Journal of Transportation Safety & Security

ISSN: 1943-9962 (Print) 1943-9970 (Online) Journal homepage: https://www.tandfonline.com/loi/utss20

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To cite this article: Onur Derse & Elifcan Göçmen (2019): Transportation mode choice using fault tree analysis and mathematical modeling approach, Journal of Transportation Safety & Security, DOI: 10.1080/19439962.2019.1665600

To link to this article: https://doi.org/10.1080/19439962.2019.1665600

Published online: 20 Sep 2019.

JOURNAL OF TRANSPORTATION SAFETY & SECURITY
https://doi.org/10.1080/19439962.2019.1665600

Transportation mode choice using fault tree analysis and mathematical modeling approach

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ABSTRACT

In this paper, transportation problem of hazardous materials (hazmat) by various transportation modes is considered. Accident probabilities related to human and ecologic risks are assumed for each transportation mode including road, rail, and marine modes. Thus, a two-stage approach following the fault tree analysis (FTA) first, a mathematical modeling approach second is provided. In the first stage, FTA is employed to analyze the risks for each transportation mode. In the second stage, a mixed integer nonlinear programing model is formulated by using the results of the FTA to minimize the transportation cost and risk cost for each mode. Computational results for the instances in the literature and generated instances are provided. Results show that the two-stage approach is able to produce high-quality solutions. Most effective parameter is human-based possibility with 82% for the road accident, vehicle-based possibility with 64% for the rail accident, material-based possibility with 76% for the marine accident during the hazmat transportation.

KEYWORDS

risk analysis; quantitative risk analysis; hazmat transport; transportation modes; fault tree analysis; mathematical model

1. Introduction

In recent years, safety-related constraints in transport problem formulations have attracted substantial attention. Transportation planning processes considering safety issues are significantly important for logistics firms. Hazmat transportation problem should be evaluated by incorporating economic, social, and environmental conditions simultaneously (Bula, Afsar, & González, 2018). Transportation of hazmat also forces logistics firms to manage the transport operations considering safety aspects. Therefore, transport modes should be evaluated critically due to the risks by transportation of hazardous materials. Explosions and crashes take place during transportation of these materials (Cherradi, El-Bouziri, Boulmakoul, & Zeitouni, 2018). Transportation modes are also important because every

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mode has special characteristics. In Turkey, road transport is mostly preferred for major transport. Rail transport is used for heavy goods and minimum transport costs. Marine transport is also preferred because it has transportation of heavy goods, liquids, and minimum cost advantages. Because road transportation has negative environmental impacts, a modal shift from the road to other modes is beneficial.

In this paper, a transportation mode including rail, road, and marine modes is examined to minimize the total costs based on fault tree analysis (FTA) results. This paper deals with hazmat that are risky materials for humans and the environment. FTA is examined to find the accident occurrences of transportation modes. Thus, transportation modes that have low risk probability and minimum transport cost are determined. The figure for the overall scheme of proposed algorithm is depicted in Figure 1. The data used in this paper is occurrence risk of an accident by transport modes. The processes are using FTA and mathematical modeling approach to minimize the total cost and risk cost for each mode.

Submitted papers of transport mode choices (Bierwirth, Kirschstein, & Meisel, 2012; Min, 1991; Serper & Alumur, 2016) are available. Besides, Barnhart and Ratliff (1993) compare the transport modes. In addition, transport mode selection has gained attention in the transport sector (Göçmen & Erol, 2019), hazmat transportation has not been discussed completely (Zhong, Wang, Yip, & Gu, 2018). Hazmat transportation problems based on risk aspect are handled by some researchers in the literature. Bubbico, et al. (2006) examine the dangerous materials by considering transport risks. Glickman, Erkut, and Zschocke (2007) formulate a risk

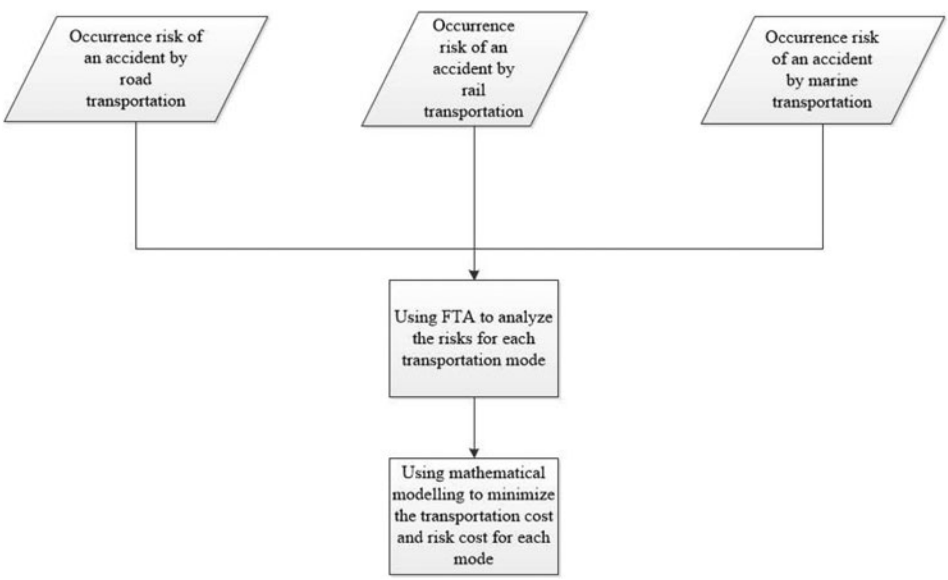

Figure 1. The depiction of the overall scheme of proposed algorithm.

model for rail transport. Erkut and Gzara (2008) develop a bilevel problem for hazmat network and propose a heuristic that gives lower risk network. Bianco, Caramia, and Giordani (2009) develop a model to minimize total risk for hazmat transport. Verma and Verter (2010) study a transport problem of dangerous goods to minimize the total transport cost and also use population effect to calculate the number of people who are affected by a risky event. Reniers et al. (2010) present a methodology of transporting dangerous materials by transport modes using a transport risk analysis tool for dangerous materials considering accident probability. Van Raemdonck et al. (2013) studied multiple transports of hazardous materialsdy using historical accident data and risk map for the transport of dangerous goods. The other papers that provides hazmat network are by Verter and Kara (2008); Milazzo et al. (2002); Schweitzer (2006); Qiao, Keren, and Mannan (2009); Amaldi, Bruglieri, and Fortz (2011); Erkut and Ingolfsson (2005); Yin, Sun, Peng, et al. (2018); and Fontaine and Minner (2018).

Few papers deal with the hazmat transportation by FTA (Cozzani, Bonvicini, Spadoni, & Zanelli, 2007). A fuzzy-based approach is applied to the risks to determine the transport mode weights to find the most optimum allocation of modes (Göçmen & Erol, 2018). However, our paper is first to discuss the intermodal hazmat transportation using the risk analysis method and mathematical modeling approach simultaneously. Other contributions are (1) a FTA is provided to determine the occurrence of accidents for each transportation modes transporting the hazmat, (2) the branches of the tree are combined with the developed branches by existing literature and developed branches by the authors, (3) the paper is first to use the outputs of the FTA for the mathematical model.

2. Material and methods

2.1. Problem definition

An intermodal hazmat transportation problem is investigated to decide the more economic and more environmentally friendly transport mode shown in Figure 2. The flow of the hazmat is from the production points to the demand points using road, marine, and rail transport. Hazmat transportation can cause the accidents that affect humans and environment. Hazmat network optimization can ensure more efficient transport and low accident rates (Sun et al. 2018). Therefore, the risk possibilities related with various parameters must be examined to determine the best transport modes. We consider four risk possibilities that are human, environment, vehicle, hazmat to obtain the possibility of the transportation modes. The purpose of the decision maker is to transport all the materials by providing the capacity, demand, and risk constraints to minimize the total transport costs of

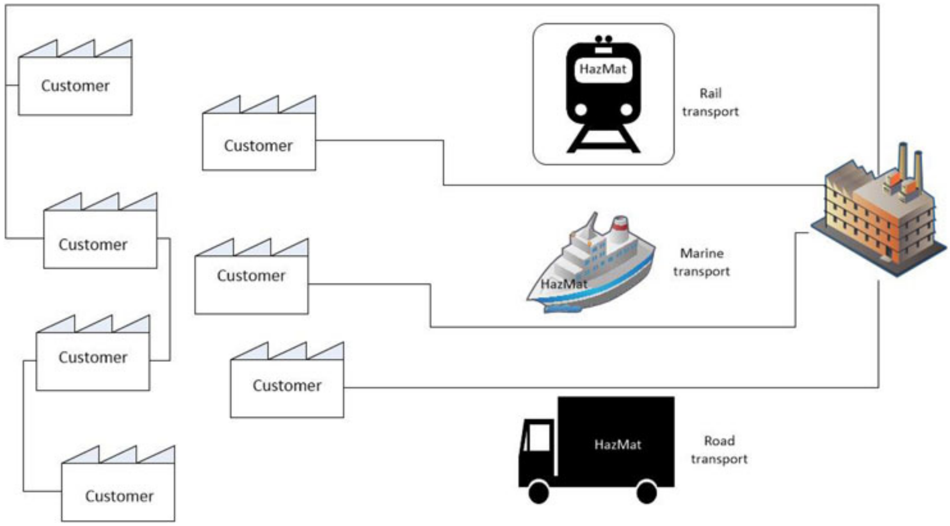

Figure 2. Hazmat transportation network.

the modes. Firstly, we apply the FTA in which there are risk possibilities based on human, environment, vehicle, and material subrisks from the literature and our observations.

In our network, a logistics firm who transports hazmats serves the customers with three transport modes. There are three ways that are railway, highway, or marine to transport these materials for each customer. Each option is decided with the accident possibilities, and the most optimum modes are obtained by the results of the mathematical modeling.

2.2. Fault tree analysis

Fault tree analysis is a risk analysis tool that examines the occurrence of the accident and defines the causes of the accidents (Goodman, 1988). The analysis starts with the main event and the event's subsections in a tree (Iverson, Kerkering, Coleman, & Spokane, 2001). Fault tree analysis method is evaluated as a more practical method for the risk analysis to prevent and control the accidents (Hu, 2016). Fault tree uses the Boolean algebra with a set of Boolean equations (Cheliyan & Bhattacharyya, 2018). Boolean algebra developed for this study is in Appendix A. Basic event is connected to subevents via OR gate. Main events and subsections are formed based on the papers of Ma, Xing, and Lu (2018); Liu, Yang, Gao, Li, and Gao (2015); Bali and Göztepe (2014); Şenel and Şenel (2013); Zhao, Wang, and Qian (2012); Gaonkar, Xie, Ng, and Habibullah (2011); Gheorghe, Birchmeier, Vamanu, et al. (2005) and our contributions. Possibilities are decided by three decision makers who are experts about the intermodal network. Fault tree analysis developed for the road transportation is given in Figure 3.

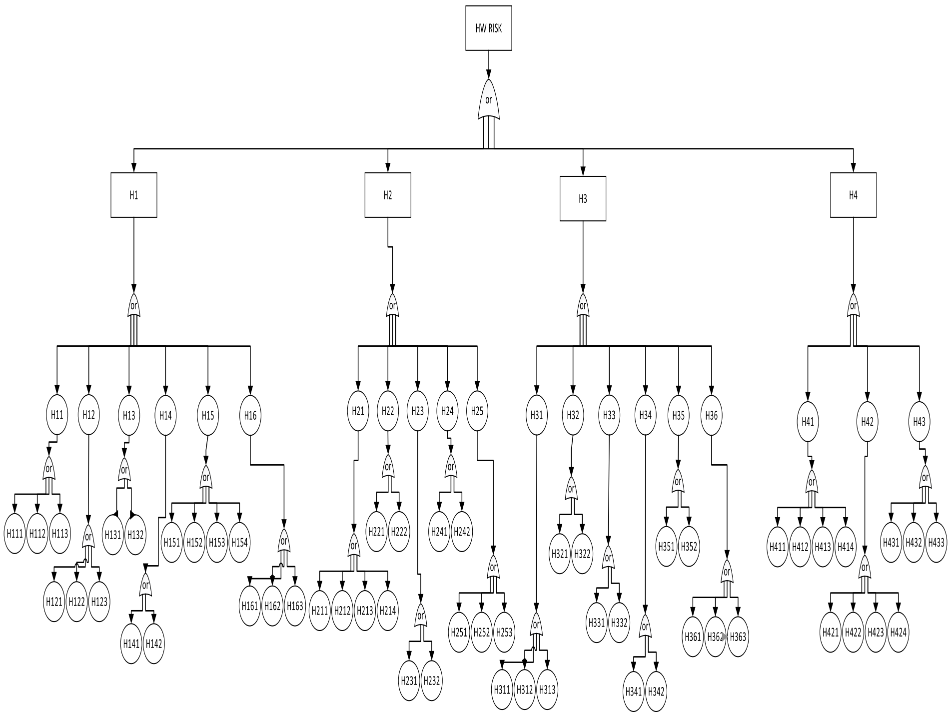

Figure 3. Fault tree analysis developed for the road transportation.

The definitions of the symbols in the tree as below:

-HW risk: Occurrence risk of an accident by road transportation

-H1, H2, H3, H4: The accident possibilities related with human, environment, vehicle and material

-H11: Age of truck driver that consists of H111 (24-35), H112 (36-45), H113(46-60)

-H12: Experience that consists of H121 (0-5), H122 (6-10), H123 (10-)

-H13: Health that consists of H131 (healthy), H132 (Unhealthy)

-H14: Education level that consists of H141 (Educated about hazmat), H142 (Noneducated about hazmat)

-H15: Driver behavior that consists of H151 (fast), H152 (improper), H153 (careless), H154 (standard)

-H16: Accident background of the driver that consists of H161(0), H162 (1-3), H163 (3-)

-H21: Weather conditions that consists of H211 (sunny), H212 (snowy),H213 (rainy), H214 (foggy)

-H22: H221 (daytime), H222 (night)

-H23: Ground that consists of H231 (dry), H232 (wet)

-H24: Lighting that consists of H241 (available), H242 (unavailable)

-H25: Traffic conditions that consists of H251 (<%50), H252 (%50-%75), H253 (>%75)

-H31: Vehicle age that consists of H311 (0-3), H312 (4-7), H313 (7-)

-H32: Infrastructure for hazmat that consists of H321 (available), H322 (unavailable)

-H33: Emergency infrastructure that consists of H331 (available), H332 (unavailable)

-H34: Vehicle type that consists of H341 (available), H342 (unavailable)

-H35:Vehicle maintenance that consists of H351 (available), H352 (unavailable)

-H36: Vehicle accident background that consists of H361 (0), H362 (1-3), H363 (3-)

-H41: Hazmat amount that consists of H411 (<10), H412 (10-24), H413 (25- 39), H414 (>40)

-H42: Hazmat type that consists of H421 (explosives), H422 (toxic gases), H423 (flammable liquids), H414 (other)

-H43: Hazmat process that consists of H431 (transport), H432 (loading), H433 (unloading)

Fault tree analysis developed for the rail transportation is given in Figure 4.

The definitions of the symbols in the tree as below:

-RW risk: Occurrence risk of an accident by rail transportation

-R1, R2, R3, R4: The accident possibilities related with human, environment, vehicle and material

-R11: Age of train driver that consists of R111 (24-35), R112 (36-45), R113 (46-60)

-R12: Experience that consists of R121 (0-5), R122 (6-10), R123 (10-)

-R13: Health that consists of R131 (healthy), H132 (Unhealthy)

-R14: Education level that consists of R141 (Educated about hazmat), R142 (Noneducated about hazmat)

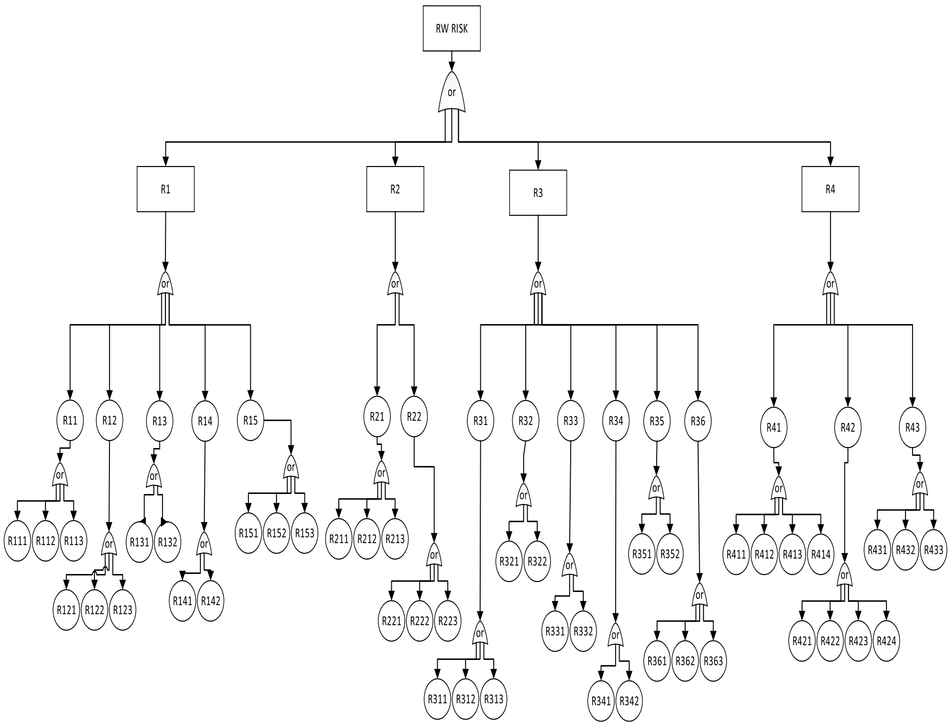

Figure 4. Fault tree analysis developed for the road transportation.

-R15: Accident background of the driver that consists of R151 (0), R152 (1-3), R153 (3-)

-R21: Weather conditions that consists of R211 (sunny), H212 (snowy), R213 (rainy),

-R22: Natural disasters R221 (earthquake), R222 (landslide), R223 (fire)

-R31: Vehicle age that consists of R311 (0-3), H312 (4-7),R313 (7-)

-R32: infrastructure for hazmat that consists of R321 (available), R322 (unavailable)

-R33: Emergency infrastructure that consists of R331 (available), R332 (unavailable)

-R34: Vehicle maintenance that consists of R341 (available), R342 (unavailable)

-R35:Power source that consists of R351 (available), R352 (unavailable)

-R36: Vehicle accident background that consists of R361 (0), R362 (1-3), R363 (3-)

-R41: Hazmat amount that consists of R411 (<10), R412 (10-24), R413 (25- 39), R414 (>40)

-R42: Hazmat type that consists of R421 (explosives), R422 (toxic gases), R423 (flammable liquids), R414 (other)

-R43: Hazmat process that consists of R431 (transport), R432 (loading), R433 (unloading)

Fault tree analysis developed for the marine transportation is given in Figure 5.

The definitions of the symbols in the tree as below:

-MT risk: Occurrence risk of an accident by marine transportation

-M1, M2, M3, M4: The accident possibilities related with human, environment, vehicle, and material

-M11: Age of ship operator that consists of M111 (24-35), M112 (36-45), M113 (46-60)

-M12: Experience that consists of M121 (0-5), M122 (6-10), M123 (10-)

-M13: Health that consists of M131 (Healthy), M132 (Unhealthy)

-M14: Education level that consists of M141 (Educated about hazmat), M142 (Noneducated about hazmat)

-M15: Operator behavior that consists of M151 (fast), M152 (improper), M153 (careless), M154 (standard)

-M16: Watchman failure that consists of M161 (available), M162 (unavailable)

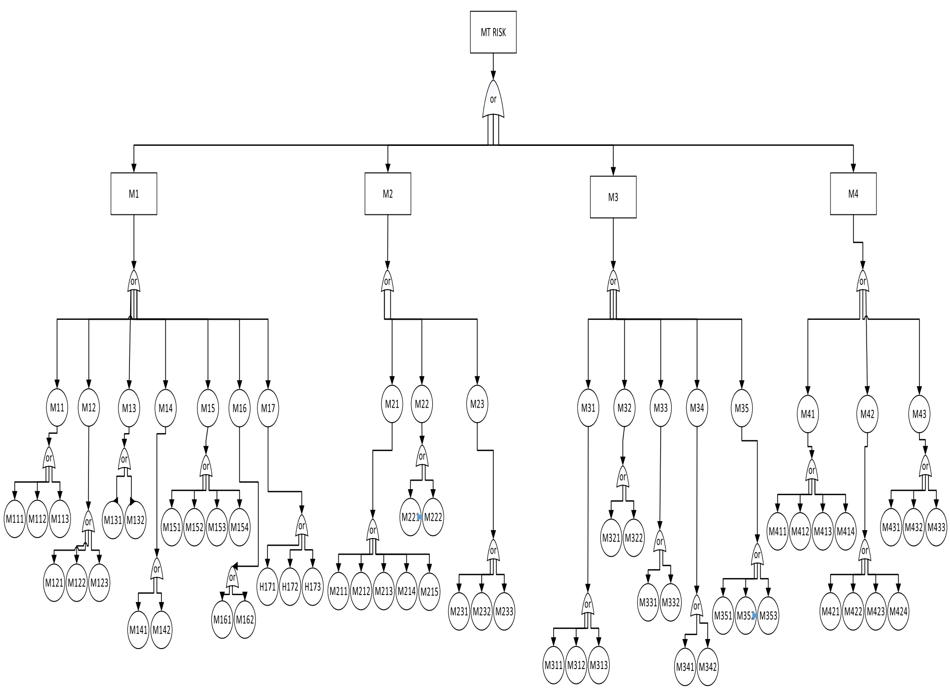

Figure 5. Fault tree analysis developed for the road transportation.

-M17: Accident background of the operator that consists of M161 (0), M162 (1-3), M163 (3-)

-M21: Weather conditions that consists of M211 (sunny), M212 (snowy), M213 (rainy), M214 (foggy), M215 (stormy)

-M22: M221 (daytime), M222 (night)

-M23: Sea condition that consists of M231 (stream), M232 (shallow), M233 (distance to land)

-M31: Vehicle age that consists of M311 (0-3), M312 (4-7), M313 (7-)

-M32: Infrastructure for hazmat that consists of M321 (available), M322 (unavailable)

-M33: Emergency infrastructure that consists of M331 (available), M332 (unavailable)

-M34: Vehicle maintenance that consists of M341 (available), M342 (unavailable)

-M35: Vehicle accident background that consists of M351 (0), M352 (1-3), M353 (3-)

-M41: Hazmat amount that consists of M411 (<10), M412 (10-24), M413 (25- 39), M414 (>40)

-M42: Hazmat type that consists of M421 (explosives), M422 (toxic gases), M423 (flammable liquids), M414 (other)

-M43: Hazmat process that consists of M431 (transport), M432 (loading), M433 (unloading)

A mathematical model is formulated for this problem.

Decision variables of problem

- Number of transport modes
- Number of hazmat to be transported
- Decision of using a transport mode

The constraints in the problem are

- All demands must be met from the producers in the regions.
- Capacity of the transport modes cannot be exceed.

Mathematical Model

The notation used for mathematical modeling of the problem is as follows;

Indices
B: regions (b = 1, … … ,B)
J: demand points (j = 1, … … ,J)
I: hazmat (i = 1,, … … ,I)
K: transportation modes (k = k1,k2,k3)
T: period (t = 1, … … T)
Parameters
a_{jit} : demands of i.material from b. region (unit)
$c1_{jbk1}$: transport cost between j and b with k1 (money)
$c2_{jbk2}$: transport cost between j and b with k2 (money)
$c3_{jbk3}$: transport cost between j and b with k3 (money)
$cp1_{k1i}$: maxmaterial number for k1 (unit)
$cp2_{k2i}$: maxmaterial number for k2 (unit)
$cp3_{k3i}$: maxmaterial number for k3 (unit)
$e1_{k1i}$: minmaterial number for k1 (unit)
$e2_{k2i}$: minmaterial number for k2 (unit)
$e3_{k3i}$: minmaterial number for k3 (unit)
$p1_{k1}$: possibility of accident for k1
$p2_{k2}$: possibility of accident for k2
$p3_{k3}$: possibility of accident for k3
Decision Variables
$kx1_{ik1bjt}$ number of i materials from b point to j point by k1 mode at t period
$kx2_{ik2bjt}$ number of i materials from b point to j point by k2 mode at t period
$kx3_{ik3bjt}$ number of i materials from b point to j point by k3 mode at t period
$m1_{k1}$ number of k1 modes
$m2_{k2}$ number of k2 modes
$m3_{k3}$ number of k3 modes

$$n1_{k1} = \begin{cases} 1, \text{ if there is a transport with k1} \\ 0, \text{ otherwise} \end{cases}$$

$$n2_{k2} = \left\{ \begin{cases} 1, \text{ if there is a transport with k2} \\ \quad 0, \text{ otherwise} \end{cases} \right.$$

$$n3_{k3} = \begin{cases} 1, \text{ if there is a transport with k3} \\ \quad 0, \text{ otherwise} \end{cases}$$

$$\begin{aligned} \min z = & \sum_{i=1}^{I} \sum_{b=1}^{B} \sum_{k=1}^{K} \sum_{j=1}^{J} \sum_{t=1}^{T} kx1_{ik1bjt} * c1_{jbk1*}\ m1_{k1} * p1_{k1} \\ & + \sum_{i=1}^{I} \sum_{b=1}^{B} \sum_{k=1}^{K} \sum_{j=1}^{J} \sum_{t=1}^{T} kx2_{ik2bjt} * c2_{jbk2*}\ m2_{k2} * p2_{k2} \\ & + \sum_{i=1}^{I} \sum_{b=1}^{B} \sum_{k=1}^{K} \sum_{j=1}^{J} \sum_{t=1}^{T} kx3_{ik3bjt} * c3_{jbk3*}\ m3_{k3} * p3_{k3} \end{aligned}$$

The objective function minimizes the sum of the total transportation costs based on FTA results.

For road transport;

$$\sum_{i=1}^{I} \sum_{b=1}^{B} \sum_{j=1}^{J} kx1_{ik1bjt} \leq \sum_{i=1}^{I} cp1_{k1i} * m1_{k1} \qquad k1 \in K,\ t \in \{1.T\}$$

This is the capacity constraint.

$$\sum_{i=1}^{I} cp1_{k1i} * m1_{k1} - \sum_{i=1}^{I} \sum_{b=1}^{B} \sum_{j=1}^{J} kx1_{ik1bjt} Z \geq \sum_{i=1}^{I} e1_{k1i} * m1_{k1} \qquad k1 \in K,\ t \in \{1.T\}$$

This constraint ensures the number of minimum hazmat.

$$\sum_{b=1}^{B}\sum_{k=1}^{K} kx1_{ik1bjt} = \mathrm{a_{jit}} \quad \mathrm{j} \in \mathrm{J},\ \mathrm{t} \in \{1.\mathrm{T}\},\ \mathrm{i} \in \{1.\mathrm{I}\}$$

This is the constraint of meeting the demands.

$$\sum_{i=1}^{I}\sum_{b=1}^{B}\sum_{j=1}^{J} n1_{k1} * kx1_{ik1bjt} \geq \mathrm{m1_{k1}} \quad \mathrm{k1} \in \mathrm{K},\ \mathrm{t} \in \{1.\mathrm{T}\}$$

For marine transport;

$$\sum_{i=1}^{I}\sum_{b=1}^{B}\sum_{j=1}^{J} kx2_{ik2bjt} \leq \sum_{i=1}^{I} \mathrm{cp2_{k2i}} * \mathrm{m2_{k2}} \quad \mathrm{k2} \in \mathrm{K},\ \mathrm{t} \in \{1.\mathrm{T}\}$$

This is the capacity constraint.

$$\sum^{i=1I} \mathrm{cp2_{k2i}} * \mathrm{m2_{k2}} - \sum_{i=1}^{I}\sum_{b=1}^{B}\sum_{j=1}^{J} kx2_{ik2bjt} \geq \sum_{i=1}^{I} \mathrm{e2_{k2i}} * \mathrm{m2_{k2}} \quad \mathrm{k2} \in \mathrm{K},\ \mathrm{t} \in \{1.\mathrm{T}\}$$

This constraint ensures the number of minimum hazmat.

$$\sum_{b=1}^{B}\sum_{k=1}^{K} kx2_{ik2bjt} = \mathrm{a_{jit}} \quad \mathrm{j} \in \mathrm{J},\ \mathrm{t} \in \{1.\mathrm{T}\},\ \mathrm{i} \in \{1.\mathrm{I}\}$$

This is the constraint of meeting the demands.

$$\sum_{i=1}^{I}\sum_{b=1}^{B}\sum_{j=1}^{J} n2_{k2} * kx2_{ik2bjt} \geq \mathrm{m2_{k2}} \quad \mathrm{k2} \in \mathrm{K},\ \mathrm{t} \in \{1.\mathrm{T}\}$$

For rail transport;

$$\sum_{i=1}^{I}\sum_{b=1}^{B}\sum_{j=1}^{J} kx3_{ik3bjt} \leq \sum_{i=1}^{I} \mathrm{cp3_{k3i}} * \mathrm{m3_{k3}} \quad \mathrm{k3} \in \mathrm{K},\ \mathrm{t} \in \{1.\mathrm{T}\}$$

This is the capacity constraint.

$$\sum^{i=1I} \mathrm{cp3_{k3i}} * \mathrm{m3_{k3}} - \sum_{i=1}^{I}\sum_{b=1}^{B}\sum_{j=1}^{J} kx3_{ik3bjt}Z \geq \sum_{i=1}^{I} \mathrm{e3_{k3i}} * \mathrm{m3_{k3}} \quad \mathrm{k3} \in \mathrm{K},\ \mathrm{t} \in \{1.\mathrm{T}\}$$

This constraint ensures the number of minimum hazmat.

$$\sum_{b=1}^{B}\sum_{k=1}^{K} kx3_{ik3bjt} = \mathrm{a_{jit}} \quad \mathrm{j} \in \mathrm{J},\ \mathrm{t} \in \{1.\mathrm{T}\},\ \mathrm{i} \in \{1.\mathrm{I}\}$$

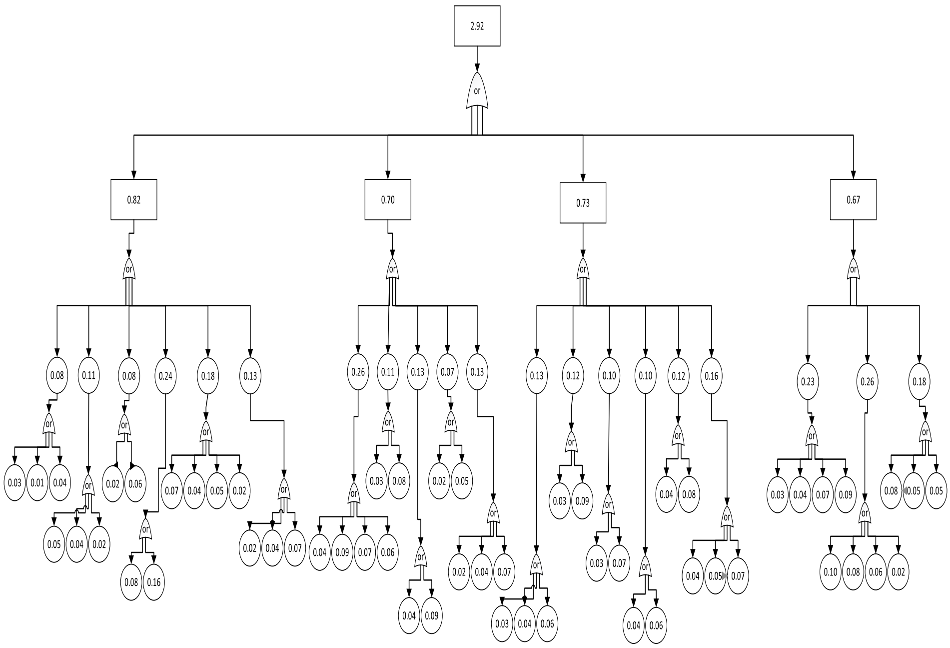

Figure 6. Accident possibilities of road transportation.

This is the constraint of meeting the demands.

$$\sum_{i=1}^{I}\sum_{b=1}^{B}\sum_{j=1}^{J} n1_{k3} * kx3_{ik3bjt} \geq \mathrm{m3}_{\mathrm{k3}} \qquad \mathrm{k3} \in \mathrm{K},\ \mathrm{t} \in \{1.\mathrm{T}\}$$

3. Results

3.1. Results of fault tree analysis

Fault tree analysis is applied for each transportation mode, and accident possibilities for hazmat transportation based on decision makers are assigned to each branch. Boolean algebra was developed, and possibility values of the basic events, four main events, and subevents are in the Appendix B. Number of hazmat transported between regions and the demand points are in Table b1. Possibility values for human factor and subcriteria are in Table b2, environment factor and subcriteria in Table b3, vehicle factor and subcriteria in Table b4, hazmat factor and subcriteria in Table b5, basic event and subevent in Table b6 are given in the Appendix B. Accident possibility of the road transportation is 2.92, in which human-based possibility is 0.82, environment-based possibility is 0.70, vehicle-based possibility is 0.73, material-based possibility is 0.67 given in Figure 6. Thus, the most effective parameter is human-based possibility for the road

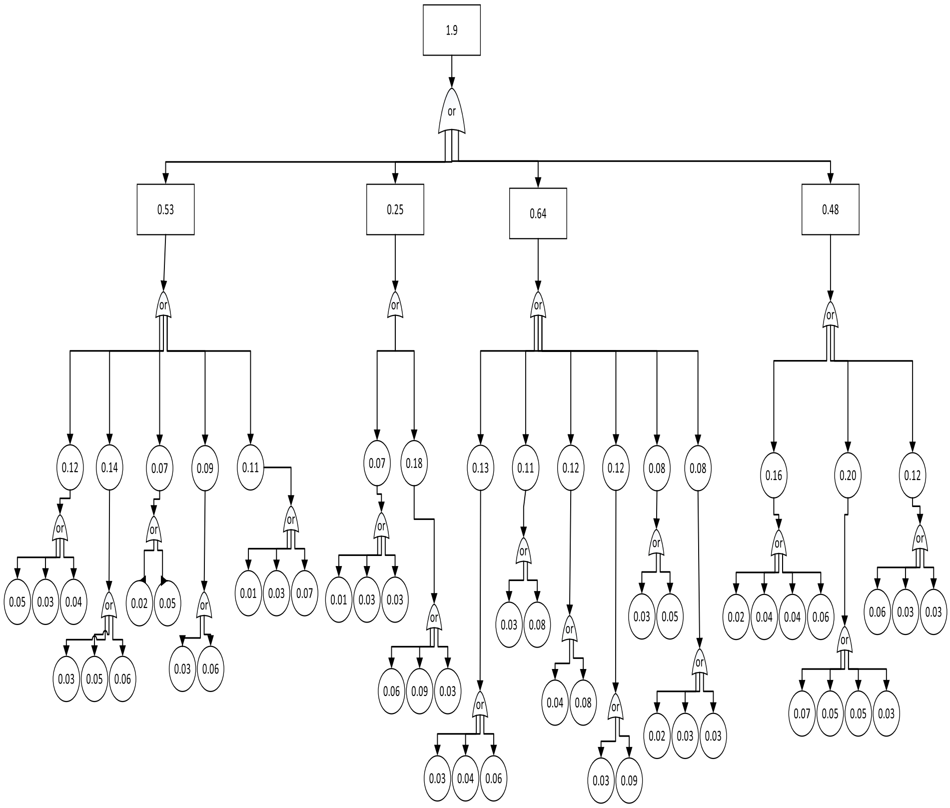

Figure 7. Accident possibilities of rail transportation.

accident transporting hazmat. Truck drivers who ensure the requirements about the hazmat transportation should be chosen to drive the trucks.

Accident possibility of the rail transportation is 1.9, in which human-based possibility is 0.53, environment-based possibility is 0.25, vehicle-based possibility is 0.64, material-based possibility is 0.48 given in Figure 7. Thus, the most effective parameter is vehicle-based possibility for the rail accident transporting hazmat. Trains that ensure the requirements about the hazmat transportation should be chosen.

Accident possibility of the marine transportation is 2.24, in which human-based possibility is 0.6, environment-based possibility is 0.41, vehicle-based possibility is 0.47, material-based possibility is 0.76 given in Figure 8. Thus, the most effective parameter is material-based possibility for the marine accident transporting hazmat. Proper hazmat that ensures the requirements of the ships about the hazmat transportation should be chosen.

The highest possibility is obtained by the road transport. The lowest possibility is of rail transport. The results can be related with that road transport are mostly preferred; and thus, accident results can be higher than the

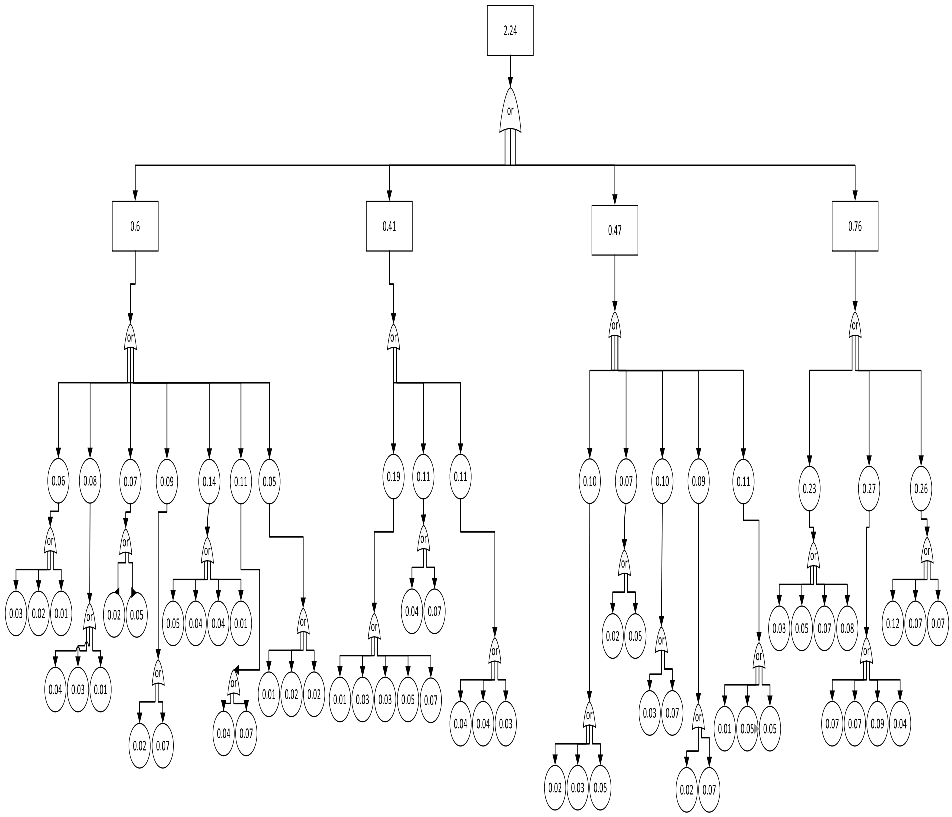

Figure 8. Accident possibilities of marine transportation.

other modes. However, road transport is affected by various environmental events.

3.2. Results of mathematical modeling

During the first stage, the outputs are obtained by FTA. The outputs of FTA called for possibilities of transport modes to be incorporated into the developed mathematical model. The results of the mathematical model ensure the utilization of the transport modes, in which total 52 trucks, one ship, and two trains are obtained. Although road transport has highest accident possibility in FTA, the highest utilization is related with truck. However, train and ship modes are included to the system, and this result can decrease the accidents. Number of hazmat from production regions to demand points by all transportation modes at periods are given in Table b1.

4. Discussion

Transportation problems have gained substantial attention economically and environmentally in recent years. Environmental concerns prompt the transport sector to consider risk issues. Incorporating risk aspect to the approaches ensures to guide the firms for their decision-making processes. Besides, researchers are aware of considering new concept such as risk and safety issues to make challenges. Risk subjects can be accepted as a new area for this sector. Hazmat transportation is critically important, and negative results of this transport can cause disasters. Therefore, these processes are conducted by considering accident possibilities. In the study, these effects are considered for the transport of the hazmat using the FTA. The most effective parameters are human-based possibility for the road accident, vehicle-based possibility for the rail accident, and material-based possibility for the marine accident. Also, the outputs of this analysis are used for the mathematical modeling approach. Thus, the most optimum transport modes are determined to minimize the total transport cost and accident possibility. Regarding the academic aspect, the study integrates two different methods, in which the output of FTA is used as an input to the mathematical modeling approach. Researchers suggest using the performance factors as inputs to the mathematical models. Regarding the practical aspect, the approach can guide the decision makers in this sector. For future works, various subrisk factors can be considered for the FTA. Failure mode and effects analysis can be used to consider occurrence, detectability, and severity of the transport modes.

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Appendix a

P (BASIC EVENT) = H1 U H2 U H3 U H4
= [(H11 U H12 U H13 U H14 U H15 U H16)] U [(H21 U H22 U H23 U H24 U H25)] U [(H31 U H32 U H33 U H34 U H35 U H36)] U [(H41 U H42 U H43)]
= [(H111 U H112 U H113) U (H121 U H122 U H123) U (H131 U H132) U (H141 U H142) U (H151 U H152 U H153 U H154) U (H161 U H162 U H163)] U [(H211 U H212 U H213 U H214) U (H221 U H222) U (H231 U H232) U (H241 U H242) U (H251 U H252 U H253)] U [(H311 U H312 U H313) U (H321 U H322) U (H331 U H332) U (H341 U H342) U (H351 U H352) U (H361 U H362 U H363)] U [(H411 U H412 U H413 U H414) U (H421 U H422 U H423 U H424) U (H431 U H432 U H433)]

Appendix b

Table b1. Number of hazmat transported between regions and the demand points.

Road					
Hazmat type		1		2	
Periods		1	2	1	2
2	3	370	1050	840	1140
3	1	183	170	900	700
3	2	1000	600	500	500
Marine					
Hazmat type		1		2	
Periods		1	2	1	2
1	3	370	1050	840	1140
2	1	183	170	900	700
2	2	1000	600	500	500
Rail					
Hazmat type		1		2	
Periods		1	2	1	2
2	1	91.500	85	450	350
3	1	91.500	85	450	350
3	2	1000	600	500	500
3	3	370	1050	840	1140

Table b2. Possibility values for the human factor and subcriteria.

Factors	Boolean Algebra	Possibility values
H11	P(H111 U H112 U H113)	0.08
H12	P(H121 U H122 U H123)	0.11
H13	P(H131 U H132)	0.08
H14	P(H141 U H142)	0.24
H15	P(H151 U H152 U H153 U H154)	0.18
H16	P(H161 U H162 U H163)	0.13
H1	P(H11 U H12 U H13 U H14 U H15 U H16)	0.82

Table b3. Possibility values for the environment factor and subcriteria.

Factors	Boolean Algebra	Possibility values
H21	P(H211 U H212 U H213 U H214)	0.26
H22	P(H221 U H222)	0.11
H23	P(H231 U H232)	0.13
H24	P(H241 U H242)	0.07
H25	P(H251 U H252 U H253)	0.13
H2	P(H21 U H22 U H23 U H24 U H25)	0.70

Table b4. Possibility values for the vehicle factor and subcriteria.

Factors	Boolean Algebra	Possibility values
H31	P(H311 U H312 U H313)	0.13
H32	P(H321 U H322)	0.12
H33	P(H331 U H332)	0.10
H34	P(H341 U H342)	0.10
H35	P(H351 U H352)	0.12
H36	P(H361 U H362 U H363)	0.16
H3	P(H31 U H32 U H33 U H34 U H35 U H36)	0.73

Table b5. Possibility values for the hazmat factor and subcriteria.

Factors	Boolean Algebra	Possibility values
H41	P(H411 U H412 U H413 U H414)	0.23
H42	P(H421 U H422 U H423 U H424)	0.26
H43	P(H431 U H432 U H433)	0.18
H4	P(H41 U H42 U H43)	0.67

Table b6. Possibility values for the basic event and main events.

Factors	Boolean Algebra	Possibility values
H1	P(H11 U H12 U H13 U H14 U H15 U H16)	0.82
H2	P(H21 U H22 U H23 U H24 U H25)	0.70
H3	P(H31 U H32 U H33 U H34 U H35 U H36)	0.73
H4	P(H41 U H42 U H43)	0.67
H	P(H1 U H2 U H3 U H4)	2.92