Routing and fleet sizing for offshore supply vessels

Photo: Harald Pettersen / Statoil

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Molde University College
Specialized University in Logistics

Outline

- Generation of green vessel schedules with speed optimization
- Evaluation of speed strategies under weather uncertainty
- Annual supply vessel fleet sizing under weather uncertainty
- Evaluation of supply vessel schedules' robustness

Photo: Marit Hommedal / Statoil

The oil and gas industry needs reliable, cost-efficient and environmental friendly transport of cargo between onshore supply bases and offshore installations

Periodic supply vessel planning

- **Literature**
  - **Fagerholt and Lindstad (2000)**: Optimal policies for maintaining a supply service in the Norwegian Sea, *OMEGA* 28.
  - **Halvorsen-Weare, Fagerholt, Nonås and Asbjørnslett (2012)**: Optimal fleet composition and periodic routing of offshore supply vessels, *EJOR* 223.
  - **Halvorsen-Weare and Fagerholt (2011)**: Robust supply vessel planning, *Lecture Notes in Computer Science,* 6701
  - **Shyshou, Gribkovskaia, Laporte and Fagerholt (2012)**: A large neighbourhood search heuristic for a periodic supply vessel planning problem arising in offshore oil and gas operations, *INFOR* 50

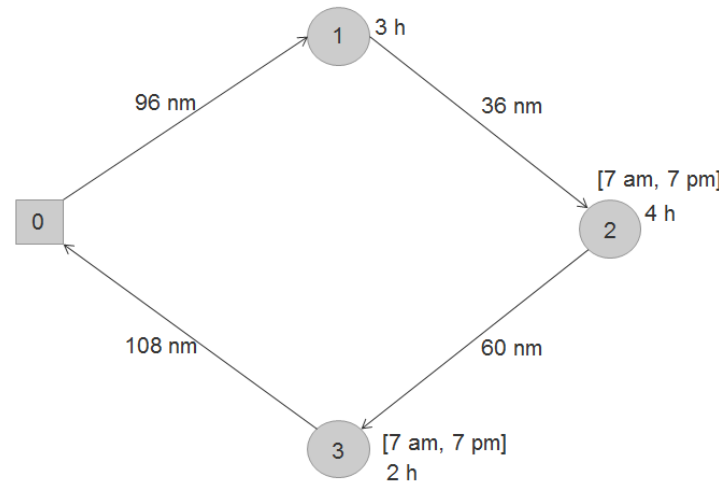
Periodic supply vessel planning

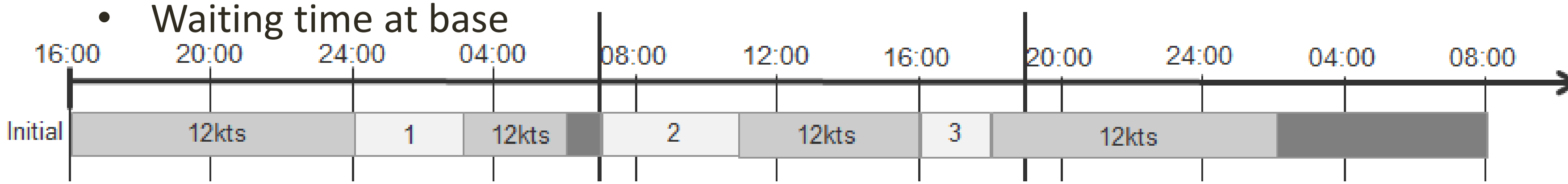
- Installations
  - Delivery and pickup demands of multiple commodities
  - One or more visits per week
  - Fairly spread departures
  - Closed at night
- Supply vessels
  - Capacity for deck cargo and bulk products
- Supply base (depot)
  - Opening hours
  - Limited number of vessels to be served per day

Illustration: Statoil

Vessel’s voyage

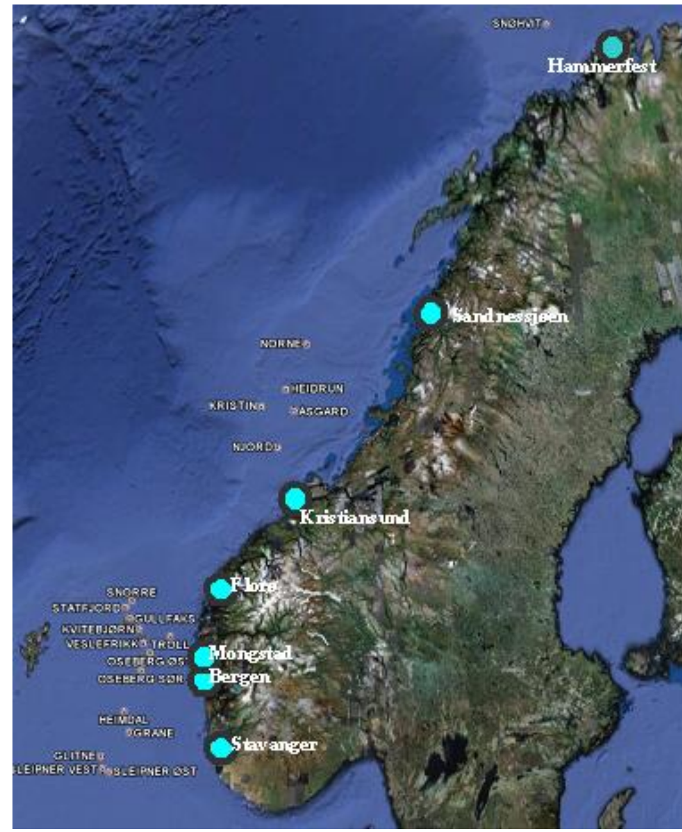
- A voyage is defined by
  - start day
  - sequence of installations to visit
- Fixed departure time from supply base
- Voyage duration of 2 or 3 days
- Voyage time window: time interval between
  - the vessel departure time from the base
  - the earliest start for unloading operations after return to the base
- Opening hours for some installations
- Voyage waiting time
  - Waiting time at installations
  - Waiting time at base

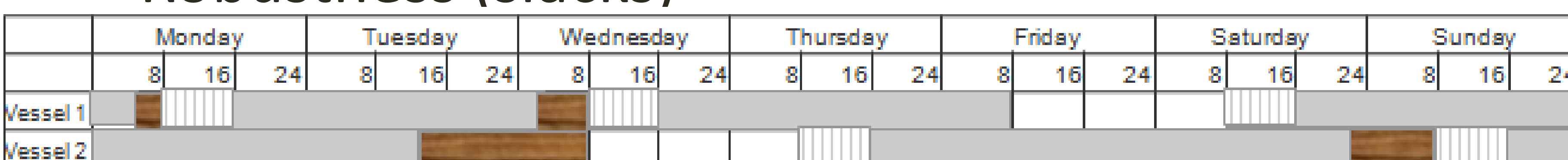




Supply vessel schedule

- Set of installations assigned to a base
- Weekly sailing schedule
- One or more vessels
- Each vessel is sailing one or more voyages per week
- Idle time in vessel schedule
  - Voyage waiting time
  - Slacks between voyages
- Robustness (slacks)

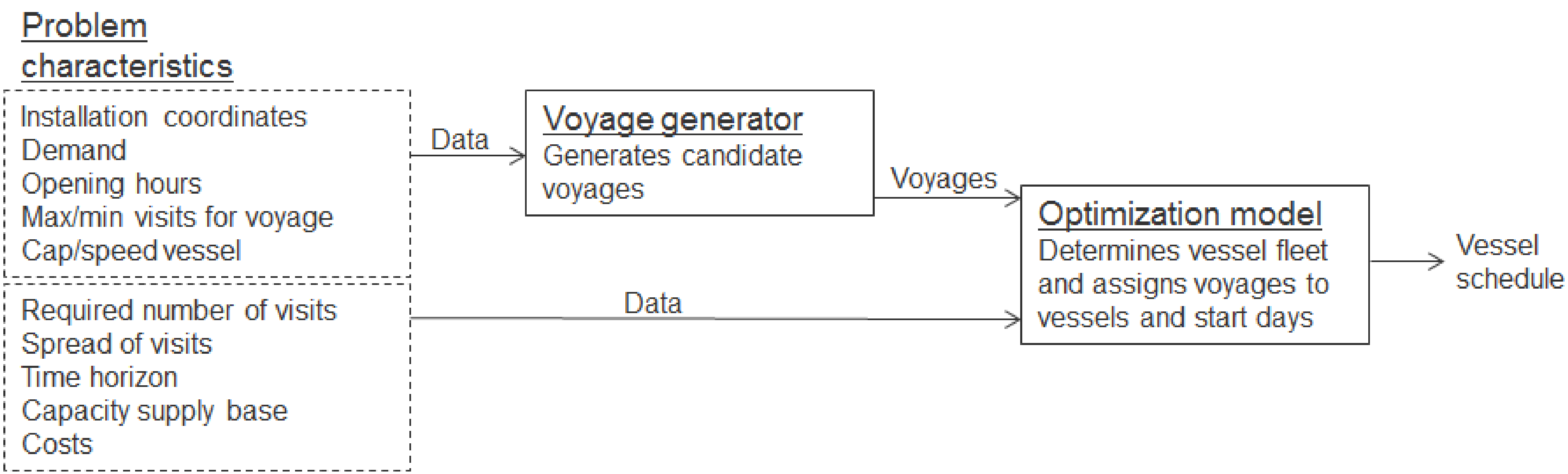




Supply vessel planning tool

Simultaneously determines the fleet composition and the schedules for the vessels

Halvorsen-Weare et al. (2012)



Speed optimization

- Supply vessel activities are the main source of emissions in the offshore oil and gas supply chain
- A fuel consumption reduction of 10 % for Statoil's supply vessel activities on the NCS represents anually
  - 15 000 tons less emitted CO_2
  - Cost savings of 3 million USD

Speed optimization

- **Literature**
  - **Fagerholt (2001)**: Ship scheduling with soft time windows– an optimization based approach, *EJOR* 131.
  - **Fagerholt, Laporte and Norstad (2010)**: Reducing fuel emissions by optimizing speed on shipping routes, *JORS* 61.
  - **Norstad, Fagerholt and Laporte (2010)**: Tramp ship routing and scheduling with speed optimization, *TRC* 19.
  - **Hvattum, Norstad, Fagerholt and Laporte (2013)**: An exact algorithm for the vessel speed optimization problem, *Networks* 62.
  - **Norlund and Gribkovskaia (2013)**: Reducing emissions through speed optimization in supply vessel operations, *TRD* 23.

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Reducing emissions through speed optimization in supply vessel operations

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ABSTRACT

This paper examines how optimizing sailing speeds can reduce supply vessels emissions in the upstream supply chain to offshore installations. We introduce several speed optimization strategies to be used in construction of periodic vessel schedules. The strategies consider vessel waiting times before the start of service at installations and at supply base. Tests carried out on real instances from Statoil's activities on the Norwegian continental shelf indicate that a 25% emissions and fuel cost reductions can be achieved without fleet size increase.

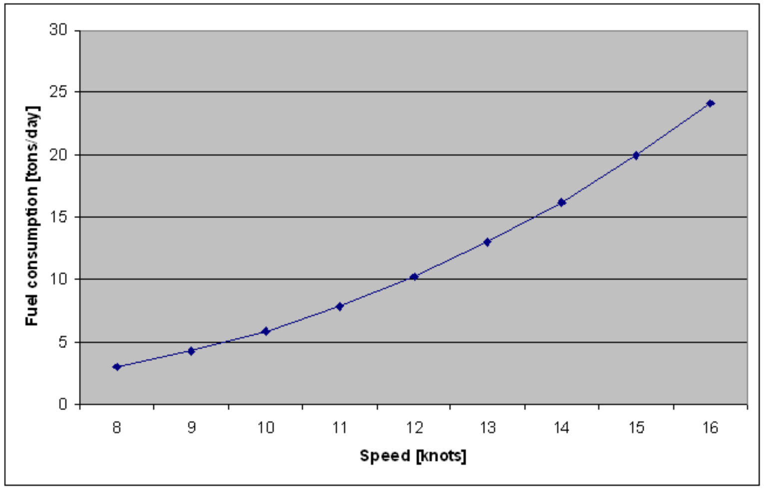
Emissions from supply vessels

- The emissions from a supply vessel is dependent on fuel type, fuel consumption and engine configuration

$$E_i = \sum_m (FC_m \cdot EF_{i,m})$$

E_i - emissions of pollutant *i*

FC_m - mass of fuel type *m*
$EF_{i,m}$ - emission factor for pollutant *i* and fuel type *m*



- Fuel consumption sailing: $FC = FC_0 \cdot (v/v_0)^3 \cdot t$
- Fuel consumption waiting: $FC = FC_w \cdot t$
- Fuel consumption loading/unloading: $FC = FC_l \cdot t$

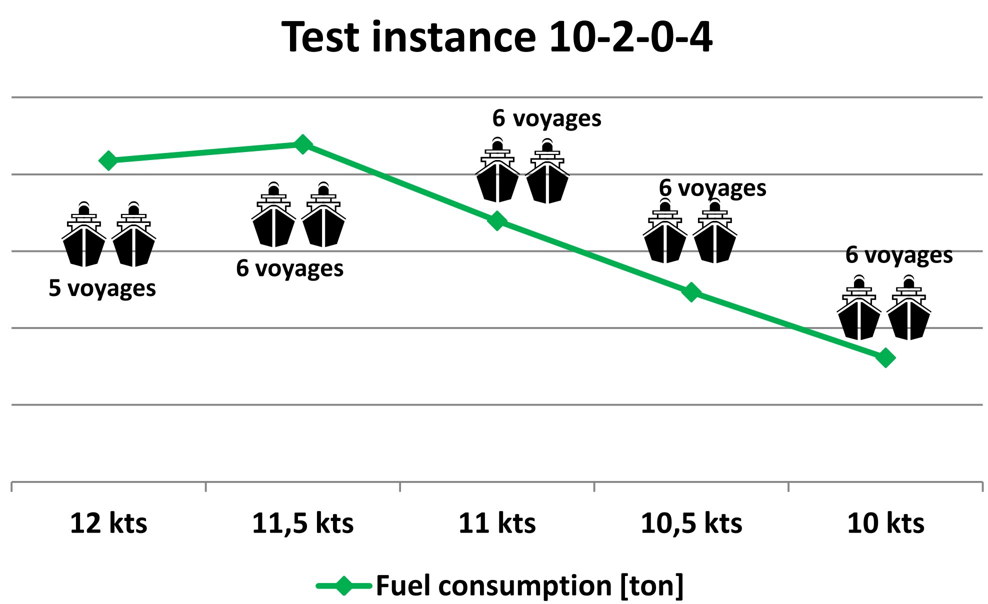
Speed optimization strategies

- Starting point: voyages with design speed
- Utilize
  - voyage waiting time
  - slacks between voyages
- Speed interval [s_{min}, s_{max}]
- Uniform fleet

All strategies are aimed to reduce fuel consumption <u>without</u> increasing fleet size

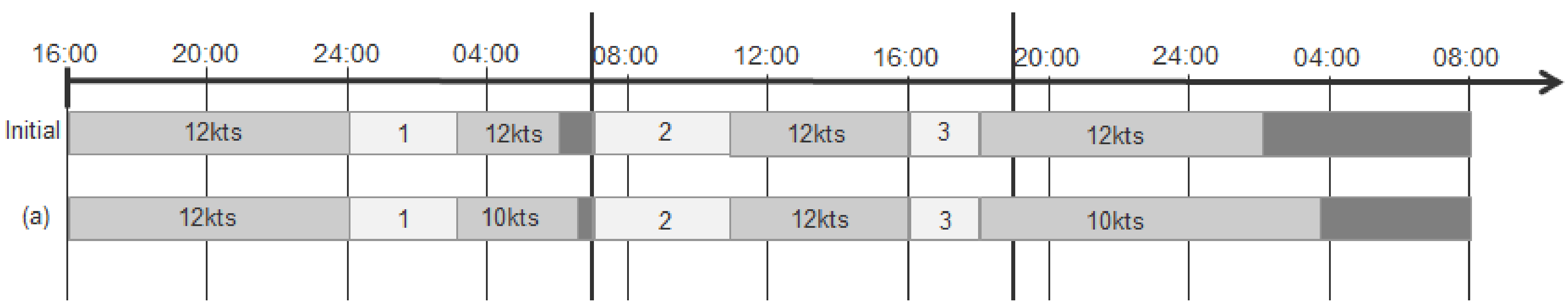
Strategy D

- Speed reduction for all voyages
- Iteratively algorithm including both voyage generation and optimization model
- Stepwise reduction of speed until
  - Speed is s_{min}
  - Increase in fleet size
- Choose the solution with lowest fuel consumption



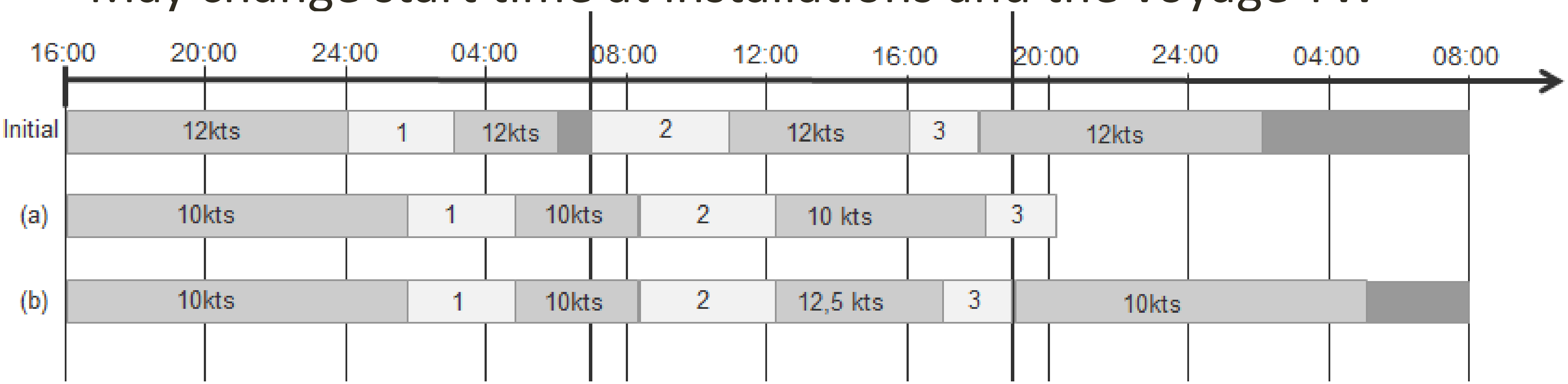
Strategy W

- Speed reduction on voyage legs with waiting time
- Applied during voyage generation
- Reduce speed on voyage leg if
  - waiting time at installation
  - waiting time for the end of the voyage TW
- Not change start time at installations and the voyage TW



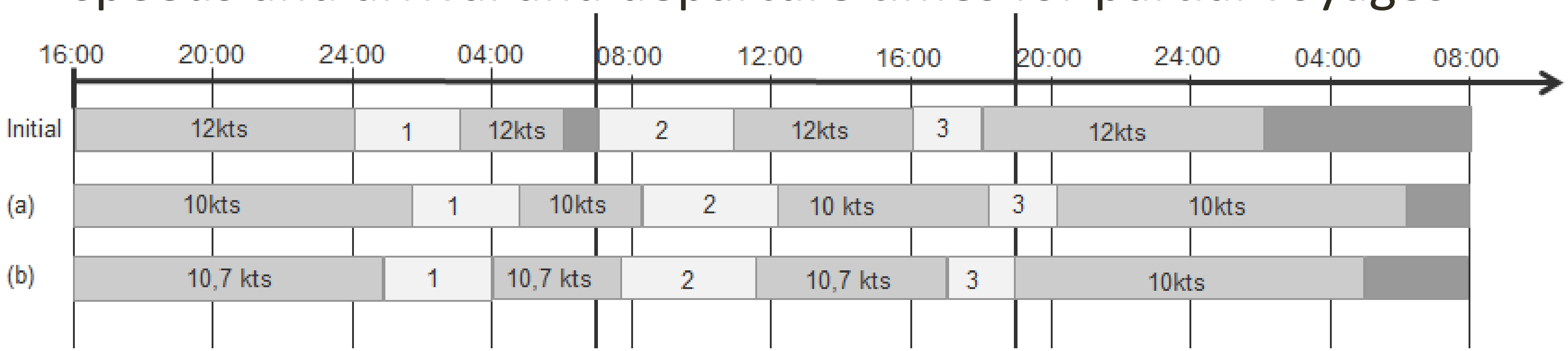
Strategy S

- Sequential speed optimization on each voyage leg
- Applied during voyage generation
- Calculate minimal voyage speed
- Find speed on each leg, adjusting to opening hours
- Possibilities to increase or decrease speed within given speed interval
- May change start time at installations and the voyage TW



Strategy R

- Idea of the recursive smoothing algorithm of Norstad et al. (2010)
- Set voyage TW according to initial voyage generated with constant speed, and TW for installations to the day if visit in initial voyage
- Calculate minimal voyage speed
- Recalculate arrival and departure times with minimal voyage speed
- If violations of installation time window, recursively recalculate speeds and arrival and departure times for partial voyages



Test instances

- Test instances from Statoil's activity (notation 7-3-0-4)
- Identical vessels
- Voyage duration of 2 or 3 days
- Speed interval [10,14] and design speed 12 kts
- With/without 4 hours slack
- 4 installations closed at night

	# installations	# installation visits
Small	5	9
Medium	7	15
Large	10	25

Results for small/medium instances

Instances	D	W	S	R	W time	# vessels
5-3-0-4	**25**	10	**25**	**25**	26	1
5-3-4-4	14	10	10	**23**	19	1
7-3-0-4	10	8	9	**19**	13	1
7-3-4-4	**22**	9	**22**	**22**	53	2

- Fuel reduction from 8 to 25 % compared to basic solution
- For instances with large waiting time the D, S and R strategy yield the largest fuel consumption reductions
- The W strategy yields smallest reduction in fuel consumption
- The S strategy preformed better than the W
- For instances with little slack the R strategy yields the largest reductions

Results for large instances

Instances	D	W	S	R	W time	# vessels
10-2-0-4	**17**	9	**17**	**17**	26	2
10-3-0-4	**21**	10	**21**	**21**	26	2
10-2-4-4	0	11	16	**19**	12	2
10-3-4-4	10	11	18	**20**	20	2

- All speed optimization strategies yield between 9 to 21 % reduction in fuel consumption
- No reduction for 10-2-4-4 with D strategy
- The R strategy yields the largest fuel consumption reduction

A priori and a posteriori

	A priori			A posteriori		
Instances	**W**	**S**	**R**	**W**	**S**	**R**
5-3-0-4	10	25	25	10	9	23
5-3-4-4	10	10	23	10	9	23
7-3-0-4	8	9	19	6	9	14
7-3-4-4	9	22	22	7	8	15

- W shows similar results, S performs worse, R is slightly worse
- Applicability of speed optimization a posteriori is valuable for operational purposes since it requires speed optimization on a smaller number of voyages

Comparative analysis

Strategy	Advantages	Disadvantages
D	• Easy to implement • Good performance when much idle time in initial schedule	• Rigid • Time consuming • No use a posteriori
W	• Easy to implement • Similar performance a priori and a posteriori	• Smallest fuel consumption reduction
S	• Good performance when much idle time in initial schedule	• Not good performance when little idle time in initial schedule • Challenging for implementation
R	• Overall best performance • Good performance a posteriori	• Challenging for implementation

Evaluation of speed strategies under weather uncertainty

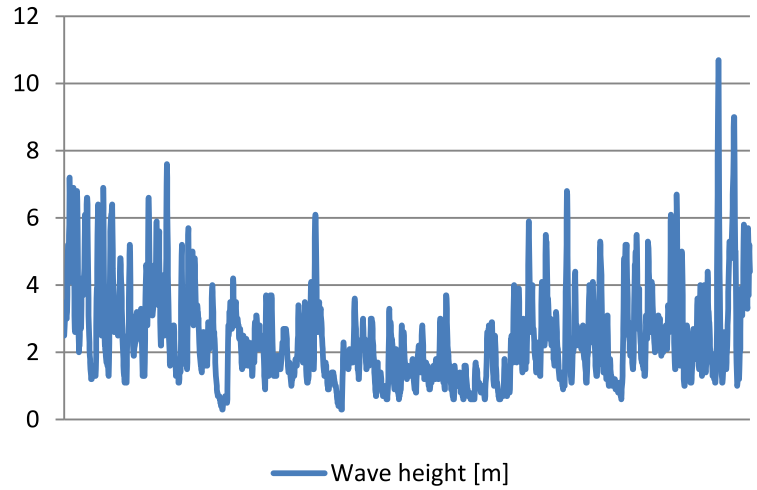
- Step 1: Voyage duration with simulation
  – Simulation of speed optimized voyages *m* times
  – Result: Probability distribution of voyage duration

  DISC(0.67, **2**, 0.87, **3**, 1, **4**) and average voyage fuel consumption

- Step 2: Average fuel consumption with optimization
  – Optimization model is run *n* times with random voyage duration selection

Weather uncertainty

- Weather impacts sailing time and service time
- If wave height exceeds 4,5 meters the vessel has to wait for better weather to service installations
- Evaluate how weather impacts on speed optimization strategies performance



Voyage duration selection

- Set of candidate voyages is built by random choice of the voyage duration

if $0 \le \xi(r) \le 0.67$ ***then***

$r \in R_{v2}$

else if $0.67 \le \xi(r) \le 0.87$ ***then***

$r \in R_{v3}$

else $r \in R_{v4}$

end if

Distribution of voyage duration
DISC(0.67, **2**, 0.87, **3**, 1, **4**)

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Routing and fleet sizing for offshore supply vessels

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ROUTE 2014
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Part 2

- Annual fleet sizing for supply vessels under weather uncertainty
  - stochastic service and sailing durations

- Evaluation of robustness of weekly sailing schedules
  - weather dependent rerouting of voyages
  - dynamic re-scheduling of not performed visits to installations

Relevant publications

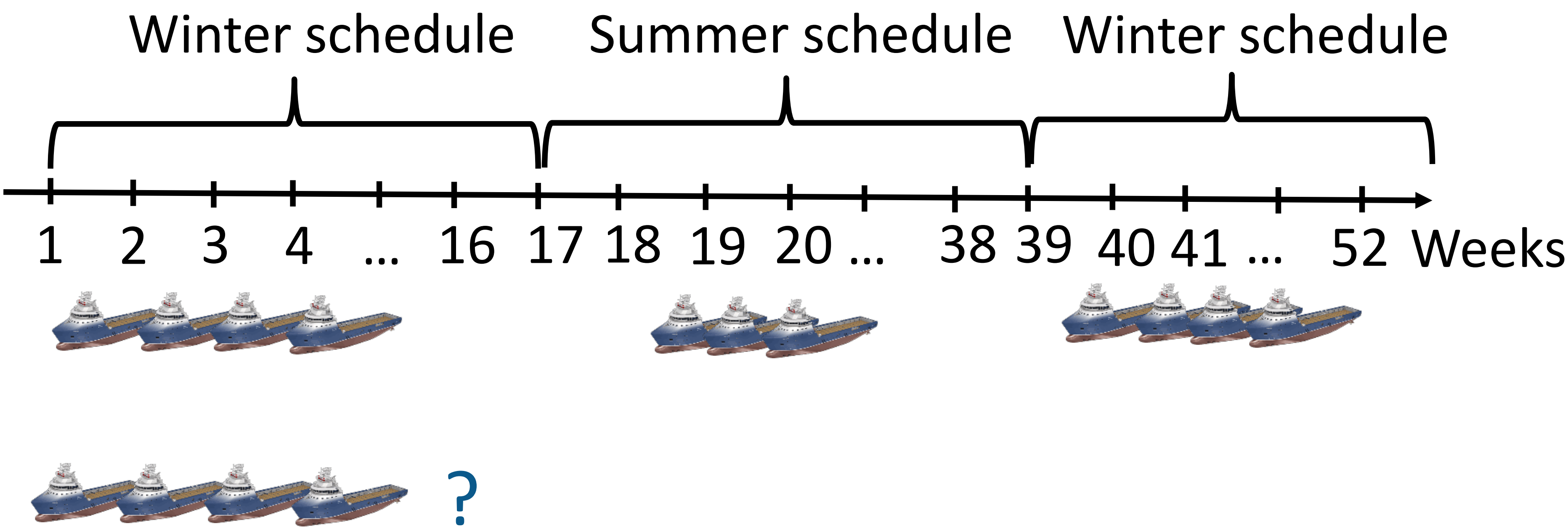
- Shyshou A, Gribkovskaia I, Barcelo J. A simulation study of the fleet sizing problem arising in offshore anchor handling operations. *European Journal of Operational Research* 2010; **203**(1):230-240.

- Halvorsen-Weare E.E., Fagerholt K, Nonås L.M., Asbjørnslett B.E. Optimal fleet composition and periodic routing of offshore supply vessels. *European Journal of Operational Research* 2012; **223**(2):508-517.

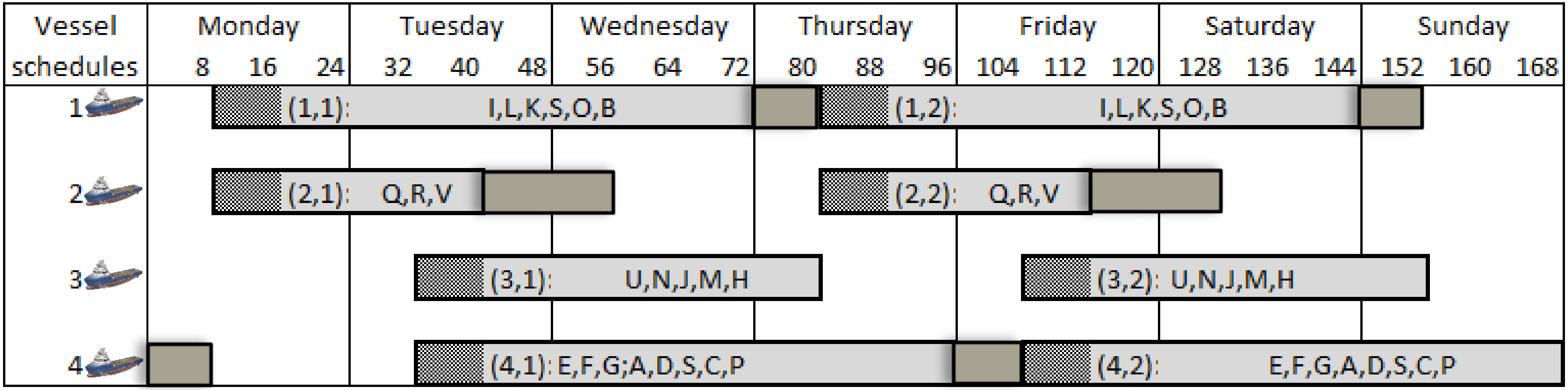
- Halvorsen-Weare E.E., Fagerholt K. Robust Supply Vessel Planning. *Lecture notes in computer science* 2011; **6701**:559-573.

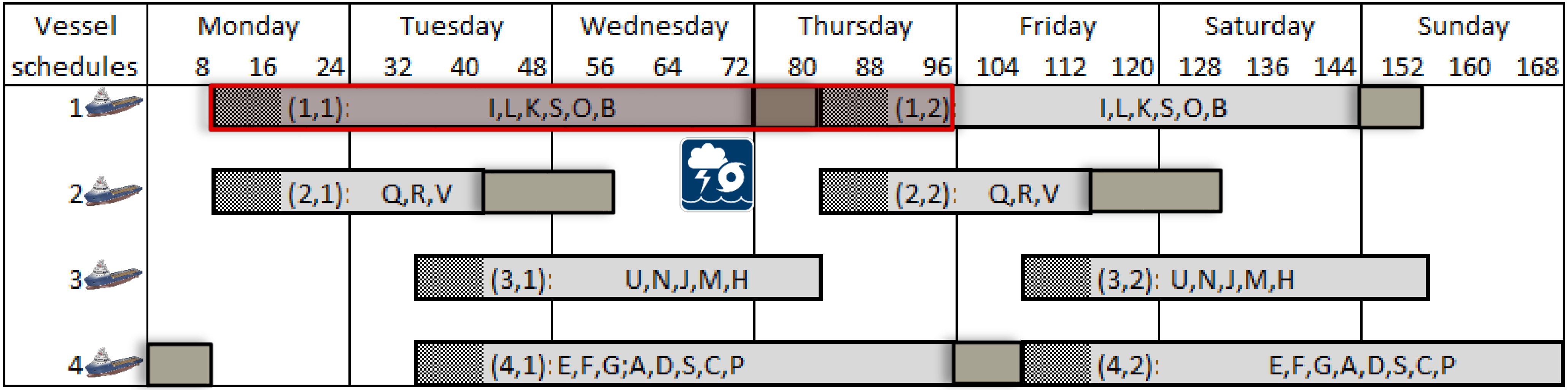
Annual fleet sizing

- Annual sailing plan
  - Several weekly sailing schedules
  - Varying number of supply vessels

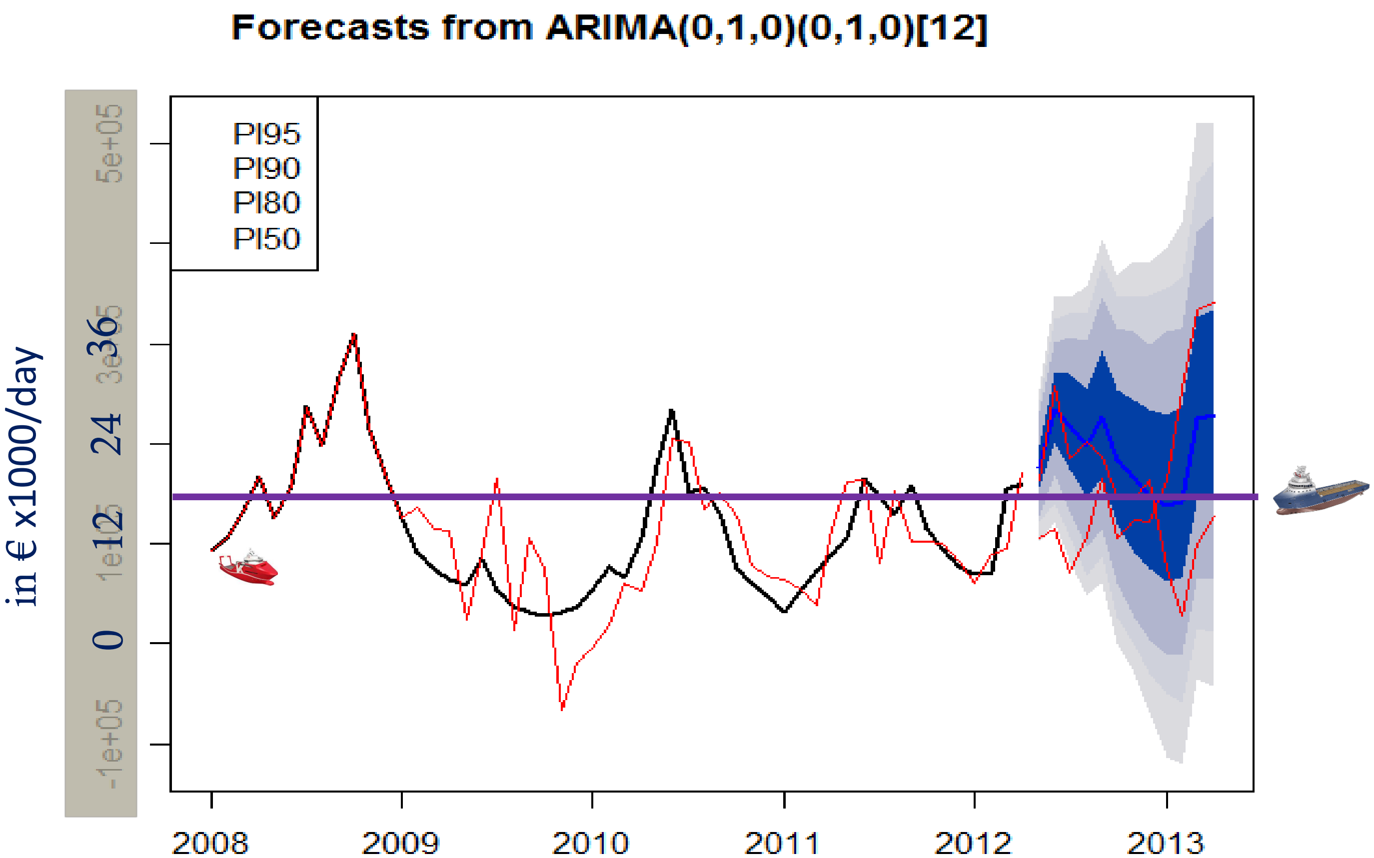


Weekly sailing schedule





Supply vessel hire rates



- Daily rates for time-charter vessels
- Daily rates for spot vessels

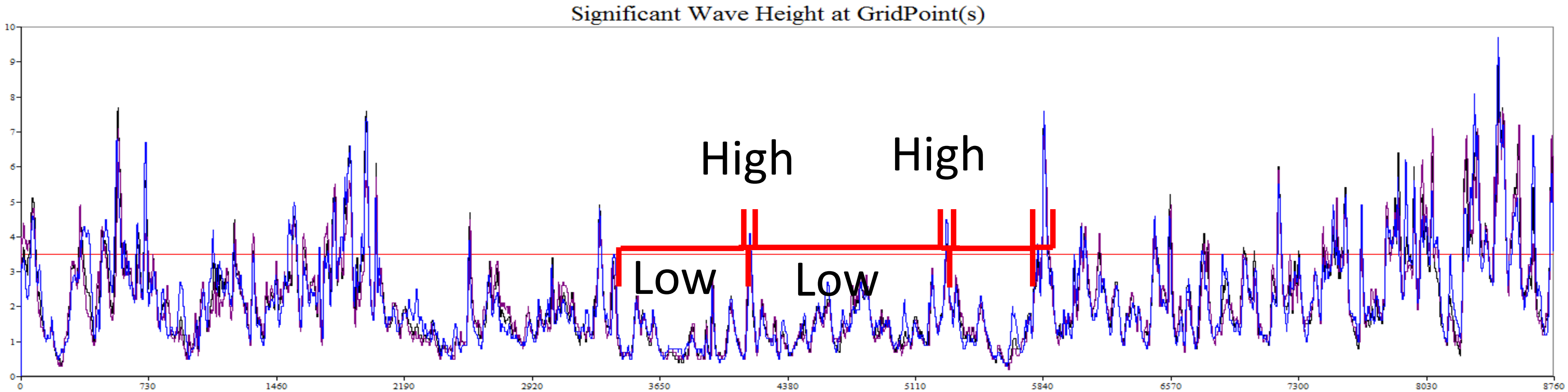
Discrete event simulation model

- The model simulates a sequence of voyages chronologically as planned in annual sailing plan
- Dynamically assigns vessels to voyages

- Stochastic factors
    - service and sailing times
- Discrete events
    - voyage starts, voyage ends,
    - arrivals to /departures from installations
- Input
    - Number of available time-charter vessels
- Output
    - Annual total costs

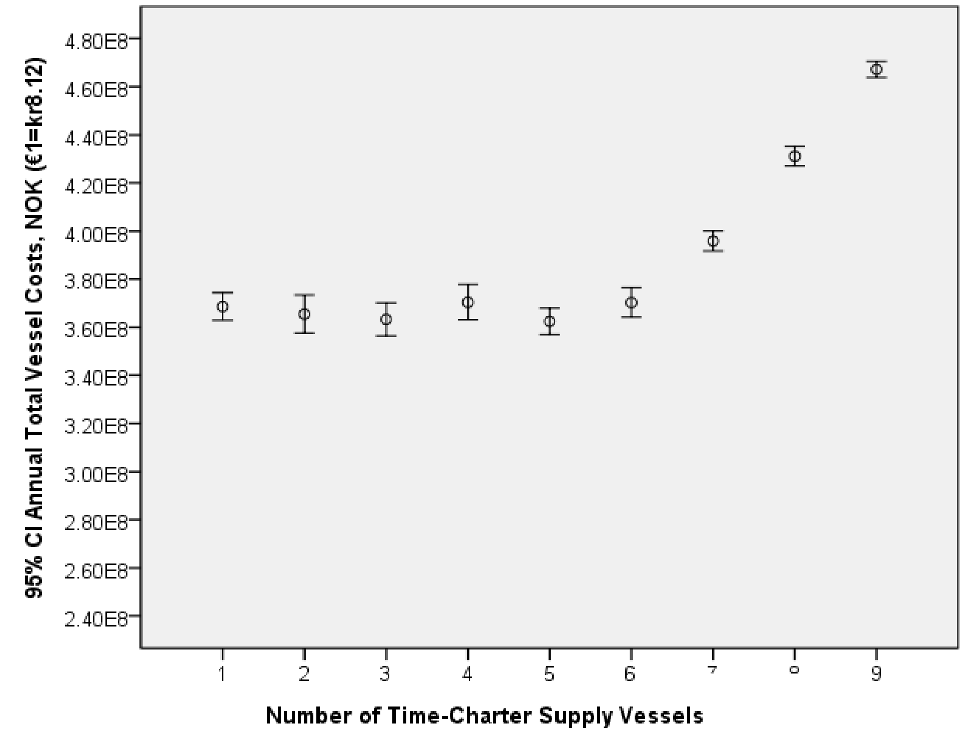
Stochastic service time

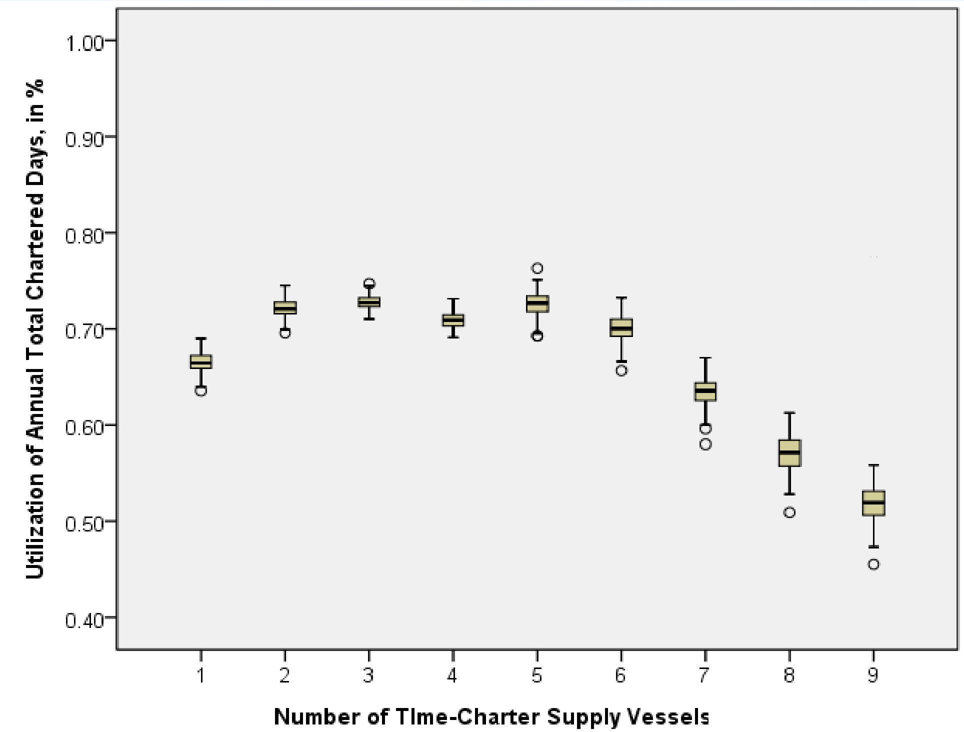
- Uncertainty in weather is quantified by significant wave height (Hs)



Hs [metres]	Wsp [knots]	WM [%]
[0 - 0.5]	4 - 6	0
(0.5 - 1]	7 - 10	0.1
(1 - 2]	11 - 16	0.15
(2 - 3]	17 - 21	0.2
(3 - 4]	22 - 27	0.3
>3.5		WOW

Test results: service time





- Test instance
  - summer schedule (15 installations, 52 visits per week)
  - winter schedule (13 installations, 43 visits per week)
- Cost-indifferent solutions

Stochastic sailing time

- Involuntary speed reduction

- Aertssen (1975)

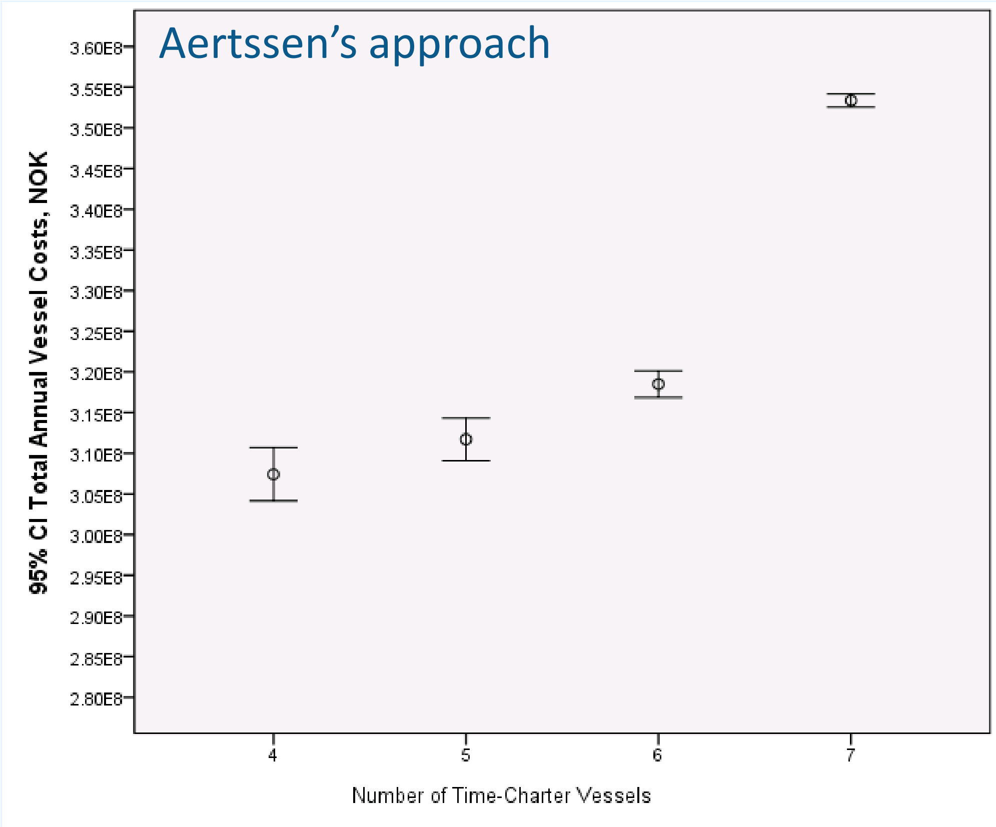
$$\frac{\Delta V}{V} \cdot 100\% = \frac{m}{L_{BP}} + n$$

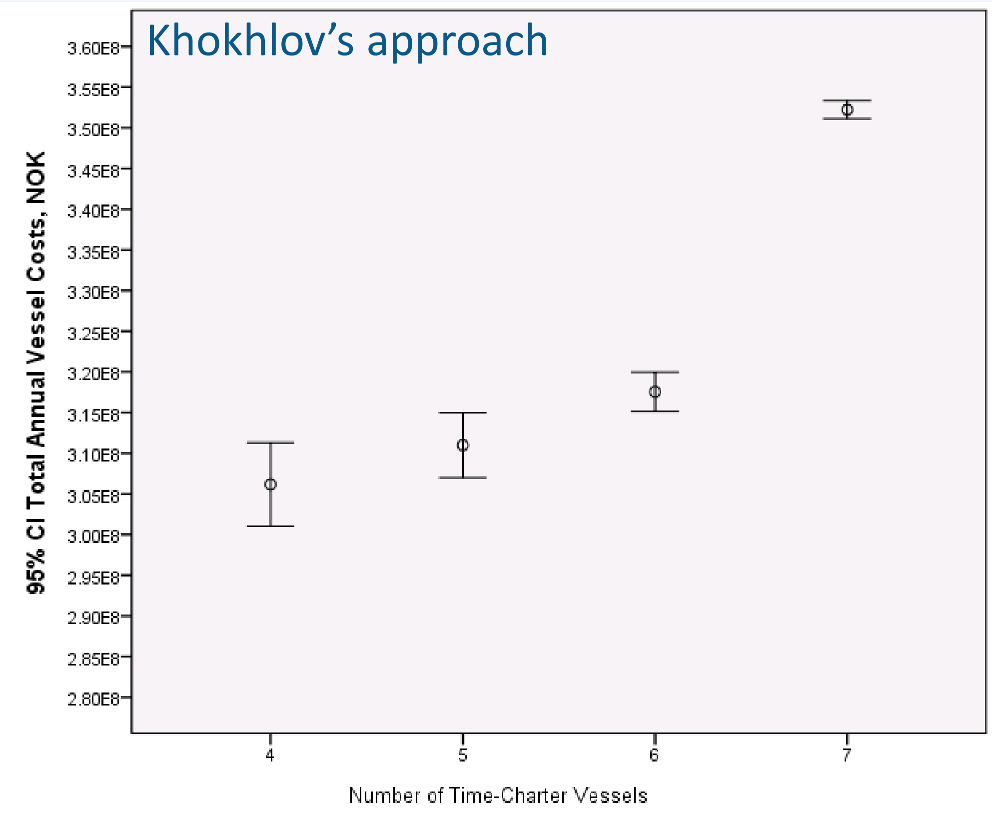
	α angle off bow head sea [0° – 30°)		α angle off bow bow sea [30° – 60°)		α angle off bow beam sea [60° – 150°)		α angle off bow following sea [150° – 180°)	
BN	m	n	m	n	m	n	m	n
5	900	2	700	2	350	1	100	0
6	1300	6	1000	5	500	3	200	1
7	2100	11	1400	8	700	5	400	2
8	3600	18	2300	12	1000	7	700	3

- Khokhlov (1967)

$$V = V_0 - (0,745 \cdot H_s - 0,245 \cdot q_w \cdot H_s) \cdot (1,0 - 1,35 \cdot 10^{-6} \cdot D \cdot V_0)$$

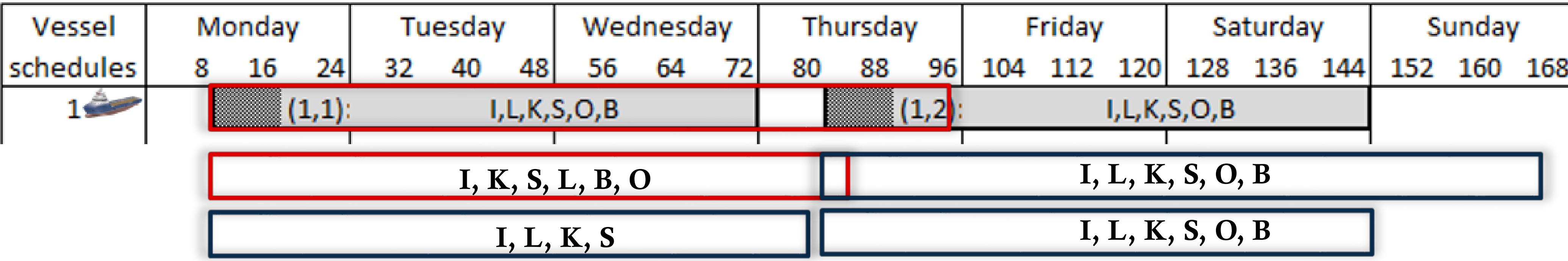
Test results: service, sailing times





Robustness of weekly sailing plan

- Deteoriated weather conditions decrease robustness of weekly vessel schedules



Problem task

- Validate how operational re-routing influence on service level of weekly sailing plan

Validation

Weekly sailing plan	How constructed	Total voyages simulated	Total voyages performed, % Without re-sequencing	With re-sequencing	With re-sequencing and cut(s)
SUMMER	expert-based	276	37.26	45.2	73.61
WINTER	expert-based	390	54.21	63.17	89.9
	opt-based	232	72.83	78.28	94.35
	opt-based with slacks	232	74.48	80.16	97.44

- Positive effect of weather dependent rerouting on the service level
- Dynamic re-scheduling of not performed visits to installations

Thank you! Questions?