Risk Assessment in Engineering

Principles, System Representation & Risk Criteria

Annex

Example – Risk Based Inspection of Offshore Structures

JCSS
Joint Committee on Structural Safety

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1 Description of the Example Structure – a Floating Production Storage and Offloading Unit – and definition of the problem

An in-service FPSO is considered for analysis in this paper. Layout and mid-ship section of the unit are shown in figures 1 and 2.

Figure 1: FPSO Layout (cargo region)

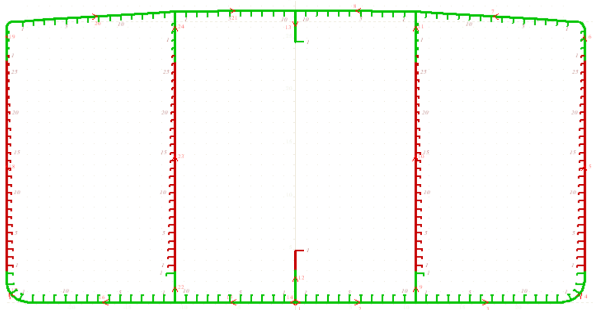

Figure 2: mid-ship FPSO section

Overall length is 344 m, moulded breath and depth are respectively equal to 52 m and 27 m. The scantling moulded draught is equal to 21m. The unit was designed according to usual rules of classification societies and is under class regime during the service life: maintenance of class is assured via annual, intermediate and special surveys where general visual inspection, close-visual inspection and thickness measurements are undertaken with the objective to guarantee that structural integrity of the unit is always kept within acceptable limits.

Inspections are undertaken using prescriptive rules from classification societies. These prescriptive rules deal with inspection frequency and scope of inspection. They are based on experience accumulated by Classification Societies and IACS (International Association of Classification Societies) for more than 150 years. Special surveys are performed in general each 5 years and intermediate surveys each 2.5 years. In case where damages are found during inspection, owners have to follow recommendations from surveyors of classification societies. Maintenance of class is delivered under the condition owners follow these recommendations (for example steel renewal of highly corroded elements, crack repairs, monitoring of damaged elements).

In this example it is shown how Risk Analysis may be used in inspection planning either as alternative to prescriptive rules or as complement to prescriptive rules. Risk Analysis is applied to the cargo region of the unit.

2 Main steps of risk analysis

Main steps of Risk Analysis as applied in this example are:

Step 1: Risk Acceptance Criteria
Step 2: Cargo area subdivision and definition of inspection plans
Step 3: Annual damage state of the unit taking into account:
- degradation mechanisms (general corrosion, pitting, fatigue)
- inspection planning
- mitigation strategy

Step 4: Risk Analysis of the unit on an annual basis:
- using damage states determined in step 3
- using **B**ayesian **P**robabilistic **N**etworks (BPN) for structural and explosion analyses

Step 5: Optimisation

Keystone characteristic of the approach lies in the fact state of the art in terms of Risk Based Inspection methodology, advanced Risk Analysis approaches as developed by the Joint Committee on Structural Safety and Probabilistic tools as BPN are merged together for solving the inspection problem:

- RBI approach is based on decision/event tree to be used for pre-posterior analysis as explained in [1] and [2]
- System modelling is based on a hierarchical modelling where the hull is defined as a system of sub-systems. This hierarchical modelling is in accordance to system representation as recommended in [1]
- Probability calculations are performed using Bayesian Networks, which are built using hierarchical modelling developed for structural integrity and explosion.

General procedure for selecting optimal inspection plan for the unit is shown in figure 3:

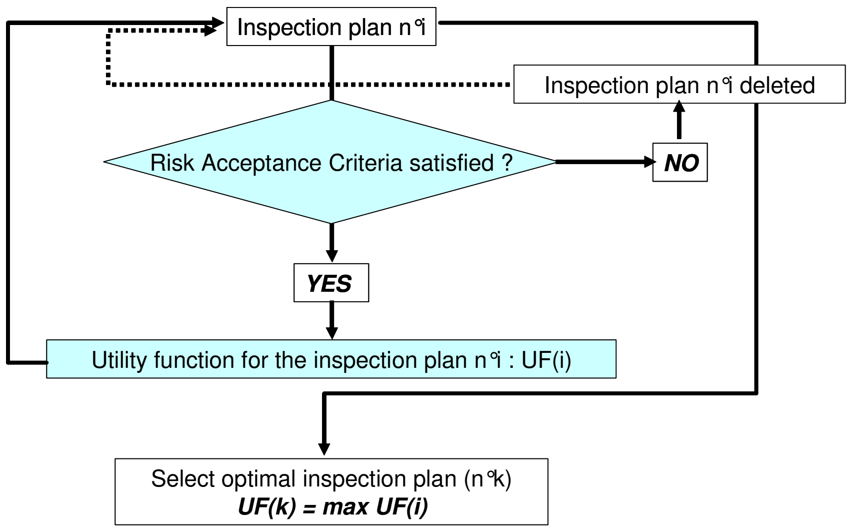

Figure 3: General optimisation procedure for inspection planning

The utility function UF in this example is the total expected cost associated to a given inspection plan. This total expected cost includes the cost of inspection, the cost of repair and the cost of failure.

3 Hierarchical modelling and Bayesian Probabilistic Network

Objective of the BPN is to:

- calculate the consequences of component failures in terms of loss of lives, environment and economics
- check the Risk Acceptance Criteria (Loss of lives, Environment) as defined at system level
- calculate the utility function (Economics) associated to each inspection plan and select the optimal one.

In order to facilitate Risk Analysis, the hull of FPSO is modelled using a ***hierarchical model***. This hierarchical model allows for determining event scenarios which start at the lowest level (initial event defined at component level), go trough the hierarchical model and end at the highest level (terminal event - dealing with the hull as a whole – which is analysed in terms of final consequences: loss of lives, environment, economics).

The BPN performs its calculations via the hierarchical model. Input data are:

- the hierarchical model itself
- probabilities and conditional probabilities along event scenarios
- consequences associated with terminal events (loss of lives, environment, economics)

The hierarchical model was developed based on two considerations: loss of structural integrity and explosion

Structural integrity

From the structural integrity point of view (loss of strength capacity) the hierarchical model is based on the Bureau Veritas Rules for the Classification of Steel Ships (Part A, Chapter 2, Appendix 3) – see [4] - , where some acceptance criteria are defined to be used for determining permissible diminutions of the different structural parts of the ship hull (admissible wastage %). Following this philosophy, each structural item is to be assessed according to four different levels / criteria: isolated area, item, group of items and zone. In order to clarify these concepts, the definition of each of them is presented hereafter:

Isolated Area: It is a part of a single structural item. This criterion takes into consideration very local aspects such as grooving of a plate or web, or local severe corrosion; however, it is not to be used for pitting for which separate criteria are considered.

Item: It is an individual element such as a plate, a stiffener, a web, etc. This criterion takes into consideration the average condition of the item, which is assessed by determining its average thickness using the various measurements taken on the same item.

Group of Items: It is a set of elements of the same nature (plates, longitudinal, girders) contributing either to the longitudinal global strength of the ship in a given zone or to the global strength of other primary transverse members not contributing to the ship longitudinal strength, e.g. bulkheads, hatch covers, web frames.

Zone: All and only longitudinal elements contributing to the longitudinal strength of the ship; in this regard, the three main zones are defined as ‘deck zone’, ‘neutral axis zone’ and ‘bottom zone’. This criterion takes into consideration the average condition of all groups of items belonging to the same zone.

Due to the great number of structural items within the cargo region, the proposed hierarchical model for the FPSO includes only the ‘group of items’ and ‘zone’ levels. It would not be practicable to build a hierarchical model including also the ‘item’ level’ (for the entire cargo region) from both timing and computational capacity points of view.

The hierarchical model for the FPSO is given in figures 4 and 5. The structural integrity hierarchical model was built considering the tank per tank and boundaries concept. Each boundary of each tank is defined as a reinforced panel (plating + secondary stiffeners + primary members). It is important to point out that some boundaries are shared between 2 adjacent tanks (longitudinal and transversal bulkheads).

A part of the BPN is show in figure 6 which deals with Side Shell (Portside). The nodes in light blue colour represent the basic degradation mechanisms: general corrosion, pitting and fatigue/cracking. These degradation mechanisms lead to strength reduction of plating, secondary stiffeners and web frames (nodes in green). The nodes in pink and yellow colour are related to the global strength reduction of the reinforced panel under consideration.

Explosion

From the explosion point of view, the hierarchical model uses basically three levels (see figure 4): the hull level, the tank level and the boundary level (lowest level), where leakages may occur.

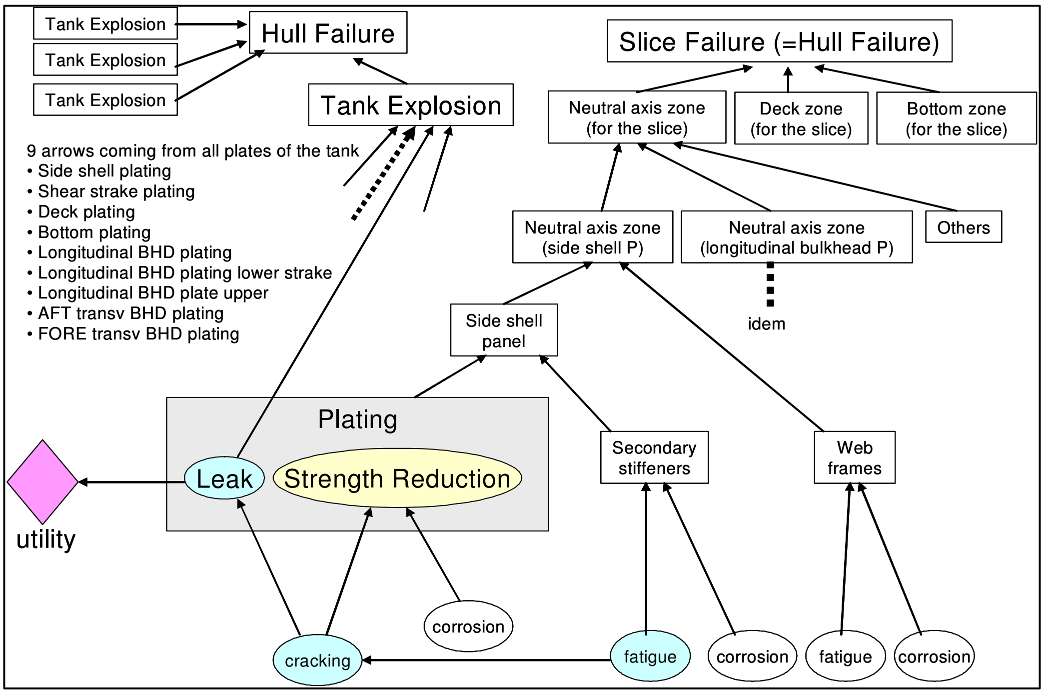

Figure 4: Hierarchical model for Risk Assessment to be used for the FPSO unit (1)

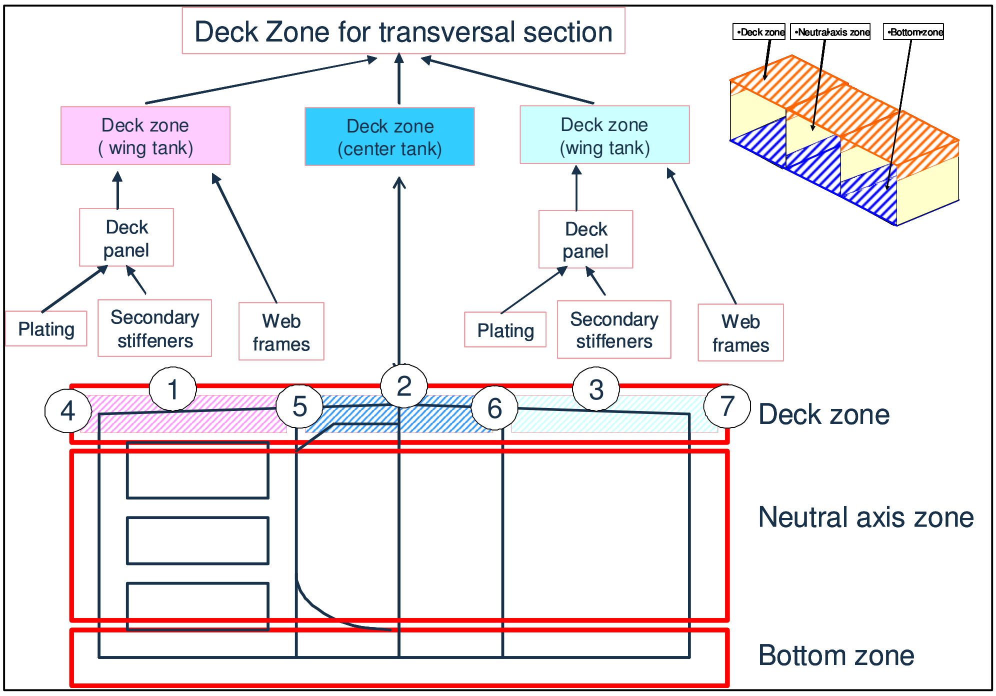

Figure 5: Hierarchical model for Risk Assessment to be used for the FPSO unit (2)

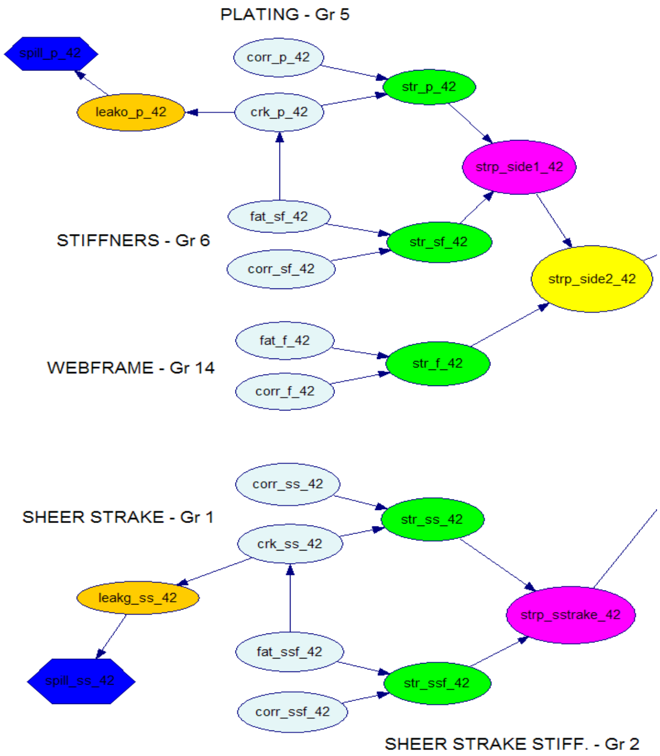

Figure 6: BPN (side shell – Portside) for Risk Assessment of the FPSO unit

Due to the fact all the 13 slices (see figure 1) of the unit are similar, a generic slice is defined and a generic BPN is built. This generic BPN is then run 13 times with at each time specific input data for the slice under consideration. The slice 3 is shown on figure 7 below for illustration:

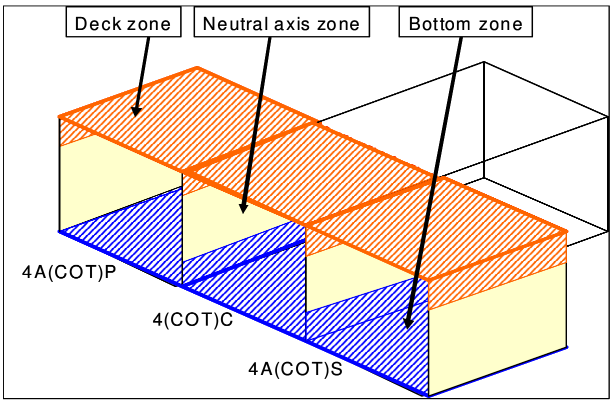

Figure 7: Slice 3 – Deck zone, Neutral axis zone and Bottom zone

The generic slice includes 13 boundaries (19 parts if we consider the usual decomposition of side shells and longitudinal bulkheads). Previous considerations in terms of generic BPN deal with the structural BPN and do not apply to the explosion BPN.

4 Formulation

Annual Risk assessment

For each year of the service life (i=1, N_A), the process is as follows:
- run the Structural integrity BPN slice per slice (see figure 1 for the definition of slices)
- run the Explosion BPN

Items of importance are:

The expected utility for Personnel (P)

$$U_P(i) = \sum_{j=1}^{13} E_{HF}(P,j) + \sum_{j=1}^{13} E_{EXP/TR}(P,j) + \sum_{l=1}^{26} E_{EXP/TK}(P,l) \tag{1}$$

The expected utility for environment (E)

$$U_E(i) = \sum_{j=1}^{13} E_{HF}(E,j) + \sum_{j=1}^{13} E_{EXP/TR}(E,j) + \sum_{l=1}^{26} E_{EXP/TK}(E,l) + \sum_{j=1}^{13}\sum_{k=1}^{19} E_{LEAK}(E,j,k) \tag{2}$$

The expected utility for economics (Asset: A)

$$U_A(i) = \sum_{j=1}^{13} E_{HF}(A,j) + \sum_{j=1}^{13} E_{EXP/TR}(A,j) + \sum_{l=1}^{26} E_{EXP/TK}(A,l) + \sum_{j=1}^{13}\sum_{k=1}^{19} E_{LEAK}(A,j,k) \tag{3}$$

All elements in formula (1), (2) and (3) are annual expected values. As illustration, $E_{HF}(P,j)$, $E_{EXP/TR}(P,j)$ and $E_{EXP/TK}(P,l)$ in (1) are respectively:

- the annual expected loss of lives – *for the slice j* – due to hull structural failure
- the annual expected loss of lives – *for the slice j* – due to explosion
- the annual expected loss of lives – *for the tank l* – du to explosion

Each expected value is calculated by multiplying the relevant occurrence probability by the corresponding consequence. For example,

$$E_{HF}(P,j) = P_{HF,j}\, x\, CONSEQ_{HF,P}(j)$$

Where:
- $P_{HF,j}$ is the annual probability of hull collapse (loss of longitudinal strength) – *for the slice j* - as calculated by the structural BPN,

- $CONSEQ_{HF,P}(j)$ is the corresponding consequence in terms of loss of lives.

Checking of acceptance criteria is done on an annual basis:

For personnel: $U_P(i) < RAC_{P,annuel}$ / $i=1, N_A$

For the environment: $U_E(i) < RAC_{E,annuel}$ / $i=1, N_A$

Optimisation

Utility function for economics is calculated for each alternative inspection plan by summation over the service life:

$$U_A = \sum_{i=1}^{N_A} U_A(i) \tag{4}$$

Utility for economics in (4) has in addition to include cost of inspection and cost of repair. So (3) is written as:

$$U_A(i) = \sum_{j=1}^{13} E_{HF}(A,j) + \sum_{j=1}^{13} E_{EXP/TR}(A,j) + \sum_{l=1}^{26} E_{EXP/TK}(A,l) + \sum_{j=1}^{13}\sum_{k=1}^{19} E_{LEAK}(A,j,k) + E(C_I) + E(C_R) \tag{5}$$

The optimal plan is the plan which minimises the utility function $U_A(i)$:

$$U_A^O = \min\left(U_A^m\right),\ m = 1, NI \tag{6}$$

Where NI is the number of inspection plans under investigation.

From RBI at component level to RBI at system level

Usually RBI is done at component level using decision tree as support for pre-posterior analysis (see figure 8)

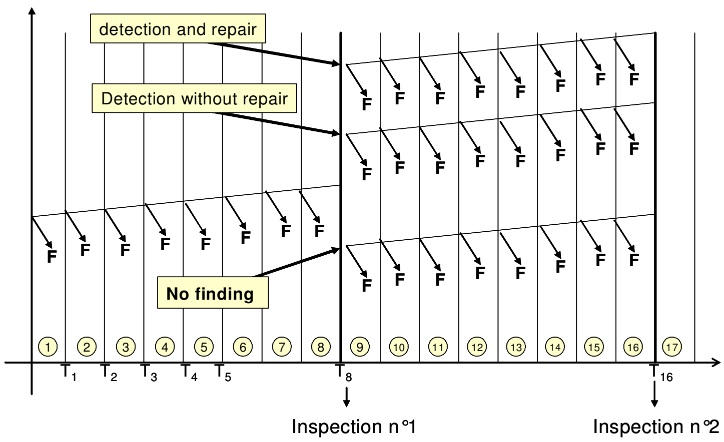

Figure 8: decision tree at component level for RBI

Due to the fact the proposed hierarchical model for the FPSO includes only the 'group of items' and 'zone' levels, formulation of failure probabilities has to be modified. Detailed RBI (reliability and reliability updating) is always performed at component level but some post-processing procedure has to be developed for entering in the Structural BPN integrity at the 'group of items' level. Also, it has to be noted that determination of inspection plans using pre-posterior analysis is here developed at system level instead of component level. This is an improvement because consequences and Risk Acceptance Criteria are generally defined at system level or sub-system level and not at component level. Taking into account consequences at system or sub-system level and performing risk analysis for RBI at system level means that system structural behaviour can be identified using linear or non-linear structural analysis tools or Bayesian Networks which are themselves fitted to results of structural system analyses or expertise. Figure 9 summarises the two options available in the best available RBI practices. The example presented in this annex is based on the method 2. Increasing use of Push Over analysis for fixed steel offshore structures and of Ultimate Strength for FPSO's / ships makes global risk analysis more easily to use in offshore and marine industries

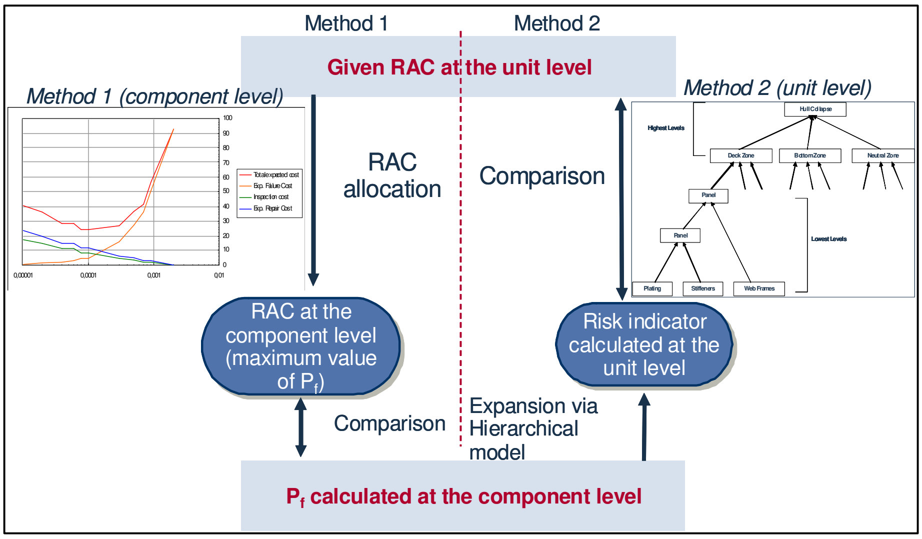

Figure 9: Development of RBI inspection plans at component or system level

5 Analysis and results

<u>Step 1</u>: Risk Acceptance Criteria

Risk Matrices used for the RBI study are given in figure 10 below. There are 4 matrices, one for the risk to personnel, one for the risk to the environment, one for the economical risk and one for the reputation. Only the three first ones are used in the study.

In the matrices, T, M and NT have the respective signification:

- T: Tolerable
- M: Moderate
- NT: Not tolerated

						Categories of Frequency				
					Frequency (per year)	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1} 1
		Description / Characteristics				**A Extremely Remote**	**B Remote**	**C Unlikely**	**D Likely**	**E Frequent**
		Personal Safety	**Patrimony / Operational Continuity**	**Environment (see Note 2)**	**Image**	Conceptually possible, but without references in the industry	Not expected to occur, although there are references on similar facilities in the industry	Unlikely to occur during the lifetime of a set of similar units	Likely to occur once during the lifetime of the facility	Likely to occur many times during the lifetime of the facility
Categories of Severity of Consequences	**V Catastrophic**	Multiple fatalities intramural or fatality extramural	Catastrophic damages which can lead to the loss of the industrial facility	Severe damages in sensitive areas or extending to other locations	International impact	**M**	**M**	**NT**	**NT**	**NT**
	IV Critical	Up to 3 fatalities intramural or serious injuries extramural	Severe damages to the systems (slow repairs)	Severe damages with localized effects	National impact	**T**	**M**	**M**	**NT**	**NT**
	III Medium	Serious injuries intramural or minor injuries extramural	Moderate damages to the systems	Moderate damages	Regional impact	**T**	**T**	**M**	**M**	**NT**
	II Marginal	Minor injuries	Slight damages to the systems / equipment	Slight damages	Local impact	**T**	**T**	**T**	**M**	**M**
	I Negligible	No injuries or, at most, first aid cases	Slight damages to the equipments without compromising operational continuity	Negligible damages	Negligible impact	**T**	**T**	**T**	**T**	**M**

Figure 10: Risk Matrices from the owner

Annual Risk Acceptance Criteria used in RBI analysis are derived from these matrices.

Step 2: Cargo area subdivision and definition of inspection plans

The cargo region is split in four groups of tanks:
- Separation tanks (4 tanks)
- Ballast tanks (4 tanks)
- Centre tanks (5 tanks)
- COT Wing tanks - *separation tanks excluded* – (12 tanks)

Additional space is the Turret Void Space.

Separation tanks are tanks where a first separation between oil/gas and water is achieved. Function of these tanks is of prime importance due to the fact crude oil/gas is firstly sent to separation tanks before to be stored in centre tanks or wing COT tanks.

5 types of inspection plans have been selected for the RBI study.

- **Type 1** is derived from BV rules which prescribe one full inspection each 2.5 years. For computational reasons, frequency interval is set to 2 or 3 instead of 2.5

{4 / 6 / 9 / 11 / 14}

- **<u>Type 2</u>** corresponds to an intermediate solution between type 1 on one hand and types 3 and 4 on another hand (see below)

{4 / 7 / 10 / 13}

- **<u>Type 3</u>** is an alternative to the type 4

{4 / 8 / 13}

- **<u>Type 4</u>** corresponds to an unrestrictive interpretation of BV rules in other words specific rules for survey of units older than 15 years are not applied

{4 / 9 / 14}

- **<u>Type 5</u>** corresponds to some extension of the inspection frequency (Only 2 inspections along the service life)

{4 / 10}

The number of inspection is decreasing from the type 1 to the type 5, moving from 5 inspections for the type 1 to only 2 inspections for the type 5.

Each group of tanks may have one of the 5 types of inspection planning. As a consequence, a set of 625 inspection plans for the unit has been tested: 5(group 1) x 5(group 2) x 5(group 3) x 5(group 4) = 625.

<u>Step 3</u>: Annual damage state of the unit taking into account:
- degradation mechanisms (general corrosion, pitting, fatigue)
- inspection planning
- mitigation strategy

The annual damage state of the unit is defined by a vector with 107 components for each slice:
1) 60 components for defining the corrosion state
2) 6 components for defining the pitting state
3) 41 components for defining the fatigue state

The annual damage state of the unit is then defined by 13 x 107 = 1391 components:
1) 780 components for defining the corrosion state of the unit
2) 78 components for defining the pitting state of the unit
3) 533 components for defining the fatigue state of the unit

As an example, figure 11 shows the annual probability of fatigue failure for a specific detail which is assumed to be inspected according to the inspection type 5 (inspections years 4 and 10) with the assumption of no finding at inspection times:

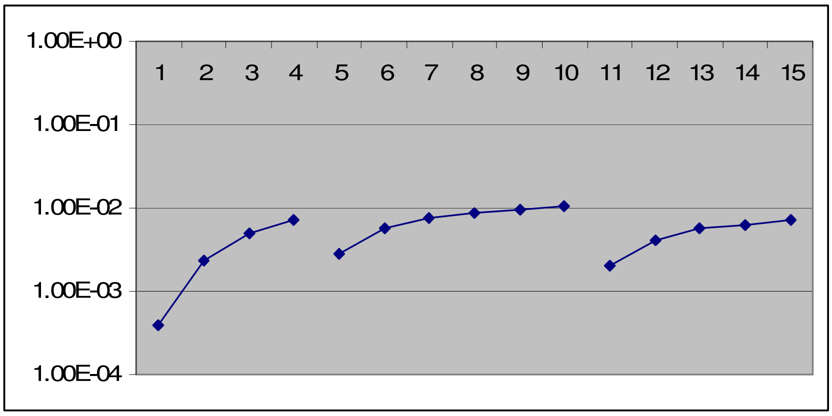

Figure 11: Annual probability of fatigue failure versus time (FDF=0.933, Thickness=11.5 mm, Type of inspection: 5)

Annual probabilities of component fatigue failure are computed using a probabilistic crack growth propagation model. The crack propagation model is derived from the Paris's law equation and uses the Newman-Raju formulation for the determination of the stress intensity factors. The geometry of the crack is assumed semi-elliptic [5].

Step 4: Risk Analysis of the unit on an annual basis:

- using damage states determined in step 3
- using **B**ayesian **P**robabilistic **N**etworks (BPN) for structural and explosion analyses

All calculations are performed according to the formulation given pages 8 and 9. That's means risk analysis is performed on an annual basis for the 625 possible inspections plans. If a particular plan does not fulfil the annual risk acceptance criteria for personnel and environment, then this plan is removed from the set of possible inspection plans (see figure 3).

From step 1, Risk Acceptance Criteria for personnel and environment were respectively set to 8 x 10^{-5} (loss of lives / year) and 9400 (m-tons).

Step 5: Optimisation

Optimisation is performed according to the formulation given page 9 and takes into account:

1) Special considerations dealing with costs of inspection which drive the optimisation procedure. In particular it was decided to keep only inspection plans with only 2 inspections of separation tanks during the service life (type 5 where the capacities are inspected years 4 and 10). It is because costs of inspection of separation tanks is extremely high

2) Constraints from class

25 acceptable inspections plans are selected (see table 1). The TAG identifying each inspection plan uses a label XYZT where:

- X is the type inspection for the ballast tanks
- Y is the type of inspection for the separation tanks
- Z is the type of inspection for the centre tanks
- T is the type of inspection for the other wing tanks (other than separation tanks)

TAG	Personnel	extra costs
2511	6.9908E-05	4746
1512	6.996E-05	4358
2521	7.0907E-05	4444
1521	7.1391E-05	4588
1531	7.1807E-05	4286
1522	7.2953E-05	4056
3511	7.3074E-05	4602
2512	7.3565E-05	4214
2541	7.4654E-05	4142
2531	7.4783E-05	4142
1542	7.548E-05	3754
3521	7.6067E-05	4300
2522	7.6558E-05	3912
1511	7.6646E-05	4890
4512	7.6761E-05	4070
1532	7.683E-05	3754
1513	7.7938E-05	3826
4521	7.8048E-05	4300
4531	7.8464E-05	3998
3541	7.8594E-05	3998
3512	7.8725E-05	4070
2542	7.9085E-05	3610
4522	7.9754E-05	3768
3531	7.9944E-05	3998
2514	7.9955E-05	3682

Table 1: 25 acceptable inspection plans

Finally, due to additional consideration from experience and expertise, 3 alternative inspection plans are selected:
1 5 2 2 (Personnel utility = 7.30×10^{-5})
1 5 4 2 (Personnel utility = 7.55×10^{-5})
2 5 2 2 (Personnel utility = 7.66×10^{-5})

Figure 12 gives annual expected values for personnel versus time for the 3 recommended inspection plans.

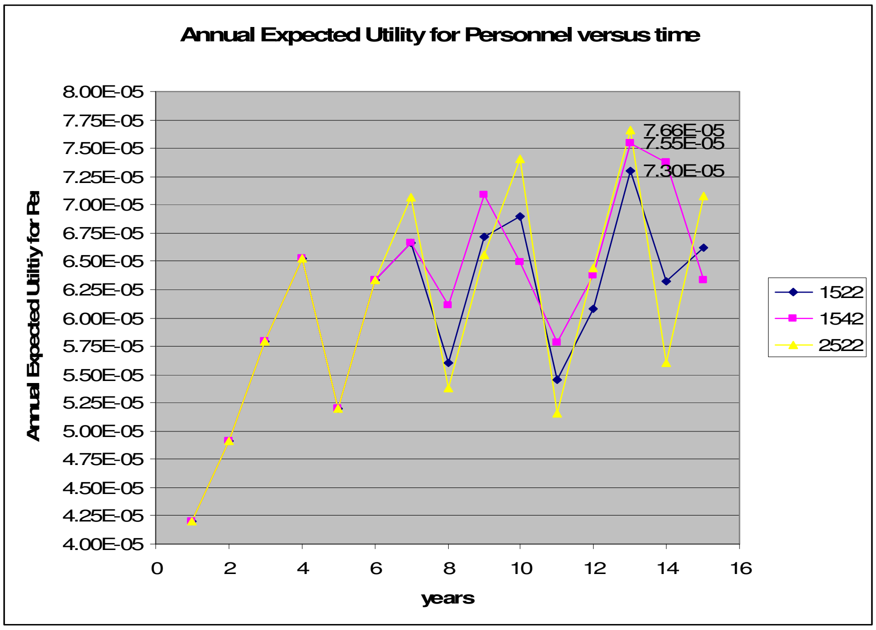

Figure 12: Inspection plans 1522, 1542 and 2522 – Annual Risk for Personnel versus time in terms of annual expected loss of lives

The inspection plan from the RBI study (plan 1542) is shown on figure 13

Tank		Frequency (years)	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Centre tanks	1 C.O.T. (C)	5	*i*					*i*					*i*		
	2 C.O.T. (C)		*i*					*i*					*i*		
	3 C.O.T. (C)		*i*					*i*					*i*		
	4 C.O.T. (C)			*i*					*i*					*i*	
	5 C.O.T. (C)			*i*					*i*					*i*	
Wing tanks (ballasts excluded)	1 C.O.T. (P)	3	*i*			*i*			*i*			*i*			*i*
	1 C.O.T. (S)		*i*			*i*			*i*			*i*			*i*
	3 C.O.T. (P)			*i*			*i*			*i*			*i*		
	3 C.O.T. (S)			*i*			*i*			*i*			*i*		
	3A C.O.T. (P)			*i*			*i*			*i*			*i*		
	3A C.O.T. (S)			*i*			*i*			*i*			*i*		
	4A C.O.T. (P)				*i*			*i*			*i*			*i*	
	4A C.O.T. (S)				*i*			*i*			*i*			*i*	
	5 C.O.T. (P)				*i*			*i*			*i*			*i*	
	5 C.O.T. (S)				*i*			*i*			*i*			*i*	
Slop	SLOP (P)	3			*i*			*i*			*i*			*i*	
	SLOP (S)			*i*			*i*			*i*			*i*		
separation tanks	2A SEP. (P)	6	*i*						*i*						*i*
	2A SEP. (S)		*i*						*i*						*i*
	4 SEP. (P)			*i*						*i*					
	4 SEP. (S)			*i*						*i*					
Ballast tanks	2 W.B.T. (P)	2.5			*i*		*i*			*i*		*i*			*i*
	2 W.B.T. (S)				*i*		*i*			*i*		*i*			*i*
	3B W.B.T. (P)				*i*		*i*			*i*		*i*			*i*
	3B W.B.T. (S)		*i*		*i*			*i*		*i*			*i*		*i*
Number of inspected tanks per year			8	9	9	2	8	9	6	11	5	5	9	7	8

Figure 13: Inspection plan from the RBI Study

6 References

[1] Risk Assessment in Engineering – Principles, System Representation & Risk Criteria, Joint Committee on Structural Safety, Edited by M.H. Faber, June 2008 (see JCSS Web Site)

[2] J. Goyet, D. Straub and M.H. Faber, "*Risk Based inspection panning of offshore installations*", Structural Engineering International, Volume 12, number 3, August 2002

[3] Constrained optimization of component reliabilities in complex systems, Kazuyoshi Nishijima, Marc Maes, Jean Goyet and Michael Havbro Faber, Structural Safety, Vol. 31, pages 168-178, 2009

[4] Rules for the Classification of Steel Ships, NR 467.A1 DT R07 E, Bureau Veritas, November 2007

[5] Newman JC and Raju IS, An empirical stress intensity factor equation for surface cracks, Engineering Fracture Mechanics, 15, pp185-192, 1981