

# An Integrated Model for Optimizing Freight Routes in Intermodal Rail-Road Transportation Networks under Link Disruption

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## Abstract

Today, in most intermodal freight networks, unexpected incidents such as congestion, traffic jams, accidents, natural disasters such as earthquakes and storms, etc., are inevitable. These events can disrupt a route or at a transshipment terminal. A high-reliability transport network is a system that can manage all kinds of disruptions by preventing, absorbing, or mitigating its effects. Effective management of disturbances in transportation networks requires vulnerability analysis and identification of critical infrastructure. In this study, a multi-objective optimization approach is proposed for integrated vulnerability analysis and disruption response planning in intermodal freight networks. In this model, the rerouting decisions are made based on the capacity of existing paths. In the optimization model, the goal is to find a balance between the cost and reliability criteria of the system. The reliability of the system is defined as the probability that a certain amount of the unit will be shipped from the specified destination over a specified time interval to the destination points. The validity of the proposed approach to managing disturbances in road-rail networks has been measured through computational experiments on real instances of Iranian transportation networks. The results show the efficiency and advantage of the integrated model for reducing operating costs and increasing the reliability of freight transport in the intermodal network after the disruption.

**Keywords:** Multi-modal transport, vulnerability assessment; multi-commodity network; disruption management; rerouting

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## 1. Introduction

Today, in most freight networks, unexpected incidents such as congestion, traffic jams, accidents, natural disasters such as earthquakes and storms, etc., are inevitable. These events can disrupt a route or at a transshipment terminal. The incident in the freight networks in the world has caused much damage. Examples of disturbances in shipping networks in the world are described below: For example, an average of 54 million tons of cargo was transported daily through the United States shipping system. The projected freight demand has put significant pressure on public and private infrastructure in the United States, as the various elements of the transportation network have reached their maximum capacity, and this has had the difficulty of operating the transportation system. Due to the earthquake in California in 1994, it is estimated that shipping companies bore up to 1.5 billion \$ due to the failure of the transportation routes caused by the disruption. As another example, the flood in the Mississippi River in 2011 has caused severe disturbances in crucial shipping routes in the state of Arkansas. The occurrence of a storm in 2012 in New York and New Jersey has caused billions of dollars' damage to shipping, bridges, and tunnels. In another example, due to the workers strike at Port Beach, California, in 2012, the daily transfer of goods to \$ 650 million was stopped.

A reliable transport network is a system that can handle all kinds of disruptions by preventing, absorbing, or mitigating its effects. In transport scheduling, providing high reliability and cost-effective services is a complex process that requires optimal decision-making at various tactical and operational levels. Accordingly, the subject matter of the research is how to handle cargo to increase reliability and reducing cost after disruptions. Effective management of disruptions requires recognizing the critical transport infrastructures, known as vulnerability analysis, which guide the transport operators to

prioritize proactive actions by adding redundancy to maximize network reliability. Vulnerability analysis in transportation networks means identifying routes or nodes in a network whose failure has the most significant impact on network performance. For example, link failure is one of the most common sources of disruption in railway networks [Shakibayifar et al., 2017]. In case of a link failure, due to the significant transportation costs, if the optimal route cannot be created on the network, the shipping company is required to pay the penalty. The importance of an infrastructure component in transport systems, e.g., link or node, is typically measured by the incremental cost incurred when that component is disturbed [Khaled et al., 2013].

The occurrence of various types of disturbances in intermodal transport networks in Iran is highly probable, and it is therefore imperative to use disruption management models to effectively respond to problems caused by interruptions in cargo routing processes. This study addresses the integrated vulnerability assessment and disruption response planning in the intermodal transportation network. The overall purpose of the planning process in the proposed model is that the transportation network can respond to a significant percentage of demand with minimal cost after a disruption. In the proposed model for vulnerability analysis, the degree of criticality of an arc in an intermodal transport network is measured by calculating the additional cost for rerouting the cargo and also based on the delay in delivery. The proposed model is capable of examining the feasibility of different scenarios for the re-routing of shipments in the intermodal transportation network. The scheduling of the freight carriers is handled according to customer demand, the remaining capacity of the routes, rail tracks, and stations, as well as the planning horizon constraint.

The rest of the article is organized as follows. The literature review is provided in Section 2. The mathematical formulations, along with the

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assumptions, are given in Section 3. In this section, the developed capacity calculation and optimization approach are described in detail. Numerical results of a case study are presented in section 4. Finally, the conclusion and suggestions for further research are summarized in Section 5.

### 2. Literature Review

Improving the performance of cargo transportation systems is essential as it has a direct influence on service level and reliability indicators. The evaluation criteria and goals that need to be optimized in the distribution of goods and services are diverse. Among these criteria are the total cost, travel time, mileage, network vulnerability, the fleet number required, vehicle delivery coefficient, fuel consumption and pollutant emissions, and etc. In this section, recent developments in disruption response planning of freight transport are reviewed, and the primary research gaps in this area are discussed.

Taxonomy of the related studies is provided in table 1. Vulnerability analysis is usually carried out in two approaches: 1) indicator-based vulnerability assessment based on multi-criteria decision models (MCDM) or 2) Network interdiction models based on optimization methods. Network-based interdiction models can identify the nodes and paths in the network based on criteria such as the greatest of the longest path (worst case) in the network after the disruption event, the least route reliability, and the least profitable exploitation of the network. Two major categories of network interdictions are the path interdiction (PIP) and flow interdiction (FIP) problems [Lim and Smith, 2007]. On the other hand, the application of indicator-based vulnerability analysis approaches is limited because they do not take into account the actual effects of disruptive disruptions because their nature is mostly based on multi-criteria decision-making and ranking methods and thus lacking the necessary performance in dynamic modeling [Whitman et

al., 2017]. Therefore, network interdiction models are more reliable tools for identifying critical network components and vulnerability analysis [Sadeghi et al., 2017]. In a general category, from a methodology perspective, network vulnerability analysis methods fall into one of the following categories:

- Scenario-based approaches that assess the possible consequences of a particular disruption scenario.
- Strategic-oriented approaches that assess scenarios that seek a sequence of hypotheses or disruptive strategies.
- Simulation methods by evaluating a suitable number of disruption scenarios and their probabilistic impacts on the network.
- Mathematical optimization modeling approaches to identify the disruption scenarios that have the most potential impact on network performance.

Kurauchi proposed a method for identifying critical paths according to the network topology. Based on this method, network vulnerability is calculated by counting the number of distinct paths with the acceptable travel time between each OD pair (similar to the concept of k-edge connectivity). In the graph theory, a connected graph is of k-edge type if it remains as a connected graph after the maximum removal of the k paths in the graph. One of the shortcomings of this vulnerability analysis method is that the relationship between supply and demand, as well as the behavior of the passengers, was ignored.[Kurauchi et al. 2009]

According to a study by Chen and Schonfeld, various types of traffic disruptions include traffic congestion, long wait queues and delayed terminals, vehicle failure, unexpected lag along the route, traffic accidents and demand fluctuations. They proposed a method for coping with disorders in transportation scheduling systems in dynamic and randomized environments. When common disturbances, i.e., traffic congestion, vehicle failure, or demand fluctuations, occur in transportation

systems, management should decide, in an optimal manner, which section of the fleet is immediately deployed and which part should be awaited. This fleet control and distribution model is capable of retrieving fleet delays. To solve this problem, a quadratic programming method and hybrid genetic algorithm have been used to minimize the operational costs. [Chen and Schonfeld, 2011]. Huang presented a new decision-making method for dealing with disruption and handling of accidents in freight transport. The first stage of the decision involves predicting the duration of the disturbance events in the shipping process, and then the model decides whether a rescheduling of the system is necessary. In the second stage, an optimization model is proposed to manage disturbances in the transportation network, which is capable of automatically generating solutions and achieving strategies to improve the response to the disorder. [Huang et al. , 2011]. Chen and Miller-Hooks proposed a stochastic programming model for disruption recovery problem in intermodal freight transport. The network resiliency was defined as the capacity of an intermodal freight transportation system to recover from disorders caused by natural disruptive phenomenon or terrorist attacks. The problem was solved using Benders decomposition and column generation techniques. The methodology was implemented on USA freight transportation network, and the result of the response planning model under random link failure was reported. [Chen and Miller-Hooks, 2012 ]. Gedik proposed a two-stage mathematical optimization framework for multi-period railroad rescheduling and rerouting problem under disruptions. The methodology focuses on freight traffic flow in a coal supply chain network. The model first assesses the network vulnerability by determining the critical links, those cause a substantial increase in delay costs, by exploring K-longest paths in the network. Consequently, to find optimal re-routing plan of the carriers, a discreet time-space formulation of the problem

was presented. Sensitivity analysis of several parameters, e.g., capacity and demand levels, was conducted to confirm the validity of the model. [Gedik et al. 2014] Khaled addressed the integrated problem of train formation planning and train routing under disruption in freight railway transport. For this purpose, a network vulnerability assessment was carried out to quantify the criticality of a node or a link by approximating the incremental cost imposed on the transport system when a failure occurs. The disruption response planning model accounts for the traffic congestion caused by the disruption. In this model, freight traffic flow is re-routed to minimize the total cost (traveling and train make-up costs) concerning the capacity of links and yards. Real-world instances of U.S. railroad were solved efficiently by a heuristic algorithm. [Khaled et al. 2015] Van Riessen proposed a decision model for analyzing the effect of disturbances in the container transport network between Rotterdam, Netherlands, and several domestic terminals in northwest Europe. A new model for container allocation was proposed. This model was used to determine the effect of three main types of traffic disruption, including the early arrival of vehicles, delays in vehicle dispatch, and cancellation of internal transportation services on network performance. The impact of a disorder has been measured in two ways: (1) measuring the additional cost of updating the plan, and (2) measuring the difference between the full cost of the update and the cost of the local modification in the plan under disruptions. Accordingly, the impact of transport disturbances on all transportation services has been evaluated on a case study. [Van Riessen et al. 2015]

Azad proposed a risk-oriented disruption management model for railway networks. Disruption was defined as an external factor affecting the capacity of the system, e.g., railcar malfunction. The proposed methodology uses pre- and post-disruption mitigation strategies to minimize the total operating cost of the

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transport system for meeting the demand. The risk mitigation strategies involve using extra capacity, e.g. hiring rail segments maintained by other competing rail operators or design new train schedules. The proposed model was implemented on a case study adopted from US railway network. The outcomes indicated that by accepting a small increase in transportation costs for constructing redundant links around critical points, the network resiliency could be improved significantly. [Azad et al. 2016]. Bababeik presented a network flow model for vulnerability analysis under multi-link failure. The model was based on a time-space network flow formulation with the capability of identifying the most vulnerable links. The methodology was validated using a hypothetical rail network with 9 nodes, 19 links, and 3 pairs of OD. A heuristic method was proposed to solve the network flow interdiction problem with a fractional enumeration of system components. The validity of the model and solution approach was confirmed by comparing to the full enumeration method. [Bababeik et al. 2017a] Xu presented two alternative bi-level mathematical optimization formulations for network vulnerability assessment under multiple link failures. The first model was based on the capacitated maximum flow formulation, and the second was formulated as a cost-oriented longest path problem. The optimization models were used to obtain upper and lower bounds for the vulnerability level of the transport system. The methodology takes the advantages of partial search instead of performing a full enumeration, thus decreasing the computational complexity of the problem. [Xu et al. 2017] Chen developed a scenario-based formulation of container port resiliency assessment, taking into account the recovered capacity of the seaport. The optimization model determines the number of containers transported and decides which recovery action must be selected to maximize the container flow under uncertain disruptive scenarios. The definition of transport resiliency

was developed in the context of the seaport, and at that point, a mixed-integer programming model was presented to quantify the port operation resilience given shippers. The validity of the model was confirmed by using a real case of Gothenburg Port. [Chen et al. 2017]

Cantillo proposed a mathematical modeling framework for evaluating the vulnerability of humanitarian transport networks under natural catastrophe events. The proposed response planning model could recognize critical links based on economic analysis. The model minimizes the distribution costs and the negative impacts caused by the supply delays. The methodology was applied to a real case adopted from the region of Colombia when an earthquake occurred in 1999. [Cantillo et al. 2018] Khanmohamadi presented a vulnerability and routing analysis model for the transport of hazardous goods in the rail network. The approach was tested using a case study on freight transport in Texas, Illinois, USA. The purpose of this article was to provide a vulnerability analysis method to find critical elements along the railway's route, especially about the transport of hazardous goods. In this study, ALOHA and ArcGIS software was used to investigate security vulnerabilities with population estimates, and to affect the transportation infrastructure due to malicious terrorist attacks. Using the demographic layers in the GIS software, the number of people living in the study area and exposed to the attack were identified. Then, a game theory approach has been used to model the interactions between terrorist strategies and transport operators. [Khanmohamadi et al. 2018]

### **3. Mathematical Model**

In this section, the problem, input parameters, and the model's constraints are described in details, together with the related notations. The mathematical optimization model is developed to minimize the cost of rerouting in an intermodal freight network and at the same time maximize the network throughput

simultaneously. It is following the situation in Iranian intermodal transport network, where the freight transport is generally vulnerable to link disruptions caused by a natural disaster, e.g. flood and earthquake. The purpose of the proposed network interdiction model is to identify the most critical components of the network using optimization approaches so that components whose failure seriously damage the system are determined. A set of origin-destination (OD) pairs and paths connecting each OD are assumed. The network includes a set of nodes, a set of link, and a set of intermodal terminals that allow change of transport mode. The number of multimodal containers defines the demand for cargo between different origin-destination. The optimization model decides which intermodal node is designated for different cargo handled between OD pairs. The magnitude of the disruption is measured by the number of link failures in the transport network. The proposed model is capable of evaluating different rerouting plan for traffic flows on a degraded intermodal network. Carriers are scheduled according to customer demand, track and node capacity as well as planning horizons. Traffic routing and scheduling are also carried out according to the structure of a transport network with available routes existing after the disruption.

### 3.1. Notations

The notations of parameters and sets along with the notations of decision variables are defined in table 2, table 3 and table 4, respectively. A multi-commodity intermodal transport network is assumed where a set of nodes and a set of arcs are given figure 1. A freight carrier service is defined as an activity that involves passing through a series of nodes, i.e., shippers, terminals and receivers, and segments between a predefined origin and destination. The delay in service is due to the limited capacity of the siding tracks, limited capacity of the road or a limited number of the rail tracks in stations.

### 3.2. Mathematical Formulation

The proposed model is based on the assumptions of the time-space network model and is used to manage cargo handling over a specified period in a disruption condition. This model is based on the minimum-cost flow problem (MCFP). The problem of network flow with the least cost is a fundamental problem in computer science and operational research. This problem is one of the most fundamental network flow models and is a basis of many applications of modeling and development of solution algorithms in transportation science. In the MCFP model, several vertices and paths are defined. The minimum and maximum capacity and the cost of transporting a unit of goods in each path are given. The goal is to find routes for the transfer of goods from origin to destinations with the lowest cost and concerning the capacity constraints of the routes.

In this section, an optimization model is proposed, which includes the integration of routing problem and scheduling of carriers in a single model. At the first level of the optimization model, it identifies those primary network paths that have the most significant impact on re-routing costs when the disruption occurs. At the first level of the model, some arcs are disrupted, and it is assumed that these arcs remain inaccessible until the end of the planning horizon. It is also assumed that the demand is non-elastic, so it does not change after the disruption (the load demand does not react to the disorder). This assumption is reasonable in freight transport systems. While forecasting and modeling the behavior of passengers under disruptive conditions is much more complicated and requires modeling with the possibility of choosing a transportation mode. In this research, the analysis of the behavior of travelers under uncertainty has not been addressed.

On the second level, the optimal routing and scheduling of carriers in the remaining network with existing nodes and access paths after the disruption is accomplished through a MILP

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model. In this model, low-cost paths are determined according to the planning requirements and to improve the service level. In the second level of the optimization model, disruption management is performed by rerouting the cargo on the intermodal network to minimize routing costs on the set of generated test instances derived from the vulnerability model.

**Table 1. Taxonomy of the related studies**

Reference	Transport modes	Disturbance	Modeling approach	Vulnerability Analysis approach	Contribution	Criteria of Vulnerability Analysis	Application	Disruption response planning
Ip and Wang, 2011	Rail	Node or link failure	Graph theory	Indicator Analysis	an optimization framework for network resiliency analysis	Average weighted number of paths with sufficient reliability	Sichuan China Rail Network with 71 nodes, 109 links	-
Chen and Miller-Hooks, 2012	Rail and road	Random corrupted links due to terrorist attack or flood	Scenario-driven stochastic programming	-	network resiliency analysis	Demand ratio after disruption	USA Transportation Network	√
Pant et al., 2014	Marine, Rail, and road	Breakdown of railways and roads leading to the port	Measuring resilience and their application in container terminals	Stochastic model	Providing novel time-dependent indicators of resiliency	Time to achieve $\alpha\%$ of system resilience	Tulsa Port of Catoosa, Oklahoma, USA	-
Gedik et al., 2014	Rail	Capacity disruption	Two-stage MIP	$K$ - <sup>th</sup> shortest path algorithm	Bi-level optimization for vulnerability assessment	re-routing cost	coal supply chain	√
Ouyang et al., 2015	Rail and air	Disturbances and accidental failure	Genetic Algorithm	Complementary strength analysis	Identify key time intervals for critical network components	Node availability	China Transportation Network	-
Khaled et al., 2015	Rail	links and yards failures	Heuristic method	system-wide optimization model	Novel mathematical model and solution technique to vulnerability assessment taking into account the congestion and capacity	the incremental cost of rerouting	USA freight network involves 200 nodes and 478 links	√
Azad et al., 2016	Rail	Link failure	optimization-based methodology	Indicator Analysis	pre- and post-disruption analysis	post-disruption costs increase	Midwest United States freight network	√

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Reference	Transport modes	Disturbance	Modeling approach	Vulnerability Analysis approach	Contribution	Criteria of Vulnerability Analysis	Application	Disruption response planning
Whitman et al., 2017	rail	Link failure	TOPSIS	Scenario-based Network interdiction model	The CI index for each component of the single-product shipping networks	Unsatisfied demand and the capacity utilization of more than 90% of the links	Swedish Railway	-
Bababeik et al., 2017a	Rail	Multiple link failure	a time-space network flow model	flow interdiction	Heuristic method	Routing cost	hypothetical network with 9 nodes, 19 links, and 3 pairs of OD	√
Bell et al., 2017	Road	Link failure	Graph theory	Capacity weighted spectral analysis	Spectral zoning model with weight significance related to the capacity for finding bottlenecks in transport networks	bottlenecks	hypothetical network with 5 nodes, 7 links	-
Chen et al., 2017	Railroad	Terrorist attacks, natural disasters	MIP	Optimization	Development of a model for measuring the flexibility (resilience) of a container transport network	Reliability of the paths connected to each node	Gothenburg port	√
Calatayud et al., 2017	Maritime	Connection path disruption in liner shipping	Optimization	Indicator Analysis	multiple complex network analysis	Network topological indices	North American Shipping	
Bababeik et al., 2017b	Rail	Link failure	Bi-level programming	flow interdiction	Presenting a bi-level model for rail network vulnerability analysis	The extra cost of rerouting	Iranian railway network	√
Cantillo et al., 2018	Road	Natural disasters (earthquakes) and multiple link failures	Multinomial Logit	Indicator Analysis	Vulnerability Assessment Model for Transportation Network to identify critical links	Economic analysis and logistics costs of distribution operations	The caffeine production area of Colombia	√

<b>Reference</b>	<b>Transport modes</b>	<b>Disturbance</b>	<b>Modeling approach</b>	<b>Vulnerability Analysis approach</b>	<b>Contribution</b>	<b>Criteria of Vulnerability Analysis</b>	<b>Application</b>	<b>Disruption response planning</b>
Present study	Rail and road	Link failure	Mathematical modeling	Flow interdiction model	A multi-objective optimization model for vulnerability assessment	cost of delay and rerouting	Iranian transportation network	√

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**Table 2. Notation of indices and sets defined in the mathematical model**

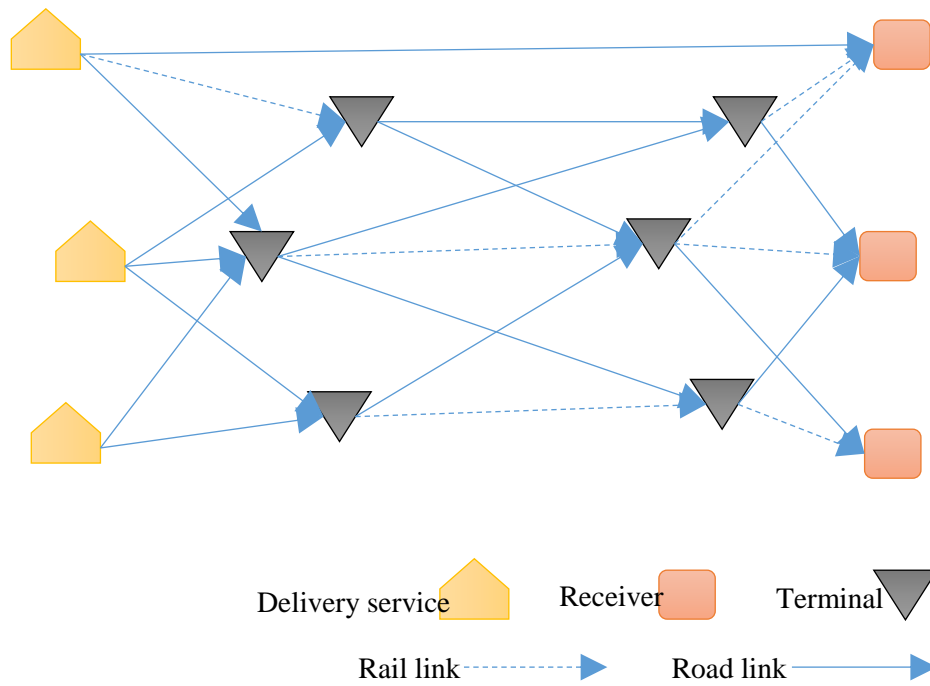
Symbol	Definition
$K$	Set of cargoes which corresponds to the different commodities
$N$	The set of nodes which corresponds to the shippers, receivers, or terminals
$A_1$	Set of road links connecting the nodes
$A_2$	Set of railway links connecting the nodes
$A$	The set of all links in the intermodal transport network ( $A=A_1 \cup A_2$ )
$S$	The set of intermodal termini which allow mode change
$H$	The set of road intersections
$R$	The set of rail intersections
$C$	Set of OD matrices pairs
$P^c$	Set of paths connecting $c^{\text{th}}$ OD matrix
$k$	Index of the cargo type, $k \in K$
$i, j, s$	Index of the nodes, $i, j, s \in N$
$c$	Index of an OD matrix, $c \in C$
$o_c$	Index of the start node of an OD matrix $c \in C$
$\vartheta_c$	Index of the end node of an OD matrix $c \in C$

**Table 3. Notation of the model parameters**

Symbol	Definition
$d_{ck}$	Original demand for cargo $k \in K$ between OD pair $c \in C$
$n$	Number of interdicted links which represents the magnitude of the disruption
$t_{ij}$	Travel time on road link $(i, j) \in A_1$
$\tilde{t}_{ij}$	Travel time on railway link $(i, j) \in A_2$
$\psi$	The penalty cost for unsupplied freight demand per unit
$\beta_{ijk}$	The cost of transporting a unit of cargo $k \in K$ by truck in the link $(i, j) \in A_1$
$\tilde{\beta}_{ijk}$	The cost of transporting a unit of cargo $k \in K$ by rail in the link $(i, j) \in A_2$
$\beta_{sk}$	The cost of transporting a unit of cargo $k \in K$ in multimodal terminal $s \in S$
$Q_{ij}$	The maximum carrying capacity of road link $(i, j) \in A_1$
$\tilde{Q}_{ij}$	The maximum carrying of railway link $(i, j) \in A_2$
$Q_s$	The maximum transferring carrying of multimodal terminal $s \in S$
$t_s$	The service time in multimodal terminal $s \in S$
$T_{kc}$	The period defined for on-time delivery of cargo $k \in K$ between OD pair $c \in C$
$M$	A sufficiently large positive number

**Table 4. Notation of the decision variables**

Symbol	Definition
$\pi_{ijc}$	=1 link $(i, j) \in A$ between OD pair $c \in C$ is interrupted; 0 otherwise (network traffic interdiction variable)
$x_{ijkc}$	The percentage of cargo $k \in K$ carried out on road link $(i, j) \in A_1$ between OD pair $c \in C$
$\tilde{x}_{ijkc}$	The percentage of cargo $k \in K$ carried out on railway link $(i, j) \in A_2$ between OD pair $c \in C$
$u_{kc}$	Unsupplied demand for cargo $k \in K$ between OD pair $c \in C$
$F_{skc}$	The percentage of cargo $k \in K$ between OD pair $c \in C$ transported at intermodal terminus $s \in S$
$Y_{skc}$	= 1 if multi-modal terminal $s$ is designated for commodity $k \in K$ between OD pair $c \in C$ , = 0 otherwise
$\delta_{ijkc}$	= 1 if road link $(i, j)$ transports the flow of commodity $k \in K$ between OD pair $c \in C$ , = 0 otherwise
$\tilde{\delta}_{ijkc}$	= 1 if railway link $(i, j)$ transports the flow of commodity $k \in K$ between OD pair $c \in C$ , = 0 otherwise



**Figure 1. The multi-commodity freight transportation network considered in this study**

$$\text{Minimize } Z_1 = \sum_{c \in C} \sum_{k \in K} d_{kc} \left( \sum_{(i,j) \in A_1} \beta_{ijk} * x_{ijkc} + \sum_{(i,j) \in A_2} \tilde{\beta}_{ijk} * \tilde{x}_{ijkc} + \sum_{s \in S} \beta_{skc} * F_{skc} \right) + \sum_{c \in C} \sum_{k \in K} \psi * u_{kc} \quad (1)$$

$$\text{Maximize } Z_2 = \min_{k \in K, c \in C} \left\{ \sum_{(i,j) \in A} d_{kc} * x_{ijkc} + d_{kc} * \tilde{x}_{ijkc} \right\}$$

s.t.

$$\sum_{(i,m) \in A_1} x_{imkc} - \sum_{(m,i) \in A_1} x_{mikc} = \begin{cases} 1 & i = o_c \\ -1 & i = \theta_c \\ 0 & \text{otherwise} \end{cases}, \quad i \in H, k \in K, c \in C \quad (2)$$

$$\sum_{(i,m) \in A_1} x_{o_c, m, k, c} = \sum_{(m,j) \in A_1} x_{m, \theta_c, k, c}, \quad k \in K, c \in C \quad (3)$$

$$x_{imkc} \leq \delta_{imkc}, \quad \forall (i, m) \in A_1, \quad k \in K, c \in C \quad (4)$$

$$x_{mikc} + \delta_{imkc} \leq 1, \quad \forall (m, i) \in A_1, \quad k \in K, c \in C \quad (5)$$

$$\sum_{(i,m) \in A_1} x_{imkc} \geq M * \sum_{(m,i) \in A_1} x_{mikc}, \quad i \in o_c, k \in K, c \in C \quad (6)$$

$$\sum_{(i,n) \in A_2} \tilde{x}_{inkc} = \sum_{(n,j) \in A_2} \tilde{x}_{nikc}, \quad i \in R, k \in K, c \in C \quad (7)$$

$$\sum_{(s,m) \in A_1} x_{smkc} - \sum_{(m,s) \in A_1} x_{mskc} = \sum_{(n,s) \in A_2} \tilde{x}_{nsmc} - \sum_{(s,n) \in A_2} \tilde{x}_{snkc}, \quad s \in S, k \in K, c \in C \quad (8)$$

$$\left| \sum_{(s,n) \in A_2} \tilde{x}_{snkc} - \sum_{(n,s) \in A_2} \tilde{x}_{nsmc} \right| \leq M * Y_{skc}, \quad s \in S, k \in K, c \in C \quad (9)$$

$$\left| \sum_{(s,m) \in A_1} x_{smkc} - \sum_{(m,s) \in A_1} x_{mskc} \right| \leq F_{skc}, \quad s \in S, k \in K, c \in C \quad (10)$$

$$\sum_{(i,j) \in (A_1 \cap P)} \delta_{ijkc} * t_{ij} + \sum_{(i,j) \in (A_2 \cap P)} \tilde{\delta}_{ijkc} * \tilde{t}_{ij} + \sum_{s \in (S \cap P)} Y_{skc} * t_s \leq T_{kc}, \quad p \in P^c, k \in K, c \in C \quad (11)$$

$$\sum_{c \in C} \sum_{k \in K} d_{kc} * x_{ijkc} \leq Q_{kc}, \quad (i, j) \in A_1 \quad (12)$$

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$$\sum_{c \in C} \sum_{k \in K} d_{kc} * \tilde{x}_{ijkc} \leq \tilde{Q}_{kc}, \quad (i, j) \in A_2 \quad (13)$$

$$\sum_{c \in C} \sum_{k \in K} d_{kc} * F_{skc} \leq Q_s, \quad s \in S \quad (14)$$

$$d_{kc} \left( 1 - \sum_{i \in H} x_{ijkc} \right) = u_{kc}, \quad k \in K, c \in C, j = \vartheta_c \quad (15)$$

$$x_{ijkc} \leq \delta_{ijkc}, \quad (i, j) \in A_1, k \in K, c \in C \quad (16)$$

$$\tilde{x}_{ijkc} \leq \tilde{\delta}_{ijkc}, \quad (i, j) \in A_2, k \in K, c \in C \quad (17)$$

$$F_{skc} \leq Y_{skc}, \quad s \in S, k \in K, c \in C \quad (18)$$

$$\delta_{ijkc} + \tilde{\delta}_{ijkc} \leq 1 - \pi_{ijc}, \quad (i, j) \in A, k \in K, c \in C \quad (19)$$

$$\sum_{(i,j) \in A_1} \sum_{c \in C} \pi_{ijc} = n \quad (20)$$

$$x_{ijkc} \in [0,1], \tilde{x}_{ijkc} \in [0,1], F_{skc} \in [0,1], Y_{skc} \in \{0,1\}, \delta_{ijkc} \in \{0,1\}, \tilde{\delta}_{ijkc} \in \{0,1\} \quad (21)$$

$$u_{kc} \in Z^+ \quad (22)$$

The first objective function (Z1) aims to minimize the total cost of handling cargo in a disrupted network. The cost function comprises of the transport rerouting cost on the road and railway links, the transmission cost at terminal nodes due to mode change, and the penalty cost for unsupplied cargo demands as a result of link disruption. The unsupplied cargo demands are supposed to take integer values as the freight demands are expressed in terms of the number of containers. The second objective function (Z2) seeks to maximize the minimum throughput of the network over different commodities ( $k \in K$ ) between OD pairs. Constraints (2) guarantee the preservation of cargo flow at highway nodes.

Constraints (3) ensures the flow of cargo at origin and destination nodes. Constraints (4) indicate if there is not any flow on a road link, then the percentage of cargo carried out on this link becomes zero. Constraints (5) define the logical relationship between the indicator variables of flow percentage of cargo and its allocation to road links. Constraints (6) ensure the flow conservation at an origin node. Likewise, constraint (7) guarantees flow preservation at rail intersections nodes. Constraints (8) and (9) indicate the preservation of cargo flows at multi-modal terminuses whether or not a terminal is allocated. Constraint (8) indicates the preservation of cargo flows in the case when a terminal is

designated. Also, constraint (9) show that the cargo flow is preserved if the terminal is not designated. Constraints (10) define the percentage of cargo transferred at multi-modal terminal nodes between several OD pairs. Constraint (11) defines the period for the delivery of cargo. Constraints (12) define the carrying capacity limit for the cargo assigned to highway paths. Likewise, constraints (13) ensure that the total cargo allocated to a railway link does not exceed its maximum capacity. Also, constraints (14) indicate that the cargo flow handled by a multi-modal terminal does not exceed the maximum transfer capacity. Constraint (15) calculates the unsupplied cargo demand due to the link disruption. Constraints (16) define the logical relationship between the percentage of cargo carried out on road link and the binary variable associated with it. Likewise, constraints (17) impose the logical relationship between the cargo routing variables. Also, constraints (18) ensure that the percentage of cargo between OD pairs transported at the multi-modal terminus is zero if the terminal is not selected. Constraint (19) ensures that in case of an interruption on the arc, no carriers pass through it. Constraint (20) defines the number of paths in the network that are interdicted due to disruptions. Finally, constraints (21) and (22) define the domain and type of decision variables. To solve the above multi-objective optimization problem, an improved version of

epsilon constraint-handling method is proposed.

#### 4. Multi-objective Optimization Approach

Multi-objective optimization is one of the most widely used research areas among optimization topics, which also have different applications in transport planning problems. In this context, a set of objective functions are denoted by  $f_i(\mathbf{x}), i = 1, 2, \dots, n$ . The general form of the constrained multi-objective optimization problem is as follows:

$$\begin{aligned} & \text{Minimize } F(\mathbf{x}) = \{f_1(\mathbf{x}), \dots, f_n(\mathbf{x})\} \\ & \text{s. t.} \\ & g(\mathbf{x}) \leq 0, \quad h(\mathbf{x}) = 0 \\ & \mathbf{x} \in R \end{aligned} \tag{23}$$

Various algorithms have been used to solve a bunch of multi-objective optimization problems. A fundamental concept called "dominance" has led the design of different multi-objective optimization algorithm to achieve an optimal frontier. According to the concept of dominance, the solution  $x_i$  dominates the solution  $x_j$  if the following two conditions are satisfied:

1. The solution  $x_i$  is not worse than any other objective functions compared with  $x_j$ .
2. The  $x_i$  solution is better than solution  $x_j$  at least for one of the objective functions.

With regard to the concept of dominance, the process of finding the optimal solution (if any) will lead to Pareto optimality. So far, several methods have been proposed for solving multi-objective optimization problems. In general, they can be divided into two categories:

- Standard methods (also called decomposition methods) that often transform the multi-objective problem to a single objective optimization model.
- Evolutionary methods which solve the multi-objective optimization problem to find the Pareto front.

In this study, an improved variation of the  $\epsilon$ -constraint method called AUGMECON2 is utilized to solve the multi-objective

vulnerability assessment model. The AUGMECON2 is implemented using GAMS programming language system. The notation of the augmented  $\epsilon$ -constraint method is given in Table . In this method, one of the objective functions is nominated as the primary objective to be optimized, and the other objectives are the constraints which have an upper bound for each of them [Mavrotas and Florios, 2013]. AUGMECON2 is the second version of the method introduced by Mavrotas (2009). This method has several advantages, including the reduction in the computation effort, mainly when the problem contains integer variables, and the model is non-convex. AUGMECON2 was demonstrated to be useful in multi-objective integer programming problems where the Pareto-optimal set is limited and countable. It generates the exact Pareto-optimal set by adequately tuning parameters and avoiding the generation of weakly Pareto optimal solutions that accelerate the optimization process.

The augmented  $\epsilon$ -constraint method consists of the following steps: In the first step, one of the objectives ( $Z_j$ ) is selected as the primary objective function to be maximized, and the other objective functions ( $k = 2, 3 \dots, p$ ) are moved into constraints. Afterward, a payoff table is constructed by the optimization of the individual objective functions. The details of calculating the payoff table for a multi-objective optimization model can be found in Mavrotas (2009). Here, the gap between the upper and lower objective values for each objective function is called the range of the objective function. In the second step, each objective function is divided into  $q_k$  equivalent intervals with  $q_k - 1$  in-between grid points. Accordingly, the total number of the runs required is  $\prod_{k=2}^p (q_k + 1)$ . In the third step, the right-hand side ( $\epsilon_k$ ) of the  $k$ th objective function changes parametrically and the resulting augmented  $\epsilon$ -constraint models are solved for each value of  $\epsilon_k$ . The procedure repeats until the Pareto optimal set is obtained.

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$$\text{maximize } Z_j(x) + \text{eps} * \sum_{k \neq j} \frac{s_k}{r_k} \quad (24)$$

s.t.

$$Z_k(x) + s_k = \varepsilon_k, \quad \forall k \neq j \quad (25)$$

$$x \in X, \quad s_k \in \mathbb{R}^+ \quad (26)$$

**Table 5. The notation of the augmented  $\varepsilon$ -constraint method**

Parameter	Description
$s_k$	Slack variables for the $k^{\text{th}}$ objective function
$r_k$	The range for the $k^{\text{th}}$ objective function
$step_k$	Discretization step of the $k^{\text{th}}$ objective
$LB_k$	The lower bound of the $k^{\text{th}}$ objective
$n_p$	Number of Pareto optimal solutions

Where, *eps* is an adjustable parameter being commonly between [10<sup>-6</sup>, 10<sup>-3</sup>]. The  $\varepsilon$ -constraint method carries out a kind of lexicographic optimization to find the Pareto optimal solutions. In AUGMECON2, the objective function is modified as follows:

$$\text{maximize } Z_1(x) + \text{eps} * \left( \frac{s_2}{r_2} + 10^{-1} * \frac{s_3}{r_3} + \dots + 10^{-(p-2)} * \frac{s_p}{r_p} \right) \quad (27)$$

The discretization step for the  $k^{\text{th}}$  objective function is given by  $step_k = \frac{r_k}{q_k}$ . The right-hand side of the  $k^{\text{th}}$  constraint of the  $t^{\text{th}}$  iteration, in the specific objective function, is also specified as:

$$\varepsilon_{kt} = LB_k + t * step_k \quad (28)$$

The slack variable corresponding to the inmost objective function (here  $p = 2$ ) is checked iteratively to find the redundant iterations. For this purpose, the bypass coefficient ( $b$ ) is considered as the integer part of the ratio  $s_2 / step_2$ . The bypass parameter specifies the number of consecutive redundant iterations. When the slack variable  $s_2$  is greater than the step size, i.e.  $step_2$ , it is inferred that in the next iteration the same solution will be achieved with the only difference being the surplus variable which will have the value  $s_2 - step_2$ .

## 5. Solution Algorithm

In this study, the intermodal rail and road re-routing decisions in a supply chain network are optimized using a K-th longest path algorithm which enables to enumerate all possible routes between nodes. The K-th longest path routing algorithm is an extension algorithm of the longest path routing algorithm in a given transport network. The proposed algorithm searches for all the longest paths in increasing order of rerouting cost.

In this study, the algorithm search for k longest paths to build new path based on the degree of associability between each path and rerouting cost, and stops constructing when the degree of this ratio exceeds its threshold. The pseudocode of the K-th longest path for finding the vulnerable link the road-rail network is presented in Table 6. The K-th longest path algorithm has the following notations: let  $G(V, E)$  represents a weighted directed graph, with a set of vertices  $V$ , corresponds to the railway's nodes, road intersections, or terminals, and set of directed edges  $E$ , which correspond to the rail or road links. Suppose  $w(u, v)$  characterizes the cost of straight arc from node  $u$  to node  $v$ . Links that do not satisfy constraints on the longest path are removed from the underlying graph. Let  $a$  and  $b$  denote the origin and destination nodes, respectively. Parameters  $K$  and  $Lu$  represent the total number of found longest paths and an indicator of a path from node  $a$  to  $u$ , respectively. To facilitate the search process, a data structure,  $S$ , is defined, which includes the generated paths.  $Lab$  represents the set of longest paths from node  $a$  to  $b$ . Likewise, parameter  $\mu u$  denotes the number of longest paths obtained to node  $u$ .

## 6. Result and Discussion

To illustrate an application of the proposed model, this paper considered a multi-modal freight system for the Islamic Republic of Iran. In this section, the statistical results of the vulnerability levels of rail-road intermodal

elements are also reported. Impacts of disruptions are calculated in terms of extra rerouting costs and delay costs. Several test examples of a freight road-rail transportation system are used to characterize the critical disruption scenarios associated with the tactical and operational level of infrastructure vulnerability. The analysis includes the advantages of rerouting decisions on the reduction of delay costs and the rate of recurrence for interdictions of infrastructure elements in the system. The case study is defined on a simplified road-rail network with maximum sizes of  $|N|=25$  and  $|A|=45$ . The test distances are taken from primary rail-road network data available on Google Map. Dimensions of the instances used to verify the solution approaches are summarized in Table . In overall, 30 test problems in three categories,

small to large size, are generated. Table reports the problem sizes in terms of the number of nodes and the number of links as well as the number of interdicted links. All the numerical experiments are performed on a laptop with an Intel(R) Core(TM) i7-7500u CPU with 2.70 GHz processor and 18 gigabytes of RAM. The mathematical model is solved using Branch and bound (B&B) and Branch and cut (B&C) algorithms embedded in CPLEX 12.6.

The characteristics of the most vulnerable links obtained by the mathematical optimization model are provided in Table . This table reports the set of most vulnerable links that are obtained for each test problem. Given the scenarios generated in Table , the mathematical optimization model is solved to find the minimum cost rerouting plan for the underlying freight transport network.

**Table 6. The pseudocode of the K-th longest path for finding the vulnerable link the road-rail network**

K-th longest path (L, K, S)				
L =empty,				
$\mu_u = 0$ , for all u in V				
INSERT path $L_a = \{a\}$ into S with cost 0				
WHILE S is not empty and $\mu_t < K$				
let $L_u$ be the longest cost path in S with cost C				
$S = S - \{L_u\}$				
$\mu_u = \mu_u + 1$				
If $u = b$ then $L_{ab} = L_{ab} \cup \{L_u\}$				
If $\mu_u \leq K$ then for each node v neighboring to u				
SUPPOSE $L_v$ be a new route with cost $C + w(u, v)$ constructed by merging the arc (u, v) to path $L_u$				
ADD $L_v$ into S				
RETURN L				

**Table 7. Dimensions of the instances used to verify the solution approaches**

Test problem No.	Problem size	Number of nodes ( $ N $ )	Number of links ( $ A $ )	Number of interdicted links (n)
1	Small	4	10	1
2	Small	4	10	1
3	Small	5	12	1
4	Small	5	12	2
5	Small	5	14	2
6	Small	5	14	2
7	Small	6	15	2
8	Small	6	15	2
9	Small	6	18	2

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Test problem No.	Problem size	Number of nodes ( $ N $ )	Number of links ( $ A $ )	Number of interdicted links ( $n$ )
10	Small	6	19	2
11	Medium	8	24	1
12	Medium	8	25	1
13	Medium	8	25	1
14	Medium	9	28	2
15	Medium	9	28	2
16	Medium	9	30	2
17	Medium	12	30	2
18	Medium	12	30	2
19	Medium	12	32	3
20	Medium	12	32	3
21	Large	15	35	1
22	Large	15	35	1
23	Large	18	35	2
24	Large	18	36	2
25	Large	18	36	2
26	Large	18	40	2
27	Large	20	40	2
28	Large	20	45	2
29	Large	25	45	3
30	Large	25	45	3

**Table 8. The characteristics of the most vulnerable links obtained by the mathematical optimization model**

Test problem No.	Most vulnerable links	Number of interdicted links ( $n$ )
1	{1-4}	1
2	{2-4}	1
3	{1-3}	1
4	{2-5,1-3}	2
5	{1-6,2-3}	2
6	{2-5,4-6}	2
7	{4-6,1-5}	2
8	{1-6,2-5}	2
9	{5-6,1-3}	2
10	{1-2,4-6}	2
11	{3-6}	1
12	{4-5}	1
13	{2-4}	1
14	{1-5,7-9}	2
15	{1-6,2-11}	2
16	{5-9,3-10}	2
17	{5-8,8-9}	2
18	{2-5,4-12}	2
19	{5-10,2-12,8-14}	3
20	{2-4,6-7,10-14}	3
21	{5-13}	1
22	{3-14}	1

Test problem No.	Most vulnerable links	Number of interdicted links (n)
23	{6-15,9-18}	2
24	{2-10,1-13}	2
25	{9-11,3-17}	2
26	{2-10,16-19}	2
27	{12-15,9-20}	2
28	{16-18,4-18}	2
29	{5-10,2-12,3-4}	3
30	{5-10,2-12,3-4}	3

For a better illustration of the outputs, the result of numerical examples is summarized in Table . The value of the objective functions, optimality gap% and the CPU time, are

presented in this table. The computational results confirm that, for each problem instance, an optimal or a near to optimal solution are obtained in a reasonable time.

**Table 9. The computational result of numerical examples**

Test problem No.	$Z_1 (\times 10^6)$	$Z_2$	CPU time (minutes)	Optimality gap% ( $Z_1$ )	Optimality gap% ( $Z_2$ )
1	3.90	182.83	4.57	0.00%	0.00%
2	15.54	34.78	10.49	0.00%	0.00%
3	19.07	925.64	12.67	0.00%	0.00%
4	19.90	11.73	38.31	0.00%	0.00%
5	24.72	42.62	52.82	0.00%	1.17%
6	57.68	137.05	84.33	0.76%	1.20%
7	59.40	874.19	89.32	1.06%	1.70%
8	62.07	239.62	115.05	1.32%	1.72%
9	64.35	738.91	115.76	1.57%	1.85%
10	76.82	459.28	120.29	1.62%	2.32%
11	81.49	163.40	135.53	1.96%	2.90%
12	102.29	98.39	183.85	1.98%	3.03%
13	103.69	618.16	191.04	2.17%	4.08%
14	105.48	96.76	191.32	2.45%	4.66%
15	110.22	983.34	219.87	2.69%	4.88%
16	111.05	157.46	221.45	2.72%	5.35%
17	117.40	447.91	230.77	3.32%	6.00%
18	122.28	854.90	233.85	4.37%	6.38%
19	129.21	131.06	252.24	4.57%	6.41%
20	130.20	921.05	263.61	4.70%	6.53%
21	133.47	184.22	280.60	4.72%	6.60%
22	137.73	567.40	295.21	5.67%	7.16%
23	141.93	626.91	318.40	5.75%	8.35%
24	144.79	128.67	343.44	6.69%	8.43%
25	145.14	34.73	346.03	6.82%	8.55%
26	145.51	768.41	355.78	7.79%	10.62%
27	145.78	962.12	359.36	8.24%	10.70%
28	146.55	507.62	379.09	8.38%	10.96%
29	149.60	626.89	390.57	8.56%	11.06%
30	163.96	853.87	395.17	9.09%	11.33%

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For each test problem, the optimality gap percentage (optimality gap% column) is calculated by equation (29). It refers to the relative difference between the lower bound (LB) and upper bound (UB) obtained from the CPLEX solver.

$$\text{Optimality gap\%} = \frac{(\text{UB} - \text{LB})}{\text{LB}} * 100 \quad (29)$$

According to the obtained result, the optimality gaps% for the first and second objective functions are about 3.63% and 5.13%, on average, which indicates the efficiency of the proposed optimization model for obtaining acceptable solutions in reasonable computational time. The results obtained can be interpreted as demonstrating the present model can solve large-sized problem instances efficiently. Due to time constraints, the near-optimal approach is applicable in practice, and one can take advantage of the proposed modeling approach to obtain an acceptable solution in a reasonable time. Alternatively, the average CPU time confirms the applicability of the proposed mathematical formulation.

The cost components vs the number of link interdictions are illustrated in Figure . As can be seen, the cost components change significantly as the number of interdicted links in the network is increased. However, delay costs increase dramatically compared to the rerouting cost as more links are interdicted. The Pareto optimal solutions generated by AUGMECON2 for test problems is depicted in Fig. Each Pareto optimal solution is associated with a single no dominated solution generated for optimizing freight routes in intermodal rail-road transportation networks under link disruption.

### 7. Summary and Conclusions

Given the growing demand for freight and the social and economic consequences of unforeseen events, it is necessary to take measures to increase readiness and reduce the costs of the transportation system at the time of operation. To cope with unexpected incidents

such as accidents, natural disaster, a vulnerability assessment is necessary to quantify the bottleneck points in the network. This study develops a multi-objective optimization model for carrier intermodal freight routing in the case of link disruption. The proposed mixed-integer linear programming model explicitly considers discrete unit flows of carriers on the intermodal road-rail network with time-varying demand and capacities. The problem underlying in this study is to optimize rerouting decisions for carrier services in a road-rail intermodal transport network. For numerical experiments, several problem instances of different sizes and characteristics are designed. The CPLEX solver solves the optimization model, and the best-found solutions are reported. Given the disturbance scenarios generated by the vulnerability assessment model, the rerouting decisions are designed based on the available capacity of existing paths. Real instances of Iranian road-rail networks test the efficiency of the proposed approach. The outcomes show the benefits of using an integrated model for reducing operating costs and improving the reliability of freight transport simultaneously. The future research direction would consist in developing a heuristic or meta-heuristic algorithm to obtain optimal solutions for problem instances of larger size. Another exciting research direction would be considering a stochastic condition for arc disruptions. The probability of losing a particular arc can be estimated using historical data of the incidents. In this case, the optimization model could aim to minimize the expected traveling cost due to unavailability of arcs. As a final point, the underlying assumptions in this study, i.e., single arc disruption or fixed fleet size, can be relaxed in order to enhance the practical aspects of the model. Another relevant field of future research is to propose a stochastic model for integrated capacity and reliability modeling of road-rail operations under random disturbances. This is

particularly relevant because the occurrence of the frequent minor disturbances results in knock-on effects on the performance of the initial routing plan. For more accuracy of the optimization model, the level of details for road

and rail infrastructure could be increased, though this can increase the size of the problem suggestively, accordingly making the model more difficult to solve to optimality.

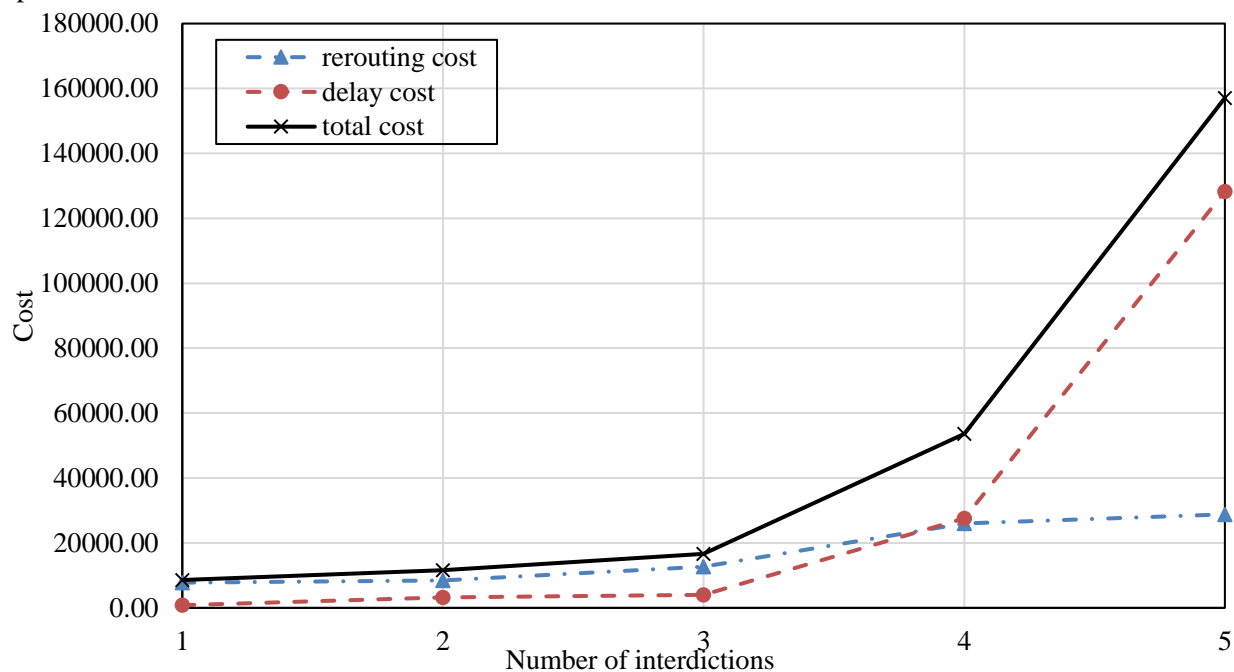


Figure 2. The cost components vs. number of link interdictions

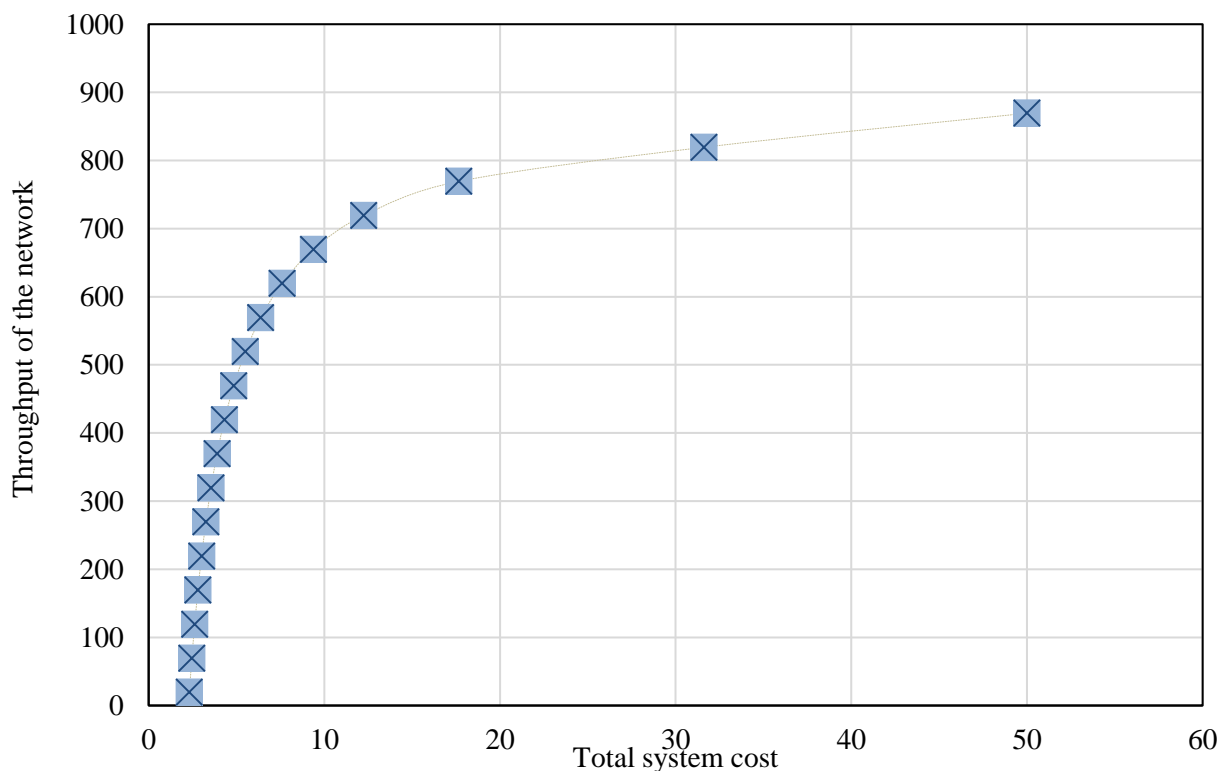


Figure 3. The Pareto optimal solutions generated for test problems

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