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A Multi-Mode Natural Gas and Liquefied Natural Gas Supply Chain Management Problem: An Application

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ABSTRACT

Natural Gas (NG) and Liquefied Natural Gas (LNG) are environmentally friendly and cost-competitive energy resources that can be utilized across the globe. In this study, we develop a mixed-integer programming model for NG and LNG supply chains, incorporating the location of liquefaction plants, regasification units, storage facilities, and distribution hubs. The model also addresses the routing of vehicles for inland LNG distribution and cryogenic vessels for sea transportation. Unlike other models in the literature, our model optimizes the location of NG and LNG facilities and vehicle routing for various modes, focusing on cost minimization using the $\boldsymbol{\varepsilon}$ -constraint method. Additionally, different transportation modes, such as sea, road, and pipeline, are integrated for enhanced efficiency and cost reduction. The developed model was applied to Turkey to assess its viability in real-world systems.

Keywords: Mixed Integer Programming; Natural Gas Supply Chain Management; Optimization; ε-constraint method.

INTRODUCTION

Due to the increasing global demand for sustainable energy resources, there is a continuous trend towards utilizing green energy, as Natural Gas (NG) is a cleaner energy source than other fossil fuels such as oil and coal (Al-Haidus et al. 2016). The first phase of NG and LNG supply chain design involves constructing NG and LNG transfer facilities, storage facilities, high-capacity regasification terminals, and distribution capabilities. In the second phase, NG and LNG are transported using various modes, including pipelines, trucks, and vessels. Considering different transportation modes and storage capabilities alongside demand uncertainty, Utku and Soyöz (2020) developed a model to optimize the LNG supply chain. Ursavas et al. (2020) created a mixed-integer programming model related to the structure of an LNG network for a waterway transport system. Another group of studies regarding LNG transportation includes the integrated mathematical model proposed by Zhang et al. (2020), which aims to minimize the total construction and operating costs of the LNG supply. Zhang et al. (2017), Kim et al. (2016), and Alvarez et al. (2019) proposed LNG supply chain designs incorporating different components, while Al-Haidous et al. (2016) and Yavuz and Utku (2021) discussed the challenges of LNG distribution and suggestions for statistical methods to compare alternative systems, respectively. In another study, Msakni et al. (2018) developed a model that optimized net profit. Zarei et al. (2020) created a multi-objective mixed-integer linear programming model for the supply chain network design of multi-product NG. Durmic et al. (2020) utilized the Full Consistency Method for supplier selection, and Ali et al. (2021) examined a complex interval-valued Pythagorean fuzzy set (CIVPFS) for green supplier chain management. To address uncertain demand in waste recycling supply chains, Giri et al. (2020), Utku and Erol (2020), and Samanta and Giri (2021) proposed models for recycling and waste management, including recycling and a two-echelon supply chain model for a single vendor and buyer, respectively.

There is a paucity of studies with respect to the integration of different transportation modes and combined location and routing models for NG and LNG supply chains. We developed a mixed-integer programming (MIP) model that includes the location of facilities in an NG and LNG supply chain and the routing of vehicles for transporting NG and LNG via various transportation modes to customers. We considered the optimal dispersion of facilities to minimize environmental and social impacts. The model's purpose is to develop an NG and LNG supply chain by configuring the infrastructure and network, while satisfying customer demand. The proposed model offers novelty by contributing to the literature in two ways: First, it considers the location and routing of facilities in NG and LNG supply chains with multiple transportation modes and demand uncertainty. Second, the model was developed using the ε-constraint method to convert the bi-objective model into a single-objective model for NG and LNG supply chain problems.

MODELING and METHODOLOGY

NG and LNG facility location and routing problems are strategic issues that result in high costs due to significant fixed and variable expenses. To realize optimal results, it is preferable to use exact methodologies that yield optimal outcomes. Therefore, a mixed-integer programming model for facility location and vehicle routing in NG and LNG supply chains was developed. The objectives were to minimize the transportation and facility location costs. The ε-constraint methodology was employed to solve multi-objective problems by converting them into single-objective problems, as demonstrated in Esmaili et al. (2011) and Janijo and Jayasree (2020). The sets, parameters, and variables of our model are as follows.

Sets	
$Node$	$Set\ of\ nodes;$
I	$Set\ of\ liquefaction\ plants\ i \in I$
J	$Set\ of\ regasification\ plants\ j \in J$
E	$Set\ of\ storage\ area\ e \in E$
H	$Set\ of\ rented\ vessel\ h \in H$
C	$Set\ of\ hub\ \ c \in C$
RP	$Set\ of\ customer\ of\ NG$
SA	$Set\ of\ customer\ of\ LNG$
RV	$Set\ of\ customer\ of\ LNG\ (sea\ transport)$
ID	$Set\ of\ liquefaction\ plants\ located\ on\ the\ West\ side, i \in ID$
IB	$Set\ of\ liquefaction\ plants\ located\ on\ the\ East\ side, i \in IB$
JD	$Set\ of\ regasification\ plants\ located\ on\ the\ West\ side, j \in JD$
JB	$Set\ of\ regasification\ plants\ located\ on\ the\ East\ side, j \in JB$
ED	$Set\ of\ storage\ area\ located\ on\ the\ West\ side, e \in ED$
EB	$Set\ of\ storage\ area\ located\ on\ the\ East\ side, e \in EB$
EP	$Set\ of\ storage\ area\ with\ sea\ transportation, p \in EP$
SAD	$Set\ of\ customer\ of\ LNG\ \ located\ on\ the\ West\ side, sa \in SAD$
SAB	$Set\ of\ customer\ of\ LNG\ (sea\ transport)\ located\ on\ the\ East\ side, sa \in SAB$
IA	$Set\ of\ Liquefaction\ plants\ that\ are\ open, i \in I$

JA Set of Regasification plants that are open, $j \in J$

EA Set of Storage area that are open, $e \in E$

CA Set of Hub that are open, $c \in C$

Parameters

CG Capacity of vessel

CA Capacity of truck

KG Vessel rental cost

KA Truck rental cost

d_{rp} Demand of customer of NG, $rp \in RP$

d_{sa} Demand of customer of LNG , $sa \in SA$

d_{rv} Demand of customer of LNG (sea transport), $rv \in RV$

s^i Potential capacity of liquefaction plants i, $i \in I$

k^j Potential capacity of regasification plants j, $j \in J$

w^e Potential capacity of storage area e, $e \in E$

m^p Potential capacity of storage area with sea transportation, $p \in EP$

r^h Potential capacity of rented vessel h, $h \in H$

t^c Potential capacity of hub c, $c \in C$

U^i LNG cost of Liquefaction plant i per m^3 , $i \in I$

Y^j NG cost of Regasification plant j per m^3, $j \in J$

G^e Holding cost of LNG for storage area e per m^3, $e \in E$

Q^h Holding cost of LNG for rented vessel h per m^3, $h \in H$

fl Fixed cost of liquefaction plant i , $i \in I$

fr Fixed cost of regasification plant j, $j \in J$

fs Fixed cost of storage area e, $e \in E$

fv Rental cost of rented vessel h, $h \in H$

fh Fixed cost of hub c, $c \in C$

$cl^{i,j}$ Cost of shipping of LNG from liquefaction plants i to regasification plant j, $i \in I, j \in J$

$ld^{i,j}$ Distance from liquefaction plants i to regasification plant j, $i \in I, j \in J$

$cs^{i,e}$ Cost of shipping of LNG from Liquefaction plants i to Storage area e per km, $i \in I, e \in E$

$sd^{i,e}$ Distance from Liquefaction plants i to Storage area e, $i \in I, e \in E$

ccs^{p}_{rv} Cost of shipping of LNG from Vessel p to customer of LNG rv for sea transport per km, $p \in EP, rv \in RV$

sdd_{rv}^{p} Distance from Vessel p to customer of LNG rv for sea transport , $p \in EP, rv \in RV$

sc_{sa}^{e} Cost of shipping of LNG from Storage area e to customer of LNG sa per km, $e \in E, sa \in SA$

ds_{sa}^{e} Distance from Storage area e to customer of LNG sa, $e \in E, sa \in SA$

$hd^{h}{}_{sa}$ Distance from Rented vessel h to LNG customer sa, $h \in H, sa \in SAD$

$hhd^{h}{}_{sa}$ Cost of shipping of LNG from Rented vessel h to LNG customer sa per km, $h \in H, sa \in SAD$

ch Cost of shipping of NG from Regasification plants j to Hub c per km, $j \in J, c \in C$

$dh^{j,c}$ Distance from Regasification plants j to Hub c, $j \in J, c \in C$

ck Cost of shipping of NG from Hub c to customer of NG rp per km, $c \in C, rp \in RP$

dk_{rp}^{c} Distance from Hub c to customer of NG rp, $c \in C, rp \in RP$

ε^{loc} Epsilon value of location objective

$Data$ Input data for ε in percentage

$BigM$ A large number

Decision Variables

yl^{i} $\begin{cases} 1, \text{If liquefaction plant } i \text{ is open}, i \in I \\ 0, \text{otherwise} \end{cases}$

yr^{j} $\begin{cases} 1, \text{If regasification plant } j \text{ is open}, j \in J \\ 0, \text{otherwise} \end{cases}$

ys^{e} $\begin{cases} 1, \text{If storage area } e \text{ is open}, e \in E \\ 0, \text{otherwise} \end{cases}$

yv^{h} $\begin{cases} 1, \text{If rented vessel } h \text{ is needed}, h \in H \\ 0, \text{otherwise} \end{cases}$

yh^{c} $\begin{cases} 1, \text{If hub } c \text{ is open}, c \in C \\ 0, \text{otherwise} \end{cases}$

yp^{p} $\begin{cases} 1, \text{If storage area } p \text{ for sea transport is used}, p \in EP \\ 0, \text{otherwise} \end{cases}$

$xr^{i,j}$ Quantity shipped of LNG from Liquefaction plants i to Regasification plants j, $i \in I, j \in J$

$zh^{j,c}$ Quantity shipped of NG from Regasification plants j to Hub c, $j \in J, c \in C$

zr_{rp}^{c} Quantity shipped of NG from Hub c to Customer of NG rp, $c \in C, rp \in RP$

$xs^{i,e}$ Quantity shipped of LNG from Liquefaction plants i to Storage area e, $i \in I, e \in E$

zs_{sa}^{e} Quantity shipped of LNG from Storage area e to Customer of LNG sa, $e \in E, sa \in SA$

$xv^{i,p}$ Quantity shipped of LNG Liquefaction plants i to Storage area e, $i \in I, p \in EP$

zv_{rv}^{p} Quantity shipped of LNG from Storage area e to Customer of LNG rv, $p \in EP, rv \in RV$

$xt^{e,h}$ Quantity shipped of LNG from Storage area e to Rented vessel h, $e \in ED, h \in H$

$zt^{h}{}_{sa}$	$Quantity\ shipped\ of\ LNG\ from\ Rented\ vessel\ h\ to\ Customer\ of\ LNG\ sa, h \in H, sa \in SAD$
GJ	$Number\ of\ vessels\ arriving\ at\ the\ regasification\ j, j \in JD$
GE	$Number\ of\ vessels\ arriving\ at\ the\ storage\ e, e \in ED$
GV	$Number\ of\ vessels\ arriving\ at\ storage\ e, e \in EP$
AJ	$Number\ of\ trucks\ arriving\ at\ the\ regasification\ j, j \in JB$
AE	$Number\ of\ trucks\ arriving\ at\ the\ storage\ e, e \in EB$
ASD	$Number\ of\ trucks\ arriving\ at\ the\ LNG\ customer\ sa, sa \in SAD$
ASB	$Number\ of\ trucks\ arriving\ at\ the\ LNG\ customer\ sa\ , sa \in SAB$

Multi-Mode Location and Routing Model (The Main Model)

In the first model, we propose a bi-objective mixed-integer programming model for the multi-objective multi-mode location and routing model that contains the components of the NG and LNG supply chain designs, as shown in Figure 1 (Appendix).

$$Min\ \sum_{i\in ID}\sum_{e\in ED} cs^{i,e} * sd^{i,e} * GE + \sum_{e\in ED}\sum_{sa\in SA} sc^{e}_{sa} * ds^{e}_{sa} * ASD + \sum_{i\in IB}\sum_{e\in EB} cs^{i,e} * sd^{i,e} * AE + \sum_{e\in EB}\sum_{sa\in SA} sc^{e}_{sa} * ds^{e}_{sa} * ASB + \sum_{i\in ID}\sum_{p\in EP} ccs^{p}_{rv} * ssd^{p}_{rv} * GV + \sum_{c\in C}\sum_{rp\in RP} ck * dk^{c}_{rp} * zr^{c}_{rp} + \sum_{j\in JD}\sum_{c\in C} ch * dh^{j,c} * zh^{j,c} + \sum_{j\in JB}\sum_{c\in C} ch * dh^{j,c} * zh^{j,c} + \sum_{i\in ID}\sum_{j\in JD} cl^{i,j} * dl^{i,j} * GJ + \sum_{h\in H}\sum_{sa\in SAD} hd^{h}_{sa} * hhd^{h}_{sa} * yv^{h} + \sum_{i\in IB}\sum_{j\in JB} cl^{i,j} * dl^{i,j} * AJ + (GJ + GE + GV + GH) * KG + (AJ + AE + ASD + ASB) * KA \quad (1)$$

$$Min\ \sum_{e\in E} fs^{e} * ys^{e} + \sum_{h\in H} fv^{h} * yv^{h} + \sum_{j\in JD} fr^{j} * yr^{j} + \sum_{j\in JB} fr^{j} * yr^{j} + \sum_{i\in ID} fl^{i} * yl^{i} + \sum_{i\in IB} fl^{i} * yl^{i} + \sum_{c\in C} fh^{c} * yh^{c} + \sum_{i\in IB}(\sum_{j\in JB} xr^{i,j} + \sum_{e\in EB} xs^{i,e}) * U^{i}) + \sum_{i\in ID}(\sum_{j\in JD} xr^{i,j} + \sum_{e\in ED} xs^{i,e}) * U^{i}) + \sum_{j\in JB}\sum_{c\in C} zh^{j,c} * Y^{j} + \sum_{j\in JD}\sum_{c\in C} zh^{j,c} * Y^{j} + \sum_{e\in EB}\sum_{sa\in SAB} zs^{e}_{sa} * G^{e} + \sum_{e\in ED}\sum_{sa\in SAD} zs^{e}_{sa} * G^{e} + \sum_{h\in H}\sum_{sa\in SAD} zt^{h}_{sa} * Q^{h} \quad (2)$$

$yl^{i} = 1,\ i \in ID, i \in IA,$ (3); $yr^{j} = 1,\ j \in JB, j \in J,$ (4); $ys^{e} = 1,\quad e \in E\ , e \in EA$ (5)

$$yh^{c} = 1 \qquad c \in C, c \in CA \quad (6)$$

$$\sum_{e\in ED} zs^{e}_{sa} + \sum_{h\in H}\sum_{sa\in SAD} zt^{h,sa} = d_{sa} \qquad \forall sa, sa \in SAD \quad (7)$$

$$\sum_{e\in EB} zs^{e}_{sa} = d_{sa} \qquad \forall sa\ , sa \in SAB \quad (8)$$

$$\sum_{e\in ED}\sum_{sa\in SAD} zs^{e}_{sa} \le \sum_{e\in ED} w^{e} * ys^{e} \quad (9)$$

$$\sum_{e\in EB}\sum_{sa\in SAB} zs^{e}_{sa} \le \sum_{e\in EB} w^{e} * ys^{e} \quad (10)$$

$\sum_{i\in ID} xs^{i,e} \le w^e * ys^e$, (11); $\sum_{i\in IB} xs^{i,e} \le w^e * ys^e, \quad \forall e \in EB$ (12)

$$\sum_{i\in ID} xs^{i,e} = \sum_h xt^{e,h} + \sum_{sa\in SAD} zs_{sa}^{e} \qquad \forall e \in ED \tag{13}$$

$$\sum_{i\in IB} xs^{i,e} = \sum_{sa\in SAB} zs_{sa}^{e} \qquad \forall e \in EB \tag{14}$$

$$\sum_{h\in H}\sum_{e\in ED} xt^{e,h} = \sum_{sa\in SAD} d_{sa} - \sum_{e\in ED}\sum_{sa\in SAD} zs_{sa}^{e} \tag{15}$$

$$\sum_{h\in H}\sum_{e\in ED} xt^{e,h} \le \sum_{h\in H} r^h * yv^h \tag{16}$$

$$\sum_{e\in ED} xt^{e,h} \le r^h * yv^h \tag{17}$$

$$\sum_{e\in ED} xt^{e,h} = \sum_{sa\in SAD} zt_{sa}^{h} \qquad \forall h \in H \tag{18}$$

$$\sum_{p\in EP} zv_{rv}^{p} = d_{rv} \qquad \forall\, rv \in RV \tag{19}$$

$$\sum_{p\in EP}\sum_{rv\in RV} zv_{rv}^{p} \le \sum_{p\in EP} m^p * yp^p \tag{20}$$

$$\sum_{i\in ID} xv^{i,p} \le m^p * yp^p \qquad \forall p \in EP \tag{21}$$

$$\sum_{i\in ID} xv^{i,p} = \sum_{rv\in RV} zv_{rv}^{p} \qquad \forall p \in EP \tag{22}$$

$$\sum_{c\in C} zr_{rp}^{c} = d_{rp} \qquad \forall rp \in RP \tag{23}$$

$$\sum_{c\in C}\sum_{rp\in RP} zr_{rp}^{c} \le \sum_{c\in C} t^c * yh^c \tag{24}$$

$$\sum_{j\in JB} zh^{j,c} + \sum_{j\in JD} zh^{j,c} \le t^c * yh^c \qquad \forall c \in C \tag{25}$$

$$\sum_{j\in JB} zh^{j,c} + \sum_{j\in JD} zh^{j,c} = \sum_{rp\in RP} zr_{rp}^{c} \qquad \forall c \in C \tag{26}$$

$$\sum_{j\in JD}\sum_{c\in C} zh^{j,c} \le \sum_{j\in JD} k^j * yr^j \tag{27}$$

$$\sum_{j\in JB}\sum_{c\in C} zh^{j,c} \le \sum_{j\in JB} k^j * yr^j \tag{28}$$

$$\sum_{i\in ID} xr^{i,j} * 600 \le k^j * yr^j \qquad \forall j \in JD \tag{29}$$

$$\sum_{i\in IB} xr^{i,j} * 600 \le k^j * yr^j \qquad \forall j \in JB \tag{30}$$

$$\sum_{i\in ID} xr^{i,j} * 600 = \sum_{c\in C} zh^{j,c} \qquad \forall j \in JD \tag{31}$$

$$\sum_{i\in IB} xr^{i,j} * 600 \le \sum_{c\in C} zh^{j,c} \qquad \forall j \in JB \tag{32}$$

$$\sum_{i\in ID}\sum_{j\in JD} xr^{i,j} + \sum_{i\in ID}\sum_{e\in ED} xs^{i,e} + \sum_{i\in ID}\sum_{p\in EP} xv^{i,p} \le \sum_{i\in ID} s^i * yl^i \tag{33}$$

$$\sum_{i\in IB}\sum_{j\in JB} xr^{i,j} + \sum_{i\in IB}\sum_{e\in EB} xs^{i,e} \le \sum_{i\in IB} s^i * yl^i \tag{34}$$

$\sum_{j\in J} xr^{i,j} \leq BigM * yl^{i}$ $\quad \forall i \in I$ (35)

$\sum_{e\in E} xs^{i,e} \leq BigM * yl^{i}$ $\quad \forall i \in I$ (36)

$\sum_{p\in EP} xv^{i,p} \leq BigM * yl^{i}$ $\quad \forall i \in ID$ (37)

$\sum_{i\in ID} \sum_{j\in JD} xr^{i,j}/CG = GJ$, (38); $\sum_{i\in ID} \sum_{e\in ED} xs^{i,e}/CG = GE$ (39)

$\sum_{p\in EP} \sum_{rv\in RV} zv^{p}_{rv}/CG = GV,$ (40); $\sum_{i\in IB} \sum_{j\in JB} xr^{i,j}/CA = AJ$ (41)

$\sum_{i\in IB} \sum_{e\in EB} xs^{i,e}/CA = AE,$ (42); $\sum_{e\in ED} \sum_{sa\in SAD} zs^{e}_{sa}/CA = ASD,$ (43)

$\sum_{e\in EB} \sum_{sa\in SAB} zs^{e}_{sa}/CA = ASB,$ (44)

$yl^{i} \in \{0,1\}, \quad i \in I,$ (45); $yr^{j} \in \{0,1\}, \quad j \in J,$ (46); $ys^{e} \in \{0,1\}, \quad e \in E,$ (47)

$yv^{h} \in \{0,1\}, \ h \in H,$ (48); $yh^{c} \in \{0,1\}, \quad c \in C,$ (49); $yp^{p} \in \{0,1\}, \quad p \in EP,$ (50)

$xr^{i,j} \geq 0, \ i \in I, j \in J,$ (51); $zh^{j,c} \geq 0, \ j \in J, c \in C,$ (52); $zr^{c}_{rp} \geq 0, \ c \in C, rp \in RP,$ (53)

$xs^{i,e} \geq 0, \ i \in I, e \in E,$ (54); $zs^{e}_{sa} \geq 0, \quad e \in E, sa \in SA,$ (55); $xv^{i,p} \geq 0, \quad i \in I, p \in EP,$ (56)

$zv^{p}_{rv} \geq 0, \ p \in EP, rv \in RV,$ (57); $xt^{e,h} \geq 0, e \in ED, h \in H,$ (58)

$zt^{h}{}_{sa} \geq 0, \ h \in H, sa \in SAD,$ (59); $J, GE, GV, AJ, AE, ASD, ASB \geq 0$ (60)

Objective functions (1) and (2) aim to minimize transportation and facility location costs, respectively. Constraints (3) – (6) ensure that existing facilities are currently operational. Constraints (7) and (8) address LNG demand. Constraints (9) and (10) allow for the opening of necessary storage areas. Capacity constraints are represented by constraints (11), (12), (17), (21), (25), (29), and (30). Flow balance constraints for storage areas are specified in constraints (13), (14), (18), (22), (26), (31), and (32). Constraint (15) permits excess LNG to be sent to rented vessels. Constraints (16), (24), (27), (28), (33), and (34) enable the opening of required rented vessels. Constraints (19) and (23) are demand constraints for customers satisfied by sea mode. Constraint (20) allows for the renting of necessary vessels. Constraints (35) through (37) permit products to be sent from newly located liquefaction plants. Constraints (38) to (40) determine the number of vessels used. Constraints (41) – (44) ascertain the number of trucks. Binary constraints are presented in constraints (45) – (50), while non-negative constraints are outlined in constraints (51) – (60).

Model for Finding ε-Constraint Bounds for the Facility Location Problem

This model determines the upper and lower bounds of the facility-location model. Objective function (65) aims to minimize the cost of facility location.

$Min \ \sum_{e\in E} fs * ys^{e} + \sum_{h\in H} fv * yv^{h} + \sum_{j\in JD} fr * yr^{j} + \sum_{j\in JB} fr * yr^{j} + \sum_{i\in ID} fl * yl^{i} + \sum_{i\in IB} fl * yl^{i} +$

$\sum_{c\in C} fh * yh^{c} + \sum_{i\in IB}(\sum_{j\in JB} xr^{i,j} + \sum_{e\in EB} xs^{i,e}) * U^{i}) + \sum_{i\in ID}(\sum_{j\in JD} xr^{i,j} + \sum_{e\in ED} xs^{i,e}) * U^{i}) +$

$\sum_{j\in JB}\sum_{c\in C} zh^{j,c} * Y^j + \sum_{j\in JD}\sum_{c\in C} zh^{j,c} * Y^j + \sum_{e\in EB}\sum_{sa\in SAB} zs^e_{sa} * G^e + \sum_{e\in ED}\sum_{sa\in SAD} zs^e_{sa} * G^e +$

$\sum_{h\in H}\sum_{sa\in SAD} zt^h_{sa} * Q^h$ (61)

$$\varepsilon^{loc} = [obj^{location}, obj^{location} * (1 + Data)] \quad (62)$$

Constraints (3)–(37) and constraints (45)–(60).

Single Objective Model with ε-Constraints

This model optimizes the problem by considering only one objective and optimizing the other objectives within the determined bounds.

$Min\ \sum_{i\in ID}\sum_{e\in ED} cs^{i,e} * sd^{i,e} * GE + \sum_{e\in ED}\sum_{sa\in SA} sc^e_{sa} * ds^e_{sa} * ASD + \sum_{i\in IB}\sum_{e\in EB} cs^{i,e} * sd^{i,e} * AE +$

$\sum_{e\in EB}\sum_{sa\in SA} sc^e_{sa} * ds^e_{sa} * ASB + \sum_{i\in ID}\sum_{p\in EP} ccs^p_{rv} * ssd^p_{rv} * GV + \sum_{c\in C}\sum_{rp\in RP} ck^c_{rp} * dk^c_{rp} * zr^c_{rp} +$

$\sum_{j\in JD}\sum_{c\in C} ch^{j,c} * dh^{j,c} * zh^{j,c} + \sum_{j\in JB}\sum_{c\in C} ch^{j,c} * dh^{j,c} * zh^{j,c} + \sum_{i\in ID}\sum_{j\in JD} cl^{i,j} * dl^{i,j} * GJ +$

$\sum_{h\in H}\sum_{sa\in SAD} hd^h_{sa} * hhd^h_{sa} * yv^h + \sum_{i\in IB}\sum_{j\in JB} cl^{i,j} * dl^{i,j} * AJ + (GJ + GE + GV + GH) * KG + (AJ + AE +$

$ASD + ASB) * KA$ (63)

$\sum_{e\in E} fs^e * ys^e + \sum_{h\in H} fv^h * yv^h + \sum_{j\in JD} fr^j * yr^j + \sum_{j\in JB} fr^j * yr^j + \sum_{i\in ID} fl^i * yl^i + \sum_{i\in IB} fl^i * yl^i +$

$\sum_{c\in C} fh^c * yh^c + \sum_{i\in IB}(\sum_{j\in JB} xr^{i,j} + \sum_{e\in EB} xs^{i,e}) * U^i) + \sum_{i\in ID}(\sum_{j\in JD} xr^{i,j} + \sum_{e\in ED} xs^{i,e}) * U^i) +$

$\sum_{j\in JB}\sum_{c\in C} zh^{j,c} * Y^j + \sum_{j\in JD}\sum_{c\in C} zh^{j,c} * Y^j + \sum_{e\in EB}\sum_{sa\in SAB} zs^e_{sa} * G^e + \sum_{e\in ED}\sum_{sa\in SAD} zs^e_{sa} * G^e +$

$\sum_{h\in H}\sum_{sa\in SAD} zt^h_{sa} * Q^h \leq \varepsilon^{loc}$ (64)

Objective function (63) minimizes the transportation cost. Constraint (64) aims to minimize the cost of facilities located within the bounds of ε^{loc}. The other constraints of the models are constraints (3)–(60).

APPLICATION OF THE MODEL IN TURKEY

The developed multi-mode NG and LNG supply chain location and routing problem was applied to Turkey to test the model in a real-world environment. The data used in the application of the model can be found in the Appendix. The problem was solved using GAMS 24.1.3. In the model, in addition to existing facilities in Turkey, candidate facilities are listed in Table 1 (Appendix). When solving only the facility location problem, considering the generated normally distributed customer demand data, we observe that three additional liquefaction plants, three regasification plants, six storage areas, and four hubs are opened, as stated in Table 1 (Appendix). However, using the ε-constraint values, the facility locations change, as shown in Table 2 (Appendix). Two liquefaction plants, three regasification plants, six storage areas, and five hubs are also opened. In Table 3 (Appendix), the routes and related transportation modes used for transporting LNG from liquefaction plants to regasification plants are presented, based on the location and routing problem solved using the ε-constraint method. In Table 4 (Appendix), the routes and related transportation modes used for transporting NG from regasification plants to hubs are presented, according to the location and routing problem solved using the ε-constraint method. The number of vehicles used in each transportation mode is listed in Table 5 (Appendix). We can observe that all transportation modes are utilized, with vessels employed in coastal regions and trucks and pipelines used in inland regions. When comparing our results with the existing literature, we determine that no study has incorporated multi-mode transportation. The results of this application provide an optimal location and routing policy for effective management of NG and LNG supply chain management.

CONCLUSION

A model for the multi-mode NG and LNG supply chain location and routing problem is developed, and the ε – constraint method is used to solve this problem by converting it into a single-objective mixed-integer programming problem. The model employs multi-mode transportation. The model was applied to Turkey using available data. This study contributes to the literature by developing an NG and LNG supply chain design model that considers the location and routing of facilities in the NG and LNG supply chain with multiple transportation modes and demand uncertainty, using the ε–constraint method to solve the problem—an approach not found in existing literature. The developed model can be used for strategic planning of NG and LNG as part of an energy portfolio for large-scale planning. Given that location and routing problems are NP-hard class problems, as the number of potential location alternatives and transportation nodes increase, solving the problem using mixed-integer programming with the ε-constraint method becomes challenging. Developing and using heuristic algorithms to solve these more complex problems, including facility location in the NG and LNG supply chain and the use of different transportation modes alongside their routes, can be a topic for future research. The location and routing model can be enhanced by incorporating stochastic demand for NG and LNG as well as lead times. Additionally, researchers may develop a combination of a digital twin and an optimization model for NG and LNG supply chains, aiding decision-makers in selecting alternative designs as another future research suggestion.

APPENDIX

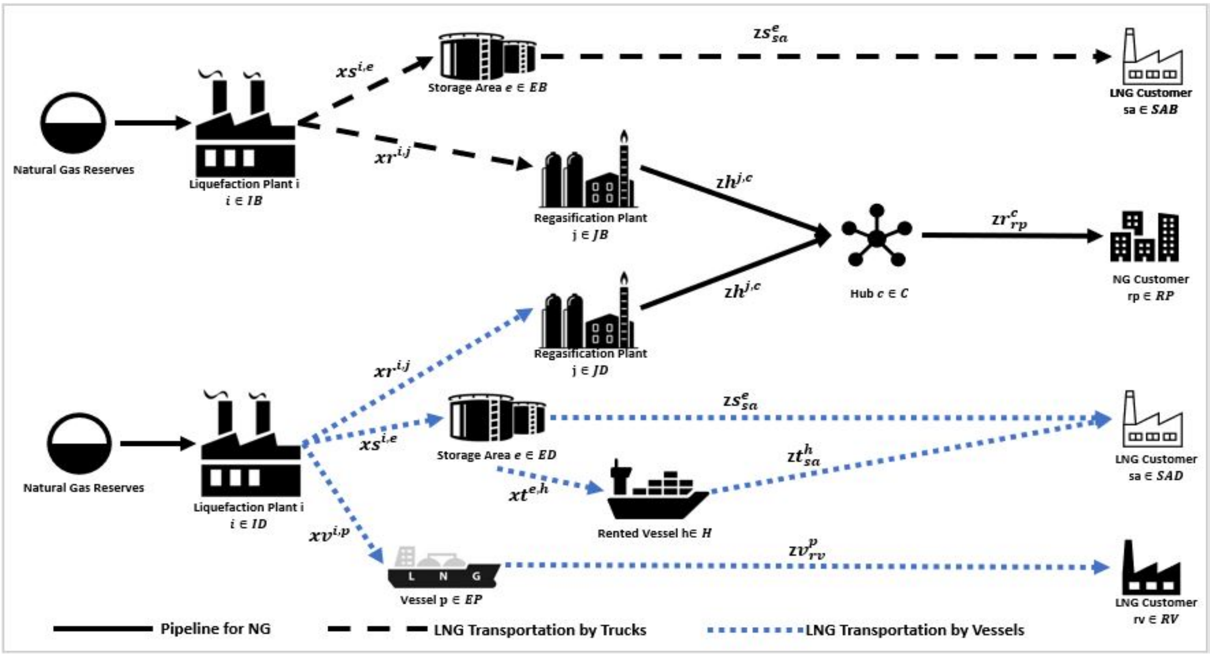

Figure 1. NG and LNG supply chain design in the proposed model.

Table 1. Results of facility location problem to determine ε-constraint values (Only the location problem)

Liquefaction Plants		Liquefaction Plants Opened
Existing Facilities	Marmara Eregli LNG Plant	Marmara Eregli LNG Plant
	Aliaga LNG Plant	Aliaga LNG Plant
Candidate Facilities	Samsun	Samsun
	Canakkale	Canakkale
	Bursa	Bursa
	Erzurum	
	Kahramanmaras	
Regasification Plants		**Regasification Plants Opened**
Existing Facilities	Aliaga FSRU	Aliaga FSRU
Candidate Facilities	Silivri	
	Tuzgolu	
	Saros	
	Dortyol	
	Mersin	
	Erzurum	Erzurum
	Kahramanmaras	Kahramanmaras
	Samsun	Samsun
Storage Areas		**Storage Areas Opened**
Existing Facilities	Silivri LNG Storage	Silivri LNG Storage
	Tuzgolu LNG Storage	Tuzgolu LNG Storage
Candidate Facilities	Marmara Eregli (1)	
	Marmara Eregli (2)	
	Marmara Eregli (3)	Marmara Eregli (3)
	Samsun	Samsun
	Mersin	Mersin
	Bursa	Bursa
	Erzurum	Erzurum
	Kahramanmaras	Kahramanmaras
Hubs		**Hubs Opened**
Existing Facilities	Eskisehir Hub	Eskisehir Hub
Candidate Facilities	Erzincan	Erzincan
	Sivas	Sivas
	Corum	Corum
	Konya	Konya

Table 2. Results of location and vehicle routing problem with location ε-constraint values

Liquefaction Plants		Liquefaction Plants Opened
Existing Facilities	Marmara Eregli LNG Plant	Marmara Eregli LNG Plant
	Aliaga LNG Plant	Aliaga LNG Plant
Candidate Facilities	Samsun	
	Canakkale	Canakkale
	Bursa	Bursa
	Erzurum	
	Kahramanmaras	
Regasification Plants		**Regasification Plants Opened**
Existing Facilities	Aliaga Fsru	Aliaga Fsru
Candidate Facilities	Silivri	
	Tuzgolu	
	Saros	
	Dortyol	
	Mersin	
	Erzurum	Erzurum
	Kahramanmaras	Kahramanmaras
	Samsun	Samsun
Storage Areas		**Storage Areas Opened**
Existing Facilities	Silivri LNG Storage	Silivri LNG Storage
	Tuzgolu LNG Storage	Tuzgolu LNG Storage
Candidate Facilities	Marmara Eregli (1)	
	Marmara Eregli (2)	
	Marmara Eregli (3)	Marmara Eregli (3)
	Samsun	Samsun
	Mersin	Mersin
	Bursa	Bursa
	Erzurum	Erzurum
	Kahramanmaras	Kahramanmaras
Hubs		**Hubs Opened**
Existing Facilities	Eskisehir Hub	Eskisehir Hub
Candidate Facilities	Erzincan	Erzincan
	Sivas	Sivas
	Corum	Corum
	Konya	Konya

Table 3. Transportation modes that are used for the transportation of LNG

LNG transportation from Liquefaction Plant to Regasification Plant	Transportation Modes
Aliaga LNG Plant - Aliaga FSRU	Vessel
Marmara Eregli LNG Plant - Kahramanmaras Regasification	Truck
Canakkale Liquefaction - Erzurum Regasification	Truck
Bursa Liquefaction - Samsun Regasification	Truck
LNG transportation from Liquefaction Plant to Storage Area	
Marmara Eregli LNG Plant - Samsun Storage	Vessel
Aliaga LNG Plant - Silivri Storage	Vessel
Aliaga LNG Plant - Mersin Storage	Vessel
Aliaga LNG Plant - Bursa Storage	Vessel
Marmara Eregli LNG Plant - Tuzgolu Storage	Truck
Marmara Eregli LNG Plant - Kahramanmaras Storage	Truck
Aliaga LNG Plant - Marmara Eregli Storage(3)	Truck
Aliaga LNG Plant - Erzurum Storage	Truck
LNG transportation from Liquefaction Plant to LNG Customer (sea transportation)	
Marmara Eregli LNG Plant – Antalya	Vessel
Marmara Eregli LNG Plant – Mersin	Vessel
Aliaga LNG Plant – Mugla	Vessel
Aliaga LNG Plant – Zonguldak	Vessel
Aliaga LNG Plant – Trabzon	Vessel

Table 4. Transportation modes that are used for the transportation of NG

NG transportation from Regasification Plant to Hub	Transportation Modes
Aliaga FSRU - Eskisehir Hub Erzurum Regasification - Erzincan Hub Maras Regasification - Sivas Hub Maras Regasification - Konya Hub Samsun Regasification - Eskisehir Hub Samsun Regasification - Corum Hub	Pipeline
NG transportation from Hub to NG Customer	
Eskisehir Hub – Bilecik Erzincan Hub – Erzurum Erzincan Hub – Diyarbakır Sivas Hub – Kayseri Sivas Hub – Diyarbakır Corum Hub – Ankara Corum Hub – Kayseri Konya Hub – Karaman	Pipeline

Table 5. Utilization of vehicles in each transportation mode

Modes of Transportation Used	Number of Vehicles Used
Number of Vessels Arriving at The Regasification Plants	12
Number of Vessels Arriving at The Storage Areas	363
Number of Vessels Arriving at LNG Customer (Sea Transportation)	57
Number of Utilized Rented Vessels	0
Number of Trucks Arriving at The Regasification Plants	1309
Number of Trucks Arriving at The Storage Areas	2078
Number of Trucks Arriving at The LNG Customer	3286

OTHER DATA USED IN THE MODEL

In the application of the multi-mode natural gas and liquefied natural gas supply chain management problem, in addition to the current facilities located in Turkey, hypothetically created candidate facilities are also considered. Two liquefaction plants are currently located in Turkey: the Marmara Ereglisi and Aliaga LNG plants. In addition to these plants, we identified five candidate liquefaction plants: Samsun, Canakkale, Bursa, Erzurum, and Kahramanmaras. Existing liquefaction plants have LNG capacities of approximately 61 thousand and 65 thousand m^3.

The Aliaga regasification plant is located in Turkey. The regasification plant also serves as a storage area. Candidate regasification plants include Silivri, Tuzgolu, Saros, Dortyol, Mersin, Erzurum, Kahramanmaras, and Samsun. The capacity of the gasification facility is approximately 20 million m^3 of NG. The LNG storage area capacities range from approximately 5,000 to 40,000 m^3. According to Article 315 of the Tax Procedure Law (Vergi Usulü Kanunu) in Turkey, the depreciation rate, one of the parameters required for facility location, is multiplied by a predetermined fee to determine plant costs. The distance between the facilities required for the vehicle-routing part of the proposed model was obtained from the official website of the Ministry of Transport and Infrastructure of the Republic of Turkey. The costs used in the sample were transportation tariffs specified by the Energy Market Regulatory Board of the Republic of Turkey. The LNG capacity of the cryogenic trucks was approximately 60 m^3. The number of vessels used for sea transportation of LNG was five tankers, and the capacity of the vessels was approximately 300 m^3 of LNG. It is assumed that the customers' NG and LNG demands are normally distributed, and a 90% Cycle Service Level is not considered to prevent the supply chain from running short of NG and LNG. The Silivri and Tuzgolu LNG storage areas are the existing storage areas. The candidate storage areas were Marmara Ereglisi (1), Marmara Ereglisi (2), Marmara Ereglisi (3), Samsun, Mersin, Bursa, Erzurum, and Kahramanmaras. The existing hub is the Eskisehir hub. The candidate hubs were Erzincan, Sivas, Corum, and Konya.

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