Multi-stage heuristic for the LNG Shipping Problem

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Mots-clés : *Multi-stage decomposition, Tensor Networks, Maritime transportation, LNG*

1 Introduction

Given the escalating threat of climate change, there's a growing emphasis on a low-carbon energy mix. Natural gas, producing up to 50% less carbon dioxide than other fossil fuels for the same power output [1], is a viable option. However, the supply chains of commodities such as *Liquefied Natural Gas (LNG)* are complex and require advanced optimisation for ensuring resilience and efficiency.

Uniper [2] buys and sells LNG and uses several ships to transport the gas between trading ports. In this work, we aim to maximise the profit for this business activity by optimally selecting contracts and assigning them to vessels. In addition, we have to pick optimal visit times for each contract and choose the propulsion mode for each leg of the journey from *LNG-only*, *fuel-only* or *combined*.

The considered problem is NP-hard[2] ; a *Mixed Integer Program (MIP)* formulation for a simplified problem version - with fixed visit times and a single propulsion mode - was already challenging to solve : It took 45 mins for a Gurobi powered approach to reach 'optimality' on a production data set when addressing the simplified problem.

This work presents a new heuristic : it decomposes the whole problem on two *Integer Linear Programs (ILP)* that communicate with each other through a set of tunable parameters. These parameters intricately influence the total cost, and we employ a quantum-inspired global optimisation routine to adjust them finely. Our heuristic finds a solution with 35% profit increase (over a benchmark provided by Uniper) and 6% increase (over the MIP solution) in less than 7 minutes *without using commercial MILP solvers.*

1.1 Problem statement

We have a set of possible contracts C and a fleet of vessels F. For each contract c (buy or sell) we know its type τ_c ; the availability period $[T_c^{start}, T_c^{end}]$, the corresponding port $p_c \in P$, the trading volume bounds $[V_c^{min}, V_c^{\max}]$. The unit profit of the contract (negative for buys) is a function of the contract type τ_c and the LNG price $\mathcal{P}_{p,c}$ in p_c at the visit time t_c.

Each vessel $s \in F$ has a maximum volume $\mathcal{V}_s^{max}$, a starting day $\mathcal{T}_s^{start}$ and location $p_s^{start} \in P$ and an ending day $\mathcal{T}_s^{end}$ and location $p_s^{end} \in P$. For stability reasons, a ship can navigate only in ballast ($V \leq 0.25\mathcal{V}_s^{max}$) or laden ($V \geq 0.75\mathcal{V}_s^{max}$) load modes. Each ship supports up to 3 propulsion modes and several available speeds - a table provides consumptions for possible speed, propulsion type and load mode tuples. Crucially, the LNG level always decreases when the ship travels - either the vessel uses it as fuel or it boils off at some finite rate.

The overall profit includes traded contracts (buy and sell) and fuel costs. The solution has to respect each contract's time windows, the vessel's volumes, and the stability requirements.

1. https ://group.met.com/en/mind-the-fyouture/mindthefyouture/natural-gas-vs-coal
2. https ://www.uniper.energy/

2 Decomposition and Subproblem Interaction

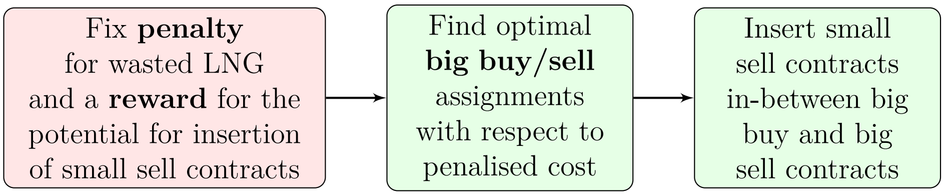

FIG. 1 – A multi-stage heuristic for the LNG shipping problem. The *penalty optimisation* (in red) is a black-box optimisation problem solved with *TetraOpt*. *Pair selection* and *Small contract insertion* are modelled as ILP and solved with SCIP - an open-source MILP solver.

Due to slow MIP solution times, we turned to heuristic methods.

Firstly, we observed that due to the stability restriction, each *big buy* contract (with traded volume $V >= 0.5\mathcal{V}_s^{max}$) is imperatively followed by precisely one *big sell* contract. We take advantage of this fact by separately optimising these big trades and small trades ($V <= 0.25\mathcal{V}_s^{max}$) in a multi-stage fashion.

To optimise big trades, we follow the initial approach by Uniper : for each feasible big contract pair we create a *laden* (or *ballast*) trip - its cost depends on the price difference and the possible trading volume, as well as on the fuel consumption. Together with *initial and destination trips*, a flow-preserving sequence of ballast and laden trips provides a possible solution to our problem.

On the second stage, the focus shifts to inserting small sell contracts between big trade contracts. For each selected big trip, we consider the contracts that can be visited between its endpoints. We use an *arc-flow formulation* for the small contract selection problem - with one binary variable $x_{s,i,j}$ if the ship s can sail from the contract i to the contract j inside one of its preselected trips. For each contract (small *and* big), we also introduce volume variables ($v_{c,s} \in [V_c^{min}, V_c^{max}]$) : one for each vessel that can visit it.

The insertion of small contracts into an optimal solution of the big-pair-only model increases the profit by 19%. Nevertheless, since the big-pair-only model is unaware of the potential cost improvement achievable by including small sell contracts, this solution is suboptimal. We address this issue by modifying the profits of our trips : $P_t \to P_t + \omega_{MD} MD_t - \omega_W W_t$ where P_t is the previous profit, MD_t reflects the potential for a small sell contract insertion and W_t estimates the possibility of LNG getting wasted is the trip is selected.

The reward and penalty coefficients (ω_{MD} and ω_W) impact the solution in a non-linear and intricate fashion. Therefore, we use a black-box optimisation solver *TetraOpt*[3] to fine-tune these parameters. TetraOpt performed well in such applications as shape optimization [1]. For our problem, TetraOpt found coefficient values leading to a solution with 35% profit increase.

To summarise, we proposed a multi-stage heuristic for the LNG shipping problem, outperforming a basic heuristic in solution quality while maintaining speed. Future work could explore incorporating more intricate problem specifications.

Références

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3. developed by Terra Quantum : https ://terraquantum.swiss/