When Feasibility of Routes is Difficult to Determine: an Example from Maritime Bulk Shipping

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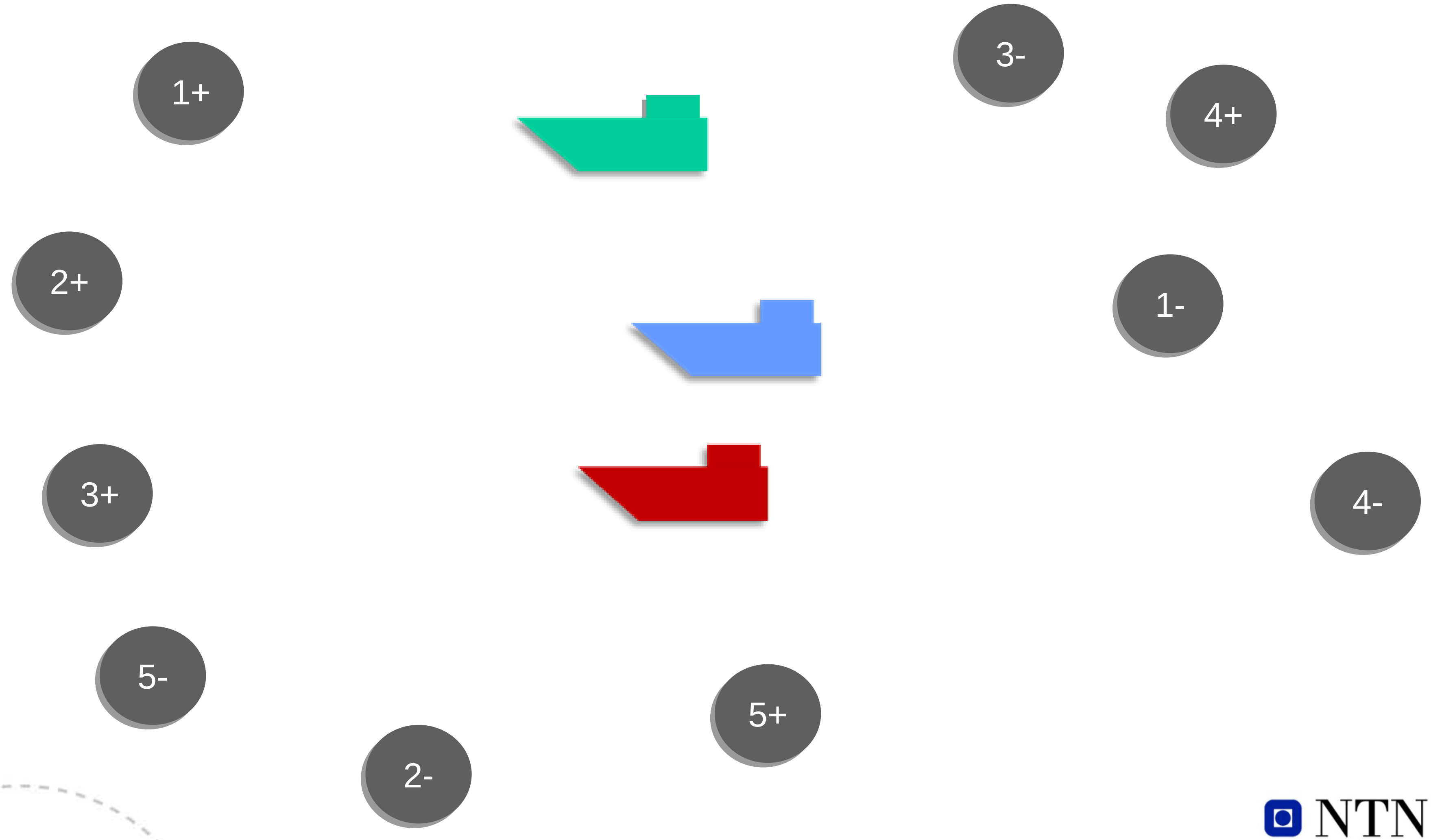
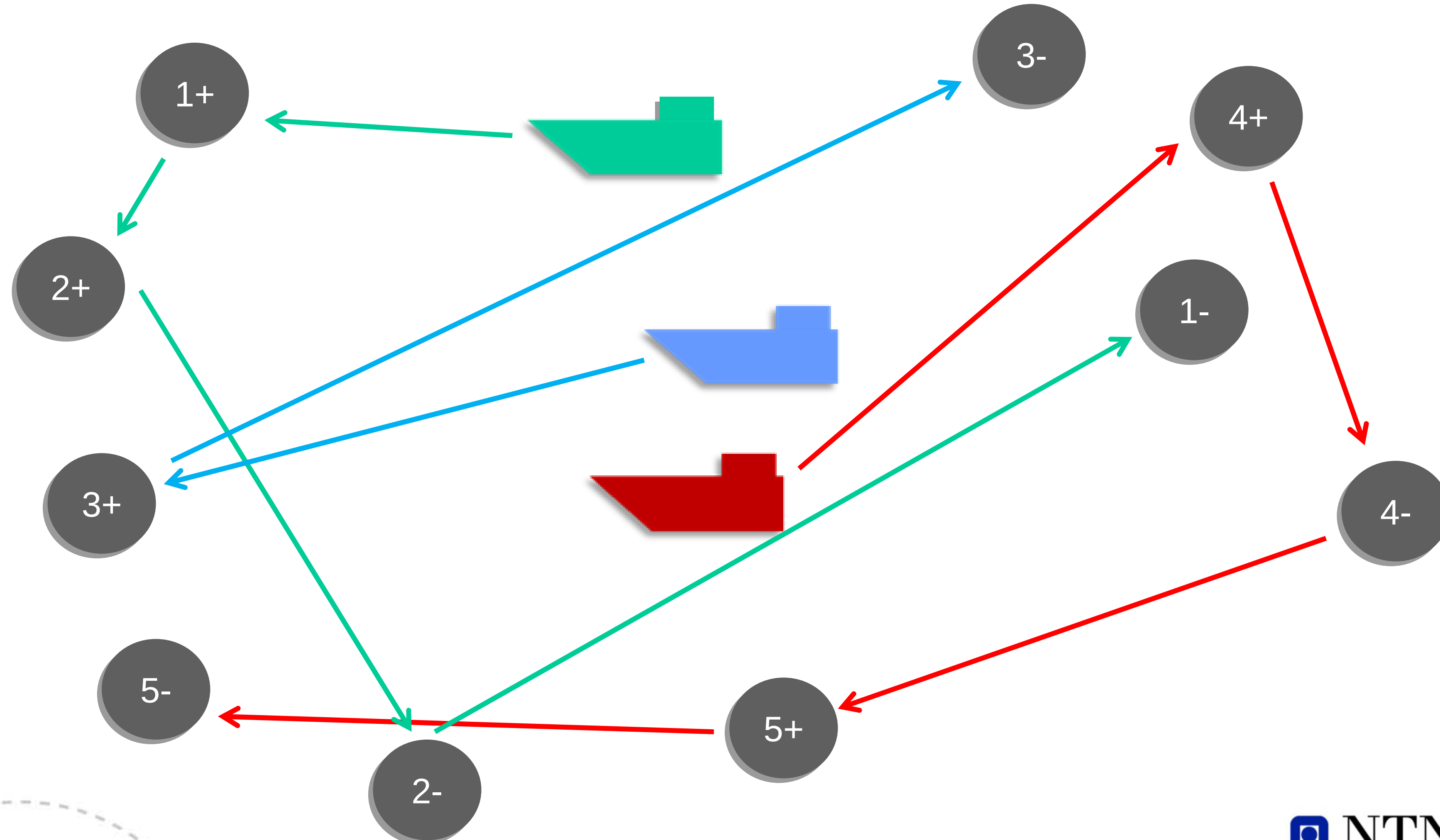
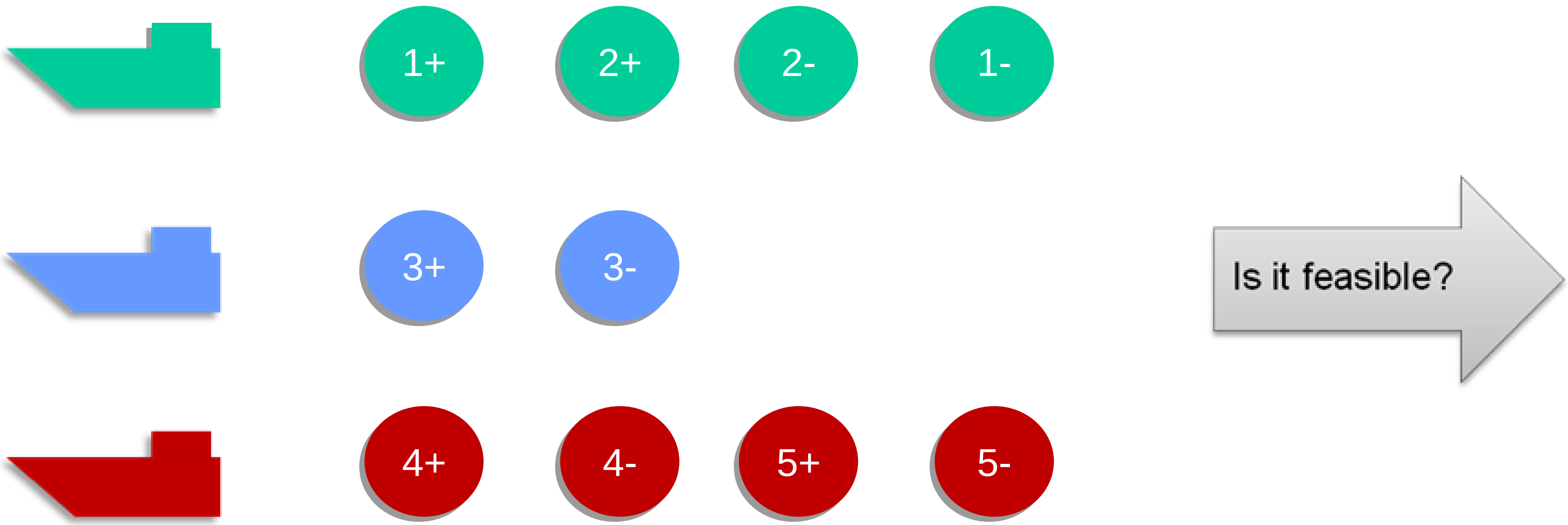
Main Problem



Vessel Routes

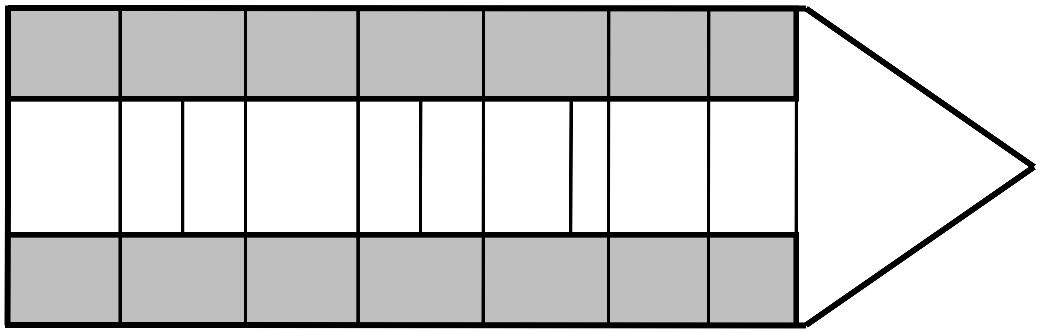


Possible Solution



Constraints (1)

- Each cargo must be allocated to one or several tanks
- Cargo quantity must not exceed the total capacity of these tanks
  - Volume
  - Weight



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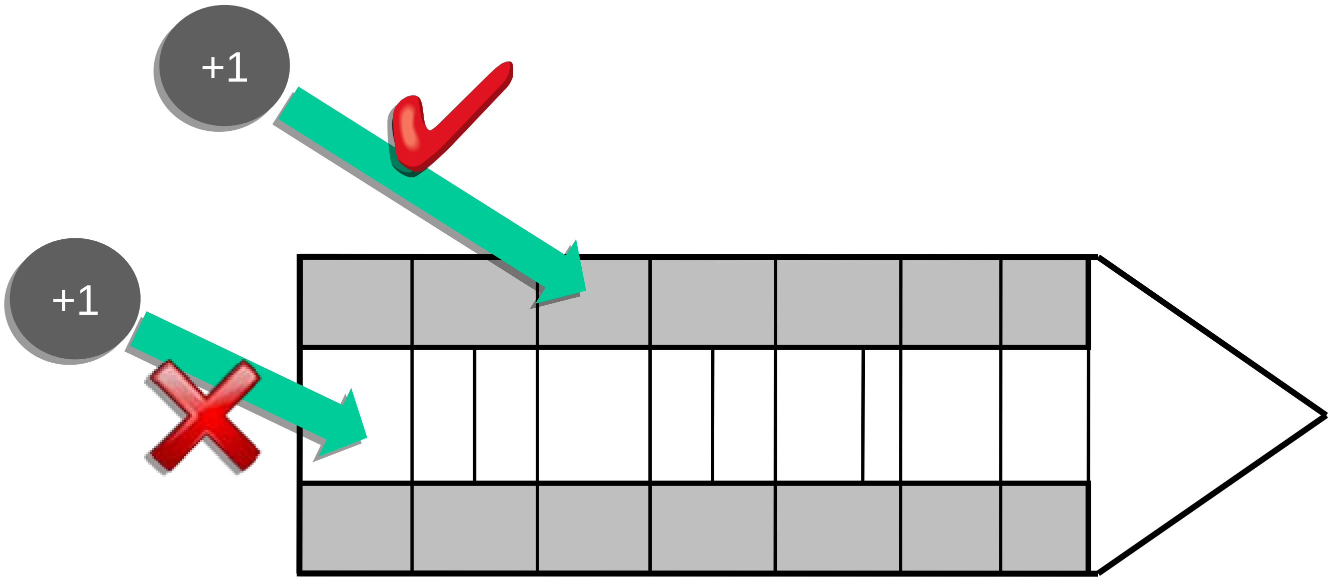
Constraints (2)

- Tanks have different coatings, and cargos can only be allocated to tanks with compatible coatings



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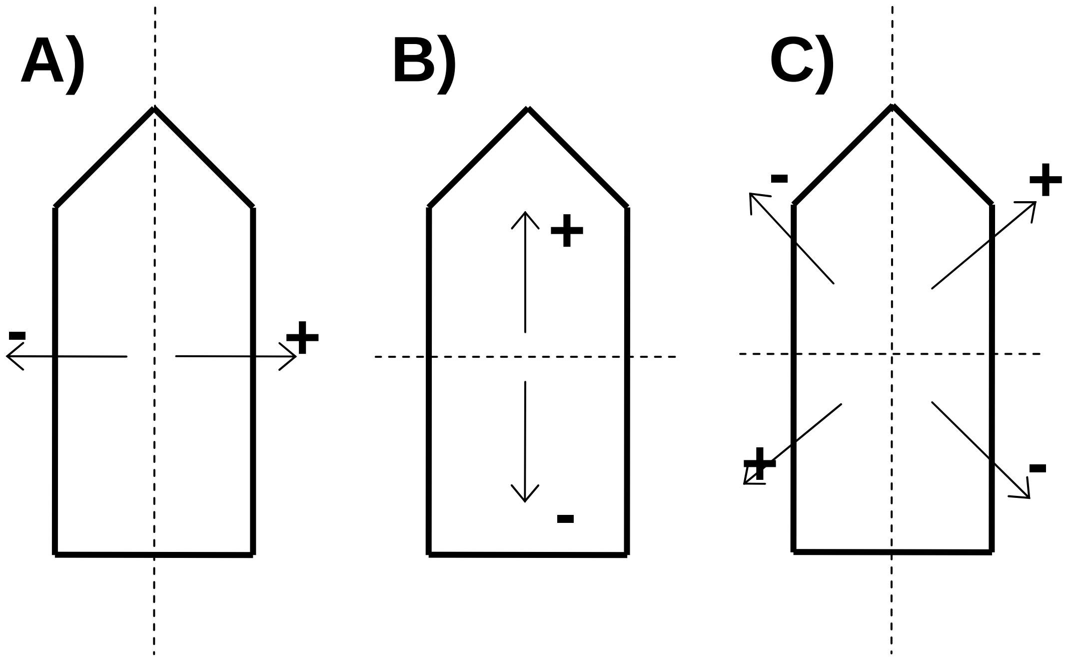
Constraints (3)

- It is not allowed to move a cargo between tanks after it has been loaded
- It is not allowed to mix cargos, even if it is the same product, in the same tank
- At the beginning of the planning horizon, some tanks may be already occupied by some cargos that have not yet been unloaded
- It may be prohibited to have tanks that are only half-full, in order to avoid sloshing cargos

Constraints (4)

- There are requirements with respect to the stability (A, B) and strength (C) of the ship



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Constraints (5)

- Due to hazmat rules, certain products cannot be allocated to neighboring tanks
- Due to hazmat rules, certain products cannot be onboard the same vessel at the same time
- Due to hazmat rules, certain products cannot be allocated in sequence to the same tank, except if the tank has been cleaned or the tank has been used by a number of other cargos in between

Model for the Single Instant TAP

$$b_t x_{lt} \le y_{lt} \le c_t x_{lt} \qquad (l \in \mathbf{L}, t \in \mathbf{T_l})$$

$$\sum_{t \in \mathbf{T_l}} y_{lt} = v_l \qquad (l \in \mathbf{L})$$

$$\sum_{l \in \mathbf{L_t}} x_{lt} \le 1 \qquad (t \in \mathbf{T})$$

$$\sum_{k \in \mathbf{L_l}} \sum_{u \in \mathbf{T_{lkt}}} x_{ku} \le M_{lt}(1 - x_{lt}) \qquad (l \in \mathbf{L}, t \in \mathbf{T_l})$$

$$m^{s-} \le \sum_{l \in \mathbf{L}} \sum_{t \in \mathbf{T_l}} m_t^s (w_l / v_l) y_{lt} \le m^{s+} \qquad (s \in \mathbf{S})$$

$$x_{lt} \in \{0, 1\} \qquad (l \in \mathbf{L}, t \in \mathbf{T_l})$$

$$y_{lt} \ge 0 \qquad (l \in \mathbf{L}, t \in \mathbf{T_l})$$

Model for the Tank Allocation Problem

$$b_t x_{lt} \leq y_{lt} \leq c_t x_{lt} \qquad (l \in \mathbf{L}, t \in \mathbf{T_l})$$

$$\sum_{t \in \mathbf{T_l}} y_{lt} = v_l \qquad (l \in \mathbf{L})$$

$$\sum_{k \in \mathbf{L_t} \cap \mathbf{N_l}} x_{kt} \leq 1 \qquad (l \in \mathbf{L}, t \in \mathbf{T})$$

$$\sum_{k \in \mathbf{L_l} \cap \mathbf{N_l}} \sum_{u \in \mathbf{T_{lkt}}} x_{ku} \leq M_{lt}(1 - x_{lt}) \qquad (l \in \mathbf{L}, t \in \mathbf{T_l})$$

$$m^{s-} \leq \sum_{l \in \mathbf{R}} \sum_{t \in \mathbf{T_l}} m_t^s (w_l / v_l) y_{lt} \leq m^{s+} \qquad (\mathbf{R} \in \mathbf{Q}, s \in \mathbf{S})$$

$$h_{lkt}(x_{lt} - z_{lt}) - \sum_{j \in \mathbf{R}} (x_{jt} + h_{lkt} z_{jt}) \leq h_{lkt}(1 - x_{kt}) \qquad (l \in \mathbf{L}, t \in \mathbf{T_l}, k \in \mathbf{P_l} \cap \mathbf{L_l}, \mathbf{R} = \mathbf{P_l} \setminus \mathbf{P_k} \setminus \{k\})$$

$$x_{lt} \in \{0, 1\} \qquad (l \in \mathbf{L}, t \in \mathbf{T_l})$$

$$y_{lt} \geq 0 \qquad (l \in \mathbf{L}, t \in \mathbf{T_l})$$

$$z_{lt} \in \{0, 1\} \qquad (l \in \mathbf{L}, t \in \mathbf{T_l})$$

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Objective functions

- Minimize the number of cleaned tanks

$$\min z = \sum_{l \in \mathbf{L}} \sum_{t \in \mathbf{T}_1} z_{lt}$$

- Maximize capacity of vacant tanks during the vessel route?
  - increasing flexibility for future changes in the route
- Maximize the probability of being able to accept future transportation requests?
  - must take all vessel routes into consideration
- Anyway, feasibility is more important!

Computational Complexity

- Finding a feasible solution is NP-complete
  - even when considering a single instant of the vessel route
    - i.e., can a given set of cargos be present on the ship simultaneously, disregarding the sequence of loading/unloading?
  - even if disregarding
    - all hazmat regulations
    - all stability/strength restrictions
    - anti-sloshing constraints
  - even if allowing loads to be mixed in tanks
    - proofs of NP-completeness then use either hazmat constraints or stability/strength constraints

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Test Instances

- First, how much time is required to solve realistically sized instances?
- Instances generated by varying
  - Ship configuration (24 tanks or 38 tanks)
  - Number of loads (10, 20, or 30)
  - Load categories (0%, 10%, 20%, or 30% of loads are hazardous)
  - Min/max levels of ship utilization (65%, 75%, or 85% full)
  - Size of loads (1-5, 3-9, or 8-16 thousand tons)
- All instances include a history of 10 loads (some of which may still be present on the ship)
- Stability w.r.t. roll is enforced

Results using CPLEX

- Two different objective functions
  - obj1: minimize the number of tank cleanings
    - potential problem: little guidance when branching
  - obj2: maximize average free capacity during the voyage

	obj1	obj2
	not feasible	not feasible
$>$ 600 seconds	4	3
$>$ 100 seconds	13	9
$>$ 10 seconds	43	48
$>$ 1 second	165	174
in total	720	720

Which Dimensions Matter?

		obj1			obj2		
subset	instances	feasible	seconds	op[illegible]	[illegible]	[illegible]	[illegible]
TAP	720	716	4.13	561	717	5.12	40
L20	240	240	1.11	231	240	0.57	38
L30	240	239	2.21	[illegible]	[illegible]	[illegible]	[illegible]
L40	240	237	9.14	[illegible]	[illegible]	[illegible]	[illegible]
C1	180	177	0.35	177	180	0.97	15
C2	180	179	2.23	165	180	5.40	7
C3	180	180	4.00	[illegible]	[illegible]	[illegible]	[illegible]
C4	180	180	9.88	95	179	10.75	12
F1	240	239	2.81	190	238	3.88	20
F2	240	240	5.14	187	239	8.65	9
F3	240	237	4.45	[illegible]	[illegible]	[illegible]	[illegible]
T24/S3	180	180	1.21	[illegible]	[illegible]	[illegible]	[illegible]
T24/S6	180	180	0.23	[illegible]	[illegible]	[illegible]	[illegible]
T38/S6	180	176	12.79	[illegible]	[illegible]	[illegible]	[illegible]
T38/S12	180	180	2.50	145	180	3.84	10

more loads = more difficult

more hazmat = more difficult

higher ship utilization = unclear

smaller loads = more difficult

more tanks = more difficult

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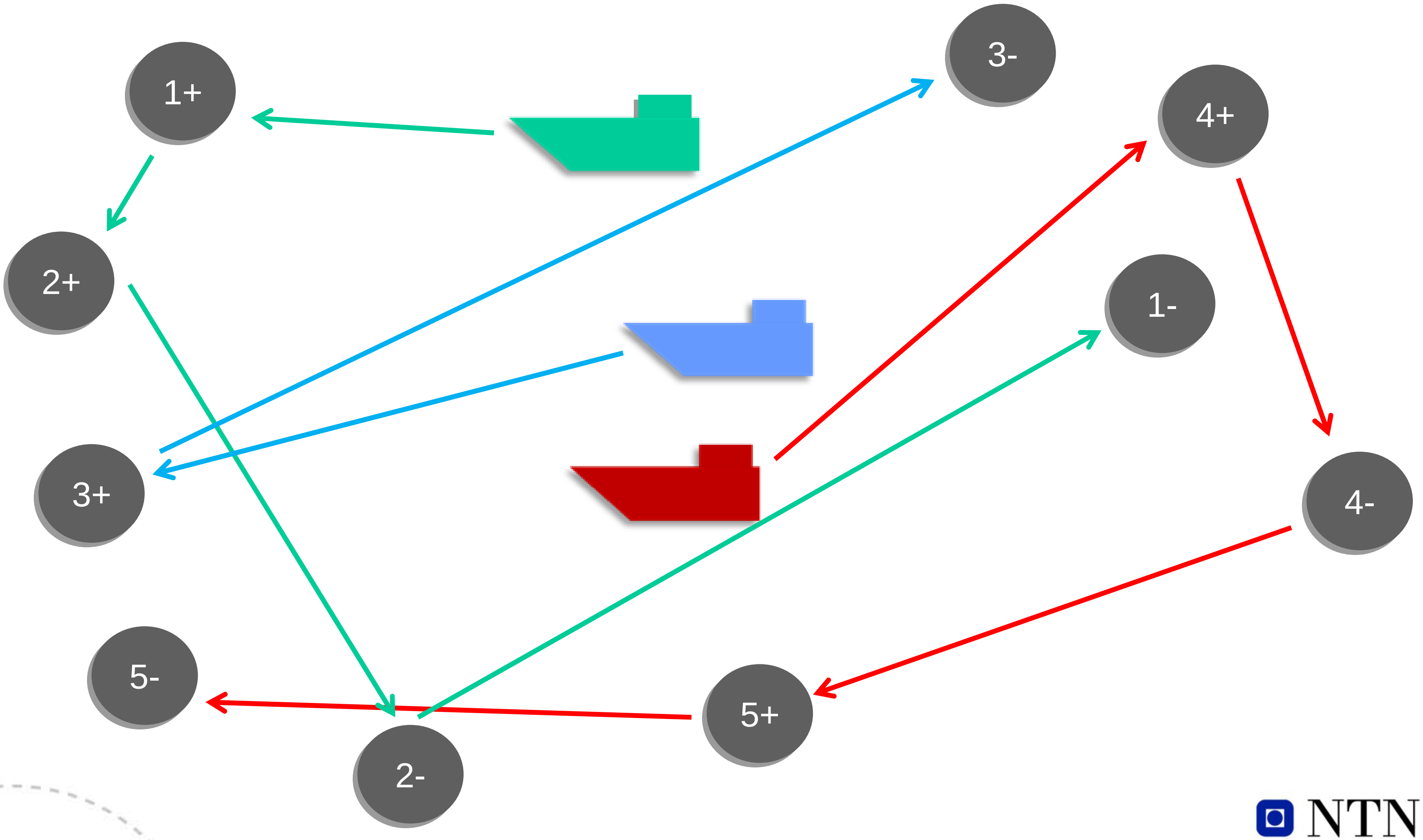
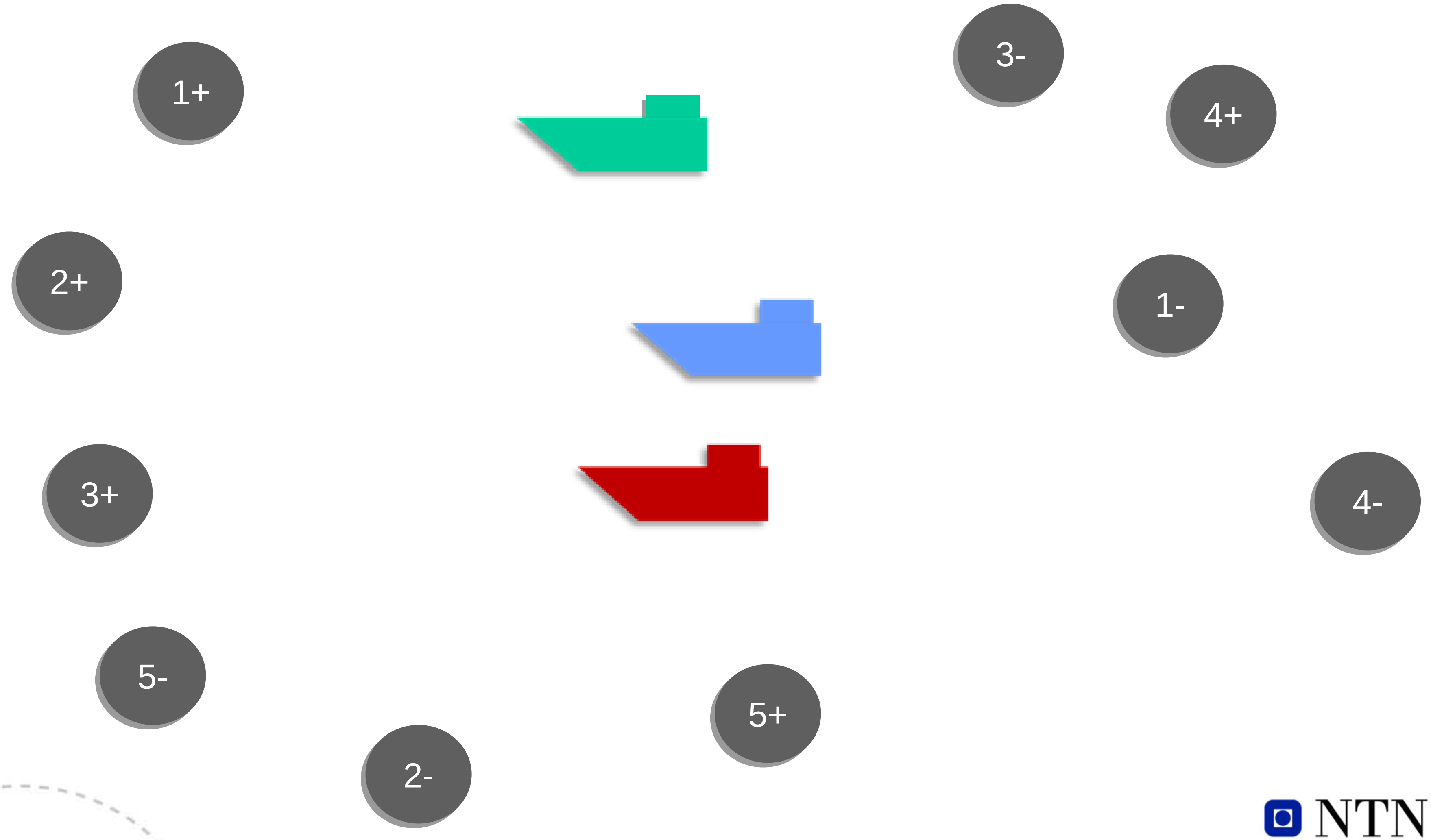
Solving TAPs and Future Work

- Most realistically sized instances solved by CPLEX within 1 second
  - OK if the goal is to find a feasible stowage plan
- Some instances cannot be solved within 10 minutes
  - CPLEX is not robust
- We can try to modify branching priorities to see if this can guide CPLEX in the difficult cases?
- We can try Constraint Programming solvers?
- We can develop special heuristics that might be better suited to find feasible solutions?

1) Finding Stowage for a Route



2) Finding Routes and Stowage Together?



Solving the Main Problem

- For now we focus on the subproblem, TAP
- Eventually, the goal is to solve the main problem: finding the best vessel routes with a feasible stowage plan
- We know that metaheuristic search, such as Tabu Search, works well for routing problems
  - Efficient neighborhood exploration
- What is the best strategy when evaluating a neighbor is NP-complete?

Future Research

- Improved neighborhood exploration
  - First Improvement
  - Neighborhood reductions
    - Granular Tabu Search
  - Surrogate Evaluation
    - Delay evaluation of stowage plan
    - How to handle infeasible stowage problems?
- Improved solution methods for the stowage problem
  - Use the stowage plan of current solution as a starting point for finding a stowage plan when evaluating a neighboring solution
- Other?

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