Molde University College
Specialized University in Logistics

Offshore supply vessel planning under demand and weather uncertainty

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Outline

- Supply vessel planning
- Deterministic
- Weather uncertainty
- Demand uncertainty
- Demand and weather uncertainty
- Collaboration

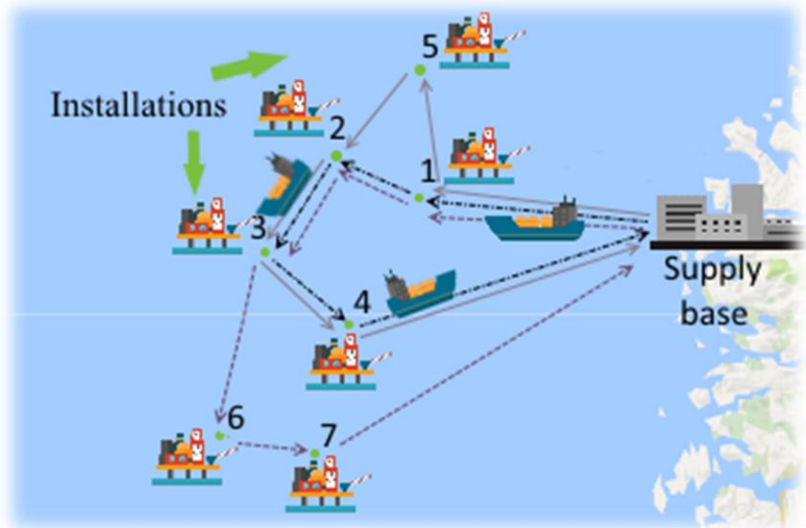
Offshore oil and gas logistics

Upstream logistics

Downstream logistics

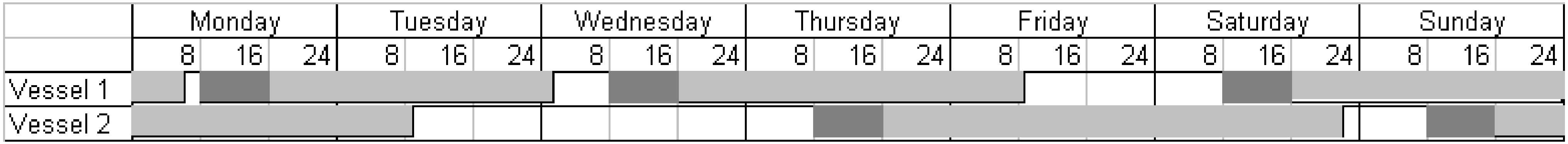
Periodic supply vessel planning

- Set of offshore installations supplied on regular basis from a supply base
- Set of platform supply vessels (PSV) delivers cargo
- Weekly master schedule for vessels (cycling)
- Repeated each week over a certain time horizon (several months or so)
- Service requirements from installations
  - departure frequency
- High costs
  - vessel charter costs (up to 20 000 EUR/day)
  - fuel cost (large distances)

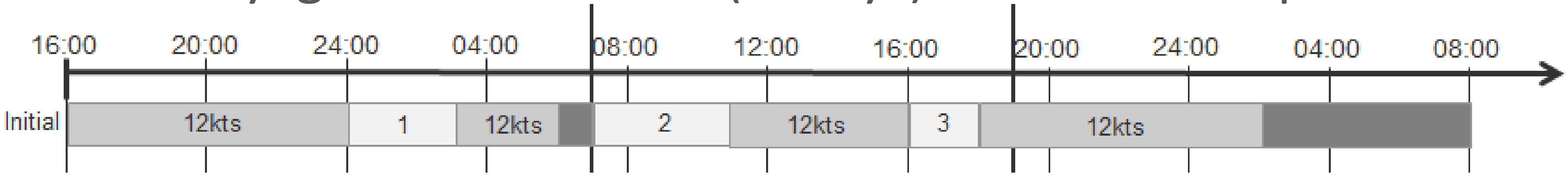


Weekly master schedule

- Each vessel is sailing one or more voyages that don't overlap



- Each voyage has a duration (in days) and a fixed departure time



- Waiting/idle time in weekly master schedule
  - Inter-voyage slacks
    - Idle days between voyages
  - Intra-voyage slacks
    - Waiting for opening hours at installations and for opening at supply base

PSVPP definition

- Installations
  - One week planning horizon
  - Departure frequency
  - Demand per visit
  - Servicing time
  - Night closed (TW)
- Vessel fleet
  - Speed
  - Capacity
  - Charter cost
  - Fuel consumption rate
- Supply base
  - Base opening hours
  - Flexible departure times
- Find
  - Optimal fleet composition with the least total cost
    - vessels charter cost
    - fuel cost (while sailing, waiting and servicing)
  - Weekly vessel schedule
    - Set of scheduled voyages
      - sequence of installations to visit
      - voyage departure time
- Constraints
  - Departure frequency
  - Spread of departures
  - Multiple time windows
  - Base capacity
  - Vessel deck capacity
  - Voyage constraints
    - limits on number of visits per voyage
    - voyage duration

Research goals

- Develop an efficient optimization-based decision support tool for the deterministic PSVPP able to construct schedules for large real-life problem instances
- Develop a methodology for the supply vessel planning under demand and weather uncertainty

Planning challenges

- Periodic routing problem
  - planning horizon: a week
  - days as periods
- Fleet composition
  - heterogeneous
- Multi-day route duration
- Time windows each day at installations and at supply base
- Spread of departures to an installation
- Uncertainty
  - Weather conditions
  - Demand

Computers and Operations Research 94 (2018) 52–64

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Computers and Operations Research

journal homepage: www.elsevier.com/locate/cor

The periodic supply vessel planning problem with flexible departure times and coupled vessels

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- A methodology enabling construction of weekly vessel schedules for large-size instances of deterministic problem

PSVPP - FC

- The extedned version of the PSVPP
  - Flexible departures: departure times options from the base
  - Coupled vessels: possibility for vessels of the same type to swap their voyages
- PSVPP- FC (Flexible departures and Coupled vessels)
- Advantages: possible cost reduction on the operational and

	Monday	Tuesday	Wednesda	Thursday	Friday	Saturday	Sunday	**Monday**	Tuesday	Wednesda	Thursday	Friday	Saturday	Sunday
PSV 1	V1		V4			V8			V3		V6	V9		
PSV2	V2		V5		V7			V2		V5		V7		
PSV3		V3		V6	V9			V1		V4			V8	

- Vessels PSV1 and PSV3 are coupled

Set-partitioning formulation

$$\min \sum_{v \in V} c_v^{TC} \delta_v + \sum_{v \in V} \sum_{r \in R} \sum_{t \in T} c_r^S x_{vrt} \quad (1)$$

$$\sum_{v \in V} \sum_{r \in R_{vt}} \sum_{t \in T} a_{ri} x_{vrt} \geq s_i, \quad \forall i \in N \quad (2)$$

$$\sum_{v \in V} \sum_{t \in T_w} \sum_{r \in R_{vt}} x_{vrt} \leq B_w, \quad \forall w \in W \quad (3)$$

$$\sum_{u \in T_t} \sum_{r \in R_{vu}} E_{vrut} x_{vru} \leq \delta_v, \quad \forall v \in V, \forall t \in T \quad (4)$$

$$\sum_{v \in V} \sum_{r \in R_{vt}} \sum_{t \in T_w} a_{ri} x_{vrt} \leq 1, \quad \forall i \in N, \ \forall w \in W \quad (5)$$

$$\underline{p}_{s_i} \leq \sum_{v \in V} \sum_{u \in D_{s_i t}} \sum_{r \in R_{vu}} a_{ri} x_{vru} \leq \overline{p}_{s_i} \qquad \forall i \in N, \ \forall t \in T \quad (6)$$

$$\delta_v \in \{0,1\} \quad (7)$$

$$x_{vrt} \in \{0,1\} \quad (8)$$

ALNS heuristic

- Adaptive Large Neighborhood Search metaheuristic
  - Three destroy operators
  - Three repair operators
- A set of improvement operators
- Acceptance criteria
  - Simulated annealing

Algorithm 1 ALNS

Set the cost of the best found solution $C^* = \infty$;
for ε restarts **do**
Construct initial solution s_0;
$s^* \leftarrow s_0$; $c^* = C(s^*)$; $s \leftarrow s$;
for ρ iterations **do**
    $\eta \leftarrow$select the number of visits and $\upsilon \leftarrow$voyages to be removed;
    $\psi \leftarrow$select destroy operator;
    $s'' \leftarrow \psi(z,q,S)$; remove visits;
    insert an idle vessel and empty voyages into s'';
    $o \leftarrow$ select insert operator;
    $s' \leftarrow o(s'', \eta, S)$; insert visits;
    remove empty voyages;
    if $S = \emptyset$ and s' is feasible **then**
        do
            `number of voyages reduction;`
            `fleet size reduction;`
            `deep greedy relocation;`
            `fleet size reduction;`
            `deep greedy swap;`
            `fleet size reduction;`
        while s' improves;
    if $\rho^{cur} \leq \varsigma\rho$
            if $C(s') \leq C(s^*)$ **then**
                $s^* \leftarrow s'$; $s \leftarrow s'$;
            else if $C(s') \leq C(s)$ **then**
                $s \leftarrow s'$;
            else if accept(s, s') **then**
                $s \leftarrow s'$;
            end if
    else if $C(s') \leq C(s^*)$ **then**
        $s^* \leftarrow s'$; $s \leftarrow s'$;
    else $s \leftarrow s^*$
  end if
 end for;
end for;
return s^*;

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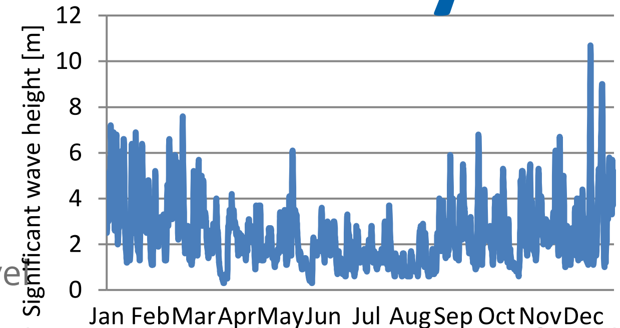
Weather uncertainty



- Weather varies dynamically
  - wave height, wave direction, wind speed
- Weather impacts sailing and service
  - longer voyages, more vessels, reduced service level
- If wave height exceeds 4,5-5 meters the vessel has to wait for better weather to service installations (WOW)
- Weather is considered as an univariate variable of significant wave height
- Uncertain weather conditions yield time- and location inter-dependent uncertain sailing and service time parameters. In this case
  - Uncertain weather conditions change over time and even in the same time period are different in different distant locations.
  - The arrival of a vessel at an installation depends on the sequence of the previous visits on the voyage, on the voyage start time and on changing weather conditions during voyage execution.
- It is problematic or even impossible to model weather conditions using analytical expressions (without assumptions and simplifications), so a discrete-event simulation is used to estimate sailing and service times and voyage duration

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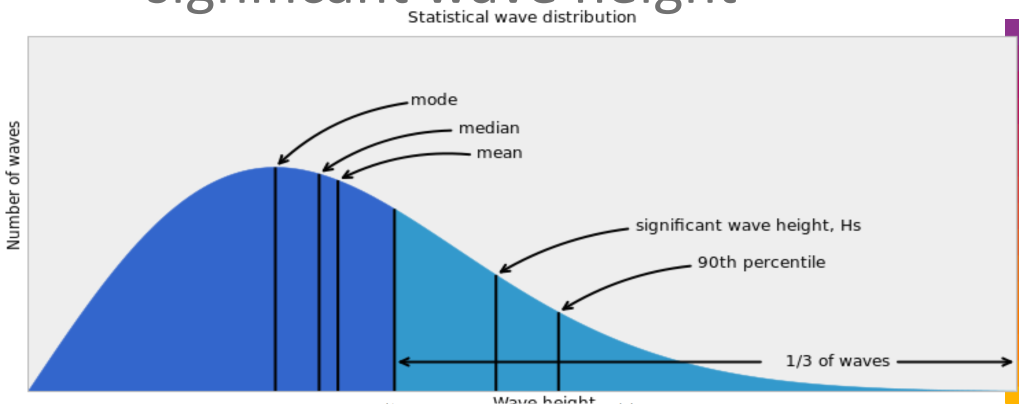
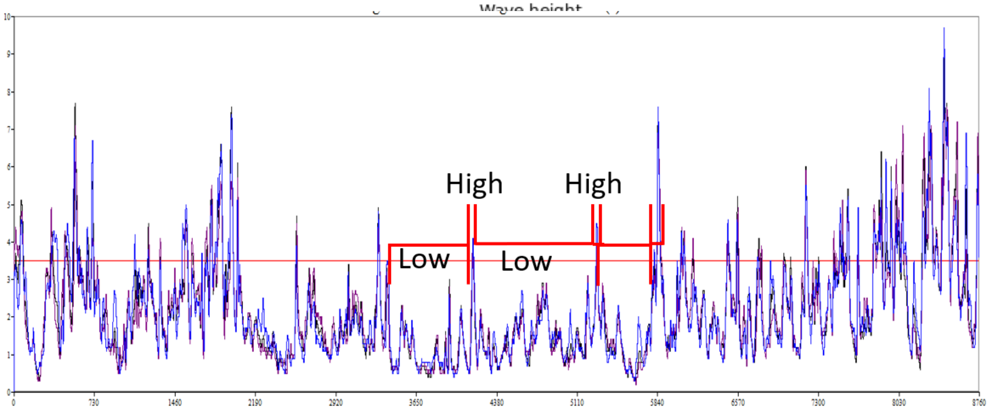
Weather data

- Define number of grid points to cover all installations
- Statistical estimates of the sea state to consider
  - significant wave height





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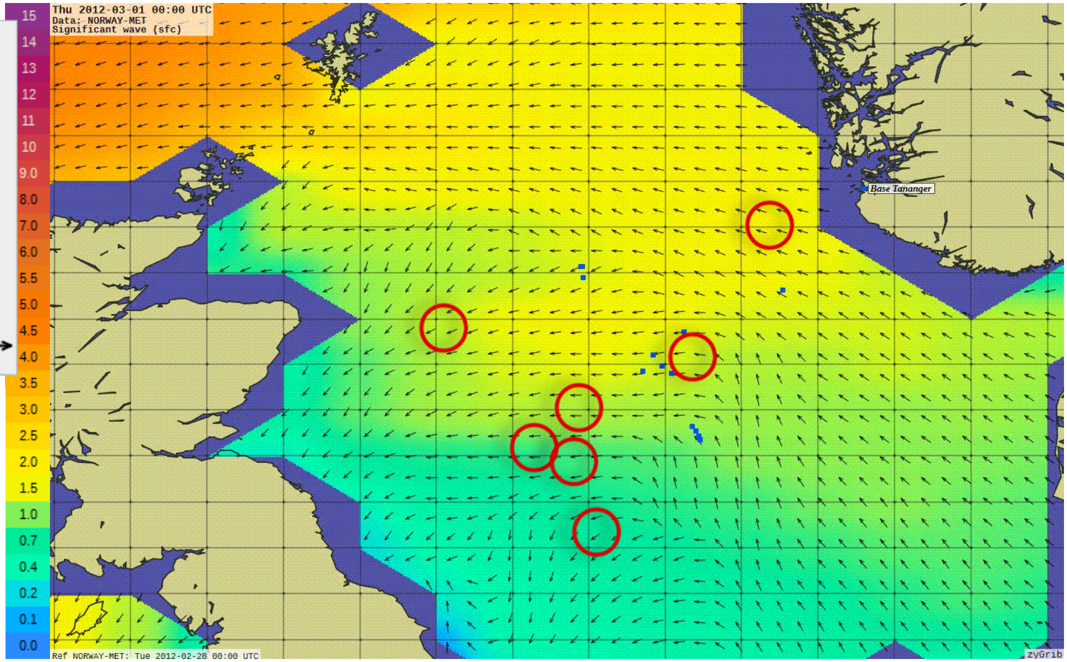

- Safety limits split weather time-series into sequence of high and low weather windows

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Omega

journal homepage: www.elsevier.com/locate/omega

Supply vessel planning under cost, environment and robustness considerations ☆

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- Simulation-optimization method enabling construction of schedules under weather uncertainty for given levels of robustness parameter

Weather modeling with Markov chain

Start state probabilities

State	State 1	State 2	State 3	State 4
Probability January	0,36	0,25	0,18	0,21
Probability July	0,92	0,05	0,02	0,01

Weather states

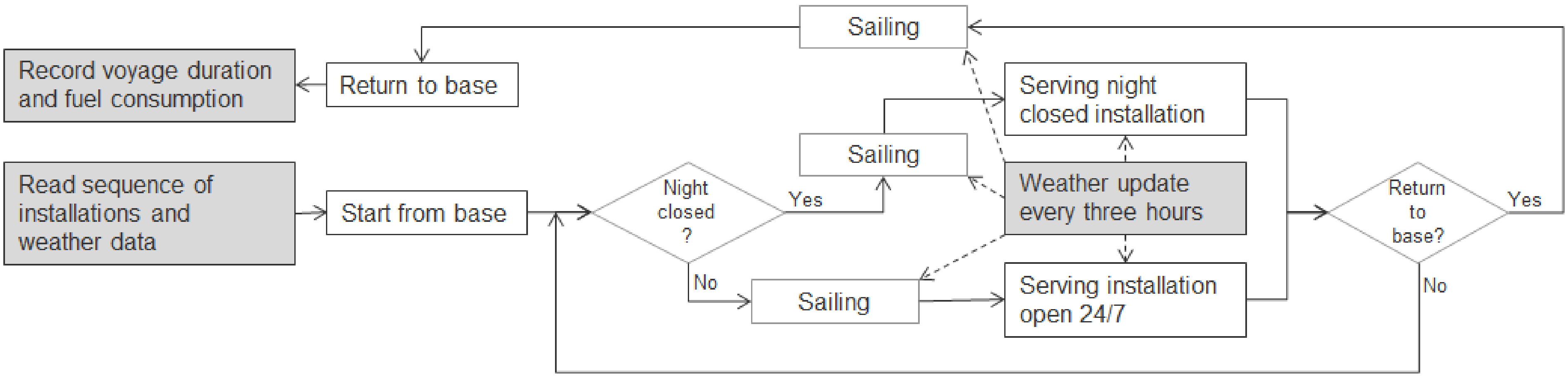
Weather state	Wave height [m]	Sailing speed decrease [kn]	Increase in service time
1	< 2.5	0	0 %
2	<2.5,3.5]	0	20 %
3	<3.5,4.5]	-2	30 %
4	>=4.5	-3	WOW

Transition matrix

January	State 1	State 2	State 3	State 4
State 1	0,92	0,08	0,00	0,00
State 2	0,12	0,74	0,13	0,01
State 3	0,00	0,21	0,65	0,14
State 4	0,00	0,00	0,13	0,87

Voyage simulation

- Each voyage is simulated to find sailing and service times dependent on weather updates every three hours
- Output from simulation is for each voyage
  - Probability distribution of voyage duration in days E(D_v) =[P_v^2, P_v^3, P_v^{3+}]
  - Average fuel consumption $FC_{v,l}^{avg}$ for each value l of the voyage duration in days



Generation of voyage input set

- Assign voyage duration in days based on the robustness parameter value *p*
- The robustness parameter represents a lower bound on the probability that each voyage is feasible within its assigned duration

set robustness level p in $[0, 1]$
for l from 2 to 3 **do**
    set $V_l = \emptyset$
end for
for every voyage v in V **do**
    set $l = 0$
    if $0 \leq p \leq P_v^2$ and $P_v^2 > 0$ **then**
        set $l = 2$
    else if $P_v^2 \leq p \leq P_v^3$ and $P_v^3 > 0$ **then**
        set $l = 3$
    end if
    if $l \neq 0$ **then**
        assign $D_v^p = l$
        set $F_v^p = FC_{v,l}^{avg}$
        insert v in set V_l
    end if
end for
set $V^p = \bigcup_l V_l$

Transportation Research Part C 90 (2018) 366–378

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Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Robust supply vessel routing and scheduling

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- Methodology enabling construction of robust schedules for large-size PSVPP instances with weather uncertainty

Weather modeling with time-series

- Data is sampled from an operational spectral wave model used by MET

    - a number of time series for a particular set of locations have been requested

    - each time-series represents a data set with 54-years of observations based on a 3-hour period

- Statistic estimates of weather conditions modeled based on

    - splitting each of the annual time-series into the number of blocks with equal amount of observations on monthly basis

    - construction of time-series consists of random sampling a sequence of blocks from a predefined subset of all historical annual time-series

- Synchronized generation of time-series for 3 univariate sea state estimates (significant wave height *Hs*, mean wave direction θ, wind speed *Wsp*)
- Simulated *Hs* and *Wsp* form univariate time-series used to derive auxiliary time-series of alternating durations of high-state and low-state weather states for generation of weather windows

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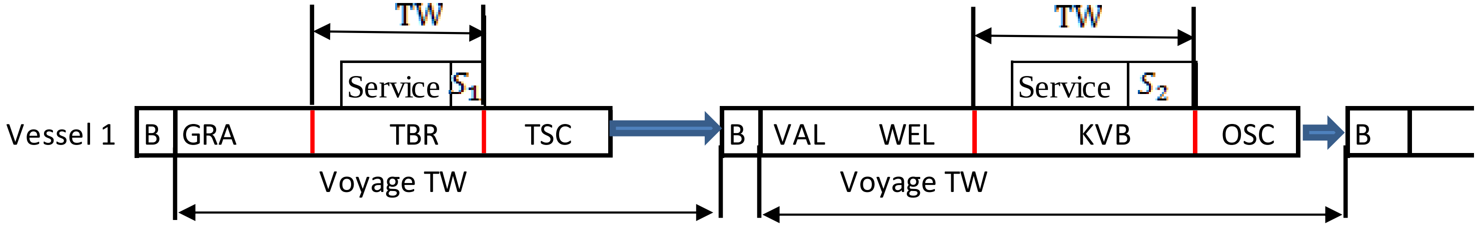
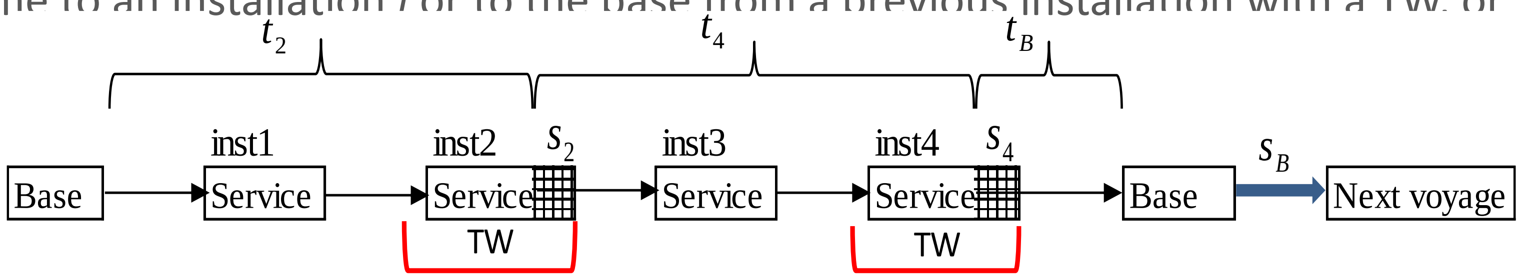
Robustness control

- Dynamic slacks
  - inter-voyage
  - intra-voyage

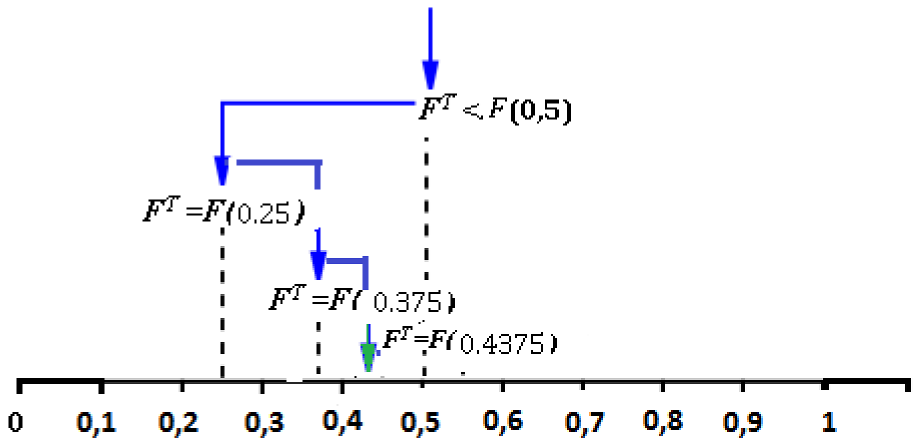


- Introduce parameter α to control voyage slacks duration
  - enforcing the minimal duration of the voyage's slacks which are dependent on voyage duration
- For voyages without TWs: $s / t \geq \alpha$
  - *s* is the required inter-voyage slack duration
  - *t* is the voyage duration
- For voyages with TWs; $s_i / t_i \geq \alpha$
  - s_i is the required intra-voyage slack at the installation *i* with a TW
  - t_i is the travel time to an installation *i* or to the base from a previous installation with a TW, or from the base



Maximum robustness search

```
Set α = 0 and set the value of η;
Run ALNS (α);
z(α): solution provided by the ALNS;
C(α): cost of the solution z(α);
n(α): number of vessels in z(α);
Set n^0 = n(α) and n^max > n^0
for j = n^0 to n^max
    Set α = α + 0.5;
        while n(α) = j do
            Run ALNS(α)
            α = 1.5α;
        end while
            α = α/2;
            Set α^0 = α;
        for i = 1 to η do
            run ALNS (α);
            if n(α) ≤ j then
                Save z(α) in a list R
                S ←Simulate z(α) in a list R
                α = α + α^0/2^i;
            else
                α = α − α^0/2^i;
            end if
        end for
end for
return R and S
```



Simulation model

Algorithm 3 Simulation model

Solution $z(\alpha)$;
Weather data;
Number of visits $v(z)$ in $z(\alpha)$;
  for $i = 1$ to ρ **do**
    Generate weather scenario for the selected time horizon;
    Set $v(i) = 0$;
    for each voyage j in $z(\alpha)$ **do**
      Simulate weather;
      Calculate the number of performed visits $v^p(j)$ within voyage j TW;
      $v(i) = v(i) + v^p(j)$;
    end for each
    $\sigma(i) = v(i)/v(z)$;
  end for
  return $\sigma = \sum_{i=1}^{\rho} \sigma(i) / \rho$

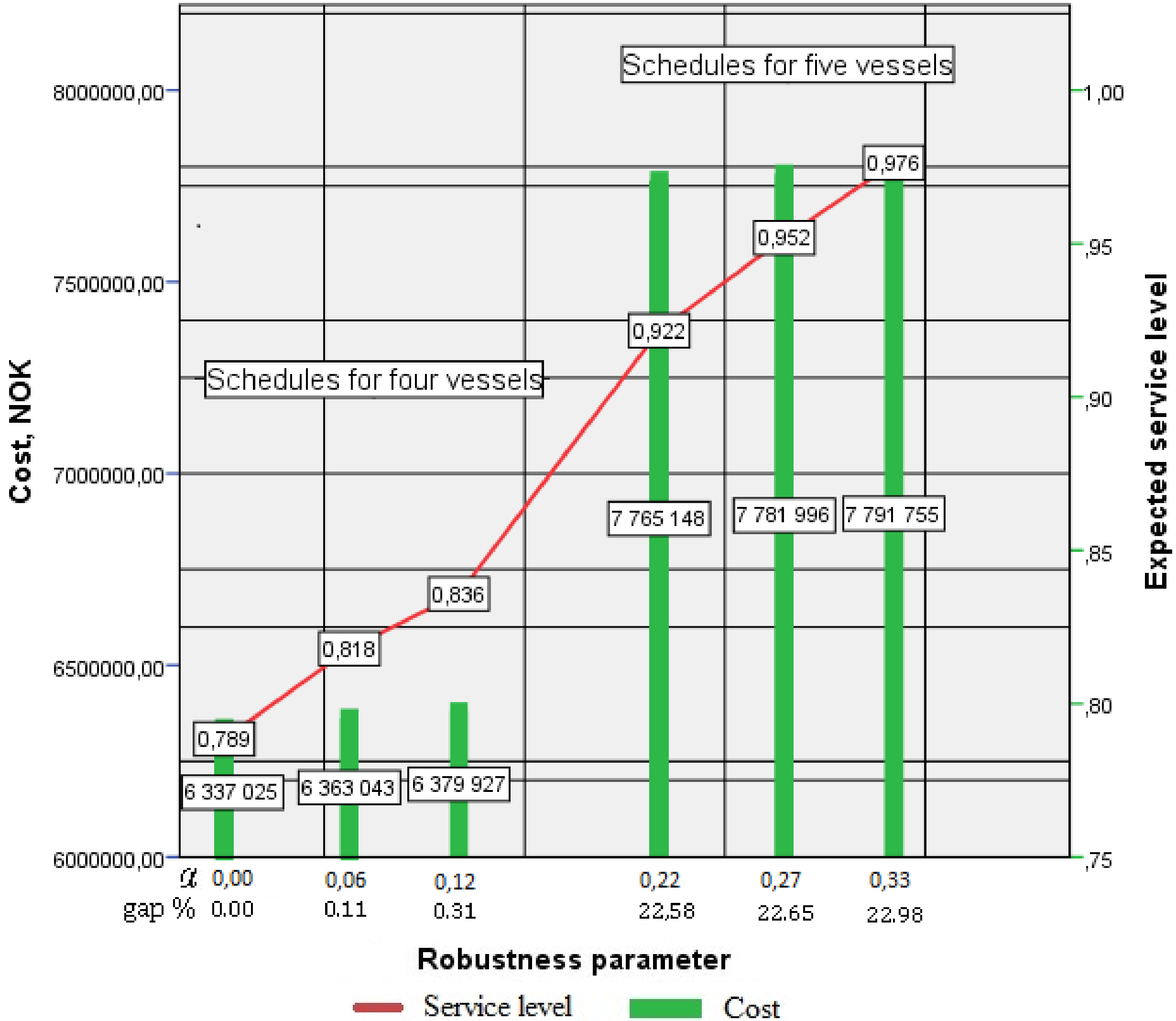
Service level:

$$\sigma = v^p / v$$

v^p - number of performed visits

v - total number of the planned visits

Trade-off analysis



Transportation Research Part C 104 (2019) 305–316

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

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Supply vessel routing and scheduling under uncertain demand

Check for updates

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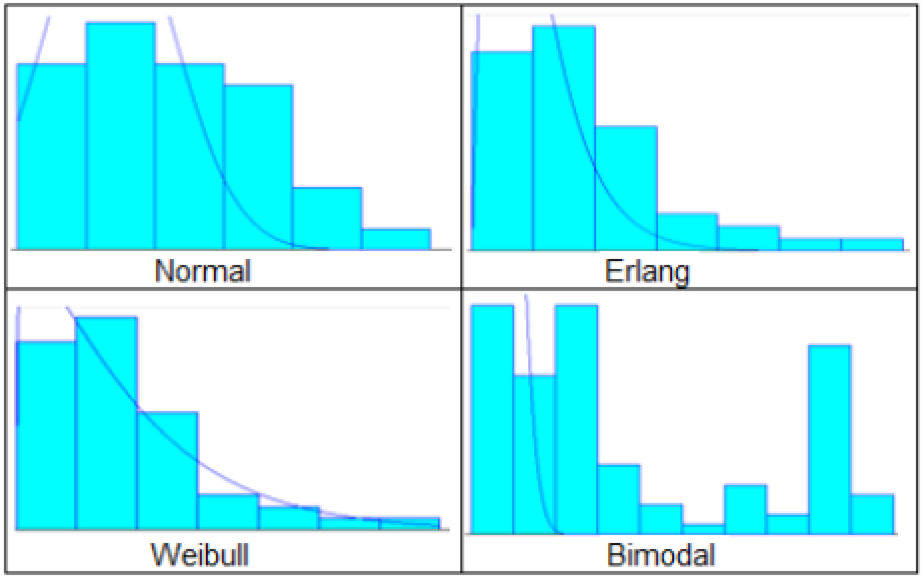
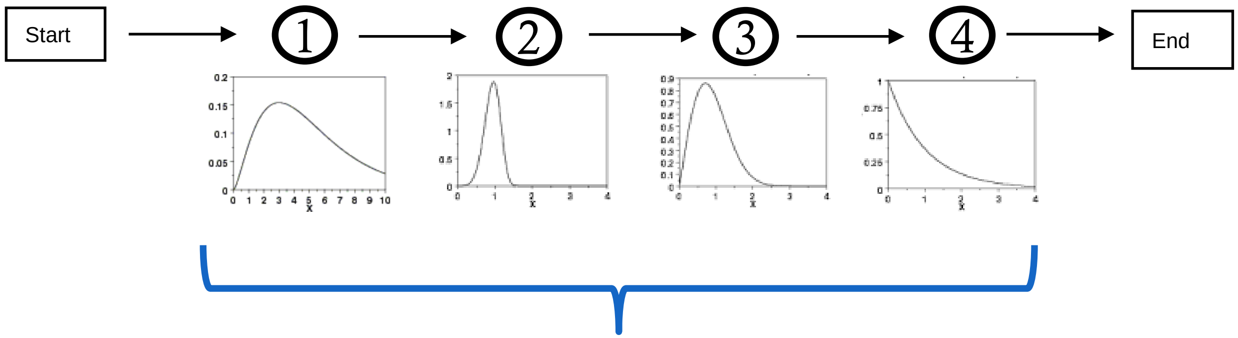
- Methodology allowing for construction of vessels schedules with minimized expected total cost under uncertain demand

Demand uncertainty



- High degree of variation
- Insufficient deck capacity
- Rescheduling
  - Extra voyages
  - Change of planned voyages
  - Spot vessels
- Reduced service level

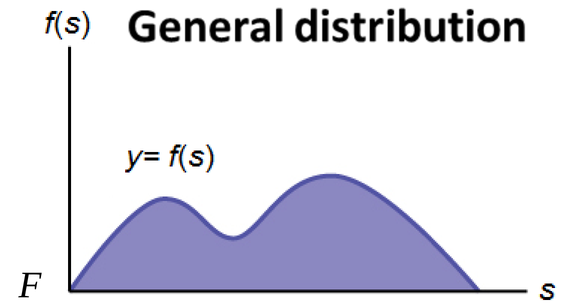
Chance-constraint optimization

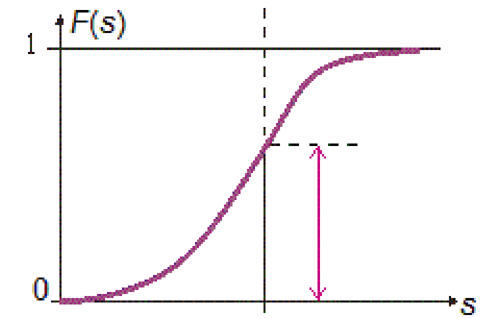


$$P\{D(v) \leq C_v\} \geq p$$

p – reliability level

$$F_v(C_v) \geq p$$





Fast Fourier Transformation:

$$\mathcal{F}(F_x * F_y) = \mathcal{F}(F_x) \cdot \mathcal{F}(F_y), \qquad (1)$$

$$F_x * F_y = \mathcal{F}^{-1}(\mathcal{F}(F_x) \cdot \mathcal{F}(F_y)). \qquad (2)$$

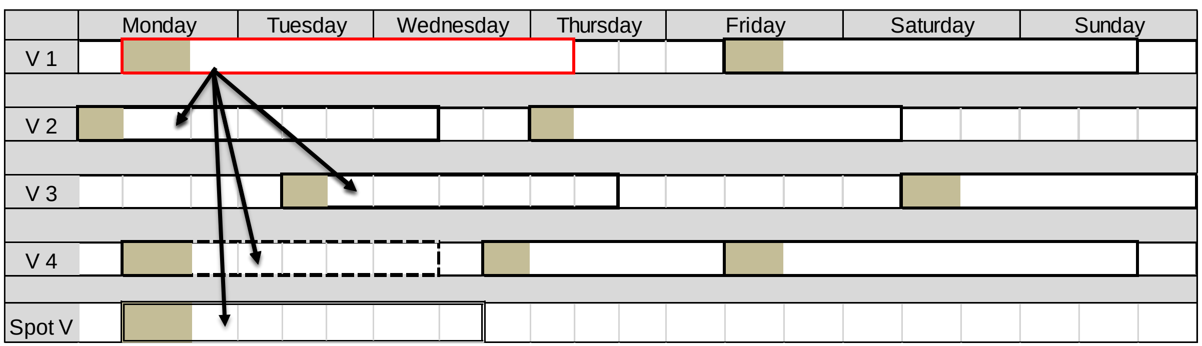
$$F_S = F_1 * F_2 * \ldots * F_n = \mathcal{F}^{-1}(\mathcal{F}(F_1) \cdot \mathcal{F}(F_2) \cdot \ldots \cdot \mathcal{F}(F_n)). \qquad (3)$$

- ALNS with incorporated chance-constraints able to construct schedules with a certain reliability level against uncertain demand

Schedule simulation

Algorithm 2 Schedule simulation

```
Modelled demand;
for i = 1 to ρ do
    for n = 1 to N do
        Solution g(α);
        for d = 1 to D do
            Simulate demand for each visit on voyages started on days d and (d + 1) mod D;
            Recalculate service times and reroute planned voyages;
            V^d ← Find infeasible voyages;
            if V^d ≠ ∅ then
                Perform the least cost recourse actions for voyages in V^d (Algorithm 3);
            end if
        end for
        Calculate cost λ_n of modified schedule g_n^{mdf}(α);
    end for
    Calculate λ_i^{av} = Σ_{n=1}^{N} λ_n / N;
end for
return λ^{exp}(α) = Σ_{i=1}^{ρ} λ_i^{av} / ρ
```



Recourse actions are performed if:

- Vessel capacity violation
- Overlap constraint violation
  - ✓ Service time dependence on cargo volume

Recourse actions:

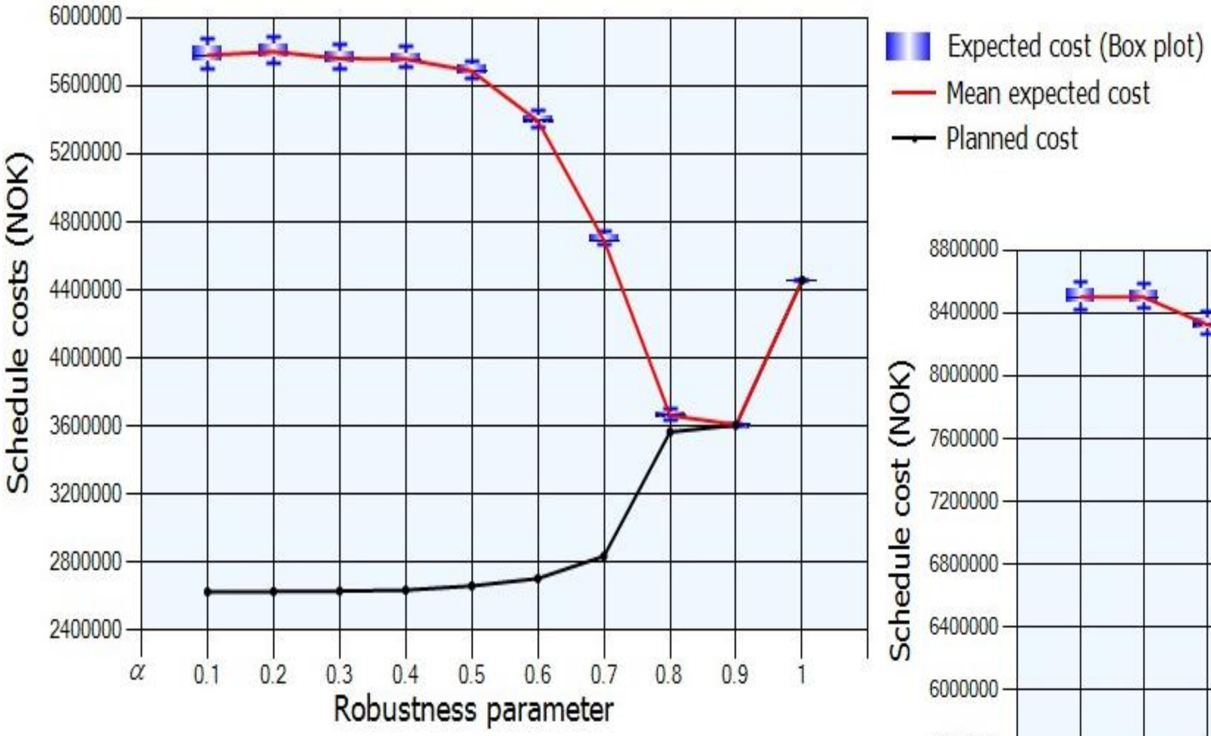
- Planned voyages
- Charter vessels unplanned voyages
- Spot vessel voyage

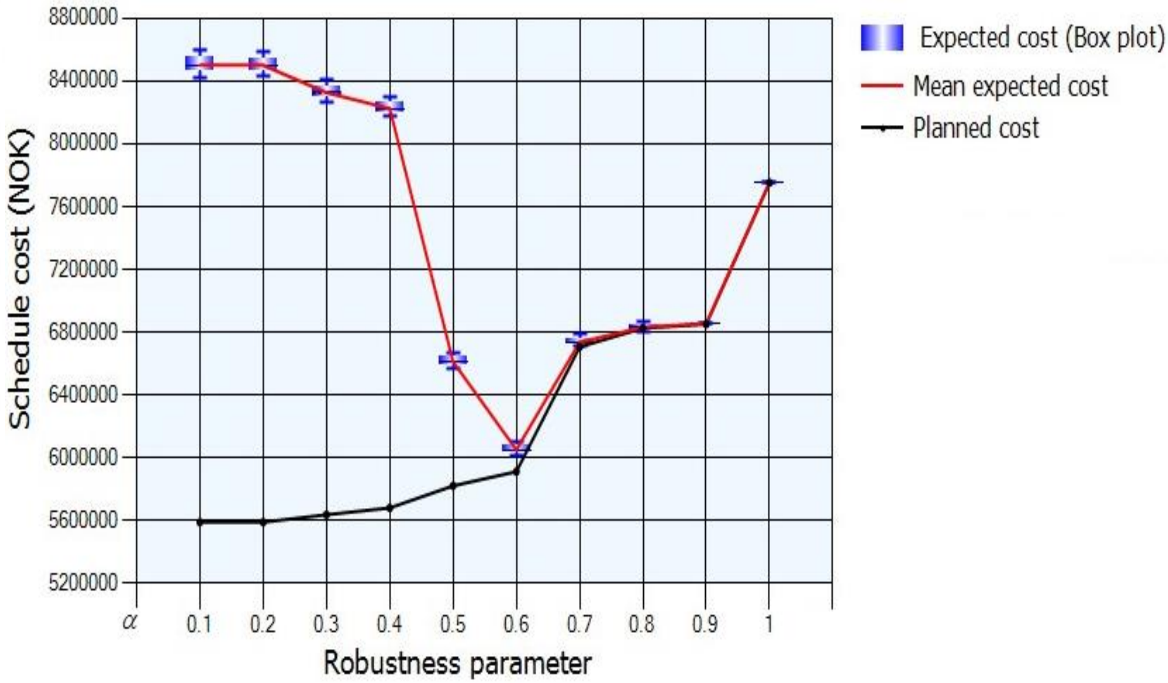
Optimization-simulation algorithm

Algorithm 4 Optimization-simulation algorithm

```
Set A of α values
ρ - the number of simulation replications;
N - the number of times the schedule is executed within the simulation horizon;
for each α ∈ A do
    g(α) ← run ALNS(α);
    Save g(α) in a list R;
    λ^exp(α) ← Schedule simulation (g(α), ρ, N);
    Save λ^exp(α) in a list C;
end for
return R and C
```

Computational experiments





INFOR: INFORMATION SYSTEMS AND OPERATIONAL RESEARCH
2021, VOL. 59, NO. 3, 411-438
https://doi.org/10.1080/03155986.2021.1907872

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Periodic supply vessel planning under demand and weather uncertainty

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- Methodology for construction of vessels schedules with the minimized expected cost under uncertain demand and weather conditions
  - ALNS metaheuristic able to construct schedules with a certain reliability level
    - Chance-constraints
    - Slacks for robustness
  - Discrete event simulation model
  - Recourse actions: operational modifications to eliminate infeasibilities caused simultaneously by uncertain demand and weather conditions
  - Score function: to resolve the trade-off between the schedules cost and the reliability level

Reliability level control

- ALNS generates schedules with defined reliability level against demand and weather uncertainty
- Introduced parameter *p* as lower bound on the probability of voyage capacity-feasibility

$$P\{D(v) \leq C_v\} \geq p$$

- Introduce parameter α to control voyage slacks duration to account for voyage TW-feasibility

$$s_i/t_i \geq \alpha$$

ALNS heuristic

- ALNS generates schedules with reliability (α, p) against demand and weather uncertainty

Algorithm 1. ALNS(α, p) for the PSVPP with uncertain demand and weather conditions

Set the cost of the best found solution $C(z^*) = \infty$;
Set the value of the highest score $Q^* = 0$;
for n restarts **do**
  Construct initial solution z_0 satisfying (5) and (6);
  $z^* \leftarrow z_0$; $c^* = C(z^*)$; $z \leftarrow z_0$;
  for η iterations **do**
    $z'' \leftarrow \psi(z,q,S)$, remove q visits;
    $z' \leftarrow \varphi(z'',q, S)$, insert q visits while satisfying (5) and (6);
    if $S=\emptyset$ and z' is feasible **then**
      while z' improves **do**
        Run the set of improvement operators while satisfying (5) and (6);
      end while z' improves;
      if $C(z') \leq C(z^*)$ **then**
        $z^* \leftarrow z'$; $z \leftarrow z'$;
        Revise candidate solutions (Ω);
      else if $C(z') \leq C(z)$ **then**
        $z \leftarrow z'$;
      else if accept(z, z') **then**
        $z \leftarrow z'$;
      end if
       if $C(z') \leq C(z^*) + \xi$ **then**
        $\Omega \leftarrow \Omega \cup z'$;
       end if
    end if
  end for;
end for;
  for each schedule ω in Ω **do**
    $Q_\omega \leftarrow$ *Calculate score* (ω) (see Section 2.2.2);
    if $Q^* \leq Q_\omega$ **then**
      $Q^* \leftarrow Q_\omega$; $\omega^* \leftarrow \omega$;
    end if
  end for
return ω^*;

Schedule simulation

Algorithm 2 Schedule simulation

Weather data
Modelled demand;
Pool S $=\varnothing$;
for $i = 1$ to ρ **do**
    while $h^w \leq H^q$;
        Generate weather scenario for the current replication i;
    end while
    for $n = 1$ to N **do**
        Solution $z(\alpha, p)$;
        for $d = 1$ to D **do**
            Simulate the demand for each visit on voyages performed on days d, $(d+1)$ mod D;
            Adjust service times;
            Reroute voyages (see section 2.3.2.1);
            $V^d \leftarrow$ Find infeasible voyages;
            if $V^d \neq \varnothing$;
                $S \leftarrow$ Perform the least cost recourse actions (V^d, S) (See section 2.3.2.3);
            end if
        end for
        calculate cost λ_n of the modified schedule $g_n^{mdf}(\alpha,\ p)$;
    end for each
    Calculate $\lambda_i^{av} = \sum_{w=1}^{|W|} \lambda_n / N$;
end for
return $\lambda^{\exp} = \sum_{i=1}^{\rho} \lambda_i / \rho$;

Optimization-simulation method

Algorithm 3 optimization-simulation

Set A and P of α and p values;
ρ – the number of simulation replications;
N- the number of schedule executions during the simulation horizon;
For each p in A
    For each α in P
        $z(\alpha, p) \leftarrow \text{ALNS}(\alpha, p)$;
        Save $z(\alpha, p)$ in list R;
        Schedule simulation $(z(\alpha, p), \rho, N)$;
        Save $\lambda^{exp}(\alpha, p)$ in a list C;
    End for
End for
return R and C;

Post-optimization procedure

- Results of preliminary experiments showed that schedules generated with the same levels of reliability parameters may have small difference in cost while relatively large (4-6%) difference in schedule probability of feasibility.
- We have discovered that among the schedules with approximately same probability of feasibility those having lower variability of voyages' probability of feasibility have a higher potential to yield the lowest expected cost.
  - We assumed that it is because with the high variability, the bottlenecks (in voyage capacity and TW) in the schedule are narrower and more costly modifications are required to ensure feasibility.
- We propose a post-optimization procedure aimed to select from the schedules with small deviation in cost from the best-cost solution a schedule with the higher probability of feasibility and the lower variability and cost

Score function

$$Q(\omega) = CF * S^{CF} + TF * S^{TF} - \overline{CF} * S^{\overline{CF}} - \overline{TF} * S^{\overline{TF}} - c(\omega) * S^{c(\omega)}$$

$CF-$ the average schedule probability of capacity-feasibility, computed as $\sum_{v \in V} CF_v |V|$;
$TF-$ the average schedule probability of TW-feasibility, computed as $\sum_{v \in V} TF_v |V|$;
CF_v- the probability of voyage $v \in V$ capacity-feasibility;
TF_v- the probability of voyage $v \in V$ TW-feasibility;
$\overline{CF}-$ the MAD of CF_v from CF, computed as $\sum_{v \in V}(|CF_v - CF|)|V|$;
$\overline{TF}-$ the MAD of TF_v from TF, computed as $\sum_{v \in V}(|TF_v - TF|)|V|$;
$c(\omega)-$ the cost of solution ω;

Parameter	F^{z^*}/F^{ω^*}	$\overline{F^{z^*}}/\overline{F^{\omega^*}}$	$c^{\exp}(z^*(\alpha,p))/c^{\exp}(\omega^*(\alpha,p))$
9-41-4	0.92	1.25	1.03
10-43-4	0.93	1.15	1.023
12-51-4	0.929	1.18	1.031
14-59-6	0.944	1.21	1.019
16-64-6	0.975	1.17	1.024
18-67-6	0.943	1.14	1.011
20-71-8	0.956	1.16	1.035
22-76-8	0.958	1.21	1.022
22-81-8	0.948	1.11	1.028
24-81-10	0.961	1.09	1.034
26-85-10	0.971	1.16	1.027
Average		1.17	1.0267

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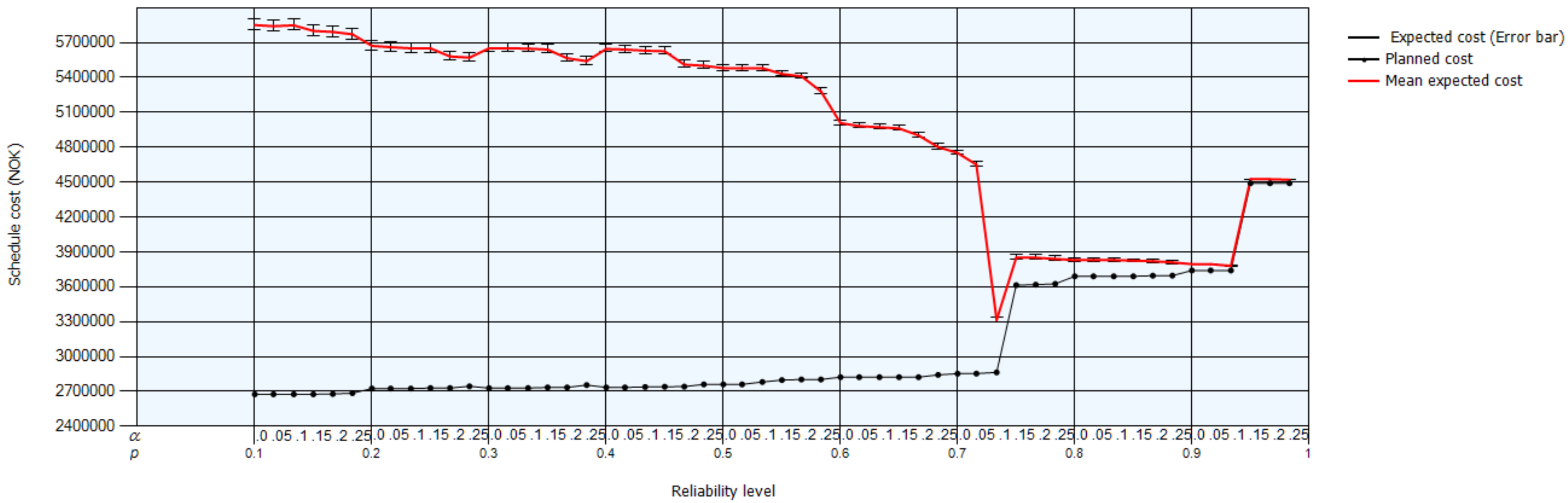
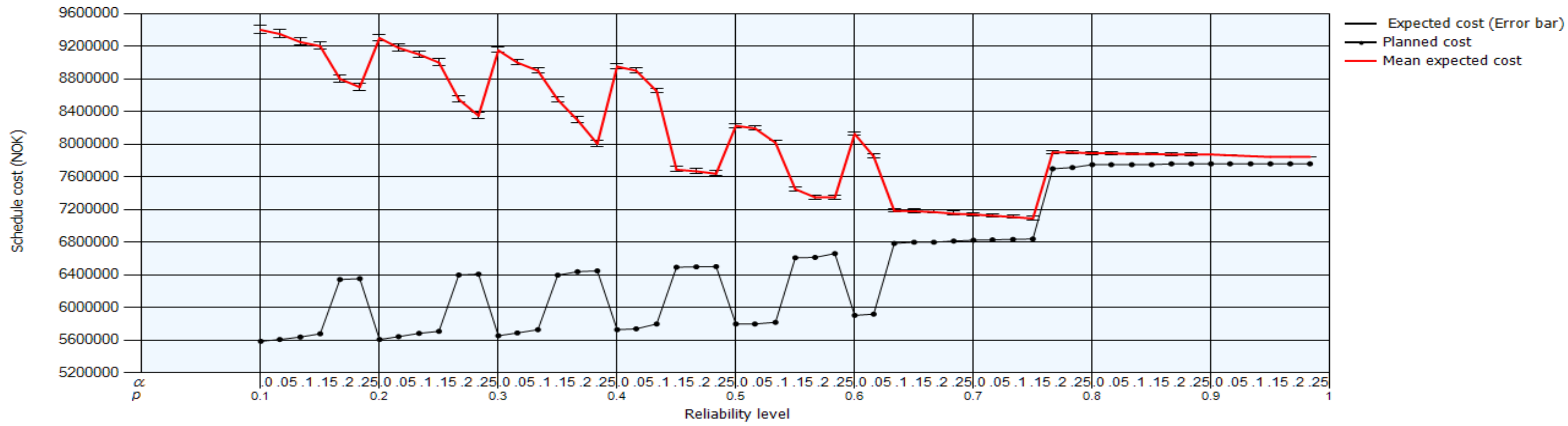
Computational experiments





Analysis of results

- The high cyclical cost surges for the instance with 26 installations resulting in the fleet size increase occur when for each value of *p* (up to 0.6) the algorithm imposes the higher requirements to the reliability level against weather uncertainty (by increasing the value of α).
- Declines in the planned cost resulting in the fleet size decrease take place when the algorithm proceeds to the next solution with the higher reliability to demand uncertainty and no reliability requirements to weather.
- The difference in the degree of the planned costs fluctuations between the two instances can be explained by the larger natural inter-voyage slacks in in the schedules for the instance with 14 installations. The schedules for the instance with 14 installations are not as tight as the schedules for the instance with 26 installations, and thus have higher feasibility probability than the required minimum set by α and *p*

Collaboration in supply vessel planning

- Collaborative planning
  - Usefulness
- Building a coalition
  - Several offshore operators
- Sharing resources
  - Supply vessels
- Sharing costs
  - Charter cost
  - Travel costs
- Sharing emissions responsibility