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RELIABILITY IN A SEA OF RISK

Welcome to Day 1

Developing an understanding of the VMEA framework

EMEC ORKNEY
THE EUROPEAN MARINE ENERGY CENTRE LTD

SP your Science Partner

CATAPULT Offshore Renewable Energy

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RELIABILITY IN A SEA OF RISK

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Day 1 Agenda

Day 1: 12:00-17:30

12:00 Lunch and registration

13:00 Introduction/Background

13:30 VMEA framework

15:00 Coffee break

15:30 Exercises on VMEA: Paper clip fatigue

17:15 Wrap up

19:00 Dinner (optional)

Day 2 Agenda

Day 2: 08:00-12:30

08:00 *Arrival*

08:30 Review of day 1

08:45 Case study: Moorings and foundations

09:30 Coffee break

10:00 Case study: Structural component

11:00 Case study: Electrical component

12:00 Summary of Key learning points

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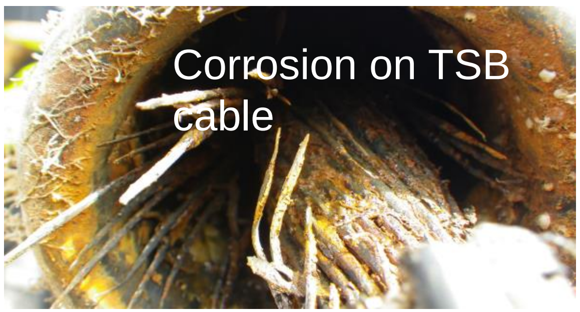
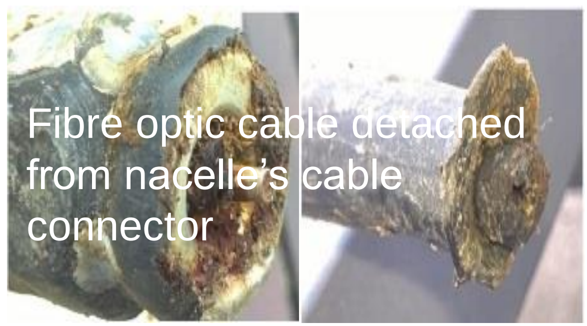
Reliability Challenges


Corrosion on TSB cable

Failed 2-3 weeks at EMEC test site

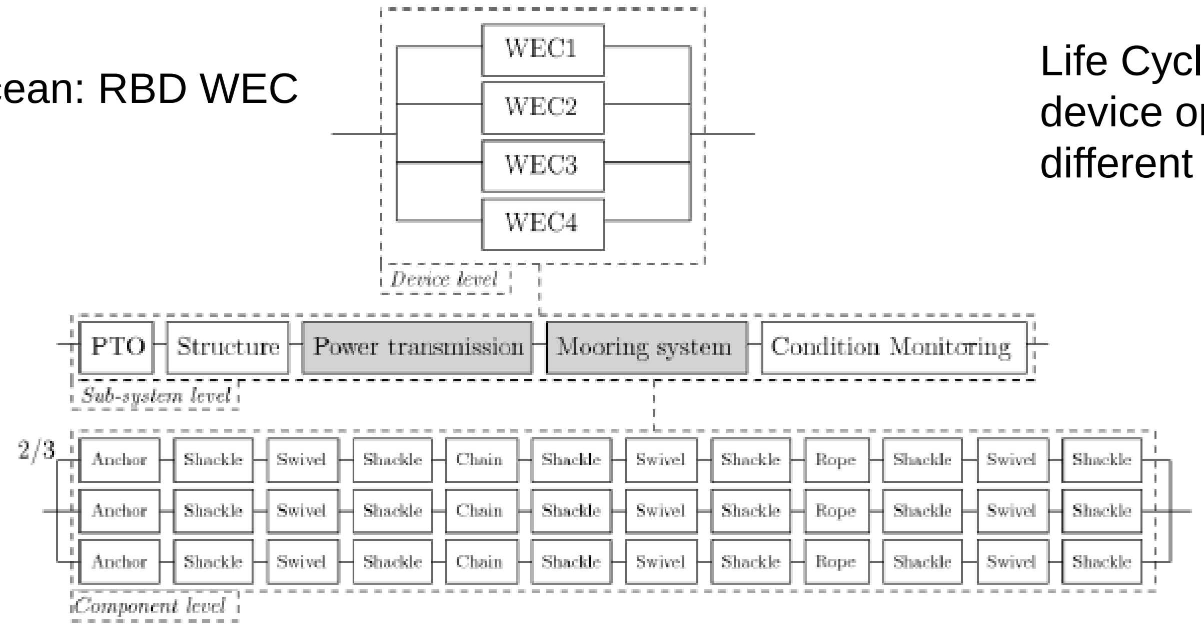

Brake caliper bolt Sheared 24 hours after torques


Fibre optic cable detached from nacelle's cable connector

Wave Rider Buoy Spring Sheared

Approaches/Tools

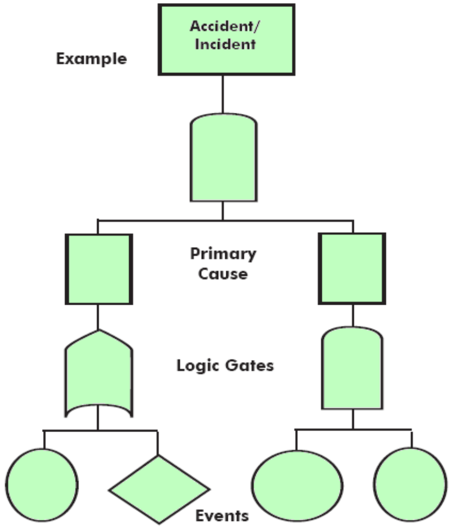
DTOcean: RBD WEC array



Life Cycle Cost (LCC) – best device options; comparison of different components

Fault Tree Analysis (FTA) – Failure analysis

FMEA/FMECA – cause/effect



Availability Assessment – total availability of WEC/TEC system /time

RiaSoR Project

Ocean ERANET funded (SE/SEA/InnovateUK)

1 year review of VMEA methodology, adaptation and application of VMEA for structural, moorings/foundations and electrical system subsystems.

<u>Deliverables to industry</u>:

1. Guideline
2. Educational / Instructional workshop and
3. Case studies on the above subsystem applications.

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Introduction to the VMEA concept

Thomas Svensson, PhD
SP Technical Research Institute of Sweden

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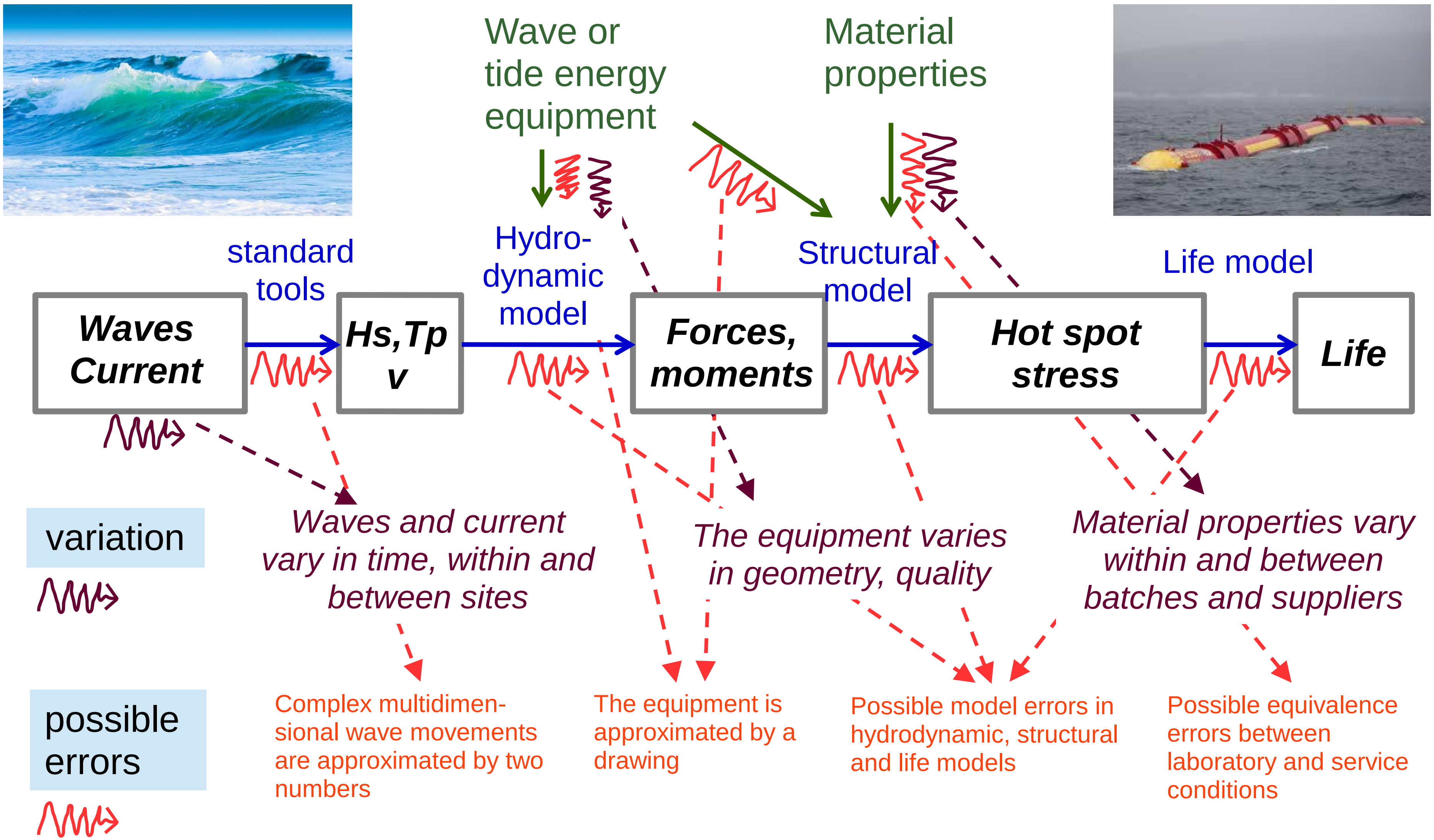
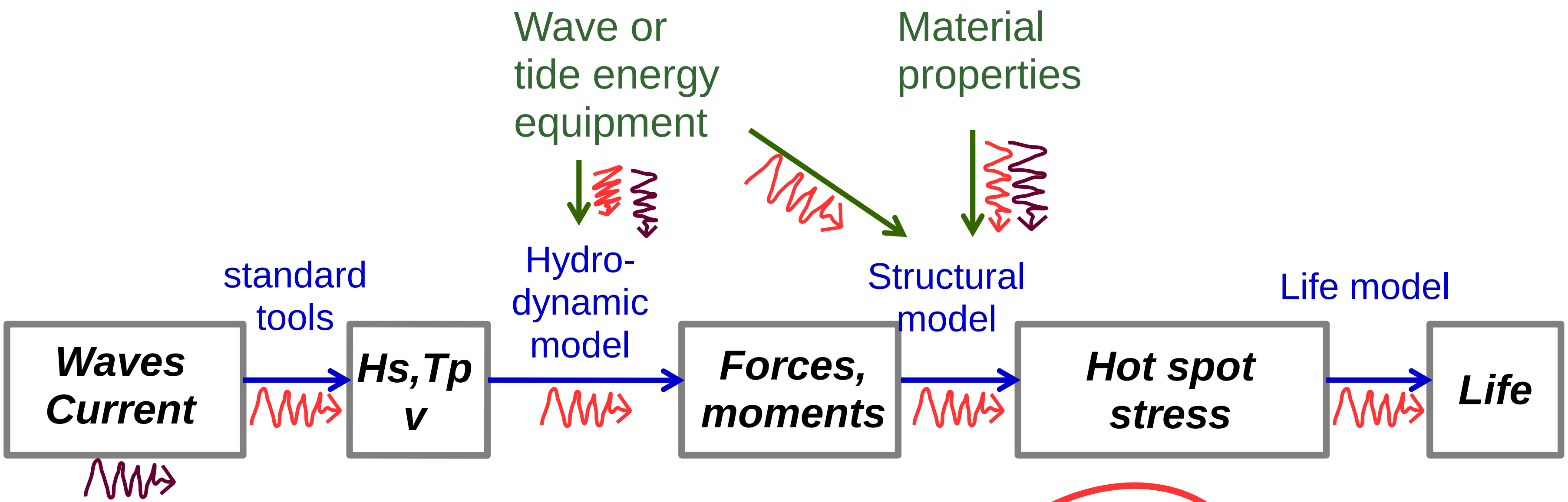
Life assessment, overview

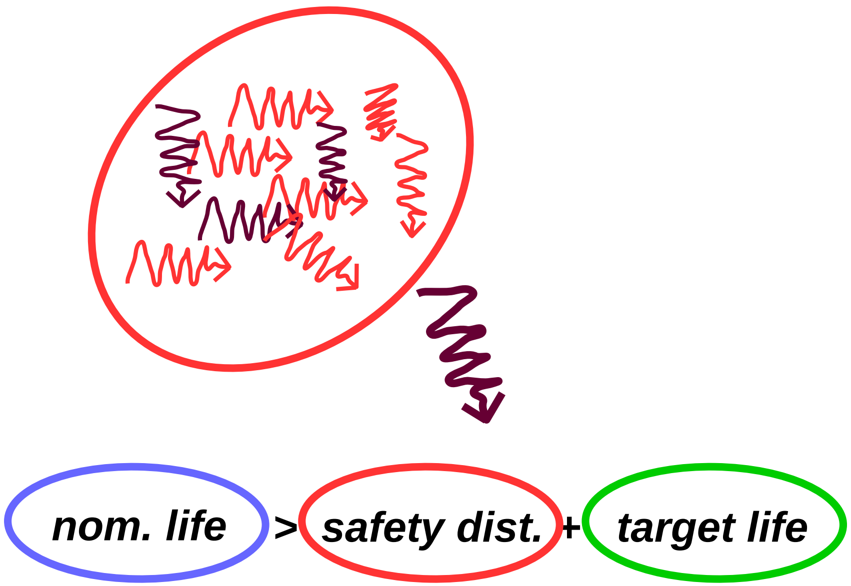


VMEA uncertainty assessment

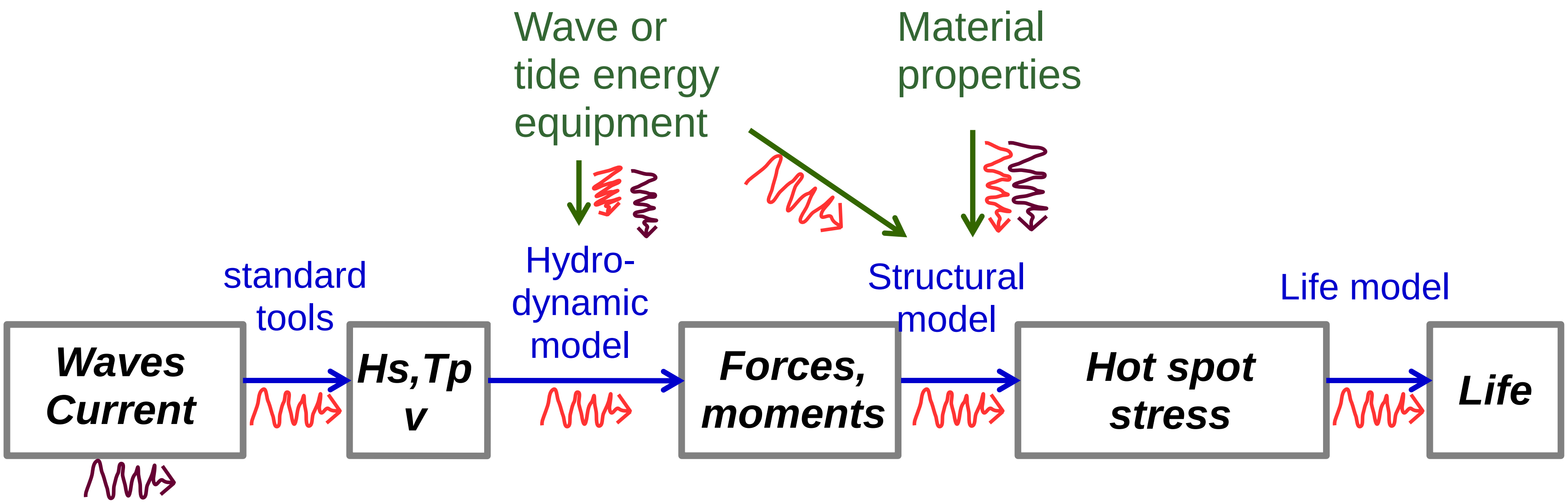


Both ***possible errors*** and ***variation*** must be taken into account when designing for life.

- The VMEA takes the ***expected calculated life*** as the starting point.
- The VMEA assigns a common ***uncertainty metric*** to each error and variation source.
- The VMEA then calculates an overall uncertainty for life which is used for the determination of a proper ***safety factor.***



VMEA uncertainty assessment



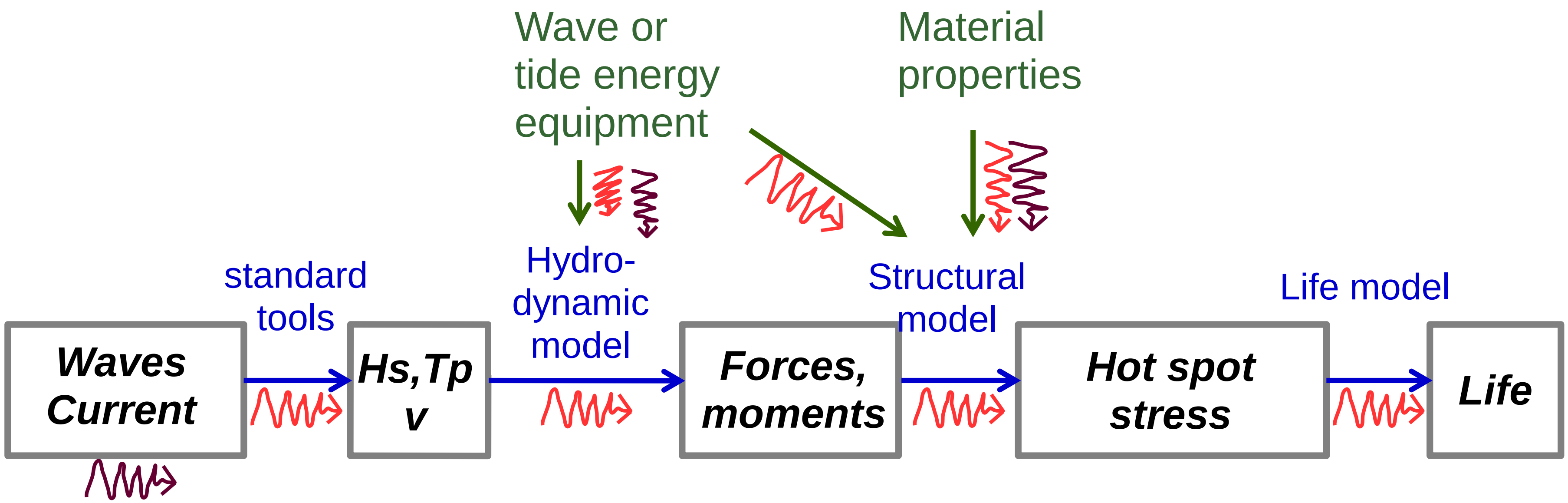
Common reliability approaches take height for uncertainties ***in each step***:

- Variation is handled by using statistical safe quantiles or worst case scenarios.
- Model errors are handled by conservatism, choosing model variants that exaggerate severity and weakness.

This practice often results in overdesigned products since it is highly non-likely that the “worst case” occurs at each uncertain point.

This may be compensated by adjustments, but the methodology lacks control over the resulting reliability.

The VMEA idea



The VMEA procedure is based on the assumption that all sources of variation and possible errors can be regarded as ***independent random variables***.

This means that the likelihood of a combination of “worst cases” can be controlled by statistical laws:

The overall uncertainty is calculated by adding the individual ***variance*** contributions:

The uncertainty metrics are combined by their sum of squares

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Beehive! Discuss…

What are the most important reliability issues in wave energy devices?

Examples of scatter sources?

Examples of possible error sources?

VMEA Methodology

Pär Johannesson, PhD

SP Technical Research Institute of Sweden

VMEA (Variation Mode and Effect Analysis)

Product Development

Concept Phase

Basic VMEA
Only limited information is available

Design Phase

Enhanced VMEA
More information is available

Detailed Design Phase

Probabilistic VMEA
More detailed information about the structure and the sources of variation

- Assign statistical variances to the different sources.
- Evaluate the physical property, e.g. time to failure.

Example:
Evaluate the variation in life, N, of the most attractive design.

$$\ln(N) = f(T, P, \Delta, W) = f(x_1, x_2, x_3, x_4)$$

$$c_i = \frac{\partial_i f}{\partial x_i}, \quad \tau_i^2 = Var(x_i)$$

		Variation size τ_i	Sensitivity c_i	Variation $c_i^2\tau_i^2$
T	Temperature	0.28	1.1	0.09
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W	Wear	0.16	3.4	0.30
	$Var(\ln(N)) = \sum_i c_i^2\tau_i^2 = 1.09$			

Result:
Uncertainty in predicted life of the Belt.
To improve the reliability, it would be most efficient to Improve the Tension properties.

Outline

- **VMEA in Product development**
- **Design Process for MECs**
- **Basic VMEA**
  - **Example: Mooring rope**
- **Probabilistic VMEA**
  - **Example: Mooring rope**

VMEA (Variation Mode and Effect Analysis) a Reliability Evaluation Method

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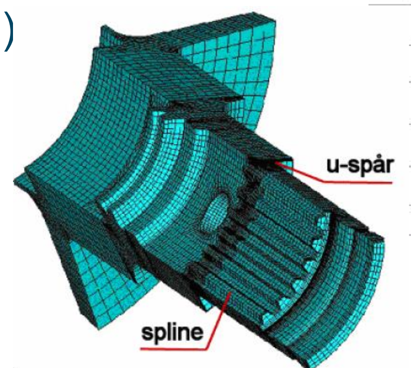
Summary table of all uncertainties during the whole design process
- *scatter of material properties*
- *statistical uncertainties*
- *geometry variation*
- *model uncertainties*
- *load uncertainties*
- *…*

Which uncertainties dominates?
(scatter or uncertainty?)

How can uncertainties be decreased?
(yielding best cost/profit)

Balanced complexity in models
(don't overdo them)



Example: Volvo Aero, fatigue life evaluation

1. "First final design life predictions".

Data and models	Influence on crack initiation life		
Type of scatter and uncertainty	scatter τ	uncertainty δ	total
Mtrl data (ln is normal-) distr.			**0.295**
-within	0.291		
-between	0.050		
-statistical uncertainty Basq-Coff-Man		0.092	**0.092**
Geometry			**0.400**
-tolerances	0.400		
Model uncertainty			**0.462**
-Basquin-Coffin-Manson-model		0.050	
-mean stress influence		0.075	
-multiaxiality, one-parameter model		0.183	
-stress analysis, plasticity		0.049	
-stress analysis, model quality		0.096	
-sequence effects - linear damage		0.400	
-temperature effects		0	
-frequency influence		0	
Other uncertainties			**0.234**
- Flight/service loads	-	0.234	
Total	0.497	0.526	**0.724**

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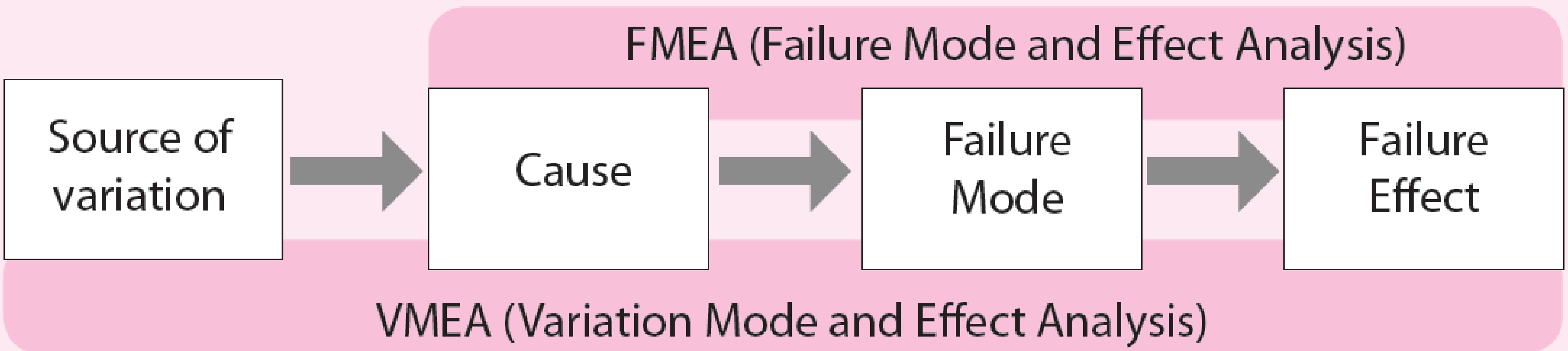
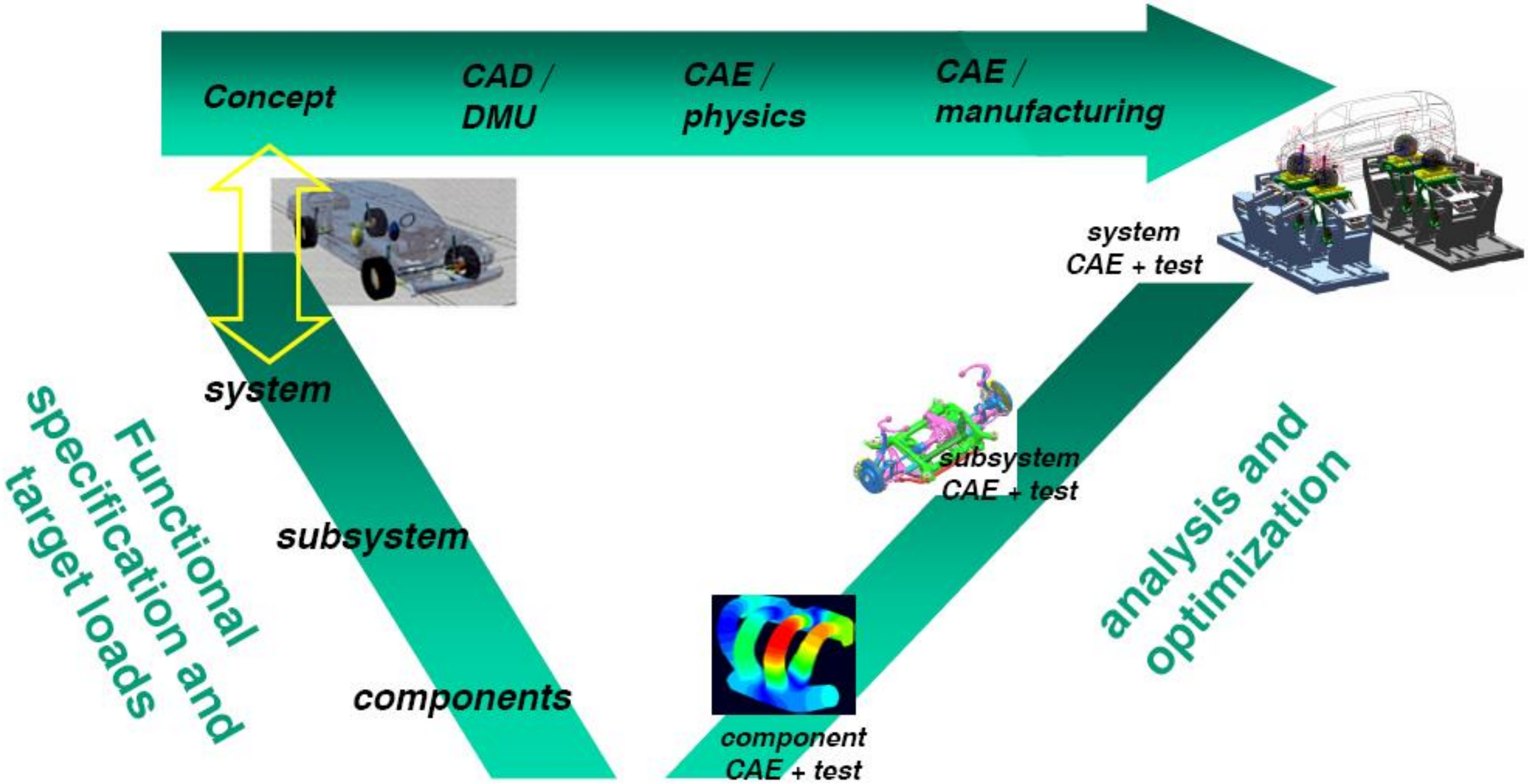
Reliability and robustness

Unreliability is caused by Variation



- The FMEA method aims at finding all possible causes of failure.
- Studies have shown that most causes are trigged by unwanted variation.
- The VMEA method aims at finding all sources of variation that can trigger a failure mode.

Reliability and System Engineering



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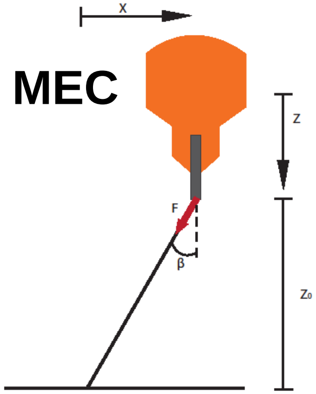
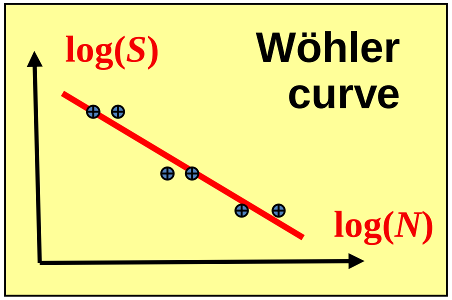
Design process for MECs

Input: Sea loads
- Histogram of sea states, (H_s, T_p).
- E.g. JONSWAP model for each sea state.

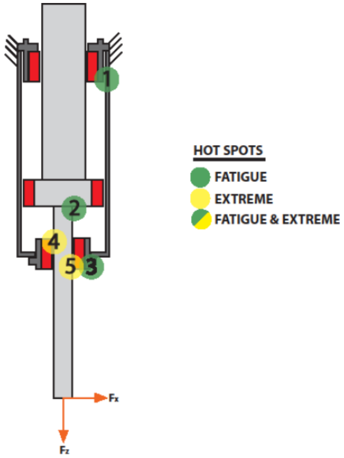
Model: Sea loads to forces
- Model for simulating motion of the buoy and forces.



Model: Forces to stress
- FEM
- Critical hotspots



Model: Fatigue life
- Wöhler curve
- Damage accumulation



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Basic VMEA

VMEA (Variation Mode and Effect Analysis)

Product Development

Concept Phase

Basic VMEA
Only limited information is available

- Select among design concepts.
- Choose a design alternative which is robust to variation.

Example:
Evaluate the AC power transmission supply alternatives:
- Hydraulic • Electric • Belt

Use engineering judgment to evaluate the variation sizes by using a simple ranking system.

Conclusions:
Choose Belt alternative.

Design Phase

Enhanced VMEA
More information is available

- Better information on the sources of variation.

Example:
Compare different designs using a Belt. Judge the sizes of the variation sources and their sensitivity to the failure of the Belt

		Variation size (1-10) σ_i	Sensitivity (1-10) α_i	Variation number $\alpha_i^2\sigma_i^2$
T	Temperature	8	2	256
P	Tension	8	10	6400
Δ	Tolerance	3	1	9
W	Wear	6	8	2304
	Total variation = $\sum_i \alpha_i^2\sigma_i^2$ = 8969			

Result:
Choose a design with low "Total variation"

Detailed Design Phase

Probabilistic VMEA
More detailed information about the structure and the sources of variation

- Assign statistical variances to the different sources.
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Evaluate the variation in life, N, of the most attractive design.

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Result:
Uncertainty in predicted life of the Belt. To improve the reliability, it would be most efficient to Improve the Tension properties.

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VMEA procedure

1. **Target Function Definition**
   For example, the life of a component, the maximum stress or the largest defect.
2. **Uncertainty Sources Identification**
   Identify all sources of uncertainty (scatter, statistical and model uncertainties).
3. **Sensitivity Assessment**
   Evaluate the sensitivity coefficients of the sources of uncertainty.
4. **Uncertainty Size Assessment**
   Quantify the size of the different sources of uncertainty.
5. **Total Uncertainty Calculation**
   Combine the contributions from all uncertainty sources.
6. **Reliability and Robustness Evaluation**
   Find the dominating uncertainties or derive safety factors.
7. **Improvement Actions**
   Identify uncertainty sources that are candidates for improvement actions.

Basic VMEA
Target Function Definition

1. Target Function Definition

Define the target function, i.e. the property to be studied, which can be the life of a component, the maximum stress or the largest defect.

Waves4Power: http://www.waves4power.com/

What do we want to study?

- Durability of a system/component
  => Life requirement
- Survivability of a system/component
  => Maximum stress

Basic VMEA
Uncertainty Sources Identification

2. Uncertainty Sources Identification

Identify all sources of uncertainty that can have an impact on the target function.

Different views and competences, cross-functional team of experts

Some helpful tools:

FMECA

POTENTIAL
FAILURE MODE AND EFFECTS ANALYSIS
Front Door L.H.

FMEA Type ______

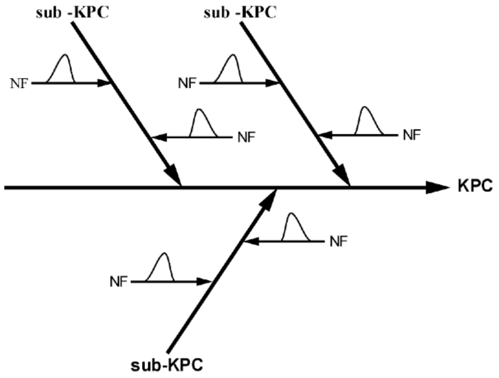
Item 1.1.1 - Front Door L.H. — Process Responsibility Body Engineering

Model Year(s)/Vehicle(s) 20XX/Lion 4dr/Wagon — Key Date 3/10/2015

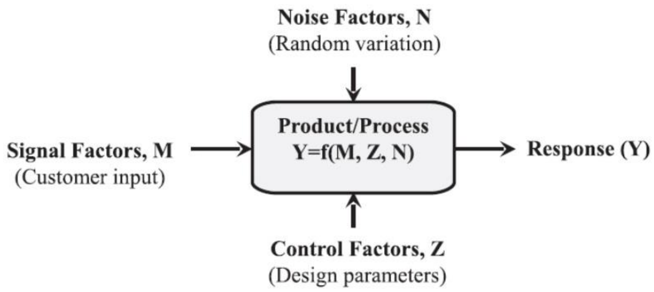
Core Team A. Tate Body Engrg, J. Smith - OC, R. James - Production, J. Jones - Maintenance

Name / Function Requirements	Potential Failure Mode	Potential Effect(s) of Failure	SEVi	Classification	Potential Cause(s) of Failure	OCCi	Current Process Controls (Prevention)	Current Process Controls (Detection)	DETi	RPNi
1.1.1 - Front Door L.H.										
Op. 70 Manual application of wax inside door/ cover inner door, lower surfaces with wax to specification thickness.	Insufficient wax coverage over specified surface	Allows integrity breach of inner door panel. Corroded interior lower door panels. Deteriorated life of door leading to: - Unsatisfactory appearance due to rust through paint over time - Impaired function of interior door hardware	7		Manually inserted spray head not inserted far enough	8		Visual check each hour - 1/shift for film thickness (depth meter) and coverage.	5	280
					Spray head clogged- Viscosity too high- Temperature too low- Pressure too low.	5	Test spray pattern at start-up and after idle periods, and preventive maintenance program to clean heads.	Visual check each hour - 1/shift for film thickness (depth meter) and coverage.	5	175
					Spray head deformed due to impact	2	Preventive maintenance program to maintain heads.	Visual check each hour - 1/shift for film thickness (depth meter) and coverage.	5	70

Fishbone diagram



P-diagram



Identification of uncertainties

Five categories of evil …

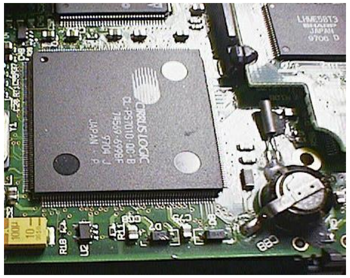
Wearout refers to deterioration of products due to ageing

External environmental conditions the products are exposed to

Internal environmental conditions the products are exposed to

Customer "behaviour" the products are exposed to

Manufacturing imperfections the products are exposed to



… in Automotive Industry …

…and we CANNOT eliminate these factors!

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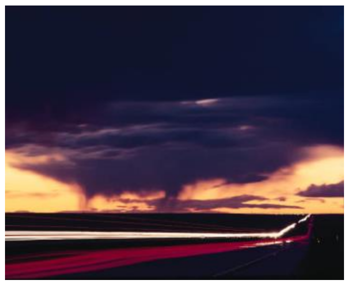
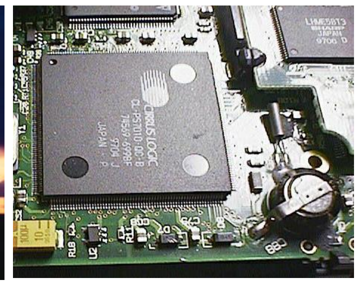
Beehive! Discuss…

Wearout refers to deterioration of products due to ageing	**External environmental conditions** the products are exposed to	**Internal environmental conditions** the products are exposed to	**Customer "behaviour"** the products are exposed to	**Manufacturing imperfections** the products are exposed to





Are these five categories relevant for Marine Energy Converters?

If so, what uncertainties can the categories represent?

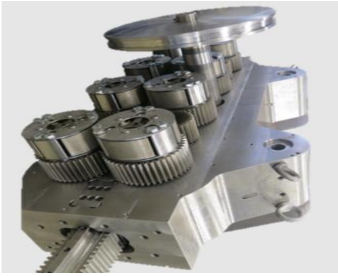
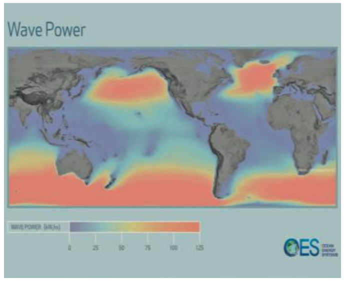
Any examples?

Identification of uncertainties

Five categories of evil … for MECs

Wearout refers to deterioration of products due to ageing	**External environmental conditions** the products are exposed to	**Internal environmental conditions** the products are exposed to	**Customer “behaviour”** the products are exposed to	**Manufacturing imperfections** the products are exposed to



Basic VMEA
Example: Mooring rope

1. **Target Function Definition**
   The **target function** is the **life of the mooring rope**.

2. **Uncertainty Sources Identification**
   The following uncertainties were identified:

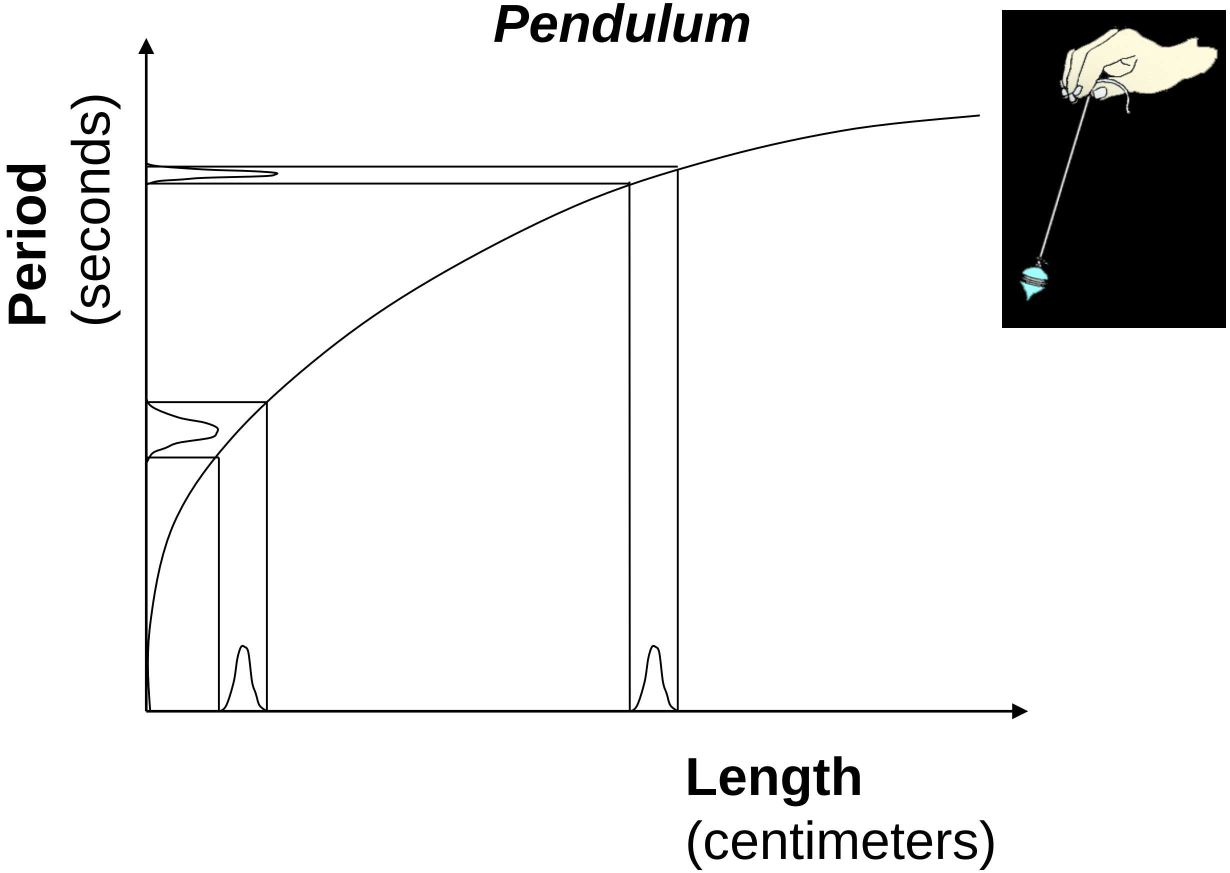
   - Load variation
   - Uncertainty in load assessment
   - Scatter in fatigue life
   - Uncertainty in the fatigue model
   - Uncertainty due to influence of environment
   - Geometry variations

CorPower: www.corpowerocean.com

Basic VMEA
Sensitivity Assessment

Variation transmission – amplification and reduction

Pendulum



Basic VMEA
Example: Mooring rope

3. **Sensitivity Assessment.**
   Evaluate the sensitivity coefficients on a scale 1-10.

4. **Uncertainty Size Assessment**
   Quantify the size of uncertainty on a scale 1-10.

Evaluate two alternatives: Steel wire & Polyester rope

Basic VMEA: Steel wire

Input		
Uncertainty sources	**Sensitivity (1-10)**	**Uncertainty (1-10)**
- Load variation	5	4
- Uncertainty in load assessment	5	6
- Scatter in fatigue life	5	5
- Uncertainty in the fatigue model	5	4
- Uncertainty due to environment	5	4
- Geometry variations	6	2
Total uncertainty		

Basic VMEA: Polyester rope

Input		
Uncertainty sources	**Sensitivity (1-10)**	**Uncertainty (1-10)**
- Load variation	5	4
- Uncertainty in load assessment	5	6
- Scatter in fatigue life	5	7
- Uncertainty in the fatigue model	5	8
- Uncertainty due to environment	5	3
- Geometry variations	6	3
Total uncertainty		

Basic VMEA
Total Uncertainty Calculation

5. Total Uncertainty Calculation

Calculate the total resulting uncertainty in the output of the target function by combining the contributions from all uncertainty sources according to their sensitivities and sizes.

Basic VMEA: Steel wire

Input			**Result**		
Uncertainty sources	**Sensitivity (1-10)**	**Uncertainty (1-10)**	**uncertainty** $\tau_i = c_i \cdot \sigma_i$	**Variation contribution** VRPN	**Portion**
- Load variation	5	4	20	400	14%
- Uncertainty in load assessment	5	6	30	900	31%
- Scatter in fatigue life	5	5	25	625	22%
- Uncertainty in the fatigue model	5	4	20	400	14%
- Uncertainty due to environment	5	4	20	400	14%
- Geometry variations	6	2	12	144	5%
Total uncertainty			**54**	**2869**	**100%**

VRPN = "Variation Risk Priority Number"

Total $VRPN$ is calculated as the Sum of Squares (SS).

$$VRPN = \tau^2 = \tau_1^2 + \tau_2^2 + \tau_3^2 + \cdots$$

Total uncertainty τ is calculated as the Root Sum of Squares (RSS).

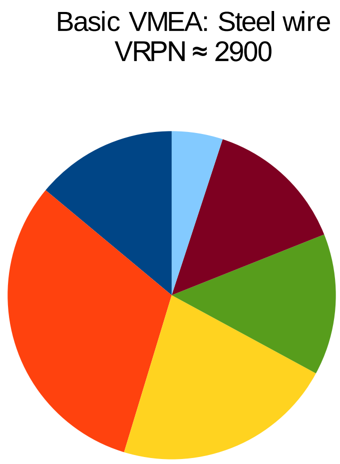
Basic VMEA
Robustness Evaluation & Improvement

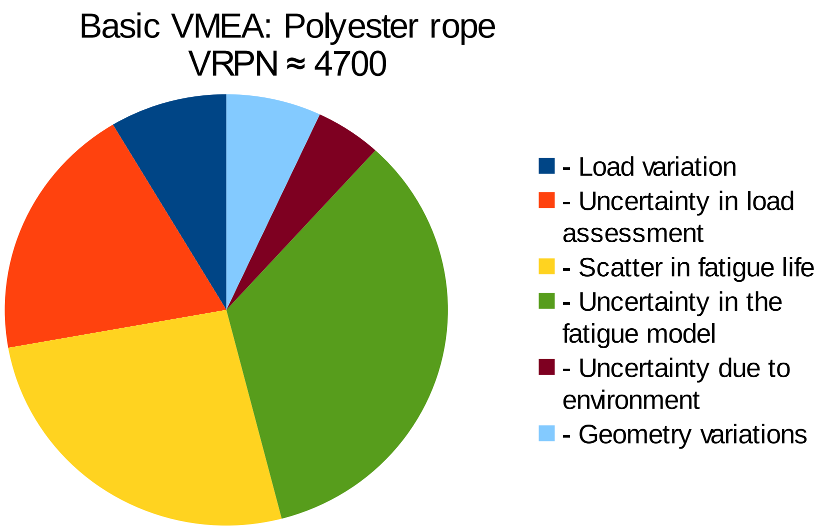
6. Robustness Evaluation

Compare the two design concepts: Steel wire & Polyester rope.
Polyester rope has larger uncertainties Steel wire concept due to large fatigue scatter and model uncertainty.

7. Improvement Actions

The steel wire is quite well understood; the main candidate for design.
The polyester rope needs further investigations concerning fatigue.





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Probabilistic VMEA

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Choose a design with low "Total variation"

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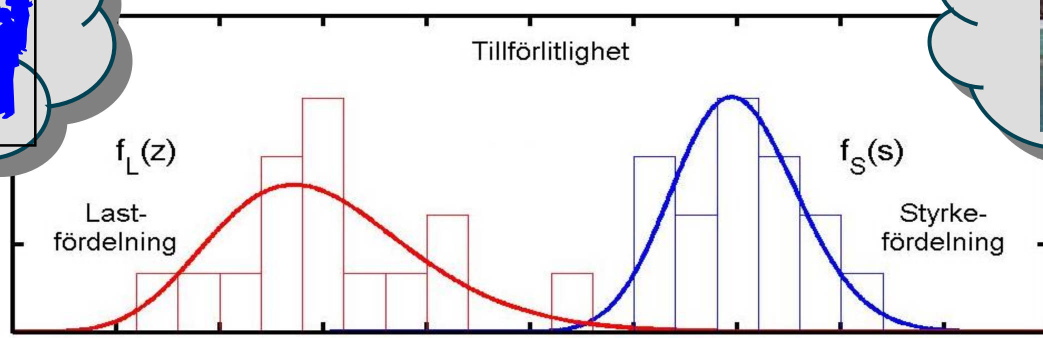
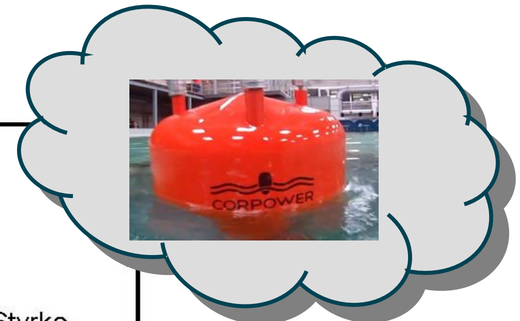
Reliability: Load-Strength Analysis

Population of customers

Load-Strength-diagram





Population of products

Uncertainty in load

- **Customer variation**
- **Usage and application area**
- **Environment** (wave, wind, climate)
- **Load estimation** (ocean, test site)
- etc

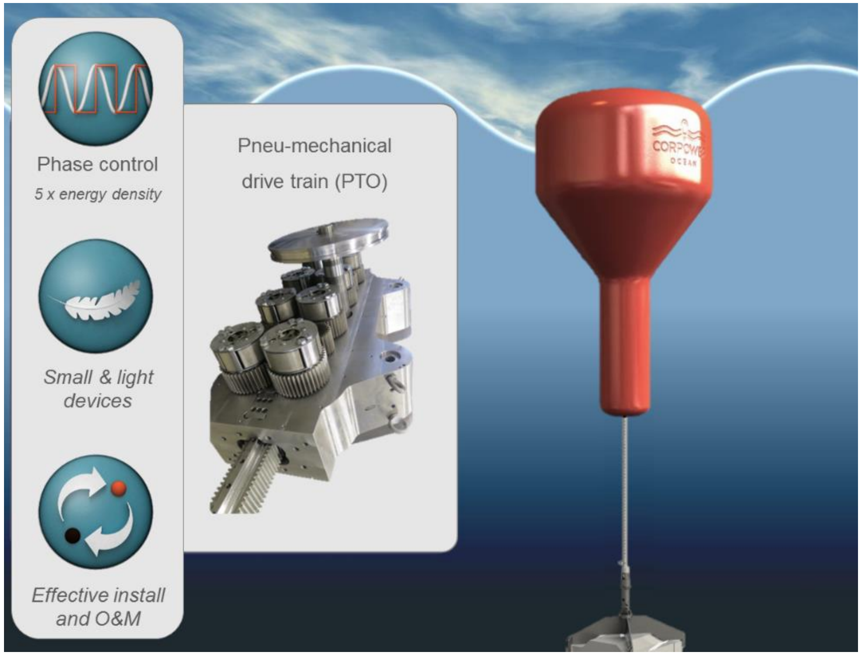
Uncertainty in strength

- **Material** (type, surface, defects)
- **Manufacturing**
- **Geometry** (tolerances, surface roughness)
- **Modelling** (FEM, Wöhler, P-M, Neuber)
- etc

P-VMEA: Mooring rope
Target Function Definition

1. Target Function Definition

Define the target function, i.e. the property to be studied, which can be the life of a component, the maximum stress or the largest defect.



CorPower: http://www.corpowerocean.com

What do we want to study?

- Durability of the mooring rope
- Life requirement, 20 years

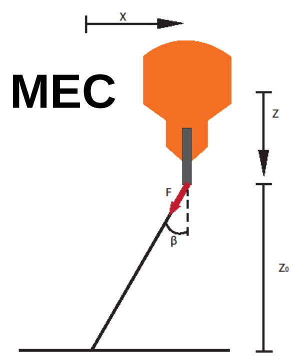
Design Process for MECs

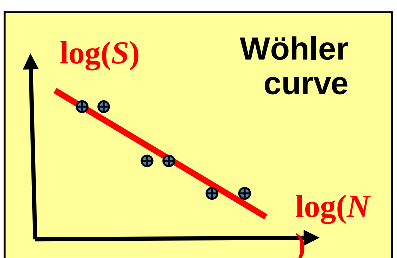
Input: Sea loads
- Histogram of sea states, (H_s, T_p).
- JONSWAP model for each sea state.

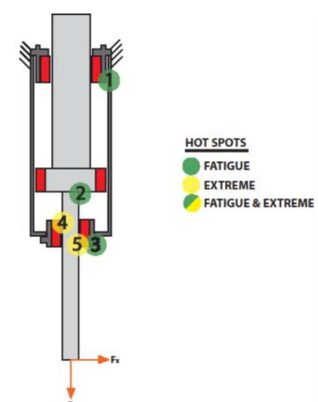
Model: Sea loads to forces
- Model for simulating motion of the buoy and forces.

Model: Forces to stress
- FEM
- Identify hotspots

Model: Fatigue life
- Wöhler curve
- Damage accumulation







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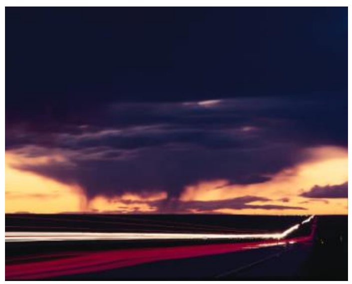
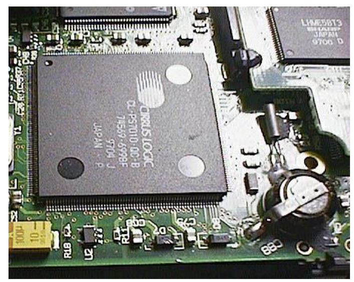
RELIABILITY IN A SEA OF RISK

Identification of uncertainties

Five categories of evil …

Wearout refers to deterioration of products due to ageing	**External environmental conditions** the products are exposed to	**Internal environmental conditions** the products are exposed to	**Customer "behaviour"** the products are exposed to	**Manufacturing imperfections** the products are exposed to

- **Scatter** — **CANNOT be eliminated!**
- **Statistical uncertainty**
- **Model uncertainty**

(Statistical uncertainty and model uncertainty:) **CAN be reduced or eliminated!**

... by better knowledge or more data.

Probabilistic VMEA
Sensitivity & uncertainty size assessment

The **metrics** in the probabilistic VMEA are:

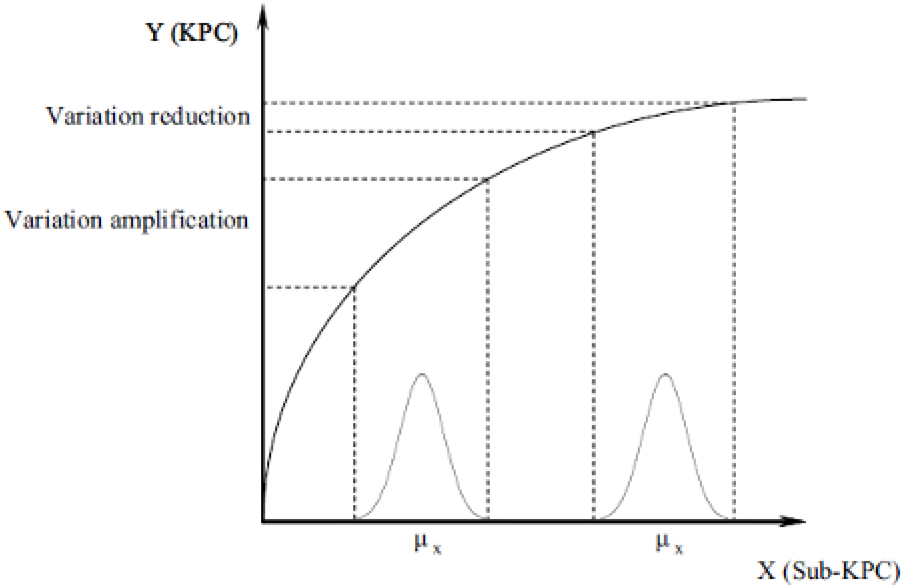
1. Sensitivities by means of mathematical ***sensitivity coefficients,***

2. Uncertainty by means of ***statistical standard deviations***

instead of 1-1- scales in the basic VMEA.

For a target function
$Y = f(X_1, X_2, X_3, \dots)$

1. *the **sensitivity coefficients*** is
   $c_i = \frac{\partial f}{\partial X_i}$
2. *the **uncertainty*** is
   the ***standard deviation***
   $\tau_i = std(X_i)$



P-VMEA: Mooring rope

Total uncertainty calculation: VMEA Table

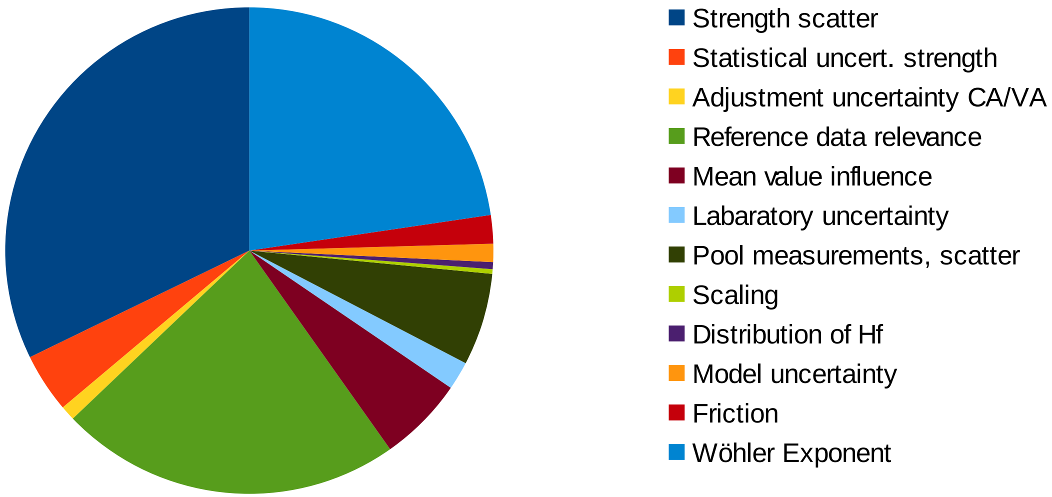
Input						Result		
Uncertainty components	Scatter	Uncert.	Sensitivity coeff cient c	t-correction factor t	standard deviation s	Scatter	Uncertainty	Total
Strength								
Strength scatter	x		0,208	1,060	0,540	0,119		
Statistical uncert. strength		x	0,208	1,000	0,200		0,042	
Adjustment uncertainty CA/VA		x	0,208	1,000	0,100		0,021	
Reference data relevance		x	1,000	1,000	0,100		0,100	
Mean value inf uence		x	1,000	1,000	0,050		0,050	
Labaratory uncertainty		x	1,000	1,000	0,029		0,029	
Total Strength uncertainty						**0,119**	**0,125**	**0,172**
Load								
Pool measurements, scatter	x		1,000	1,300	0,040	0,052		
Scaling		x	1,000	1,000	0,012		0,012	
Distribution of Hf		x	1,000	1,000	0,014		0,014	
Model uncertainty		x	1,000	1,000	0,023		0,023	
Friction		x	1,000	1,000	0,029		0,029	
Total Load uncertainty						**0,052**	**0,041**	**0,066**
Wöhler Exponent		x	0,200	1,000	0,500		0,100	
Total Exponent uncertainty						0,000	0,100	**0,100**
Total uncertainty						**0,130**	**0,165**	**0,210**

Total uncertainty: $\tau = \sqrt{\tau_1^2 + \tau_2^2 + \tau_3^2 + \cdots} = 0.210$

P-VMEA: Mooring rope

Uncertainty contributions

Probabilistic VMEA for steel wire
Pie chart of uncertainty contributions



The **three dominating sources** are:

1. Strength scatter
2. Reference data relevance (uncertainty)
3. Wöhler exponent (uncertainty)

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P-VMEA: Mooring rope Reliability Evaluation

Total uncertainty						0,130	0,165	0,210

Total uncertainty: $\tau = \sqrt{\tau_1^2 + \tau_2^2 + \tau_3^2 + \cdots} = 0.210$

Reliability Evaluation

wire diameter (mm) 110

Input		Result	
Median strength [MN]	2,25	Safety factor	1,41
Median Load [MN]	1,60		

Result (log-scale)	
Strength, mS	0,81
Load, mL	0,47
Distance	0,34

Load-Strength, Nominal values: $\ln S_{nom} - \ln L_{nom} = 0.81 - 0.47 = 0.34$

Evaluation - Extra safely factor		Variation safety factor	1,41
Required extra safety factor	1	Extra safety factor	1,00

Variation dist.	0,34
Extra dist.	0,00

	Safety margin	Safety factor
95% prediction interval:	$1.64 \cdot \tau = 0.34$	$\exp(1.64 \cdot \tau) = 1.41$
Extra safety factor:	$\delta_E = 0$	$\gamma_E = \exp(0) = 1$

Load-Strength judgement:

Nominal: $\ln S_{nom} - \ln L_{nom} = 0.81 - 0.47 = 0.34$

Requirement: $1.64 \cdot \tau + \delta_E = 0.34$

P-VMEA: Mooring rope Improvement Actions

7. Improvement Actions

Identify uncertainty sources that are candidates for improvement actions.

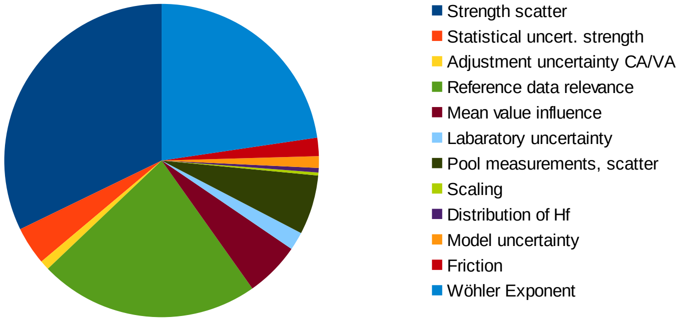
Improvement Actions:

Design change:

Wave spring replaces latching mechanism
=> Reduce loads

The largest uncertainties are connected to the strength, possible improvements:

- specifying wire rope quality, and
- arrange laboratory wire tests.



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Summary

VMEA (Variation Mode and Effect Analysis)

Product Development

Concept Phase

Basic VMEA
Only limited information is available

- Select among design concepts.
- Choose a design alternative which is robust to variation.

Example:
Evaluate the AC power transmission supply alternatives:
• Hydraulic • Electric • Belt

Use engineering judgment to evaluate the variation sizes by using a simple ranking system.

Conclusions:
Choose Belt alternative.

Design Phase

Enhanced VMEA
More information is available

- Better information on the sources of variation.

Example:
Compare different designs using a Belt.
Judge the sizes of the variation sources and their sensitivity to the failure of the Belt

		Variation size (1-10) σ_i	Sensitivity (1-10) α_i	Variation number $\alpha_i^2\sigma_i^2$
T	Temperature	8	2	256
P	Tension	8	10	6400
Δ	Tolerance	3	1	9
W	Wear	6	8	2304
	Total variation = $\sum_i \alpha_i^2\sigma_i^2$= 8969			

Result:
Choose a design with low "Total variation"

Detailed Design Phase

Probabilistic VMEA
More detailed information about the structure and the sources of variation

- Assign statistical variances to the different sources.
- Evaluate the physical property, e.g. time to failure.

Example:
Evaluate the variation in life, N, of the most attractive design.

$$\ln(N) = f(T, P, \Delta, W) = f(x_1, x_2, x_3, x_4)$$

$$c_i = \frac{\partial_i f}{\partial x_i}, \quad \tau_i^2 = Var(x_i)$$

		Variation size τ_i	Sensitivity c_i	Variation $c_i^2\tau_i^2$
T	Temperature	0.28	1.1	0.09
P	Tension	0.22	3.8	0.70
Δ	Tolerance	0.08	0.5	0.002
W	Wear	0.16	3.4	0.30
	Var(ln(N))= $\sum_i c_i^2\tau_i^2$= 1.09			

Result:
Uncertainty in predicted life of the Belt.
To improve the reliability, it would be most efficient to Improve the Tension properties.

Thanks for your attention!

RISE – Research Institutes of Sweden

SP, Swedish ICT, and Innventia have merged, with the aim of together creating a more united institute sector and becoming a stronger innovation partner for both the Swedish business community and broader society. In the new year we will officially change our name to RISE. Pia Sandvik is the MD of the new macro-institute.

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RELIABILITY IN A SEA OF RISK

Coffee Break

15:00 – 15:30

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RELIABILITY IN A SEA OF RISK

Exercise: Paper clip fatigue

Objective:

Study the reliability of paperclips with regard to their bending strength.

Task:

1. Each participant bends a paperclip 30 degrees back and forth until it fails. Count the number of half bending reversals.

2. Do the same test on a new paperclip, now by bending 45 degrees back and forth.

	A	B	C	D
			Target life	
	Max variation in usage: +/-			
	Number of half reversals to failure			*Logs*
	30 degrees	*45 degrees*		*30 degi*
	140	47		
	49	45		
	44	6		
	72	13		
	54	8		
	17	26		

3. As a group, record the results on the prepared spreadsheet.

   The spreadsheet will calculate the:
   - Log lives,
   - Mean values and
   - Standard deviation.

4. As a group, conduct a VMEA analysis by inputting the results into the VMEA sheet.

Exercise: Paper clip fatigue

	30 degrees	*45 degrees*
mean	4.0	2.9
standard deviation	0.69	0.88
number of obs.	6	6
Fatigue strength at 30 degrees	**4.0**	
Log life scatter	**0.69**	
t-correction	**1.3**	
Log life scatter pooled	0.79	
t-correction pooled	1.1	
Fatigue strength at 45 degrees	2.9	
Sensitivity coefficient	**0.071**	
Load variation (sd)	**5.77**	
Target log life	**1.61**	

= tinv(0.05,5)/1.96

= (4.0-2.9)/15

= 10/sqrt(3)

Exercise: Paper clip fatigue

	30 degrees	45 degrees
mean	4.0	2.9
standard deviation	0.69	0.88
number of obs.	6	6
Fatigue strength at 30 degrees	**4.0**	
Log life scatter	**0.69**	
t-correction	**1.3**	
Log life scatter pooled	0.79	
t-correction pooled	1.1	
Fatigue strength at 45 degrees	2.9	
Sensitivity coefficient	**0.071**	
Load variation (sd)	**5.77**	
Target log life	**1.61**	

The first row in the VMEA sheet represents uncertainty due to scatter.

1. The calculated standard deviation “Log life scatter” is placed in the s-cell.
2. The t-correction number is put in the t-cell.
3. The sensitivity coefficient is put to unity.
4. The type of uncertainty is marked as a cross in the correct cell.

Input						**Result**		
Uncertainty components	**scatter**	**uncert.**	**Sensitivity coefficient c**	**correction factor t**	**standard deviation s**	**Scatter**	**Uncertainty**	**Total**
Strength								
Scatter								
Nominal fatigue strength								
Total Strength uncertainty						**0.000**	**0.000**	**0.000**
Load								
Variation in usage								
Total Load uncertainty						**0.000**	**0.000**	**0.000**
Total uncertainty						**0.000**	**0.000**	**0.000**

Exercise: Paper clip fatigue

	30 degrees	45 degrees
mean	4.0	2.9
standard deviation	0.69	0.88
number of obs.	6	6
Fatigue strength at 30 degrees	**4.0**	
Log life scatter	**0.69**	
t-correction	**1.3**	
Log life scatter pooled	0.79	
t-correction pooled	1.1	
Fatigue strength at 45 degrees	2.9	
Sensitivity coefficient	**0.071**	
Load variation (sd)	**5.77**	
Target log life	**1.61**	

The second row in the VMEA sheet represents uncertainty in the estimated life.

1. The standard deviation is divided by the square root of the number of tests and put in the s column.
2. The t-correction number is the same as for the scatter
3. The sensitivity coefficient is put to unity.
4. The type of uncertainty is marked as a cross in the correct cell.

Input						**Result**		
Uncertainty components	**scatter**	**uncert.**	**Sensitivity coefficient c**	**correction factor t**	**standard deviation s**	**Scatter**	**Uncertainty**	**Total**
Strength								
Scatter								
Nominal fatigue strength								
Total Strength uncertainty						**0.000**	**0.000**	**0.000**
Load								
Variation in usage								
Total Load uncertainty						**0.000**	**0.000**	**0.000**
Total uncertainty						**0.000**	**0.000**	**0.000**

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Exercise: Paper clip fatigue

	30 degrees	45 degrees
mean	4.0	2.9
standard deviation	0.69	0.88
number of obs.	6	6
Fatigue strength at 30 degrees	**4.0**	
Log life scatter	**0.69**	
t-correction	**1.3**	
Log life scatter pooled	0.79	
t-correction pooled	1.1	
Fatigue strength at 45 degrees	2.9	
Sensitivity coefficient	**0.071**	
Load variation (sd)	**5.77**	
Target log life	**1.61**	

The first row under the Load heading represents the variation in usage

1. The Load variation number is put in the s-cell.
2. The t-correction number is unity
3. The Sensitivity coefficient is put in the c column.
4. The type of uncertainty is marked as a cross in the correct cell.

Input						**Result**		
Uncertainty components	**scatter**	**uncert.**	**Sensitivity coefficient c**	**correction factor t**	**standard deviation s**	**Scatter**	**Uncertainty**	**Total**
Strength								
Scatter								
Nominal fatigue strength								
Total Strength uncertainty						**0.000**	**0.000**	**0.000**
Load								
Variation in usage								
Total Load uncertainty						**0.000**	**0.000**	**0.000**
Total uncertainty						**0.000**	**0.000**	**0.000**

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Exercise: Paper clip fatigue

Reliability Evaluation

Input		**Result**		**Result (log-scale)**	
Median life (reversals)	1	Safety factor	1,00	Life	0,00
Target life (reversals)	1			Target life	0,00
				Distance	0,00
Evaluation - Extra safely factor		Variation safety factor	1,00	Variation dis	0,00
Required extra safety factor	2	Extra safety factor	1,00	Extra dist.	0,00

- The fatigue strength at 30 degrees is put in the life cell (log scale).
- The target log life is put in the Target life cell.
- The spreadsheet then calculates the nominal safety factor and compares it with the calculated statistical safety factor and the demanded extra safety factor.

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RELIABILITY IN A SEA OF RISK

Day 1

Review and wrap up

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THE EUROPEAN MARINE ENERGY CENTRE LTD

SP your Science Partner

CATAPULT
Offshore Renewable Energy

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RELIABILITY IN A SEA OF RISK

Please join us for tea at The Dhabba,
44 Candleriggs, Merchant City, at 7pm.

08:00 Arrival for Day 2

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