the TH method

Z_1=min cost 20756	Z_1^{PIS}=20756	$\mu_1(v) = 0.94$
	Z_1^{NIS}= 22745	
Z_2=min fuel 352	Z_2^{PIS}=352	$\mu_2(v) =0.87$
	Z_2^{NIS}=402	

$\mu_i(v)$ indicates the satisfaction degree of the *i*-th section of the objective function for the solution. By considering results obtained by the TH method, we can say that the model and its solution can satisfy 82% hazmat transportation. This is a good result showing that transportation is safe. In the sixth step, the following model should be solved.

Max λ (v) = 0.82γ+ (1- γ)(0.94θ_1 + 0.87 θ_2)

s.t.
  μ_h(v)≥0.82   *h*=1,2

All constraints of main model (1-11) and $\gamma \epsilon [0,1]$
The minimum satisfaction section of the objective function is controlled by γ. The decision maker determines γ and θ_h. Each run determines the coefficient of γ and relative importance of θ by solving this model as MIP model. If the decision maker is satisfied with the current efficient solution, stop; otherwise try again for making his/her satisfaction is obtained.

5. Conclusions

In this paper, we have developed a freight transportation model with hazmat transportation, green transportation and fuzziness issue for making the presented model real. This model could be used to design a plan to meet the demand for transporting hazmat and non-hazmat materials with safety. A small numerical example has been solved for this model by Lingo 11.0 and the associated results are analyzed.

These results have shown that the developed model is efficient, because the model presenting the less cost for transporting hazmat and non-hazmat materials has been consistent with the environment and reality. In addition, the TH method has been applied to trade-off between different objective functions. For future study, the assumption that two hazmat boxes cannot be in the same wagon can be replaced with a more realistic one. In addition, heuristic or meta-heuristic algorithms can be suggested for solving the given problem.

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