The LNG Inventory Routing Problem with Pick-Up Contracts

Henrik Andersson

Marielle Christiansen

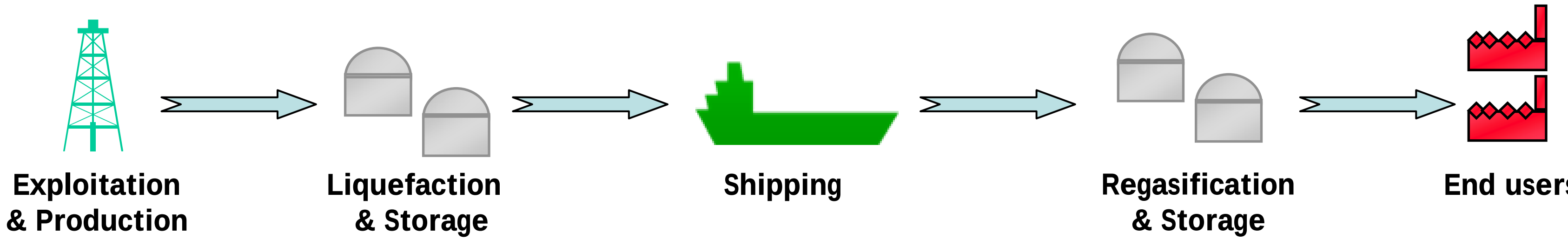
Roar Grønhaug

NTNU
Norwegian University of Science and Technology

Agenda

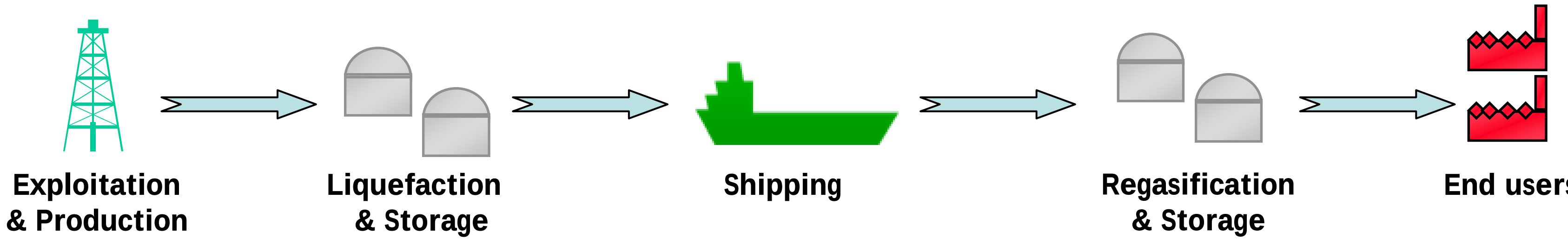
- The Liquefied Natural Gas Supply Chain
- Problem characteristics
  - Regasification terminals
  - Ship movements
  - Liquefaction plants
  - Contracts
- Model summary
- Solution approach

The LNG Supply Chain



- **Exploitation & Production**
- **Liquefaction / Storage**
- **Shipping**
- **Regasification / Storage**
- **End users**

The LNG Supply Chain



- **Exploitation & Production**
- **Liquefaction / Storage**
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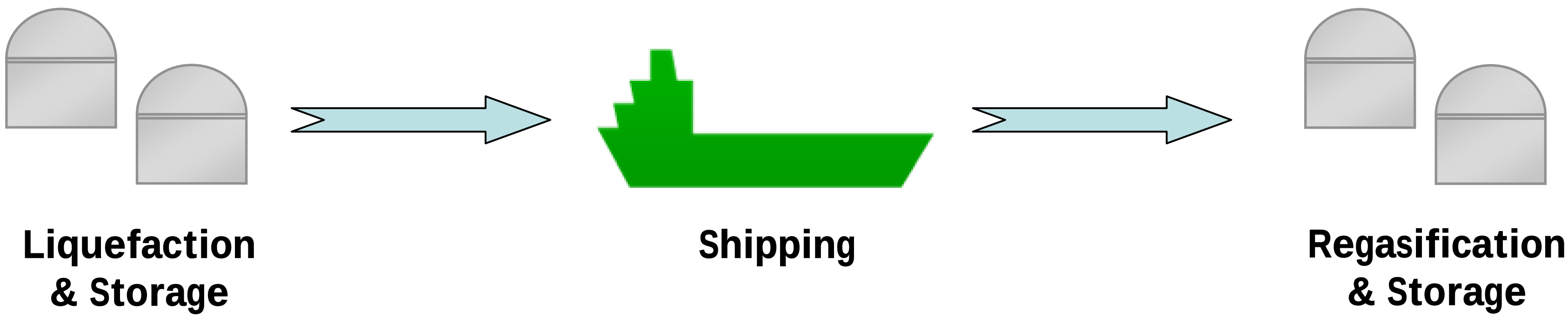
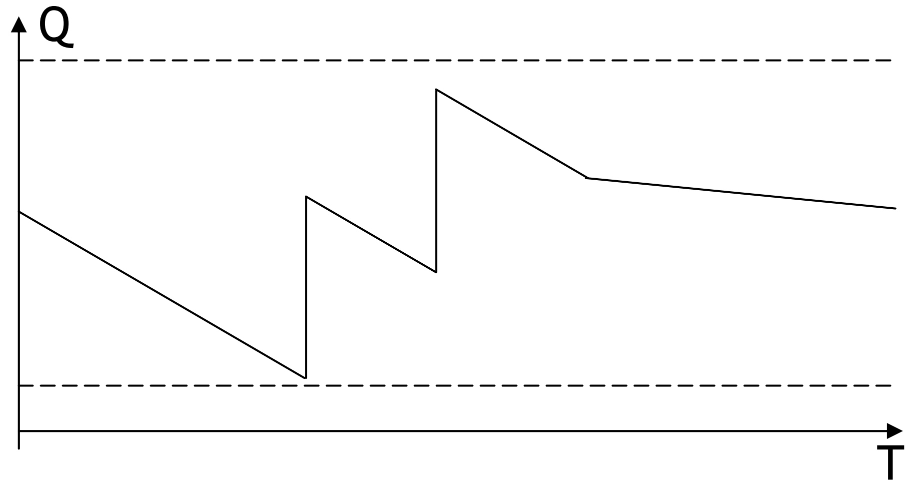
Problem characteristics



- Liquefaction plants
  - Contracts
  - Port availability
- Regasification terminals
  - Inventories
  - Sales
  - Port availability
- Ship movements
  - Paths
  - Boil-off

Regasification terminals

- Assuming full control at the regasification terminals
  - $I_L \leq$ Inventory $\leq I_U$
  - $S_L \leq$ Sales $\leq S_U$
  - Inventory balance
  - Berth constraints



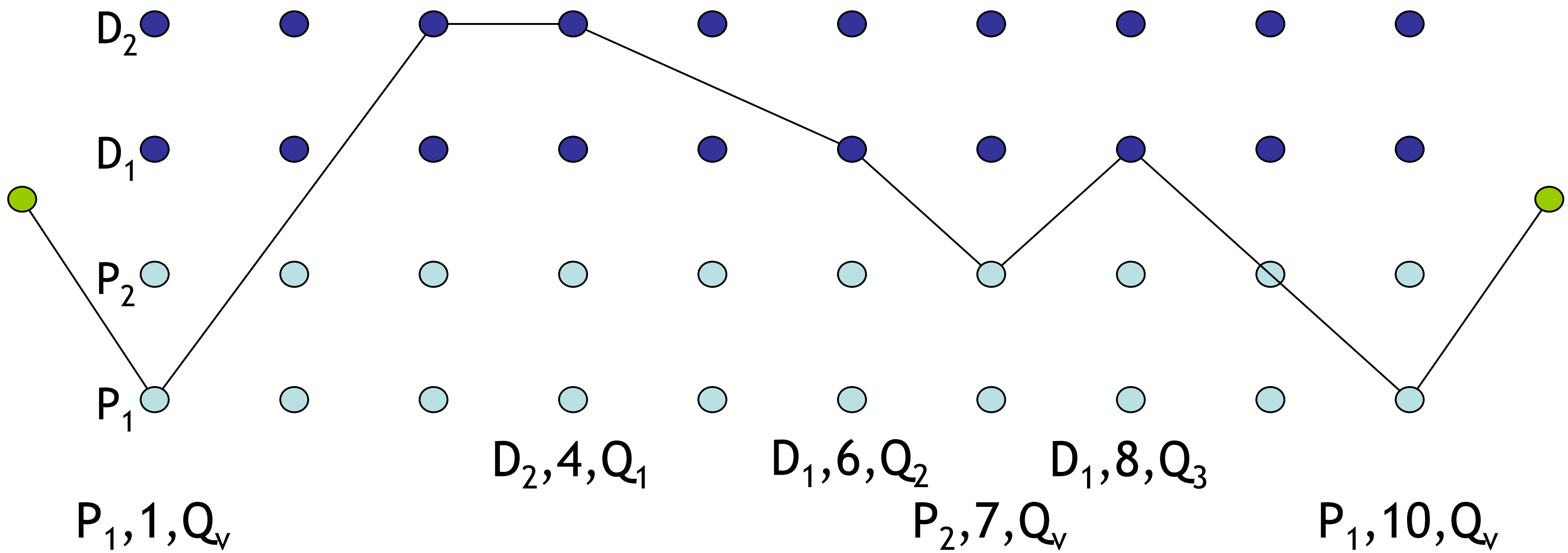
Ship movements

Information about the ship movements is contained in paths consisting of:

- Geographical route
  - Visits and sequence
- Schedule
  - Times for loading and unloading
- Quantity
  - Loaded and unloaded

Ship movements; Network

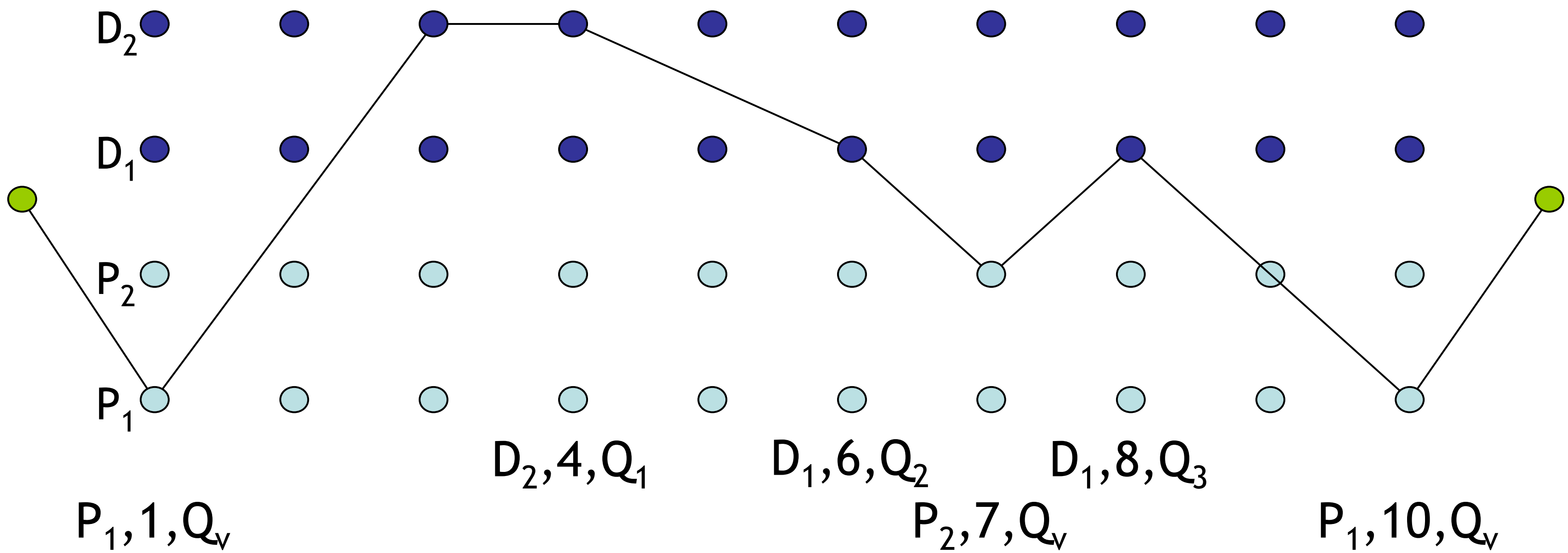
- The ship movements can be represented in a time-space network



  – Each path in the network corresponds to at least one set of (route, schedule, quantities)

Ship movements; Quantities

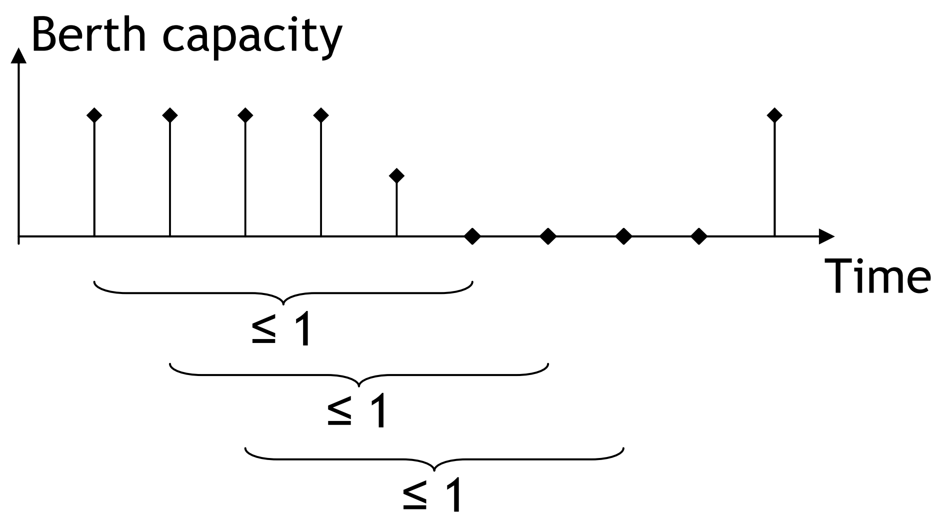
- Boil-off
  - Can be used as fuel for the ship



$$Q_1 + Q_2 = Q_v \cdot (1\text{-}B) \cdot (7\text{-}1) \qquad Q_3 = Q_v \cdot (1\text{-}B) \cdot (10\text{-}7)$$

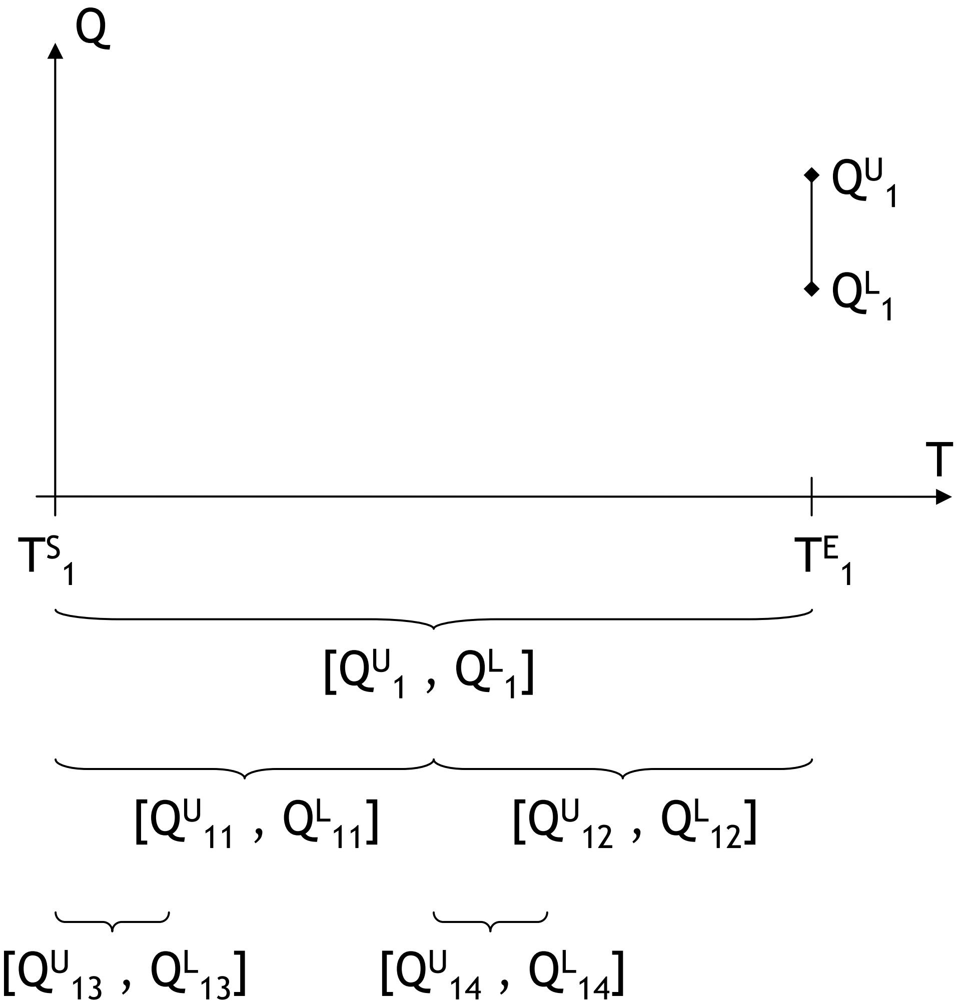
Liquefaction plants

- One of many actors at the liquefaction plants
- Contracts instead of inventories
- Berth constraints
- Inter-arrival gaps



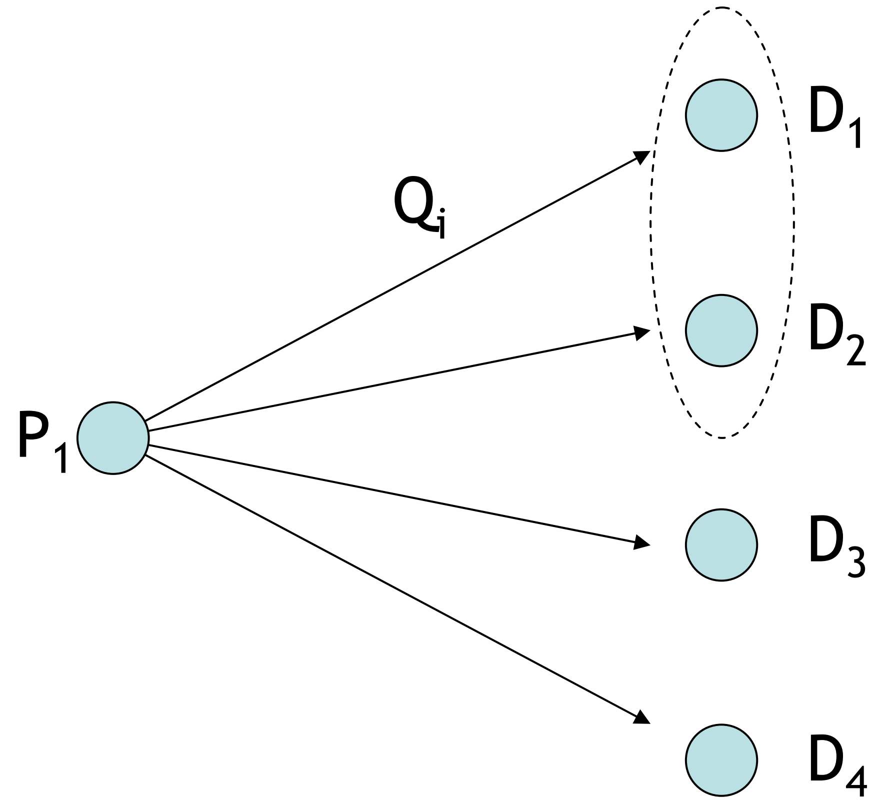
Contract characteristics

- Upper and lower limits on quantities
- Start date and end date
- Partitions to regulate the quantity loaded



Contract characteristics

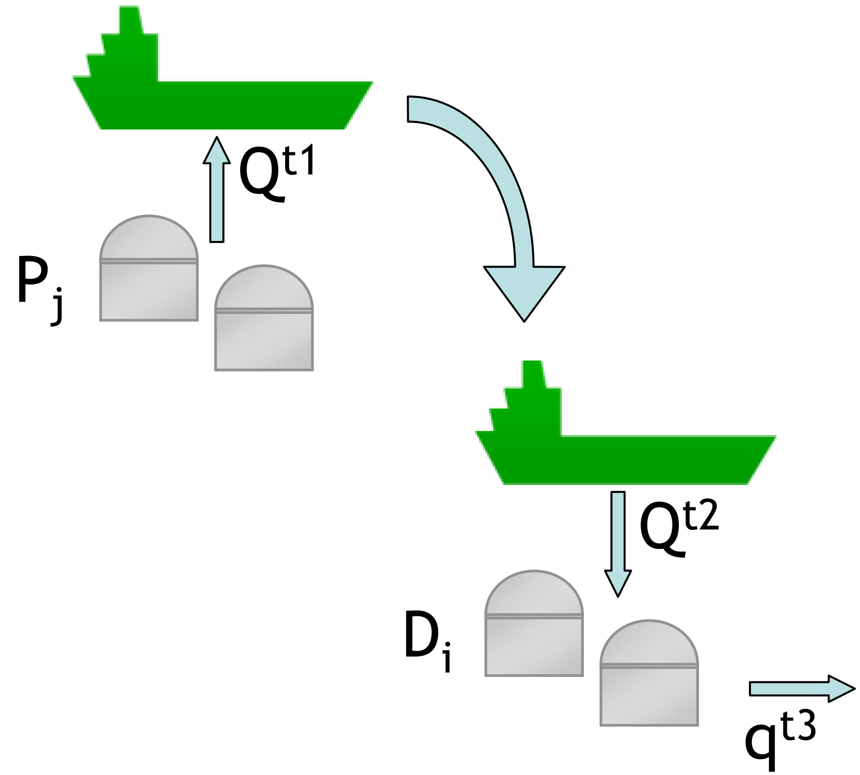
- Connected to one liquefaction plant
- Designated regasification terminals
- Destination restrictions



$$Q_1 + Q_2 \geq W(Q_1 + Q_2 + Q_3 + Q_4)$$

Contract characteristics

- Destination and time dependent prices
  - Contract
  - Quantity loaded
  - Unloading time
  - Destination



Cost : $C_{Di}^{t2} \cdot Q^{t1}$

Revenue : $R_{Di}^{t3} \cdot q^{t3}$

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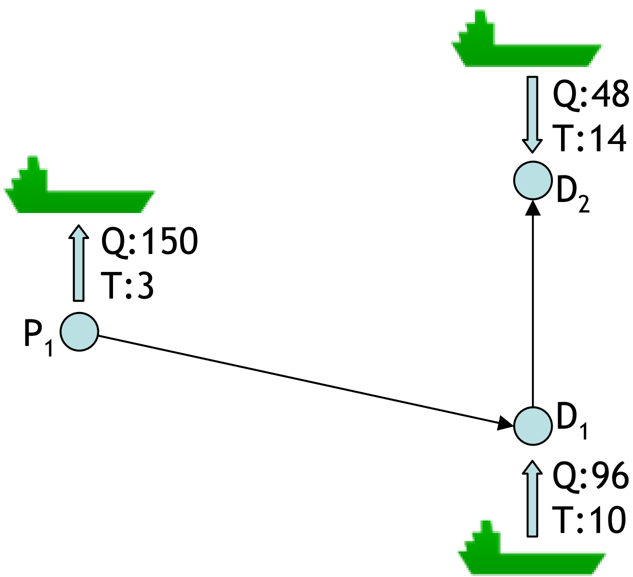
Loading and unloading

- Due to boil-off, we do not use quantities to connect the loading and unloading
- Instead we use shares

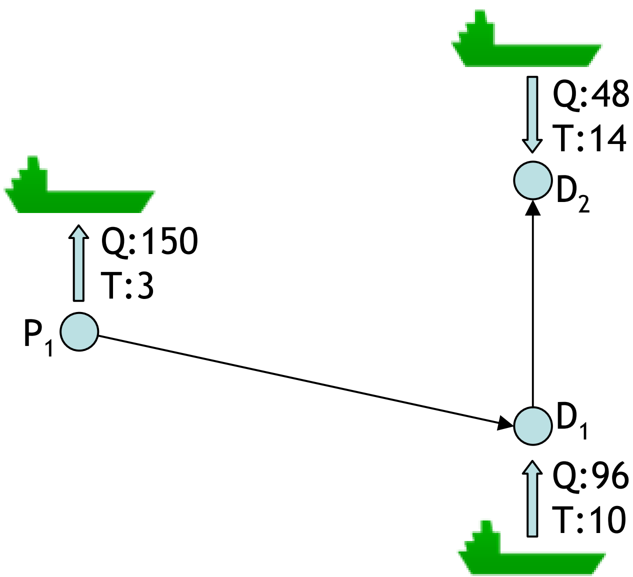


Share loaded at P_1 :	1
Share unloaded at D_1:	2/3
Share unloaded at D_2:	1/3

Loading and unloading; Contracts

- Assume 2 contracts, both connected to P1

a^{CP}_{ct}	The share used for contact *c* when loading in time period *t*
a^{CD}_{ict}	The share used for contact *c* when unloading at regasification terminal *i* in time period *t*



Share loaded at P_1 : 1
Share unloaded at D_1: 2/3
Share unloaded at D_2: 1/3

$$a^{CP}_{13} + a^{CP}_{23} = 1$$

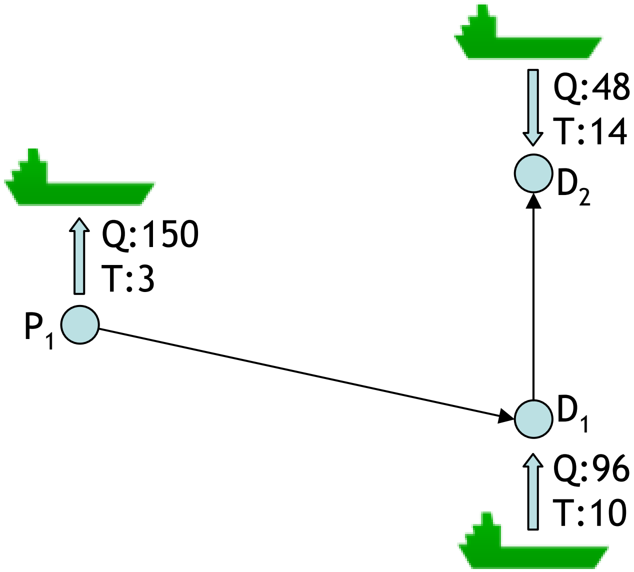
$$a^{CD}_{D1110} + a^{CD}_{D1210} = 2/3$$

$$a^{CD}_{D2114} + a^{CD}_{D2214} = 1/3$$

Connecting loading and unloading

$$\sum_{\tau=T_c^S}^{t}\left(a_{c\tau}^{CP} - \sum_{i\in N^D} a_{ic\tau}^{CD}\right) \geq 0, \quad c \in C, t \in T$$

$$\Downarrow$$



$$a^{CP}{}_{13} + a^{CP}{}_{23} = 1$$

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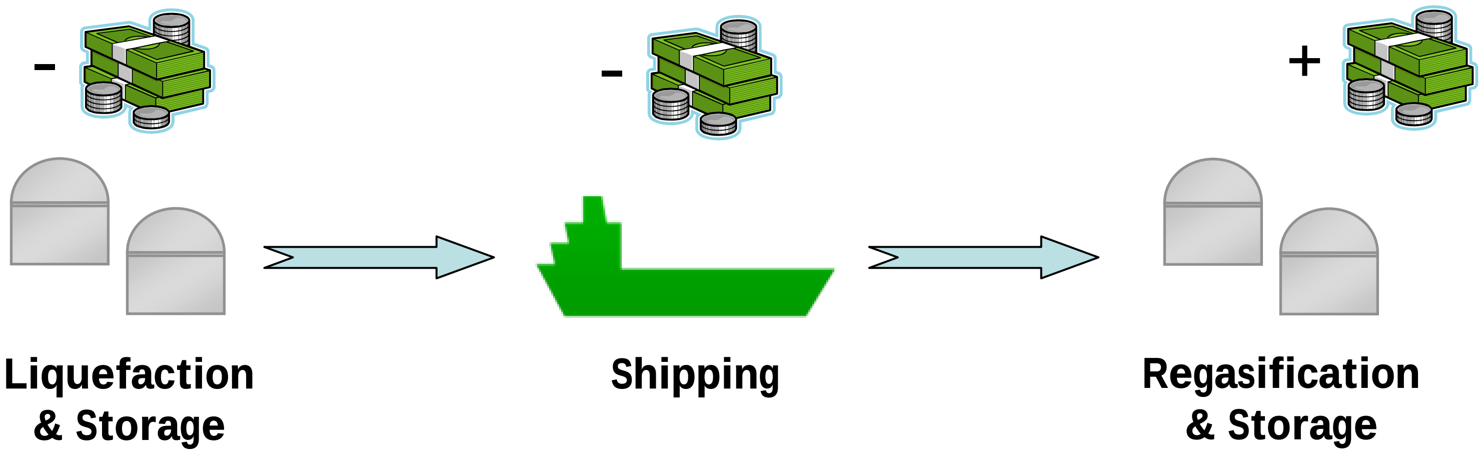
$$a^{CD}{}_{D2114} + a^{CD}{}_{D2214} = 1/3$$

Model summary; Constraints

- Regasification terminals
  - Inventory balance constraints
  - Limits on inventory levels and sales
  - Berth constraints
- Ship movement
  - Convexity constraints
  - Implicit feasibility through the path information
- Liquefaction plants
  - Berth constraints
  - Inter-arrival gaps
- Contracts
  - Limits on quantity loaded on each contract
  - Destination restrictions
- General
  - Connection constraints
    - Contracts
    - Loading
    - Unloading
    - Path information

Model summary; Objective



- Maximize

  Revenue from selling gas

  – Cost of purchasing gas

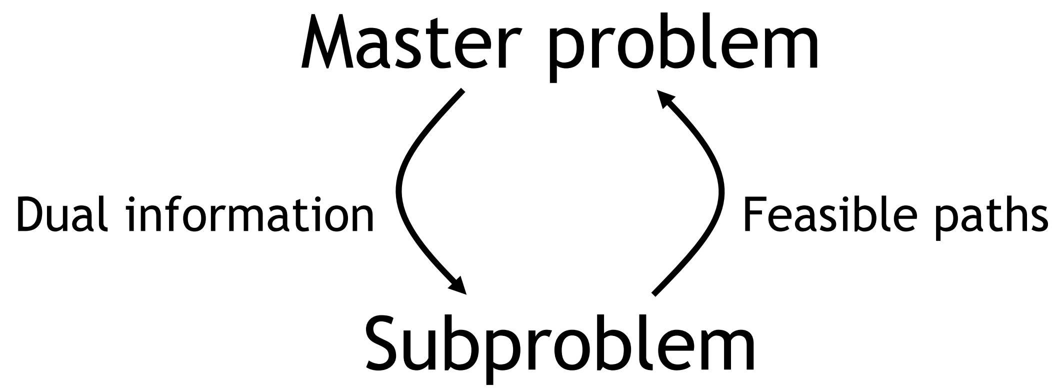
  – Ship operating costs

Solution approach; Branch-and-price

- Branch-and-price
  - Solve the model with a restricted number of paths using branch-and-bound
  - Each node in the branch-and-bound tree is solved using column generation

Solution approach

- Master problem
  - All of the above constraints
  - Implicit path feasibility



- Subproblem
  - Explicit path feasibility
  - Boil-off and quantity calculations

Summary

- An important part of the LNG supply chain has been modeled
- Pick-up contracts with destination restrictions
- Path-based model
  - Separates path assignment and path feasibility
- Branch-and-price
  - Works well for similar problems

Questions