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Designing a resilient oil supply network with an intelligent solution algorithm

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CHRONICLE

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ABSTRACT

Energy crisis in recent decades has demonstrated strong interdependence between national security and energy security. We are also witness of sever conflicts in oil-rich zones such as Middle-East and West of Suez. This study is the first attempt to provide a flexible multi-objective mathematical model which not only mitigates catastrophic risks by filtering and taking plausible oil-supply disruption scenarios into account, but also reduces oil-supply disruption probability by considering and optimizing political, economic and financial dimensions of oil procurement. Mentioned model determines a resilient portfolio of oil suppliers under each scenario and decides which ports or pipelines must be prepared for receiving oil. Furthermore, the proposed model in the second phase enhances oil-availability in crisis time by storing strategic oil stocks in appropriate geographic points. Also regarding to complexity of the second phase model, a meta-heuristic algorithm has been provided to solve the mentioned model. Finally validity of proposed model is checked by solving it for Greece case problem; sensitivity analysis shows that provided model significantly mitigates catastrophic risks threating energy security by balancing political affairs and reinforcing infrastructural facilities with the least possible cost.

1. Introduction

On one hand, Lesbirel (2013) mentions that security is the most important concern of nations, on the other hand Pasqualetti and Sovacool (2012) claim that security of nations strongly relies on security of their energy procurement. Also according to Berle et al. (2013), World Economic Forum (WEF) has introduced energy security as one of the major emergent global risks which results in social vulnerabilities. Manole et al. (2013) believe that the effects of a damage to a critical energy infrastructure are not only restricted to one country or region, but also it harms the international economy. International Energy Agency, IEA (2007), points out oil import dependency as one of the primary threats for energy security of nations; so Lesbirel (2013) warns that security of oil importing countries is threatened by disruptions in oil market which might lead to economic and social disasters. Unfortunately this peril is inevitable in short term and mid-term and decision makers in energy and security sector must consider the oil supply security as their first priority. Therefore it is essential to

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propose a comprehensive decision making framework in order to achieve a resilient oil supply network. Mentioned framework should include both restrictions and requirements of oil import and consider risk and resiliency factors of this area.

1.1 Literature Review

In order to develop a comprehensive model for resilient oil supply network, some leading studies in fields of oil security, supplier selection and risk management are reviewed in this section.

1.1.1. Oil Security

Energy is introduced by Blum and Legey (2012) as a key-element of economic development, therefore continuity, adequacy and affordability of energy supply must be guaranteed.

Das et al. (1990) introduce disruptive sources threatening global oil market, including natural disasters, economic volatility, political instability and war. For instance, Yadlin and Guzansky (2012) and Manole et al. (2013) mention that major portion of energy containers (oil and gas) are passing through the riskiest regions of the world; at the same time energy facilities are one of terrorists' main targets. Lesbirel (2013) states that we have learnt from past that political and social attributes of countries involved in global oil supply network must be considered, whether a country is an oil supplier or an intermediate in this network. Also Clarke et al. (2012) claim that regional, political and social factors play an important role in maintaining energy supply security. Zhang et al. (2013) provided a supply chain-based framework to evaluate oil import security which illustrates that external supply has been transformed to a new risk. Sovacool & Mukherjee (2011) have introduced dependency, diversification, safety, reliability and resiliency as components of supply security. Johansson (2013) proposed a comprehensive typology to cover the mutual interaction between energy and security, also Sovacool et al. (2011) provide an indicator for energy security assessment.

1.1.2. Supplier Selection

According to a comprehensive survey by Ho et al. (2010), one of the most important criteria for supplier selection is risk measures. Regarding to importance of risk mitigation in supplier selection, Sawik (2010), Sawik (2011a) and Sawik (2011b) have provided supplier selection models with various assumptions using Value at Risk (VaR) and Conditional Value at Risk (CVaR). However international politics do not affect imports in United States, Mityakov et al. (2012) believe that petroleum products are exceptions. Therefore correlation of economic and geopolitical interests between involved countries in supply network must be taken into account.

1.1.3. Risk Management

Briggs et al. (2012) have categorized petroleum supply chain risks in four categories: source dependence, facility dependence, transit dependence and structural risks. Briggs et al. (2012) and Haldar et al. (2012) claim that past experiences demonstrate that actions for reducing probability of risks are as essential as actions for managing consequences of risks. Also according to Grossi & Kunreuther (2005) and Pettit (2008) we have learnt from past that maximum loss of catastrophic events is significantly greater than mean or median of their loss. Pettit (2008) and Haldar et al. (2012) state that resiliency not only reduces probability of disruptions but also enhances ability of a system in recovering from disruptions.

1.2. Research Gap and Problem Description

On one hand Blum and Legey (2012) mention that energy security is not a new concept, but it requires new approach which covers both supply security and demand security; on the other hand Despite the efficiency and necessity of using mathematical programming and optimization in order to safeguard oil supply security; to the best of our knowledge there is no study to fill this gap. This article is seeking to reduce the probability of disruption for an oil net-importer country and prepare it for recovering rapidly from an oil-supply disruption which means having a resilient oil supply network. Therefore, in the first phase a novel applicable model has been proposed which takes economic, political and resiliency factors into account in addition to satisfaction of technical requirements. Authors have utilized multi-objective programming in order to achieve following goals:

- Minimizing catastrophic risk using CVaR approach;
- Mitigating vulnerability by maximizing dependency of supplier countries to oil-export incomes;
- Minimizing political risk of suppliers;
- Select a secure and efficient portfolio of oil suppliers and determining oil entry points from each supplier under each scenario.

In order to achieve mentioned goals, the supply risk management approach proposed by Zeng et al. (2005) has been used in this paper. Steps of mentioned risk management method are given in Table 1.

Table 1
Supply risk management steps Zeng et al. (2005)

Management Process	Techniques
Risk Identification	Scenario Analysis
	Process Mapping
	Cost-Benefit Analysis
Risk Assessment	Decision Trees
	Simulation
	Sensitivity Analysis
	Discounted Cash Flow Analysis
Risk Prioritization	Probability of Occurrence
	Severity of Impact
Risk Management	Supplier Choice
	Diversification
	Stockpiling
	Pooling Resources
	Legal Actions
	Maintenance Agreements
	Residual Risks

In the second phase, a general non-linear mathematical model has been proposed in order to assign location of strategic oil-storage terminals considering availability and security matters. Due to the complexity of proposed model, a novel meta-heuristic algorithm has been provided to solve the mentioned model.

2. Risk Analysis

2.1. Risk Identification

As mentioned by Beccue and Huntington (2005) plausible scenarios of oil disruption in short period (up to 6 months) and their probability are brought in Table 2.

Table 2
Each supplier's magnitude and probability of disruption (Beccue & Huntington, 2005)

Region	P(No)	P(Small)	P(Medium)	P(All)
Saudi Arabia	0.5	0.35	0.11	0.04
Other Persian Gulf	0.11	0.7	0.17	0.02
West of Suez	0.2	0.6	0.2	0
Caspian Sea	0.75	0.2	0.05	0

Magnitude of each disruption is defined by Beccue and Huntington (2005) in Table 3.

Table 3

Disruption amount (Beccue & Huntington, 2005)

Shortfall Description	Disruption Interval (% of Supply)	Disruption Value (% of Supply)
No Shortfall	0-10	5
Small Shortfall	10-30	20
Medium Shortfall	30-80	50
All	80-100	90

2.2. *Risk Assessment and Prioritization*

According to each scenario and its corresponding probability which is mentioned in Table 2, there are potentially 256 oil disruption scenarios; while number of scenarios must be reduced to about 10 scenarios as Haimes (2004) suggested. Therefore risk-filtering approach proposed by DoD (2000) is utilized to exploit important scenarios. Required definitions for this approach are brought in Table 4 and Table 5.

Table 4

Probability description DoD (2000)

Likelihood	Probability
Frequent	0.1<P
Probable	0.01<P<0.1
Occasional	0.001<P<0.01
Remote	0.000001<P<0.001
Improbable	P<0.000001

Table 5

Consequence description

Consequence	Characteristic
Catastrophic	At least one "All"
Critical	At least one "Medium"
Marginal	At least two "Small"
Negligible	Else

Regarding to what mentioned by DoD (2000), 13 scenarios lies into the High-priority zone, which are illustrated in Table 6:

Table 6

The most important disruption scenarios

No.	**Saudi**	**Gulf**	**Suez**	**Caspian**	**Probability**	**Likelihood**	**Consequence**
1	No	Small	Small	Medium	0.0105	Probable	Critical
2	No	Small	Medium	No	0.0525	Probable	Critical
3	No	Small	Medium	Small	0.014	Probable	Critical
4	No	Medium	No	No	0.01275	Probable	Critical
5	No	Medium	Small	No	0.03825	Probable	Critical
6	No	Medium	Small	Small	0.0102	Probable	Critical
7	No	Medium	Medium	No	0.01275	Probable	Critical
8	Small	Small	Medium	No	0.03675	Probable	Critical
9	Small	Medium	Small	No	0.026775	Probable	Critical
10	Medium	Small	No	No	0.01155	Probable	Critical
11	Medium	Small	Small	No	0.03465	Probable	Critical
12	Medium	Small	Medium	No	0.01155	Probable	Critical
13	All	Small	Small	No	0.0126	Probable	Catastrophic

Note that sum of probabilities in Table 6 is 0.285, so probability of regular condition is 0.715.

3. Model Description

3.1. First Phase: Mathematical Modeling for Oil-Supply Risk Management

In this section a flexible multi-objective mathematical model is provided which not only selects the best portfolio of oil suppliers and their share under each scenario, but also determines appropriate entry points for importing oil and amount of oil imported through each entry point under each scenario.

Following assumptions have been made for the first phase model formulation:

- In order to maintain generality of proposed model, the term "oil" in this study refers to crude oil and its derivatives. To convert oil derivatives to their crude oil equivalent, coefficients mentioned in
- Table **7** which are suggested by IEA (2007) are used.

Table 7
Crude oil equivalents of oil derivatives IEA (2007)

Product	Coefficient
crude oil (deducting naphtha)	0.96
oil product (excluding naphtha)	1.065
gasoline and naphtha	1.2
middle distillates	1.2
heavy fuel oil	1.2

- Generality and simplicity of cost terms are achieved through using major oil transportation costs mentioned by Pootakham and Kumar (2010) which are categorized in
- Table **8**.

Table 8
Major cost components of oil transportation types (Pootakham & Kumar, 2010)

Transportation Type	Fixed Cost	Incurred time	Variable Cost
Pipeline	Construction	Initial	Pump power
	Insulation	Initial	
	Maintenance	Annual	
	Operational	Annual	
	Booster	Initial	
Tanker	Load & Unload	Annual	Distance

- Oil supplier selection is a strategic decision problem which makes it a long-term issue; therefore time-value of money is taken into account and all annual costs are converted to their present value equivalent by discount factor calculated in Eq. (1).

$$\sum_{t=1}^{T}(1+g)^{t}\times(1+ir)^{-t} = \left[\frac{1-\left(\frac{1+g}{1+ir}\right)^{T+1}}{\frac{ir-g}{1+ir}}\right] \quad (1)$$

where T is length of planning horizon, g is annual growing factor of costs and ir is annual interest rate.

- Brown and Kennelly (2013) state that oil-producing countries can counterbalance interests of oil-importing countries by oil revenues. So according to Shaffer (2013) as dependency of suppliers' Gross Domestic Product (GDP) on oil-export increases, oil security of oil-importing country increases. Consequently maximizing oil-dependency of selected suppliers is an objective of proposed model.

- According to Jansen et al. (2004), OECD (2007), Mansson et al. (2012) and Chuang & Ma (2013), diversification is the best policy to mitigate losses when we have no knowledge about disruptive events. Consequently, in order to achieve supplier diversity, "co-vary diversity reliability index" calling HHI_3 suggested by Chuang and Ma (2013) is supposed to be minimized in provided model.
- In this study, CVaR is the indicator of catastrophic risk which is conditional expected loss. For more details about CVaR, (see Rockafellar & Uryasev, 2002).
- Strategic decision variables have identical values in all scenarios while values of tactical decision variables change by the variation of scenarios.
- As mentioned by Le Coq and Paltseva (2009) switching between ports is much easier than pipelines. Therefore in order to satisfy resiliency conditions, Jewell (2011) suggests to have at least 5 oil-importing ports or 9 oil pipelines. Consequently this condition has been taken into account in the following model.
- Since Morrow et al. (1998) claim that democracy in both supplier and consumer countries raises trade and leads to peace, weighted average democracy level of selected oil-importing countries must meet a minimum level.

3.2. Model Description

Sets:	
I	Set of potential oil supplier countries;
J	Set of potential oil receiver ports in demanding country;
S	Set of pipeline capacities;
Θ	Set of plausible oil disruption scenarios.
Parameters**:**	
dep_i	Dependency of i^{th} supplier's GDP to oil export;
σ_{ik}	Mutual conflict between supplier i and k;
A	Loss percentile exceeds VaR;
π_θ	Realization probability of θ^{th} scenario;
Cc	Cost of contracting with each supplier;
Pp	Port preparation cost for receiving oil;
FCL_i^s	Fixed Cost of pipeline with capacity s from supplier i;
G	Annual cost increase gradient;
Ir	Annual interest rate;
T	Length of planning horizon;
dl_i	Length of pipeline from i^{th} supplier to demanding country;
C	Electricity cost for pumping one barrel (159 liter) of oil along one kilometer via pipeline;
NI	Annual oil net import of demanding country;
FCT_{ij}	Cost of each oil truck travel from supplier i to j^{th} port of demanding country;
$Cap_{i\theta}$	Annual export capacity of supplier i under scenario θ;
V_s	Annual capacity of s^{th} type of oil pipeline;
res_p	Minimum number of ports required to have a resilient oil supply networks (5);
res_l	Minimum number of pipelines required to have a resilient oil supply networks (9);
TUC	Capacity of one oil carrying truck;
dem_i	Democracy score of supplier i;

Dem_{min} Minimum aspiration level of overall democracy degree of selected oil supplier countries.

Variables:

$x_{i\theta}$ Share of oil being imported from supplier *i* under scenario θ in total oil import;
VaR Value at Risk;
T_θ Tail cost for scenario θ;
w_i 1 if contract with i^{th} supplier is signed, 0 else;
y_j 1 if port *j* is selected as an oil importing port, 0 else;
yl_i^s 1 if pipeline with capacity *s* is constructed from supplier *i*, 0 else;
$txl_{i\theta}$ Proportion of oil imported from supplier *i* via pipeline under scenario θ;
$NC_{ij\theta}$ Number of Carriers annually transport oil from supplier *i* to port *j* of demanding country under scenario θ.
$xp_{ij\theta}$ Proportion of oil imported from supplier *i* via port *j* under scenario θ;
$xl_{i\theta}^s$ Proportion of oil imported via pipeline with capacity *s* from supplier *i* under scenario θ;
$q_{ij\theta}$ Auxiliary variable;
z_1 , z_2 Resiliency guarantee binary variables.

Model:

$$\max Oil_{Dep} = \sum_\theta \sum_i dep_i \times x_{i\theta} \tag{2}$$

$$\min HHI_3 = \sum_i \sum_{k \le i} \sum_\theta \sigma_{ik} \times x_{i\theta} \times x_{k\theta} \tag{3}$$

$$\min CVaR = VaR + (1-\alpha)^{-1} \times \sum_\theta \pi_\theta \times T_\theta \tag{4}$$

subject to

$$\sum_i cc \times w_i + \sum_j pp \times y_j + \sum_i \sum_s FCL_i^s \times yl_i^s + \left[\frac{1 - \left(\frac{1+g}{1+ir} \right)^{T+1}}{\frac{ir-g}{1+ir}} \right] \times \left[\sum_i dl_i \times c \times txl_{i\theta} \times NI + \sum_i \sum_j FCT_{ij} \times NC_{ij\theta} \right] - VaR - T_\theta \le 0 \quad \forall \theta \tag{5}$$

$$\sum_i x_{i\theta} = 1 \quad \forall \theta \tag{6}$$

$$NI \times x_{i\theta} \lesssim Cap_{i\theta} \times w_i \quad \forall i, \theta \tag{7}$$

$$\sum_i xp_{ij\theta} \le y_j \quad \forall j, \theta \tag{8}$$

$$NI \times xl_{i\theta}^s \le V_s \times yl_i^s \quad \forall i, s, \theta \tag{9}$$

$$\sum_s xl_{i\theta}^s = txl_{i\theta} \quad \forall i, \theta \tag{10}$$

$$x_{i\theta} = txl_{i\theta} + \sum_j xp_{ij\theta} \quad \forall i, \theta \tag{11}$$

$$\sum_j y_j \geq res_p \times z_1 \qquad (12)$$

$$\sum_i \sum_s yl_i^s \geq res_l \times z_2 \qquad (13)$$

$$z_1 + z_2 \geq 1 \qquad (14)$$

$$NC_{ij\theta} \geq \frac{NI \times xp_{ij\theta}}{TUC} \qquad \forall i, j, \theta \qquad (15)$$

$$\sum_i dem_i \times x_{i\theta} \gtrsim Dem_{min} \qquad \forall \theta \qquad (16)$$

$$xl_{i\theta}^s \times NI \geq 0.5 \times V_s \times yl_i^s \qquad \forall i, s, \theta \qquad (17)$$

$$NC_{ij\theta} \geq 100 \times q_{ij\theta} \qquad \forall i, j, \theta \qquad (18)$$

$$xp_{ij\theta} \leq q_{ij\theta} \qquad \forall i, j, \theta \qquad (19)$$

$$VaR, T_\theta, txl_{i\theta}, x_{i\theta}, xp_{ij\theta}, xl_{i\theta}^s \geq 0 \qquad \forall i, j, s, \theta \qquad (20)$$

$$w_i, y_j, yl_i^s, z_1, z_2, q_{ij\theta} \in \{0,1\} \qquad \forall i, j, s, \theta \qquad (21)$$

$$NC_{ij\theta} \geq 0 \;\; , \;\; integer \qquad \forall i, j, \theta \qquad (22)$$

Eq. (2) maximizes weighted average dependency of selected oil suppliers on oil export; Eq. (3) minimizes modified Herfindhal-Hirschman Index in order to satisfy diversity considering individual and mutual risks of suppliers; Eq. (4) minimizes α-percent Conditional Value at Risk; Eq. (5) calculates tale cost for each scenario; Eq. (6) Guarantees that all oil import requirement would be met under each scenario; Eq. (7) assures that oil import from each supplier does not happen unless contract is signed with corresponding supplier, in addition imported oil from each supplier under each scenario will not exceed its export capacity; Eq. (8) maintains that oil cannot be imported via any port under any scenario unless corresponding port has been prepared; Eq. (9) does not allow oil import via pipeline more than its capacity; Eq. (10) calculates total amount of oil imported via pipeline in each scenario; Eq. (11) computes total amount of oil imported from each supplier, whether via port or pipeline, in each scenario; Eq. (12), Eq. (13) and Eq. (14) maintain oil supply resiliency conditions; Eq. (15) guarantees sufficiency of number of oil carrying trucks; Eq. (16) Assures that weighted average democracy score of selected suppliers must be more than a pre-defined minimum level; Eq. (17), Eq. (18) and Eq. (19) prevent resulting inefficient solution vectors when the problem is being solved for *Oil-dependency* and *HHI3* objective functions regardless of incurred costs; Eq. (20), Eq. (21) and Eq. (22) determine domain of decision variables.

3.3 Second Phase: Location of Oil Storage Terminals

In the previous section, security of oil supply network has been guaranteed from outbound aspects; while proposed model in this section maintains security of oil storage terminals. Proposed model in this section is based on following assumptions:

- According to the IEA standard, IEA (2007), oil net importer countries require to increase their emergency oil reserve to at least 90 days of maximum net import.
- In order to maintain the generality of proposed model, power of distances has been considered as a parameter which could be assigned by decision maker.
- Since by increasing capacity of terminals, importance of objectives increase, importance of proposed objective functions is proportional to square of terminal capacities.

Indices and Sets:

M	Index of oil-receiving ports (m=1,..,M) ;
n و n'	Index of oil-storage terminals [n(n')=1,…,N]; ($2 \leq N \leq [\frac{TS}{Cap_{min}}]$)
K	Index of oil-importing country refineries (k=1,…,K);

Parameters:

λ	Weight of objective function related to minimization of sum of distances between terminals and both ports and refineries($0 \le \lambda \le 1$);
wp	Importance of adjacency between terminals and ports;
wr	Importance of adjacency between terminals and refineries ($wp + wr = 1$);
lgp_m	Longitude of port *m*;
ltp_m	Latitude of port *m*;
a_m	Importance of port *m* for adjacency to oil-storage terminals ($\sum_{m=1}^{M} a_m = 1$);
lgr_k	Longitude of refinery *k*;
ltr_k	Latitude of refinery *k*;
b_k	Importance of refinery *k* for adjacency to oil-storage terminals ($\sum_{k=1}^{K} b_k = 1$);
P	Power of distance terms;
TS	Total amount of oil required for storage (barrels);
Cap_{min}	Minimum capacity of an oil-storage terminal (barrels);
Lg_{min}	Minimum allowed longitude for construction of an oil-storage terminal;
Lg_{max}	Maximum allowed longitude for construction of an oil-storage terminal;
Lt_{min}	Minimum allowed latitude for construction of an oil-storage terminal;
Lt_{max}	Maximum allowed latitude for construction of an oil-storage terminal;

Decision Variables

lgt_n	Longitude of n^{th} oil-storage terminal;
ltt_n	Latitude of n^{th} oil-storage terminal;
ξ_n , $\xi_{n'}$	Capacity of $n(n')^{th}$ oil-storage terminal (barrels);

Model:

$$\min D_1 = \sum_{m=1}^{M}\sum_{n=1}^{N} a_m \left(\left|lgt_n - lgp_m\right|^p + \left|ltt_n - ltp_m\right|^p\right)^{\frac{1}{p}} \times \left(\frac{\xi_n}{TS}\right)^2 \quad (23)$$

$$\min D_2 = \sum_{n=1}^{N}\sum_{k=1}^{K} b_k \left(\left|lgr_k - lgt_n\right|^p + \left|ltr_k - ltt_n\right|^p\right)^{\frac{1}{p}} \times \left(\frac{\xi_n}{TS}\right)^2 \quad (24)$$

$$\max D_3 = \sum_{n=1}^{N-1}\sum_{n'=n+1}^{N} \left(\left|lgt_{n'} - lgt_n\right|^p + \left|ltt_{n'} - ltt_n\right|^p\right)^{\frac{1}{p}} \times \left(\frac{\xi_n}{TS}\right)\left(\frac{\xi_{n'}}{TS}\right) \quad (25)$$

$$\min D = \lambda\left(wp.D_1 + wr.D_2\right) - (1-\lambda)D_3 \quad (26)$$

subject to

$$\sum_{n=1}^{N} \xi_n = TS \quad (27)$$

$$\xi_n \ge Cap_{min} \qquad \forall n \quad (28)$$

$$Lg_{min} \le lgt_n \le Lg_{max} \qquad \forall n \quad (29)$$

$$Lt_{min} \le ltt_n \le Lt_{max} \qquad \forall n \quad (30)$$

$$lgt_n \;, ltt_n \;, \xi_n \ge 0 \qquad \forall n \quad (31)$$

Eq. (23) minimizes weighted sum of distance of oil-storage terminals from oil-receiving ports. Eq. (24) minimizes weighted sum of distance of oil-storage terminals from refineries. Eq. (25) maximizes weighted geographic dispersion of oil-storage terminals. As measuring units of three mentioned objective functions are identical, Eq. (26) transforms proposed multi-objective model into a single-objective one. Constraint (27) guarantees that enough capacity for oil storage would be constructed. Constraint (28) maintains capacity of oil-storage terminals at a minimum economic level. Constraints

(29) and (30) guarantees that location of oil-storage terminals will be in the acceptable geographic region. (31) Assigns domain of decision variables.

4. Solution Method

4.1. Crisp Single-Objective Equivalent Model

We are encountered with a fuzzy multi-objective model where each objective has its distinct measuring unit and importance. So the interactive programming approach provided by Torabi & Hassini (2008) calling TH approach is used in this study. Also fuzzy constraints are transformed to their crisp equivalent according to Eq. (32) and Eq. (33).

$$AX \lesssim b \rightarrow AX \leq b + (1-\beta)t \tag{32}$$

$$AX \gtrsim b \rightarrow AX \geq b - (1-\beta)t \tag{33}$$

where β is satisfaction level of soft constraints and t is the maximum tolerable deviation from desirable right hand side value.

4.2. Proposed Meta-Heuristic Algorithm For Second Phase Model

Regarding to the complexity of proposed model in the second phase, a meta-heuristic algorithm based on Deferential Evolutionary (DE) has been designed and provided in this section. DE is a population-based algorithm introduced by Storn and Price (1997), it has five main factors: solution representation, initial population, mutation, offspring and selection. Notations used in the proposed algorithm are as follows:

NP	Size of population;
ii	Index of population in each generation (ii=1,…,NP);
G_{max}	Number of generations;
gg	Index of generation (gg=1,…,G_{max});
$O_{ii,gg}$	The ii^{th} population in the gg^{th} generation;
$rand[0,1]$	A random number between 0 and 1 with uniform distribution;
N	Number of oil-storage terminals.

4.2.1. Solution Representation

Each solution has been illustrated by a 3×N matrix which is shown in Fig. **1**.

$$\begin{bmatrix} lgt_1 & \cdots & lgt_n & \cdots & lgt_N \\ ltt_1 & \cdots & ltt_n & \cdots & ltt_N \\ \xi_1 & \cdots & \xi_n & \cdots & \xi_N \end{bmatrix}$$

Fig. 1. Solution representation of the proposed DE algorithm

Therefore each generation is a three-dimensional matrix with NP×3×N elements. The schematic view of each generation is illustrated in Fig. **2**.

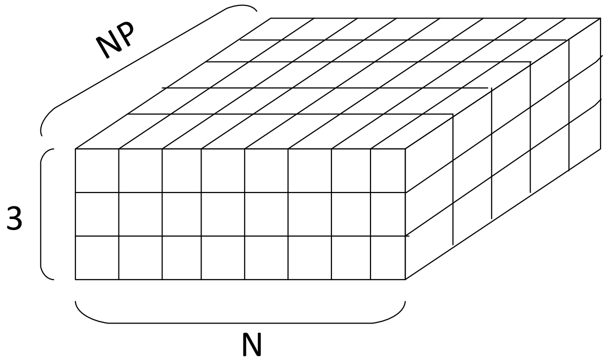

Fig. 2. Schematic view of a generation

4.2.2. Initial Population

In order to generate feasible members for initial population, following procedure has been utilized for decision variables:

$$lgt_{ii,gg} = Lg_{min} + \left(Lg_{max} - Lg_{min}\right) rand\,[0,1] \tag{34}$$

$$Ltt_{ii,gg} = Lt_{min} + \left(Lt_{max} - Lt_{min}\right) rand\,[0,1] \tag{35}$$

$$\xi_{ii,gg} = rand\,[0,1] \rightarrow \xi_{ii,gg} = \frac{Cap_{min}}{TS} + (1 - N\,\frac{Cap_{min}}{TS})\frac{\xi_{ii,gg}}{\sum_{n=1}^{N}\xi_{ii,gg}} \tag{36}$$

4.2.3. Mutation

Mutation operation is performed in order to create variety in solutions and consequently avoid local optimums. For mutation operator in DE, it is required to opt-out three random members (rr_1, rr_2, rr_3) and then calculate the mutation vector as follows:

$$\Delta_{ii,gg} = O_{rr_1,gg} + \tau(O_{rr_2,gg} - O_{rr_3,gg}) \tag{37}$$

where τ is the mutation factor between 0 and 1.

4.2.4. Off-Spring

According to DE algorithm, elements of each new population are selected by the following rule:

$$\Psi_{kk,ii,gg} = \begin{cases} \Delta_{kk,ii,gg} & \text{if } \left(rand\,[0,1] \le CR\right) \text{or } kk = \varphi, \\ O_{kk,ii,gg} & \text{otherwise.} \end{cases} \tag{38}$$

where CR is the constant off-spring parameter and it is between 0 and 1. It is notable that φ is a random number which results in at least one mutated element in new members. Since mutation and off-spring operators might generate infeasible solutions, mentioned procedure in Fig. **3** has been utilized to make the obtained solutions feasible.

4.2.4 Selection

The first step in generating a new population for a new generation is selection. In the proposed algorithm, value of objective function for each generated solution is compared with its corresponding solution and more befitting solution vector transfers to the next generation.

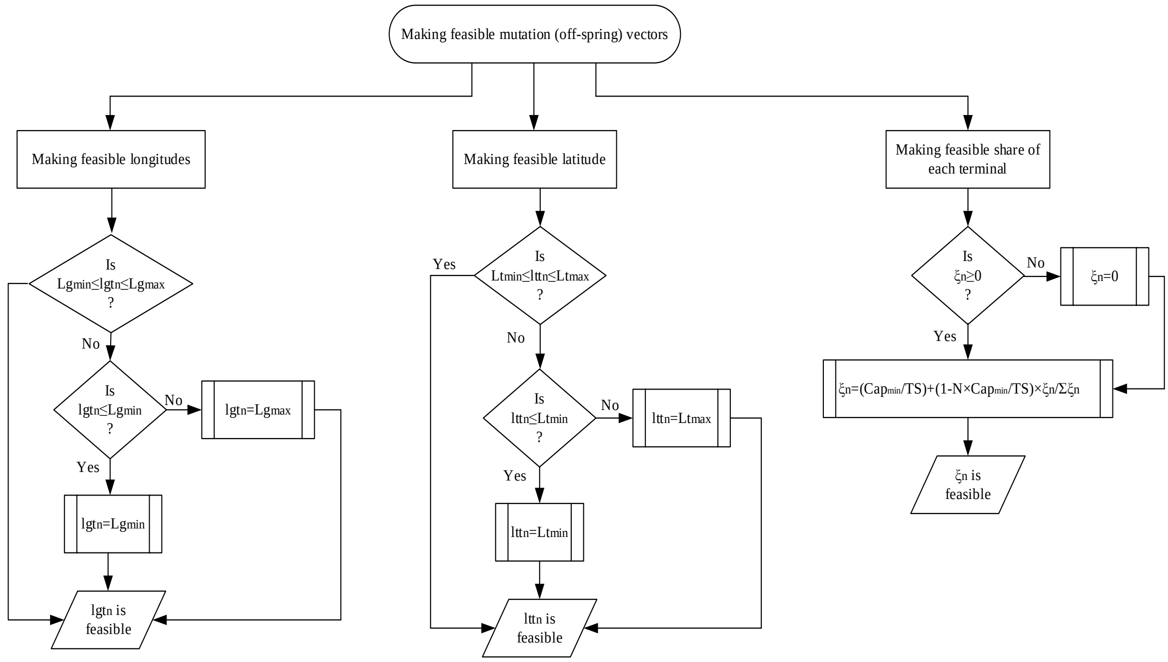

Fig. 3. Making feasible mutation (off-spring) vectors

5. Numerical Example

Since proposed model in this study is for an oil net importer and according to Pachiu (2013), energy supply is the major concern of European Union (EU) in field of energy security; authors have chosen Greece to verify the provided model.

5.1. Data Gathering

However there are about 125 oil-exporting countries, regarding to CIA (2009) 20% percent of suppliers have 80% of market share round the world. Consequently in this study only major oil-exporters are considered as potential oil suppliers. Required characteristics of potential suppliers including Dependency of their GDP on oil-export, Length of a potential oil pipeline from suppliers to Greece and Democracy score of each oil-exporter; are stated in Table A. 1. Note that democracy score varies from 1 for full-dictatorship to 10 for ideal democracy. Mutual conflicts between each two suppliers depicted in Table A. 2 are adapted by subtracting correlation proposed by Voeten (2012-08) from 1. Mentioned conflict ranges from 0 to 2 as its lowest and highest values respectively. According to CIA (2009) net import of oil by Greece is 181259000 barrels per year. Authors have also considered length of planning horizon 10 years; growth rate of annual cost 10%, annual interest rate 15% and minimum aspiration level of democracy 2 units. In order to defuzzify constraint (7) a tolerance level is required for export capacity of oil-suppliers. So excess capacities provided in Table A. 4 are used as tolerance level. These values are proportional to values brought in Table A. 3. Among all available ports of Greece, in this study seven ports have been chosen as potential candidate entry points for importing oil: Korinthos, Messolongi, Patra, Pireas, Preveza, Thessaloniki and Volos.

Approximate costs of carrying one oil truck from oil-exporters to each port is calculated for 350$/kM and 2000$ for loading/unloading which are provided in Table A. 5. Moreover three pipeline capacities are considered: 100000, 200000 and 400000 barrels per day, where construction cost of each type from each exporter is given in Table A. 6. Contraction cost with an exporter is considered 500000$ and cost for preparing a port for importing oil is considered 1000000000$. Electricity cost of pumping one barrel oil along one kilometer is considered 15.9$. Capacity of each oil carrying truck is considered 20000 barrels. According to what mentioned in section 2.2, capacity of each supplier under each scenario and corresponding probability are provided in Table 9.

Table 9
Probabilities and Capacities of each scenario (million barrels per year)

Supplier	Scenario													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Algeria	494.6	309.2	309.2	587.4	494.6	494.6	309.2	309.2	494.6	587.4	494.6	309.2	494.6	618.3
Angola	540.5	270.2	135.1	128.4	102.7	82.2	41.1	20.5	16.4	15.6	12.5	6.2	5	675.6
India	301.3	301.3	301.3	301.3	301.3	301.3	301.3	301.3	301.3	301.3	301.3	301.3	301.3	301.3
Iran	736.7	736.7	736.7	460.4	460.4	460.4	460.4	736.7	460.4	736.7	736.7	736.7	736.7	920.9
Iraq	633.6	633.6	633.6	396	396	396	396	633.6	396	633.6	633.6	633.6	633.6	792.1
Kazakhstan	253.7	482	405.9	482	482	405.9	482	482	482	482	482	482	482	507.4
Kuwait	621.1	621.1	621.1	388.2	388.2	388.2	388.2	621.1	388.2	621.1	621.1	621.1	621.1	776.4
Libya	461.4	230.7	115.3	109.6	87.7	70.1	35.1	17.5	14	13.3	10.7	5.3	4.3	576.7
Malaysia	235.4	235.4	235.4	235.4	235.4	235.4	235.4	235.4	235.4	235.4	235.4	235.4	235.4	235.4
Norway	797.2	797.2	797.2	797.2	797.2	797.2	797.2	797.2	797.2	797.2	797.2	797.2	797.2	797.2
Qatar	303.1	303.1	303.1	189.4	189.4	189.4	189.4	303.1	189.4	303.1	303.1	303.1	303.1	378.9
Russian Federation	914.3	1737.2	1462.9	1737.2	1737.2	1462.9	1737.2	1737.2	1737.2	1737.2	1737.2	1737.2	1737.2	1828.7
Saudi Arabia	2647.4	2647.4	2647.4	2647.4	2647.4	2647.4	2647.4	2229.4	2229.4	1393.4	1393.4	1393.4	278.7	2786.8
UAE	699.3	699.3	699.3	437.1	437.1	437.1	437.1	699.3	437.1	699.3	699.3	699.3	699.3	874.2
USA	700.8	700.8	700.8	700.8	700.8	700.8	700.8	700.8	700.8	700.8	700.8	700.8	700.8	700.8
Probability of Occurrence	0.0105	0.0525	0.014	0.0128	0.0383	0.0102	0.0128	0.0368	0.0268	0.0116	0.0347	0.0116	0.0126	0.7152

5.2. Results and Discussion

5.2.1. Operational Results of First Phase Model

GAMS 23.6.2 software has been utilized to solve the provided model for Greece resilient oil supplier selection. According to Torabi & Hassini (2008), in order to use TH approach first of all, pay-off table must be confounded as Table 10.

Table 10
Pay-off table for Greece resilient oil supplier selection problem

	Oil Dependency (%)	HHI_3	CVaR (billion dollars)
Oil Dependency	66.41	0.61	83.45
HHI_3	10.62	0	86.172
CVaR	47.2	0.656	51.277
PIS	66.41	0	51.277
NIS	10.62	0.656	86.172

It is notable that over this section, α is considered as 0.95. Moreover in order to use TH approach for solving a multi-objective problem, importance weight of each objective (w_i) must be determined in addition to a weight for minimum satisfaction level of all objectives (γ). Therefor the importance weights of *Oil Dependency*, HHI_3 and *CVaR* are considered as 0.3, 0.6 and 0.1 respectively. Detailed and practical results for γ=0.5 are provided in

Table **11**. According to achieved plan, oil-supply contracts must be signed with Algeria, Kuwait, Libya, Qatar, Russia and Saudi Arabia. Also among all candidate ports, five ports are selected by the proposed model to be prepared for receiving oil: Korinthos, Pireas, Preveza, Thessaloniki and Volos. Consequently mentioned plan results in 50.42% for weighted average oil-dependency of suppliers, 0.198 units of co-vary diversity and 61.822 billion dollars as its CVaR. As observed, provided model in this study results in a contingency plan which not only mitigates political and economic risks, but also reduces catastrophic risks remarkably by a negligible increase in initial and infrastructural costs. To see details of scenarios 1 to 13, refer to Table 6. Note that the 14th scenario denotes the regular condition.

5.2.2. Operational Results of Second Phase Model

In this section, according to the selected ports and share of each one resulting from first phase, proposed model for assigning location and capacity of oil-storage terminals has been solved for Euclidean (p=2) distance measure. It is notable that algorithm parameters are as follows: τ=0.05, CR=0.35, NP=300 and G_{max}=1500. By considering distances as straight lines (Euclidean), optimum number of oil-storage terminals is 5 and characteristics of each terminal have been provided in Table 12 and graphical view of obtained results are depicted in Fig. 4. Also, the flow of achieving optimum solution by proposed algorithm has been illustrated in Fig. 5.

Table 11

Annual oil-supply plan of Greece under each scenario

Scenario	Supplier	Port	Number of oil-carrying trucks
1	Kuwait	Pireas	2150
	Libya	Korinthos	3323
	Qatar	Korinthos	1698
	Saudi Arabia	Pireas	1892
2	Algeria	Korinthos	1819
	Kuwait	Thessaloniki	1809
	Libya	Volos	2838
	Qatar	Pireas	1250
	Saudi Arabia	Korinthos	1346
3	Kuwait	Thessaloniki	2206
	Libya	Korinthos	3103
	Qatar	Pireas	1839
	Saudi Arabia	Pireas	1915
4	Algeria	Pireas	1511
	Kuwait	Thessaloniki	1865
	Libya	Korinthos	2469
	Qatar	Korinthos	1594
	Saudi Arabia	Pireas	1623
5	Algeria	Korinthos	1523
	Kuwait	Thessaloniki	1870
	Libya	Korinthos	2425
	Qatar	Korinthos	1622
	Saudi Arabia	Volos	1622
6	Algeria	Pireas	1667
	Kuwait	Volos	1879
	Libya	Korinthos	2843
	Qatar	Preveza	1093
	Saudi Arabia	Volos	1581
7	Algeria	Korinthos	1858
	Kuwait	Pireas	1672
	Libya	Korinthos	1753
	Qatar	Thessaloniki	948
	Russia	Volos	1512
	Saudi Arabia	Volos	1320
8	Algeria	Pireas	1919
	Kuwait	Thessaloniki	3768
	Libya	Korinthos	720
	Russia	Volos	2656
9	Algeria	Korinthos	1787
	Kuwait	Thessaloniki	4182
	Libya	Korinthos	448
	Russia	Thessaloniki	2646
10	Algeria	Korinthos	2235
	Kuwait	Volos	2205
	Libya	Korinthos	666
	Russia	Thessaloniki	2088
	Saudi Arabia	Pireas	1870
11	Algeria	Volos	2657
	Kuwait	Thessaloniki	2647
	Libya	Korinthos	533
	Russia	Thessaloniki	3227
12	Algeria	Korinthos	2347
	Kuwait	Thessaloniki	2376
	Libya	Korinthos	266
	Russia	Volos	2123
	Saudi Arabia	Volos	1949
13	Algeria	Pireas	2583
	Kuwait	Thessaloniki	3437
	Libya	Korinthos	213
	Russia	Thessaloniki	2830
14	Algeria	Korinthos	1743
	Kuwait	Thessaloniki	1812
	Libya	Preveza	2747
	Qatar	Pireas	1329
	Saudi Arabia	Volos	1432

Table 12
Geographic position and capacity of each oil-storage terminals, considering Euclidean distance measure

No.	Longitude	Latitude	Capacity (Barrels)
1	23.71	37.97	14700000
2	22.96	40.64	7350000
3	20.75	38.96	7350000
4	22.93	37.94	7350000
5	22.94	39.36	7350000

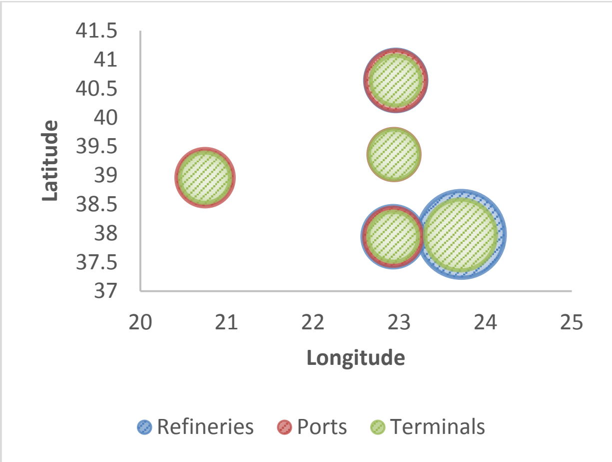

Fig. 4. Graphical view of ports, terminals and refineries considering Euclidean distance measure

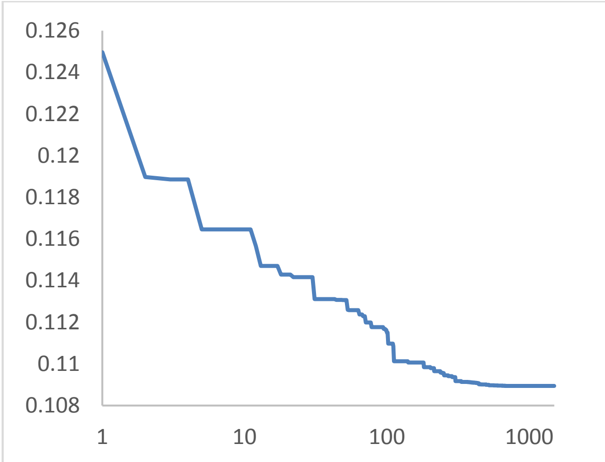

Fig. 5. The procedure of obtaining optimum solution by the proposed DE algorithm

5.2.3. *Sensitivity Analysis*

Fig. **6** illustrates variation in satisfaction degree of each objective corresponding to variation of γ, which proves efficiency of utilized approach. Because despite wide range of changes in γ, satisfaction degrees do not vary substantially and balanced solutions are achieved.

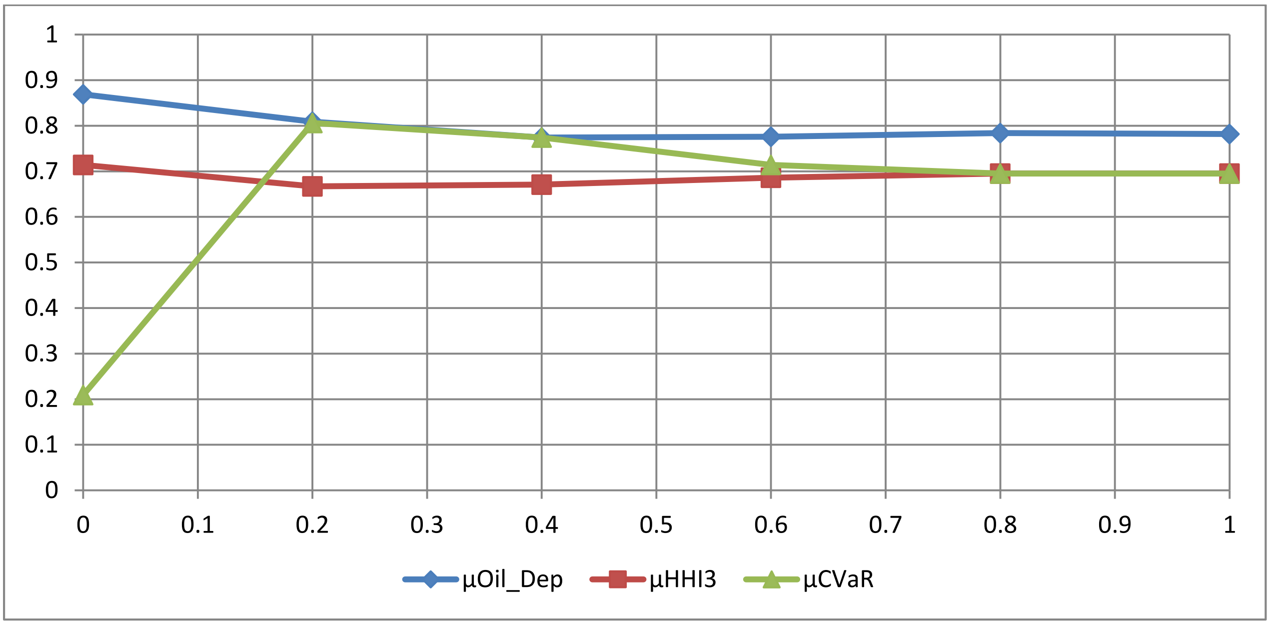

Fig. 6. Variation of satisfaction degrees regarding to changes in γ

There are two key parameters (α and Dem_{min}) which must be assigned by decision maker. Therefore model has been run for different values of α and Dem_{min}, then their interaction and their impact on each objective are investigated.

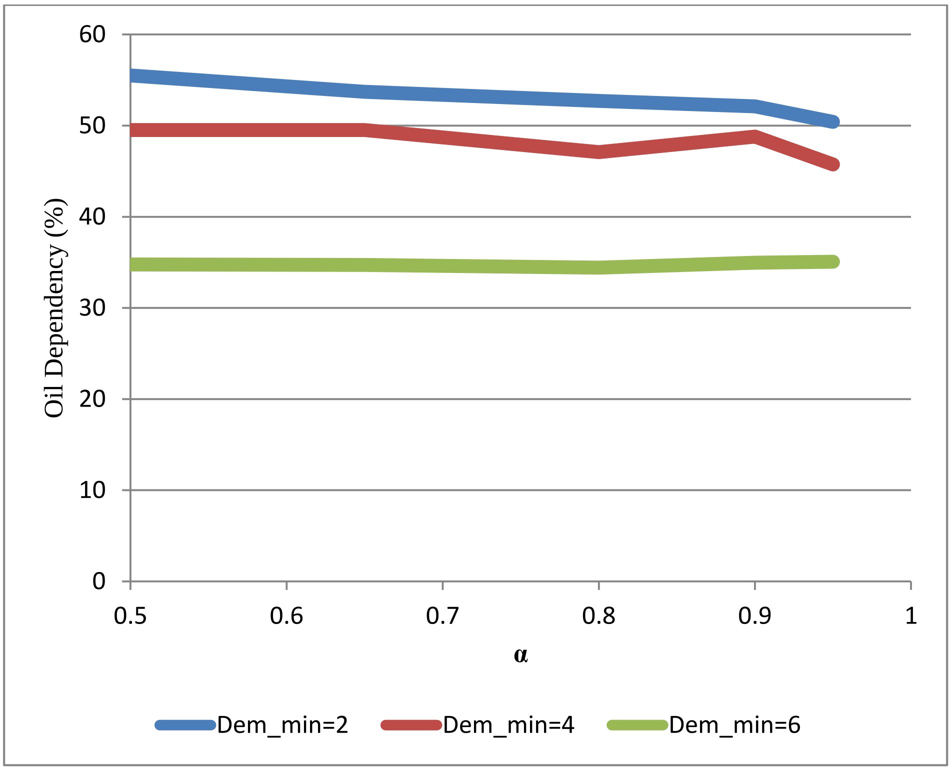

Fig. 7. Variation of oil-dependency corresponding to variation of α and Dem_{min}

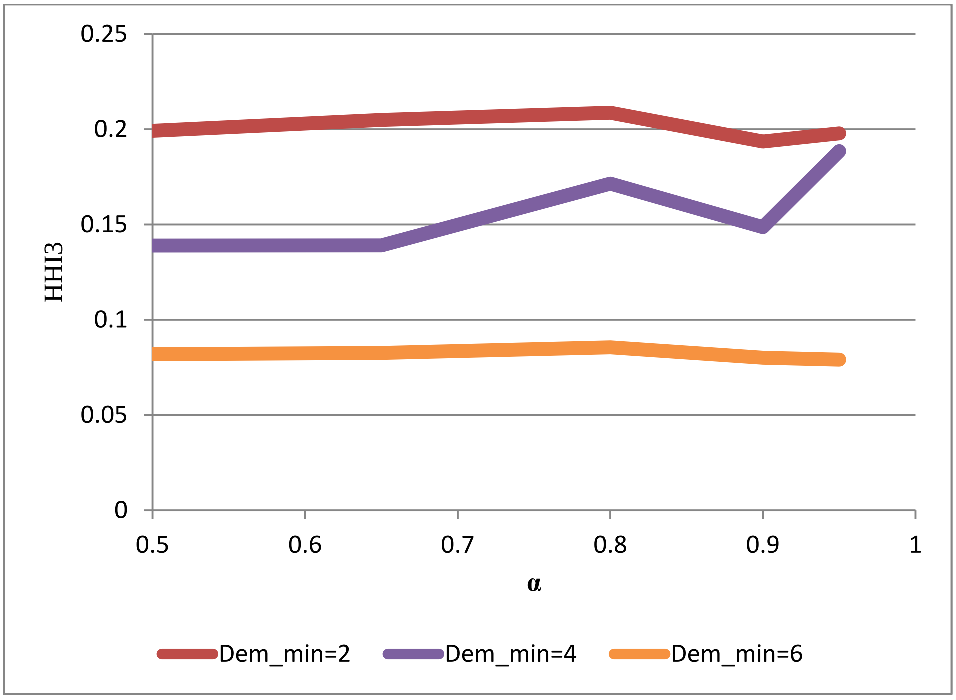

Fig. 8. Variation of co-vary diversity index corresponding to variation of α and Dem_{min}

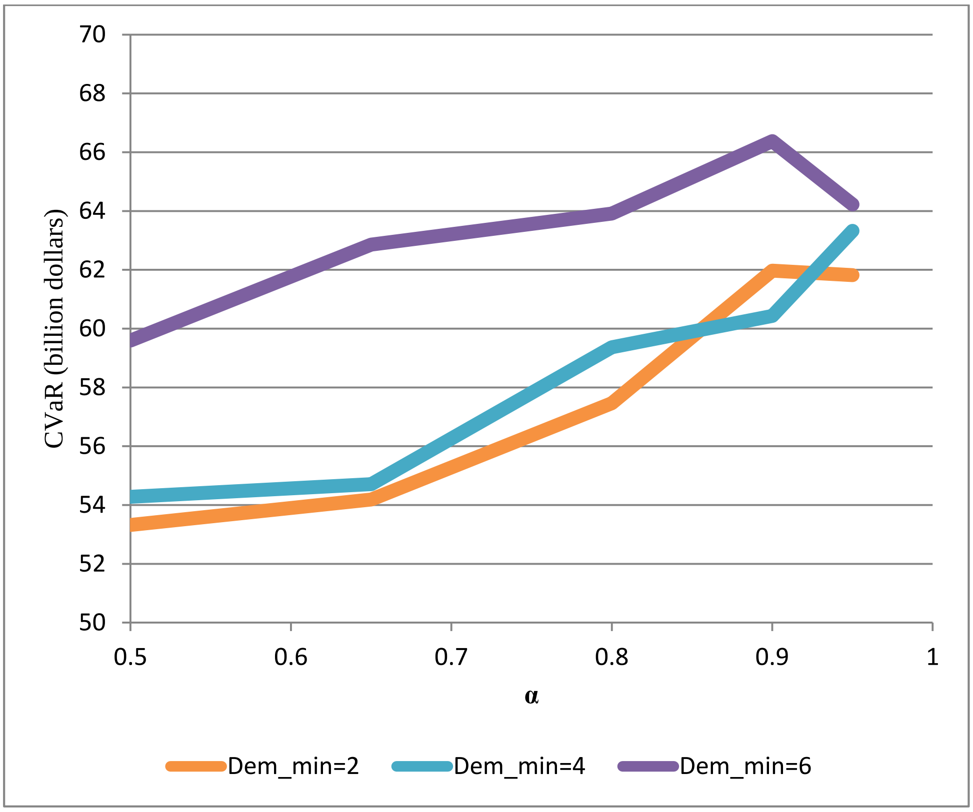

Fig. 9. Variation of Conditional Value at Risk corresponding to variation of α and Dem_{min}

- ✓ Fig. 7 illustrates that a plan with larger minimum level of democracy results in lower dependency of selected supplier countries to oil-export incomes and consequently decreases geopolitical bargaining power of oil-importer. So decision maker(s) must establish a balance between level of political development and economic dependency of selected oil-suppliers.
- ✓ Fig. 8 proves that democracy leads to resiliency. Because as minimum level of democracy increases, mutual conflict between suppliers and importer decreases.
- ✓ Fig. 7 and Fig. 8 show that large minimum level of democracy results in plans which have negligible sensitivity to α. Therefore as selected suppliers perform better in field of interior affairs in their own countries, more consistent oil-supply plans can be achieved.
- ✓ Fig. 9 confirms statement declared by Haimes (2004) that suggests small investments for structure improvement which leads to significant mitigation in catastrophic risks. Regarding to Fig. 9, less than 20% increase in structural costs results in more than 45% decrease in catastrophic risks.
- ✓ Fig. 8 and Fig. 9 depict that however increasing minimum democracy level incurs more cost to an oil-importer, this increase leads to higher level of stability in proposed plan; in other words: you gain as you pay.

6. Conclusion and Future Research

After a comprehensive multidisciplinary survey about oil security, supplier selection and risk management; it has been found out that there is a broad research gap in field of selecting a resilient portfolio of oil suppliers. Therefore authors have provided a novel quantitative approach for oil supplier selection in order to overcome oil-supply disruption. Proposed model in the first phase of this study not only takes technical requirements and limitations of oil procurement into account, but also considers qualitative factors such as democracy and political conflicts by using their quantitative indicators. On one hand resiliency is satisfied by taking catastrophic risks into account using scenario-based CVaR approach and on the other hand resiliency is guaranteed by considering political, economic and financial issues simultaneously.

For the proposed model in the second phase, a continuous facility layout model has been provided for determining location and capacity of oil-storage terminals. The proposed model enhances security of oil-storage terminals network by maximizing their dispersion, in addition to improve efficiency of network by minimizing distances between entry, storage and refining ports. Due to the complexity of proposed CFLP model, a meta-heuristic algorithm based on Differential Evolution (DE) has been proposed for solving the mentioned model. Finally validity of proposed models is proved by solving it for Greece case problem. Further investigations show that plans with higher political quality are remarkably more consistent.

In future studies, social unrests in oil exporter countries can be taken into account. Moreover by prevalence of environmental issues, it is appropriate to consider emission-related factors. Furthermore a similar study can be performed on portfolio of energies comprising oil, natural gas and oil-products.

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Appendices

Table A. 1
Characteristics of major oil exporters

No.	Oil exporter	Oil-Dependency (Share of Oil Export income in GDP)*	Length of Pipeline to Greece	Democracy Score**
1	Algeria	33.96%	1830	3.44
2	Angola	59.71%	5315	3.32
3	India	3.87%	5005	7.28
4	Iran	12.28%	3170	1.94
5	Iraq	44.15%	1930	4
6	Kazakhstan	28.74%	3970	3.3
7	Kuwait	61.08%	2400	3.88
8	Libya	74.47%	1110	1.94
9	Malaysia	9.03%	8730	6.19
10	Norway	10.62%	2600	9.8
11	Qatar	59.29%	2970	3.09
12	Russian Federation	14.03%	2230	4.26
13	Saudi Arabia	48.16%	2630	1.84
14	UAE	32.54%	3255	2.52
15	USA	0.79%	8250	8.18

* EconomyWatch) ** Economist (2010)

Table A. 2
Mutual conflicts between major oil suppliers

	Algeria	Angola	India	Iran	Iraq	Kazakhstan	Kuwait	Libya	Malaysia	Norway	Qatar	Russian Federation	Saudi Arabia	UAE	USA
Algeria	0.869	0.000	0.107	0.034	0.066	0.033	0.032	0.034	0.031	0.453	0.032	0.039	0.065	0.032	1.736
Angola		0.844	0.122	0.077	0.035	0.000	0.035	0.036	0.035	0.391	0.036	0.045	0.036	0.000	1.708
India			0.844	0.077	0.075	0.118	0.073	0.080	0.073	0.500	0.073	0.136	0.109	0.074	1.733
Iran				0.960	0.070	0.111	0.034	0.036	0.034	0.596	0.000	0.128	0.000	0.035	1.878
Iraq					0.750	0.035	0.000	0.034	0.032	0.440	0.000	0.122	0.000	0.000	1.654
Kazakhstan						0.750	0.034	0.073	0.067	0.431	0.034	0.080	0.070	0.000	1.640
Kuwait							0.782	0.000	0.000	0.462	0.000	0.078	0.000	0.000	1.660
Libya								0.782	0.000	0.553	0.000	0.085	0.000	0.035	1.720
Malaysia									0.750	0.491	0.000	0.077	0.000	0.032	1.667
Norway										0.000	0.471	0.391	0.480	0.431	1.087
Qatar											0.800	0.080	0.000	0.000	1.692
Russian Federation												0.739	0.083	0.080	1.644
Saudi Arabia													0.782	0.000	1.720
UAE														0.740	1.692
USA															0.957

Table A. 3
Probable excess capacity of major oil suppliers in regular condition Beccue & Huntington (2005)

Region	Excess Capacity (MMDB#)	Probability
Saudi Arabia	0	0.1
	1.5	0.75
	3	0.1
	5	0.05
Other Persian Gulf	0	0.7
	1	0.2
	2	0.05
	3	0.05

MMDB: million barrels per day

Table A. 4
Excess capacity of Persian Gulf countries under each scenario

Exporter	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Iran	0.089	0.089	0.089	0.056	0.056	0.056	0.056	0.089	0.056	0.089	0.089	0.089	0.089	0.111
Iraq	0.076	0.076	0.076	0.048	0.048	0.048	0.048	0.076	0.048	0.076	0.076	0.076	0.076	0.095
Kuwait	0.074	0.074	0.074	0.047	0.047	0.047	0.047	0.074	0.047	0.074	0.074	0.074	0.074	0.093
Qatar	0.037	0.037	0.037	0.023	0.023	0.023	0.023	0.037	0.023	0.037	0.037	0.037	0.037	0.046
Saudi Arabia	1.591	1.591	1.591	1.591	1.591	1.591	1.591	1.340	1.340	0.838	0.838	0.838	0.168	1.675
UAE	0.084	0.084	0.084	0.053	0.053	0.053	0.053	0.084	0.053	0.084	0.084	0.084	0.084	0.105

Table A. 5
Approximate freight cost of one truck from oil-exporters to each port

	Korinthos	Messolongi	Patra	Pireas	Preveza	Thessaloniki	Volos
Algeria	572500	660000	625000	607500	695000	782500	712500
Angola	1792250	1879750	1844750	1827250	1914750	2002250	1932250
India	1764250	1886750	1869250	1746750	1904250	1694250	1729250
Iran	1122000	1244500	1227000	1104500	1262000	1052000	1087000
Iraq	702000	789500	772000	667000	807000	632000	649500
Kazakhstan	1402000	1472000	1507000	1332000	1437000	1227000	1262000
Kuwait	866500	954000	936500	831500	971500	796500	814000
Libya	320500	408000	373000	355500	443000	530500	460500
Malaysia	3068000	3190500	3173000	3050500	3208000	2998000	3033000
Norway	964500	947000	982000	947000	859500	807000	842000
Qatar	1031000	1206000	1171000	996000	1276000	1066000	1013500
Russian Federation	842000	877000	912000	807000	772000	667000	702000
Saudi Arabia	912000	1087000	1052000	877000	1157000	947000	894500
UAE	1130750	1305750	1270750	1095750	1375750	1165750	1113250
USA	2854500	2802000	2767000	2872000	2837000	2977000	2924500

Table A. 6
Construction cost of each pipeline category from each oil-exporter ($)

	100000 MMDB	200000 MMDB	400000 MMDB
Algeria	768600000	1244400000	2013000000
Angola	2232300000	3614200000	5846500000
India	2102100000	3403400000	5505500000
Iran	1331400000	2155600000	3487000000
Iraq	810600000	1312400000	2123000000
Kazakhstan	1667400000	2699600000	4367000000
Kuwait	1008000000	1632000000	2640000000
Libya	466200000	754800000	1221000000
Malaysia	3666600000	5936400000	9603000000
Norway	1092000000	1768000000	2860000000
Qatar	1247400000	2019600000	3267000000
Russian Federation	936600000	1516400000	2453000000
Saudi Arabia	1104600000	1788400000	2893000000
UAE	1367100000	2213400000	3580500000
USA	3465000000	5610000000	9075000000