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

DOI : 10.36909/jer.17465

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ABSTRACT

Natural Gas (NG) and Liquefied Natural Gas (LNG) are environmentally friendly and price-competitive energy resources that can be used in every part of the world. In this study, we develop a mixed-integer programming model for the NG and LNG supply chain that includes the location of liquefaction plants, regasification units, storage facilities, and distribution hubs together with the routing of the vehicles for inland distribution of LNG and cryogenic vessels for sea transportation. Unlike other models in the literature, the location of the NG and LNG facilities and routing of vehicles of different modes are optimized by considering the minimization of costs by using the $\boldsymbol{\varepsilon}$ – Constraint method, and different transportation modes, like sea, road, and pipeline, are used together for better effectiveness and cost reduction. The developed model is applied to Turkey to check whether the model is viable for real-world systems.

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

INTRODUCTION

Due to the global demand for sustainable energy resources rising, there is a continuous trend for the use of green energy, since NG demand is a cleaner energy source than the other fossil energies such as oil and coal (Al-Haidus et al. 2016). The first phase of the NG and LNG supply chain design includes building NG and LNG transfer facilities, storage facilities, high-capacity regasification terminals, and distribution capabilities. In the second phase, the NG and LNG are transported by different transportation modes via pipelines, trucks, and vessels. By considering different modes of transportation and storage capabilities with demand uncertainty, Utku and Soyöz (2020) develop a model to optimize the LNG supply chain. For only the waterway transport system, Ursavas et al. (2020) develop a mixed-integer programming model related to the structure of an LNG network through. Another group of studies related to LNG transportation is an integrated mathematical model that is proposed by Zhang et al. (2020) that 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) propose LNG supply chain designs including different components while Al-Haidous et al. (2016) and Yavuz and Utku (2021) are the problems of LNG distribution and suggestions of statistical methods for the comparisons of alternative systems, respectively. In a different study, Msakni et al. (2018) develop a model that optimizes the net profit. One of the multiobjective is mixed-integer linear programming model for a supply chain network design of multi-product NG is Zarei et al. (2020). Durmic et al. (2020) use the Full Consistency Method for the supplier selection and Ali et al. (2021) study a complex interval-valued Pythagorean fuzzy set (CIVPFS) for the green supplier chain management. To cope with the uncertain demand for a waste recycling supply chain, Giri et al. (2020), Utku and Erol (2020), and Samanta and Giri (2021) propose models for recycling, waste management including recycling, and a two-echelon supply chain model for a single vendor and buyer, respectively.

We see that in the literature there is a gap that takes into account the use of different transportation modes and an integrated location and routing model for the NG and LNG supply chain. We develop a MIP model that includes the location of facilities in an NG and LNG Supply chain and routing of the vehicles for the transportation of the NG and LNG via different transportation modes to the customers. We consider the proper dispersion of the facilities for the minimization of the environmental and social aspects. The purpose of the model is to develop an NG and LNG supply chain by making a configuration of the supply chain infrastructure and network together with the satisfaction of customer demand. According to the literature discussed above, the proposed model has novelty by contributing to the literature in two ways: First, the model considers the location and routing of the facilities in the NG and LNG supply chain with multiple transportation modes and demand uncertainty. Second, the model is developed by using the ε-constraint method to convert the bi-objective model to a single objective model for an NG and LNG supply chain problem.

MODELING and METHODOLOGY

NG and LNG facility location and routing problems are strategic problems that end with high costs as a result of the high fixed and variable costs. In order to obtain optimal results, if possible, it's better to use exact methodologies that help optimum results. Thus, a mixed-integer programming model for the location the routing of the vehicles for an NG and LNG supply chain is developed. The objectives are the minimization of the cost of transportation and the location of the facilities. The ε-constraint methodology is used to solve the multiobjective problems by converting them into single-objective problems as in Esmaili et al. (2011) and Janijo & 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^p_{rv} $Distance\ from\ \ Vessel\ p\ to\ customer\ of\ LNG\ rvfor\ sea\ transport\ , p \in EP, rv \in RV$

sc^e_{sa} $Cost\ of\ shipping\ of\ LNG\ from\ Storage\ area\ e\ to\ customer\ of\ LNG\ sa\ per\ km,$

$e \in E, sa \in SA$

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

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

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

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

ε^{loc} $Epsilon\ value\ of\ location\ objective$

$Data$ $Input\ data\ for\ \varepsilon\ in\ percentage$

$BigM$ $A\ large\ number$

$Decision\ Variables$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$zt^{h}{}_{sa}$ $Quantity\ shipped\ of\ LNG\ from\ Rented\ vessel\ h\ to\ Customer\ of\ LNG\ sa, h \in H, sa \in SAD$

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	$Number\ of\ trucks\ arriving\ at\ the\ LNG\ customer\ sa\ , sa \in SAB$

The 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 design as shown in Figure 1 (in the Appendices section).

$$Min\ \sum_{i\in ID}\sum_{e\in ED} cs^{i,e} * sd^{i,e} * GE + \sum_{e\in ED}\sum_{sa\in SA} sc_{sa}^{e} * ds_{sa}^{e} * ASD + \sum_{i\in IB}\sum_{e\in EB} cs^{i,e} * sd^{i,e} * AE + \sum_{e\in EB}\sum_{sa\in SA} sc_{sa}^{e} * ds_{sa}^{e} * ASB + \sum_{i\in ID}\sum_{p\in EP} ccs_{rv}^{p} * ssd_{rv}^{p} * GV + \sum_{c\in C}\sum_{rp\in RP} ck * dk_{rp}^{c} * zr_{rp}^{c} + \sum_{j\in JD}\sum_{c\in C} ch * dh^{j,c} * zh^{j,c} + \sum_{j\in JB}\sum_{c\in C} ch * dh^{j,c} * zh^{j,c} + \sum_{i\in ID}\sum_{j\in JD} cl^{i,j} * dl^{i,j} * GJ + \sum_{h\in H}\sum_{sa\in SAD} hd_{sa}^{h} * hhd_{sa}^{h} * yv^{h} + \sum_{i\in IB}\sum_{j\in JB} cl^{i,j} * dl^{i,j} * AJ + (GJ + GE + GV + GH) * KG + (AJ + AE + ASD + ASB) * KA \quad (5)$$

$$Min\ \sum_{e\in E} fs^{e} * ys^{e} + \sum_{h\in H} fv^{h} * yv^{h} + \sum_{j\in JD} fr^{j} * yr^{j} + \sum_{j\in JB} fr^{j} * yr^{j} + \sum_{i\in ID} fl^{i} * yl^{i} + \sum_{i\in IB} fl^{i} * yl^{i} + \sum_{c\in C} fh^{c} * yh^{c} + \sum_{i\in IB}(\sum_{j\in JB} xr^{i,j} + \sum_{e\in EB} xs^{i,e}) * U^{i}) + \sum_{i\in ID}(\sum_{j\in JD} xr^{i,j} + \sum_{e\in ED} xs^{i,e}) * U^{i}) + \sum_{j\in JB}\sum_{c\in C} zh^{j,c} * Y^{j} + \sum_{j\in JD}\sum_{c\in C} zh^{j,c} * Y^{j} + \sum_{e\in EB}\sum_{sa\in SAB} zs_{sa}^{e} * G^{e} + \sum_{e\in ED}\sum_{sa\in SAD} zs_{sa}^{e} * G^{e} + \sum_{h\in H}\sum_{sa\in SAD} zt_{sa}^{h} * Q^{h} \quad (6)$$

$$yl^{i} = 1,\ \ i \in ID, i \in IA,\ (7);\ \ yr^{j} = 1,\ \ j \in JB, j \in J,\ (8);\ ys^{e} = 1,\ \ \ e \in E\ , e \in EA \quad (9)$$

$$yh^{c} = 1 \qquad c \in C, c \in CA \quad (10)$$

$$\sum_{e\in ED} zs_{sa}^{e} + \sum_{h\in H}\sum_{sa\in SAD} zt^{h,sa} = d_{sa} \qquad \forall sa, sa \in SAD \quad (11)$$

$$\sum_{e\in EB} zs_{sa}^{e} = d_{sa} \qquad \forall sa\ , sa \in SAB \quad (12)$$

$$\sum_{e\in ED}\sum_{sa\in SAD} zs_{sa}^{e} \leq \sum_{e\in ED} w^{e} * ys^{e} \quad (13)$$

$$\sum_{e\in EB}\sum_{sa\in SAB} zs_{sa}^{e} \leq \sum_{e\in EB} w^{e} * ys^{e} \quad (14)$$

$\sum_{i \in ID} xs^{i,e} \leq w^e * ys^e$, (15); $\sum_{i \in IB} xs^{i,e} \leq w^e * ys^e$, $\forall e \in EB$ (16)

$$\sum_{i \in ID} xs^{i,e} = \sum_{h} xt^{e,h} + \sum_{sa \in SAD} zs_{sa}^{e} \quad \forall e \in ED \quad (17)$$

$$\sum_{i \in IB} xs^{i,e} = \sum_{sa \in SAB} zs_{sa}^{e} \quad \forall e \in EB \quad (18)$$

$$\sum_{h \in H} \sum_{e \in ED} xt^{e,h} = \sum_{sa \in SAD} d_{sa} - \sum_{e \in ED} \sum_{sa \in SAD} zs_{sa}^{e} \quad (19)$$

$$\sum_{h \in H} \sum_{e \in ED} xt^{e,h} \leq \sum_{h \in H} r^h * yv^h \quad (20)$$

$$\sum_{e \in ED} xt^{e,h} \leq r^h * yv^h \quad (21)$$

$$\sum_{e \in ED} xt^{e,h} = \sum_{sa \in SAD} zt_{sa}^{h} \quad \forall h \in H \quad (22)$$

$$\sum_{p \in EP} zv_{rv}^{p} = d_{rv} \quad \forall\, rv \in RV \quad (23)$$

$$\sum_{p \in EP} \sum_{rv \in RV} zv_{rv}^{p} \leq \sum_{p \in EP} m^p * yp^p \quad (24)$$

$$\sum_{i \in ID} xv^{i,p} \leq m^p * yp^p \quad \forall p \in EP \quad (25)$$

$$\sum_{i \in ID} xv^{i,p} = \sum_{rv \in RV} zv_{rv}^{p} \quad \forall p \in EP \quad (26)$$

$$\sum_{c \in C} zr_{rp}^{c} = d_{rp} \quad \forall rp \in RP \quad (27)$$

$$\sum_{c \in C} \sum_{rp \in RP} zr_{rp}^{c} \leq \sum_{c \in C} t^c * yh^c \quad (28)$$

$$\sum_{j \in JB} zh^{j,c} + \sum_{j \in JD} zh^{j,c} \leq t^c * yh^c \quad \forall c \in C \quad (29)$$

$$\sum_{j \in JB} zh^{j,c} + \sum_{j \in JD} zh^{j,c} = \sum_{rp \in RP} zr_{rp}^{c} \quad \forall c \in C \quad (30)$$

$$\sum_{j \in JD} \sum_{c \in C} zh^{j,c} \leq \sum_{j \in JD} k^j * yr^j \quad (31)$$

$$\sum_{j \in JB} \sum_{c \in C} zh^{j,c} \leq \sum_{j \in JB} k^j * yr^j \quad (32)$$

$$\sum_{i \in ID} xr^{i,j} * 600 \leq k^j * yr^j \quad \forall j \in JD \quad (33)$$

$$\sum_{i \in IB} xr^{i,j} * 600 \leq k^j * yr^j \quad \forall j \in JB \quad (34)$$

$$\sum_{i \in ID} xr^{i,j} * 600 = \sum_{c \in C} zh^{j,c} \quad \forall j \in JD \quad (35)$$

$\sum_{i\in IB} xr^{i,j} * 600 \leq \sum_{c\in C} zh^{j,c}$ $\forall j \in JB$ (36)

$\sum_{i\in ID}\sum_{j\in JD} xr^{i,j} + \sum_{i\in ID}\sum_{e\in ED} xs^{i,e} + \sum_{i\in ID}\sum_{p\in EP} xv^{i,p} \leq \sum_{i\in ID} s^{i} * yl^{i}$ (37)

$\sum_{i\in IB}\sum_{j\in JB} xr^{i,j} + \sum_{i\in IB}\sum_{e\in EB} xs^{i,e} \leq \sum_{i\in IB} s^{i} * yl^{i}$ (38)

$\sum_{j\in J} xr^{i,j} \leq BigM * yl^{i}$ $\forall i \in I$ (39)

$\sum_{e\in E} xs^{i,e} \leq BigM * yl^{i}$ $\forall i \in I$ (40)

$\sum_{p\in EP} xv^{i,p} \leq BigM * yl^{i}$ $\forall i \in ID$ (41)

$\sum_{i\in ID}\sum_{j\in JD} xr^{i,j}/CG = GJ$, (42); $\sum_{i\in ID}\sum_{e\in ED} xs^{i,e}/CG = GE$ (43)

$\sum_{p\in EP}\sum_{rv\in RV} zv_{rv}^{p}/CG = GV$, (44); $\sum_{i\in IB}\sum_{j\in JB} xr^{i,j}/CA = AJ$ (45)

$\sum_{i\in IB}\sum_{e\in EB} xs^{i,e}/CA = AE$, (46); $\sum_{e\in ED}\sum_{sa\in SAD} zs_{sa}^{e}/CA = ASD$, (47)

$\sum_{e\in EB}\sum_{sa\in SAB} zs_{sa}^{e}/CA = ASB$, (48)

$yl^{i} \in \{0,1\}$, $i \in I$, (49); $yr^{j} \in \{0,1\}$, $j \in J$, (50); $ys^{e} \in \{0,1\}$, $e \in E$, (51)

$yv^{h} \in \{0,1\}$, $h \in H$, (52); $yh^{c} \in \{0,1\}$, $c \in C$, (53); $yp^{p} \in \{0,1\}$, $p \in EP$, (54)

$xr^{i,j} \geq 0$, $i \in I, j \in J$, (55); $zh^{j,c} \geq 0$, $j \in J, c \in C$, (56); $zr_{rp}^{c} \geq 0$, $c \in C, rp \in RP$, (57)

$xs^{i,e} \geq 0$, $i \in I, e \in E$, (58); $zs_{sa}^{e} \geq 0$, $e \in E, sa \in SA$, (59); $xv^{i,p} \geq 0$, $i \in I, p \in EP$, (60)

$zv_{rv}^{p} \geq 0$, $p \in EP, rv \in RV$, (61); $xt^{e,h} \geq 0, e \in ED, h \in H$, (62)

$zt^{h}{}_{sa} \geq 0$, $h \in H, sa \in SAD$, (63); $J, GE, GV, AJ, AE, ASD, ASB \geq 0$ (64)

The objective function (5) and (6) aim to minimize the transportation cost and the cost of facility location, respectively. (7) – (10) ensure that the existing facilities are currently open. (11) and (12) are LNG demand constraints. Constraints (13) and (14) allow the opening of the required storage areas. (15), (16), (21), (25), (29), (33), (34) are capacity constraints. (17), (18), (22), (26), (30), (35) and (36) are flow balance constraints for storage areas. The constraints (19) allow the excess LNG to be sent to the rented vessels. Constraints (20), (28), (31), (32), (37), and (38) allow the opening of the required rented vessels. Constraints (23) and (27) are demand constraints for the customers satisfied by sea mode. Constraints (24) allow renting the required vessel. Constraints (39) – (41) allow products to be sent from the newly located liquefaction plants. Constraints (42) – (44) determine the number of vessels used. Constraints (45) – (48) determine the number of trucks used. Constraints (49) – (54) are binary constraints and the constraints (55) – (64) are the non-negativity constraints.

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

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

$$Min\ \sum_{e\in E} fs * ys^e + \sum_{h\in H} fv * yv^h + \sum_{j\in JD} fr * yr^j + \sum_{j\in JB} fr * yr^j + \sum_{i\in ID} fl * yl^i + \sum_{i\in IB} fl * yl^i + \sum_{c\in C} fh * yh^c + \sum_{i\in IB}(\sum_{j\in JB} xr^{i,j} + \sum_{e\in EB} xs^{i,e}) * U^i) + \sum_{i\in ID}(\sum_{j\in JD} xr^{i,j} + \sum_{e\in ED} xs^{i,e}) * U^i) + \sum_{j\in JB}\sum_{c\in C} zh^{j,c} * Y^j + \sum_{j\in JD}\sum_{c\in C} zh^{j,c} * Y^j + \sum_{e\in EB}\sum_{sa\in SAB} zs_{sa}^e * G^e + \sum_{e\in ED}\sum_{sa\in SAD} zs_{sa}^e * G^e + \sum_{h\in H}\sum_{sa\in SAD} zt_{sa}^h * Q^h \quad (65)$$

$$\varepsilon^{loc} = \left[obj^{location}, obj^{location} * (1 + Data)\right] \quad (66)$$

The constraints from (7) to (41) and the constraints from (49) to (64).

The Single Objective Model with ε-Constraints

This is the model that optimizes the problem by considering only one objective and trying to optimize the other objectives within the bounds determined.

$$Min\ \sum_{i\in ID}\sum_{e\in ED} cs^{i,e} * sd^{i,e} * GE + \sum_{e\in ED}\sum_{sa\in SA} sc_{sa}^e * ds_{sa}^e * ASD + \sum_{i\in IB}\sum_{e\in EB} cs^{i,e} * sd^{i,e} * AE + \sum_{e\in EB}\sum_{sa\in SA} sc_{sa}^e * ds_{sa}^e * ASB + \sum_{i\in ID}\sum_{p\in EP} ccs_{rv}^p * ssd_{rv}^p * GV + \sum_{c\in C}\sum_{rp\in RP} ck_{rp}^c * dk_{rp}^c * zr_{rp}^c + \sum_{j\in JD}\sum_{c\in C} ch^{j,c} * dh^{j,c} * zh^{j,c} + \sum_{j\in JB}\sum_{c\in C} ch^{j,c} * dh^{j,c} * zh^{j,c} + \sum_{i\in ID}\sum_{j\in JD} cl^{i,j} * dl^{i,j} * GJ + \sum_{h\in H}\sum_{sa\in SAD} hd_{sa}^h * hhd_{sa}^h * yv^h + \sum_{i\in IB}\sum_{j\in JB} cl^{i,j} * dl^{i,j} * AJ + (GJ + GE + GV + GH) * KG + (AJ + AE + ASD + ASB) * KA \quad (67)$$

$$\sum_{e\in E} fs^e * ys^e + \sum_{h\in H} fv^h * yv^h + \sum_{j\in JD} fr^j * yr^j + \sum_{j\in JB} fr^j * yr^j + \sum_{i\in ID} fl^i * yl^i + \sum_{i\in IB} fl^i * yl^i + \sum_{c\in C} fh^c * yh^c + \sum_{i\in IB}(\sum_{j\in JB} xr^{i,j} + \sum_{e\in EB} xs^{i,e}) * U^i) + \sum_{i\in ID}(\sum_{j\in JD} xr^{i,j} + \sum_{e\in ED} xs^{i,e}) * U^i) + \sum_{j\in JB}\sum_{c\in C} zh^{j,c} * Y^j + \sum_{j\in JD}\sum_{c\in C} zh^{j,c} * Y^j + \sum_{e\in EB}\sum_{sa\in SAB} zs^e_{sa} * G^e + \sum_{e\in ED}\sum_{sa\in SAD} zs^e_{sa} * G^e + \sum_{h\in H}\sum_{sa\in SAD} zt^h_{sa} * Q^h \leq \varepsilon^{loc} \quad (68)$$

The objective function (67) minimizes the transportation cost. The constraints (68) aim to minimize the cost of the facilities located within the bounds of ε^{loc}. The other constraints of the models are the constraints (7) to (64).

APPLICATION OF THE MODEL IN TURKEY

The developed multi-mode NG and LNG supply chain location and routing problem is applied to Turkey to test the problem in a real environment. The data that is used in the application of the model is presented in the Appendices section. The generated problem is solved by using GAMS 24.1.3. In the model, in addition to the current facilities that are located in Turkey, there are candidate facilities stated in Table 1 (in the Appendices section). When we solve only the facility location problem considering the generated normally distributed customer demand data, we see that three liquefaction plants, three regasification plants, six storage areas, and four hubs are additionally opened as stated in Table 1 (in the Appendices section); however, using the ε-constraint values the location of the facilities change as in Table 2 (in the Appendices section). That is: two liquefaction plants, three regasification plants, six storage areas, and five hubs are opened. In Table 3 (in the Appendices section), routes and the related transportation modes used for the transportation of LNG from liquefaction plants to regasification plants are presented according to the location and routing problem which is solved using the ε-constraint method. In Table 4 (in the Appendices section), routes and the related transportation modes used for the transportation of NG from regasification plants to hubs are presented according to the location and routing problem which is solved using the ε-constraint method. Consequently, the number of vehicles that are used in each transportation mode is stated In Table 5(in the

Appendices section). We see that all transportation modes are used. In the coastal regions vessels are used while in the inland regions the trucks and pipelines are used. When we compare with the existing literature until now, we see that no study includes multi-mode transportation. The results of the application give us an optimal location and routing policy for effective management of the 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 $\boldsymbol{\varepsilon}$ – constraint method is used to solve this problem by converting the problem to a single objective mixed integer programming problem. A multi-mode transportation capability is made use of in the model. The model is applied to Turkey by 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 the facilities in the NG and LNG supply chain with multiple transportation modes with demand uncertainty by using the ε – constraint method to solve the problem that is not included in the literature. The developed model can be used for the strategic planning of NG and LNG as part of an energy portfolio for large-scale planning. Since the location and routing problems are NP-hard class problems, as the number of potential location alternatives and the nodes of the transportation increases, it becomes difficult to solve the problem by using mixed-integer programming using ε – constraint method. Developing and using heuristic algorithms to solve these kinds of higher levels of complex problems including the location of the facilities in the NG and LNG supply chain and the use of the different transportation modes together with their routes can be a future study. The location and routing model can be enhanced by using stochastic demand of NG and LNG and lead times. Additionally, the researchers may develop a combination of a digital twin and an optimization model of NG and LNG supply chain that helps the decision-makers to decide on alternative designs as another future research suggestion.

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APPENDICES

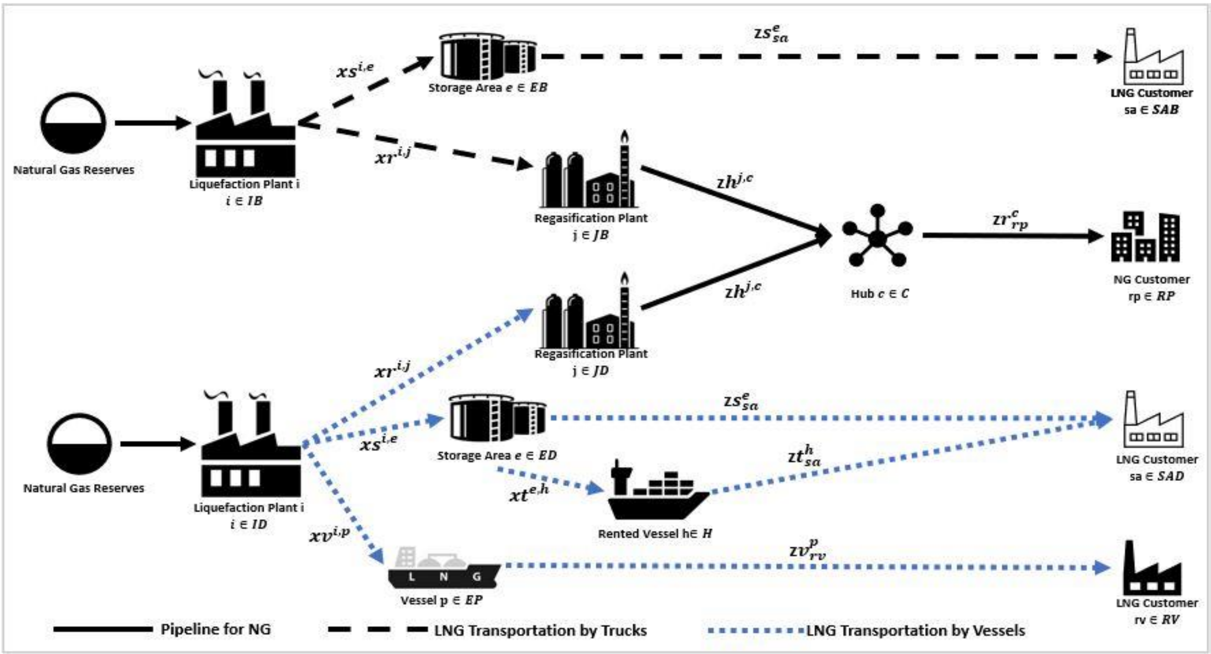

Figure 1. The NG and LNG Supply chain design in the proposed model

Table 1. Results of facility location problem to find 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 Tuzgolu LNG Storage	Silivri LNG Storage Tuzgolu LNG Storage
Candidate Facilities	Marmara Eregli (1) Marmara Eregli (2) Marmara Eregli (3) Samsun Mersin Bursa Erzurum Kahramanmaras	 Marmara Eregli (3) Samsun Mersin Bursa Erzurum Kahramanmaras
Hubs		Hubs Opened
Existing Facilities	Eskisehir Hub	Eskisehir Hub
Candidate Facilities	Erzincan Sivas Corum Konya	Erzincan Sivas Corum 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 Aliaga LNG Plant	Marmara Eregli LNG Plant Aliaga LNG Plant
Candidate Facilities	Samsun Canakkale Bursa Erzurum Kahramanmaras	 Canakkale Bursa
Regasification Plants		Regasification Plants Opened
Existing Facilities	Aliaga Fsru	Aliaga Fsru
Candidate Facilities	Silivri Tuzgolu Saros Dortyol Mersin Erzurum Kahramanmaras Samsun	 Erzurum Kahramanmaras Samsun
Storage Areas		Storage Areas Opened

Existing Facilities	Silivri LNG Storage Tuzgolu LNG Storage	Silivri LNG Storage Tuzgolu LNG Storage
Candidate Facilities	Marmara Eregli (1) Marmara Eregli (2) Marmara Eregli (3) Samsun Mersin Bursa Erzurum Kahramanmaras	Marmara Eregli (3) Samsun Mersin Bursa Erzurum Kahramanmaras
Hubs		Hubs Opened
Existing Facilities	Eskisehir Hub	Eskisehir Hub
Candidate Facilities	Erzincan Sivas Corum Konya	Erzincan Sivas Corum 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. The use of the 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 Rented Vessels Used	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 that are located in Turkey, there are candidate facilities hypothetically created. There are currently two liquefaction plants located in Turkey. These are The Marmara Ereglisi LNG Plant and The Aliaga LNG Plant. In addition to these plants, we determine five candidate liquefaction plants for the application: Samsun, Canakkale, Bursa, Erzurum, and Kahramanmaras. The existing liquefaction plants have LNG capacities of approximately 61 thousand and 65 thousand m3.

The regasification plant that is located in Turkiye is Aliaga Regasification Plant. This regasification plant is also used as a storage area. The candidate regasification plants are: Silivri, Tuzgolu, Saros, Dortyol, Mersin, Erzurum, Kahramanmaras, and Samsun. Regasification facility capacities are approximately 20 million m3 of NG. The LNG storage area capacities are also about 5000 to 40 000 m3. According to Article 315 of Tax Procedure Law (Vergi Usulü Kanunu) in Turkiye, the depreciation rate, which is one of the parameters required for facility location, is multiplied by the predetermined fee to determine the plant costs. The distance between the facilities required for the vehicle routing part of the proposed model is taken from the official site of the Ministry of Transport and Infrastructure of The Republic of Turkey. Costs used in the sample are transportation tariffs that are specified by the decision of the Energy Market Regulatory Board of The Republic of Turkey. The LNG capacities of cryogenic trucks are accepted as approximately 60 m3. The number of vessels used for the sea transportation of the LNG is 5 tankers and the capacity of vessels is taken as approximately 300 m3 LNG. It is assumed that the customers' NG and LNG demands are normally distributed and a %90 Cycle Service Level is considered not to make the supply chain be in short of NG and LNG. The existing storage areas are Silivri LNG Storage Area and Tuzgolu LNG Storage Area. The candidate storage areas are Marmara Ereglisi (1), Marmara Ereglisi (2), Marmara Ereglisi (3), Samsun, Mersin, Bursa, Erzurum, and Kahramanmaras. The existing Hub is Esksehir Hub. Candidate hubs are Erzincan, Sivas, Corum and Konya Hubs.