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An MILP model for optimization of a small-scale LNG supply chain along a coastline

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HIGHLIGHTS

- A model for optimizing small-scale LNG supply chains is presented.
- The model minimizes total costs associated to fuel procurement.
- The use of the model is illustrated by a case study which considers an LNG supply chain in Finland.
- The model provides valuable information to aid in LNG supply chain design decisions.

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ABSTRACT

The world energy demand is continuously increasing and natural gas is one of the strongest candidates to cover the growth. However, natural gas is unavailable in many energy intensive areas and the best way to introduce natural gas to new, scattered, areas is by transporting it as liquefied natural gas (LNG). LNG can be shipped from a large LNG import terminal to consumers through a network of smaller satellite terminals with a combination of sea- and land-based transports. Building up a small-scale supply chain network is expensive and capital intensive. This paper presents a mathematical model to aid in the supply chain design decisions by minimizing the total costs associated with fuel procurement. The use of the model is illustrated by a case study, where the optimal supply chain of LNG for covering certain parts of the energy requirements of a country is designed under different cost structures for LNG and for its land-based transportation.

1. Introduction

The energy consumption in the world is persistently rising at the same time as environmental aspects of energy consumption gain more attention. Natural gas has, with large known remaining reserves and its propitious environmental properties, emerged as a suitable fuel candidate for meeting the growing energy demand and also replacing existing, more polluting, fuels such as fuel oil and coal. Natural gas is transported from the gas fields to the consumers in two main ways, either by gas pipes or with ships as a liquid. Ship transports of liquefied natural gas (LNG) have recently been gaining ground due to the high costs of long distance gas pipe transport and the geographical limitations of gas pipe distribution. Furthermore, LNG is seen as one of the main solutions for complying with the sulphur restrictions imposed by the International Maritime Organization (IMO) inside Emission Control Areas (ECA).

LNG is produced by cooling natural gas to below −162 °C at a liquefaction plant in the vicinity of a gas field. LNG can then be economically transported over long distances by specially designed LNG ships which keep the fuel in a liquid state. From the liquefaction plant LNG is transported to regasification terminals, where LNG is traditionally vaporized and fed into a local gas pipeline network. Small-scale LNG distribution has recently also been gaining interest. LNG can be transported further from the regasification terminal to satellite terminals by smaller LNG ships and thence to consumers by LNG trucks. The advantage of small-scale LNG distribution is that no extensive pipeline grid is needed as the transport is predominantly carried out by ships and trucks. Consequently, smaller sparsely distributed demands can be served economically without the considerable investment cost of an outspread gas pipeline grid.

The supply chain design is crucial, as a good design structure can result in considerable savings in both the investment costs as well as the operational costs. A typical small-scale LNG supply chain generally includes a larger LNG regasification terminal as a

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Nomenclature

Set/indices

C	consumers $c \in C$
P	ports $p \in P$
P^S	satellite ports $P^S \in P$
S	ship sizes $s \in S$
T	time periods $t \in T$

Integer variables

N_s	no. of ships of size s required
$Y_{p,t,s}$	no. of times port p is the farthest port in a voyage by a ship of size s in time period t

Binary variables

$b_{p,c}$	is 1 if LNG is transported from port p to consumer c
$y_{p,t,s}$	is 1 if a part load stop is made at port p by a ship of size s in time period t
z_p	is 1 if a satellite terminal is required at port p

Continuous variables

A_c	amount of alternative fuel used at consumer c
c^{tot}	total costs
c^{trn}	transport costs
$D_{p,t}$	fuel demand of the consumers served by port p in time period t
$L_{p,t,s}$	amount of LNG shipped to port p with ship size s in time period t
$Q_{p,t}$	storage amount at port p at the end of time period t
$Q_p^{\max}$	maximum storage capacity needed at port p

Parameters

a	constant for calculating the annual contribution of an investment cost
c_c^{alt}	price of the alternative fuel for consumer c
c^{LNG}	price of LNG
c_S^{prp}	propulsion cost for a ship of size s
$c^{tr,dis}$	distance dependent cost parameter for truck deliveries
$c^{tr,fix}$	cost parameter for the fixed part of truck deliveries
C_s	capacity of ship of size s
$D_{c,t}^{con}$	fuel demand at consumer c in time period t
$d_{p,c}^{con}$	distance from port p to consumer c
d_p^{fw}	distance along fairway from the supply port to port p
d_p^{rst}	distance from the fairway to port p
I^{cap}	capacity dependent investment cost of an LNG terminal
I^{fix}	fixed part of the investment cost of an LNG terminal
l	monthly storage loss fraction for storing LNG
r_s	rental cost of a ship of size s
u	rate of loading and unloading the LNG ships
v_s	speed of a ship of size s
τ_t	length of the time period t

supply terminal and smaller satellite terminals to receive and handle LNG, as well as a fleet of LNG ships and trucks for transporting the LNG to consumers. The number and location of satellite terminals, necessary storage capacities, ship sizes and truck transport distances all have an effect on the costs and overall performance of a small-scale LNG supply chain, which quickly renders the design task intractable. This article presents an optimization model to aid the design process for small-scale LNG supply along a coastline. A coastline supply chain is typically required when a large import terminal is built in an area with a long continuous coastline.

Optimization of supply chains and maritime transporting has been widely researched and there are a large number of papers published on this topic. A comprehensive literature survey regarding combined inventory routing is presented by Anderson et al. [1] and supply chain problems and design are thoroughly discussed by Shah [2]. Schulz et al. [3] present two different types of mixed integer non-linear program (MINLP) models for optimizing the supply chain of a continuous industry and Al-Khayyal and Hwang [4] study maritime routing and scheduling for a heterogeneous fleet of ships by minimizing costs with a mixed integer linear program (MILP) model. Maritime routing and scheduling with load splitting is studied by Stålhane et al. [5] using a path-flow formulated MILP model.

There are also a fair number of publications regarding LNG and its supply chain. Goel et al. [6] present an MILP model with an arc-flow formulation to find an optimal fleet and terminal infrastructure for an LNG supply chain, where deliveries are made from a set of production terminals to a set of regasification terminals. A similar model for a general maritime routing problem is also presented by Song and Furman [7]. Also Halvorsen-Weare and Fagerholt [8] study a worldwide LNG ship routing and scheduling problem using an arc-flow formulated MILP model where the problem is split into a set of routing sub-problems and a scheduling problem. Halvorsen-Weare and Fagerholt study the same problem further with a cargo-based assignment MILP model in [9] where an uncertainty factor is also implemented to improve robustness. Fodstad et al. [10] developed an MILP model to coordinate vessel routing and inventory levels within a worldwide LNG supply chain, also considering split loads and different spot markets. Furthermore, Stålhane et al. [11] study distribution of multiple types of LNG from one producer to customers worldwide, considering contractual obligations and spot market opportunities. Common to all of the above-mentioned models is that they quickly become too large to solve to optimality with deterministic methods. Consequently, heuristic approaches are needed and used to produce near-optimal results, to narrow down the search space or to produce starting points for the solvers.

Small-scale LNG distribution and supply chains are a fairly unexplored area and publications regarding particularly small-scale LNG supply chain optimization are scarce. Small-scale distribution of multiple oil products between islands has been studied by Agra and colleagues. Both a discrete time and a continuous time mixed integer formulation of the problem are presented in [12] and heuristic approaches for making real life problem sizes solvable are discussed in [12]. Small-scale LNG distribution differs somewhat from large-scale distribution and large-scale models are rarely adequate directly for small-scale purposes. Small-scale LNG ships are of the size 1000–20,000 m^3, whereas the large-scale LNG ships handle volumes up to 300,000 m^3. Distances are shorter and supply contracts may be more flexible in small-scale distribution. Also split loads, which are often omitted from large scale supply models, may be economically feasible in small-scale distribution. Currently small-scale LNG supply is being utilized mainly in Norway and Japan.

2. Problem description

Regional supply from a large-scale regasification terminal to end-users can be carried out by a combination of ship and truck transports utilizing satellite terminals along a coastline. Fig. 1

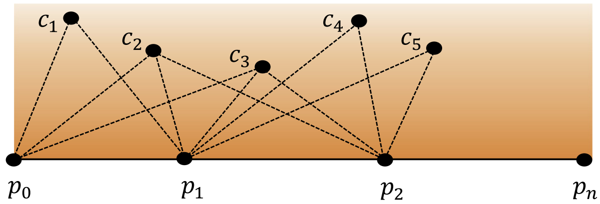

Fig. 1. Supply terminal p_0 and satellite terminals $p_1 \ldots p_n$ along a hypothetical coastline with consumers c scattered inland. Dashed lines illustrate possible truck transport routes between terminals and consumers.

illustrates the distribution problem where LNG from the supply port, p_0, is to be transported to the consumers, C_i, either directly or by shipping it via satellite terminals, p_i. The satellite terminals facilitate the transport of LNG to more remote consumers as the required truck transport distances get shorter. The objective is to find an optimal structure for the supply chain, i.e., the set of satellite terminals needed, size and number of the ships required and storage capacities necessary to obtain a minimum combined cost configuration.

Firstly, a part of the problem can be regarded as a one dimensional special case of a maritime inventory routing problem (MIRP) where LNG needs to be shipped to the satellite terminals along the coastline with minimum costs. Secondly, the other part of the problem includes the land transport and resembles a capacitated vehicle routing problem (CVRP), where transports have to be made from a satellite terminal to several consumers minimizing the costs. Both of the above-mentioned problem types are typically complex and difficult to solve, and a simultaneous solution of them seems to be required for finding an optimal small-scale supply chain design.

3. Mathematical formulation

A number of simplifications and assumptions were made in order to solve the intricate supply chain problem at hand. Firstly, a shipping strategy was incorporated in the model. Instead of forcing the optimization process to decide how, when and in which order the ships travel between the terminals, ship routing is determined by the shipping strategy. Every voyage is assumed to start the shipments at the farthest terminal with remaining demand and continue to the other terminals on the return voyage in geographical order, until the whole cargo is unloaded. This is a reasonable assumption as all the terminals are situated on the coastline along the same route. The shipping strategy also makes for an effective simplification as no variables are needed for ship scheduling. The appropriateness of the mathematical implementation of the shipping strategy in the optimization model was tested by comparing the routing results of the shipping strategy to the optimal results for a set of routing problems along a coastline. The comparison showed that the assumed strategy, in fact, is very accurate. In 40 randomly generated routing problems with the number of satellite terminals varying between 4 and 10, only 17 cases with non-optimal routing were recorded, and for these the relative difference in the objective function value compared to the optimal solution was never greater than 2%. The strategy minimizes the total shipping distance along the fairway and the potential errors occur in the number of port visits required. As long as the distances from the fairway to the ports are relatively short compared to the length of the fairway, the error of the strategy remains insignificant.

Secondly, when dealing with the LNG truck transports, it is fair to assume that every consumer has capacity to receive a full truck load. This simplifies, or rather almost eliminates, the CVRP part of the problem since without load splitting only full load deliveries from the terminals to the consumers are considered. These simplifications are crucial as they enable the model to be solved deterministically even for large problems.

The problem formulation regards a set of consumers, C, which need to be supplied with fuel, the fuel being either LNG from a set of ports, P, or a locally distributed alternative fuel. It can be noted that the alternative fuel should be more expensive than LNG for an LNG utilization potential to exist. LNG can be transported from a supply terminal, p_0, to a set of satellite terminals, $P^S \in P$, by a set of different ship sizes, S. In order to model possible fluctuations in demand and to introduce the possibility of LNG storage, the optimization time interval is divided into a set of consecutive time periods, T.

The variables used in the model include continuous variables, such as shipped amounts of LNG, L, amounts of alternative fuel used, A, storage amounts, Q, and port demands, D, and integer and binary variables, such as port visit variables, Y and y, port existence variables, z, and transport decision variables, b. The transport of LNG and the associated costs are modelled using linear equations and constraints, thus creating a mixed-integer linear programming (MILP) problem to be solved.

3.1. Objective function

The objective is to minimize the combined fuel procurement costs for the consumers. In this way a practical comparison between the total costs of LNG and the already existing local fuel can be made and a realistic picture of the LNG potential is attained. As the alternative fuel is assumed to be available at the location of the demand, the cost of usage can be calculated as the amount of fuel used multiplied by the price of the fuel. The cost of the LNG includes the price of LNG at the supply terminal, the cost of transporting the LNG and the annual contribution of the investment costs of the satellite terminals. The objective function takes the form

$$c^{tot} = \sum_{c \in C} c_c^{alt} \cdot A_c + c^{\text{LNG}} \left[\sum_{p \in P^s} \sum_{t \in T} \sum_{s \in S} L_{p,t,s} + \sum_{c \in C} \left(b_{p_0,c} \cdot \sum_{t \in T} D_{c,t}^{con} \right) \right] + a \sum_{p \in P^S} \left(I^{fix} \cdot z_p + I^{cap} \cdot Q_p^{\max} \right) + c^{trn}, \tag{1}$$

where the amount of alternative fuel used is calculated from

$$A_c = \sum_{t \in T} D_{c,t}^{con} \cdot \left(1 - \sum_{p \in P} b_{p,c} \right) \quad \forall c \in C \tag{2}$$

and c^{trn} denotes the transport cost. The transport cost of LNG includes ship rental and propulsion costs as well as the cost of truck transport, which renders the transport cost a bit more complicated to calculate than the other costs. The equation for the transport cost is

$$c^{trn} = \sum_{s \in S} r_s \cdot N_s + 2 \cdot \sum_{p \in P^s} \sum_{t \in T} \sum_{s \in S} c_s^{prp} \left(d_p^{fw} \cdot Y_{p,t,s} + d_p^{rst} (Y_{p,t,s} + y_{p,t,s}) \right) + \sum_{p \in P} \sum_{c \in C} \left[\left(c^{tr,fix} + c^{tr,dis} \cdot d_{p,c}^{con} \right) \cdot \sum_{t \in T} \left(D_{c,t}^{con} \right) \cdot b_{p,c} \right], \tag{3}$$

where the first term represents the rental cost, the second term the propulsion cost for ships and the third term calculates the truck transport cost. Firstly, when the rental cost is considered, the type of charter contract has to be decided. In this case a long-term charter contract has been assumed and the rental cost is a fixed annual cost for every ship chartered. Secondly, the propulsion cost consists of two parts; the first part is for the distance of a voyage travelled on the fairway and the second part is the distance travelled from the fairway to the different ports. For every voyage, the distance travelled along the fairway is determined solely by the farthest port visited because all ports are located along the same route. However, the distances from the fairway to the ports are individual for each port, and they need to be included separately for every port visit within a voyage. The factor of two in front of the term arises because also the return trip distance needs to be taken into account. Finally, the cost of a truck delivery is assumed to comprise a fixed starting cost and a distance dependent cost. To get the total truck transport cost, the cost parameter for the fixed part, $c^{tr,fix}$, is multiplied by the amount of LNG transported by trucks and the distance dependent parameter, $c^{tr,dis}$, is multiplied by the amount of LNG and distance of the truck transports.

3.2. Constraints

In order to guarantee that the demand for every consumer is satisfied, demand constraints need to be established. Firstly, the consumer demands are assigned to the port demand variables, so

$$D_{p,t} = \sum_{c\in C}(D^{con}_{c,t} \cdot b_{p,c}) \quad \forall p \in P^s,\ \forall t \in T \tag{4}$$

and secondly, LNG has to be shipped to the satellite ports according to the port demand variables. Taking storage possibilities into account, the set of constraints becomes

$$\sum_{s\in S} L_{p,t,s} + (1-l)Q_{p,t-1} - Q_{p,t} \geqslant D_{p,t} \quad \forall p \in P^s,\ \forall t \in T \setminus 1 \tag{5}$$

where the cost of storing LNG is calculated by applying a storage loss factor l on the LNG stored from the previous time period. When the problem is solved for a time interval which is repeated continuously, such as a year, the LNG stored in the last time period can be considered available in the first time period. Therefore, in the case of modelling a year with twelve time periods (months), the storage level in the end of December is available in the beginning of January. With this in mind, the constraints for the first time period can be written as

$$\sum_{s\in S} L_{p,1,s} + (1-l)Q_{p,t^{\max}} - Q_{p,1} \geqslant D_{p,1} \quad \forall p \in P^s, \tag{6}$$

where $t^{\max}$ denotes the last time period. A set of constraints to restrict the number of port connections to one for every consumer is also required, so

$$\sum_{p\in P} b_{p,c} \leqslant 1 \quad \forall c \in C. \tag{7}$$

Furthermore, in order to organize the shipping according to the assumed shipping strategy, constraints for the port visit variables need to be defined. For the integer variables Y to take the correct value, the summed ship capacity of the number of voyages in a time period has to be greater than the shipped amount of LNG, so

$$\sum_{p'=p}^{p^{\max}} (C_s \cdot Y_{p',t,s} - L_{p',t,s}) \geqslant 0 \quad \forall p \in P^s,\ \forall t \in T,\ \forall s \in S. \tag{8}$$

The summation is done to the farthest port, $p^{\max}$, for each satellite terminal port and the number of ship loads is, thus, always sufficient to cover the amount of LNG to be shipped. Another set of constraints is needed to set the value of the binary variables y. The variables define the part loads shipped to the ports and they become binaries because, according to the shipping strategy, the maximum amount of part loads per port is one. The set of constraints can be written as

$$L_{p,t,s} - C_s \cdot Y_{p,t,s} \leqslant C_s \cdot y_{p,t,s} \quad \forall p \in P^s,\ \forall t \in T,\ \forall s \in S, \tag{9}$$

stating that a part load stop is required if the amount of shipped LNG is not covered by the number of full load transports determined by the Y variable. A third set of shipping constraints is still needed to set the number of ships necessary to cover the LNG shipments. This is done by calculating the duration of use for a ship size and forcing the number of ships to increase as the duration exceeds the length of the time period, so

$$\tau_t \cdot N_s \geqslant 2 \cdot \sum_{p\in P^s} \left(\frac{d_p^{fw} \cdot Y_{p,t,s} + d_p^{rst}(Y_{p,t,s} + y_{p,t,s})}{v_s} + \frac{L_{p,t,s}}{u} \right) \quad \forall t \in T, \forall s \in S, \tag{10}$$

where the ship usage duration is calculated on the right side. The duration consists of travel time and the duration for loading and unloading. The travel time is calculated in a similar manner as the propulsion cost in Eq. (3), whereas the duration of loading and unloading is simply the amount of LNG shipped divided by the rate of loading and unloading. The factor of two in front of the right side term arises because the ships have to return from the voyages and the amount of LNG loaded has to be unloaded as well.

Finally, the remaining sets of constraints are investment cost related, such as

$$Q_p^{\max} \geqslant \sum_{s\in S} L_{p,t,s} + Q_{p,t} \quad \forall p \in P^s,\ \forall t \in T \tag{11}$$

and

$$M \cdot z_p \geqslant Q_p^{\max} \quad \forall p \in P^s \tag{12}$$

where the maximum storage capacities and satellite terminal existence variables are determined, respectively, where M is a large

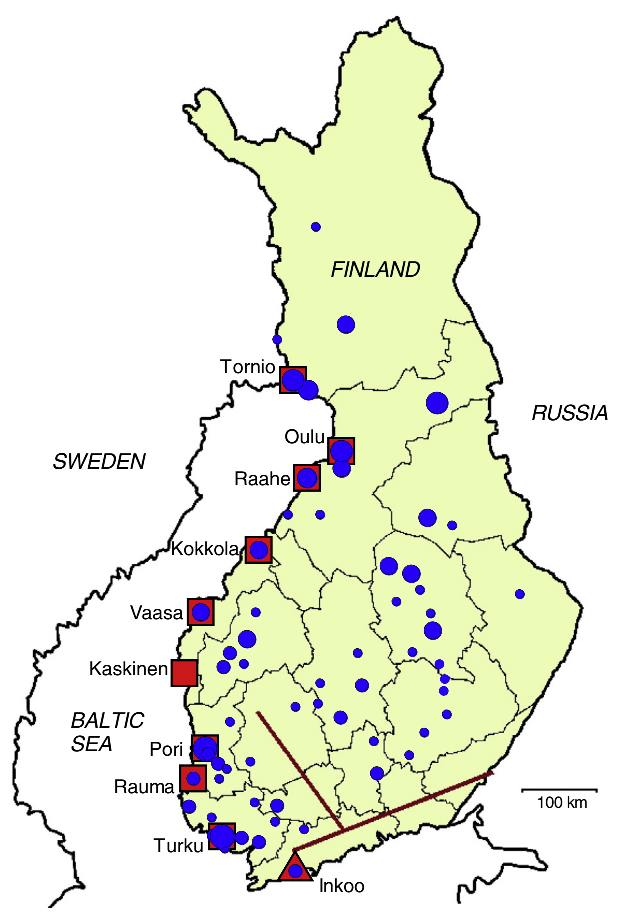

Fig. 2. Location of the case study demands (●), ports considered for satellite terminals (■) and the supply port (▲) shown on a map of Finland. Dot sizes express the demand size and the solid line marks the gas pipe from Russia.

enough number for the constraints to be satisfied when the binary variables $z = 1$ and when the maximum storage variables are greater than zero.

4. Case study

A large-scale LNG regasification terminal is being planned to Southern Finland. In the case study, the model was utilized to examine the LNG supply from the terminal to consumers in Finland. The fuel oil consumption in district heating production in Finnish municipalities along with the potential consumption of larger industries and industrial areas was considered as the LNG consumption potential. The consumption within a municipality was regarded as one consumer at the location of the municipality centre. Consumers in the near vicinity of the existing gas pipe were given zero demand and were thus omitted. With this setup, the case study included 69 consumers throughout Finland. Nine larger ports with suitable positions along the Finnish Baltic Sea coast were considered as possible satellite terminal locations. The supply port location was assumed to be in Inkoo and the possible satellite terminal ports were Turku, Rauma, Pori, Kaskinen, Vaasa, Kokkola, Raahe, Oulu and Tornio. More details about the potential customers, their energy demand and the locations of them and the ports are provided in the Appendix A. The locations of the demands and the ports on the map of Finland are illustrated in Fig. 2. Ships of the sizes 1100 m^3, 7551 m^3 and 15,600 m^3 were considered in the model according to the ship sizes in use or ordered in the already established Norwegian small-scale LNG supply chain. The ships are assumed to use LNG as a fuel and the propulsion cost is, therefore, proportional to the price of LNG.

The optimization was performed for a whole year divided in twelve 30-day periods. The distances from the ports to the consumers were calculated based on position coordinates and the truck transports were given an upper limit of 300 km. The annual demand for the district heating fuel oil was distributed over twelve months assuming high consumption in the winter decreasing to no consumption in the summer, whereas the industrial consumption was assumed to remain constant throughout the year. The fuel oil price was set to 90 €/MWh and a series of optimization runs were performed with LNG prices varying from 30 €/MWh to 89 €/MWh. This way an overall picture of the supply chain configuration could be formed and a sense of the sensitivity of the solution to changes in the LNG price could be attained. Another set of optimization runs, where the truck transport cost was increased and the price of LNG was kept constant at 50 €/MWh, was also conducted. As the truck transport cost has two parts, both the fixed part and the distance dependent part were increased by the same factor. The starting values for these parameters were 1 €/MWh and 0.01 €/km MWh for the fixed part and the distance dependent part, respectively, and optimization runs were performed for values up to 5 €/MWh and 0.05 €/km MWh.

The computation was performed using the IBM ILOG CPLEX Optimization Studio 12.5 optimization software on a computer running a 64-bit Windows 7 operating system with a 3.5 GHz Intel Core i7 processor and 16 GB of RAM. The test case problem included 630 binary, 360 integer and 1924 continuous variables.

4.1. Results

The results of the MILP model provide information about where to build LNG satellite terminals and their sizes, which municipalities to serve with LNG from which port and how the shipping should be arranged in order to attain a supply chain configuration with minimum combined costs.

4.1.1. Varying LNG price

According to the optimization runs, LNG satellite terminals should be built in Oulu and Tornio and all of the consumers in Southern Finland would be served directly from the supply terminal in Inkoo. Deliveries from Oulu would handle the whole Central Finland and the large consumers in the north would be supplied by the terminal in Tornio. Three consumers would be left using fuel oil because they cannot be reached by any of the suggested terminals. This configuration is optimal for LNG prices up to 82 €/MWh, which indicates that the optimal supply chain structure is very robust to changes in the LNG price. The cost of LNG terminals and transportation per unit of LNG supplied has to be smaller than the price difference between LNG and fuel oil, since the price difference is the driving force for LNG usage. At higher LNG prices the price difference between LNG and fuel oil is so small that building satellite terminals become economically infeasible. The consumers that cannot be served directly from the supply terminal would be left using fuel oil. As the LNG price increases the economical distance for truck transports decreases, until no consumers are served at the LNG price of 89 €/MWh. The satellite terminal locations and LNG distribution to the consumers for the different optimal supply chain configurations are illustrated in Fig. 3.

One ship of the largest size is needed to carry out the LNG shipments in all the solutions which include shipping. The ship is not fully utilized and the duration of use for every month is under 20 days. The storage levels are also low for all solutions. This can partly be explained by the low ship utilization, as there is little

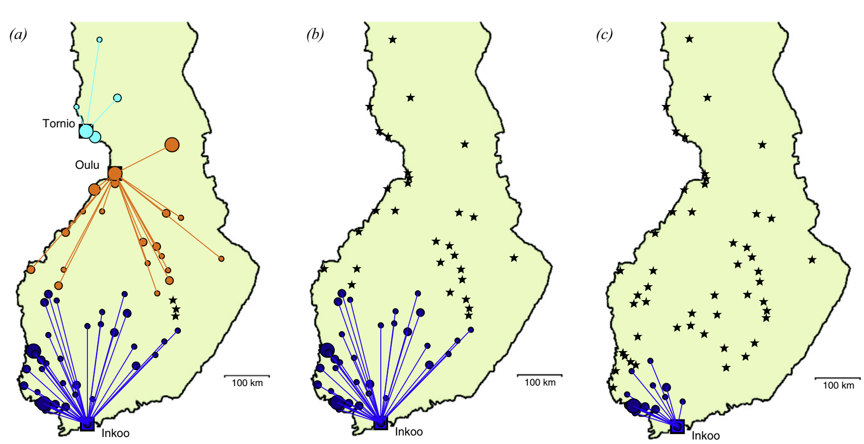

Fig. 3. Optimal terminal locations and LNG supply for different LNG prices: (a) 30–82 €/MWh, (b) 83–85 €/MWh and (c) 87 €/MWh. Lines connect consumers (●) with the terminal (■) from which the consumers are supplied. Stars mark consumers using fuel oil.

benefit in storing LNG to the next month as long as the ship is available for use. Minimizing storage levels would result in higher shipping costs and vice versa. Potentially, a trade-off between shipping and storing may occur when altering the LNG price, but since both the cost of storing LNG and propulsion costs are proportional to the LNG price, the trade-off phenomena are limited. However, the storage levels also affect the investment cost and higher LNG prices can favour storage use. In fact, a small shift in storage use and ship transports can be noted at the LNG price of 59 €/MWh in Fig. 4, where the optimal supply chain properties as a function of the LNG price are shown.

The results from the optimization runs suggest that the supply chain configuration presented in Fig. 3a is a robust solution with regard to the LNG price. There is room for a substantial change in the LNG price until a different optimal configuration arises. The storage use is, as well, very similar for all the solutions and the changes in storage needs caused by a rise in the LNG price would probably be insufficient to motivate a change in the storage capacities at the terminals. Truck deliveries directly from Inkoo cover as much of Southern Finland as the 300 km limit for truck deliveries allows for LNG prices up to 85 €/MWh. This leads to the conclusion that truck transports, with the used parameters, are quite affordable.

4.1.2. Varying truck transport costs

In order to gain a better understanding of in which way changes in truck transport costs would affect the solution, optimization runs with a varying trucking cost were undertaken. The truck transport cost parameters were multiplied by a trucking cost factor, α, and the value of this factor was changed in the range $\alpha \in [1, 5]$ and the system was optimized. The results indicate that already small changes in α can change the solution from that presented in Fig. 3a. The changes are, nevertheless, relatively moderate. Optimal satellite terminal locations and LNG distribution to consumers for three different truck transport cost parameter values are illustrated in Fig. 5.

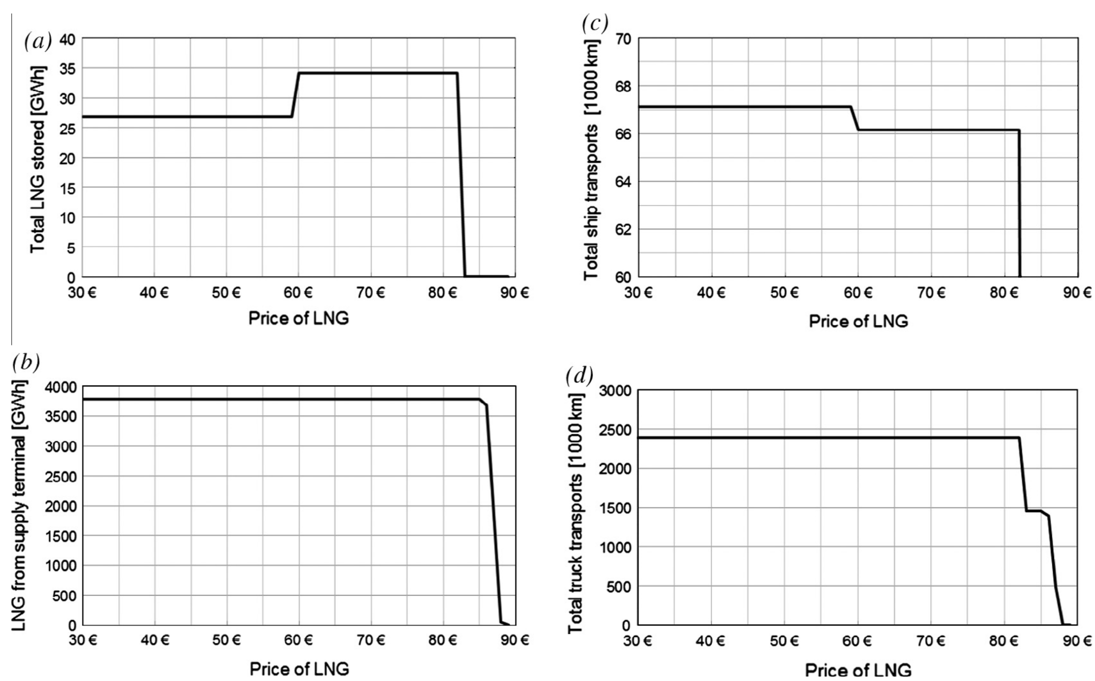

Fig. 4. Optimal supply chain properties as a function of the LNG price: (a) LNG stored over time periods, (b) annual amount of LNG trucked directly from the supply port, (c) annual ship transports, and (d) annual truck transports.

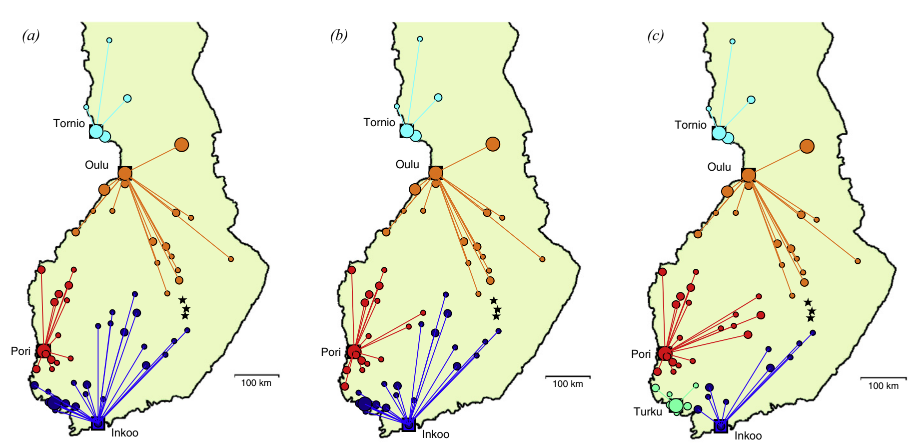

Fig. 5. Optimal LNG supply and terminal locations for different trucking cost factor values: (a) α = 1.2, (b) α = 1.6, and (c) α = 2.8–5.0. Lines connect consumers (●) with the terminal (■) from which the consumers are supplied. Stars mark consumers using fuel oil.

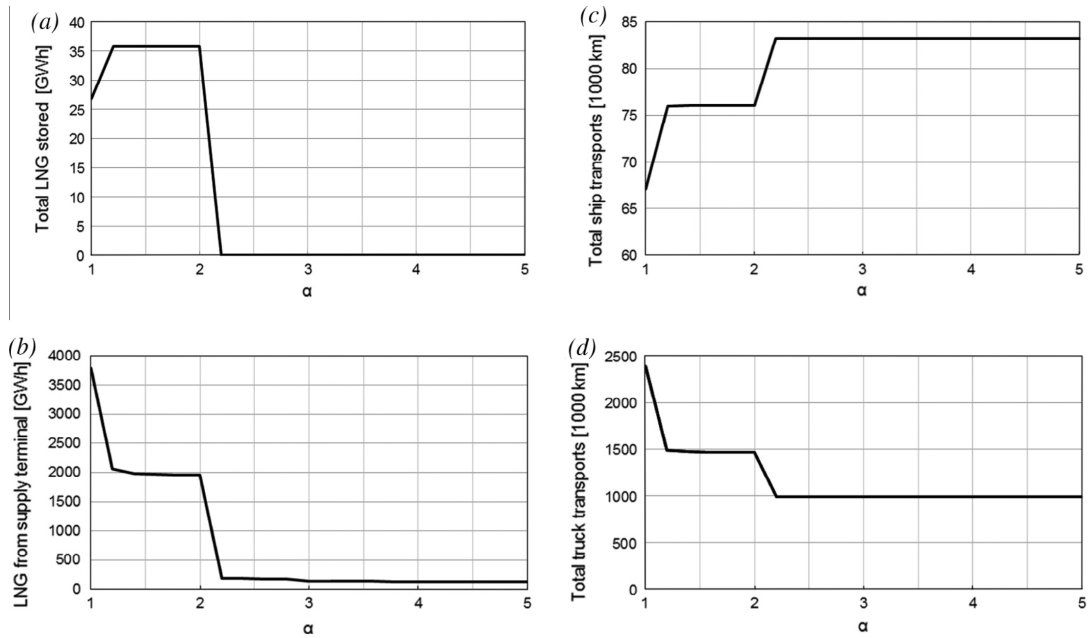

Fig. 6. Optimal supply chain properties as a function of the trucking cost factor: (a) LNG stored over time periods, (b) annual amount of LNG trucked directly from the supply port, (c) annual ship transports, and (d) annual truck transports.

Compared to the supply chain configuration presented in Fig. 3a, which corresponds to a trucking cost factor $\alpha = 1.0$, an extra satellite port is needed in Pori for $\alpha \in [1.2, 5.0]$. Small changes between solutions, as seen between Fig. 5a and b, may occur, but the general configuration remains the same. Furthermore, in addition to the terminal in Pori, one more satellite port is needed in Turku for $\alpha > 2$. Apart from these differences, the optimal supply chain configurations for different truck transport costs are quite similar and the satellite port locations and LNG delivery to consumers remain practically unchanged, especially in Northern Finland.

The results show that with more expensive truck transports, the optimal supply chain configuration includes more satellite terminals. This is reasonable, as the required truck transport distances become shorter with more satellite terminals. The amount of LNG distributed directly from the supply terminal decreases as a result of more satellite terminals and, consequently, more ship transports are required. This behaviour can be seen in Fig. 6, where the optimal supply chain properties as a function of the trucking cost factor are shown. Surprisingly, storage utilization is zero in the case with four satellite terminals. This is, however, most likely not a direct result of the increase in truck transport cost, but merely a consequence of differences in ship scheduling induced by changes in ship utilization.

5. Conclusions

This article has presented an MILP model for small-scale LNG supply chain optimization for supply along a coastline. The model minimizes costs related to fuel procurement and provides an optimal supply chain configuration with regard to satellite port locations, ship sizes and utilization and customer distribution. A case study analysis revealed that an LNG supply chain would be economically feasible even if LNG prices would differ considerably from the current level. Optimization runs conducted with different LNG prices produced the same optimal solution for LNG prices between 30 €/MWh and 82 €/MWh. Although the supply chain configuration for the base case studied is robust with regard to changes in the LNG price, it is somewhat sensitive to an increase in the trucking cost. However, the different solutions produced by altering the truck transport cost are essentially modifications of the base-case solution. In conclusion, the case study revealed the locations of the recommended satellite terminals (Oulu and Tornio), also indicating that in the future, depending on the development of the truck transport costs, it might be feasible to build two additional satellites (Pori and Turku). The locations of the terminals are strongly determined by the large consumers and the sensitivity of the supply chain regarding changes in the consumer demand structure is studied in a follow up paper.

The presented model is intended to support decision making regarding small-scale LNG supply chains. This is an early development of the small-scale LNG model and further research is needed for improvements and development of the model. The usage of LNG introduces a positive local environmental impact, since LNG burns much cleaner than fuel oil and in future work environmental aspects are planned to be included to the model. The model has already proven to provide valuable information regarding supply chain configuration and could be particularly helpful in evaluation and utilization of the LNG usage potential of a new market. In the case study of the present paper, most of the program runs were solved in a matter of minutes, which indicates that additional features can still be included in the model and that it is possible to study even larger problems. The longest solution times were

Table A1
Sea transport distances used in the case study, expressed in km.

Port	Distance from Inkoo	
	Fairway	Fairway-to-port
Turku	245	45
Rauma	390	20
Pori	430	15
Kaskinen	515	15
Vaasa	635	40
Kokkola	800	20
Raahe	895	20
Oulu	960	50
Tornio	1040	0

Table A2
Position data and consumer energy demand used in the case study.

Consumer	Lat	Long	Demand (GW h)											
			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Eura	61.13	22.15	0.75	0.75	0.25	0.25	0.00	0.00	0.00	0.00	0.25	0.25	0.75	0.75
Forssa	60.82	23.59	2.91	2.91	0.97	0.97	0.00	0.00	0.00	0.00	0.97	0.97	2.91	2.91
Harjavalta	61.31	22.12	3.04	3.04	1.01	1.01	0.00	0.00	0.00	0.00	1.01	1.01	3.04	3.04
Hartola	61.58	26.01	1.61	1.61	0.54	0.54	0.00	0.00	0.00	0.00	0.54	0.54	1.61	1.61
Heinola	61.20	26.04	6.56	6.56	2.19	2.19	0.00	0.00	0.00	0.00	2.19	2.19	6.56	6.56
Iisalmi	63.56	27.19	3.38	3.38	1.13	1.13	0.00	0.00	0.00	0.00	1.13	1.13	3.38	3.38
Ilomantsi	62.67	30.94	0.68	0.68	0.23	0.23	0.00	0.00	0.00	0.00	0.23	0.23	0.68	0.68
Inkoo	60.05	24.01	2.27	2.27	0.76	0.76	0.00	0.00	0.00	0.00	0.76	0.76	2.27	2.27
Jalasjärvi	62.49	22.75	0.94	0.94	0.31	0.31	0.00	0.00	0.00	0.00	0.31	0.31	0.94	0.94
Joensuu	62.60	29.76	4.50	4.50	1.50	1.50	0.00	0.00	0.00	0.00	1.50	1.50	4.50	4.50
Joroinen	62.18	27.82	2.01	2.01	0.67	0.67	0.00	0.00	0.00	0.00	0.67	0.67	2.01	2.01
Juva	61.89	27.87	0.68	0.68	0.23	0.23	0.00	0.00	0.00	0.00	0.23	0.23	0.68	0.68
Jyväskylä	62.24	25.75	7.91	7.91	2.64	2.64	0.00	0.00	0.00	0.00	2.64	2.64	7.91	7.91
Jämsä	61.87	25.18	2.04	2.04	0.68	0.68	0.00	0.00	0.00	0.00	0.68	0.68	2.04	2.04
Kaarina	60.41	22.38	0.56	0.56	0.19	0.19	0.00	0.00	0.00	0.00	0.19	0.19	0.56	0.56
Kajaani	64.23	27.73	3.39	3.39	1.13	1.13	0.00	0.00	0.00	0.00	1.13	1.13	3.39	3.39
Kalajoki	64.26	23.94	1.35	1.35	0.45	0.45	0.00	0.00	0.00	0.00	0.45	0.45	1.35	1.35
Kankaanp.	61.80	22.40	0.98	0.98	0.33	0.33	0.00	0.00	0.00	0.00	0.33	0.33	0.98	0.98
Karkkila	60.53	24.23	1.84	1.84	0.61	0.61	0.00	0.00	0.00	0.00	0.61	0.61	1.84	1.84
Kauhajoki	62.45	22.21	2.06	2.06	0.69	0.69	0.00	0.00	0.00	0.00	0.69	0.69	2.06	2.06
Kauhava	63.11	23.06	0.82	0.82	0.27	0.27	0.00	0.00	0.00	0.00	0.27	0.27	0.82	0.82
Kemi	65.74	24.57	25.06	25.06	22.80	22.80	21.67	21.67	21.67	21.67	22.80	22.80	25.06	25.06
Kempele	64.91	25.51	0.94	0.94	0.31	0.31	0.00	0.00	0.00	0.00	0.31	0.31	0.94	0.94
Keuruu	62.26	24.70	1.61	1.61	0.54	0.54	0.00	0.00	0.00	0.00	0.54	0.54	1.61	1.61
Kitee	62.10	30.14	0.54	0.54	0.18	0.18	0.00	0.00	0.00	0.00	0.18	0.18	0.54	0.54
Kittilä	67.66	24.91	0.60	0.60	0.20	0.20	0.00	0.00	0.00	0.00	0.20	0.20	0.60	0.60
Kiuruvesi	63.65	26.61	2.29	2.29	0.76	0.76	0.00	0.00	0.00	0.00	0.76	0.76	2.29	2.29
Kokemäki	61.26	22.35	0.60	0.60	0.20	0.20	0.00	0.00	0.00	0.00	0.20	0.20	0.60	0.60
Kokkola	63.84	23.13	4.55	4.55	3.85	3.85	3.50	3.50	3.50	3.50	3.85	3.85	4.55	4.55
Kuopio	62.89	27.68	25.73	25.73	8.58	8.58	0.00	0.00	0.00	0.00	8.58	8.58	25.73	25.73
Kurikka	62.62	22.39	2.64	2.64	0.88	0.88	0.00	0.00	0.00	0.00	0.88	0.88	2.64	2.64
Lapinlahti	63.37	27.39	1.13	1.13	0.38	0.38	0.00	0.00	0.00	0.00	0.38	0.38	1.13	1.13
Leppävirta	62.49	27.77	3.24	3.24	1.08	1.08	0.00	0.00	0.00	0.00	1.08	1.08	3.24	3.24
Lieksa	63.31	30.03	1.31	1.31	0.44	0.44	0.00	0.00	0.00	0.00	0.44	0.44	1.31	1.31
Liminka	64.80	25.43	2.64	2.64	0.88	0.88	0.00	0.00	0.00	0.00	0.88	0.88	2.64	2.64
Loimaa	60.85	23.04	1.48	1.48	0.49	0.49	0.00	0.00	0.00	0.00	0.49	0.49	1.48	1.48
Mikkeli	61.69	27.27	1.86	1.86	0.62	0.62	0.00	0.00	0.00	0.00	0.62	0.62	1.86	1.86
Mynämäki	60.68	21.99	0.54	0.54	0.18	0.18	0.00	0.00	0.00	0.00	0.18	0.18	0.54	0.54
Mänttä	62.03	24.62	0.52	0.52	0.17	0.17	0.00	0.00	0.00	0.00	0.17	0.17	0.52	0.52
Mäntyh.	61.42	26.87	0.94	0.94	0.31	0.31	0.00	0.00	0.00	0.00	0.31	0.31	0.94	0.94
Naantali	60.47	22.03	3.77	3.77	1.26	1.26	0.00	0.00	0.00	0.00	1.26	1.26	3.77	3.77
Oulainen	64.26	24.81	0.99	0.99	0.33	0.33	0.00	0.00	0.00	0.00	0.33	0.33	0.99	0.99
Oulu	65.01	25.47	79.86	79.86	74.40	74.40	71.67	71.67	71.67	71.67	74.40	74.40	79.86	79.86
Paimio	60.44	22.71	2.17	2.17	0.72	0.72	0.00	0.00	0.00	0.00	0.72	0.72	2.17	2.17
Parainen	60.31	22.30	0.51	0.51	0.17	0.17	0.00	0.00	0.00	0.00	0.17	0.17	0.51	0.51
Pielavesi	63.23	26.75	1.11	1.11	0.37	0.37	0.00	0.00	0.00	0.00	0.37	0.37	1.11	1.11
Pori	61.49	21.80	137.48	137.48	134.71	134.71	133.33	133.33	133.33	133.33	134.71	134.71	137.48	137.48
Raahe	64.69	24.48	36.07	36.07	34.97	34.97	34.42	34.42	34.42	34.42	34.97	34.97	36.07	36.07
Raisio	60.49	22.17	2.53	2.53	0.84	0.84	0.00	0.00	0.00	0.00	0.84	0.84	2.53	2.53
Rauma	61.13	21.51	1.99	1.99	0.66	0.66	0.00	0.00	0.00	0.00	0.66	0.66	1.99	1.99
Rovaniemi	66.50	25.73	8.18	8.18	2.73	2.73	0.00	0.00	0.00	0.00	2.73	2.73	8.18	8.18
Ruovesi	61.98	24.07	0.84	0.84	0.28	0.28	0.00	0.00	0.00	0.00	0.28	0.28	0.84	0.84
Salo	60.39	23.12	4.18	4.18	1.39	1.39	0.00	0.00	0.00	0.00	1.39	1.39	4.18	4.18
Sastamala	61.34	22.92	1.72	1.72	0.57	0.57	0.00	0.00	0.00	0.00	0.57	0.57	1.72	1.72
Savonl.	61.87	28.87	4.76	4.76	1.59	1.59	0.00	0.00	0.00	0.00	1.59	1.59	4.76	4.76
Seinäjoki	62.79	22.84	3.88	3.88	1.29	1.29	0.00	0.00	0.00	0.00	1.29	1.29	3.88	3.88
Siilinjärvi	63.09	27.65	0.84	0.84	0.28	0.28	0.00	0.00	0.00	0.00	0.28	0.28	0.84	0.84
Somero	60.63	23.52	0.73	0.73	0.24	0.24	0.00	0.00	0.00	0.00	0.24	0.24	0.73	0.73
Sotkamo	64.13	28.40	0.51	0.51	0.17	0.17	0.00	0.00	0.00	0.00	0.17	0.17	0.51	0.51
Suonenj.	62.63	27.11	1.86	1.86	0.62	0.62	0.00	0.00	0.00	0.00	0.62	0.62	1.86	1.86
Taivalk.	65.58	28.24	125.00	125.00	125.00	125.00	125.00	125.00	125.00	125.00	125.00	125.00	125.00	125.00
Tornio	65.85	24.15	167.54	167.54	166.01	166.01	165.25	165.25	165.25	165.25	166.01	166.01	167.54	167.54
Turku	60.45	22.25	166.42	166.42	138.81	138.81	125.00	125.00	125.00	125.00	138.81	138.81	166.42	166.42
Ulvila	61.43	21.87	2.34	2.34	0.78	0.78	0.00	0.00	0.00	0.00	0.78	0.78	2.34	2.34
Uusik.	60.81	21.43	16.59	16.59	5.53	5.53	0.00	0.00	0.00	0.00	5.53	5.53	16.59	16.59
Vaasa	63.10	21.63	22.16	22.16	14.11	14.11	10.08	10.08	10.08	10.08	14.11	14.11	22.16	22.16
Varkaus	62.31	27.89	3.28	3.28	1.09	1.09	0.00	0.00	0.00	0.00	1.09	1.09	3.28	3.28
Ylitornio	66.33	23.68	0.94	0.94	0.31	0.31	0.00	0.00	0.00	0.00	0.31	0.31	0.94	0.94
Äänek.	62.62	25.68	0.64	0.64	0.21	0.21	0.00	0.00	0.00	0.00	0.21	0.21	0.64	0.64

noted for parameter values at which the solution changes and these cases took 10–20 h to solve. Ultimately, the model is best used as a decision making tool where solving times of hours, or even days, are acceptable.

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Appendix A

This appendix holds information about the case study used for illustrating the optimization model. Table A1 reports the distances from the supply port along the fairway and from the fairway to the ports in kilometers. Table A2, in turn, lists the geographical locations of the municipalities and industrial sites potentially supplied by LNG and their estimated energy requirements over the months of the year. It should be pointed out that the energy data was used mainly for the purpose of illustration as the underlying values are based on gross estimates and the yearly consumption of fuel oil used in the municipalities for district heating.

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