RISK-BASED DECISION SUPPORT FOR OFFSHORE WIND TURBINE INSTALLATION AND OPERATION & MAINTENANCE

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Agenda

- **Research Motivation**
- **Description of the software tool in question.**
- **Short term validation input.** Weather and vessel model**.**
    - Position
    - Input variables
    - Hywind Rotor-Lift installation phases
    - Limit states under consideration
- Types of limit states
- Procedure for estimating **Probabilities of Failed Operations**
- **Proof of concept. DEMO**
- **Probability based Decision Making.**
    - Limit State Probabilities of Failure
    - Operation Failure rate
    - Weather window estimation
- **Long term validation for summer 2014.**
- Risk Based Decision Making
- **Conclusions and discussion**

Motivation

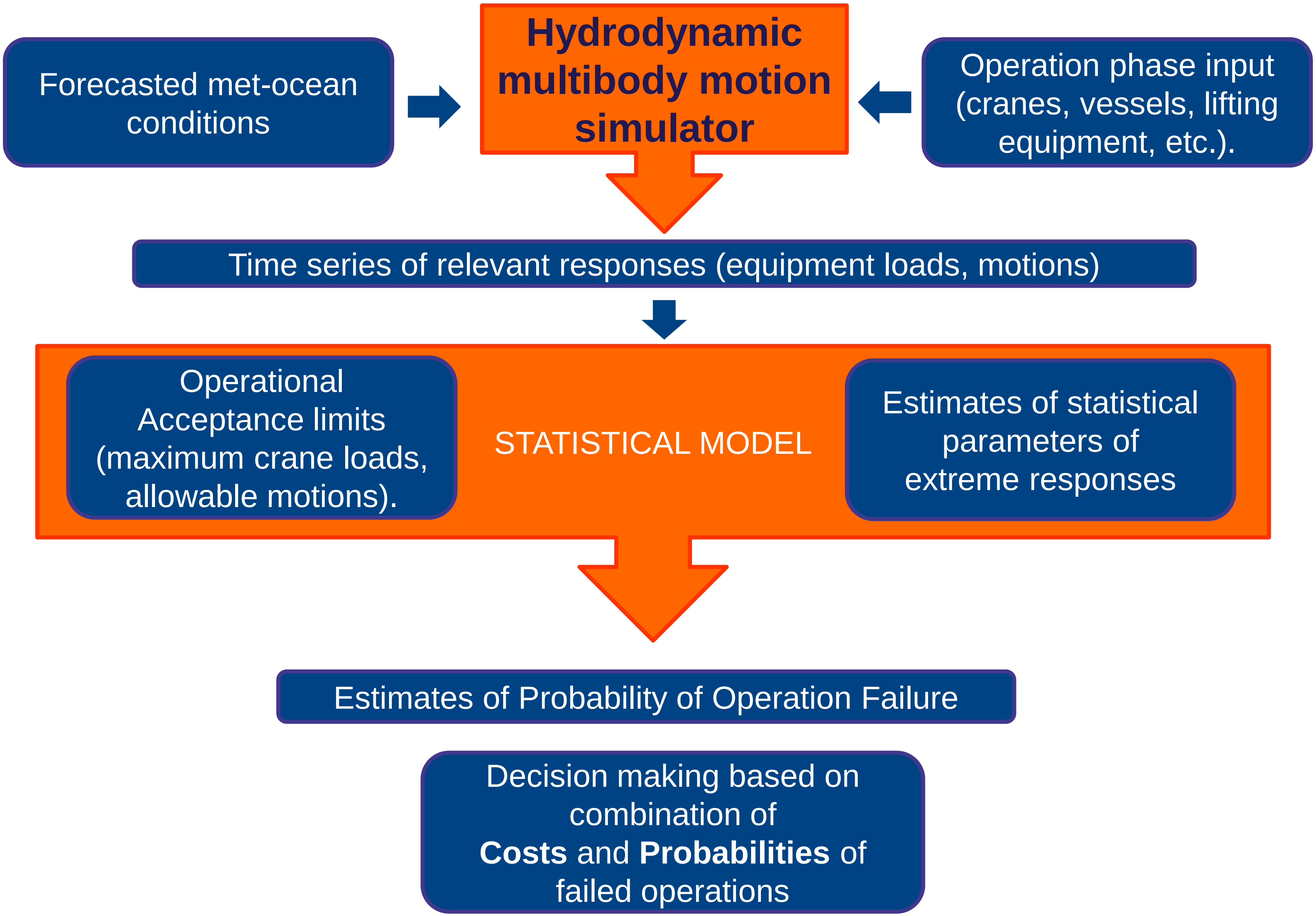
State-of-the-art in assessing whether a weather sensitive offshore operation is safe to commence is only based on significant wave height Hs and wind speed at the location in question.

The actual limitations of installation are mostly physical:

- strength of the installation equipment used - crane cable loads, tug wire tensions, etc.
- Limits on the equipment being installed – maximum acceleration limits on wind turbine nacelle/rotor components.
- safe working environment conditions – motions and accelerations at the height/location of the installation limiting or prohibiting the installation crews work.

Transition from limits on weather conditions to limits on physical response criteria in decision making would improve the predictions of weather windows for installation and potentially reduce the cost of energy.

DECOFF method and Topology Expected Software Tool



DECOFF – Example test case

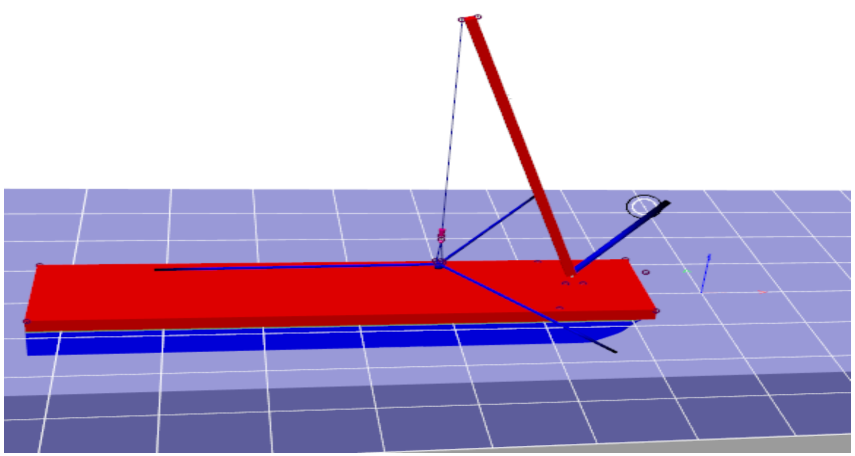
Hywind Rotor-Lift Operation

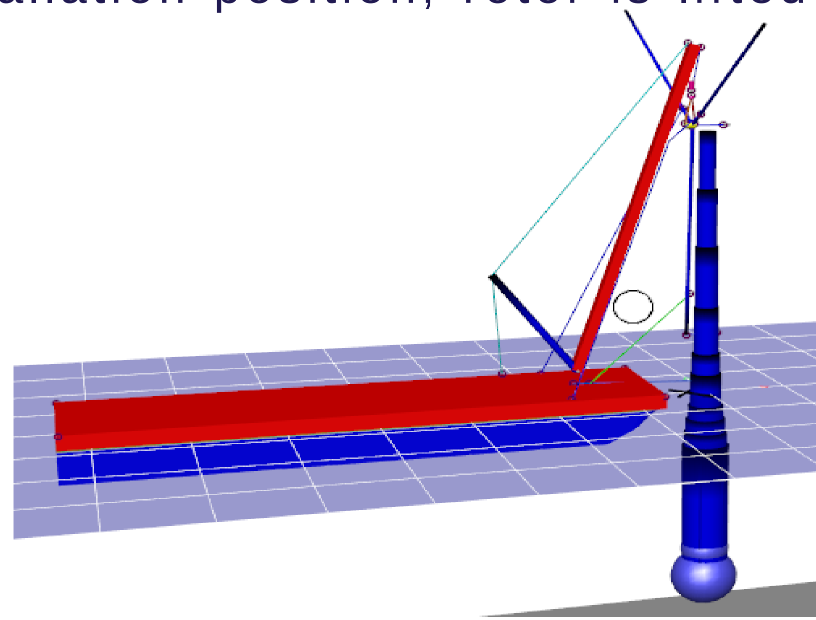
- **Phase 1**: Transition to field, 8 hours
- **Phase 2**: Preparation for lift, 3 hours
- **Phase 3**: Rotor lift up, 0.2 hours
- **Phase 4**: Rotate rotor, 0.2 hours
- **Phase 5**: Lift-up close to nacelle, 0.4 hours
- **Phase 6**: Connecting rotor to nacelle, 0.3 hours

Total duration 12.1 hours

Test case:

- Phases 3-6 – barge is at the installation position, rotor is lifted up and bolted to the nacelle.





Limiting operational parameters

Hywind Rotor-Lift Operation

Phase 1 – Transition to field – 8 hours

Phase 2 – Preparation for lift – 3 hours

Phase 3 – Rotor lift up – 0.2 hours

Phase 4 – Rotate rotor – 0.2 hours

Phase 5 – Lift-up close to nacelle – 0.4 hours

Phase 6 – Connecting rotor to nacelle – 0.3 hours

Phase 3 Operation Limits

- Crane Load
- Lift Wire Tension
- Tug Wire Tension
- Airgap between blades and waves
- Rotor acceleration
- Rotor rotational acceleration
- Rotor Sway motion
- Rotor Surge motion

Phase 6 Operation Limits

- Relative yaw angle between rotor and special tool
- Relative tiltangle between rotor and special tool
- Relative axial velocity
- Relative radial velocity
- Airgal between blade 3 and tower

Short term Validation. Simulation input - weather

Location: 7 º W 55.25 º N

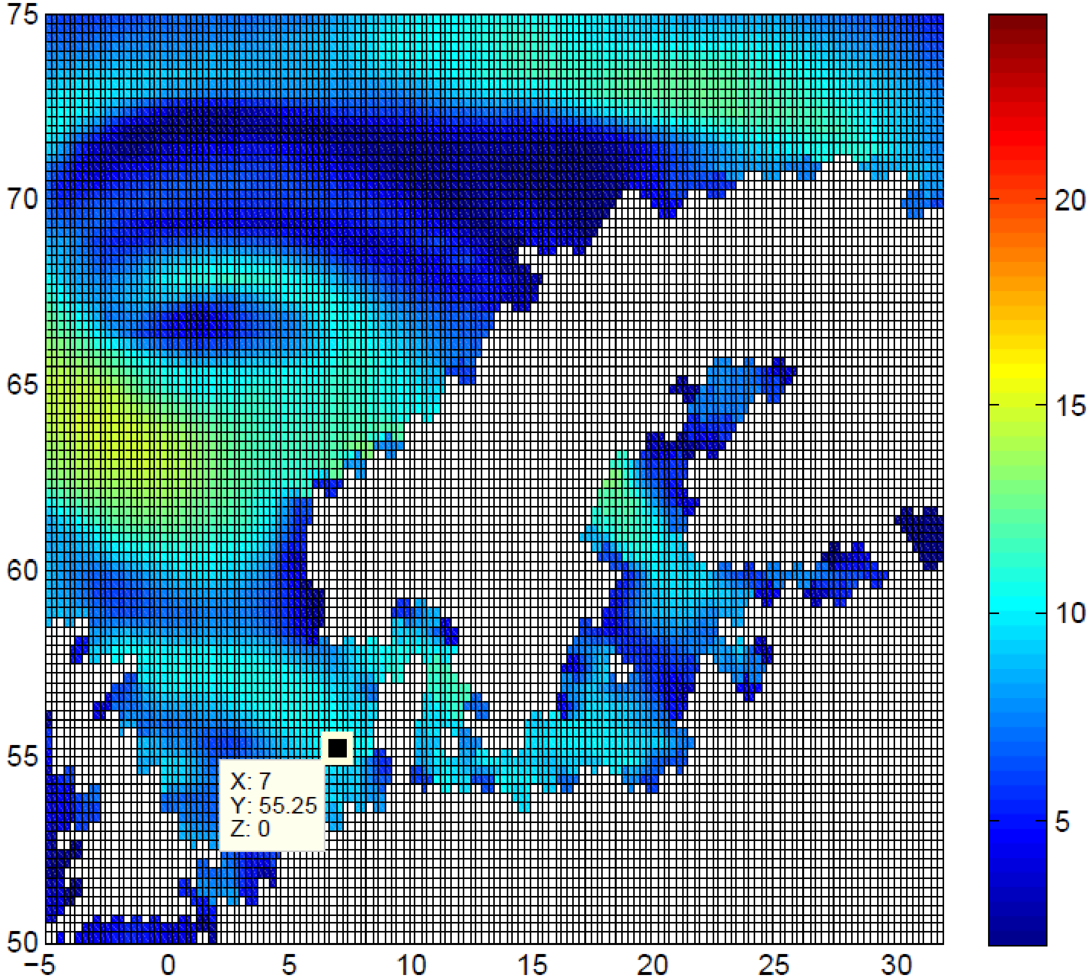
FINO 3 site

Forecast: ECMWF 2013

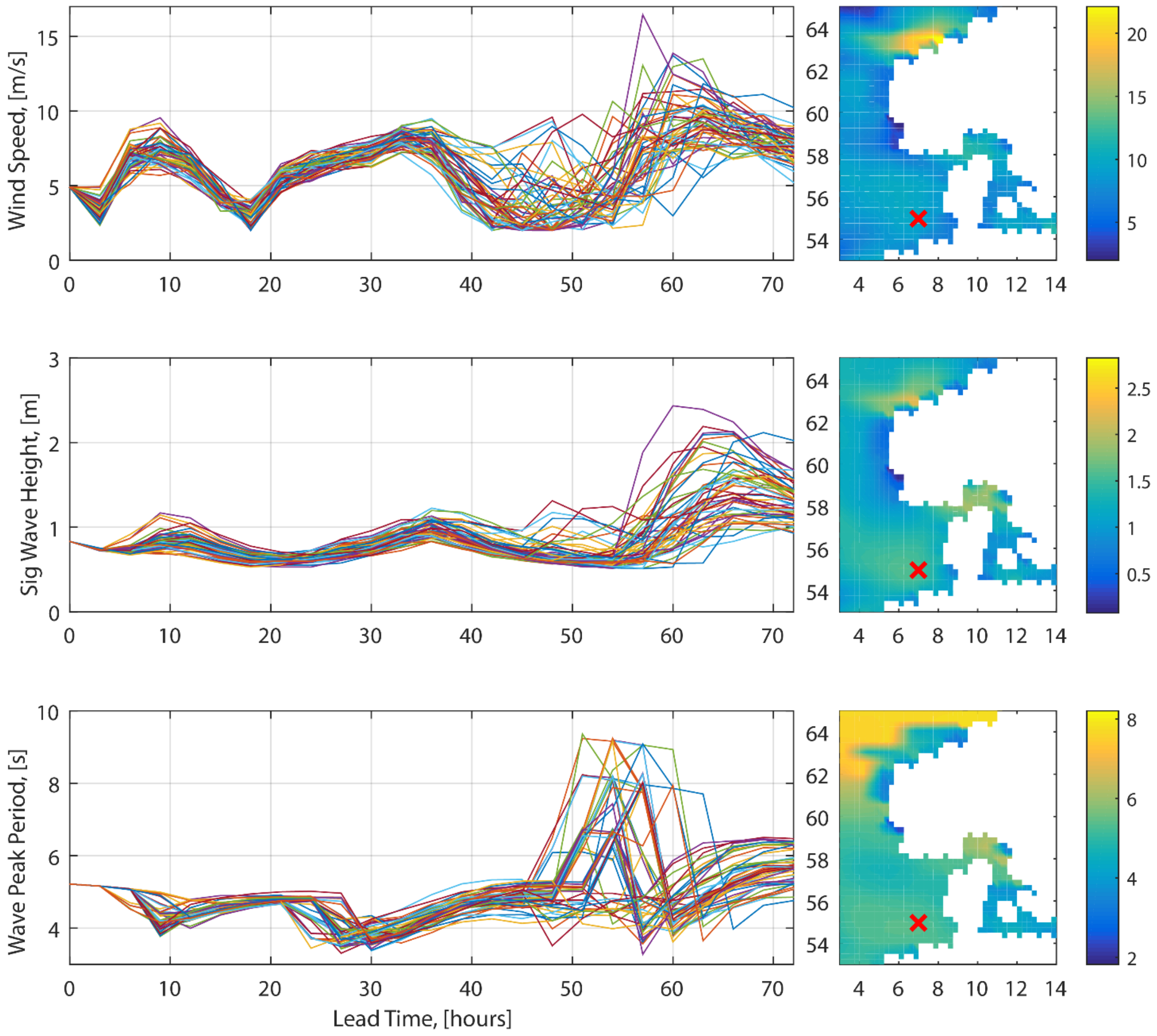
2013-08-06

51 ensemble members containing up to **250 hours lead time** forecast.

- Wind speed and direction.
- Sig wave height and peak and direction.
- Swell sig wave height and mean period and direction.

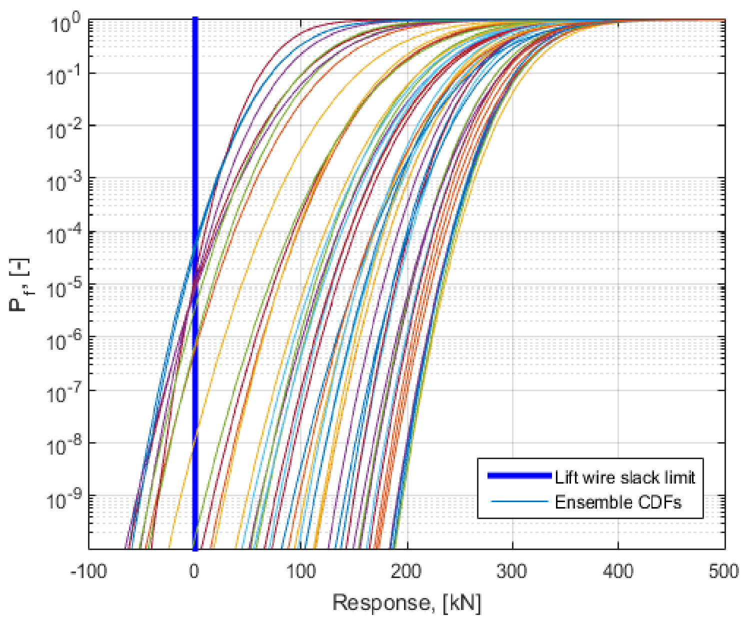


Short term Validation. Simulation input - weather



Types of limit states

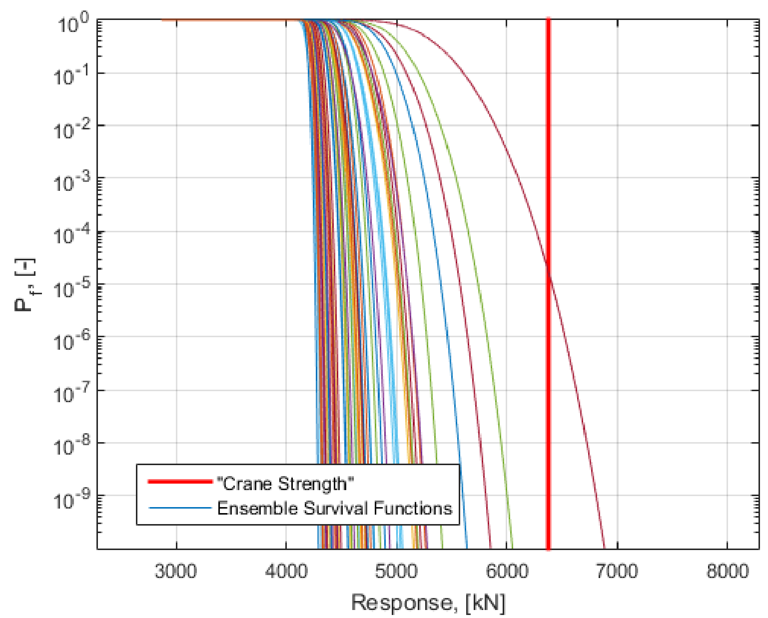
Non-exceedance limit state. The response has to be above the acceptance limit (no slack in lifting cables, tug wires, tower clearance etc.)



Evaluation of non-exceedance function at accetpance limit R_{max}.

$$P_{F,ens} = F_{non-exc,ens}(R_{max})$$

Exceedance limit state. The response has to be below a certain acceptance limit (maximum motions, loads on lifting equipment etc.)

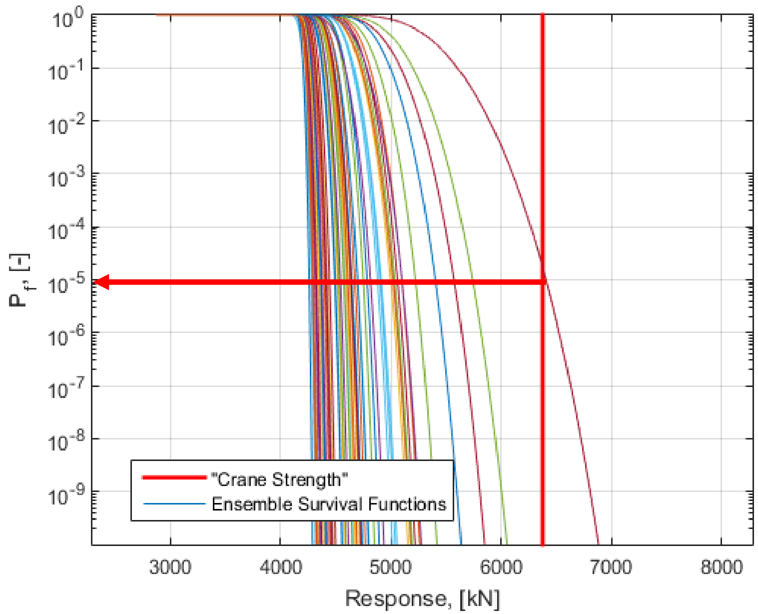


Evaluation of exceedance function at accetpance limit R_{max}.

$$P_{F,ens} = P_{exc,ens}(R_{max})$$

Types of limit states continued

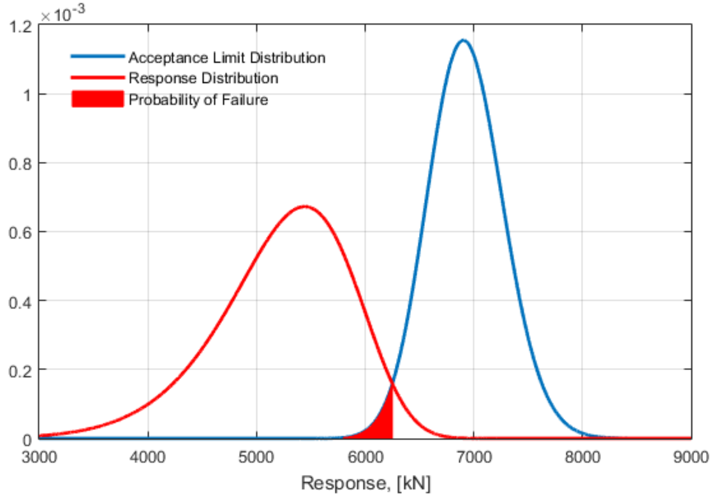
Deterministic limit state. Defined by a single value of acceptance/ failure limit.



Evaluation of CDF at the acceptance limit R_{max}.

$$P_{F,ens} = P_{F,exc,ens}(R_{max})$$

Non-deterministic limit state. Defined by a distribution of the acceptance limit.

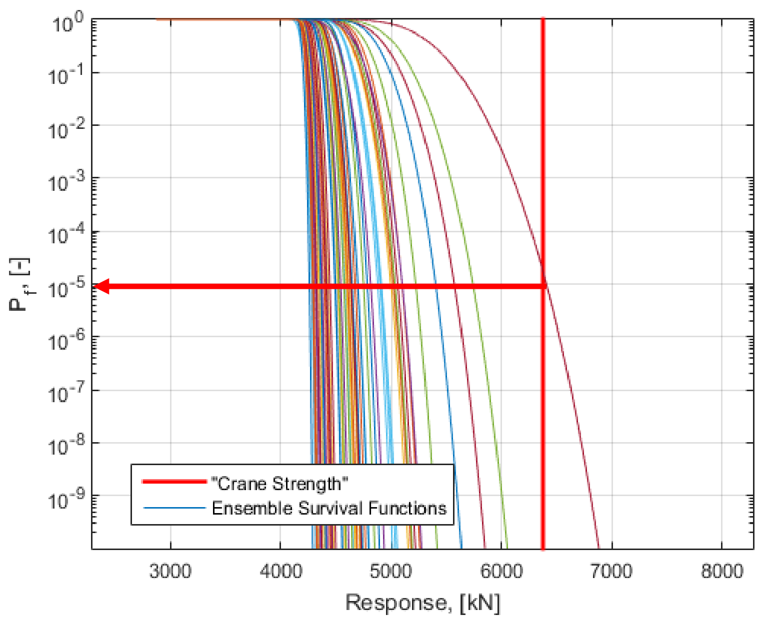


Inegral of response CDF multiplied with „stregth“ PDF within acceptance limit range.

$$P_{F,ens} = \int P_{exc,ens}(R) \cdot f(R|\mu_{ln}, \sigma_{ln})dR$$

Types of limit states continued

Deterministic limit state. Defined by a single value of acceptance/ failure limit.



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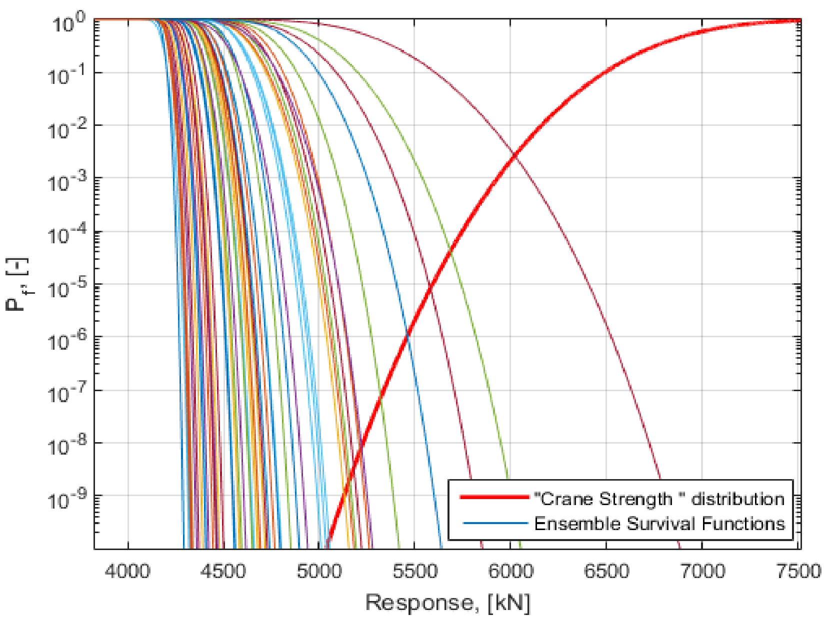


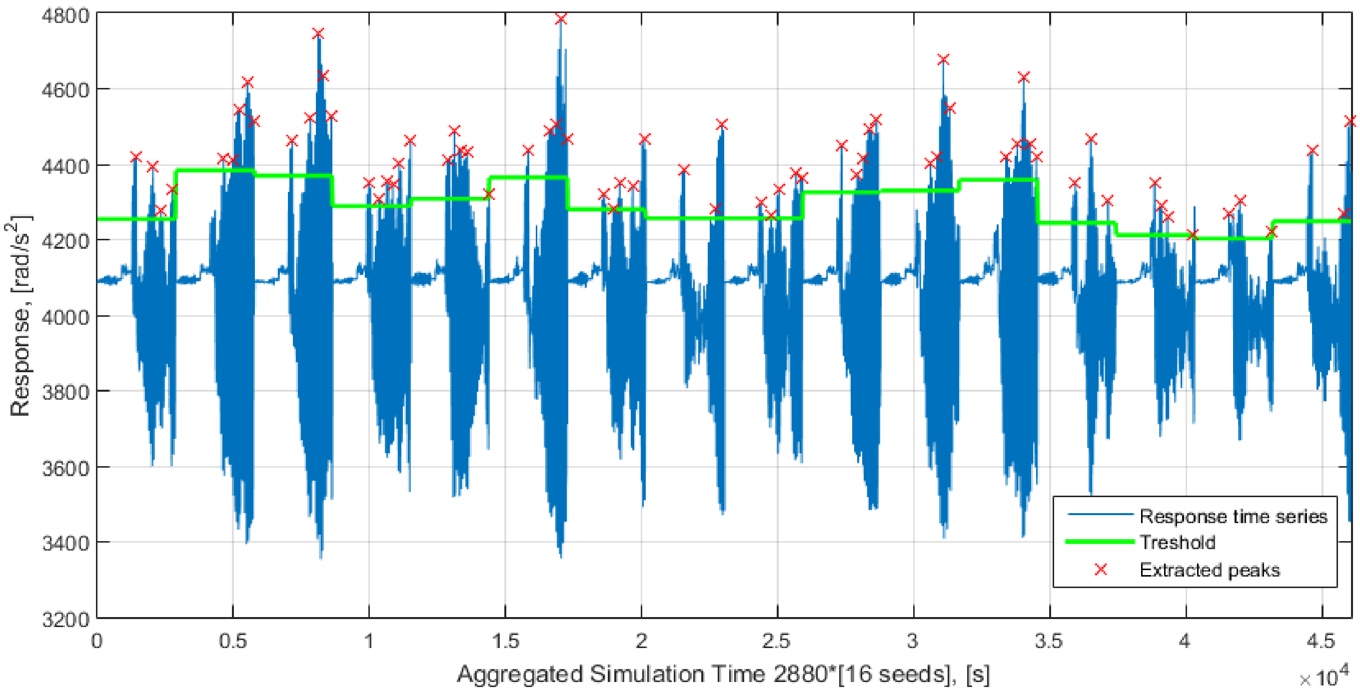
Inegral of response CDF multiplied with „stregth" PDF within acceptance limit range.

$$P_{F,ens} = \int P_{exc,ens}(R) \cdot f(R|\mu_{ln}, \sigma_{ln})dR$$

Procedure of Failure Probability estimation

Weather forecasts are passed through hydro-elastic simulator and response time series are analysed statistically in order to obtain Probabilities of Failed operations:

1. Peak Over Threshold method is applied to extract extreme values of relevant responses (R) (with $E(R) + 1.4 \cdot \sqrt{VAR(R)}$ threshold and 5 response cycles time separation).



Procedure of Failure Probability estimation

2. Weibull or Normal distribution (adjusted for number of peaks after POT) is fitted to the extremes using Maximum Likelihood parameter estimation.

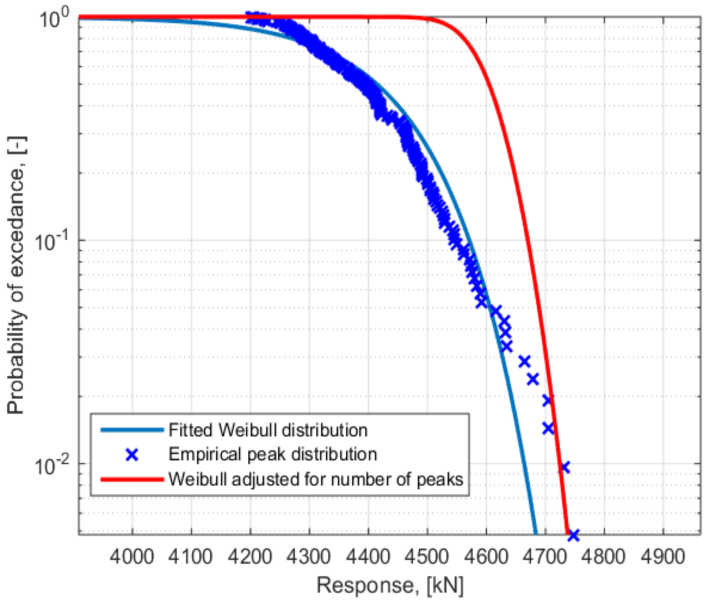
3. Steps 1-2 are repeated for 51 forecast ensembles.

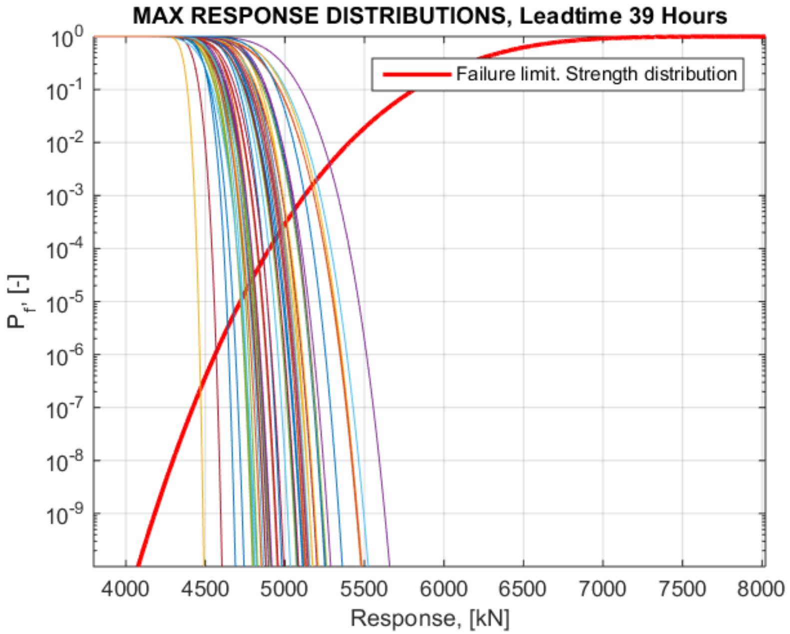
4. The Probability of Failure for one limit state is an average over 51 ensembles. Combining up all the limits states in one phase gives Probability of failure within an operation phase.

$$P_{F,Lim\ State} = \frac{\sum_{i=1}^{N} P_{F,Ensemble}}{number\ of\ ens}$$

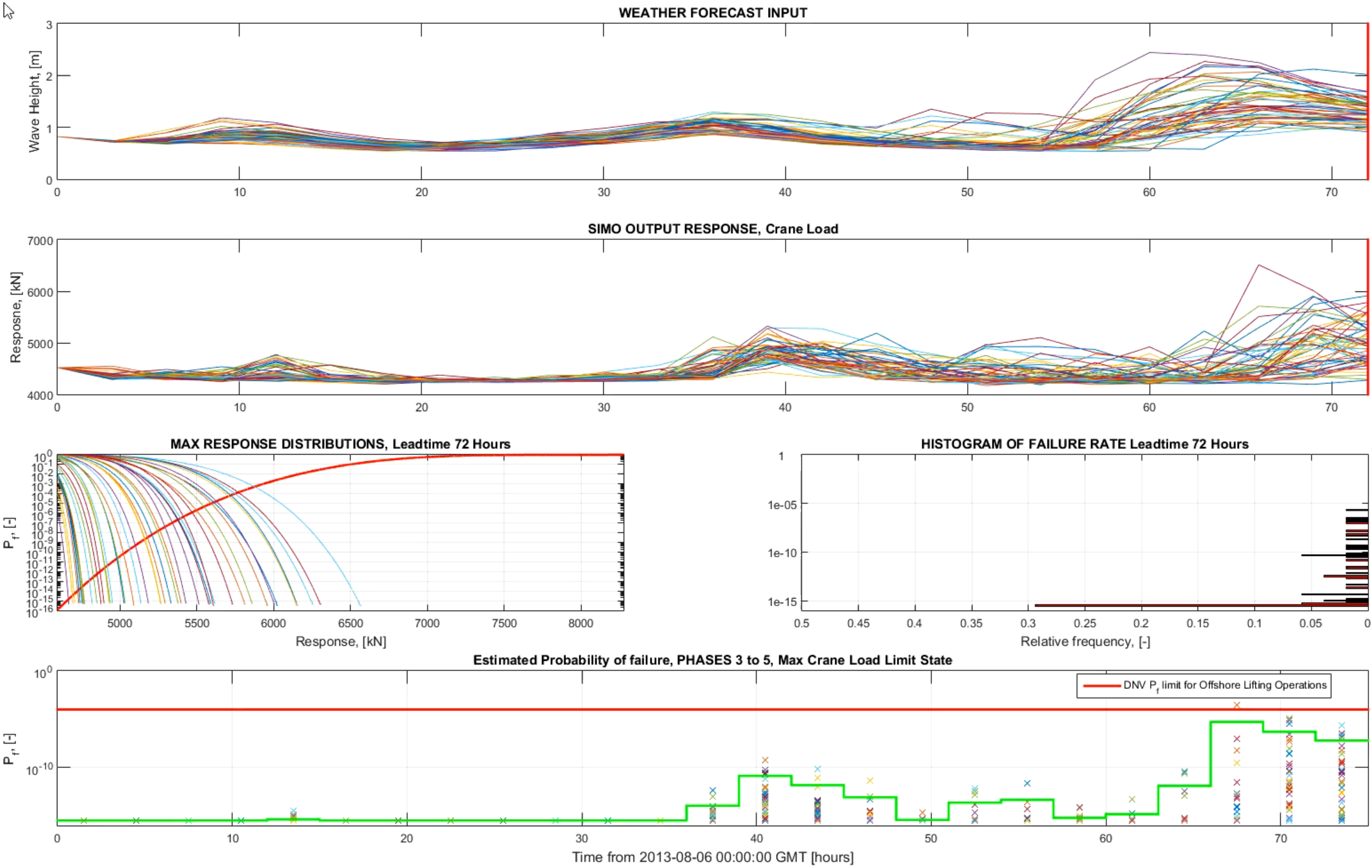
$$P_{F,Operation} = 1 - \prod_{i=1}^{N_{Lim\ States}} (1 - P_{F,\text{Lim}\ State,i})$$

$$P_{F,Operation} = 1 - \prod_{i=1}^{N_{Phases}} (1 - P_{F,Phase,i})$$





Proof of Concept. Short Term Validation



Combination of Limit state Probabilites of Failure

Hywind Rotor-Lift Operation

Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6-7
Transition to field 8 hours	Preparation for lift 3 hours	Rotor lift up 0.2 hours	Rotate rotor 0.2 hours	Lift-up close to nacelle 0.4 hours	Connecting rotor to nacelle 0.3 hours

$P_{F,\text{ CraneLoad, Ph 3}} + P_{F,\text{ CraneLoad,Ph 4}} + P_{F,\text{ CraneLoad, Ph5}} =$ $P_{F,\text{ Crane Load}}$

+

$P_{F,\text{ Air Gap Blade Water,Ph 2}} + P_{F,\text{ Air Gap Blade Water,Ph 2}} =$ $P_{F,\text{ Air Gap Blade Water}}$

+

$P_{F,\text{ Rotor Sway , Ph 3}} + P_{F,\text{ Rotor Sway, Ph 4}} + P_{F,\text{ Rotor Sway, Ph 5}} =$ $P_{F,\text{ Rotor Sway}}$

+

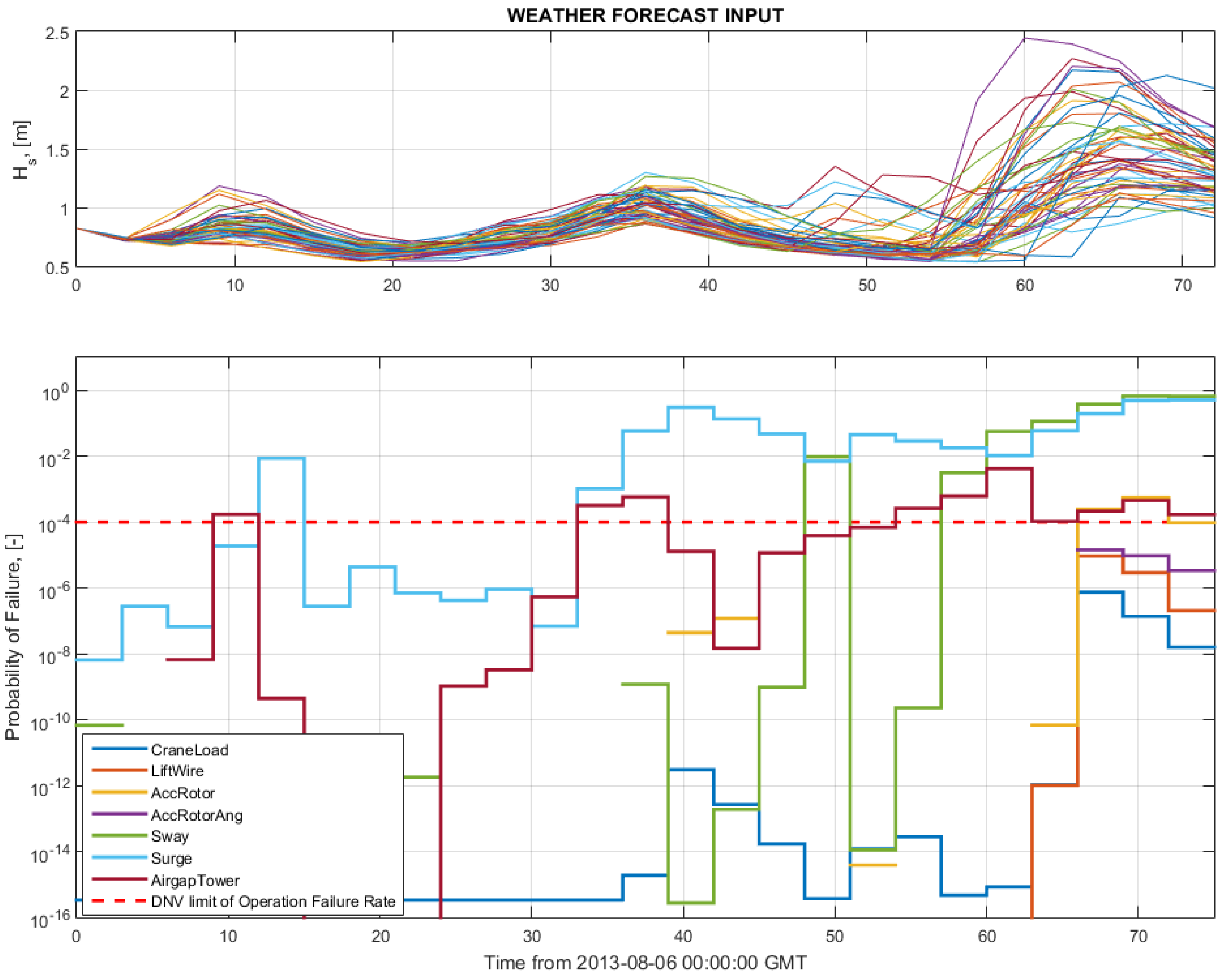
$P_{F,\text{ Acceleration, Ph 3}} + P_{F,\text{ Acceleration, Ph 4}} + P_{F,\text{ Acceleration, Ph 5}} =$ $P_{F,\text{ Acceleration}}$

+ .... =

$P_{F,\text{ Operation}}$

$$P_{F,Operation} = 1 - \prod_{i=1}^{N_{Lim\ States}} (1 - P_{F,\text{Lim } State,i})$$

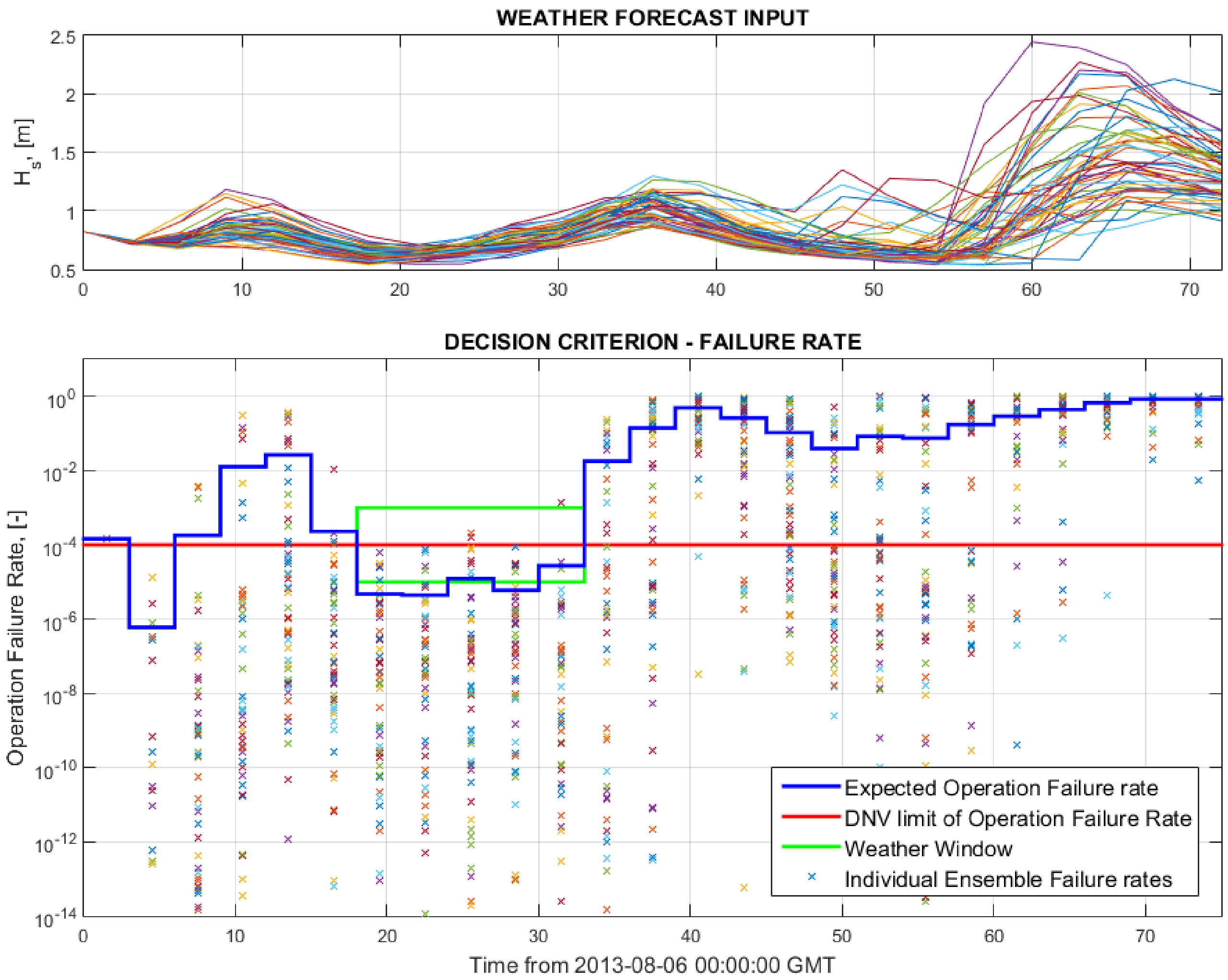
Limit state Probabilities of Failure



Operation Failure Rate

$$P_{F,Operation} = 1 - \prod_{i=1}^{N_{Lim\ States}} (1 - P_{F,\mathrm{Lim}\ State,i})$$

5. A sum over all the phases gives the total Operation failure rate. Based on $P_{F,Op}$ weather windows, suitable for installation, could be found.



Risk based decision making

$$C_{total} = C_{waiting} + C_{equipment} + \sum_{i=1}^{N_{phases}} \left(\sum_{j=1}^{N_{LS}} P_{LS,i,j} C_{LS,i,j} \right)$$

Having Probabilities of Failure related to a particular limit state and combining those with monetary consequences of failure with particular limit state Risk Based decision making is possible.

What is needed:

- Cost in NOK (€) related to Operation Failure with a particular limit state.
- Cost in NOK (€) of complete Operation Failure for less detailed analysis (one failure results in loss of all equipment and complete Operation Failure).

Long term validation. Input

- **Location**: *7 º W 55.25 º* N **FINO 3 site.**
- **Forecast**: *ECMWF* **May 1st to August 1st 2014.**

  measurements **@FINO3.**
- **Parameters used:**
  - Wind speed and direction.
  - Significant wave height and peak and direction.
  - Swell sig wave height and mean period and direction.
- **Hydrodynamic model:** Hywind Rotor Lift operation.
- **Benchmarking:** The proposed method is validated against a standard "***Alpha-Factor***" from DNV-HS-101.
- **Different benchmarking cases:**
  - Tabulated ***Alpha-Factors*** from DNV-HS-10.
  - Site specific ***Alpha-Factors*** for FINO3 site according to DNV-HS-10.
  - **DECOFF** method with **ECMWF forecasts @FINO3**.
  - **DECOFF** method with **measurements @FINO3**.

Long term validation. Alpha-Factor method

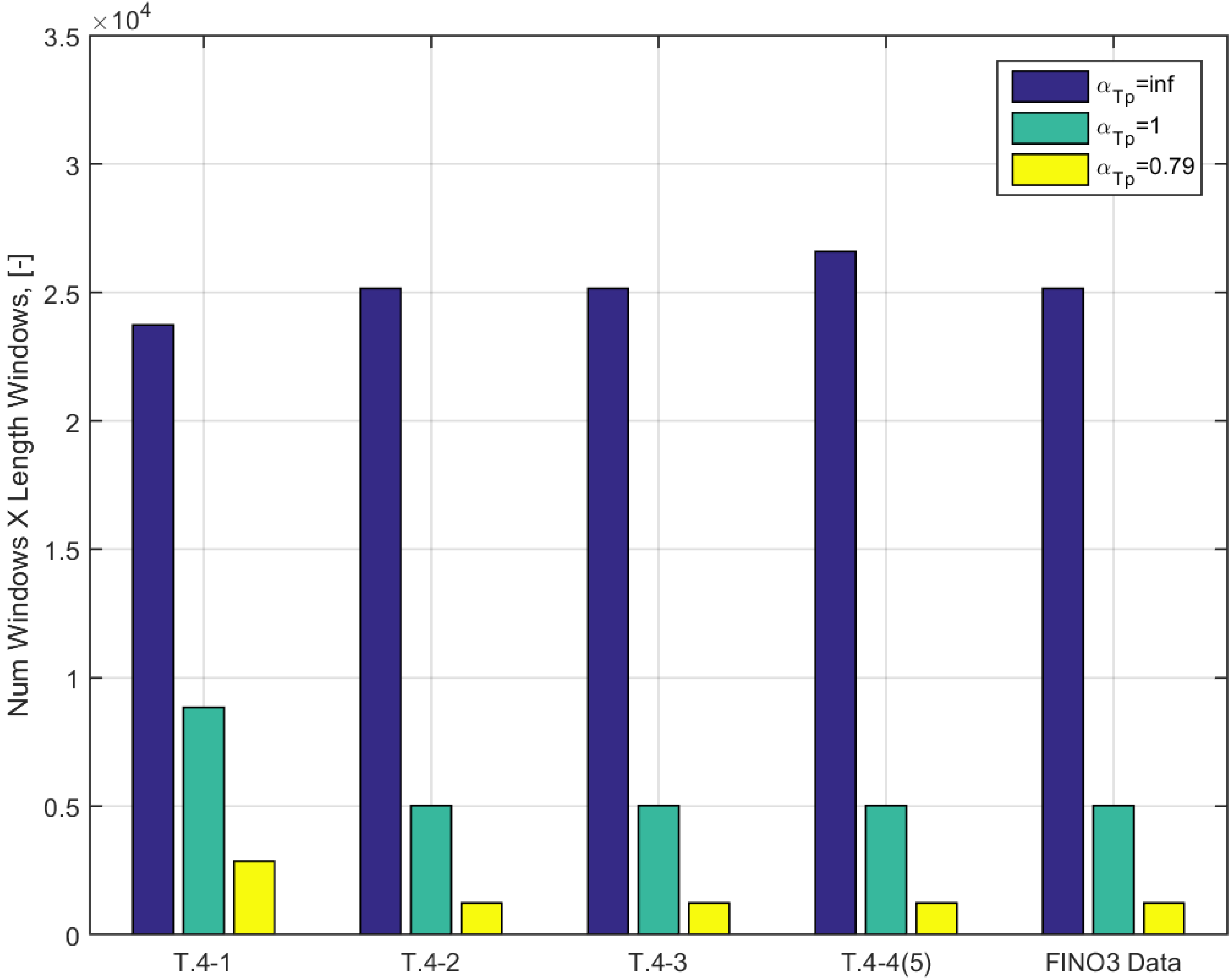
Weather limits for Hywind Rotor Lift operation:

- H_s=1.5m, T_p=5s, W_s=7m/s.

Case	α_{Hs} for H_s = 1.5m	α_{Tp} for T_p = 5s			α_{Ws} for W_s = 7m/s	Quantile
T 4-1. WFQ = C	0.705	inf	0.78	1	0.8	mean
T 4-2. WFQ = B	0.740	inf	0.78	1	0.8	maximum
T 4-3. WFQ = A+M	0.780	inf	0.78	1	0.8	maximum
T 4-4. WFQ = A+C	0.925	inf	0.78	1	0.8	maximum
T 4-5. WFQ = A+M+C	0.925	inf	0.78	1	0.8	maximum
FINO3 measurements	0.810	inf	0.78	1	0.8	maximum

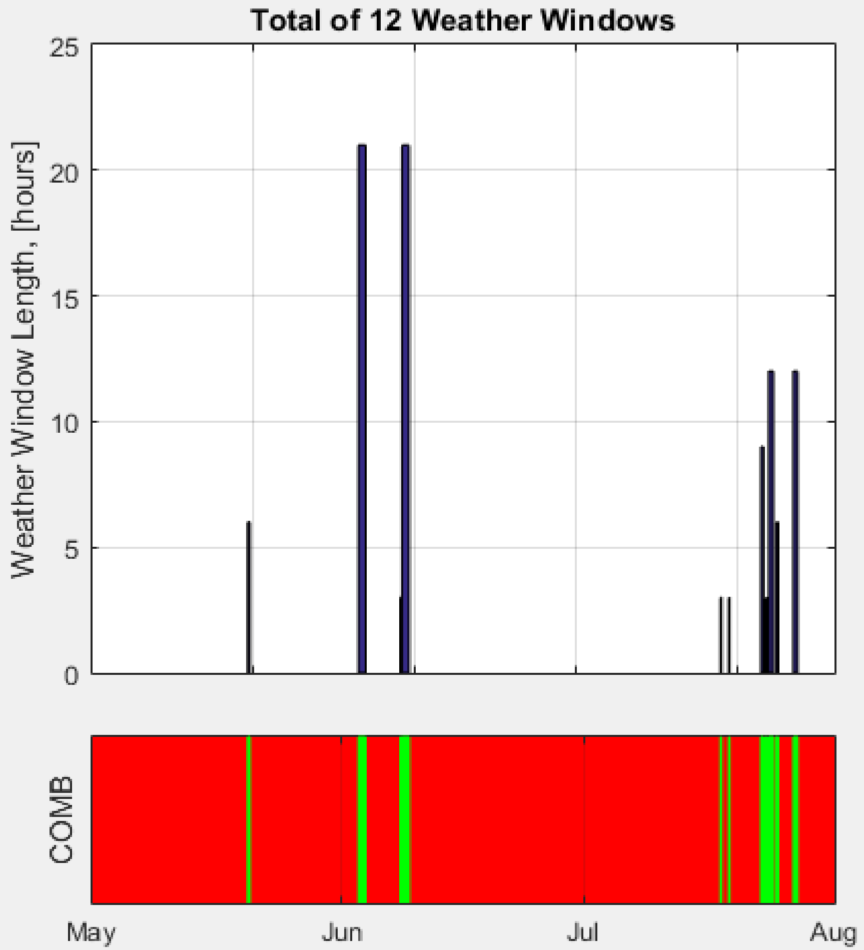
T x-y – table indicator for reference in DNV-HS-10;
WFQ – weather forecast quality class **A, B** or **C**.
+M – meteorologist on site, +**C** – calibrated based on measurement data.

Long term validation. Alpha-Factor method

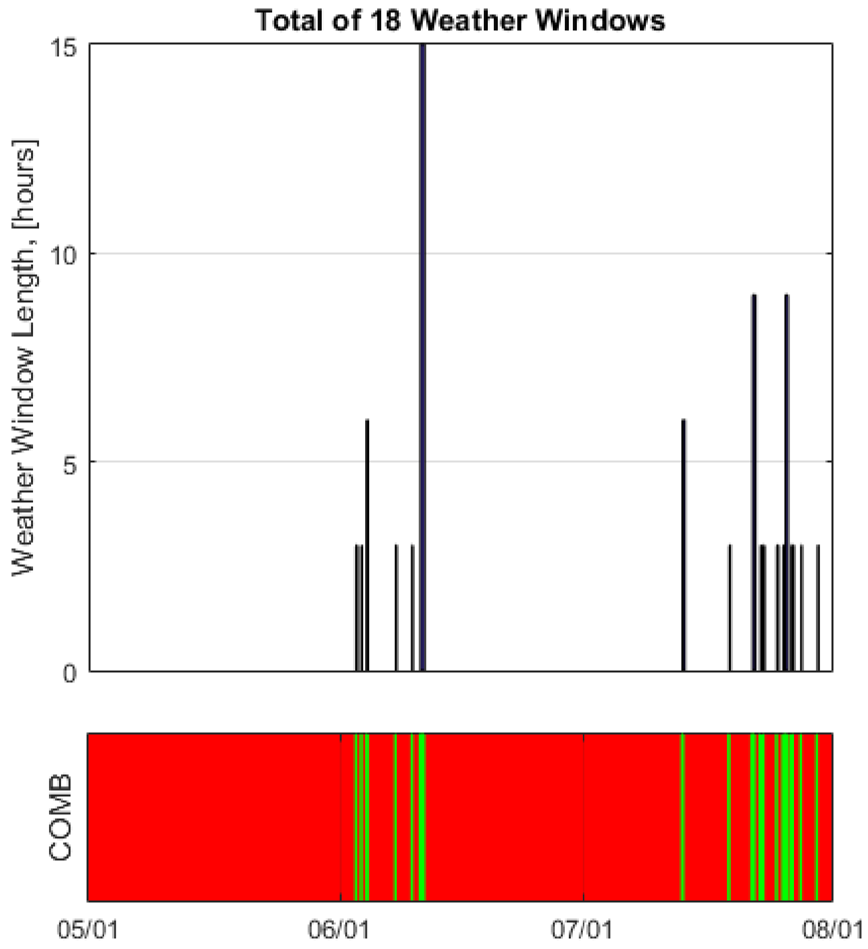


Long term validation. Results

Alpha-Factor method

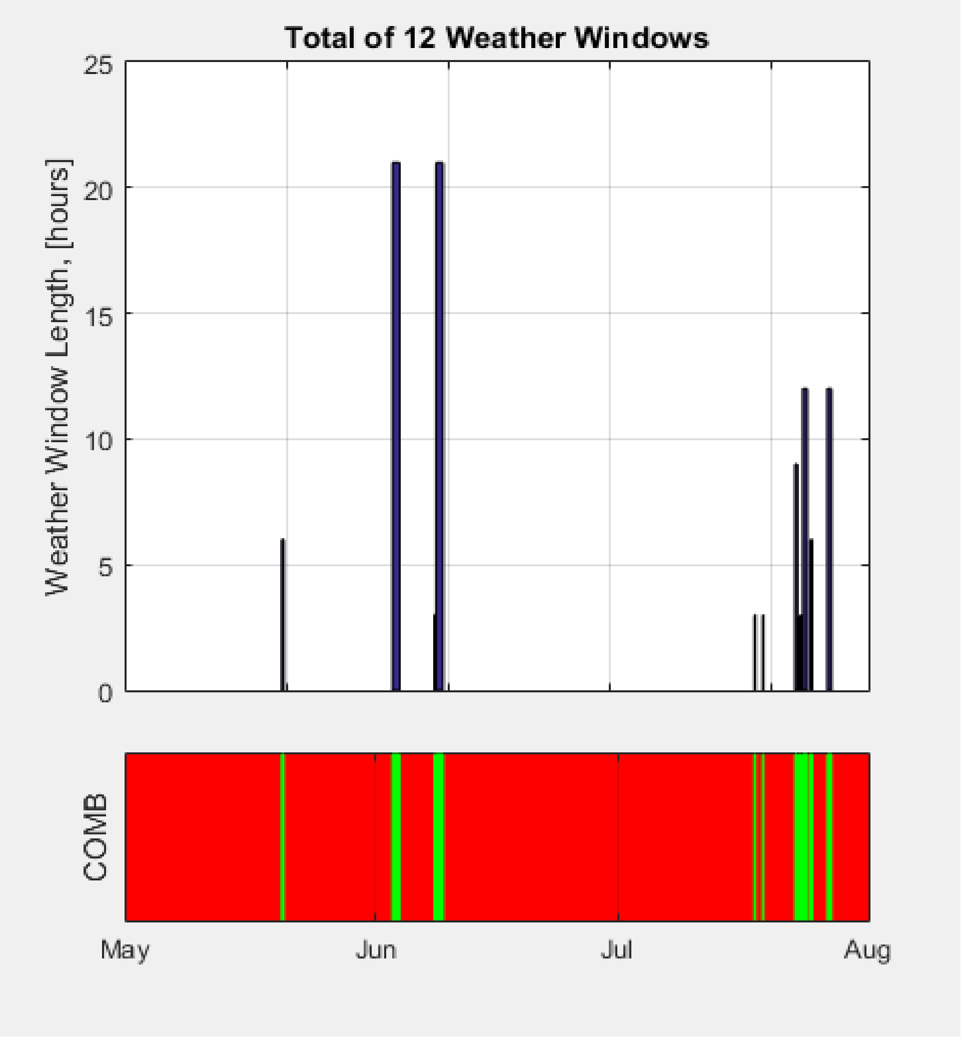


DECOFF method with ECMWF

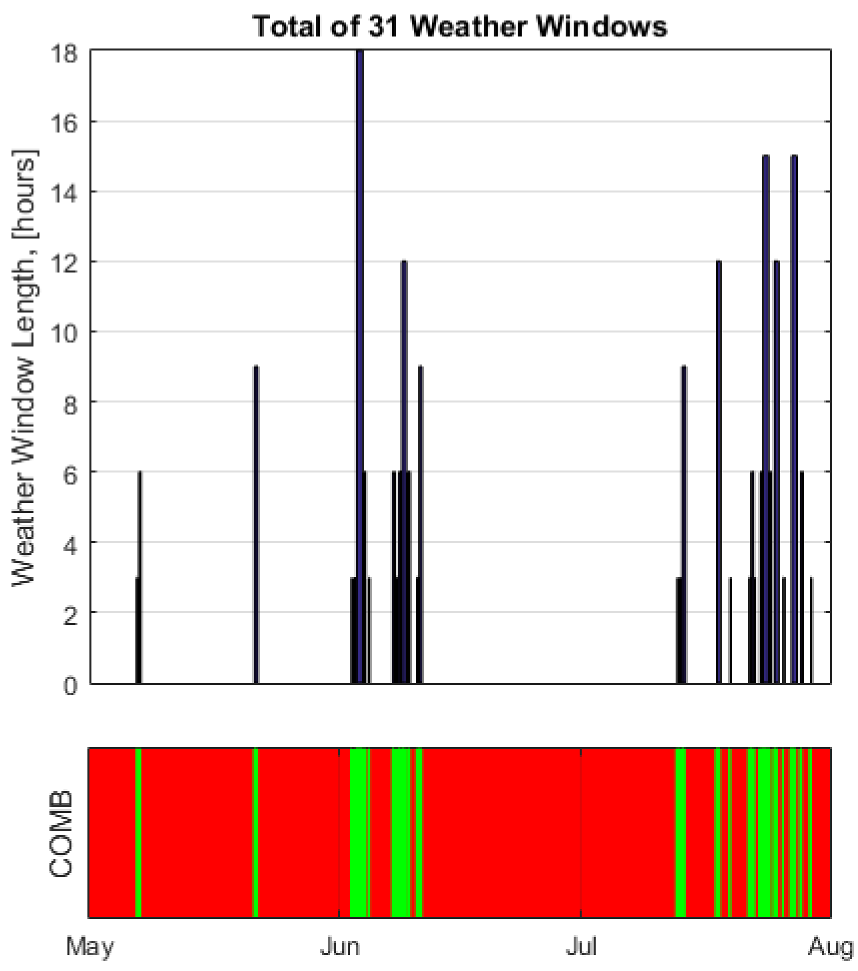


Long term validation. Results

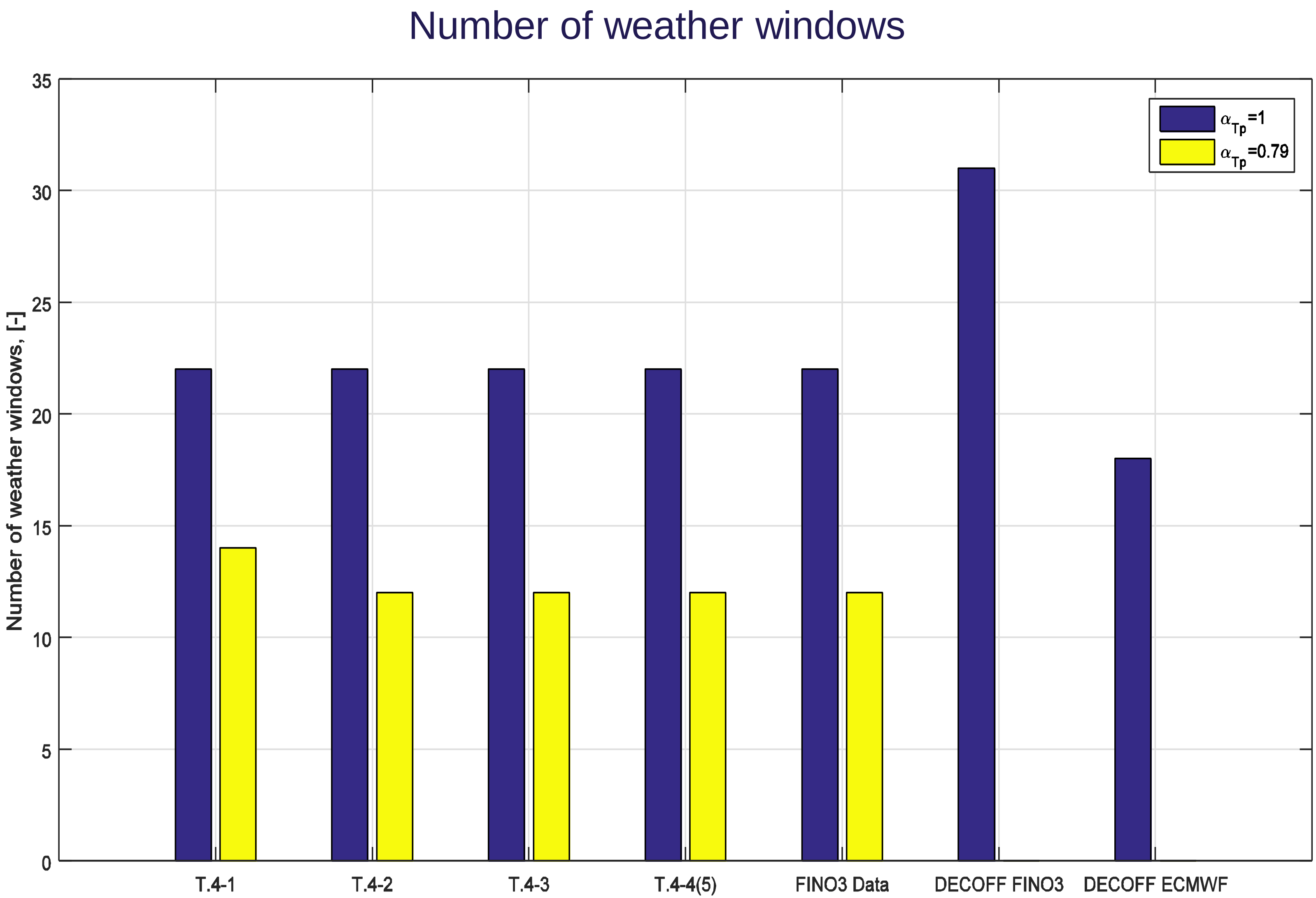
Alpha-Factor method



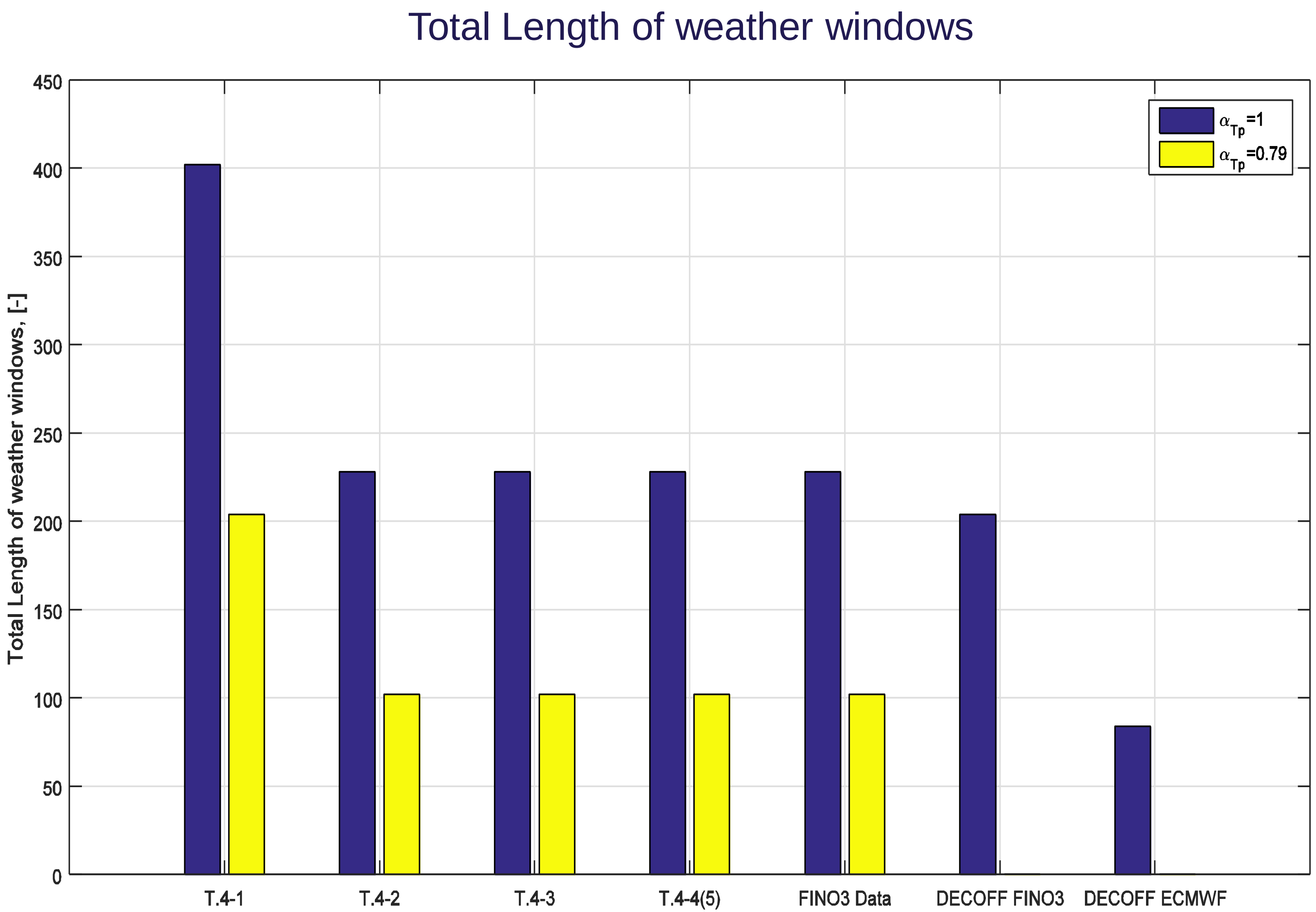
DECOFF method with FINO3 measurements



Long term validation. Results



Long term validation. Results



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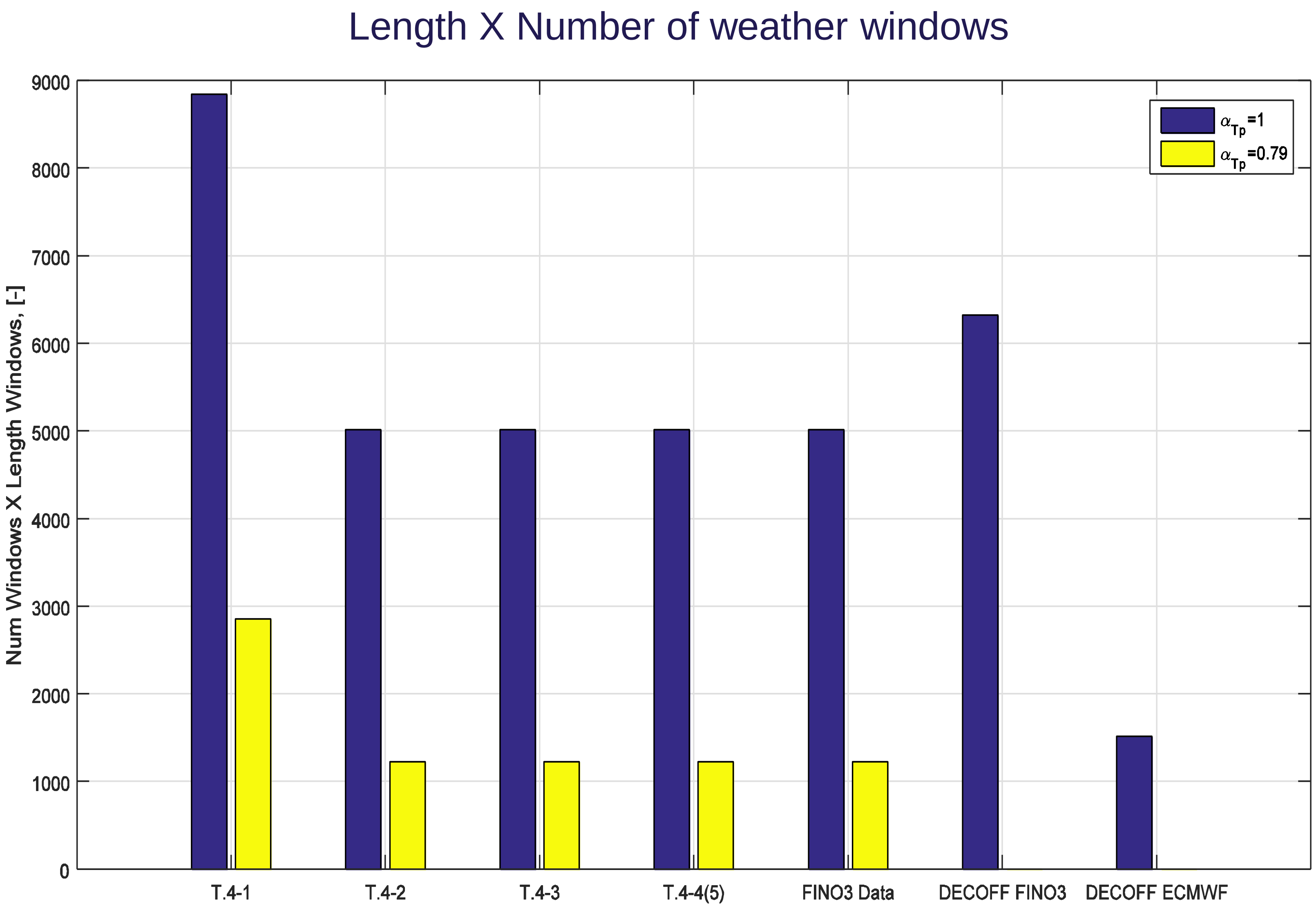

Conclusions and discussion

- After extensive testing it can be concluded that the procedure for estimation of Probability of Failed Operations produces consistent results and could be used to assist in decision making for Offshore Wind Turbine installation.

- The proposed new ***DECOFF method*** performs better or at least as good as the standard “***Alpha-factor”*** *method (when* ***number of windows x total window length*** *measure is used).*

- Weather forecast uncertainty plays a central role in predicting weather windows. With increasing uncertainty the length and number of weather windows decreases. This is on par with the standard “***Alpha-factor”*** *method.*

- Using better, less uncertain, weather forecasts (calibrated weather forecasts, downscaling etc.) would be very beneficial in the performance of ***DECOFF method***.

- Easy extension to Oil and Gas an other relevant industries.

Future work

Possible future work would include but should not be limited to:

- Updating the model with Structural Reliability techniques in order to reduce the demand on a lot of simulations necessary to obtained reliable results.
- Splitting the limit states in Serviceability and Ultimate.
- Including Costs of Failure to produce a “Risk-Based” aspect allowing to evaluate different weather windows in terms of expected Risk rather than just Probability of Failure.
- Improving the accuracy of weather forecasts.
- Extending the methodology to more general Offshore Operations (Oil and Gas, Wind turbine installation on monopoles/jackets etc.).

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THANK YOU FOR YOUR ATTENTION!

ANY QUESTIONS? COMMENTS?

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