WHEN TRUST MATTERS

NorMoor JIP Phase 4

On Chain Reassessment & Life Extension

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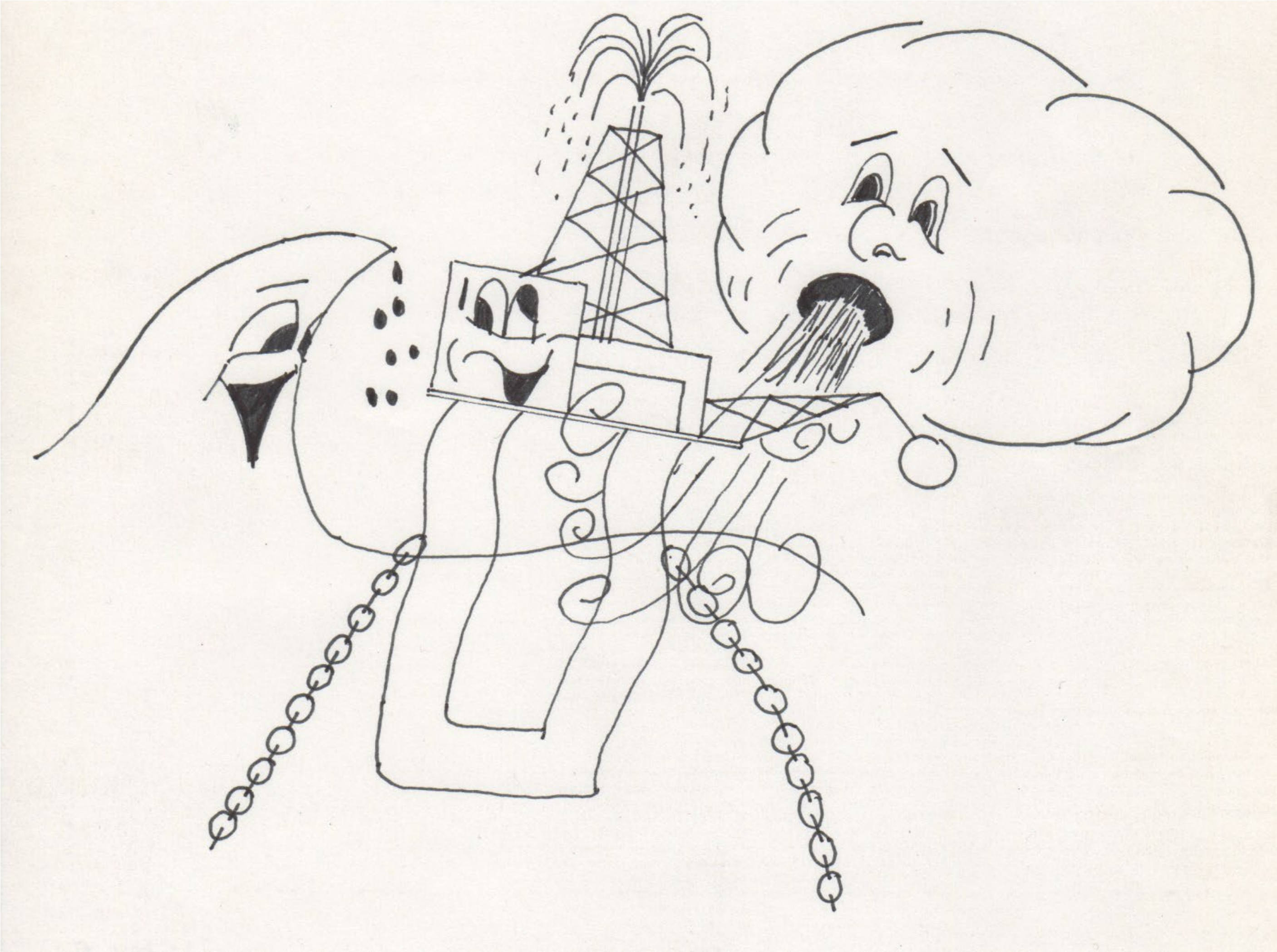
16 June 2022

The Challenge



Content

- NorMoor JIP
  - Background and objective
- Fatigue limit state (Phase 3)
  - Scope & recommendations
  - Feeds directly into the plans for Phase 4
- NorMoor phase 4
  - Life extension for mooring chain

NorMoor JIP – Background & Objective

- To ensure mooring system integrity:
  - Need a safe design to start with!!!

- Current status for mooring design:
  - Mooring standards are interpreted and applied in different ways
  - The safety level implied by the regulations is not known
  - The present safety factors were set when frequency domain analysis was prevalent

- Objective of the NorMoor JIP was to provide
  - a more consistent analysis methodology
  - calibrated safety factors for time domain

NorMoor JIP (2011 – 2024?)

- DNV initiated JIP
- Design requirements for ULS, ALS, FLS
  - Analysis methodology
  - Calibration of SF's
- Results from ULS and ALS implemented in DNV-OS-E301
- Phase 3 FLS completed May 2022
- Phase 4 On chain reassessment and life extension
  - Kick-off fall 2022

NorMoor JIP – test cases

- 7 different floaters
- 3 geographical locations:
  - Haltenbanken
  - GOM (not for FLS)
  - Brazil
- Water depths
  - 100-2100m depending on location
- Mooring systems applied:
  - Chain, chain+wire & chain+polyester
  - All designs are according to code requirements

NorMoor Scope for FLS

Analysis methodology for the tension history

- Environmental description
- Analysis options: FD & TD, length of analyses, marine growth, pretension, inst. tolerances etc.
- Damage prediction: Rainflow vs. closed form solutions

Improve the fatigue strength formulation

- Test data for new and used chain
- Mean stress and corrosion effects

New recommendation for

- design analysis & associated safety factor
- at a quantified target reliability level using structural reliability analysis

Mooring fatigue analyses

Hs [m]	Tp [s] 2	4	6	8	10	12	14	16	18	20	22
1		0.005	0.011	0.021	0.031	0.035	0.031	0.021	0.011	0.005	0.002
2			0.020	0.038	0.055	0.062	0.055	0.038	0.020	0.008	0.003
3			0.015	0.028	0.041	0.047	0.041	0.028	0.015	0.006	0.002
4				0.017	0.025	0.029	0.025	0.017	0.009	0.004	0.001
5				0.010	0.015	0.017	0.015	0.010	0.005	0.002	0.001
6				0.006	0.009	0.010	0.009	0.006	0.003	0.001	0.000
7					0.005	0.006	0.005	0.004	0.002	0.001	0.000
8					0.003	0.004	0.003	0.002	0.001	0.000	0.000
9					0.002	0.002	0.002	0.001	0.001	0.000	0.000
10						0.001	0.001	0.001	0.000	0.000	0.000
11						0.001	0.001	0.001	0.000	0.000	
12							0.000	0.000	0.000	0.000	
13							0.000	0.000	0.000		
14								0.000	0.000		
15								0.000	0.000		

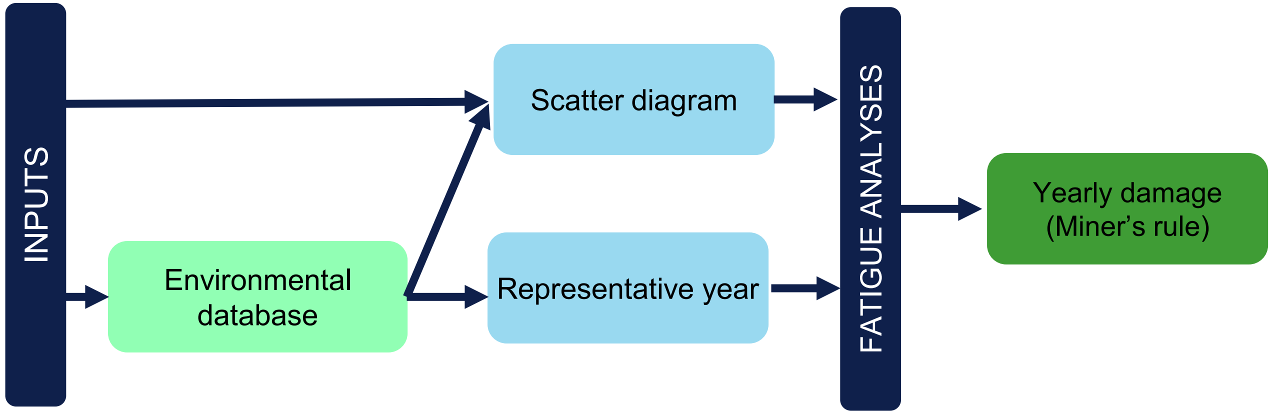
Scatter Diagram

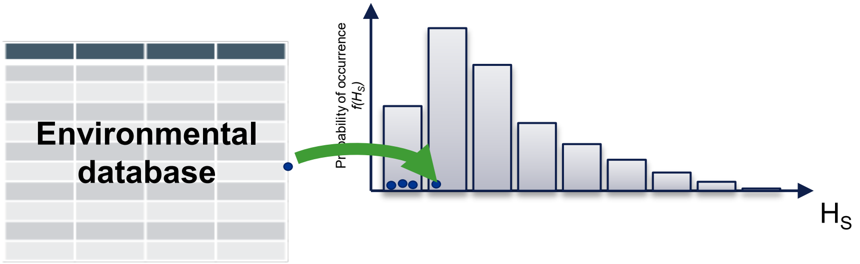
Calculated from the environmental database

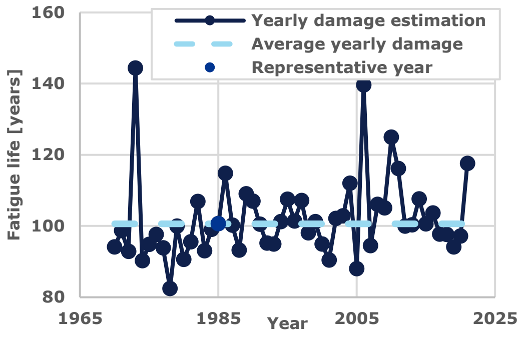
- H_S, T_P and wave direction
- For each cell, wind and current shall be assumed

Importance sampling

- Analysis cases selected using a sampling function
- Targeted computational effort
  - converged for 1000-2000 seastates
- The closer to the damage distribution, the less statistical error
- The sampling function does not affect the predicted damage



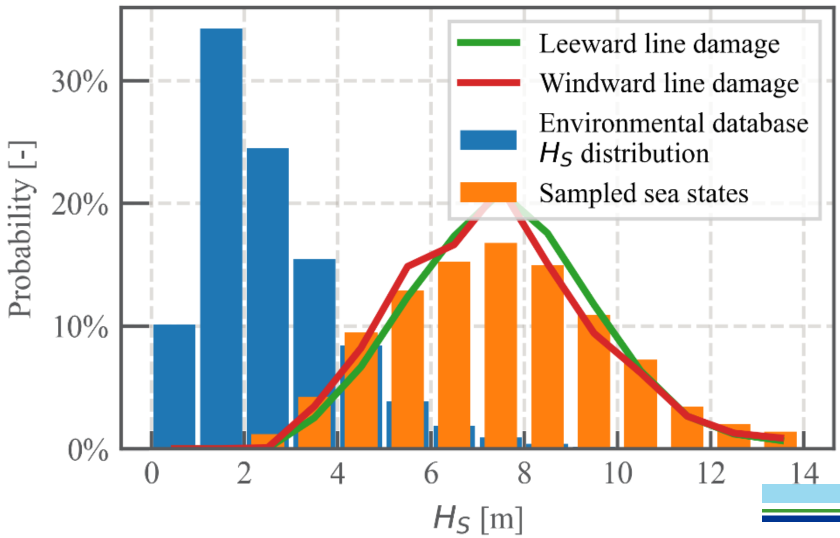




Representative year

Calculated using

- Damage indicator – often H_S^3 - H_S^6
- But, is the selected year really representative?



Fatigue strength formulation

- **Fatigue strength, present codes**:
  - Fatigue test data for new chain, tested with mean load of 20% of the minimum breaking load

- **NorMoor JIP Phase 3**:
  - Test data for new and used chain
    - Different mean load levels (stress)
    - Different degree of corrosion (pitting corrosion)
  - Fatigue strength modelled as a function of:
    - Mean stress
    - Corrosion category
  - Applied this strength model in the code calibration

Source	Number of tests	Grade	Diameter (mm)	New/Used
Noble Denton JIP	26	R3 (14), R4 (12)	76	New
TWI JIP	22	R4 (6), R5 (16)	76, 127	New
Vicinay	25	R3 (1), R4 (9), R4S (1), R5 (13), R6 (1)	70 - 171	New
Equinor	78	R3 (9), R4 (69)	114 - 152	Used
FOCCs JIP	6	ORQ (2), R3 (1), R4 (3)	76 - 130	Used
Vår Energy	4	R4	92	Used
Total	**161**			

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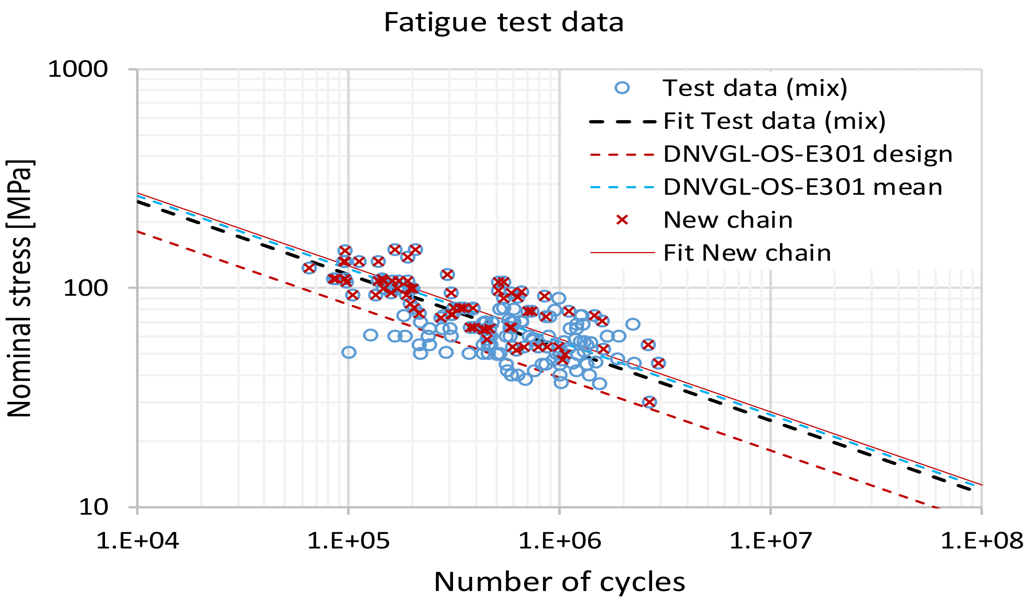
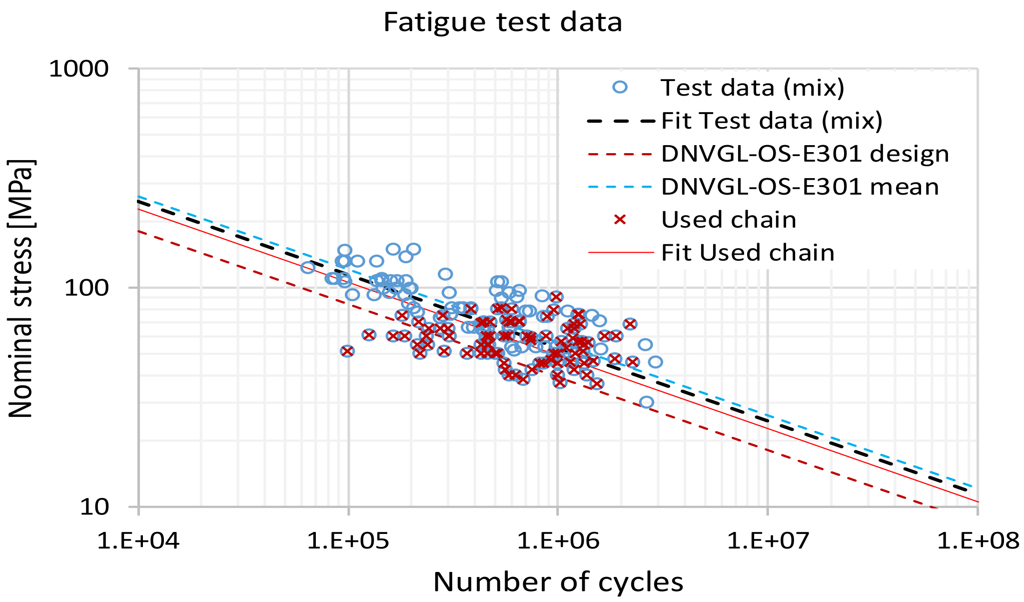
Raw test data, illustration

New chain



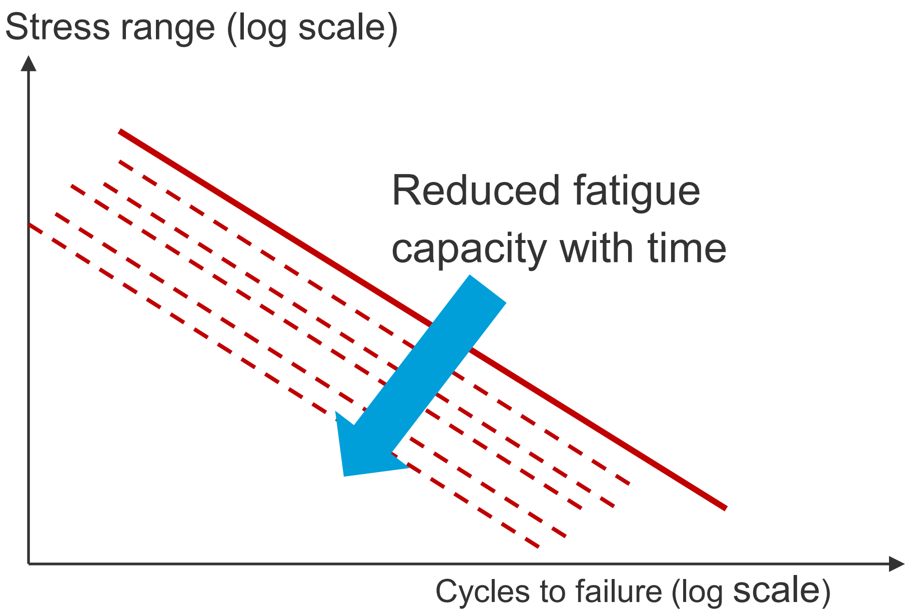
Used chain



Degradation effects & mean load (stress) effects

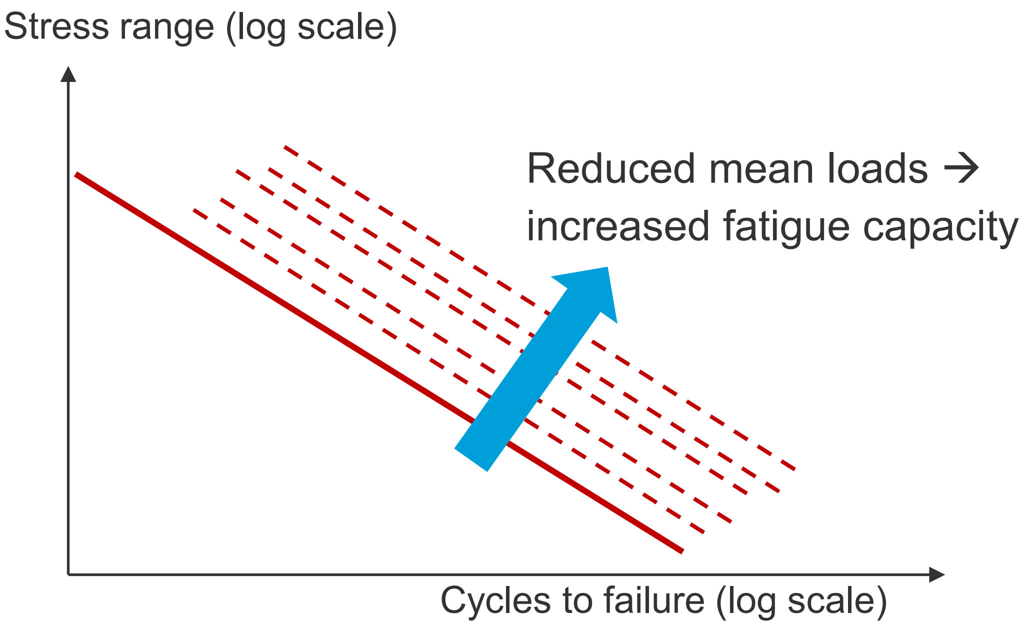
Degradation with time:

- Can be modelled by reducing $logA$ with time



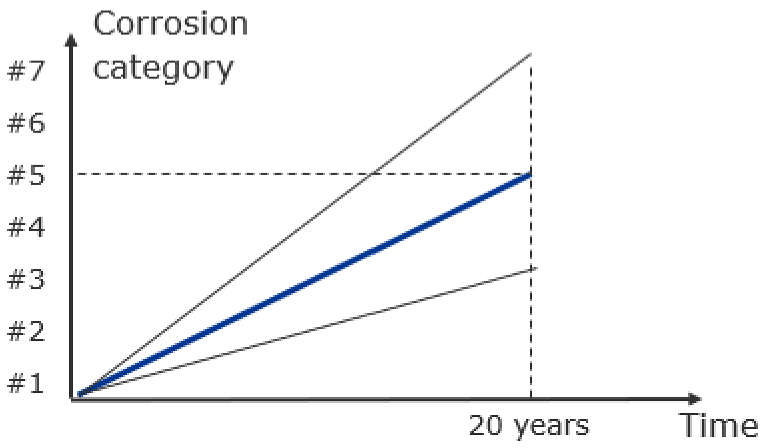
Mean load effect:

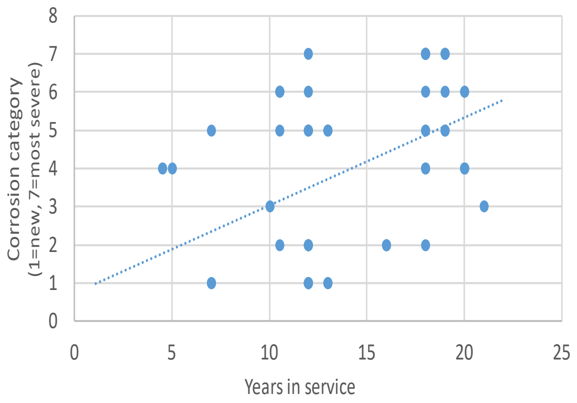
- Reduced mean loads → increased fatigue capacity
- Can be modelled by mean stress dependent $logA$

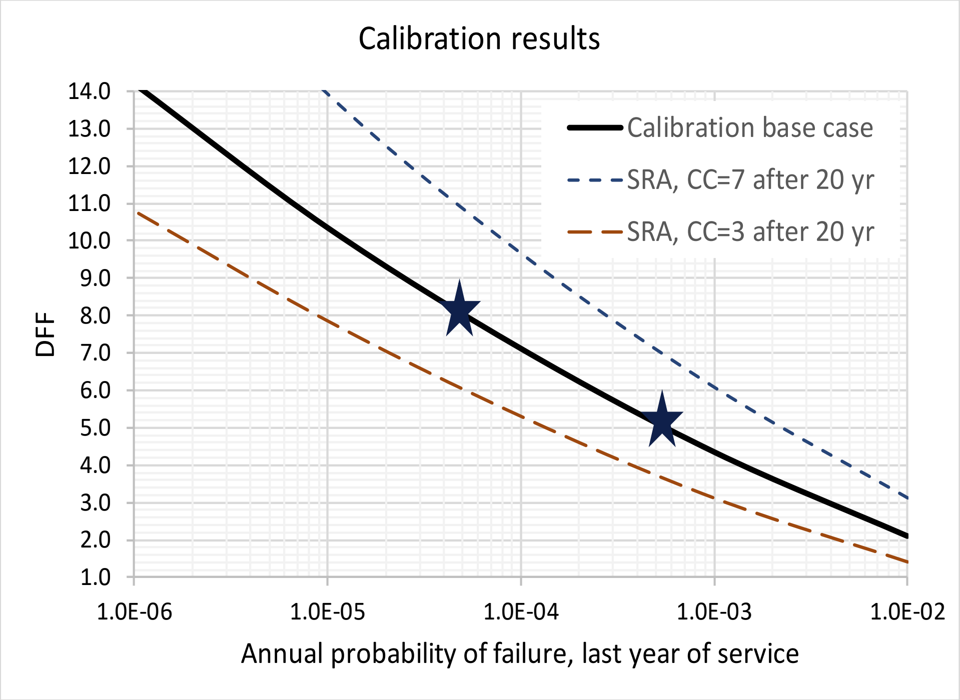


Calibration results for different corrosion assumptions

- Recommendation assumes:
  - corrosion category 5 in year 20
  - linear development of the corrosion
- A more pessimistic assumptions on the development of corrosion leads to increase in the required safety factor







Recommendation
OMAE2022-81463

- Design equation:

New

$$1 - d_C \cdot DFF \cdot \underbrace{DF_{mean} \cdot DF_{method} \cdot DF_{heading}}_{\text{New}} \geq 0$$

d_C : Characteristic accumulated fatigue damage during the design life calculated using present S-N curve in DNV-OS-E301

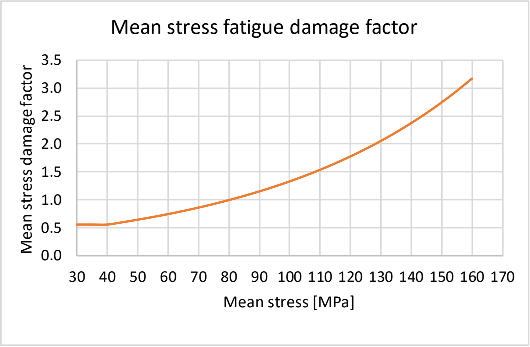
$$DFF = 5 \qquad when\ d_F \leq 0.8$$

$$DFF = 5 + 3\left(\frac{d_F - 0.8}{0.2}\right) \qquad when\ 1.0 \geq d_F > 0.8$$

where d_F is the damage ratio between adjacent lines

- The new recommendation:
  - Average savings based on our test set is 7% on the chain area.
  - Assumed corrosion condition 5 after 20 years

$DF_{mean} =$



DF_{method} method on environmental modelling (representative year)

$DF_{heading}$ factor used if mean stress is based on pretension

NorMoor Phase 3 papers

1. OMAE2022-81441: **Mooring Fatigue Damage Prediction Based on Importance Sampling**
    - Importance sampling method description
    - comparison to scatter diagram and representative year approach

2. OMAE2022-81465: **Analysis of Chain Fatigue Test Data for New and Used Mooring Chains**
    - Analysis of the chain fatigue test data
    - Fatigue strength description as a function of mean stress and corrosion category

3. OMAE2022-81463: **Recommendations for a Fatigue Design Analysis Calibrated Using Structural Reliability Analysis**
    - Summary paper for Phase 3 describing
        - The structural reliability analysis and calibration
        - The recommendation for fatigue analyses and associated safety factors

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NorMoor JIP – Phase 4

On chain reassessment

&

life extension

NorMoor phase 4 - Motivation

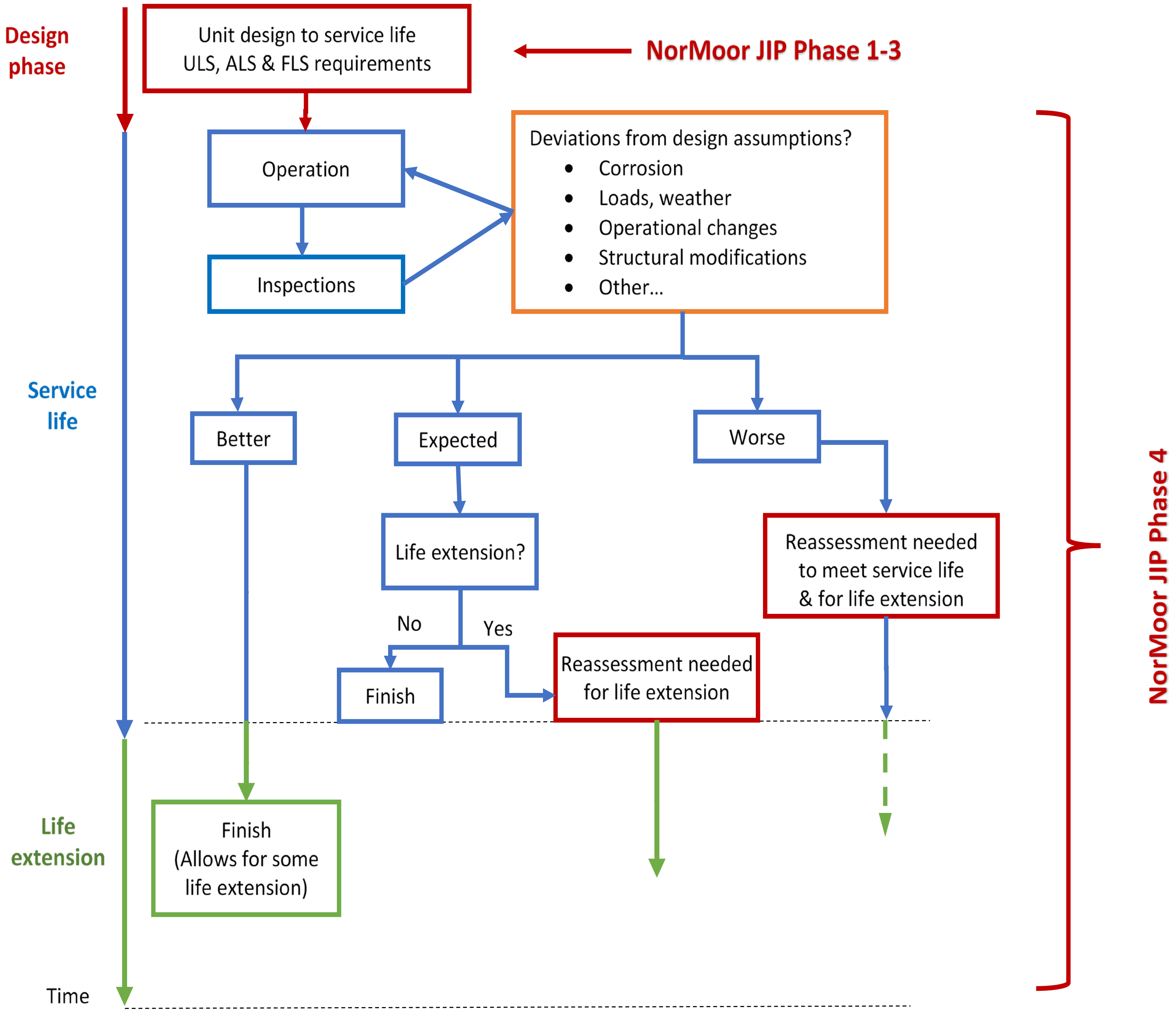
- The age of the worlds production units is growing
  - Life extension will require reassessment of mooring chains to predict future degradation
- Reduce conservatism when estimating fatigue damage and life extension
  - This implies prolonged life for an existing mooring system compared to a more conservative approach.
  - As an example, for a 16-line system the savings per facility for life extension are:
    - Life extension 2 years: 3 million $ saved
    - Life extension 5 years: 7.5 million $ saved

- Meet needs within offshore floating wind:
  - Fatigue of mooring chain is a significant value driver
  - Degradation models and methodology for reassessment important

Utsira Nord
1.5GW = 100 turbines
~ 360km mooring line length (Rotterdam - Paris)
~ 20 FPSO projects
Each meter length needs correct quality

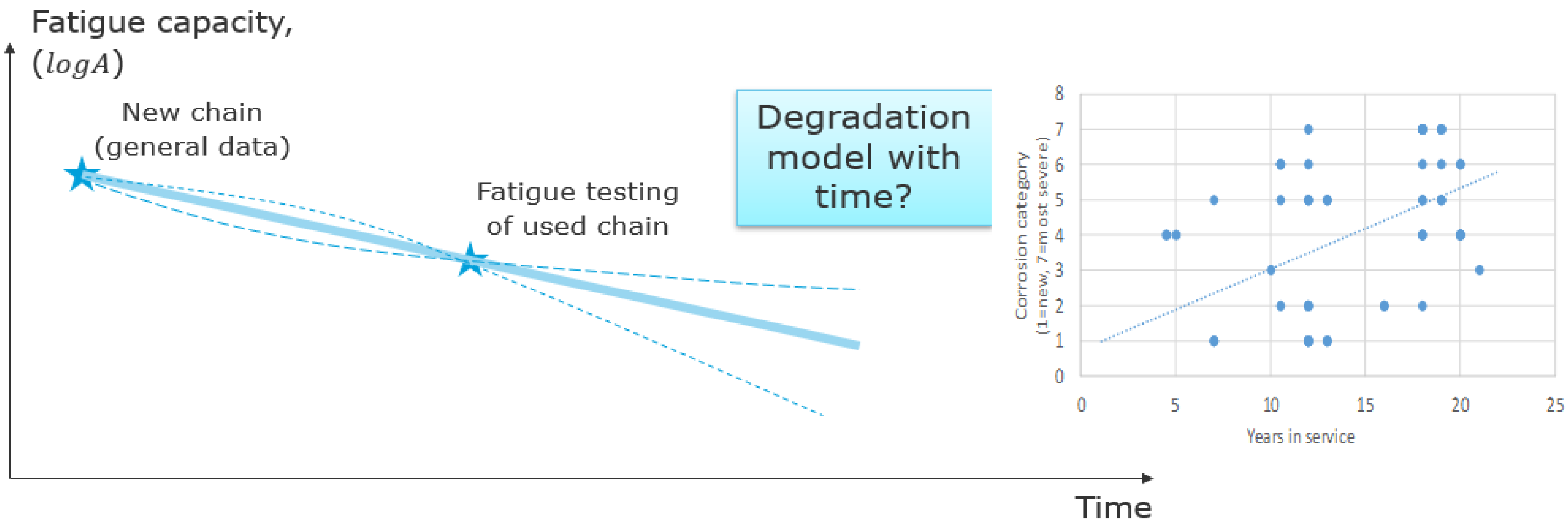
Reassessment

- For life extension
- To meet service life



Degradation model

- The industry needs a degradation model for chain reassessment
- Several options may be studied
- One option is to consider reducing $logA$ with time, this includes
  - Asses the current condition of the chain
    - Preferably by fatigue testing
    - By inspection (corrosion, surface condition)
  - Extrapolate into the future



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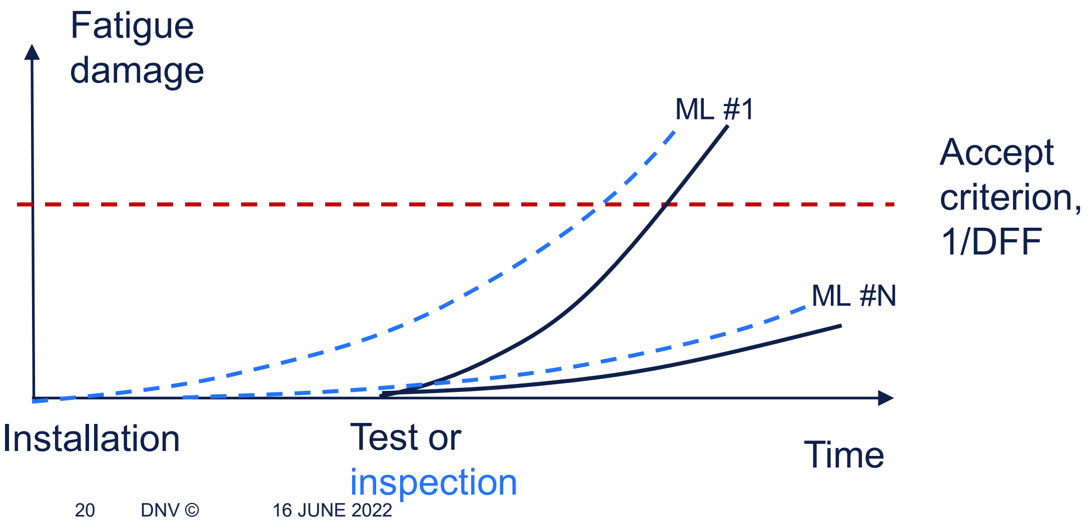
Calibration of reassessment methodology (illustration)

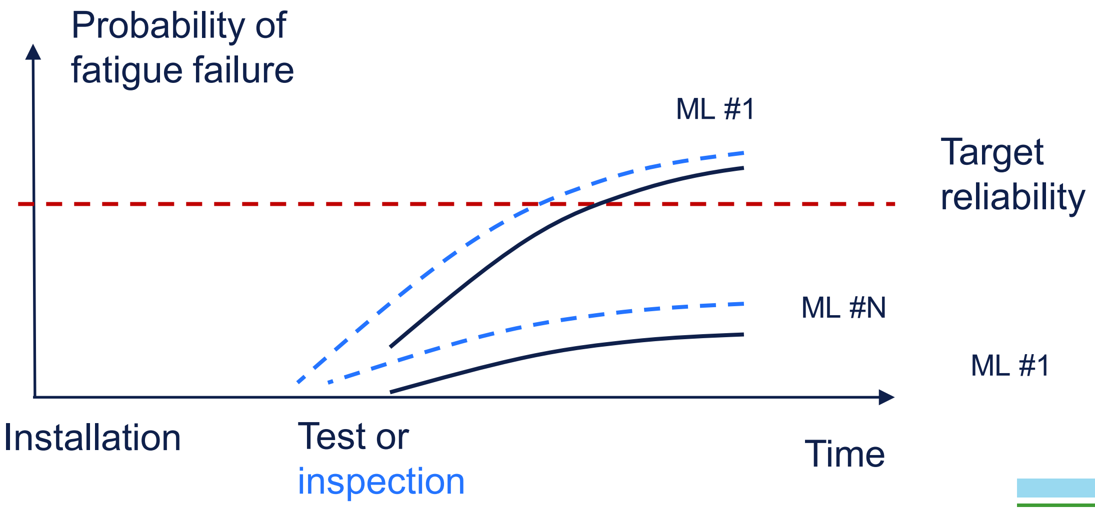
- In the JIP we will
  - Calibrate the methodology for reassessment, at target reliability level
  - utilise fatigue strength degradation model, accounting for mean load and corrosion

Identify when replacement is required for which line and how long segment of that line.

Deterministic analysis guide



Calibrated by structural reliability analysis



Reassessment – the challenge

For life extension and reassessment of chain an established industry practice is needed

How to calculate year of replacement?

Which line and line segment needs to be replaced – and when?

Is it sufficient to inspect your mooring lines?

- How to evaluate inspection results
- Pitting, corrosion and wear

When do you need to test your chains?

- How to use the fatigue and strength test results
- Shall previous tension history be included when recalculating fatigue life based on the tests?

What to do if loads have changed compared to design assumptions

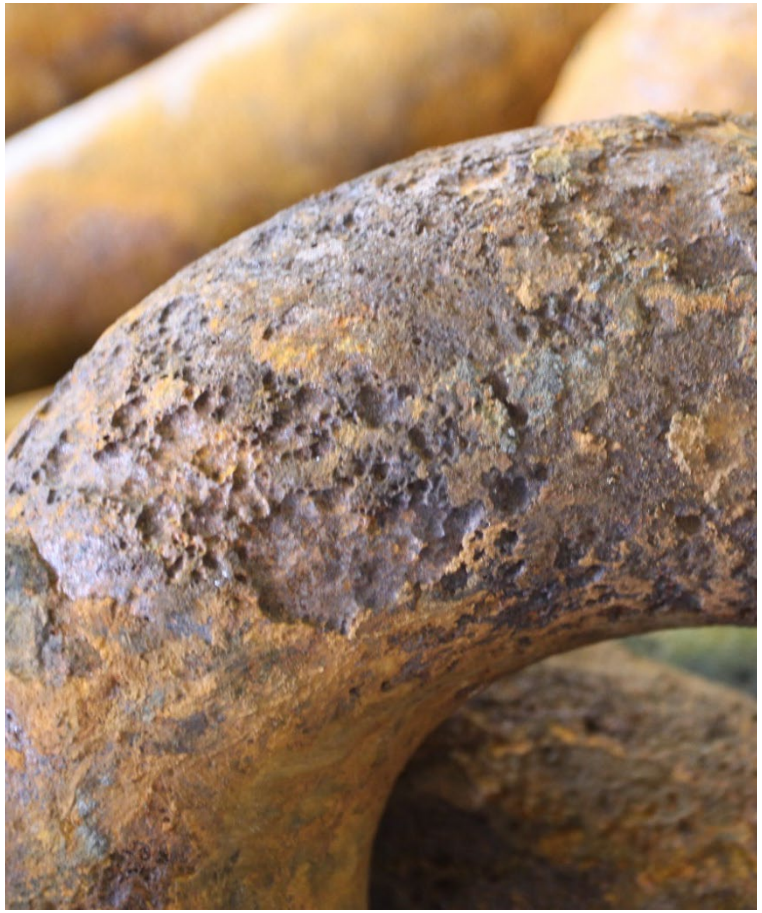
Join NorMoor JIP Phase 4?

The NorMoor JIP have since the kick-off in 2011 successfully

1. Updated design requirements for ULS, ALS and FLS
2. Consistent analysis methodology
3. Safety factors calibrated at an appropriate, quantified, target reliability level

Phase 4:

- Need good guidance for the operation phase:
  - Lack of a methodology for reassessment of chain & criteria for chain replacement in today's rules and regulations
  - Equally important for all moored floating units, oil & gas units, floating wind etc.
- Phase 4 participants to date:
  - Confirmed: Equinor, Neptune Energy & Aker BP
  - Petrobras, Shell, BP and SBM are positive
  - New participants are welcome!
- Kick-off: fall 2022



Thank you!

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Proposal for a Joint Industry Project

NorMoor JIP Phase 4

Table of Contents

1 BACKGROUND

For an offshore unit it is important to ensure that the design is safe and sound during its entire service life. This is ensured by designing the unit towards the requirements for 3 limit states[1]; ULS ALS and FLS. And further by follow up the unit during its entire service life, see Figure 1-1.
The NorMoor JIP have since the kick-off in 2011 successfully updated the requirements for the 3 limit states and established a mooring design code with a consistent analysis methodology and with safety factors that are in line with this methodology and calibrated at an appropriate target reliability level. This work is now completed, and the results provide a basis for regulators, such as ISO, to update their rules for all three limit states.
Now with the design requirements updated, the natural next step is to look at the operational phase. During the operational phase the design assumptions may change. The metocean conditions turn out to be more severe than applied in design analyses, inspections reveal more corrosion than assumed in design etc. or the initial assumed design life is extended. These issues need further guidance in the industry.
More work is needed in order to ensure a good guidance on how to solve potential challenges during operation and for life extension assessment, e.g. how to reassess mooring chain fatigue capacity, and how to define criteria for replacement of mooring chain. A methodology for reassessment of chain accompanied by criteria for chain replacement is lacking in today's rules and regulations and is suggested as further work in this Phase 4 of the NorMoor JIP.

The methodology developed in this Phase 4 will be equally important for all moored floating units, for floating oil and gas units, floating wind, fish farms etc, see more in sec. 1.1.

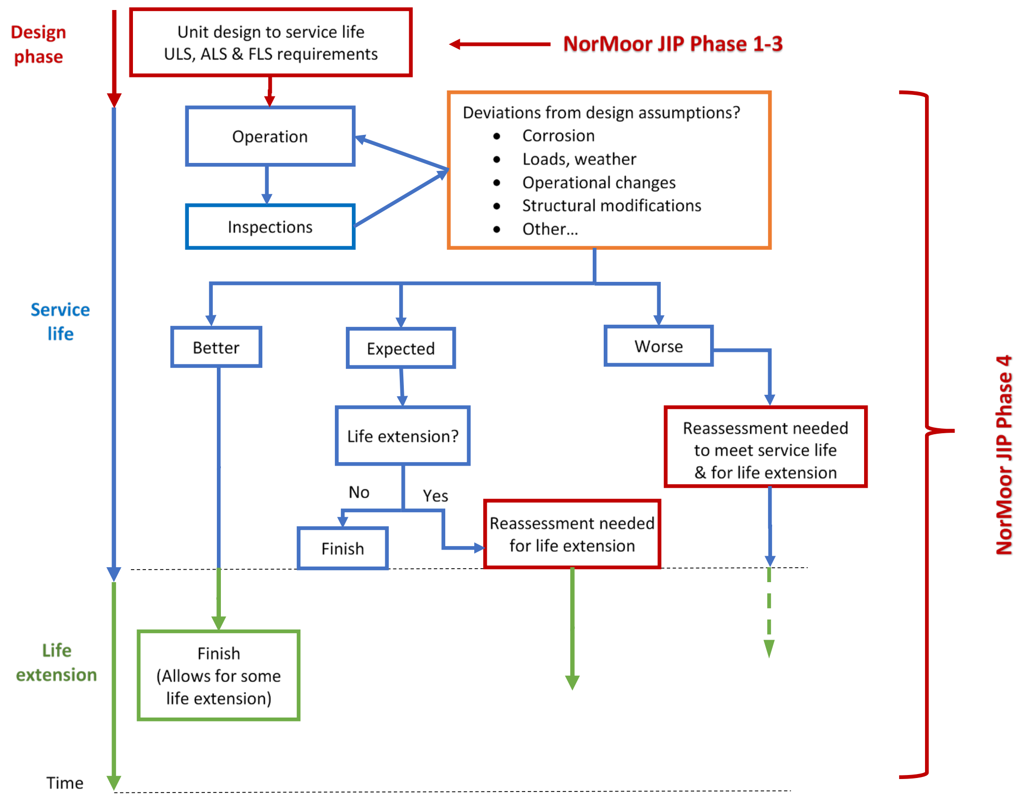

Figure 1-1 The design, operation and life extension of mooring chains

1
1. Ultimate limit state (ULS) – capacity requirements for intact mooring system
2. Accidental limit state (ALS) – capacity requirements for damaged mooring system
3. Fatigue limit state (FLS) – capacity requirements to withstand cyclic loading

1.1 Why NorMoor JIP Phase 4?

The age of the fleet of the world's production units is growing, and fatigue is the governing limit state for life extension. Furthermore, as part of the energy transitions the focus on floating wind is escalating. Commercial scale wind parks are being planned with several hundred individual mooring lines, and safe and efficient mooring of floating wind turbines are essential to keep production availability at desired levels. For floating wind mooring, fatigue of the mooring lines is governing for the design, and therefore also for life extension for these systems.

While Phase 3 of the NorMoor JIP was an important step to improve the design requirements for FLS, life extension will further require a reassessment of the mooring chains in order to predict future degradation.

When a unit is reaching its design life it is necessary to perform a condition assessment of the mooring chains and reassess the fatigue capacity to see if life extension can be achieved with the existing mooring system. However, a methodology for reassessment of chain accompanied by criteria for chain replacement is lacking in today's rules and regulations and is suggested as further work in this Phase 4 of the NorMoor JIP.

The results and deliveries from Phase 1, 2 and 3 of the JIP have shown that more cost-effective mooring systems can be obtained, without jeopardizing the safety level. Now in Phase 4 by developing methodology for reassessment of mooring systems based on state-of-the-art degradation models for chain in combination with mooring fatigue analyses we will:

- Reduce conservatism when estimating fatigue damage and life extension. This implies prolonged life for an existing mooring system compared to a more conservative approach. As an example, for a 16-line system the savings per facility2 for life extension are:
    - Life extension 2 years: 27 MNOK saved
    - Life extension 5 years: 72 MNOK saved
- Meet important needs within offshore floating wind development. For wind farms fatigue of mooring chain is a significant value driver, and degradation models and methodology for reassessment are therefore of particular importance.

1.2 Objective

The main objective of the recommended further work in a phase 4 of the NorMoor JIP is to:

- Develop a methodology for reassessment and life extension of mooring systems based on fatigue capacity from a limited number of unit specific fatigue test results and inspection in combination with mooring fatigue analysis.
- Establish criteria for when chain replacement is required for a specific line and sub-segment of line.

[2] Typical North sea system at moderate water depth, and suitable for changing the mooring lines (winches on-board the facility). Cost of engineering, wire rope and shut down not included. Based on 1000 m chain per line, 10 MNOK each, and new anchors, 2.5 MNOK each. Anchors installed first, day rate 2MNOK. Chain installation, day rate 1 MNOK. Assumed installation time is 1 day per line and anchor and 3 days mob/demob for each. I.e. total installation time for a 16 line system is 38 days. Based on net present value at interest rate 5%.

2 PROJECT DESCRIPTION

In Phase 4 of the NorMoor JIP a methodology will be developed for how to best carry out and utilise fatigue test data and chain inspection in combination with mooring analyses for a specific installation for reassessment and life extension. An industry practice for this purpose is not yet established.

Phase 3 of the NorMoor JIP has got access to and utilized a large amount of fatigue test data for both new and used chain. A quantification of the degradation of the fatigue capacity depending on the state of corrosion has been possible and shown to be significant. Analyses of the test data for used chain also show that the degradation with time is highly uncertain, and varies significantly from one geographical location to another, for different mooring lines and locations along the same line within a mooring system and for variations in the chain material composition. The effects from such variations are difficult to foresee up front for an actual case.

Thus, careful considerations are needed, and it is important to ensure that appropriate methodology and acceptance criteria are applied such that the maximum benefit from improved knowledge from testing and inspections is taken, without compromising on safety. It is the intention to maintain and benefit from contact and cooperation with the LifeMoor project if LifeMoor continues with its 2nd phase.

2.1 Degradation modelling

Key input for estimating the degradation in the future will be the condition and corresponding fatigue test of the used chain. Different degradation modelling approaches will be explored and evaluated towards the test data to the extent possible.

A starting point will be to model the degradation with time by a reduction in $logA$ estimated from the difference in fatigue strength derived from tests of the used chain versus relevant data for new chain (fatigue test data from the actual chain when it was installed are unlikely to be available).

Models, linear or non-linear, for degradation with time by reducing logA are illustrated in Figure 2-1. To the right in Figure 2-1 it is illustrated that the degree of corrosion, categorised from 1 (new) to 7 (most severe), does not fit well to a function of time. Therefore, specific fatigue testing of the used chain in the actual mooring system is strongly advised.

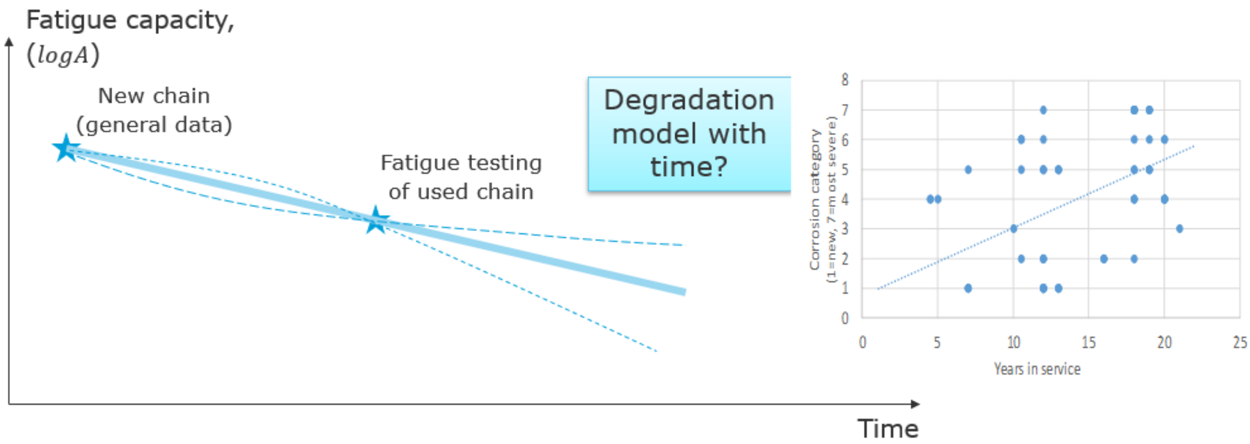

Figure 2-1 Degradation models with time, by reducing $logA$.

2.2 Reassessment methodology

Since the degradation of chain is case and location dependent, specific fatigue testing of the used chain in the actual mooring system will always give the most reliable result.

However, it is not always possible or desirable to collect test samples for the actual case. It would therefore be beneficial in such cases, and as an initial assessment while waiting for the test to be carried out, if we could establish a conservative approach based on inspection of the actual chain and generic fatigue strength data for used chain. This approach could then be supported by fatigue tests for the actual case if the desired life extension is not achieved or if improved results are required, including determination of year when replacement might be needed.

Thus, the plan is to establish a two-step procedure for the reassessment of the chains. A) based on visual inspection and measurements for the actual chain and generic fatigue strength data for used chain, and B) based on fatigue testing of the actual chain. This is illustrated in Figure 2-2

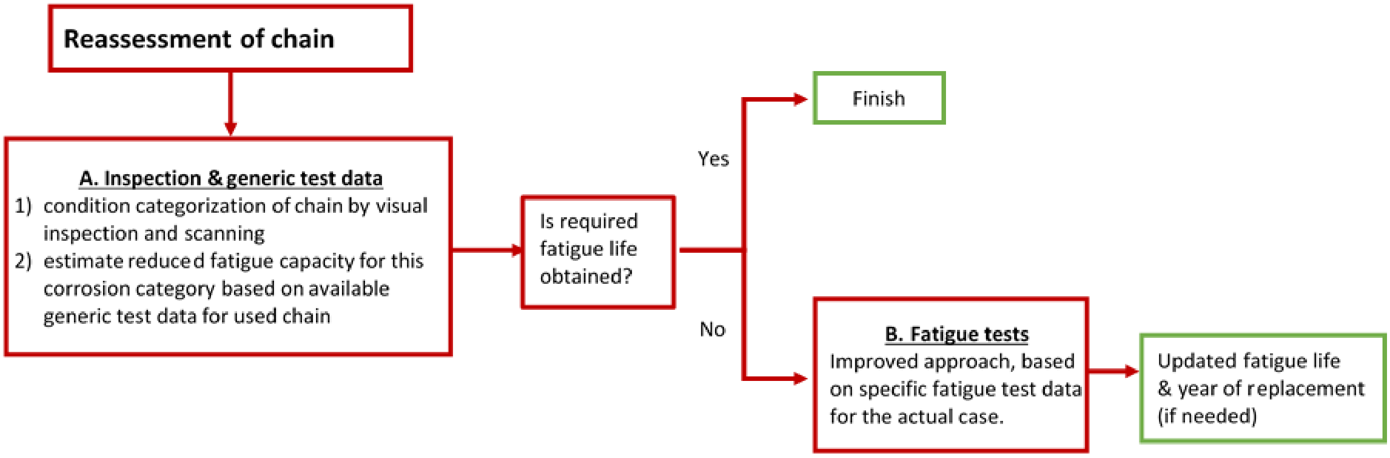

Figure 2-2 Reassessment of chain, conservative approach A and refined approach B.

2.3 Scope of work

The following tasks are proposed and includes both description and example analysis of a selected case. This depends on the willingness from PARTICIPANTS to share data.

1. **Fatigue capacity:**
   Describe how the fatigue capacity of used chain can be derived from a limited number of fatigue test results and used for reassessment or life extension. This includes guidance on the selection of chains for testing will be provided, e.g.: from which mooring line and which part of the mooring line and can similar degradation (conservatively) be assumed for the other lines. Considerations with respect to degradation and wear as well as historical loading need to be made. The effect of statistical uncertainty due to limited number of tests will be evaluated and studied as part of the structural reliability analysis. Benefit from the database of fatigue tests data of new and used chain with different mean loads and different corrosion category analysed, as analysed in phase 3 of the JIP, will be utilised when predicting a degradation model into the future.
   Fatigue capacity corresponding to step A) based on inspection and scanning, without testing, will also be part of this task.

2. **Breaking strength:**
   Describe the assessment of chain breaking strength based on a combination of strength test results and geometry measurements. Wear below or beyond standard replacement requirements will be discussed (e.g.: for chain in the touch-down area), and the corresponding reduction in breaking

strengths evaluated. It is of interest to study how well the actual breaking strength can be determined based on geometry measurements, and the hope is that any available test data from JIP PARTICIPANTS can be made available to the project and serve as support for the guidance that will be developed.

3. **Mooring analysis:**
   Results from mooring fatigue analyses are to be used as input to the reassessment procedure. This includes both extreme load and fatigue. The effect of mean tension on fatigue will be considered, and the tension variation along the mooring line between fairlead and anchor will get attention, and load reduction in the chain mooring line on the seabed due to bottom friction will be analysed.

4. **Reassessment approach for fatigue:**
   Based on the above bullet points, the implementation and acceptance criteria for chain replacement will be described with respect to fatigue. This will include estimates of the future development of the fatigue strength, and inspection regarding wear and corrosion should be part of a condition monitoring program to confirm development in line with estimate and detect any abnormal developments. The acceptance criteria will be established in parallel with the structural reliability analysis described in task 5 and the calibration in task 6. If the results from the reassessment shows that chain replacement is needed after a certain number of years, further testing might then be considered as an alternative prior to replacement, which in turn might allow for further delay of the replacement. One topic for consideration is to what extend the fatigue strength based on the test results are sufficient to neglect fatigue damage contribution from the years before testing, i.e., restart the damage accumulation from zero or not after testing.

   Illustration of the reassessment methodology: The overall principle for the suggested reassessment procedure is illustrated in Figure 2-3 with a fictitious example. The upper left chart shows a red square which is $logA$ from tests. The $logA$ as a function of time here follows a linear curve, and the starting point is the red dot which is an estimated fatigue strength of the chain when new. The blue line refers to present practice, with a design $logA$ from the standard. The lower left figure illustrates the annual fatigue damage using the two models. It is seen how the annual damage increases with time when using the degradation model. The figure to the right shows the accumulated fatigue damage as function of time based on the annual fatigue damages from all years. The grey curve shows a re-start of the fatigue damage accumulation after the testing, under that argument that the fatigue tests provide the fatigue capacity for the *remaining* life, whereas the orange curve shows damage accumulation including the history. Results can be calculated for each mooring line and for several sub-segments along each mooring line where reduction in the tension towards the anchor for the part lying on the seabed is accounted for. A replacement plan can then be made for which part of which line that needs to be replaced when.

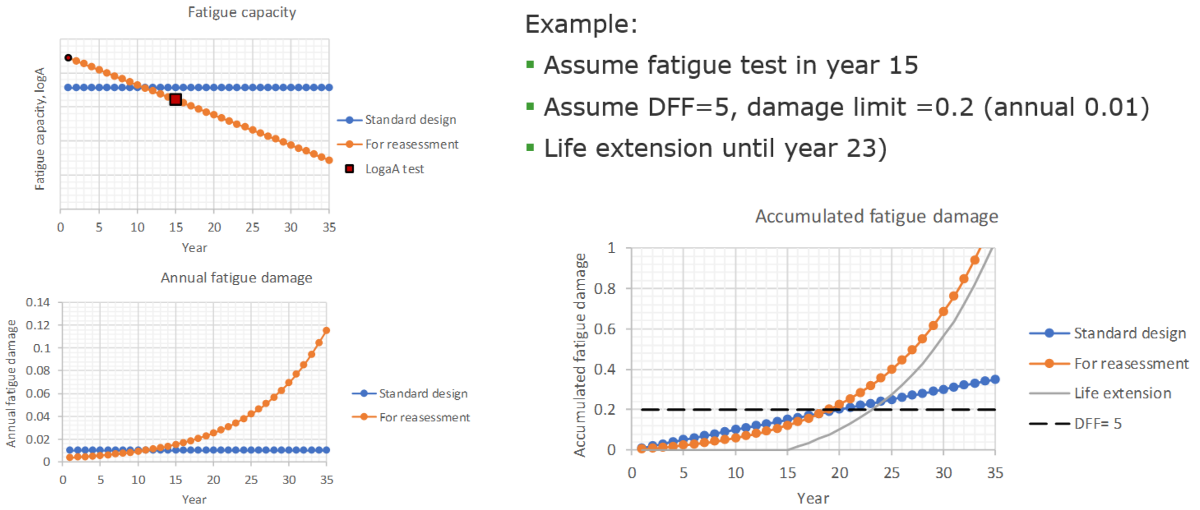

Figure 2-3 Illustration of one option for reassessment based on fatigue testing. Example with testing in year 15, and permissible life extension to year 23.

5. Reassessment approach for strength:

The reduction in the cross-sectional area at the time of testing will be compared to that of new chain. This will be used to make a prediction of the area reduction in the future. The relationship between the breaking load derived from the chain cross-sectional area and yield strength versus tests will be utilised to estimate the year when the applicable safety factors in ULS or ALS are no longer satisfied. Associated uncertainties will be evaluated such that the criterion for replacement ensures that the required safety level is maintained. A detailed structural reliability analysis is not considered necessary.

6. Structural reliability analysis, fatigue:

It is proposed to support the reassessment methodology by structural reliability analysis and calculate the probability of fatigue failure in the last year of service. Unit specific test data with associated uncertainty, including statistical uncertainty, will be considered.

The structural reliability analysis model applied in phase 3 of the NorNoor JIP will be adapted to the degradation model based on test results. The probability of failure in the last year of service will be calculated, as illustrated in Figure 2-4. If it is of interest to the PARTICIPANTS, the target reliability level might be studied by cost-benefit analysis.

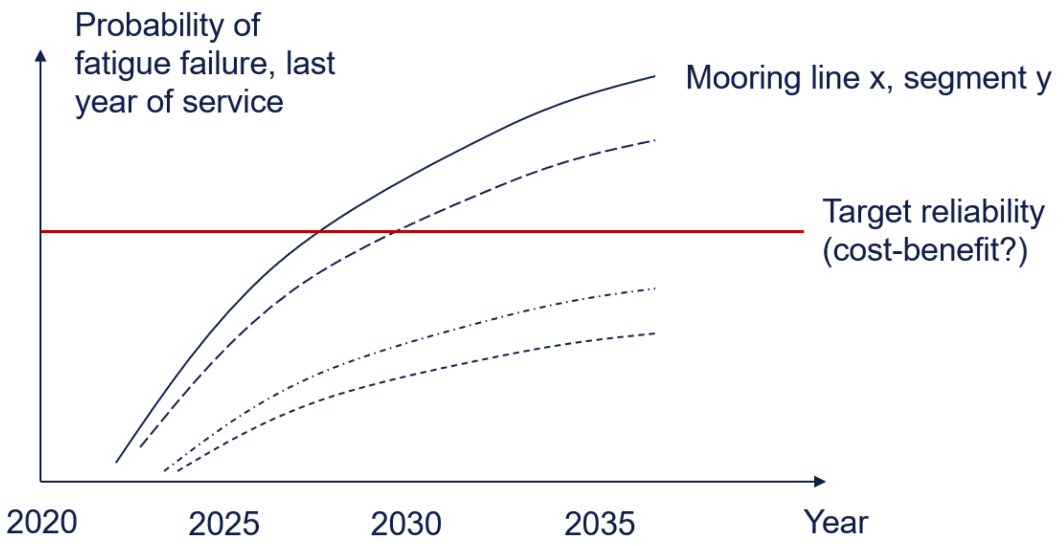

Figure 2-4 Illustration of structural reliability analysis results, probability of failure as a function of time.

7. **Calibration of the reassessment procedure:**
   The result from the SRA in task 5 will be compared to the result of the deterministic reassessment procedure to see if the target safety level is obtained or not. Potential adjustments (calibration) of the reassessment procedure, i.e. related to the use of the test data, the selection of characteristic inputs or magnitude of the safety factor, will be proposed such that the target is met.

2.4 Deliverables

The results will be documented in JIP reports.

Although not part of the scope in the NorMoor JIP, the results from the JIP will be used in forthcoming updates of DNV RP's and Standards.

3 BUDGET & INVOICING

3.1 Budget

The minimum budget of Phase 4 is 5 MNOK, which is intended to cover the full scope outlined in section 2.3 . Funding beyond this will allow an increased scope. The NorMoor JIP phase 4 will commence when there is firm commitment from PARTICIPANTS corresponding to 70% of the minimum budget.

The list of sub-tasks gives some indication of priorities. Tasks may be excluded, reduced in content, or extended by decision of the steering committee, depending on the number of PARTICIPANTS and the associated budget. Similarly, changes may be needed if the work extent turns out to be more or less demanding than expected, for reasons that are difficult to foresee at present.

Tentative estimates:

Task	Description	Budget (MNOK)
1	Fatigue capacity	0.5
2	Breaking strength	0.3
3	Mooring analysis	0.5
4	Reassessment approach, fatigue	0.7
5	Reassessment approach, overload	0.3
6	Structural reliability analysis, fatigue	0.7
7	Calibration	0.5
8	Summary report	0.3
9	PM and meetings	0.7
10	Contingency	0.5
Total		5.0

3.2 Participation fee

The participation fee for phases 4 is reduced somewhat from the previous phases, since the total budget is less for this phase.

- Operators, 850 kNOK
- Other companies 350 kNOK
- Authorities: same conditions as in phase 1, 2 and 3.

Manufacturers: to be discussed with the Steering Committee

3.3 Invoicing Schedule

Unless otherwise agreed, the PARTICIPANT FEES will be invoiced according to the following schedule:

Prices in NOK	2022	2023
Operators	450 000	400 000
Other companies	200 000	150 000

4 TIME SCHEDULE

Phase 1 was completed in November 2014, Phase 2 in 2017, and Phase 3 will be completed this fall. In order to avoid interruption and keep up momentum, it is proposed to continue with Phase 4 in 2022:

- Kick-off, Q2 2022
- Finish, Q4 2023

5 TENTATIVE PARTICIPANT LIST

The following companies are PARTICIPANTS in Phase 3 of the PROJECT and have shown interest also in a phase 4

Oil companies

Energy companies	**Other companies**	**Manufaturers & Authorities**
BP	Single Buoy Moorings	Vicinay
Aker BP	NOV-APL	Petroleum Safety Authority in Norway (PSA)
Equinor	DNV	Norwegian Maritime Authority (NMA)
Neptune Energy		Health and Safety Executive (HSE)
Total		
Shell		
Petrobras		

6 CONTRACTUAL

DNV proposes that the General Conditions of the Agreement for NorMoor JIP, DNV Reg. No.: 1-2U80EX, Rev.1, 2011-01-20 and the amendment thereto will continue in full force for the Project Phase 4.

This proposal for NorMoor JIP Phase 4 will also be submitted to new participants. If new companies decide to participate in NorMoor Phase 4, the Agreement will be updated and based on the same contractual terms as mentioned above, i.e. General Conditions of the Agreement for NorMoor JIP, DNV Reg. No.: 1-2U80EX, Rev.1, 2011-01-20.

7 CONTACT PERSONS

The contact persons shown in the table below will be pleased to answer any queries you may have in respect of this proposal.

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