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Bi-objective road and pipe network design for crude oil transport in the Sfax region in Tunisia

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Abstract

In this paper, we examine a bi-objective road and pipe network design for crude oil transport in the Sfax region in Tunisia. In particular, we search for the minimum spanning trees (MST) that connect the different oil fields with the port of La Skhirra. In the determination of the minimum spanning trees, two objectives are taken into account, i.e. accident risk and construction costs. By using an improved ε-constraint resolution technique, the Pareto optimal combinations of risk and cost are found. Results indicate that the network solutions by pipe outperform the solutions by road. When the minimum spanning trees for the two extremes on the Pareto curves, i.e. the cost minimum and risk minimum, are compared, one could note considerable differences in the links that form the MST. This implies that policy makers have an important role in deliberating between costs and risks.

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Keywords: crude oil transport; Sfax; bi-objective optimisation; minimum spanning trees; ε-constraint resolution

1. Introduction

The transportation of hazardous materials (HAZMATs) differs from the transportation of other materials especially in terms of the risk associated with an accidental release of hazardous materials during transportation. To reduce the occurrence of dangerous events it is necessary to provide appropriate answers to safety management associated with dangerous goods shipments [1]. In this context, the main concern for policy makers is controlling the risk induced by hazmat transportations over the population and the environment.

Differently from the classical network design problem, Hazmat network design has received little attention from researchers [2]. The most important contributions in this field correspond to the following contributions. Erkut and Alp [3] formulated a minimum spanning tree design problem as an integer programming problem with an objective

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of minimizing the total transport risk. They demonstrated their approach focusing on the road network of the city of Ravenna, Italy. Berman et al. [4] presented a methodology to determine the optimal design of a specialized team network so as to maximize its ability to respond to such incidents in a region, using a maximal arc-covering model. Erkut and Gzara [5] focused on the different levels of decision making when considering network design for hazardous material transportation, by providing a heuristic solution where the government designates a network, and the carriers choose the routes on the network. In the context of route choices, Lozano et al. [6] and Li and Leung [7] determined the optimal paths for carriers to minimize risks. Xie et al. [2] developed a model that simultaneously optimized the location of multimodal transfer yards and transportation routes in the context of HZAZMAT transportation. With respect to the balancing between hazmat risk minimization and cost minimization, Fan et al. [8] proposed a heuristic approach to the vehicle routing problem.

Regarding the construction of a multimodal transport network for HAZMAT transportation from the perspective of a government, balancing both investment (construction) costs and risk mitigation, virtually no literature exists. Therefore, the main objective of this paper is to determine the minimum network that assures the transportation of HAZMAT materials, in particular crude oil, from the different oil fields in the Sfax region towards the port of La Skhirra. The paper is structured as follows. First the study area is described in terms of data related to the network design problem. Consequently, the optimization methodology is elaborated and results are discussed. Finally, the policy recommendations and main conclusions are formulated.

2. Data

This paper aims at finding the minimum spanning tree (MST) that connects the different oil fields in the Sfax region to the port of La Skhirra. In particular, four fields of crude oil (Rhamoura, El-Ain, Guebiba , El-Hajeb), two treatment and storage facilities (Sidi-Litayem , Tank battery) and the port of La Skhirra will each be represented by a node in a network, where all node combinations are considered as possible links. The Cercina offshore oil field is not regarded, as the only feasible solution involves a pipe-line connection.

To calculate accident risk, the population at risk needs to be taken into account. Table 1 presents the description of the different oil fields and the nearby population. Note that the numbers that are indicated also correspond to the minimum spanning trees that will be presented in the results. The risk related to the transport of hazmat is calculated by considering the risk along an edge, where the risk is calculated using a linear risk model within an edge segment. This is a common approach for risk assessment of hazmat transportation, as is outlined by Erkut and Alp [3] and Erkut et al. [9]. For reasons of simplification we do not take account the link topographies. In contrast, we do take into consideration the population in the proximity of the link. Concerning the assessment of risks for the road network, the number of accident related to hazmat transportation is very low: the probability of an accident on the highway network is 10^{-6}. The risk consequence is calculated according the number of people present in the impact area. We adopt a circular shape as an impact area. The radius of the danger circle for road mode is calculated according the evacuation distance when a hazmat incident occurs for flammable and explosive Hazmat. This distance is r=1.6 km [10], corresponding to a circular danger area of 8.0384 km^2. We then calculate the percentage of this impact area of the total superficies of each delegation for road mode. With respect to the assessment of risks for the pipeline network, the same approach is followed. Note that this in context, pipelines are typically constructed "underground", and thus the probability of accident in the pipe network is lower than the road mode (10^{-7}). Besides, for the transport by pipeline, the radius of the danger circle is calculated according the evacuation distance when a hazmat incident occurs for flammable Hazmat, r=0.8 km [10], corresponding to a circular danger area of 2.0096 km^2.

Table 1. Description of the different nodes for the bi-modal oil transport network

ID	Field	City/municipality	Number of inhabitants in 2010	Area (km²)
1	Rhamoura	SfaxVille	108,279	27.09
2	El-Ain	SfaxSud	114,664	197.73
3	Tank battery	SfaxSud	114,664	197.73
4	Guebiba	Thyna	58,029	89.40
5	El-Hajeb	Thyna	58,029	89.40
6	Sidi-Litayem	MenzelChekir	34,300	1564.00
7	La Skhirra	La Skhirra	30,705	904.03

To calculate the construction costs of the road network, an average cost of 4.24 million DT (1DT ≅ 0.45 EUR) by km is considered, which corresponds to the average realization costs of highways in the Sfax region. Similarly, using data from the Tunisian government and shipping companies of petroleum, and average construction cost of 0.45 million DT is obtained for the construction of 1km pipeline. By multiplying the average construction per km by the crow flies distance between the two fields the total construction costs for the pipelines are calculated.

Table 2 presents the risk (R) matrices and cost (C) matrices for both the road network and the pipeline network, considering potential links between all the nodes in the network. Values in italic correspond to already existing links in the network.

Table 1. Description of the different nodes for the bi-modal oil transport network

C^{road}	2	3	4	5	6	7	R^{road}	2	3	4	5	6	7
1	24	24	44	36	144	336		0.01368	0.02275	0.01405	0.01405	0.01072	0.00190
2		16	32	28	100	352			0.00466	0.00498	0.00498	0.00165	0.00317
3			*16*	20	*88*	*340*				*0.00480*	0.00344	*0.00021*	*0.00317*
4				16	*72*	300					0.00522	*0.00184*	0.00353
5					96	300						0.00184	0.00353
6						456							0.00021
C^{pipe}	2	3	4	5	6	7	R^{pipe}	2	3	4	5	6	7
1	3.60	*5.85*	6.30	4.95	16.65	37.80		0.000569	*0.000569*	0.000351	0.000351	0.000268	0.000532
2		*3.15*	4.95	2.25	*10.80*	36.00			*0.000115*	0.000125	0.000120	*0.000041*	0.000079
3			2.25	2.25	*11.25*	36.45				0.000120	0.000125	*0.000078*	0.000079
4				*1.35*	6.75	33.75					*0.000130*	0.000046	0.000088
5					11.25	34.20						0.000046	0.000088
6						*37.35*							*0.000005*

3. Methodology

3.1. Minimum spanning tree problem definition

To determine the network that is required to connect the oil fields and the port, a MST problem is solved for each transport mode, i.e. a separate MST for the pipe line network and the road network. The objective is to find a spanning tree of minimum weight in an undirected graph $G = (V,E)$, with node set V ($|V| = n$), edge set E and a weight function w: $E \rightarrow W$ (every edge has an associated weight). Recall that an edge in an undirected graph is an unordered pair e of distinct nodes in V. Let $E_1 \subseteq E$; if (V,E_1) forms a tree and the edges touch all nodes this is called a spanning tree for G. The weight of a tree is simply the sum of the weight of the edges in the tree.

The mathematical cut-set formulation is based on the fact that the tree is connected and has $n - 1$ edges. The decision variables are a set of binary variables x_e, equal to 1 if and only if edge e is in the tree. The formulation is given by the following set equations:

$$Min \sum_{e \in E} w_e x_e \tag{1}$$

Subject to:

$$\sum_{e \in E} x_e = |V| - 1 \tag{2}$$

$$\sum_{e \in \delta(U)} x_e \geq 1 \qquad \forall\, U \subset V \tag{3}$$

$$x_e \in \{0,1\} \qquad \forall\, e \in E \tag{4}$$

where the cutset $\delta(U) \subset E$ is a subset of edges with one end in U and the other end in $V \backslash S$. The constraints represented by formula 3, guarantee that we do not obtain a solution with sub-cycles.

3.2. Solution methodology

The resolution of a bi-objective (construction cost and accident risk) network design leads to the generation of Pareto optimal solutions, i.e. solutions for which no objective function value can be improved without worsening the value of another one.

The bi-objective problem is turned into a single-objective optimization by retaining a single objective function to optimize with the constraint that the other objective function has to be lower or equal to a value Ɛ [11]. In this study, we introduce the risk function as a constraint of the costs minimization problem. We generate the next Ɛ value, directly based on the previous obtained optimal solution instead of classically generating the Ɛ values by determining a range of values in which it should vary.

Figure 1 represents the algorithm used for obtaining the different Pareto-optimal solutions of the bi-objective model by means of the exact $\mathcal{E}$-constraint method. The initialization step of the algorithm is to minimize the costs without risks constraints. To guarantee Pareto optimality, the model where risks are minimized subject to the fact that costs are equal to or lower than the obtained costs' value is thus solved. The resulted risk value is assigned to the variable *maxR*, and corresponds to the first value of epsilon. A first Pareto optimal solution ($C[0]$,$R[0]=maxR$), is thus generated. Then the minimization of the risk is performed without any constraints on the value of cost. The resulted risk value is assigned to the variable *minR*. According to the desired number of Pareto optimal solution, *p*, a loop step is defined as $s=(maxR-minR)/p$. The loop starts with the minimization of the costs under constraint that risk values should be strictly lower than $maxR-s$, solving this model gives a cost value $C[1]$. To ensure the Pareto optimality, the same model is again solved by minimizing risks, subject to the fact that the costs are less or equal to $C[1]$. A second Pareto optimal solution ($C[1]$,$R[1]$), is then generated. The value of $C[1]$ is higher than the one of $C[0]$ but the value of $R[1]$ is smaller than the one of $R[0]$. One thus goes down along the Pareto front. $R[1]$ is thus the second value of epsilon that is identified. The loop continues until the minimum value of risks is reached.

R=∞, i=0
Solve MC(∞)
if MC(∞) has a solution **then**
    C[0] ← Value[$\sum_{e\in E} c_e x_e$]
    Solve MR(C[0])
    maxR←Value[$\sum_{e\in E} r_e x_e$]
    P[0]=(C[0],maxR)
    Solve MR(∞)
    minR←Value[$\sum_{e\in E} r_e x_e$]
    i←i+1
    s=(maxR-minR)/p
    for (R[i]=maxR-s to minR step s) {
        Solve MC(R[i])
        if MC(R[i]) has a solution **then**
            C[i]← Value[$\sum_{e\in E} c_e x_e$]
            Solve MR(C[i])
            R[i]← Value[$\sum_{e\in E} R_e x_e$]
            P[i]=(C[i],R[i])
    }
Else Stop

With

- MC(R) is the following model:
$$Min \sum_{e\in E} c_e x_e$$
where c_e is the transportation cost of edge e
s.t. (1)-(3)
and $Min\ \sum_{e\in E} r_e x_e < R$
where r_e is the risk of edge e
- MR(C) is the model defined by:
$$Min \sum_{e\in E} r_e x_e$$
s.t. (1)-(3)
and $Min\ \sum_{e\in E} c_e x_e \leq C$

Fig. 1. Algorithm for the generation of pareto optimal solutions

4. Results

The optimization procedure using the $\mathcal{E}$-constraint resolution method has been applied both to the pipeline and road network, and yields the Pareto frontiers displayed in Figure 2. A distinction has been made between the models which take into account existing infrastructure (partial investment), and the solutions that develop the entire network (full investment). From the figure, one could clearly see that the pipeline network solutions outperform the road network solutions, both in terms of cost and risk objectives, and thus suggest that a unimodal, i.e. pipeline, network solution is to be preferred in this case. Note that this conclusion is valid in the context of the evaluation of infrastructure construction costs and accident risks for crude oil transport. The results however do not incorporate effects induced by (road network) investments such as the cascade of economic effects related to changed accessibility. By definition, the Pareto frontiers of the partial investment solutions lie closer to the origin then the ones of the full investment scenarios, implying that investment decisions should take into account existing infrastructure in the overall determination of the network configuration.

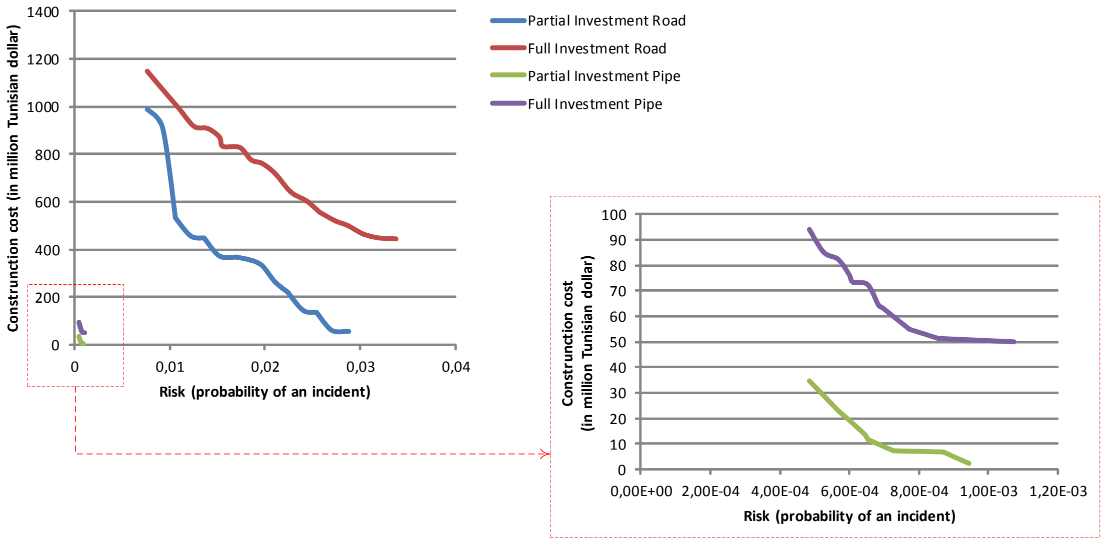

Fig. 2. Pareto frontiers of the optimal combinations of cost and risk for the calculated minimum spanning trees (MST)

Each of the points on the different Pareto frontiers corresponds to a different minimum spanning tree. Figure 3 visualizes minimum spanning trees corresponding to the starting and ending points of the different Pareto frontiers, i.e. the cost-optimal and risk-optimal solutions for each of the different networks. From the different solutions, one could observe that the optimal networks (minimum spanning trees) differ considerably depending on the criterion used, especially when a full investment is envisaged. These differences between the risk-optimal and cost-optimal network solutions highlight the role of the decision maker to clearly balance both objectives. The results thus clearly illustrate that depending on the relative weight that is given to each criterion, other network links need to be constructed.

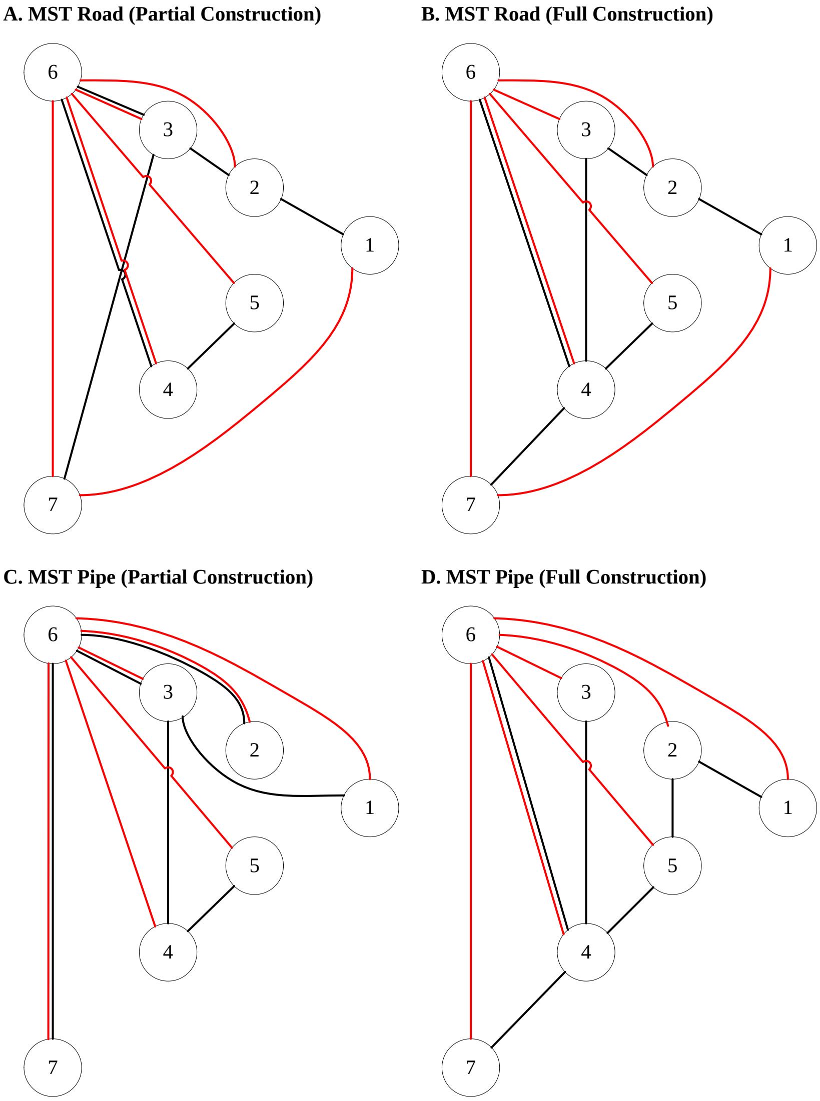

Fig. 3. Schematic representation of the minimum spanning trees (MST) for cost optimal (black) and risk optimal (red) solutions

5. Conclusions

In this paper, we have determined a bi-objective (construction cost and accident risk) bi-modal (pipe and road) network design for oil transport in the Sfax region of Tunisia. From a methodological point of view, we have shown that the Ɛ-constraint resolution technique can be efficiently applied to calculate minimum spanning trees. Considerable differences have been found between the minimum spanning trees that that confine the Pareto optimal combinations, highlighting the important role for policy makers in deliberating between the different objectives, in this case the construction costs and accident risks.

From a policy perspective, the results tend to favor the development of a pipeline network for connecting the different oil fields with the main harbor area. Notwithstanding, some preoccupation is needed in this regard, as the current network design focuses primarily on the transport of crude oil, and thus ignores the potential benefits of (road) infrastructure development on other (transport) economic activities.

Future research should focus on the development of a more detailed network, where possible transshipments from road to pipe or vice-versa could be integrated. Nonetheless, it could be expected, that especially from a risk perspective, such combined solutions might not be (sub)-optimal. The dominance of the pipe alternative evidenced in our case study supports this suggestion. A further enhancement in the analysis would be related to the use of an overall calamity assessment, rather than the use of a single risk index.

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