EERA DeepWind'2016, 13th Deep Sea Offshore Wind R&D Conference

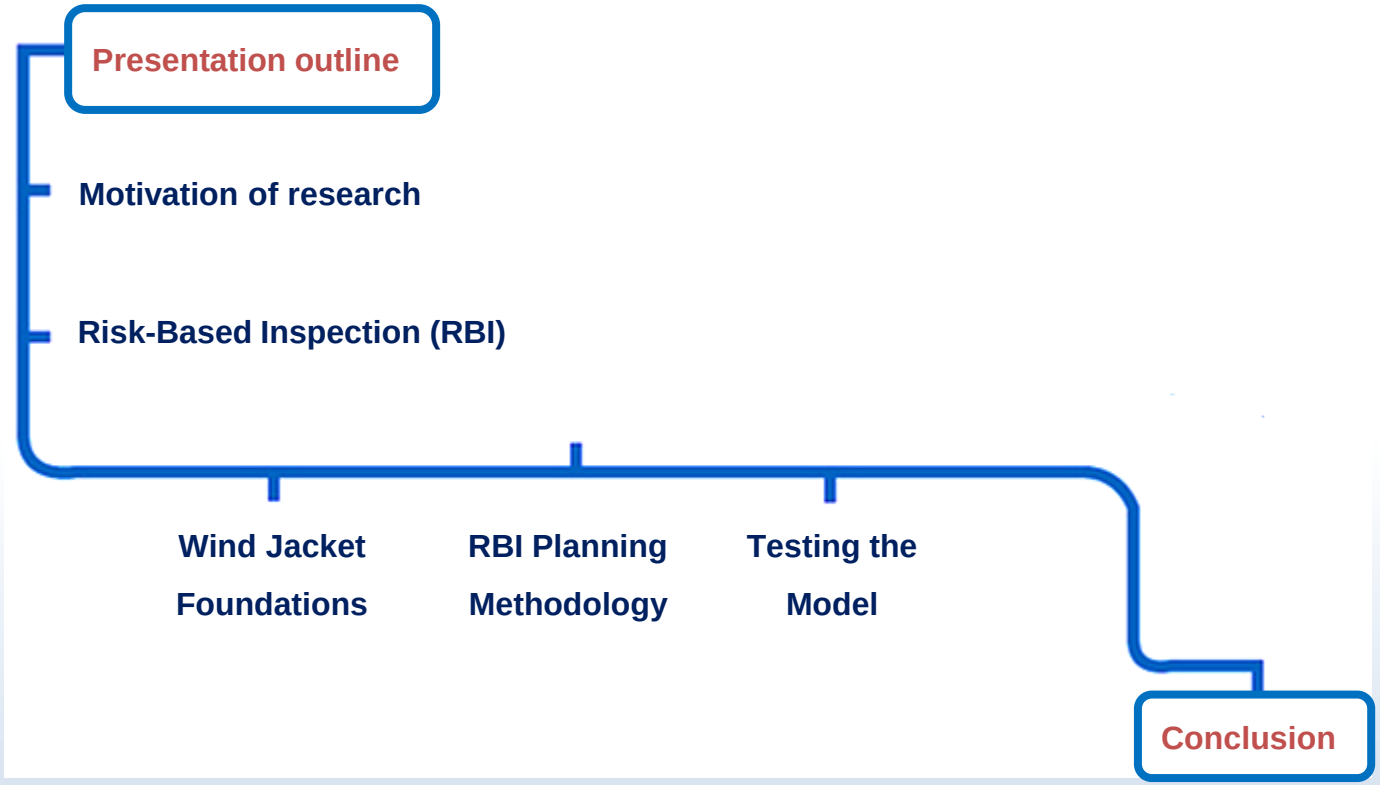
A Risk-Based Inspection Methodology for Offshore Wind Jacket Structures

Mahmood Shafiee

Lecturer in Engineering Risk, Reliability & Maintenance

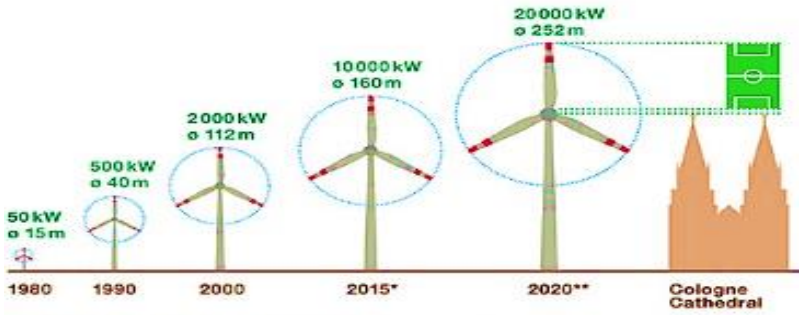
Cranfield University, UK

m.shafiee@cranfield.ac.uk


Presentation outline
Motivation of research
Risk-Based Inspection (RBI)
Wind Jacket Foundations
RBI Planning Methodology
Testing the Model
Conclusion

Motivation

- NREL , EWEA
  Offshore wind energy has experienced an exponential growth worldwide over the past decade
- The installed offshore wind energy capacity continues to rise
- 2004: 622 MW → 2014: 8 GW (annual growth rate of around %30)



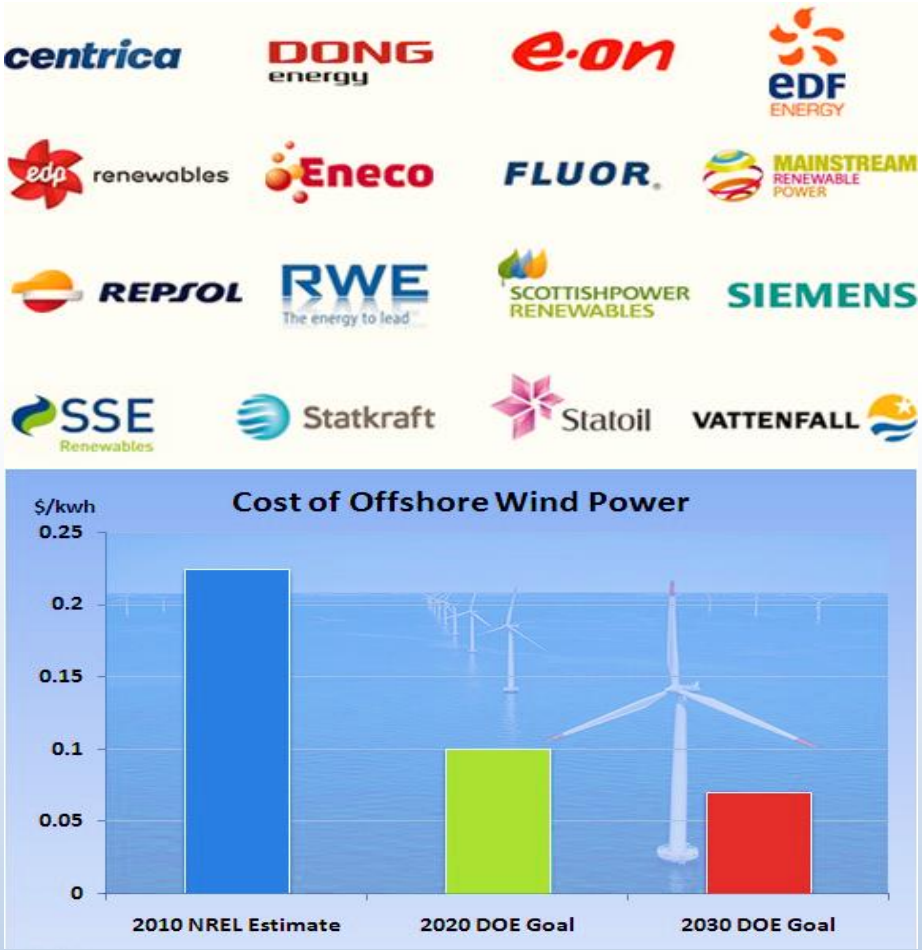
Cumulative installed capacity of offshore wind power in the European Union (EU)

Motivation

- ***Cost reduction*** is of increasing importance for all offshore wind energy players

- To make the electricity generated by offshore wind turbines more price-competitive

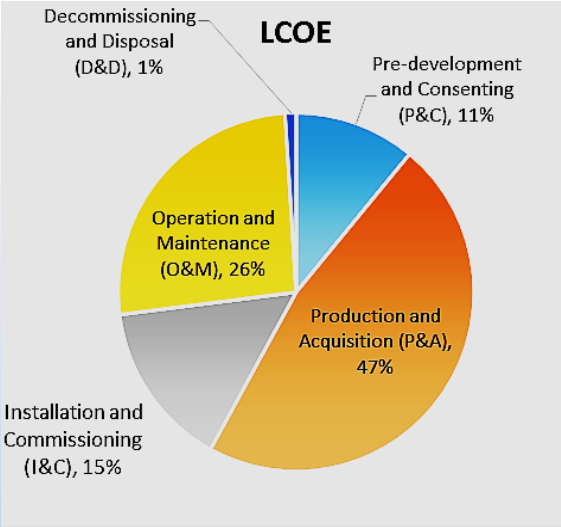
- The cost per kilowatt hour of electricity generated by offshore wind turbines is approximately 22 cents, but it should reduce to 7 ¢/kwh by 2030



22 ¢/kwh → 7 ¢/kwh ?

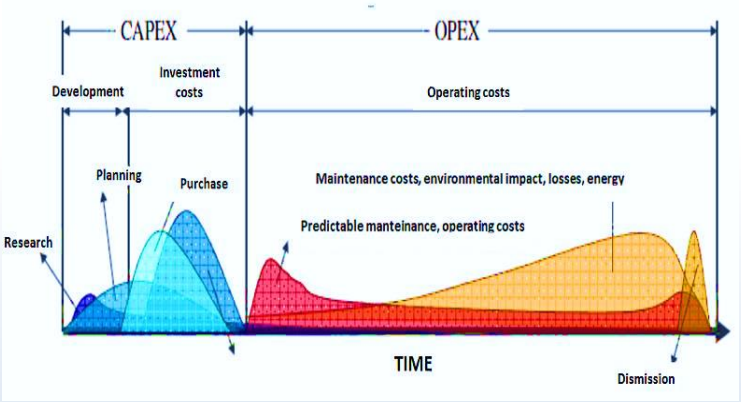
Motivation

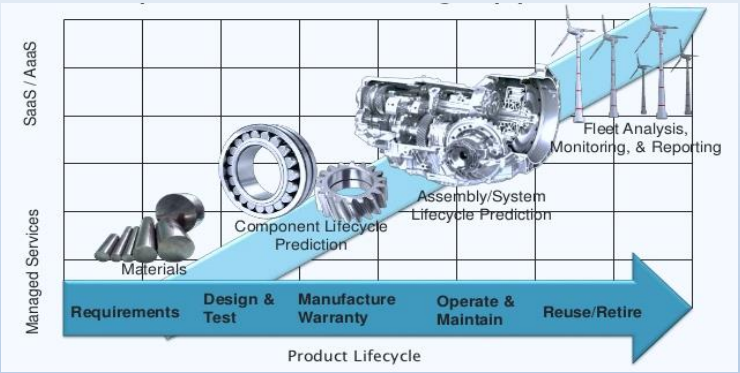
- operation and maintenance (O&M) costs account for about 25 to 40% of the overall energy generation cost
- A significant portion of annual maintenance budget is wasted due to insufficient or inefficient maintenance activities



Cost drivers of a typical 5MW offshore wind turbine

• One of the most effective ways to minimize the inspection & repair costs is to apply risk-based inspection methods and tools



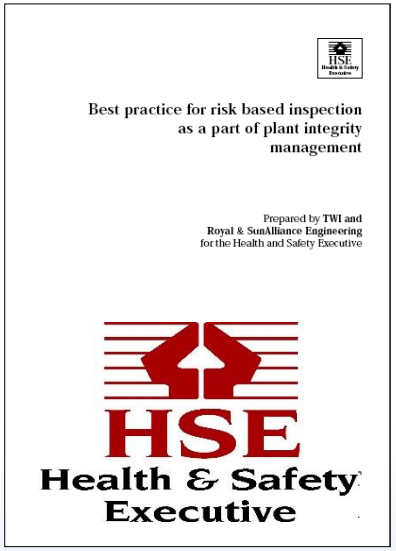


Risk-Based Inspection (RBI)

- Risk-based Inspection technique has been applied to a wide range of industries

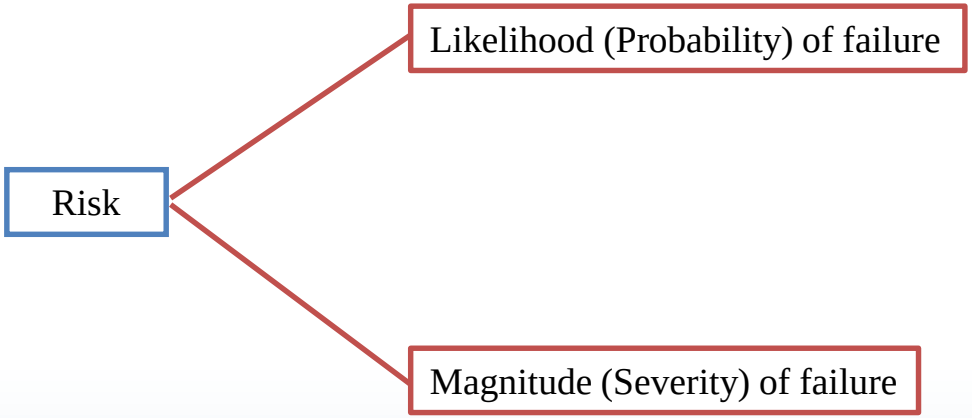
- Many institutes and organizations (like HSE, API, DNVGL, ABB, TWI) have developed risk-based inspection solutions for different structures by taking into account the regulatory requirements and guidelines (e.g. API RP 580 ; DNVGL-RP-C210)

- The main aim of RBI tool is to achieve safe operating conditions at minimum inspection cost, and protect human life and the environment from any possible damage during operation



Risk-Based Inspection (RBI)

Risk is a combination of *likelihood* and *magnitude*



How could risk assessment information be used in making more cost-effective inspection decisions?

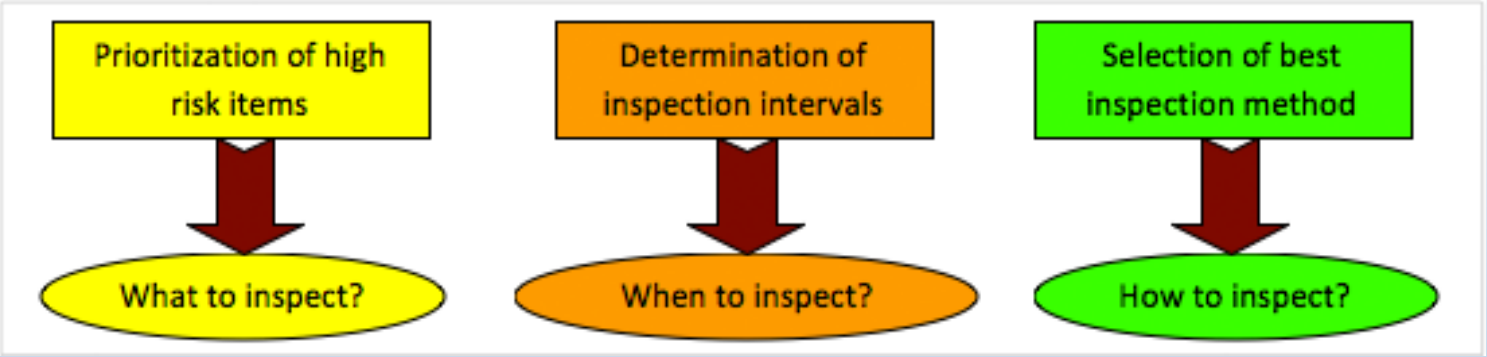
Is this cost-effective to choose same inspection strategy for high / medium / low risk assets?

		Impact				
		Trivial	Minor	Moderate	Major	Extreme
Probability	Rare	Low	Low	Low	Medium	Medium
	Unlikely	Low	Low	Medium	Medium	Medium
	Moderate	Low	Medium	Medium	Medium	High
	Likely	Medium	Medium	Medium	High	High
	Very likely	Medium	Medium	High	High	High

M Shafiee

Risk-Based Inspection (RBI)

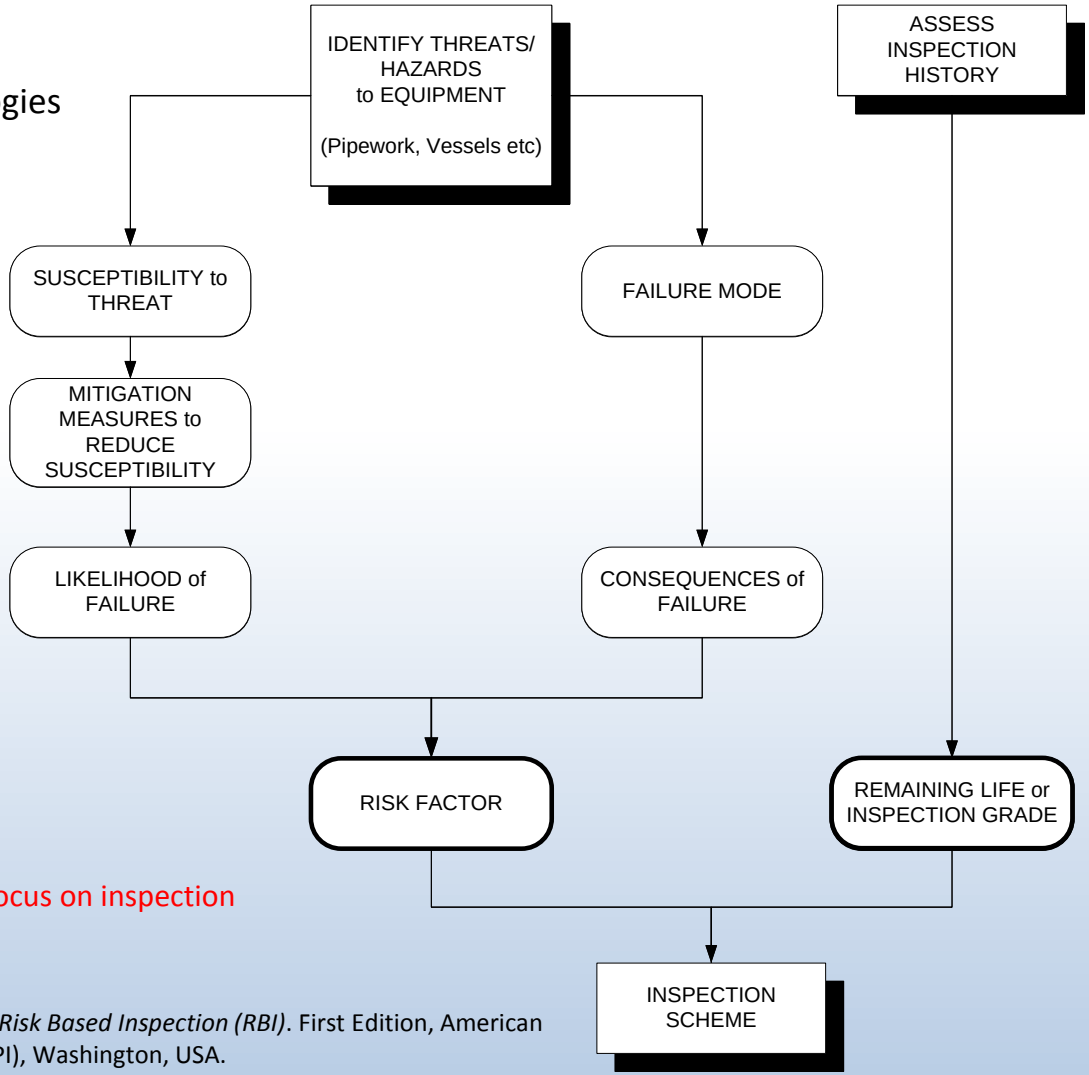
- RBI is a technique which prioritises inspection tasks according to the information provided by risk assessment procedure
- RBI is a technique which determines the frequency of inspection for different assets based on their criticality levels
- RBI is a technique which assists inspectors to find the most appropriate inspection method for assets



API RP 580 Methodology

There are several RBI methodologies available in energy industries

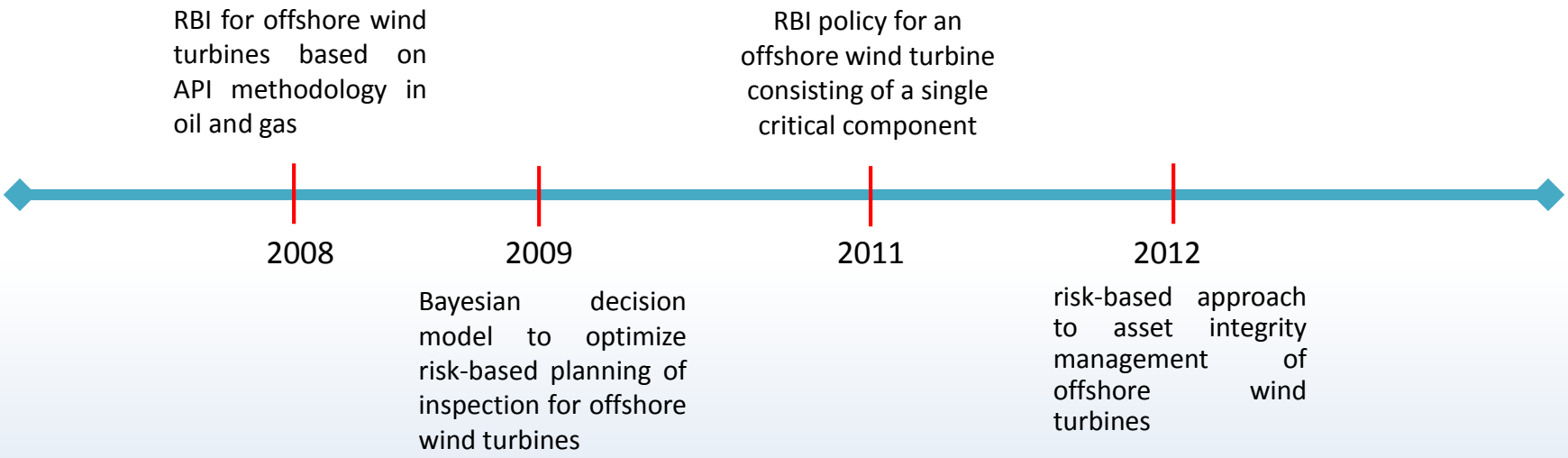
Topside facilities
Onshore Terminals
Subsea Pipeline



The larger the risk level, the more the focus on inspection

Ref: API RP 580 (2002) *Risk Based Inspection (RBI)*. First Edition, American Petroleum Institute (API), Washington, USA.

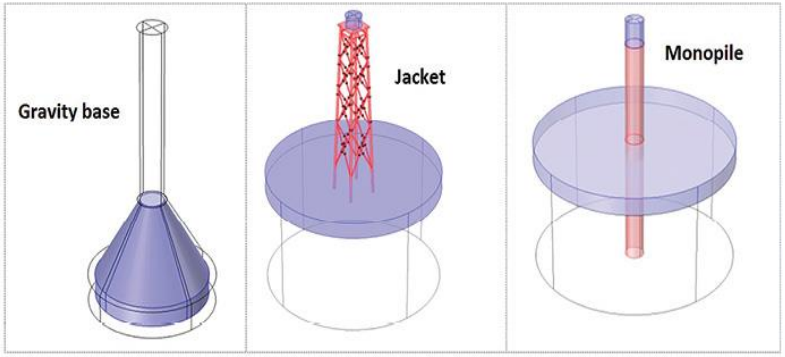
RBI Applications to Wind Energy Structures



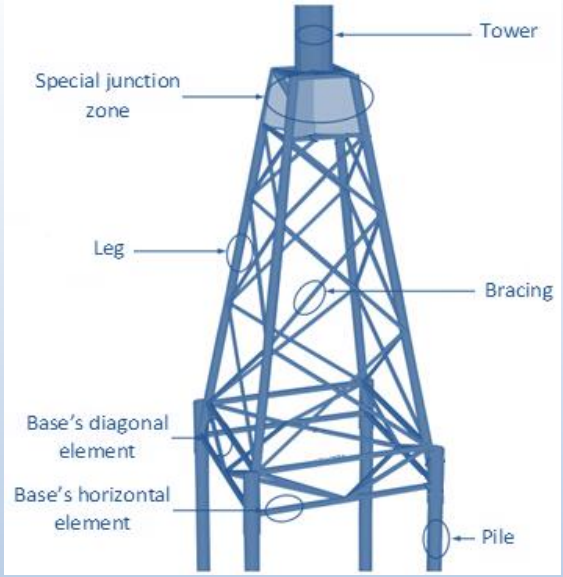
To the best of authors' knowledge, there have been few attempts made by researchers on developing RBI optimization methodologies for offshore wind jacket structures

Offshore Wind Jacket Structures

- **Jacket structures** are one of the most common fixed structures used in the offshore oil and gas and wind energy industries. The number of installations is steadily increasing every year as the offshore energy market continues to rise



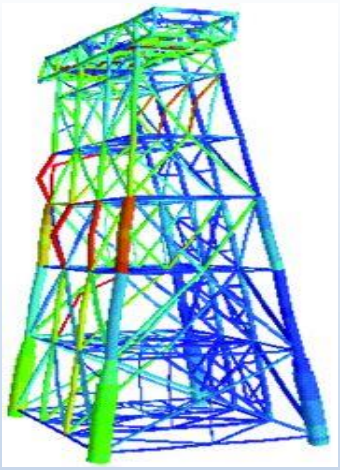
- A jacket support structure is a welded tubular space frame consisting of three or more near-vertical legs supported by a lateral bracing system



M Shafiee

Offshore Wind Jacket Structures

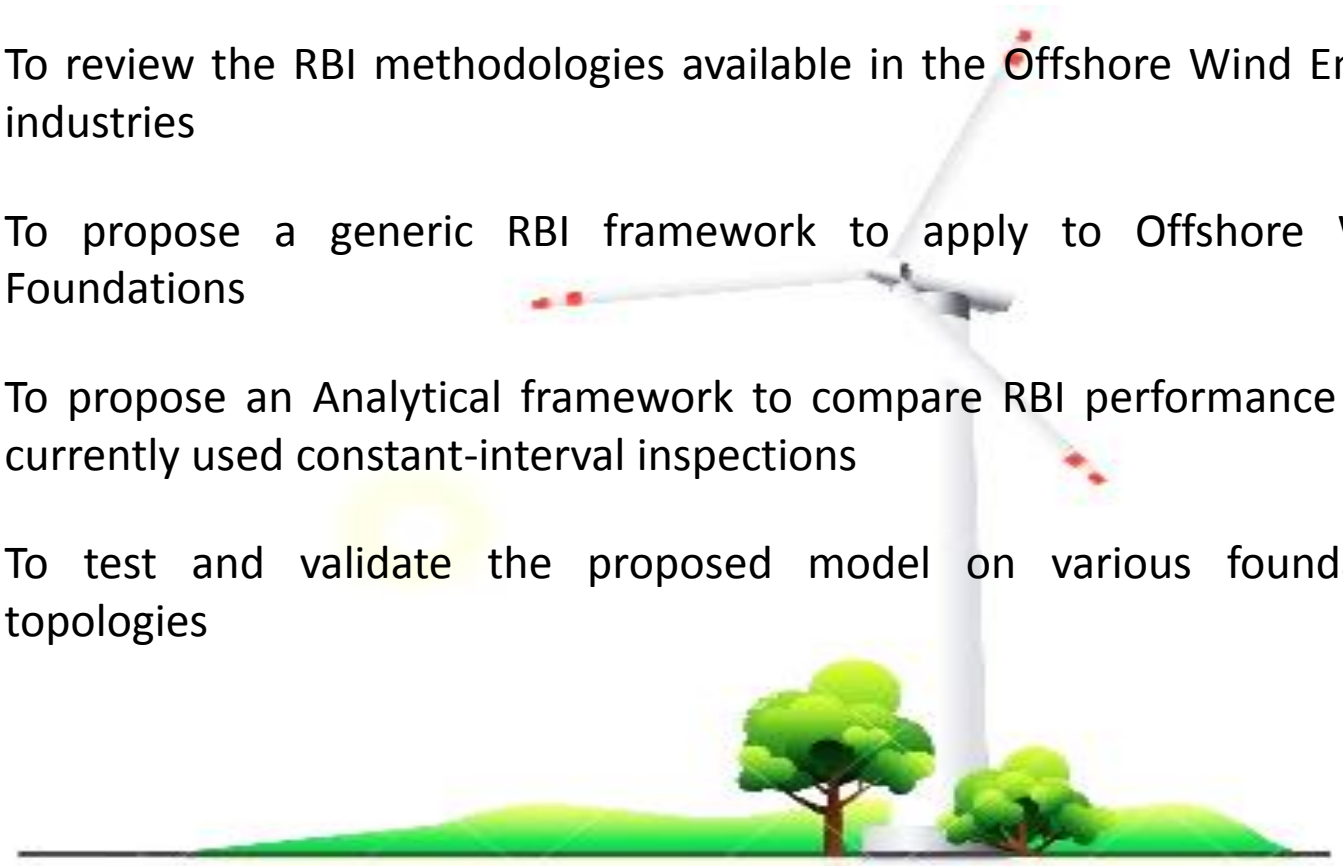
- The function of a jacket structure is to support the topside facilities or wind turbines and to serve as a template for the foundation system. These structures can transfer the loads from the topside to the seabed through the driven piles
- The offshore jacket structures should be designed with ***sufficient strength and*** stiffness to withstand the wind and wave forces, forces due to current acting on the sea, tides, temperature forces, ice forces, earthquakes, etc.

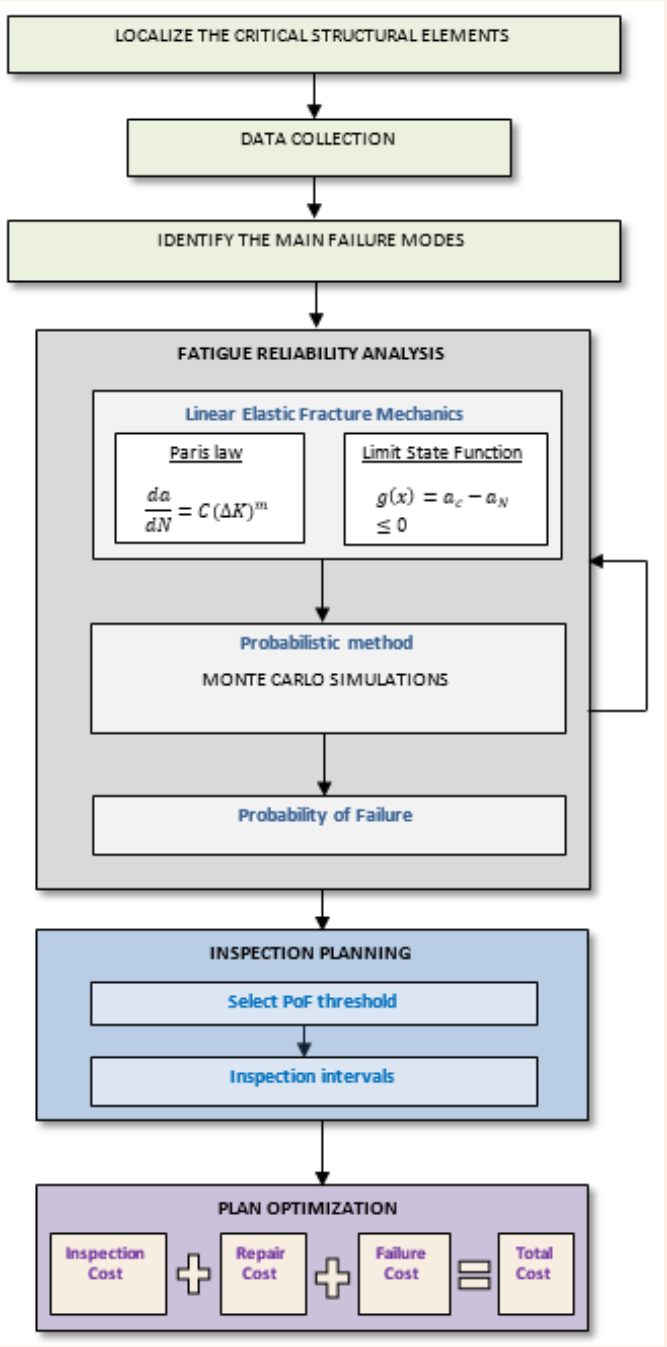


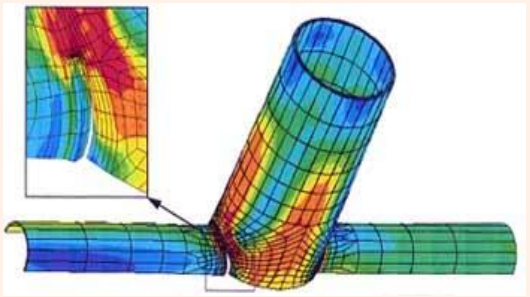
Wind turbine substructures (jackets)

Aims and Objectives

- To review the RBI methodologies available in the Offshore Wind Energy industries
- To propose a generic RBI framework to apply to Offshore Wind Foundations
- To propose an Analytical framework to compare RBI performance with currently used constant-interval inspections
- To test and validate the proposed model on various foundation topologies



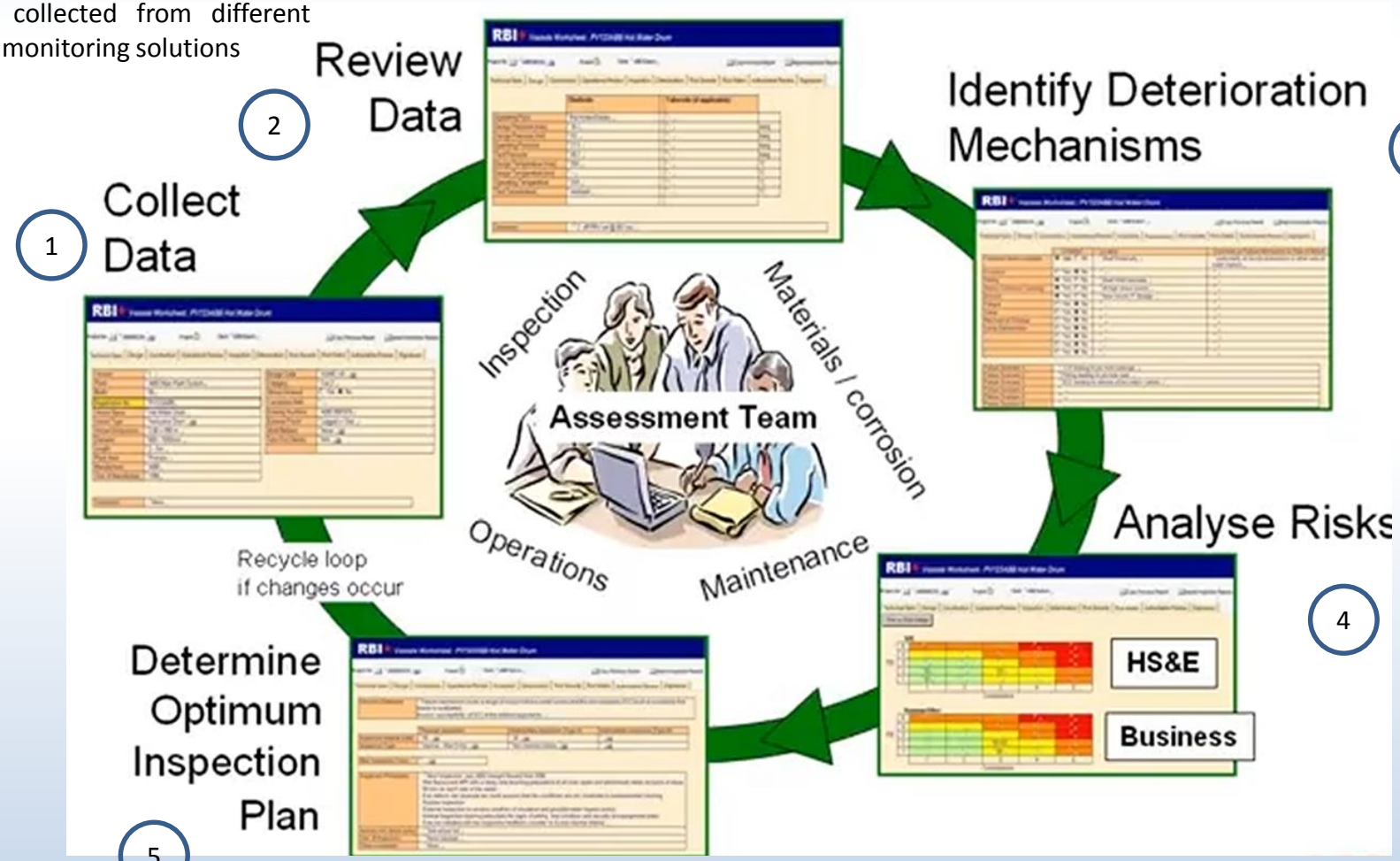

LOCALIZE THE CRITICAL STRUCTURAL ELEMENTS
DATA COLLECTION
IDENTIFY THE MAIN FAILURE MODES
FATIGUE RELIABILITY ANALYSIS
Linear Elastic Fracture Mechanics
Paris law
$\frac{da}{dN} = C(\Delta K)^m$
Limit State Function
$g(x) = a_c - a_N \leq 0$
Probabilistic method
MONTE CARLO SIMULATIONS
Probability of Failure
INSPECTION PLANNING
Select PoF threshold
Inspection intervals
PLAN OPTIMIZATION
Inspection Cost
Repair Cost
Failure Cost
Total Cost



RBI Methodology

The condition assessment data (e.g., sea-state data, deterioration modes and causes, damage propagation, etc.) are collected from different condition monitoring solutions

Different damage mechanisms are identified and the associated root causes are investigated



The level of risk of failure for wind foundations is used to schedule appropriate inspection and preventative repair tasks

The risk of potential damage to foundation is evaluated by combining the likelihood of structural damage and the magnitude of consequences

M Shafiee

RBI Methodology

Data collection & review

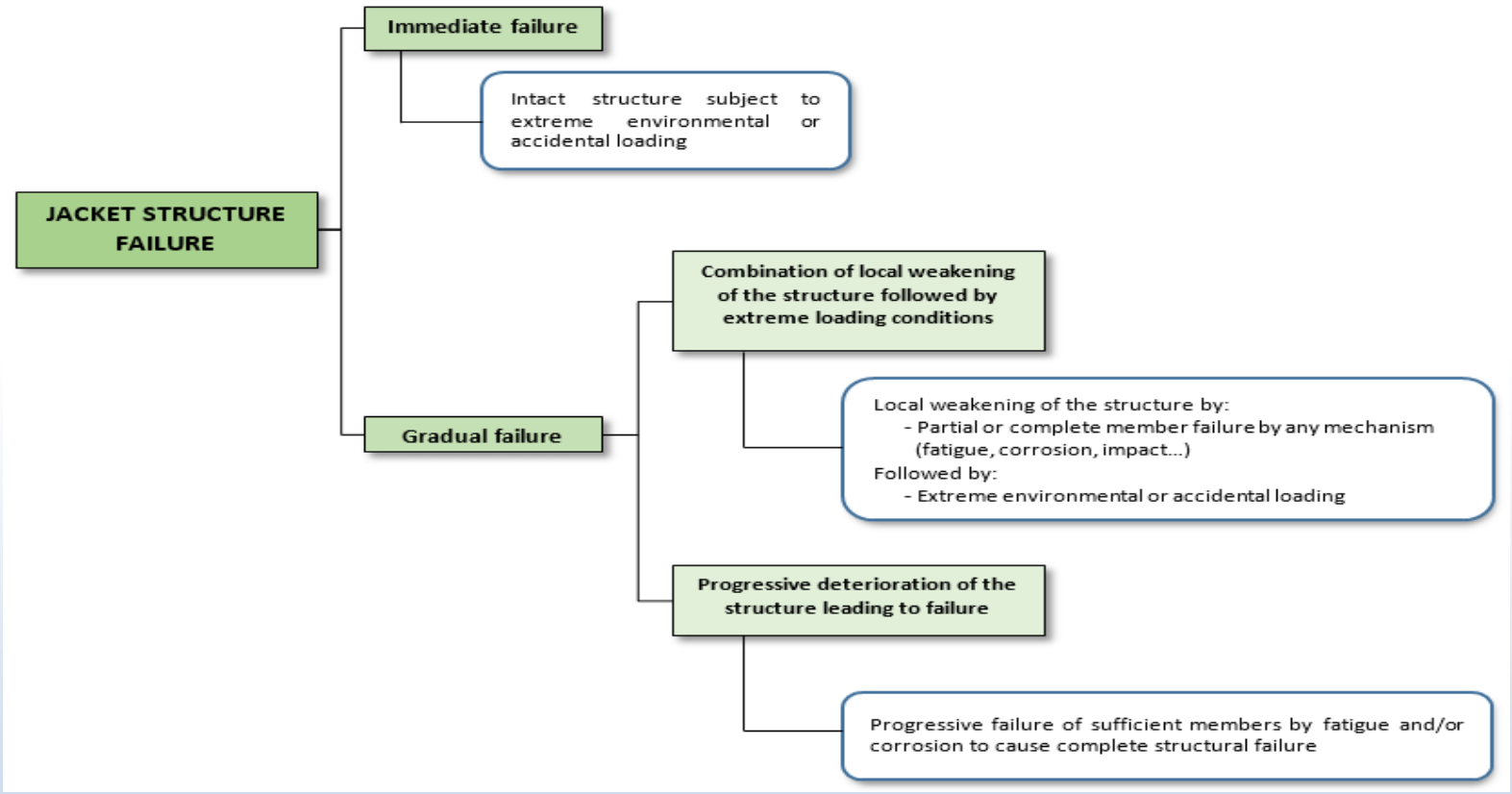
Collect data and populate the RBI document to include:

- Technical Specification – Type of Jacket, Design codes, etc.
- Operating Conditions – Temperature, pressure, weather conditions
- Construction – Material Specification, Thickness, Corrosion Allowance.
- Inspection History – Previous Reports, Repairs, Modifications.

Discussion and review of the data to agree, add and amend as necessary to form an accurate record of the jacket condition and operating parameters

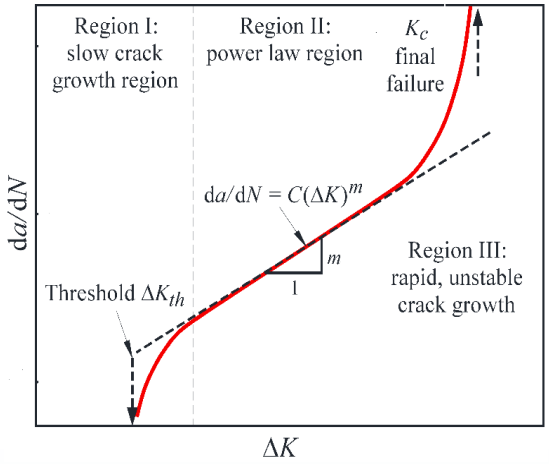
RBI Methodology

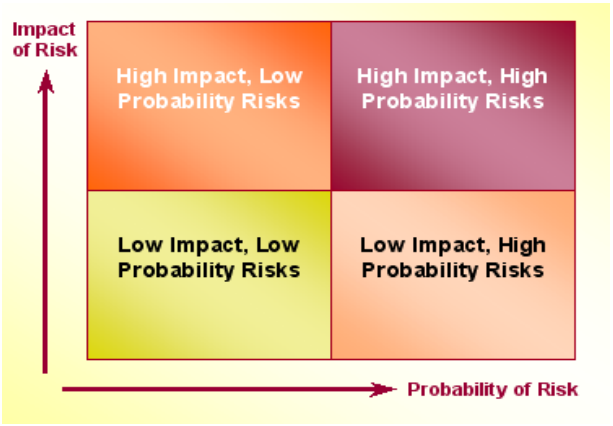
Identification of Damage Mechanisms and Root Causes

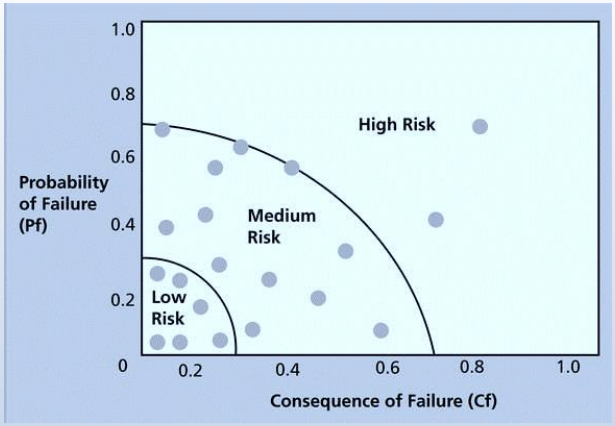


RBI Methodology

Risk (Or PoF) Analysis





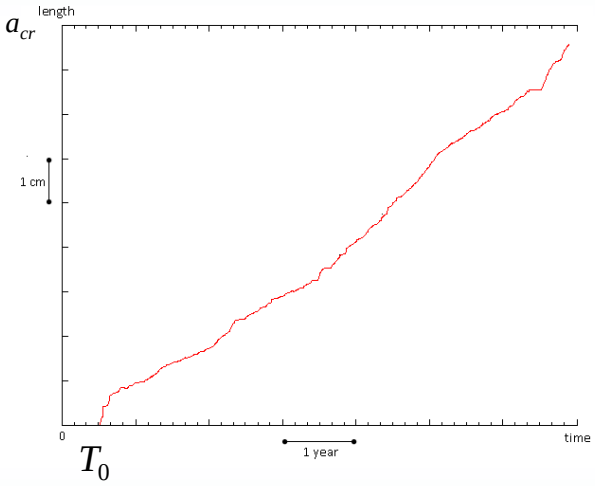


- Qualitative approach
  - Based on descriptive data using engineering judgement and experience

- Quantitative approach (Black box)
  - Based on probabilistic or statistical models

RBI Methodology

Risk (Or PoF) Analysis



Time of failure

Specified time

Critical crack depth

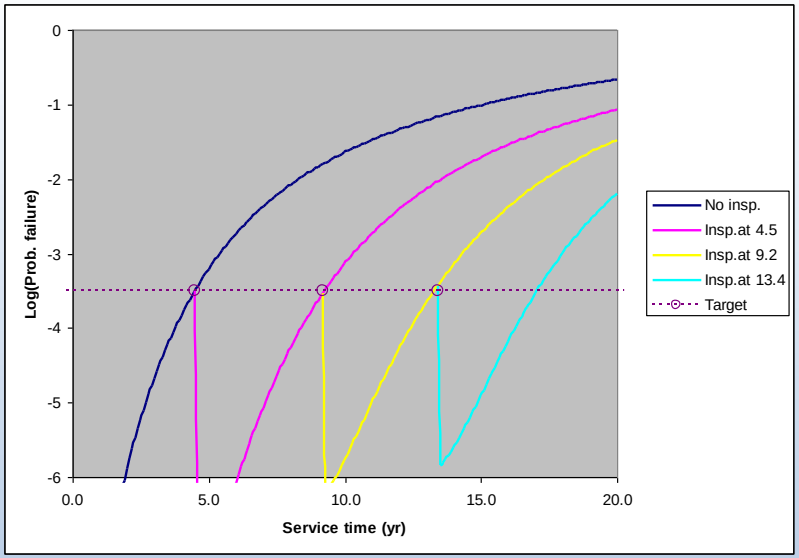
Crack depth at time *t*

$$P\left[T_f \le t\right] = P\left[a_{cr} - A(t) < 0\right]$$

$$= P\left[T_0 + T_G(a_{cr}) - t < 0\right]$$

Time for crack initiation

Time for crack growth to critical depth



RBI Methodology

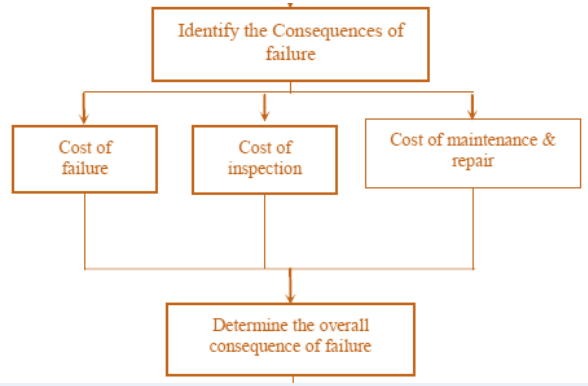
Failure Cost Analysis

Three cost factors are considered for this purpose:

C_I: cost of inspection

C_R: cost of imperfect repair

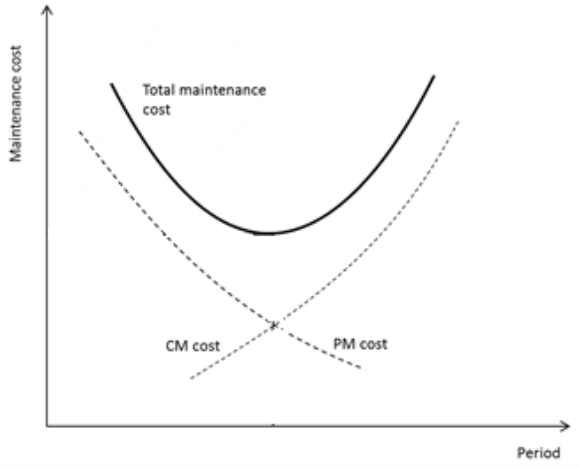
C_F: cost of failure



$$C_T = \sum[C_I(t) + C_R(t) + C_F(t)] \times (1+r)^t$$

RBI Methodology

Optimal Inspection Planning



Determine an Optimum Inspection Plan:

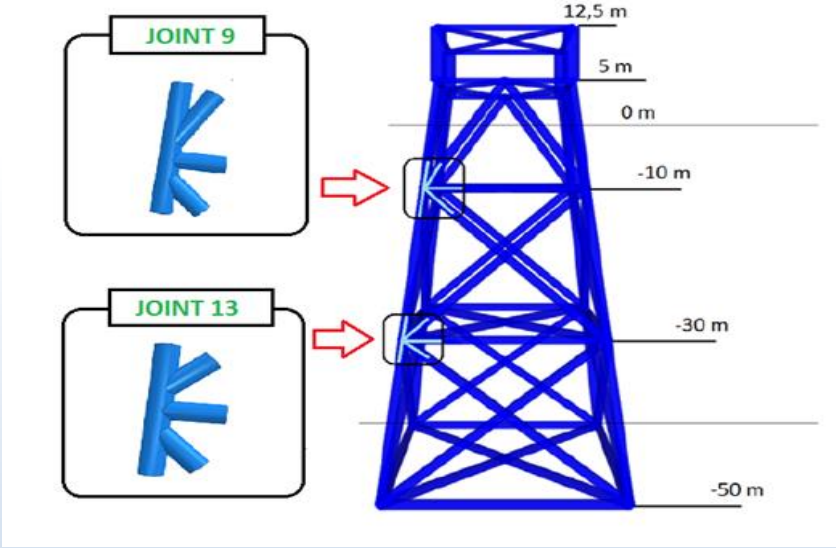
Min C_T

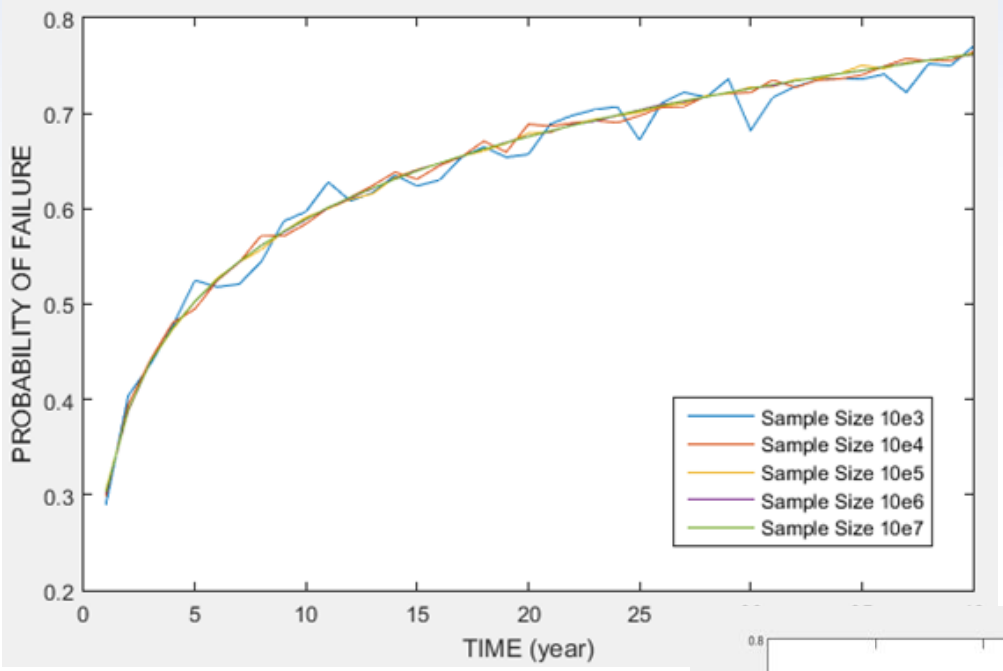
S.t. $R \geq R_0$

- Focus effort on high risk assets
- Choose appropriate inspection techniques for each identified deterioration mechanism
- Identify appropriate periodicities
- Consider ways to reduce risk (Inspection does not reduce consequence!)

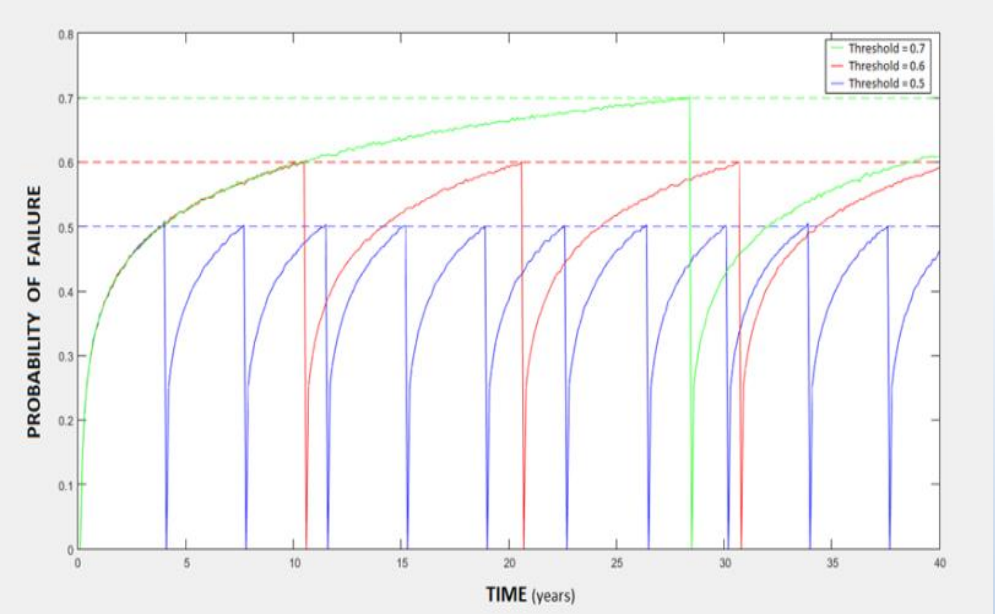
Application

The proposed RBI planning methodology is being applied to two welded tubular joints of a steel jacket structure

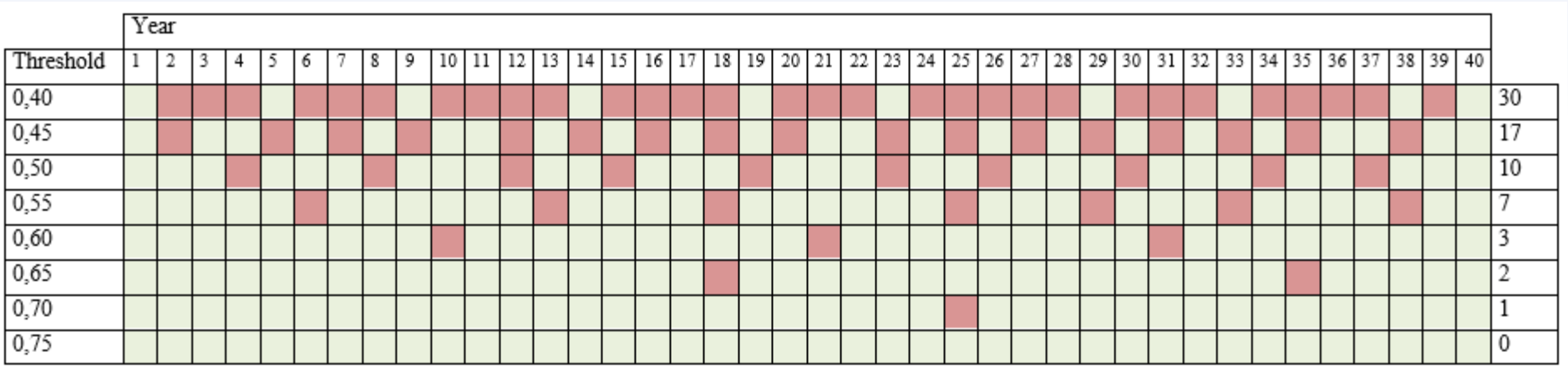




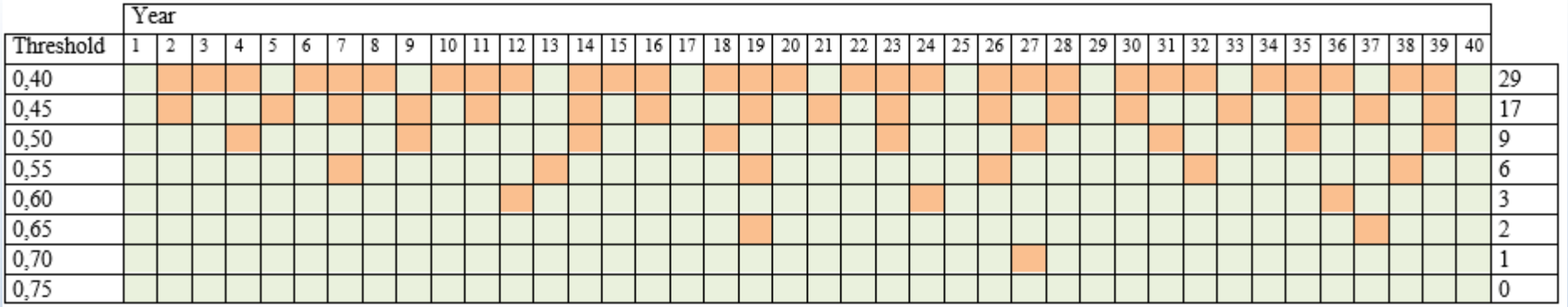
Likelihood of failure for joint 9 using MCS technique



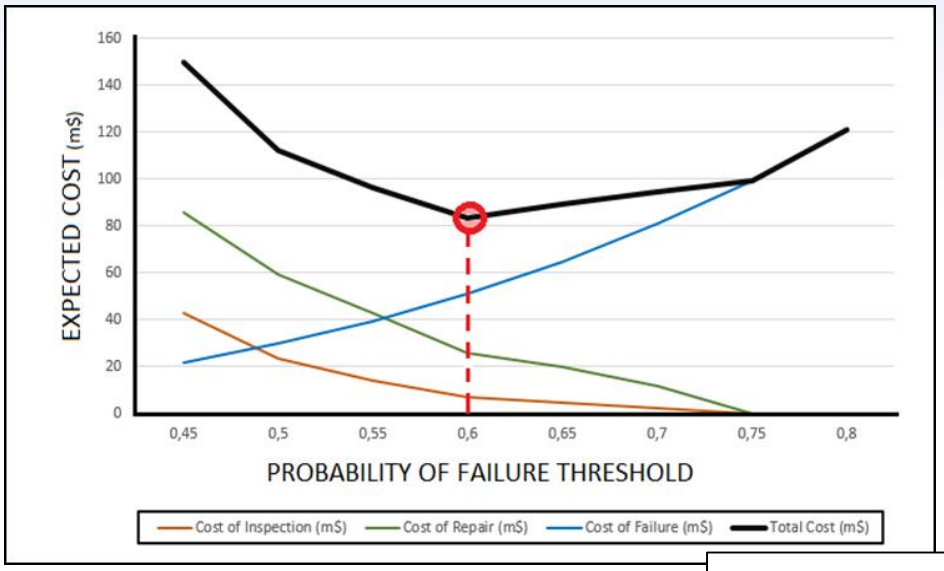
Inspection plan on the basis of likelihood of failure

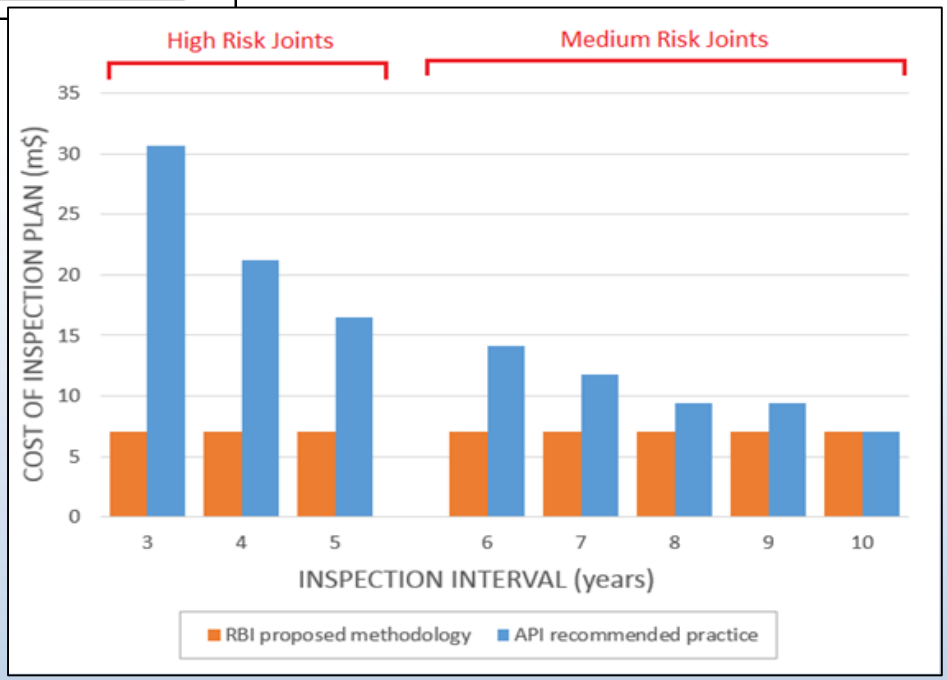


Inspection schedule of joint 9 for different POF thresholds



Inspection schedule of joint 13 for different POF thresholds


EXPECTED COST (m$)
160
140
120
100
80
60
40
20
0
0,45
0,5
0,55
0,6
0,65
0,7
0,75
0,8
PROBABILITY OF FAILURE THRESHOLD
Cost of Inspection (m$)
Cost of Repair (m$)
Cost of Failure (m$)
Total Cost (m$)


High Risk Joints
Medium Risk Joints
COST OF INSPECTION PLAN (m$)
35
30
25
20
15
10
5
0
3
4
5
6
7
8
9
10
INSPECTION INTERVAL (years)
RBI proposed methodology
API recommended practice

Conclusion

- The existing RBI methodologies in the wind energy industry were reviewed
- A generic RBI methodology for offshore wind jacket structures was proposed
- The performance of the proposed RBI methodology (in terms of cost) was compared with constant-interval inspections suggested by API

Thank you for your attention

&

welcome your questions!

Mahmood Shafiee

m.shafiee@cranfield.ac.uk