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

STATISTICAL MODELLING OF FAILED OPERATIONS

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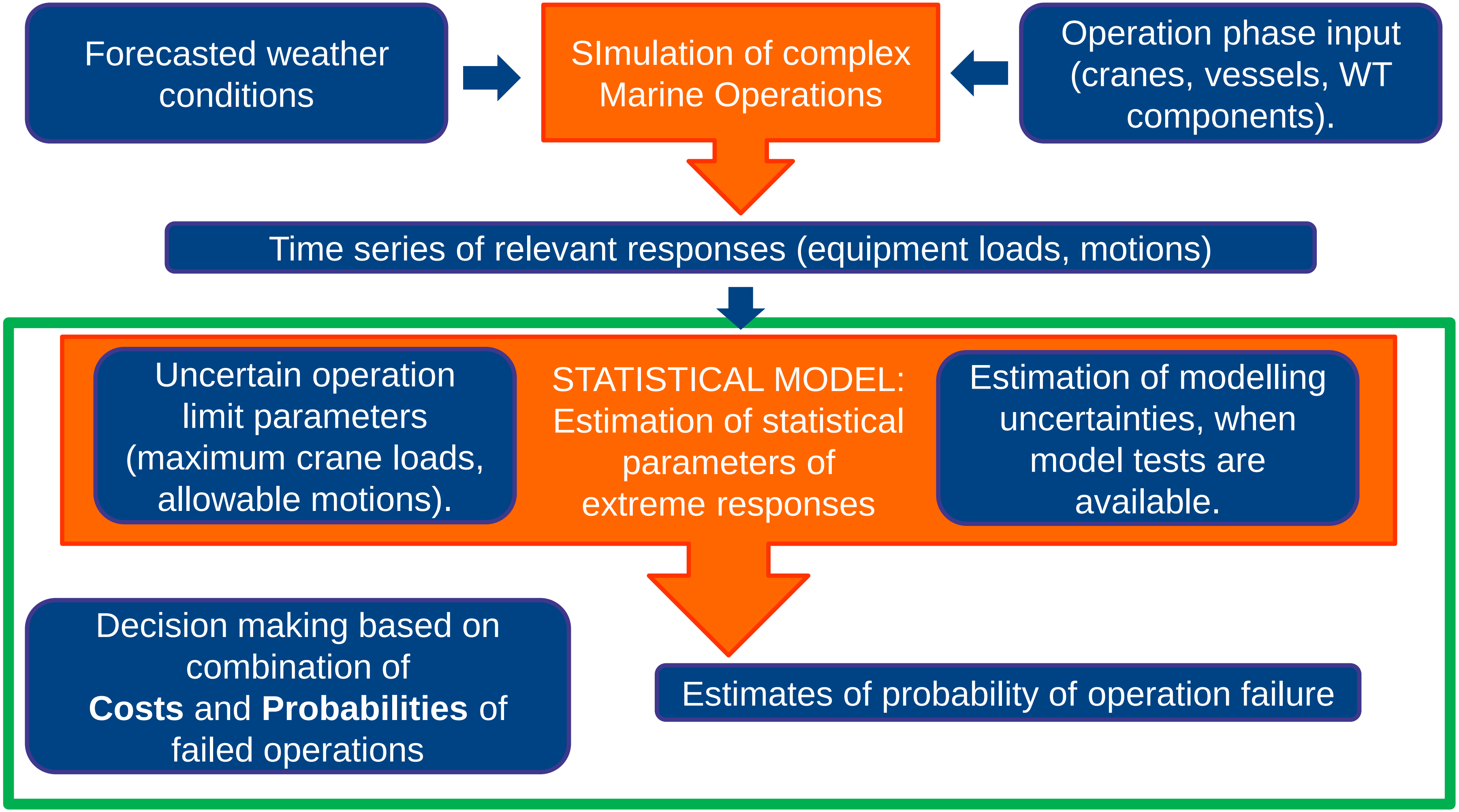
Short agenda

- **Research Motivation**
- **Description of the tool in question.**
- **Simulation 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**
- **DEMO**
- **Probability based Decision Making.**
    - Limit State Probabilities of Failure
    - Operation Failure rate
    - Weather window estimation
- **Risk Based Decision Making**
- Influence of acceptance limit **Partial Safety Factors** on Probabilities of Failed Operations.

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.s
    - 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.



Development of framework for statistical interpretation of hydro-elastic simulator output in terms of:

- Estimation of statistical parameters for extreme response distributions;
- Estimation of Probabilities of failed Operations using data on critical response parameter levels and distributions of extreme responses.

Simulation input - weather

Location: 7 ^{0} W 55.25 ^{0} N

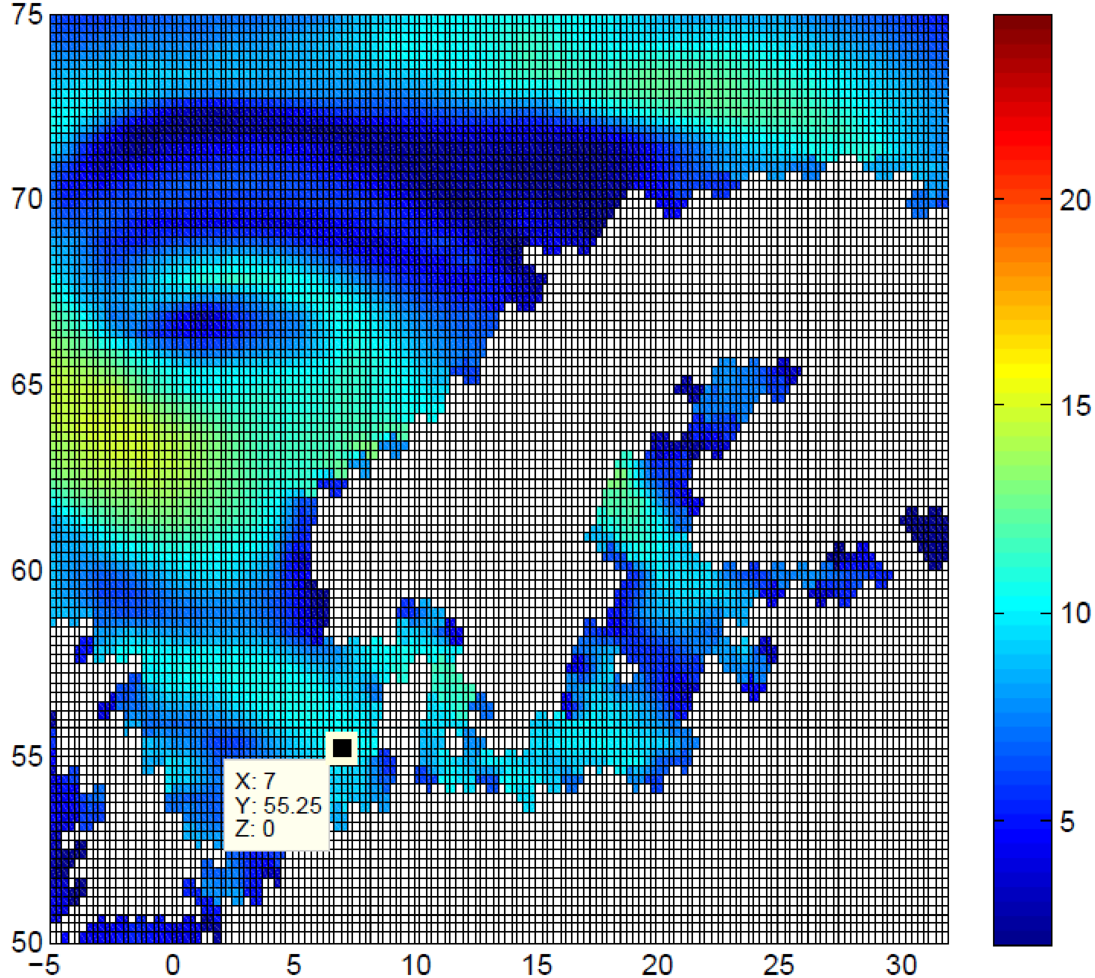
FINO 3 site

Forecast: ECMWF 2013

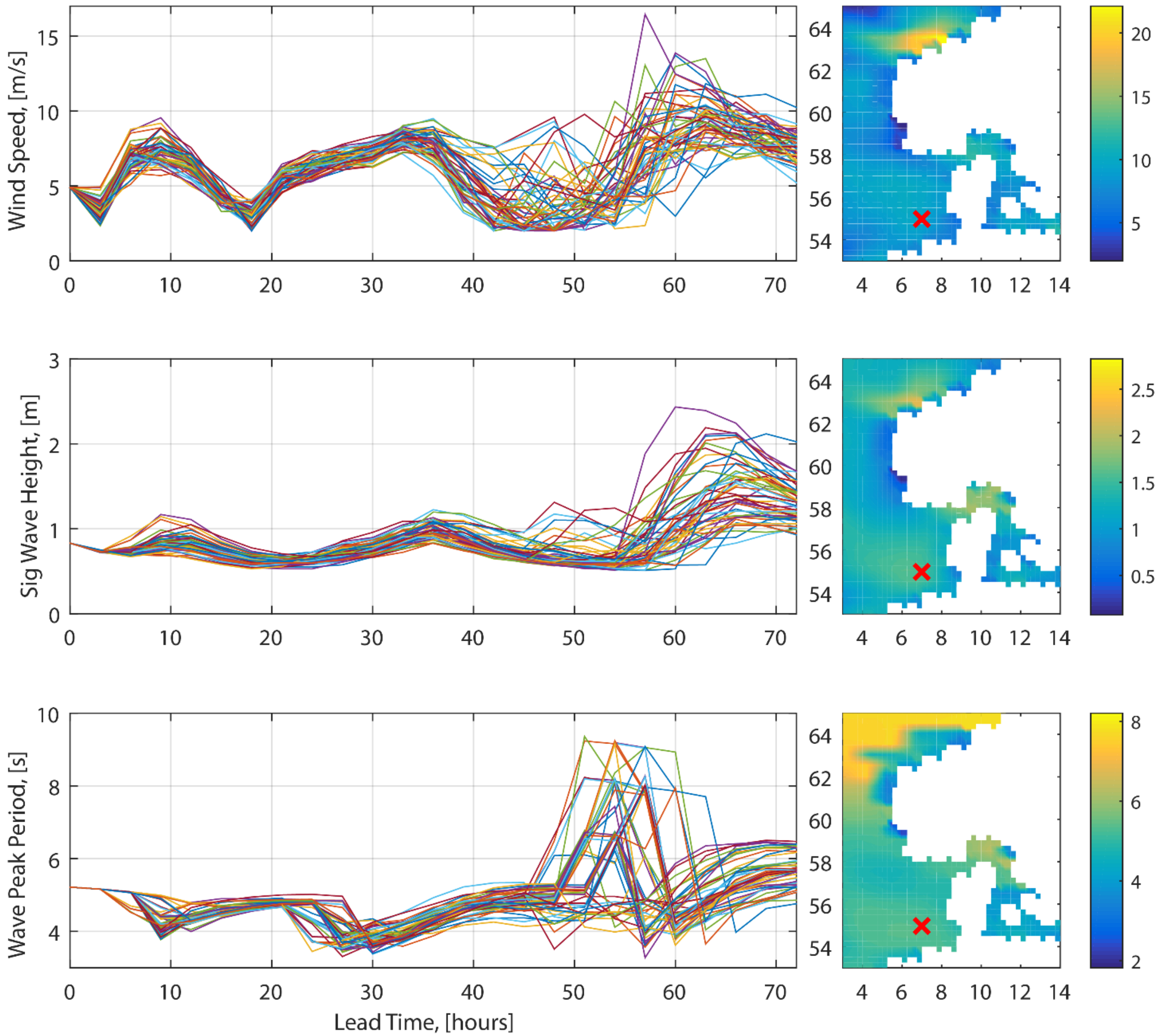
2013-08-06

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

- Wind speed and direction.
- Sig wave height and peak period (JONSWAP 1D) and direction.
- Swell sig wave height and mean period (Pierson-Moscowitz spectrum) and direction.



Simulation input - weather



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

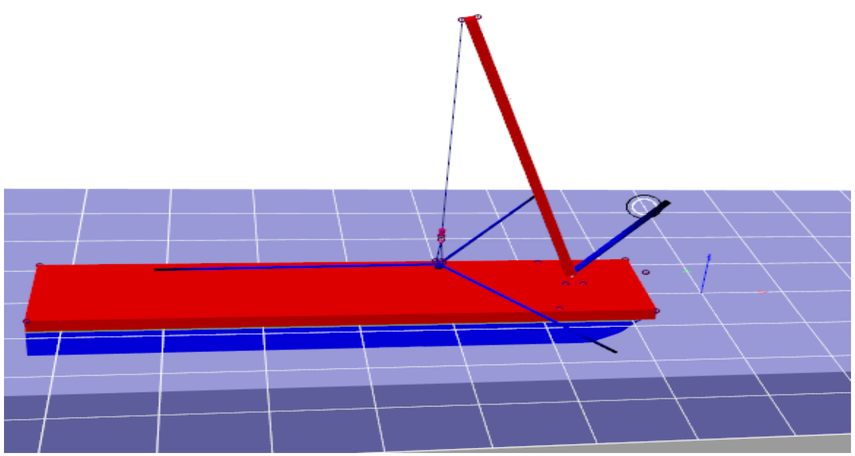
Phase 5
Lift-up close to nacelle
0.4 hours

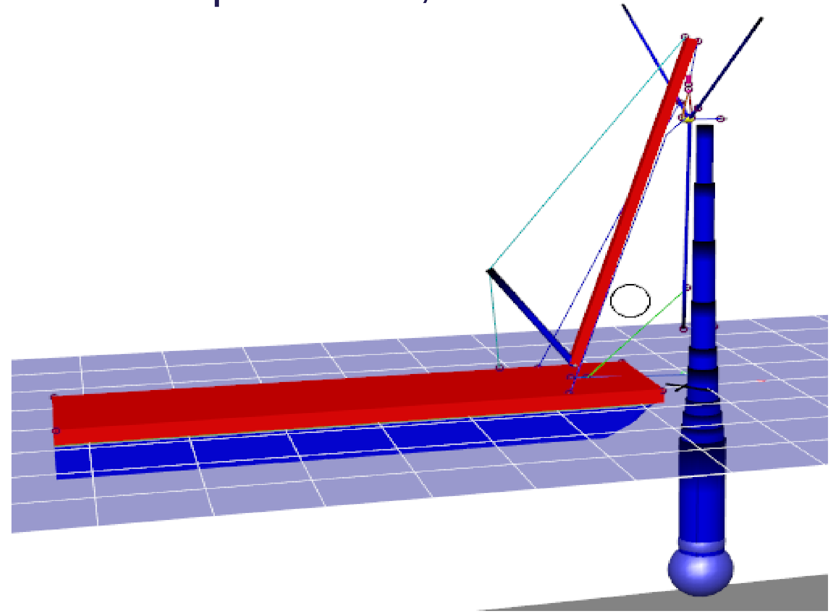
Phase 6
Connecting rotor to nacelle
0.3 hours

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

Phase 3 Operation Limits

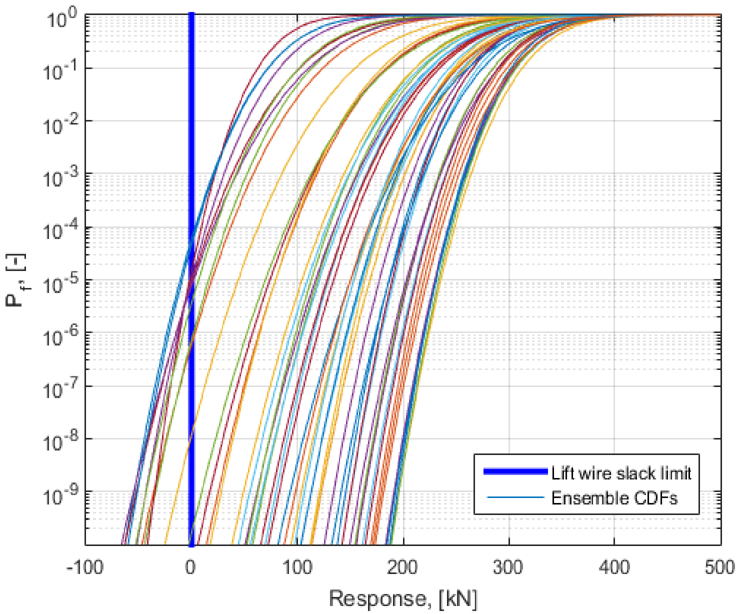
- Crane Load
- Lift Wire Tension
- Tug Wire Tension
- Airgap between blades and waves
- Rotor acceleration
- Rotor rotational acceleration
- Rotor Sway motion
- Rotor Surge motion

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

Types of limit states

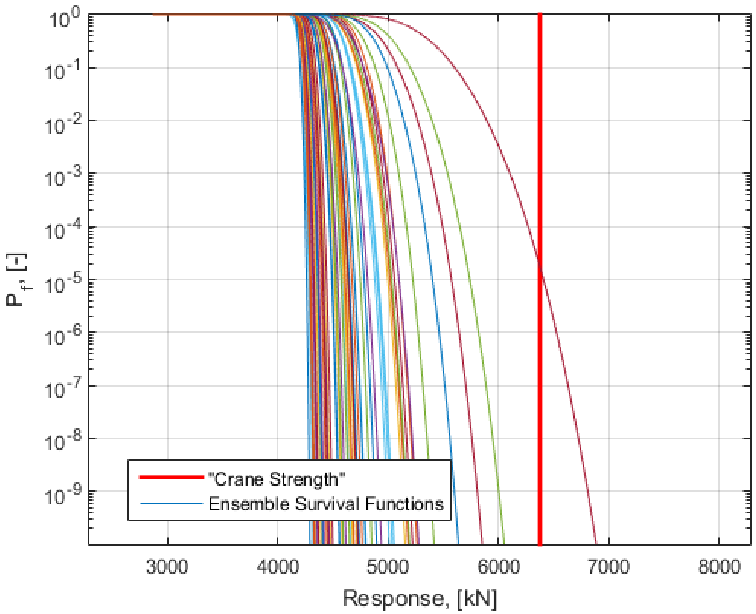
Non-exceedance limit state. The response has to be above the acceptance limit (no slack in lifting cables, tug wires, tower clearance etc.)



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.)

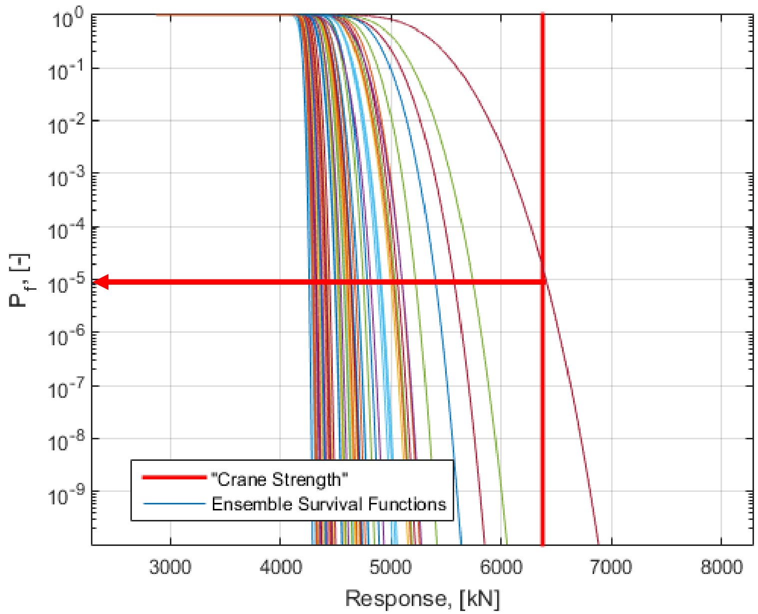


Evaluation of exceedance function at accetpance limit R_{max}.

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

Types of limit states continued

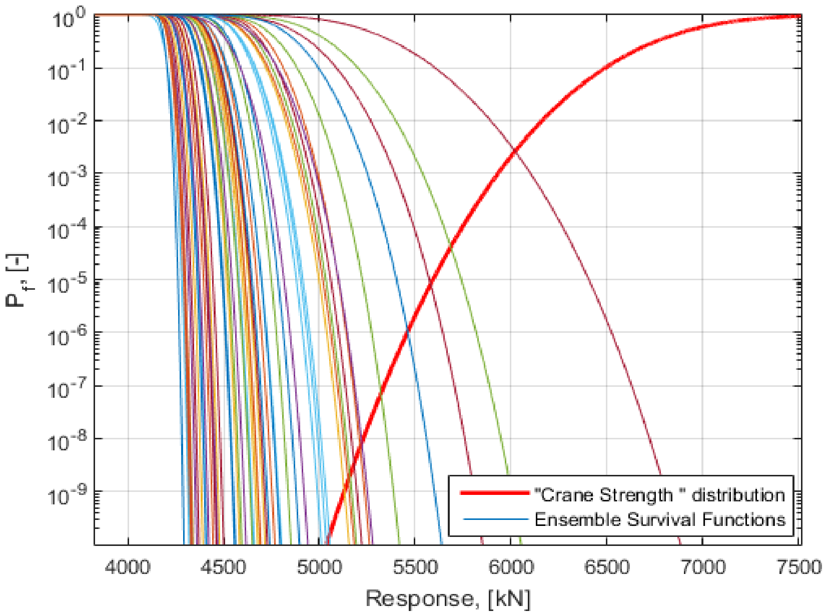
Deterministic limit state. Defined by a single value of acceptance/ failure limit.



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.

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

Limit state - Phase - Operation Failure Probability

Hywind Rotor-Lift Operation

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

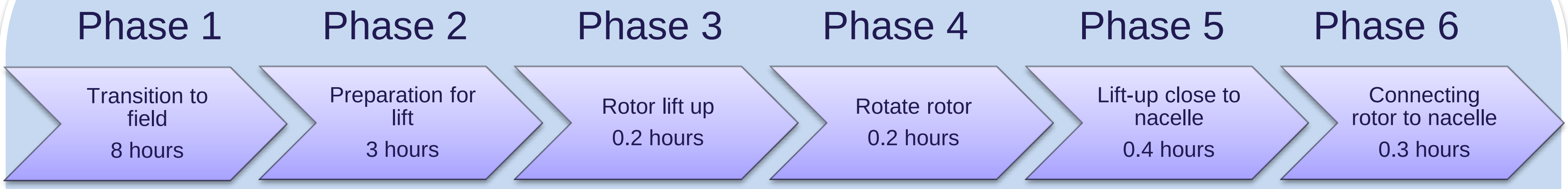
Phase 3 Operation Limits

- Crane Load — $P_{F, CraneLoad}$
- Lift Wire Tension — $P_{F, Tug Wire Tension}$
- Tug Wire Tension — $P_{F, Lift Wire Tension}$
- Airgap between blades and waves — $P_{F, Airgap Blades}$
- Rotor acceleration — $P_{F, Rotor Acceleration}$
- Rotor rotational acceleration — $P_{F, Rotor Rotational Accel}$
- Rotor Sway motion — $P_{F, Rotor Sway}$
- Rotor Surge motion — $P_{F, Rotor Surge}$

$$1-((1-P_{F, Phase 1})x(1-P_{F, Phase 2}) \times (1-P_{F, Phase 3}) \times (1-P_{F, Phase 4}) \times (1-P_{F, Phase 5}) \times (1-P_{F, Phase 6})) = P_{F, Operation}$$

Limit state - Phase - Operation Failure Probability

Hywind Rotor-Lift Operation



$1-((1-P_{F,\ CraneLoad,\ Ph\ 3})\times(1-P_{F,\ CraneLoad,Ph\ 4})\ \times(1-P_{F,\ CraneLoad,\ Ph5}))=$ $1-P_{F,\ Crane\ Load}$

x

$1-(1-P_{F,\ Air\ Gap\ Blade\ Water,Ph\ 2})\times(1-P_{F,\ Air\ Gap\ Blade\ Water,Ph\ 2}))=$ $1-P_{F,\ Air\ Gap\ Blade\ Water}$

x

$1-((1-P_{F,\ Rotor\ Sway\ ,\ Ph\ 3})\times(1-P_{F,\ Rotor\ Sway,\ Ph\ 4})\times(1-P_{F,\ Rotor\ Sway,\ Ph\ 5}))=$ $1-P_{F,\ Rotor\ Sway}$

x

$1-((1-P_{F,\ Acceleration,\ Ph\ 3})\times(1-P_{F,\ Acceleration,\ Ph\ 4})\times(1-P_{F,\ Acceleration,\ Ph\ 5}))=$ $1-P_{F,\ Acceleration}$

x .... =

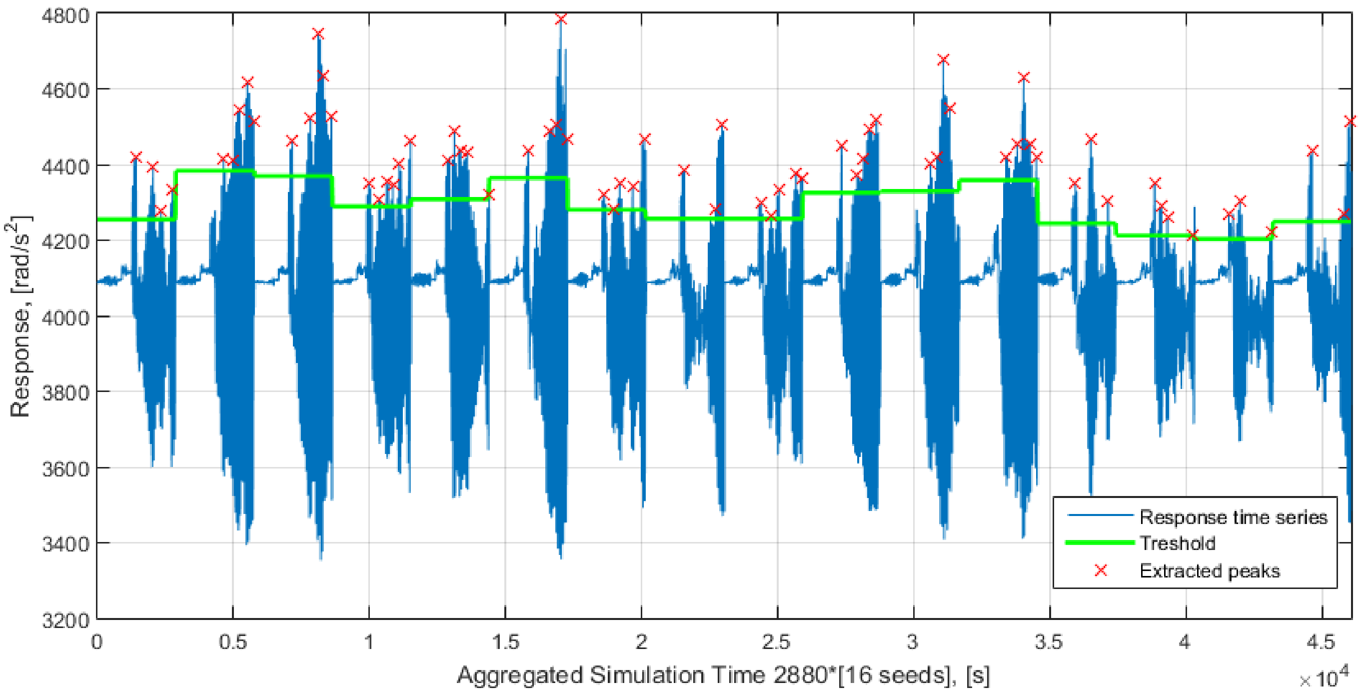
$$P_{F,Operation} = 1 - \prod_{i=1}^{N_{Lim\ States}} (1 - P_{F,\mathrm{Lim}\ State,i})$$

$P_{F,\ Operation}$

Procedure of Failure Probability estimation

Weather forecasts are passed through hydroelastic 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.

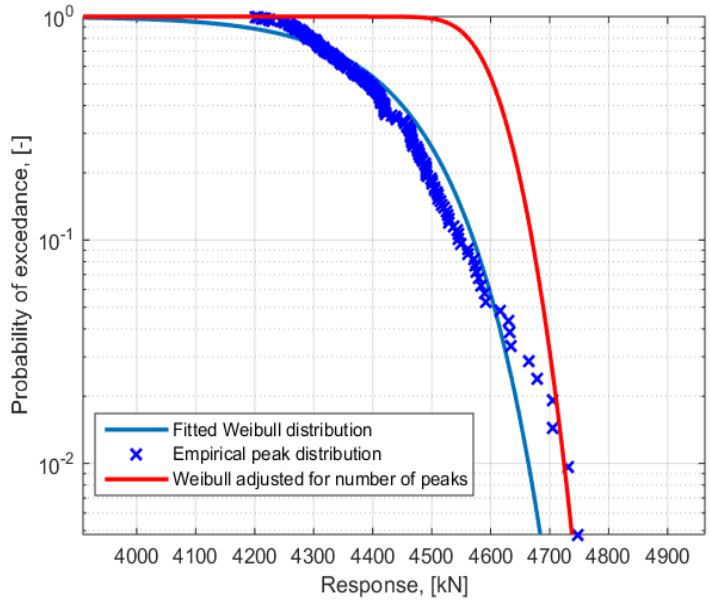
3. Steps 1-2 are repeated for 51 forecast ensembles.

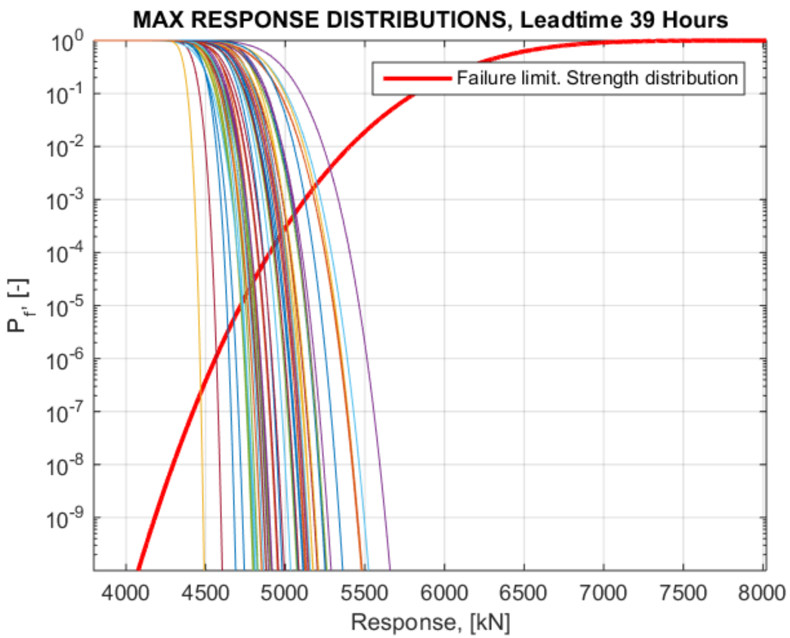
4. The Probability of Failure for one limit state is an average over 51 ensembles. Combining up all the limits states in one phase gives Probability of failure within an operation phase.

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

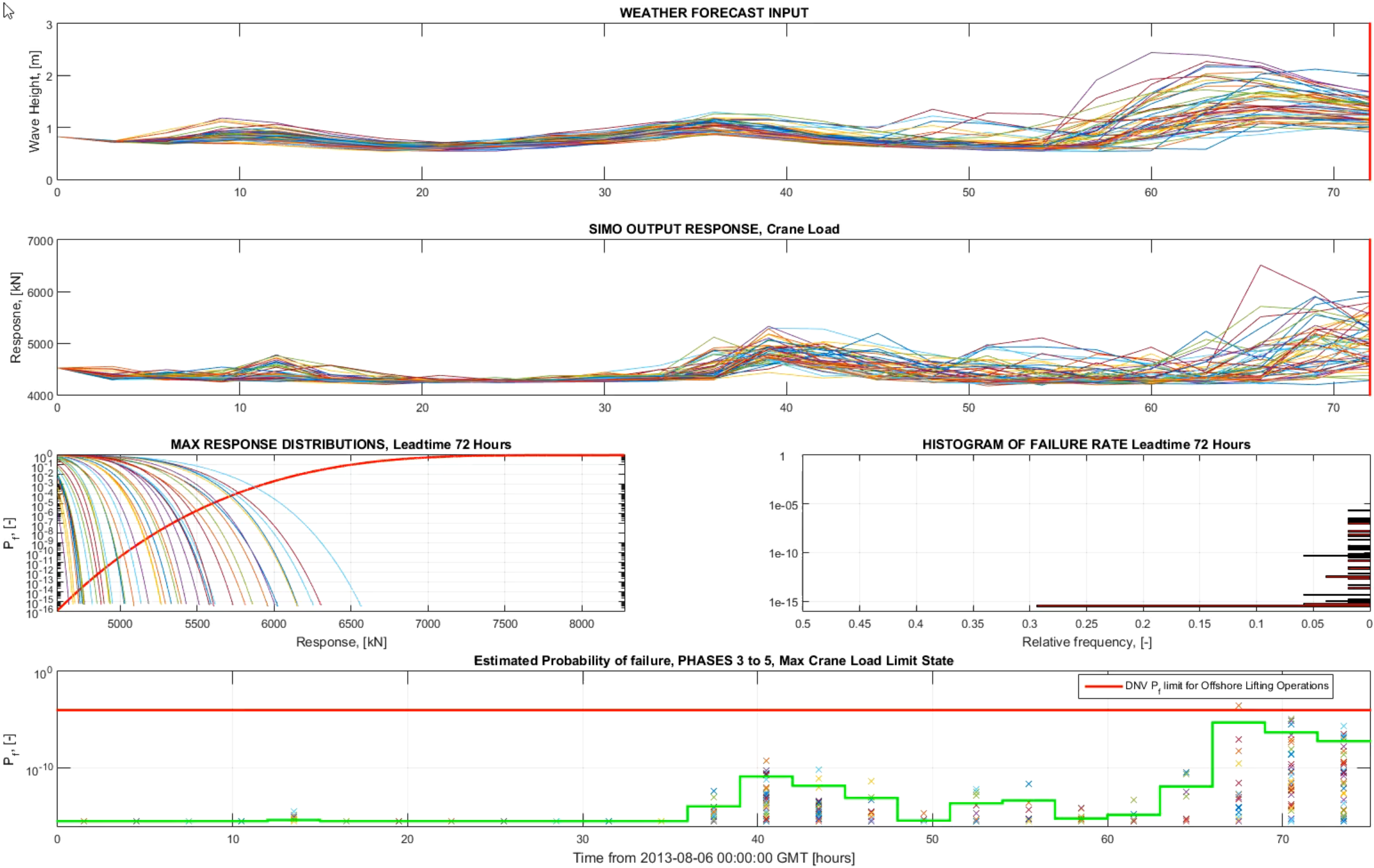
$$P_{F,Operation} = 1 - \prod_{i=1}^{N_{Lim\ States}} (1 - P_{F,\mathrm{Lim}\ State,i})$$

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

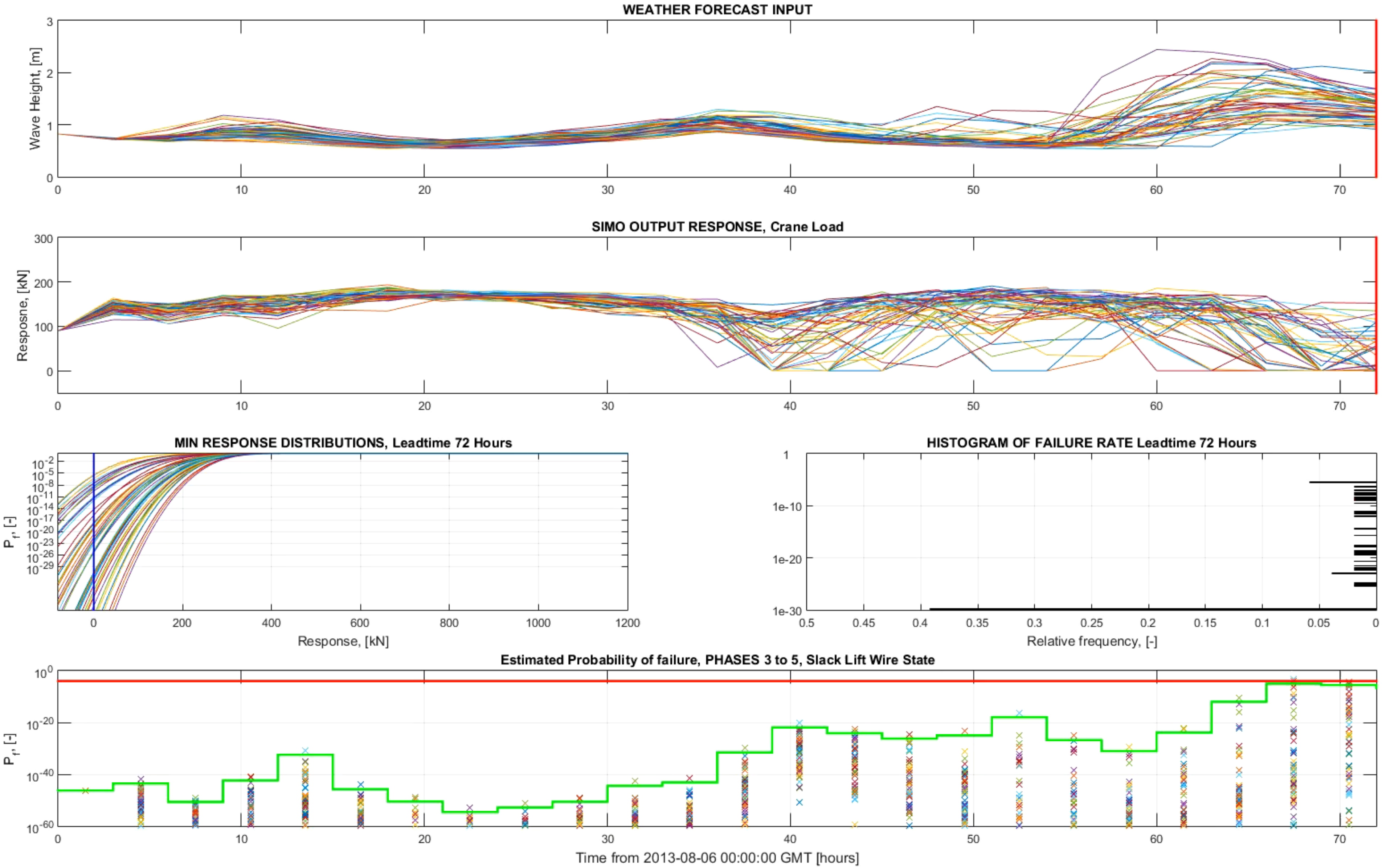




DEMO. Phases 3 to 5. Maximum Crane Load Limit State



DEMO. Phases 3 to 5. Slack Lift Wire Limit State



Operation Failure Probabilites

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

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

\+

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

\+

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

\+

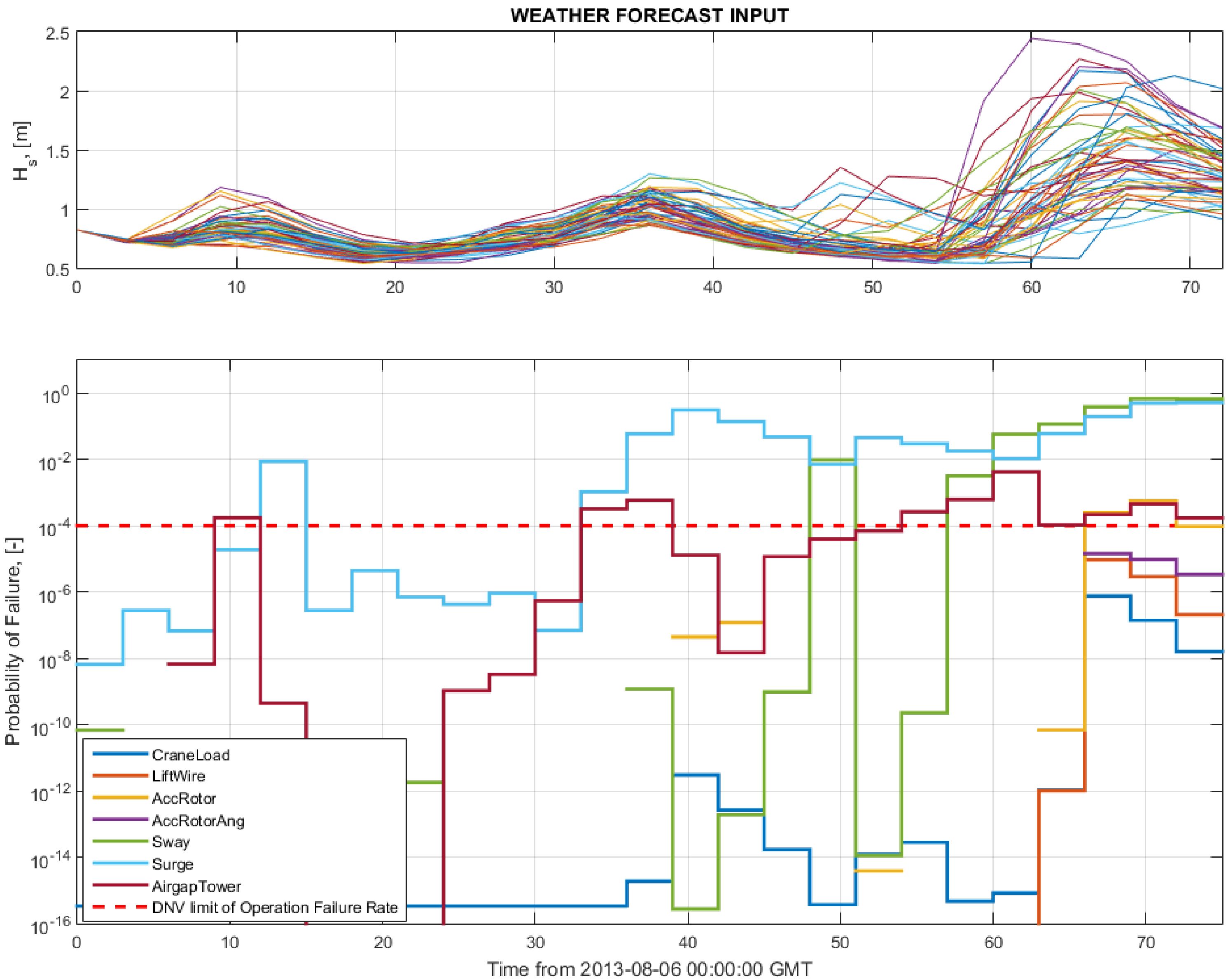
$P_{F,\ Acceleration,\ Ph\ 3} + P_{F,\ Acceleration,\ Ph\ 4} + P_{F,\ Acceleration,\ Ph\ 5} =$ $P_{F,\ Acceleration}$

\+ .... =

$P_{F,\ Operation}$

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

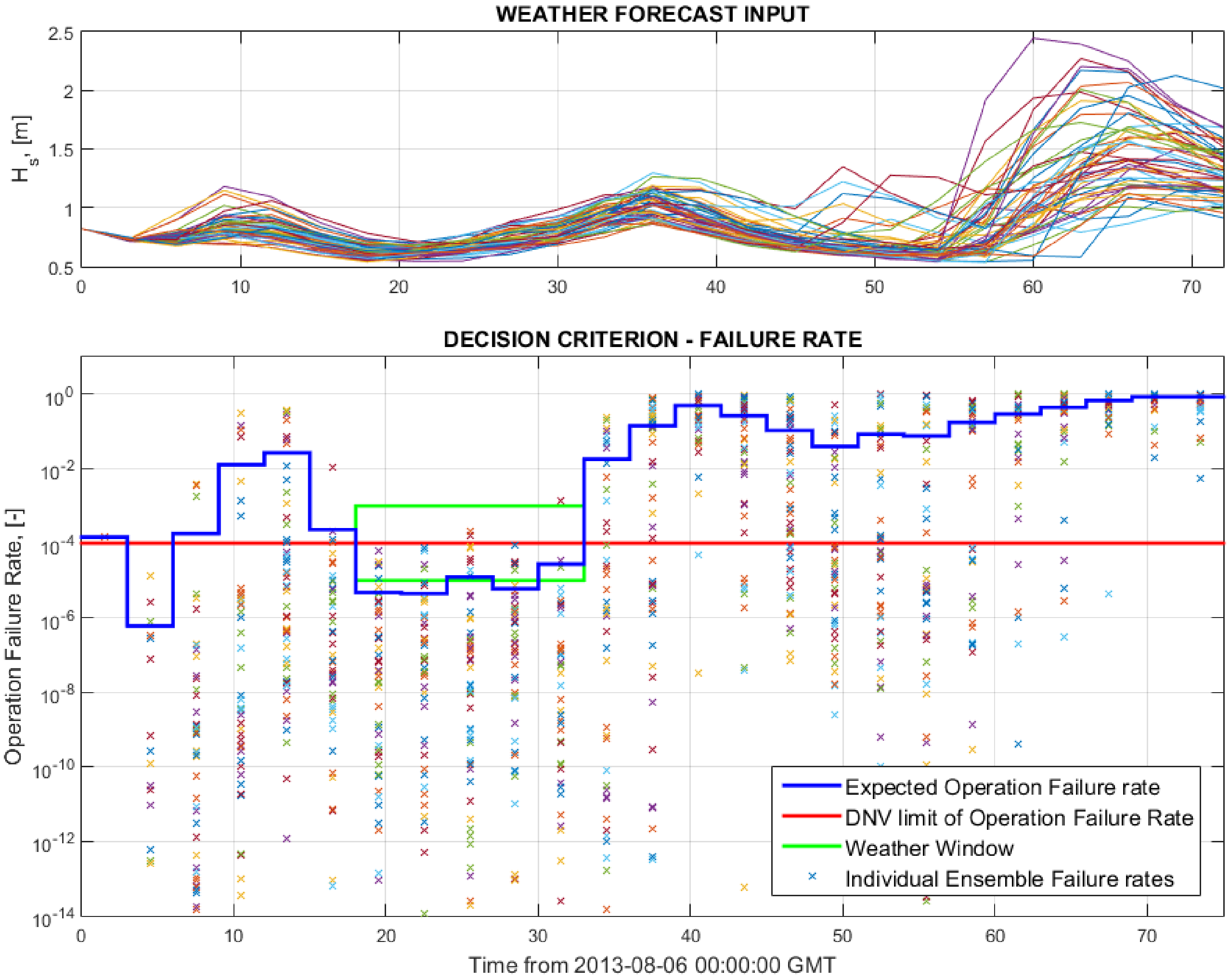
Limit state probabilities of failure



Operation Failure Rate

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

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:

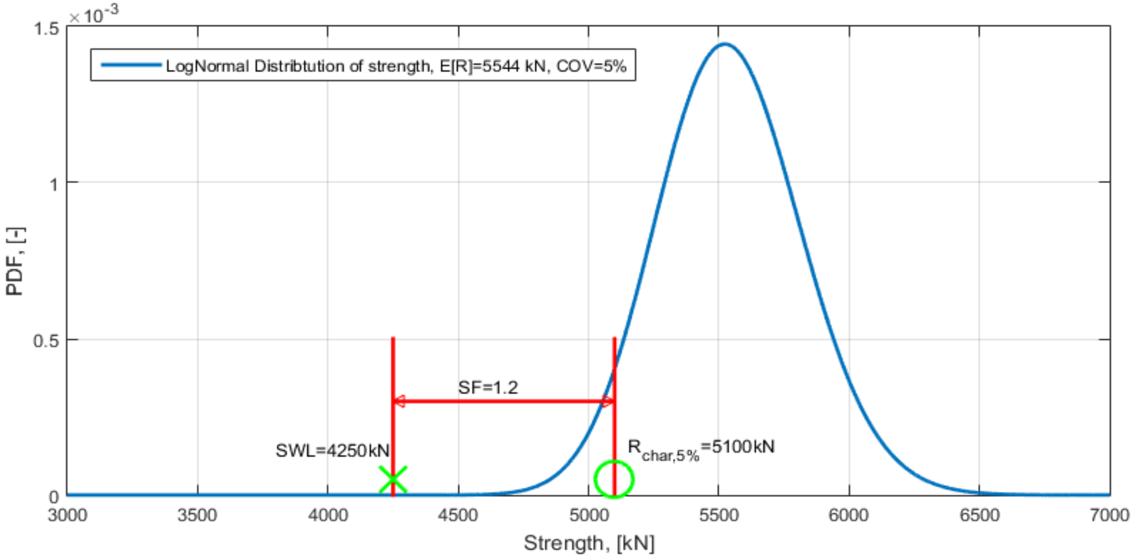
- Cost in NOK related to Operation Failure with a particular limit state.
- Cost in NOK of complete Operation Failure for less detailed analysis (one failure results in loss of all equipment and complete Operation Failure).

Insight on Safety factors for Acceptance limits

Crane load limit state involves Safe Working Load, which has a safety factor (SF) of 4-6 to account for material factors, skew loads, wear, end termination of slings etc.

It is possible to account for material strength uncertainties by using a distribution of material strength instead of a partial safety factor.

$$SF = \prod_{i=1}^{N_{factors}} \gamma_{prat,i}$$



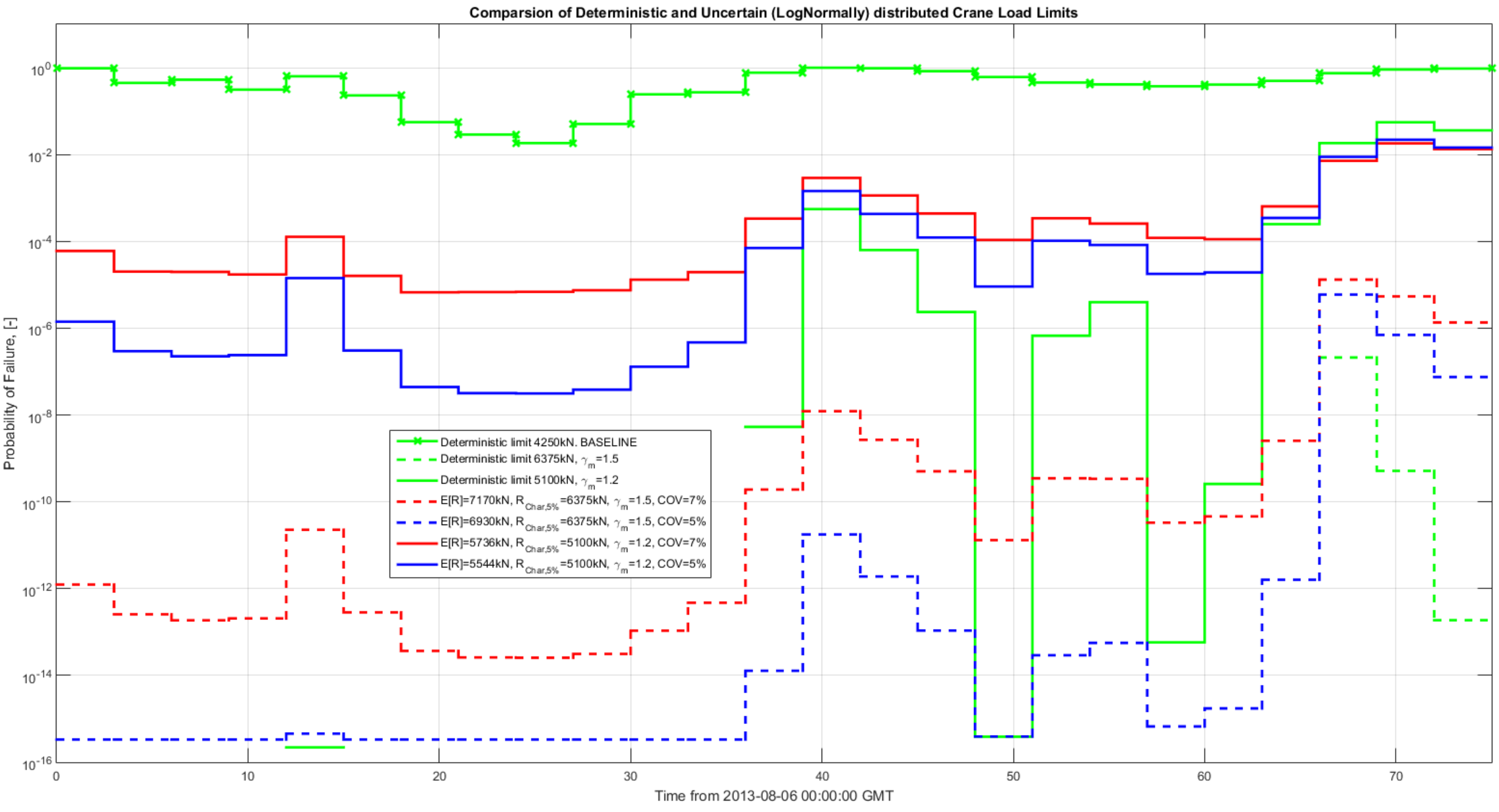
Safety factors for Acceptance limits. Sensitivity analysis

Sensitivity analysis was performed using most common LogNormal distribution for strength variation, safety factors were also varied.

Safety factor, [-]	Coefficient of Varation COV, [%]	Expected value of Strength, [kN]	Standard deviation of strength, [kN]	LogNormal Parameters		Characteristic strength, 5% quantile, [kN]
				μ_{LN}	σ_{LN}	
1.2	5	5544	277,2	8.619	0.05	5100
1.2	7	5736	401.5	8.653	0.07	5100
1.5	5	6930	346.5	8.842	0.05	6375
1.5	7	7170	501,9	8.875	0.07	6375

Typically, a partial safety factor of 1.2-1.5 is used for material strength (wire rope cable strength) and strength variation of 5-7%.

Results of sensitivity analysis



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.
- Although, due to lack of available information about the actual physical operational limits, it has to be noted that the example case only acts as a proof of concept.

- Using uncertain strength parameters and removing the material partial safety factors reduces the Probabilities of Failure.

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THANK YOU FOR YOUR ATTENTION!

ANY QUESTIONS? COMMENTS?

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