VIENNA 2018 TRA
TRANSPORT RESEARCH ARENA
A digital era for transport
solutions for society, economy and environment

Proceedings of 7th Transport Research Arena TRA 2018, April 16-19, 2018, Vienna, Austria

Design and management of a LNG distribution network for sea traffic in the Mediterranean Area

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Abstract

In order to reduce the dependence on oil and mitigating the environmental impact in the transport sector, European Union establishes minimum requirements for the construction of infrastructures for alternative fuels, which include, among others, Liquefied Natural Gas (LNG). By 31 December 2025, ports should be equipped with a suitable number of LNG supply points, in order to allow the navigation of LNG-powered ships in both inland waterways and sea. In this scenario, the problems of designing and managing the infrastructure for LNG distribution, consisting of coastal and inland supply points, are of primary importance. In the paper, the problem of designing an infrastructure for LNG distribution in the Mediterranean Area is taken into consideration, and the specific problem of assigning and managing such local resources as bunker-ships, tank trucks and trains (that can be moved to/from and between the supply points to increase the capacity to satisfy the LNG demand), is dealt with and formalized as a mathematical programming problem.

Keywords: Liquefied Natural Gas; LNG network; LNG distribution; LNG demand; optimization; mathematical programming.

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1. Introduction

The European Union is facing unprecedented challenges resulting from increased dependence on energy imports and scarce energy resources, and the need to limit climate change. The EU Commission's White Paper entitled "Roadmap to a Single European Transport Area – Towards a Competitive and Resource Efficient Transport System" called for a reduction in the dependence of transport on oil. Such a reduction needs to be achieved by means of an array of policy initiatives, including the definition of sustainable alternative fuels strategies as well as the development of the appropriate infrastructures. In this connection, the Communication from the Commission entitled "Clean Power for Transport: A European alternative fuels strategy", specifies that electricity, hydrogen, biofuels, natural gas, and liquefied petroleum gas are currently the principal alternative fuels with a potential for long-term oil substitution, also in light of their possible simultaneous and combined use by means of, for instance, dual-fuel technology systems.

The goal of this study is to design and manage a LNG distribution network, with specific reference to the Italian territory and the relative Mediterranean Area. As mentioned in the Directive 2014/94/EU, a final/permanent European network for LNG distribution will be available starting from 2025, whereas only some nodes and arcs will be set up before 2025. Thus, from 2018 (when the first LNG-powered vessels are expected to start operating in the Mediterranean Area) up to 2025, it will be necessary to use tank trucks/trains to serve the nodes of the network; in addition, in order to increase the supply capacity of the temporary network, some "bunker-ships" can be used to refuel LNG-powered vessels on the open sea. Besides, the considered scenario also encompasses roll-on/roll-off (ro-ro) ships carrying LNG-powered vehicles. This means that the LNG distribution network will have to satisfy the LNG demand of both vessels navigating between nodes and vehicles starting their trips at nodes. In this framework, the model which is proposed in the paper has the objective of optimally assigning, in the various time intervals, the above mentioned local resources taking into account the actual status of the infrastructure for LNG distribution.

The case study relevant to the sea traffic in the Mediterranean is reported in the paper. Since a LNG distribution network doesn't exist at the moment, some assumptions have been made by the Authors to identify the nodes and the hierarchy of them. For what concerns the arcs of the network, they have been defined by taking into consideration the most important actual links between nodes and the available modes of transport (road, train, and sea) between nodes. Once defined the network, the problem of optimally assigning and managing resources has been formalized as a mathematical programming problem: the solution of such a problem provides the amounts of LNG to be transported between nodes (with the available modes), in the various time intervals (days), which allow satisfying the demand of LNG-powered vessels and minimize direct and indirect costs. As a matter of fact, the model proposed in this paper is compatible with the recent guidelines defined by European Commission about infrastructures for news fuels.

2. Literature review

Energy efficiency and energy from renewable sources are of primary concern for any kind of system, including transportation. The Commission has reviewed the EU's energy efficiency target, in line with the request by the European Council of October 2014, and considers that the EU should set a target binding at the EU level of 30% by 2030. The Commission proposes to extend beyond 2020 the energy saving obligations set in the Energy Efficiency Directive requiring energy suppliers and distributors to save 1.5% of energy per year.

Eurostat Statistics Explained presents the following situation. The total energy consumption of all transport modes in the EU-28 amounted to 359 Mtoe in 2015. By considering the last 3 decades, there was a marked change in the development of energy consumption for transport after 2007. Until that year consumption had consistently increased, rising each year from the start of the time series in 1990. However, in 2008, as the global financial and economic crisis started, the consumption of energy for transport purposes fell 1.5 %. This fall intensified in 2009 (-3.2 %), continued at a more subdued pace in 2010 (-0.3 %) and 2011 (-0.5 %), and decreased again more strongly in 2012 (-3.0 %) and 2013 (-1.0 %), before increases of 1.3 % and 1.7 % were registered in 2014 and 2015. Overall, between the relative peak of 2007 and the low of 2013, energy consumption for transport in the EU-28 fell by 9.3 %. In absolute terms, the largest decreases in energy consumption among the different transport modes were recorded for transport via inland waterways and for rail transport: for both these modes, the EU-28 consumption was between 1.9 and 2.0 Mtoe lower in 2015 than in 1990. There was almost no change in the energy consumed by domestic aviation, while the consumption of energy for international aviation rose by 21.5 Mtoe between 1990 and 2015; for comparison the 55.5 Mtoe increase recorded for road transport was more than 2.5 times as high. These changes in energy consumption reflect the use of each transport mode, but can also be influenced by technological changes, especially when they relate to fuel-efficiency gains or losses.

The European Council set a target of at least 27% for the share of renewable energy consumed in the EU in 2030. This minimum target is binding at the EU level, but will not be translated into nationally binding targets. The Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources amended and subsequently repealed Directives 2001/77/EC and 2003/30/EC. The aims of the new Directive are: i) to achieve a 20 % improvement in energy efficiency by 2020; to build a more sustainable future by setting a 20 % target for the overall share of energy from renewable sources, iii) to reduce greenhouse gas emissions by 20%. In addition, the Directive 2014/94/EU of the European Parliament and of the Council of 22 October 2014 rules the deployment of alternative fuels infrastructure, as stated in article 1 of that Directive: "[…]. This Directive sets out minimum requirements for the building-up of alternative fuels infrastructure, including recharging points for electric vehicles and refueling points for natural gas (LNG and CNG) and hydrogen […]".

The study about LNG concerns many aspects: economic aspect, chemical composition and thermal–physical properties of LNG, competition pattern of the global liquefied natural gas (LNG) trade by network analysis, etc.; these aspects have been often considered in the past and the most of scientific studies are relevant to them. However, the problem considered in this paper, that is, to design and analyse a LNG network in a real area and for a real case, has not been addressed extensively. Among the others, two works have been recently published. A model of a pipeline network for gas distribution has been proposed by Markéta Mikolajková et al. (2017); it considers the supply of gas, either from external gas networks or as injected biogas or gasified liquefied natural gas (LNG), at terminals; in that work, the optimization objective is to minimize the annualized investment cost of LNG tank and the yearly operation cost of combined system. GangChen et al. (2017) developed an optimization planning model of the combined system's LNG reserve, considering the effect of LNG supplying risk on the combined gas and electricity system's operation under the multi-gas-source supply background.

3. Model

3.1. Decision problem

The objective of the model is to define the LNG's supply at operational level. The model is a discrete-time model with sampling time that can be set from one day (minimum interval) to one week (maximum interval). The model is a mixed-integer linear programming (MILP) problem and can be solved within a "receding horizon" framework. The model basically consists of:

- a demand model, consisting of a set of LNG-powered vessels/ships;
- a supply model, consisting of the distribution network for LNG.

The problem has the objective of determining:

- where and when the ships have to be refuelled;
- how many LNG the nodes have to store (inventory level) to satisfy the demand;
- how many LNG have to be transported between nodes to guarantee the necessary inventory levels.

The optimization problem has the objective of minimizing both the direct costs, as costs of travels and operations with LNG tanks, and the indirect ones, as climate change and social damage.

3.2. Demand model

One ship v of set V, travel around a default route. The default route is defined as network (series of nodes to be visited) and time of travel (time in which v visit node i). In a route, there are nodes S^C and B. The set of these nodes is $N_v \subseteq S^C \cup B$ (the reader can refer to the supply system for the definition of the types of nodes).

$$x_{v,j} \cdot r_{v,0,j} = \left(x_{v,j} - \sum_{j \in \mathcal{N}_v} c_{v,0,j} \right) \cdot r_{v,0,j} \tag{1}$$

$$x_{v,j} \cdot r_{v,i,j} = \left(x_{v,i} + \sum_{k=1}^{K} p_{v,i}(k) - \sum_{j \in \mathcal{N}_v} c_{v,i,j} \right) \cdot r_{v,i,j} \tag{2}$$

$$x_{v,j} \cdot r_{v,0,j} \geq s_v \cdot r_{v,0,j} \tag{3}$$

$$x_{v,j} \cdot r_{v,i,j} \geq s_v \cdot r_{v,i,j} \tag{4}$$

$$p_{v,i}(k) + M \cdot \left[1 - \delta_{v,i}(k)\right] \geq 0 \tag{5}$$

$$p_{v,i}(k) - M \cdot \delta_{v,i}(k) \leq 0 \tag{6}$$

$$\delta_{v,i}(k) \leq t'_{v,i}(k) \tag{7}$$

Equations (1)–(7) actually define the demand model for the considered problem, and they are relative to the LNG-powered ships that need to be refuelled. The route is defined through a parameter $\mathrm{r}_{\mathrm{v,i,j}} \in \{0,1\}$ and $\mathrm{r}_{\mathrm{v,i,j}} = 1$ if ship v travel from j to i. The parameter $t_{v,i} \in \mathbb{N}$ specifies the time interval in which the ship v visits node i. (note that both parameters $\mathrm{r}_{\mathrm{v,i,j}}$ and $t_{v,i}$ are necessary since, when $t_{v,i} = t_{v,\mathrm{j}}$ for some $i \neq j$, the parameter $\mathrm{r}_{\mathrm{v,i,j}}$ specifies which node is first and which node is second. The parameter $\mathrm{c}_{\mathrm{v,i,j}}$ represents the consumption of LNG from node i to node j, whereas $\mathrm{c}_{\mathrm{v,0,j}}$ defines how many LNG is consumed from the current position to the first node. The initial inventory level (quantity of LNG on board at the beginning) is a given information provided automatically by a suitably defined ICT infrastructure; such a piece of information is represented by parameter $\mathrm{x}_{\mathrm{v,0}}$, defined for $\forall v \in V$. The ship v can supply itself only in nodes i such that $t_{v,i} = k$, but it has been used the parameter $t'_{v,i}(\mathrm{k})$ that can assume binary values. When $t_{v,i} = k$ the value of parameter $t'_{v,i}(\mathrm{k})$ is 1, whereas it is 0 when $t_{v,i} \neq k$.

The main decision variables for the demand model are:

- $\delta_{\mathrm{v,i}}(\mathrm{k}) \in \{0,1\}$, binary variable whose value is 1 if ship v is refuelled in node i during interval k;
- $p_{v,i}(k) \in \mathbb{R}$, continuous variable that specifies the quantity of LNG loaded to the ship v in node i during interval k;

and the state of the system (for the part relative to the demand model) is:

- $x_{v,i} \in \mathbb{R}$, inventory on board of ship v when it arrived in node i; there is a “safety level” which specifies the minimum inventory, that is, $\mathrm{x}_{\mathrm{v,i}} \geq \mathrm{S}_{\mathrm{v}} \, \forall \, i \in N_v$.

3.3. Supply system

The model for the supply part is a graph with three types of nodes and three types of links. For what concerns nodes, the three types are: main nodes (P), secondary nodes (S) and naval nodes (B). The main nodes can be terrestrial (P^T) or coastal (P^C), with $P = P^T \cup P^C$; the main nodes can be connected by road, railway and sea, and it is assumed that they have infinity inventory which means that they can deliver how many LNG is needed. Also the secondary nodes can be terrestrial (S^T) or coastal (S^C), and the modes of transport between secondary nodes are road, railway and sea. The secondary nodes have limited inventory, but the condition is that all ships have to have the necessary quantity of LNG. The naval nodes are connected only by ships to coastal nodes, and it is assumed that its inventory is zero after this node supplies a LNG ship; as a matter of fact, the naval node (B) is a virtual node corresponding to a ship that can refuel another ship in the sea; a naval node must be associated with a specific port (clearly, a coastal node). Summing up, the set of nodes is $N = P \cup S \cup B$; let i and j be two generic nodes of the supply model. For what concerns links, the three types are: road link (A^R), rail link (A^T), sea link (A^S). The links have a maximum capacity and a lead time is associated with each link. The set ok links are $A = A^R \cup A^T \cup A^S$, and a link is denoted with (i,j) being $i,j \in N$ two nodes of the graph.

Following are the main sets and parameters which characterize the supply system:

- $Pre\ (i) \in N$, set of nodes j that $(j,i) \in A$;
- $Post\ (i) \in N$, set of nodes that $(i,j) \in A$;
- $M_{i,j} \subseteq \{R,T,S\}$, set of transport modality (R: road, T: train, S: sea), $M_{i,j}$ is defined $\forall\ (i,j) \in A$.

- $l_{i,j,m} \in \mathbb{N}$: lead time from node i to node j in modality m. The lead time specifies the number of time intervals that are required to transfer LNG from node i to node j in modality m. $l_{i,j,m} = 0$ means that LNG is transferred from i to j in the same interval k.
- $u_{i,j,m}(k) \in \mathbb{R}$, maximum capacity of LNG of link between node i and node j for modality m.

The main decision variables for the supply system are:

- $\gamma_{i,j,m}(k) \in \{0,1\}$, binary variable whose value is 1 if a non-null quantity of LNG is transferred from node i to node j in modality m (with start in time interval k);
- $q_{i,j,m}(k) \in \mathbb{R}$, quantity of LNG which is transferred from node i and node j for modality m (with start in time interval k);

and the state of the system (for the part relative to the supply model) is:

- $y_i(k) \in \mathbb{R}$, inventory of node i at the beginning of time interval k (that is, at instant $k-1$); also in this case there is a “safety level” (minimum inventory b_i): $y_i(k) \geq b_i \ \forall i \in S$.

The following equations actually define the supply model for the considered problem.

$$y_i(k+1) = y_i(k) + \sum_{j \in \mathrm{Pre}(i)} \sum_{M \in \mathcal{M}_{i,j}} q_{j,i,m}\big(k - l_{j,i,m}\big) - \sum_{j \in \mathrm{Post}(i)} \sum_{M \in \mathcal{M}_{i,j}} q_{i,j,m}(k) - \sum_{v \in \mathcal{V}} p_{v,i}(k) \tag{8}$$

$$y_i(k) \geq b_i \tag{9}$$

$$\sum_{j \in \mathrm{Pre}(i)} q_{i,j,S}(k) = \sum_{v \in \mathcal{V}} p_{v,i}(k) \tag{10}$$

$$q_{i,j,m}(k) \leq u_{i,j,m} \tag{11}$$

$$q_{i,j,m}(k) + M \cdot \big[1 - \gamma_{i,j,m}(k)\big] \geq 0 \tag{12}$$

$$q_{i,j,m}(k) - M \cdot \gamma_{i,j,m}(k) \leq 0 \tag{13}$$

3.4. Cost terms

Two types of costs are considered in this paper: direct costs and indirect costs.

Direct costs are the cost to transport LNG (fixed and variable), the holding cost, and the cost of ship’s travel.

- Let $a_{i,j,m}$ be the fixed cost to transfer a non-null quantity of LNG from node i to node j with modality m; if $q_{i,j,m}(k) = 0$ (that is, $\gamma_{i,j,m}(k) = 0$), there isn’t any cost of transport. $a_{i,j,S,v}$ fixed cost in case of transport to naval node (B). The fixed cost of transport of LNG is:

$$\sum_{k=1}^{K} \left\{ \sum_{\substack{(i,j) \in \mathcal{A} \\ j \notin \mathcal{B}}} \sum_{m \in \mathcal{M}_{i,j}} a_{i,j,m} \cdot \gamma_{i,j,m}(k) + \sum_{v \in \mathcal{V}} \sum_{\substack{(i,j) \in \mathcal{A} \\ j \notin \mathcal{B}}} a_{i,j,S,v} \cdot \delta_{v,j}(k) \right\} \tag{14}$$

- Let $b_{i,j,m}$ be the cost to transfer a quantity of LNG from node i to node j with modality m; this cost term is typical of transport on road, as the trucks have low capacity and the number of trucks is proportional to the quantity transported. The variable cost of transport ($b_{i,j,m}$) is:

$$\sum_{k=1}^{K} \sum_{(i,j) \in \mathcal{A}} \sum_{m \in \mathcal{M}_{i,j}} b_{i,j,m} \cdot q_{i,j,m}(k) \tag{15}$$

- Let h_i be the unitary holding cost of LNG. The overall holding cost is:

$$\sum_{k=1}^{K} \sum_{i \in \mathcal{S}} h_i \cdot y_i(k) \tag{16}$$

- Cost of travel of ship. This cost is:

$$\sum_{v \in \mathcal{V}} \sum_{i,j \in \mathcal{N}_v} x_{v,i} \cdot d_{v,i,j} \tag{17}$$

where $d_{v,i,j}$ is the length of the route between nodes i and j.

Indirect costs are defined in relation to how many links are active, the level of safety on links, and the environmental sustainability for transport LNG from node i to node j. They are the following.

- Number of active links. The traffic to move LNG is a problem, so the number of movements is penalized.

$$\sum_{k=1}^{K} \sum_{(i,j) \in \mathcal{A}} \sum_{m \in \mathcal{M}_{i,j}} \gamma_{i,j,m}(k) \tag{18}$$

- Safety of links. $\sigma_{i,j,m}$ is a parameter that indicated the level of safety of link (i,j). This level of safety is different for each modality of transport: sea is safer than rail and rail is safer than road.

$$\sum_{k=1}^{K} \sum_{(i,j) \in \mathcal{A}} \sum_{m \in \mathcal{M}_{i,j}} \sigma_{i,j,m} \cdot \gamma_{i,j,m}(k) \tag{19}$$

- Environmental sustainability for transport links. $\varepsilon_{i,j,m}$ is a parameter that indicated a level of environmental sustainability of link (i,j). This parameter is different for each modality of transport: rail is less polluting than sea and sea is less polluting than road.

$$\sum_{k=1}^{K} \sum_{(i,j) \in \mathcal{A}} \sum_{m \in \mathcal{M}_{i,j}} \varepsilon_{i,j,m} \cdot q_{i,j,m}(k) \tag{20}$$

Equation (20) represents the overall direct cost. w^{Dft} , w^{Dvt} , w^{Dh}, and w^{Dc} are weights that define the relevance of a specific cost term in the direct cost function.

$$\begin{aligned} C^D = {} & w^{\mathrm{Dft}} \sum_{k=1}^{K} \left\{ \sum_{\substack{(i,j) \in \mathcal{A} \\ j \notin \mathcal{B}}} \sum_{m \in \mathcal{M}_{i,j}} a_{i,j,m} \cdot \gamma_{i,j,m}(k) + \sum_{v \in \mathcal{V}} \sum_{\substack{(i,j) \in \mathcal{A} \\ j \notin \mathcal{B}}} a_{i,j,S,v} \cdot \delta_{v,j}(k) \right\} + \\ & + w^{\mathrm{Dvt}} \sum_{k=1}^{K} \sum_{(i,j) \in \mathcal{A}} \sum_{m \in \mathcal{M}_{i,j}} b_{i,j,m} \cdot q_{i,j,m}(k) + w^{\mathrm{Dh}} \sum_{k=1}^{K} \sum_{i \in \mathcal{S}} h_i \cdot y_i(k) + w^{\mathrm{Dc}} \sum_{v \in \mathcal{V}} \sum_{i,j \in \mathcal{N}_v} x_{v,i} \cdot d_{v,i,j} \end{aligned} \tag{21}$$

Equation (21) represents the overall indirect cost. w^{In}, w^{Is} , and w^{Ie} are weights that define the relevance of a specific cost term in the indirect cost function.

$$\begin{aligned} C^I = {} & w^{\mathrm{In}} \sum_{k=1}^{K} \sum_{(i,j) \in \mathcal{A}} \sum_{m \in \mathcal{M}_{i,j}} \gamma_{i,j,m}(k) + w^{\mathrm{Is}} \sum_{k=1}^{K} \sum_{(i,j) \in \mathcal{A}} \sum_{m \in \mathcal{M}_{i,j}} \sigma_{i,j,m} \cdot \gamma_{i,j,m}(k) + \\ & + w^{\mathrm{Ie}} \sum_{k=1}^{K} \sum_{(i,j) \in \mathcal{A}} \sum_{m \in \mathcal{M}_{i,j}} \varepsilon_{i,j,m} \cdot q_{i,j,m}(k) \end{aligned} \tag{22}$$

3.5. The optimization problem

On the basis of the previous considerations, the problem which allow determining the amounts of LNG to be transported between nodes (with the available modes), in the various time intervals (days), thus satisfying the demand of LNG-powered vessels and minimizing direct and indirect costs, is the following.

$$\min(C^D + C^I) \tag{23}$$

subject to (1)–(13), (21), and (22).

4. Case study

The specific case of the Mediterranean Area is considered in this work. In this connection, a future scenario in which some important coastal and inland nodes of the Italian territory are equipped with LNG supply systems has been supposed (it could be relative to the interval 2018-2025). In this section, the design and the configuration of the LNG distribution network for such a future scenario is addressed.

The first step has been that of connecting main nodes (P) with secondary nodes (S). The terrestrial main node is Rotterdam and the coastal main nodes are Marsiglia, Barcellona and Skikda; it can be observed that all of them are outside Italy. Many secondary nodes are present in Italy: in the considered scenario, the secondary terrestrial nodes are five (Milano, Torino, Padova, Parma, Roma) whereas the secondary coastal nodes are twelve (Genova, Venezia, Livorno, Ancona, Civitavecchia, Napoli, Bari, Cagliari, Palermo, Messina, Siracusa e Gioia Tauro).

The matrices in Tables 1, 2, and 3, and the graph shown in Figure 1 (that actually illustrates the distribution network) define the links between secondary terrestrial nodes, links between secondary coastal nodes and links between secondary terrestrial and coastal nodes. The three matrices specify the modalities of transport that can be used to connect each pair of nodes (R=Road, T=Train, S=Sea).

Table 1: O/D matrix – Links between secondary terrestrial nodes

O/D	Torino	Milano	Padova	Parma	Roma
Torino	0	R - T	0	R	0
Milano	R - T	0	R - T	R	0
Padova	0	R - T	0	R	0
Parma	R	R	R	0	R
Roma	0	0	0	R	0

Table 2: O/D matrix – Links between secondary coastal nodes

O/D	Ge	Ve	Li	An	Civitav.	Na	Ba	Ca	Pa	Me	Sr	G.Tauro
Genova	0	0	S - R	0	0	0	0	0	0	0	0	0
Venezia	0	0	0	S	0	0	0	0	0	0	0	0
Livorno	S - R	0	0	0	S - R	0	0	0	0	0	0	0
Ancona	0	S	0	0	0	0	S	0	0	0	0	0
Civitavecchia	0	0	S - R	0	0	S	0	S	0	0	0	0
Napoli	0	0	0	0	S	0	T	S	S	0	0	S
Bari	0	0	0	S	0	T	0	0	0	0	S	0
Cagliari	0	0	0	0	S	S	0	0	0	0	0	0
Palermo	0	0	0	0	0	S	0	0	0	S	S	0
Messina	0	0	0	0	0	0	0	0	S	0	S	S
Siracusa	0	0	0	0	0	0	S	0	S	S	0	0
G.Tauro	0	0	0	0	0	R - S	0	0	0	S	0	0

Besides the information included in Tables 1, 2, and 3, in the considered scenario it is assumed that the main node Rotterdam is connected to Milano and Padova only by train, and the capacity of such a link (quantity of LNG that can be transported per time period from the main node to a secondary one) is about 300 tons. For what concerns the coastal main nodes, Barcellona brings LNG to Civitavecchia and Livorno by sea (with a maximum capacity equal to 10 tons, because LNG belongs to the class of dangerous goods), Marsiglia brings LNG to Genova by road and sea and to Livorno only by sea, and finally Skikda is connected with Cagliari and Palermo by sea.

Table 3: O/D matrix – Links between secondary terrestrial and coastal nodes

O/D	Torino	Milano	Padova	Parma	Roma
Genova	R - T	R - T	0	R	0
Venezia	0	0	R	0	0
Livorno	0	0	0	0	0
Ancona	0	0	0	R - T	T
Civitavecchia	0	0	0	R	R
Napoli	0	0	0	0	R - T
Bari	0	0	0	0	0
Cagliari	0	0	0	0	0
Palermo	0	0	0	0	0
Messina	0	0	0	0	0
Siracusa	0	0	0	0	0
G.Tauro	0	0	0	0	0

In the considered scenario, five routes have been taken into consideration. They are defined in Tables 4–8. The vessels travelling on such routes are those equipped with LNG-powered engines and therefore they must be refuelled with LNG stored at Mediterranean ports.

Table 4: Route Genova – Napoli – Gioia Tauro – Palermo – Genova.

Route	Miles- route	Hours of navigation	Consumption-route
Genova-Napoli	334	12	58.5
Napoli-Palermo	167	6	29.25
Palermo-Gioia T.	120	4	19.5
Gioia T.-Genova	478	17	82.8

Table 5: Route Civitavecchia – Cagliari – Napoli - Messina.

Route	Miles- route	Hours of navigation	Consumption-route
Civitavecchia-Cagliari	231	8	39
Cagliari-Napoli	265	9.5	46
Napoli-Messina	117	4	19.5

Table 6: Route Siracusa – Bari – Ancona – Venezia.

Route	Miles- route	Hours of navigation	Consumption-route
Siracusa-Bari	345	12.5	61
Bari-Ancona	207	7.5	36.5
Ancona-Venezia	117	4	19.5

Table 7: Route Palermo-Siracusa-Bari-Venezia.

Route	Miles- route	Hours of navigation	Consumption-route
Palermo-Siracusa	187	7	34
Siracusa-Bari	345	12	58.5
Siracusa-Bari	324	11.5	56

Table 8: Route Genova – Livorno – Civitavecchia – Napoli - Gioia Tauro – Bari – Ancona - Venezia.

Route	Miles- route	Hours of navigation	Consumption-route
Genova-Livorno	79	3	15
Livorno-Civitavecchia	117	4	19.5
Civitavecchia-Napoli	145	5	24.3
Napoli-Gioia T.	165	6	29
Gioia T.-Bari	337	12	58.5
Bari-Ancona	215	7.5	36.5
Ancona-Venezia	117	4	19.5

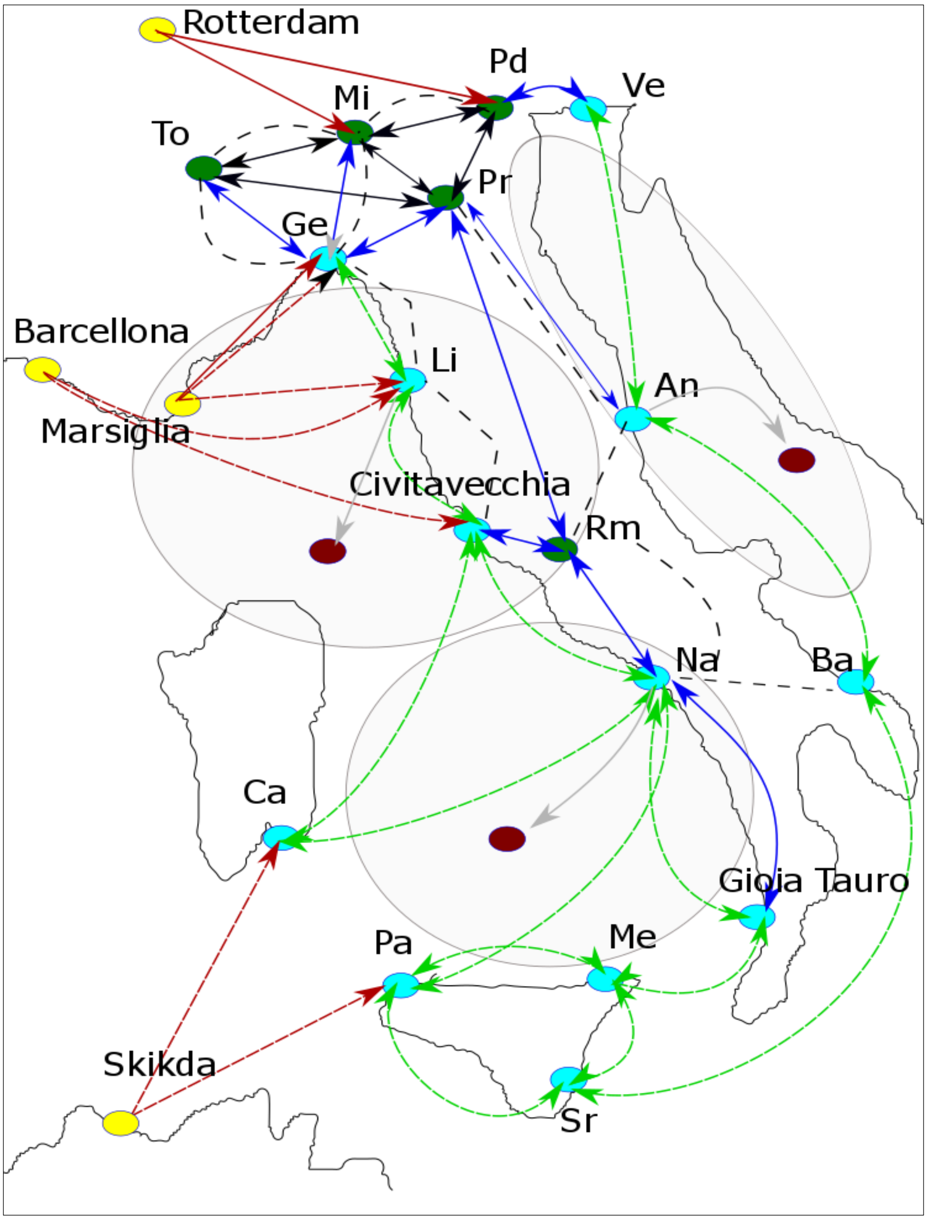

Fig. 1: The LNG distribution network in the considered scenario

The graphic notation used to represent the links of the network illustrated in Figure 1 is the following:

- solid lines represent links with road modality;
- dashed lines (low-frequency dash) represent links with train modality;
- dashed lines (high-frequency dash) represent links with sea modality;
- arrow-shaped blue lines represent a road connection between a secondary terrestrial node and a secondary coastal node;
- arrow-shaped black lines represent a road connection between two secondary terrestrial nodes;
- arrow-shaped red lines represent links between a main node and a secondary node;
- arrow-shaped green lines represent a sea connection between two secondary coastal nodes;
- arrow-shaped grey lines represent a link between a secondary coastal node (in particular, Livorno, Napoli, or Ancona) and a virtual naval node; as discussed in the previous sections, a naval node is a virtual node that can to be collocated in every point in a certain area of the sea (in Figure 1, it is the area highlighted with a light grey circle); the bunker-ship can get LNG in a secondary coastal node and bring it to the highlighted area to refuel a vessel; the three areas are: North-West of Mediterranean Sea for the bunker-ship associated with the port of Livorno, South-West of Mediterranean Sea for the bunker-ship associated with the port of Napoli, and North-East of Mediterranean Sea (that is, the Adriatic Sea) for the bunker-ship associated with the port of Ancona.

5. Conclusion and further developments

The problem of distributing LNG fuel to some coastal supply points has been addressed in this paper, in accordance with the recent guidelines provided by European Commission that asked the adoption of new alternative fuels to reduce emissions. As future real scenarios are not clear at the present moment, the model proposed in this paper is a general model that can be adopted in many future scenarios. The main objective of the problem is to find the minimum cost to transport LNG to coastal nodes that require fuel, taking into account some constraints about the time to deliver and the quantity to be provided to each port; in doing so, both direct and indirect costs are considered. One of the innovative part of this model is to consider bunker-ships; a bunker-ship can supply fuel to a LNG-powered vessel in the middle of the sea; in this way, the vessel saves time significantly, as it avoids entering the port to refuel. Bunker-ships are modelled in the proposed problem as virtual nodes of the distribution network. Besides, bunker-ships can be very useful in a situation in which a port drains its LNG reserve: in such an emergency situation, bunker-ships can be used to move quickly LNG from one (possibly near) port to the port with no-stock.

The case study analyses five routes, each of them characterized by the data relative to fuel consumption, miles and hours of navigation between each coastal node; such data are fundamental in the considered model as they allow determining the dynamics of the fuel level into the vessels and, consequently, the amount of LNG which is needed in each port of the Mediterranean Area (and also at which time interval the LNG must be available at the port). From the technological point of view, it is assumed that there is a direct information link between ship and port of destination: vessels can use this link to communicate the actual LNG consumption and the quantity of LNG that the ship has on board.

The further developments are many and interesting. From the applicative point of view, it is possible to extend the model to other areas of interest and to adapt the model to different future scenarios as the one in which all vessels are LNG-powered. For what concerns the model, it can be extended by considering variable routes of the vessels (now the ships travel by following a default route), and the optimal route is determined by solving the optimization problem. Finally, another extension is to consider a security parameter in addition to the safety parameter that is considered in the model presented here; security aspects are very important and they will be included in the further developments of the model.

6. References

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