Application of Delay-Time Analysis via Monte Carlo Simulation

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Abstract: This paper presents a methodology for the application of delay time analysis via Monte Carlo Simulation. The aim of the paper is to demonstrate the efficacy and worth of delay-time analysis and how the application can provide engineers with more information when making maintenance decisions. The methodology has been developed and applied to two case studies.

Keywords: Delay-time, inspection, maintenance, ship operations, simulation

1. Introduction

Maintenance is a huge area of interest and research for engineers. A number of papers based on maintenance strategy and decision have been published (Barbera et al. 1996) (Qi et al. 1999) (Wang et al. 2000) (Wang & Majid 2000) (El-haram & Horner 2002) (Emblemsvåg & Tonnig 2003) (Beebe 2003) (Backlund & Akersten 2003) (Wang & Hwang 2004). Maintenance costs form a significant part of the overall operating costs in ship operations (Mokashi et al. 2002). Pillay & Wang (2003) defined maintenance as the combination of all technical and administrative actions, including supervision actions, intended to retain an entity in, or restore it to a state, in which it can perform a required function. The International Safety Management (ISM) Code states that all ship operators 'should establish and implement procedures to identify equipment and technical systems the sudden operational failure of which would result in hazardous situations' (ISM 2002). In meeting these requirements the company should ensure that:

- Inspections are held at appropriate intervals.
- Any non conformity is reported with its possible cause, if known.

- Appropriate corrective actions are taken.
- Records of these activities are maintained.

Soncini (1996) suggested that most ship owners understand the need of having good control over accounting and purchasing and are found to be at the same level as their land based counterparts; however the same cannot be said when it comes to maintenance and stock control. Pinelton et al. (1999) introduced the 'maintenance concept', defined as the set of various maintenance interventions (corrective, preventive, condition based, etc.) and the general structure in which these interventions are brought together. The total cost of maintenance is difficult to calculate due to the number of factors involved.

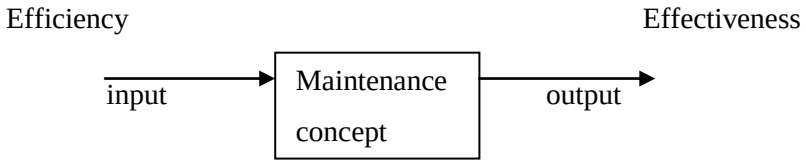

Fig 1. Optimum maintenance concept.

Fig 1. shows the 'optimum' maintenance concept presented in Pintelon (1999). The efficiency of a concept is dependent upon the input. Ultimately all maintenance concepts are dependent upon appropriate information being available concerning equipment. To enable marine engineers to make educated informed decisions concerning maintenance decisions methods must be developed which provide the marine engineer with information about unreliability, availability and downtime.

It has been shown in a previous paper (Cunningham et al. 2010) that Monte Carlo Simulation can be applied in the marine environment to give information about system unreliability based on system failure rates. Input variables and maintenance decision can be 'tested' within the simulation and the effects on system unreliability assessed. In this paper Delay-Time Analysis (DTA) methods will be implemented using Monte Carlo Methods to automate the process and produce results. DTA can be easily achieved through simulation methods but limited work exists that outlines a methodology to demonstrate this method. The simulation method can be used as a way of validating studies carried out using analytical DTA. The paper briefly presents the simplest delay-time model and a methodology for a simulation based approach is developed. Extensions have been made to the analytical delay-time method in order to relax the simplifying assumptions at a cost of increased mathematical complexity. It will be shown in the following paper that DTA via simulation can relax modelling assumptions in the same way, with very little added complexity.

2. Background

2.1 The Delay-Time Concept

The majority of current reliability and maintenance practice is based on time to first failure, or time between failures. Christer (1999) published a review considering the developments in DTA, stating that 'maintenance concepts based on Reliability Centered Maintenance (RCM) or Total Productive Maintenance (TPM) are prescriptive and often lack scientific concept, testing, verification or validation'. Delay-time modelling is a concept which has been developed to be relevant in the operating culture of today's industry (Christer 1999). DTA provides engineers with a tool which can help to minimise downtime, D(T) of a machine or plant item, based on an inspection period, T. The delay-time concept bifurcates the failure process as shown in fig 2.

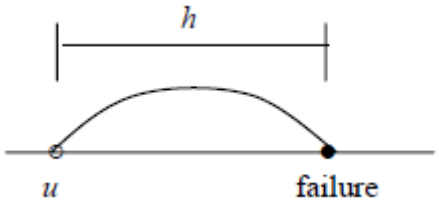

Fig 2. Diagram showing the delay-time concept.

DTA is based on the idea of all failures having an individual 'tell-tale' sign. This is represented in fig 2 by the point, u, on the time line. The point u is called the initial point and is the point from which normal inspection activity could highlight the defect. If unattended the component will go on to fail at point u+h; where h is the time to failure of the component from point u, here-in referred to as the delay-time. If an inspection is scheduled to take place in the time period (u,u+h), then the failure could be discovered and arrested before it leads to full failure. If this initial point, u, exists for a number of failure conditions, then the delay-time represents a window in which failure could be prevented. To fully understand the benefit of the delay-time concept, consider the following example presented in Christer (1999).

Fig 3. Diagram showing the failure points.

Consider fig 4 incorporating the same failure point pattern as fig 3. along with the initial points associated with each failure arising under a breakdown system. Had an inspection taken place at point (A), one defect could have been identified and the seven failures reduced to six. Likewise had

inspection taken place at points (B) and point (A), 4 defects could have been identified and the seven failures now reduced to three.

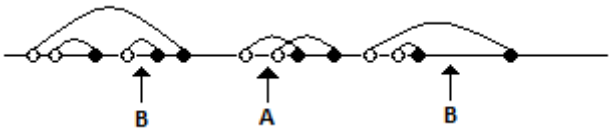

Fig 4. Diagram showing the failure points and the initial points.

This example demonstrates that assuming we can model the way in which defects arrive, referred to as the arrival rate of defects kf, and their delay-time h, the delay-time analysis concept can be applied to understand the relationship between inspection frequency and system failures (Christer 1995).

Here the simplest delay time model used in the literature is briefly presented. It is asssumed that there is a complex plant, or multi-component plant which has a large number of components with many failure modes, and the correction of one defect or failure has nominal impact in the steady state upon the overall plant failure characteristics. The following assumptions are given for the basic complex plant maintenance modelling scenario:

1. An inspection takes place every T time units and requires d_s time units, where $d_s << T$.
2. Inspections are perfect in that all (and only) defects present are identified.
3. Defects identified are repaired during the inspection period.
4. Defects arise according to a Homogeneous Poisson Process (HPP) with the rate of occurrence of defects, λ, per unit time.
5. The delay time, H, of a random defect is described by a pdf. $f(h)$, cdf. $F(h)$, and is independent of the initial point U.
6. Failure will be repaired immediately at an average d_f.
7. The plant has operated sufficiently long since new to be considered effectively in a steady state.
8. Defects and failures only arise whilst plant is operating.

These assumptions characterise the simplest non-trivial inspection maintenance problem (Christer et al. 1995). It is now possible to proceed to construct the mathematical model of the relationship between T and an objective function of interest.

From assumptions 1-4, it is obvious that the number of system failures is identical and independent over each inspection interval, and it is possible to simply study the behaviour of such a failure process over one interval, e.g. the first interval $[0,T)$. Suppose the expected downtime per unit time, $D(T)$, is taken as a measure of our objective function. The relationship between T and $D(T)$ can be established directly by using the renewal reward theorem, (Ross 1981) as

$$D(T) = \lim_{t\to\infty} \frac{E(\text{Downtime over t})}{t} = \frac{d_f E[(N_f(T)] + d_s}{T + d_s}$$

where $E[N_f(T)]$ is the expected number of failures within [0,T). Clearly if $E[N_f(T)]$ is available, $D(T)$ can be readily calculated. It is shown that $E[N_f(T)]$ is given by:

$$E[N_f(T)] = \int_0^T \lambda F(t)dt$$

3. Development of Methodology

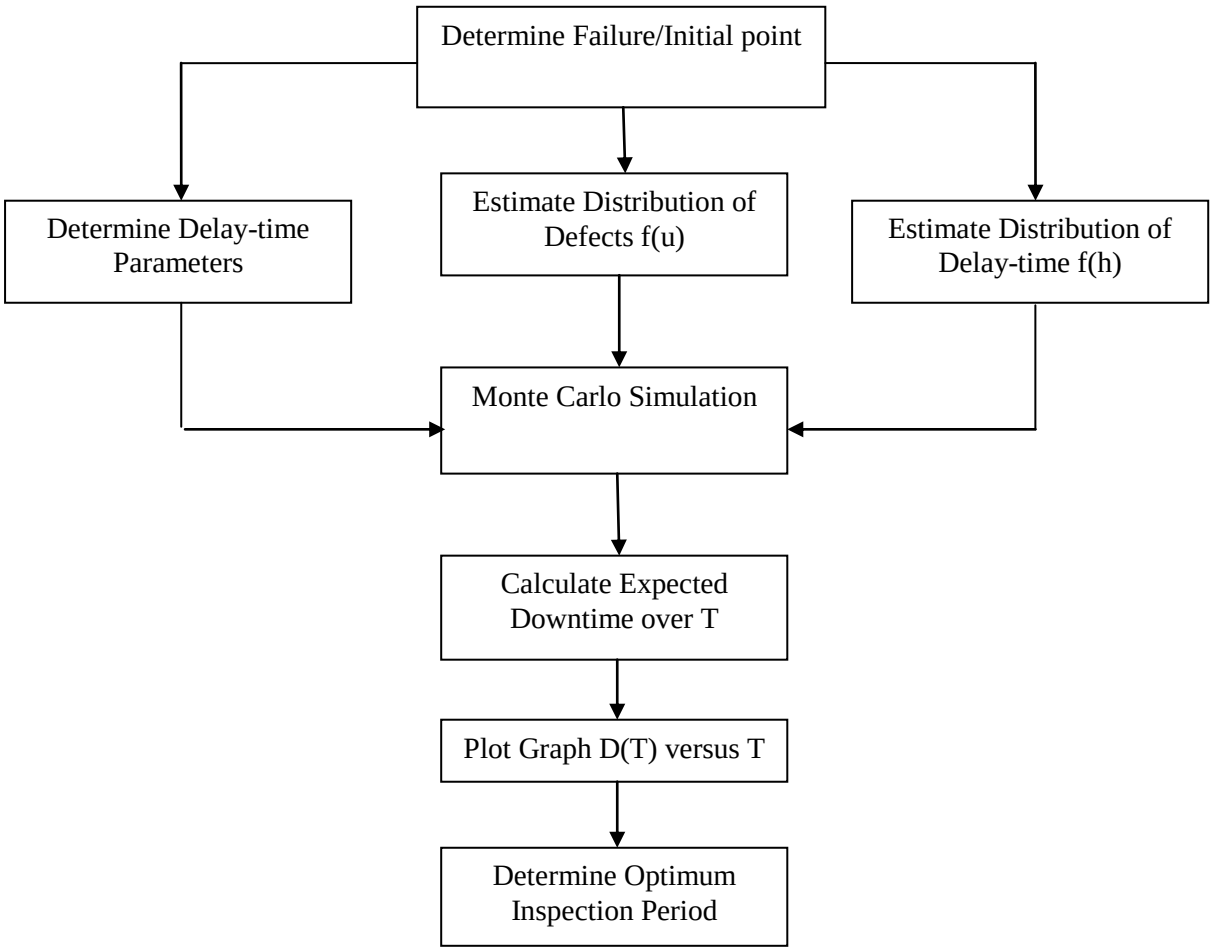

Fig 5 Proposed methodology for performing a delay-time analysis via Monte Carlo Simulation

Fig 5 shows the methodology that has been developed for the analysis. The diagram illustrates the various steps contained within the analysis and shows the information required before an analysis can be conducted. In the following, some important steps in the methodology will be explained and expanded upon. Where appropriate, examples will be given to aid the description.

Delay-time simulation involves the consideration of a number of defects and associated delay-times within a given time line. It is assumed that in order for a breakdown to occur, there exists a defect, u, which is a pre-curser to failure. Each u value has an associated delay-time, h, that represents a time window, in which, if normal inspection activity occurs the defect could be recognised and the systems transition into a failed state prevented. Simulation of the delay-time involves consideration of the system over a mission time, T_m. T_m should be sufficiently long such that downtime due to breakdown and inspection can be considered negligible. The process involves the estimation of a suitable distribution of defects, f(u) and a suitable distribution of delay-times, f(h). The program can be described in the following steps:

1. Generate a value, U_1, which represents a time of defect, where f(u) is the probability density function of the defect time.
2. Generate an associated delay-time, h_1, which represents the opportunity window in which inspection could arrest a developing failure, where f(h) is the probability density function of the delay-time.
3. Perform a test to see if the defect is found at the time of inspection.
4. Generate the next defect time, u_2, from the point u_1 and an associated delay-time h_2.
5. Repeat step 3.

The process outlined above is repeated until the cumulative value, CU, is greater than the mission time T_m where,

$$CU = u_1 + u_2 + \ldots + u_n$$

Fig 6 shows the generation of a number of u values within the mission time.

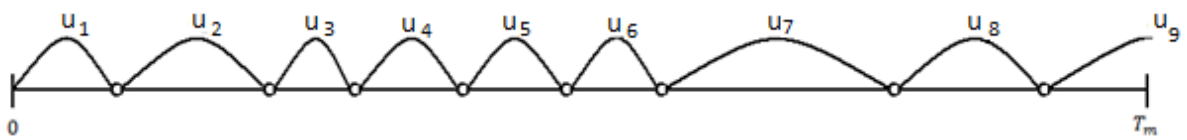

Fig 6 Diagram showing the generation of U values within the mission time

Fig 7 shows the generation and addition of the related h values.

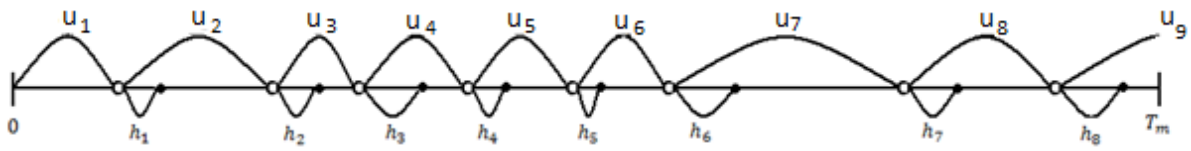

Fig 7 Diagram showing the generation and addition of h values within the mission time

Fig 8 shows the form of the program used to conduct the simulation in the form of a flowchart.

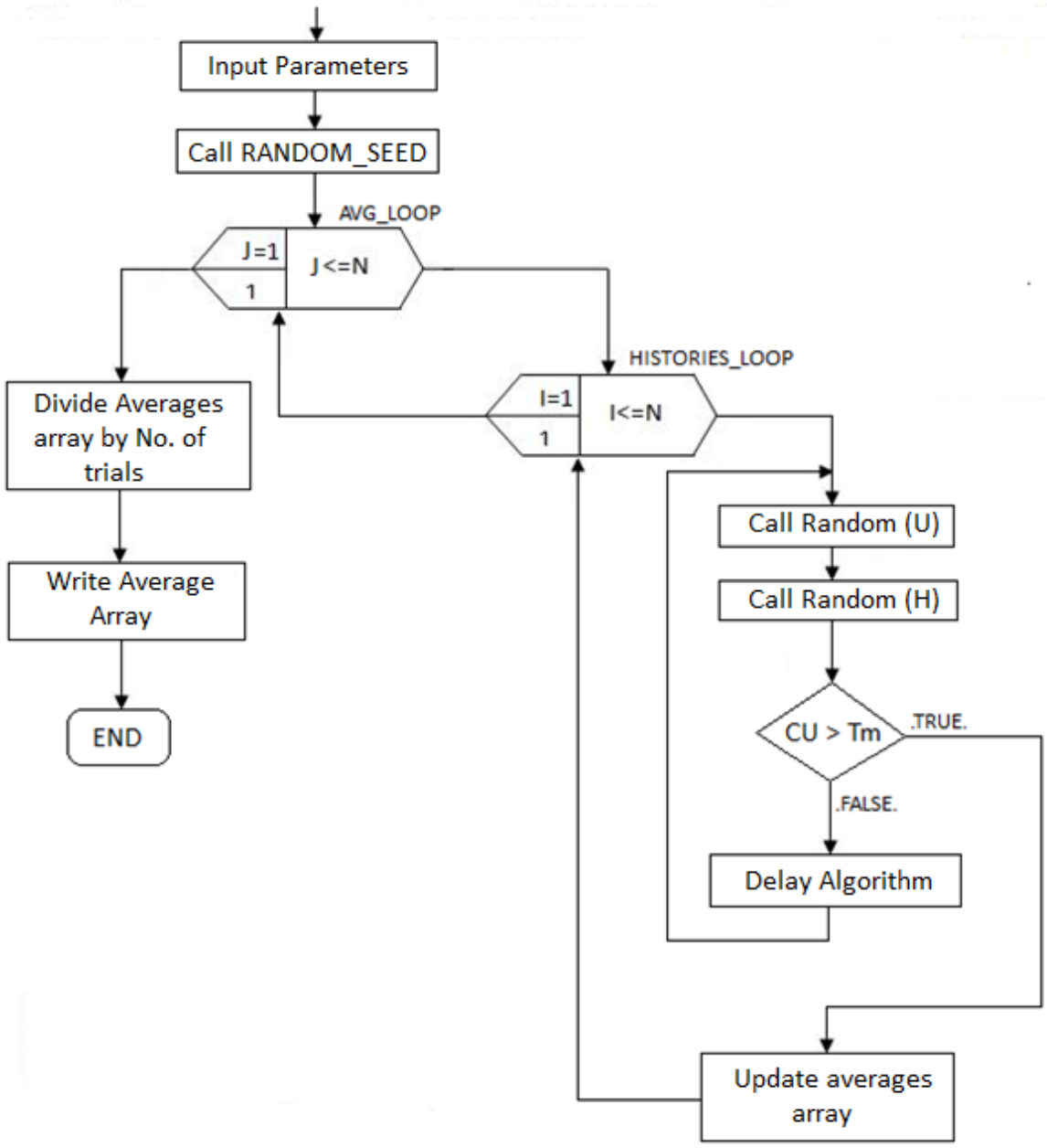

Fig 8 Flowchart representation of the Monte Carlo Simulation code

The code shown in fig 8 starts by taking input parameters, defined by the user and uses the Call RANDOM_SEED function to randomise all seed values. The code then progresses into the counting loop AVG_LOOP and calls a random value of u and h within a counting loop, HISTORIES_LOOP. DELAY ALGORITM then performs the test which decides if this particular combination of u and h leads to a failure or a breakdown. AVG_LOOP is a second counting loop which repeats the process a set number of times, N, for a given value of T. At the end of each iteration of AVG_LOOP, the array which contains the average values is updated. This averaging process allows more accuracy in the final results. The Monte Carlo Simulation returns the total expected failures for the whole mission at each value of T considered. In the following the Delay Algorithm will be explained in more detail. It takes one of three forms depending upon the analysis, section 3.1.1 presents the Delay Algorithm for perfect inspections, section 3.1.2 presents the Delay Algorithm when imperfect inspections are considered and section 3.1.3 presents the Delay Algorithm when imperfect inspections and imperfect repairs are considered.

3.1.1 Delay Algorithm – Perfect Inspection

The DELAY ALGORITM is a part of the Monte Carlo Simulation shown in fig 8 which is used to decide whether the current combination of u and h values leads to a breakdown or inspection failure. The flowchart form of the algorithm for perfect inspections is shown in fig 9. Under the presupposition of perfect inspections it is assumed that all defects are identified and rectified within the inspection interval.

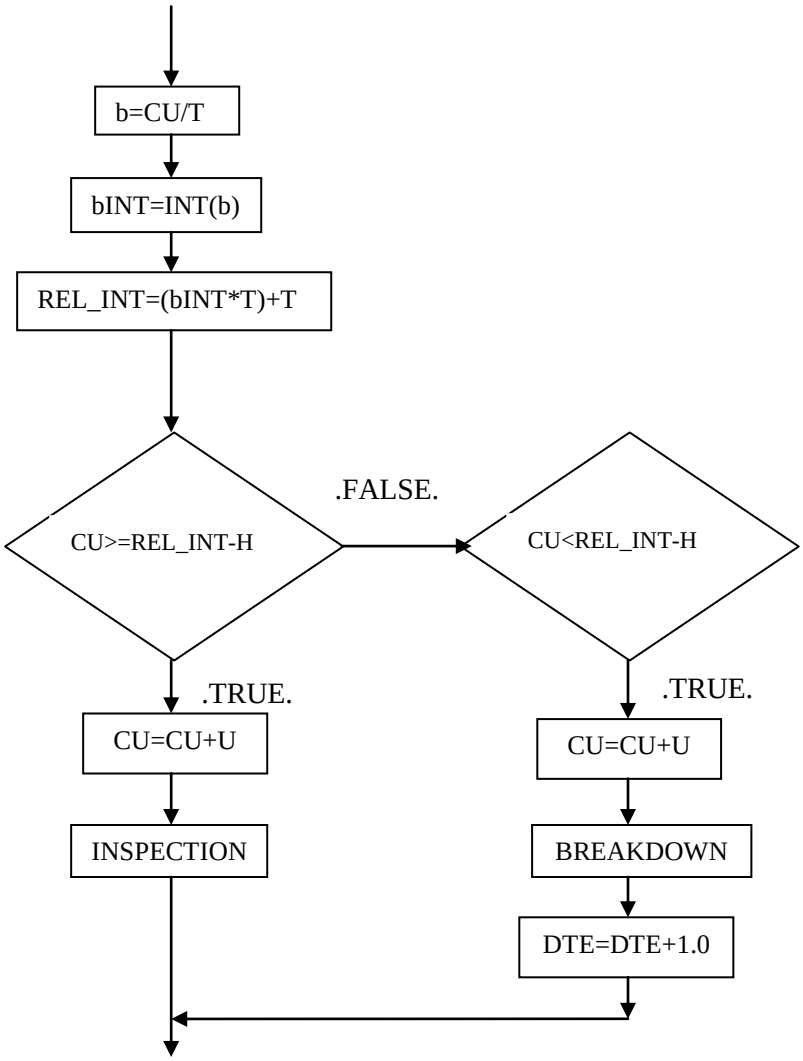

Fig 9 Flowchart representing the Delay Algorithm for perfect inspections

To fully explain how the algorithm works a simple example is considered. The Monte Carlo Simulation is run for a single trial, when T=2 and the random values of u and h are generated as 13 and 0.7 respectively. The delay-time algorithm works using the cumulative value of u, however this is the first iteration of the code and thus the cumulative value CU and u are equal. The value CU is divided by T to examine how many inspections can occur, giving the exact value b. In this example when CU=13 hours and T=2 hours, b=6.5 inspections. This is shown in fig 10.

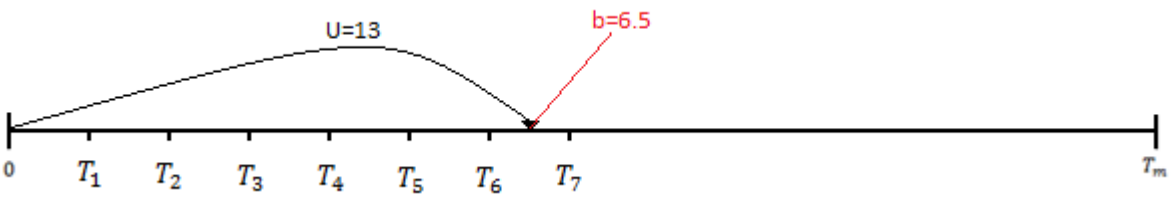

Fig 10 Figure showing the point b where b=CU/T

In order to be able to perform a test to see if an inspection or breakdown occurs whole values of T are required. The algorithm uses an intrinsic FORTRAN function INT(b) to achieve this. If b is of type real and | b | >= 1, INT(b) is the integer whose magnitude is the largest integer that does not exceed the magnitude of b and whose sign is the same as the sign of b. When the example is considered, b=6.5, INT(b) returns the value 6. In the flowchart shown in fig 9, bINT=6. It is now known that the defect, u, lies between the sixth and seventh inspection interval. In DTA it is always the time at the upper bound of the relevant interval which is of interest. From the lower bound of the interval the upper bound is simple to calculate. Fig 11 shows the interval of interest, bINT and REL_INT on the timeline.

$$REL\_INT = (bINT \times T) + T$$
$$= (6 \times 2) + 2$$
$$= 14$$

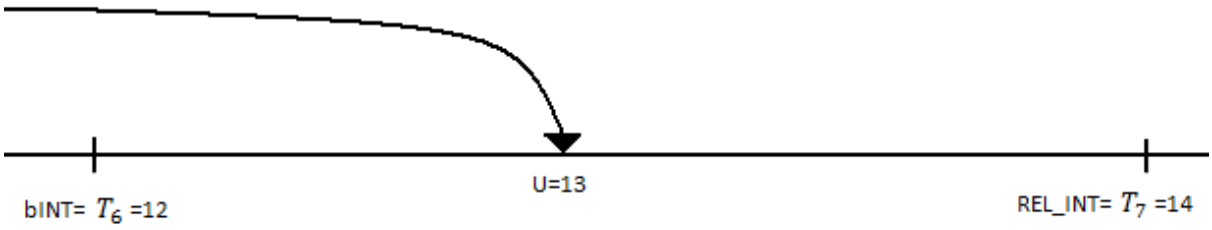

Fig 11 Diagram showing bINT and REL_INT on the timeline

The next part of the algorithm is where the test is performed to see if the delay-time is sufficient such that the defect will be recognised and repaired at the next inspection. On the timeline this is represented by the point REL_INT-H which is shown in fig 12.

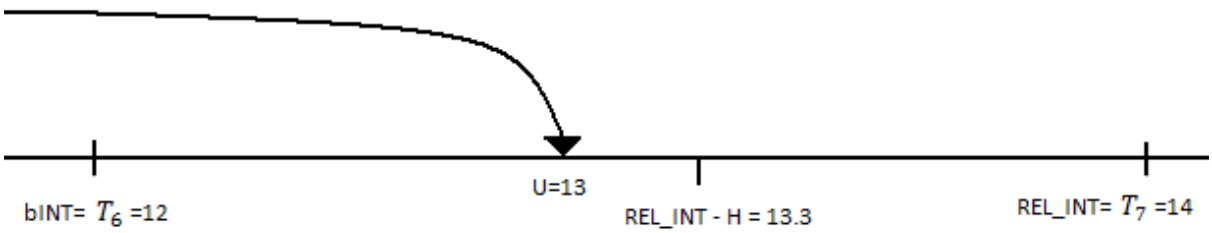

Fig 12 Diagram showing the point REL_INT-H

The algorithm performs the calculation,

$$REL\_INT - H = 14 - 0.7 = 13.3$$

The test is performed to see if $CU \geq (REL\_INT - H)$ or $CU < (REL\_INT - H)$, if the first condition is found to be true an inspection occurs, if the latter is found to be true a breakdown occurs. In the case of breakdown the counter DTE, is increased by one. In both cases of inspection and failure the present u value is added to the cumulative value CU.

3.1.2 Delay Algorithm – Imperfect Inspection

The flowchart form of the algorithm for imperfect inspections is shown in fig 13. The presupposition of perfect inspections has been relaxed. The algorithm now takes into account the probability of an inspection being perfect or imperfect which is preset by the analyst.

All the assumptions previously outlined for analysis still hold true apart from the assumption of perfect inspection. In the case of imperfect inspection it is assumed that at the point of inspection there is a probability, r, that a defect present will be identified. Conversely there is a probability, $1 - r$, that a defect will go unnoticed at inspection and will continue to develop into a full breakdown. Christer (1999) demonstrated how the analytic model can be extended to include imperfect inspections. It should be noted that imperfect inspection when using analytical methods is achieved at the cost of a significant increase in mathematical complexity. The simulation does not suffer from the same increase in complexity. It can be seen from the flowchart shown in fig 13 that the flowchart for imperfect inspection is very similar to the flowchart for perfect inspections.

The inclusion of imperfect inspections into the simulation model is achieved through the introduction of a discrete distribution which represents the probability of perfect and imperfect inspections. The distribution is made of two distinct intervals, $(0,1 - r)$ and $(1 - r, 1)$. The random number, RI, is called where $RI = U\sim(0,1]$ and a test is performed to examine in which interval RI falls. This test decides whether a defect is recognised and repaired at inspection or unnoticed and left to develop into a breakdown failure. For the analysis in the following case studies inspections are considered imperfect 10% of the time. Woods (1984) suggest that in emergency situations this incorrect inspection rate could be as high as 60 %. The value of 10% in light of this can be considered appropriate as the inspections do not take place under emergency conditions.

3.1.3 Delay Algorithm – Imperfect Inspections, Imperfect Repair

Imperfect repair involves the consideration of delay-time analysis with a non-homogeneous defect arrival rate, k_f. The assumption that k_f is constant is a reasonable assumption for most systems that have been running for a sufficiently long period to be considered mature. Imperfect repair, first considered by Brown & Proschan (1983), can be closely linked to models considering 'minimal repair at failure' (Barlow & Proschan 1965), (Blumenthal et al. 1976). Further study and extension of the Brown & Proschan model was conducted by Whitaker & Samaniego (1989). Baker & Wang (1993) considered delay-time analysis where the assumption of constant k_f is relaxed. The model considers the effect of component age on the arrival rate of defects and the consequence of inspection activity and its possible hazardous or beneficial effect on the lifetime of a component.

The model developed in this work considers the effect of minimal repair after an inspection action. It is still assumed that in the case of a breakdown failure the repair of components is perfect and the system is put back online in a 'good as new state'. After a breakdown repair the system is put back online with the original steady-state arrival rate of defects, k_f. To examine the effect of non steady-state conditions it is assumed that when a defect is identified at inspection and the defect subsequently repaired, this repair action is non-perfect. This non-perfect repair action has the effect of increasing the arrival rate of defects by 20%. The flowchart form of the algorithm for imperfect inspections with imperfect repair is shown in fig 14.

3.2 Calculate Expected Downtime over T

The Monte Carlo Simulation outlined provides the total expected number of failures over a given mission time. The equation for downtime per unit time requires the expected value of failures over T. In order to achieve this, results given by the simulation have to be divided by N. N is equal to the total number of inspections, T, possible within the given mission time, T_m, i.e. $N = \frac{T_m}{T}$.

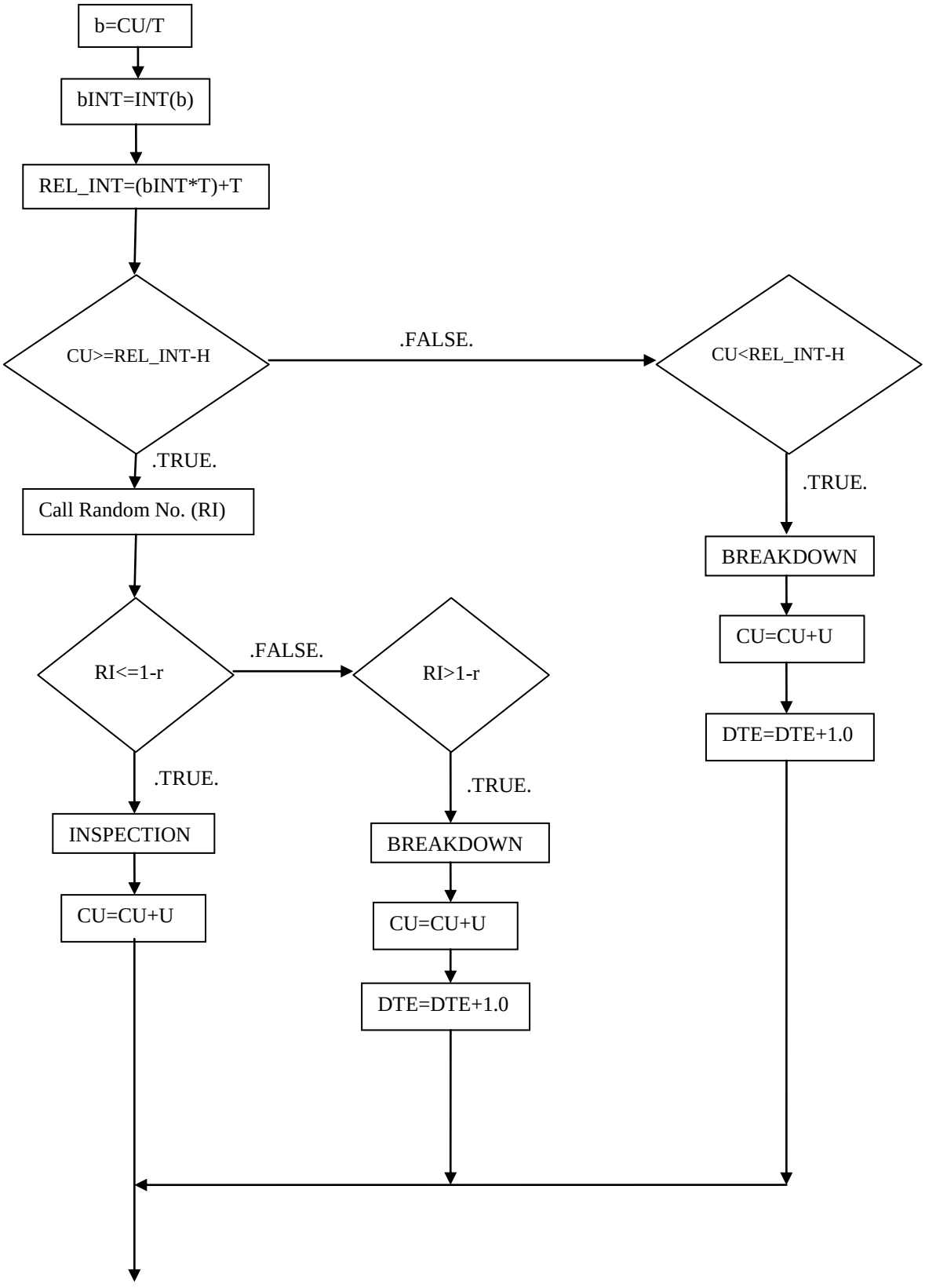

Fig 13 Flowchart representing the Delay Algorithm for imperfect inspections

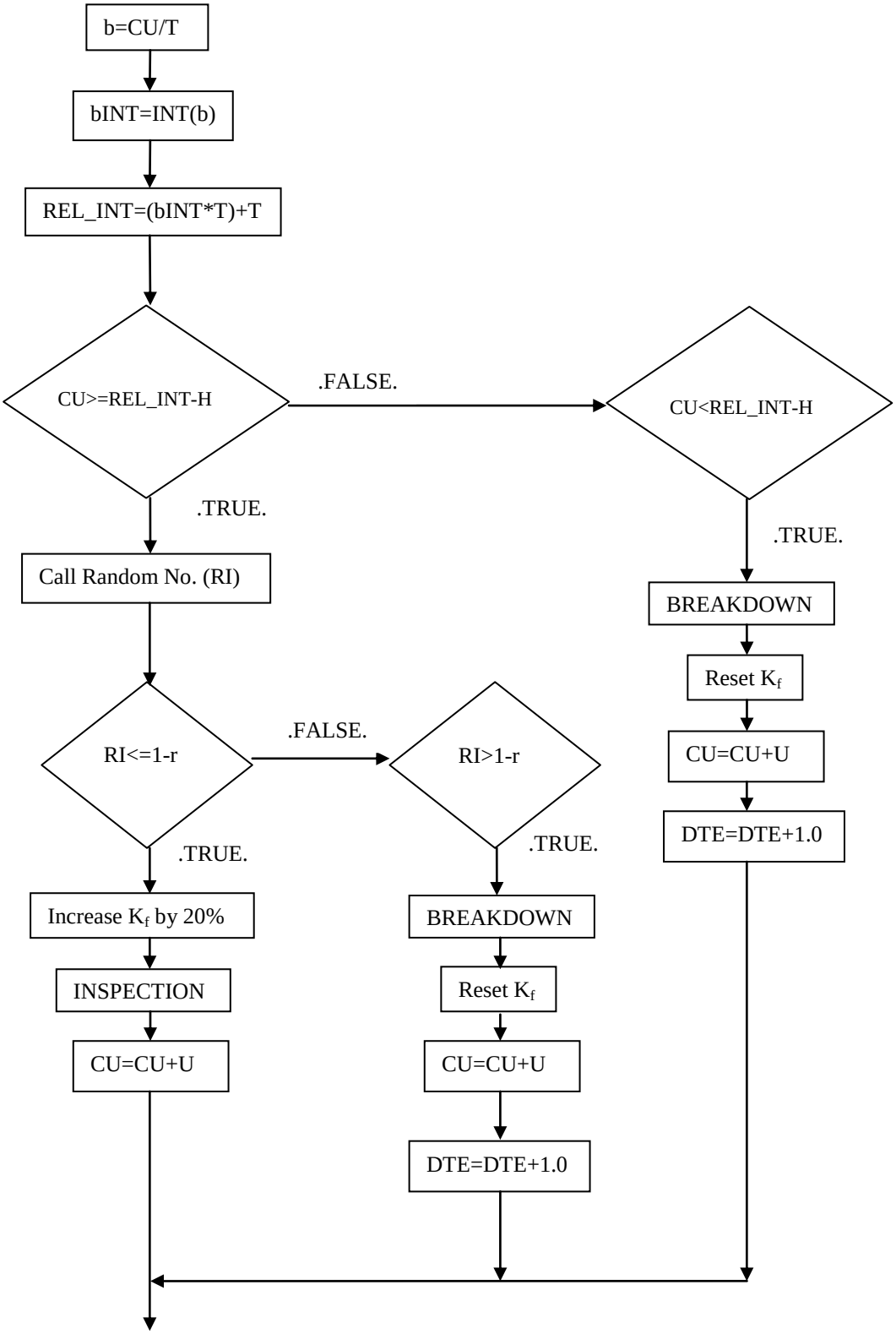

Fig 14 Flowchart representing the Delay Algorithm for imperfect inspections and imperfect inspection repairs

4. Case Studies

With the intent of demonstrating the method for DTA via simulation two case studies are presented. In the first the data for the case study was taken from an existing journal paper (Pillay et al. 2001). In the second case study a new model is presented based on a centrifugal pump, where repair data is based on OREDA data (OREDA 2002) and expert judgement.

4.1 Fishing Vessel Case Study

The delay-time model is based on the operation of a main hydraulic winch operating system on board a fishing vessel. The vessel has length overall of 60m and gross tonnage of 1266. Fig 15 shows a schematic of the main hydraulic piping system.

The data for the analysis is taken directly from Pillay et al. (2001) and is shown in table 1.

Table 1 Table showing the input parameters for the analysis

Inspection Downtime	**ds**	0.25 hrs
Breakdown Downtime	**db**	108 hrs
Arrival rate of defects	**kf**	0.0223 hrs^{-1}

The downtime for breakdown repair takes into account any delays caused while waiting for spares to be sent to the vessel.

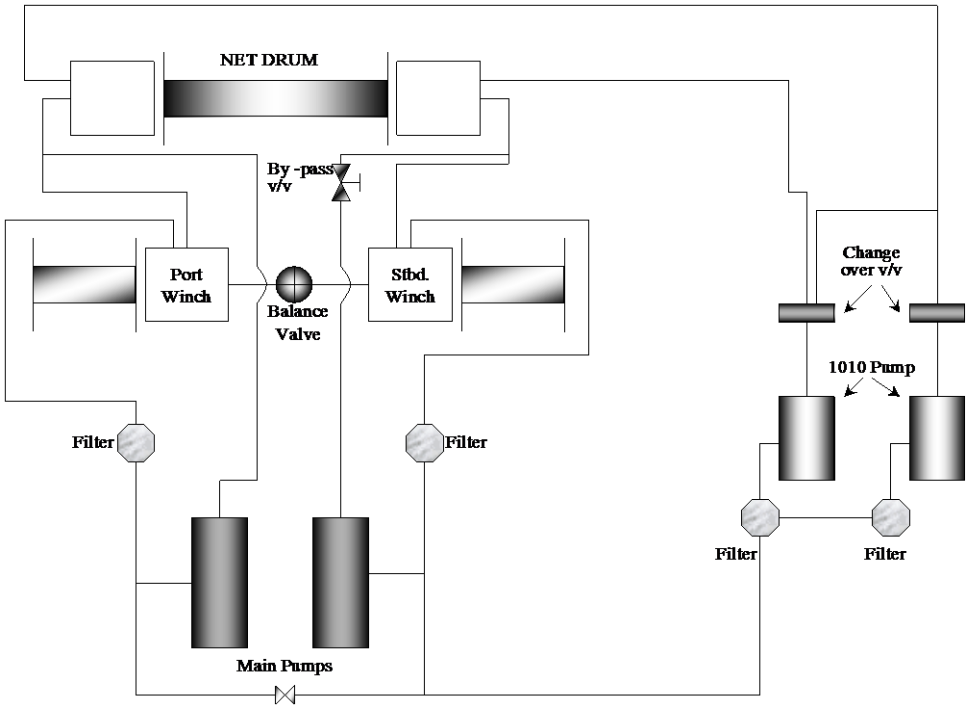

Fig 15 Hydraulic winch operating system

4.2 Cooling System – Centrifugal Pump

The system is taken from the MV Hamnavoe, a Ro-Ro passenger ferry on which the lead author of this paper served time during a cadetship. The full system is shown in fig 16.

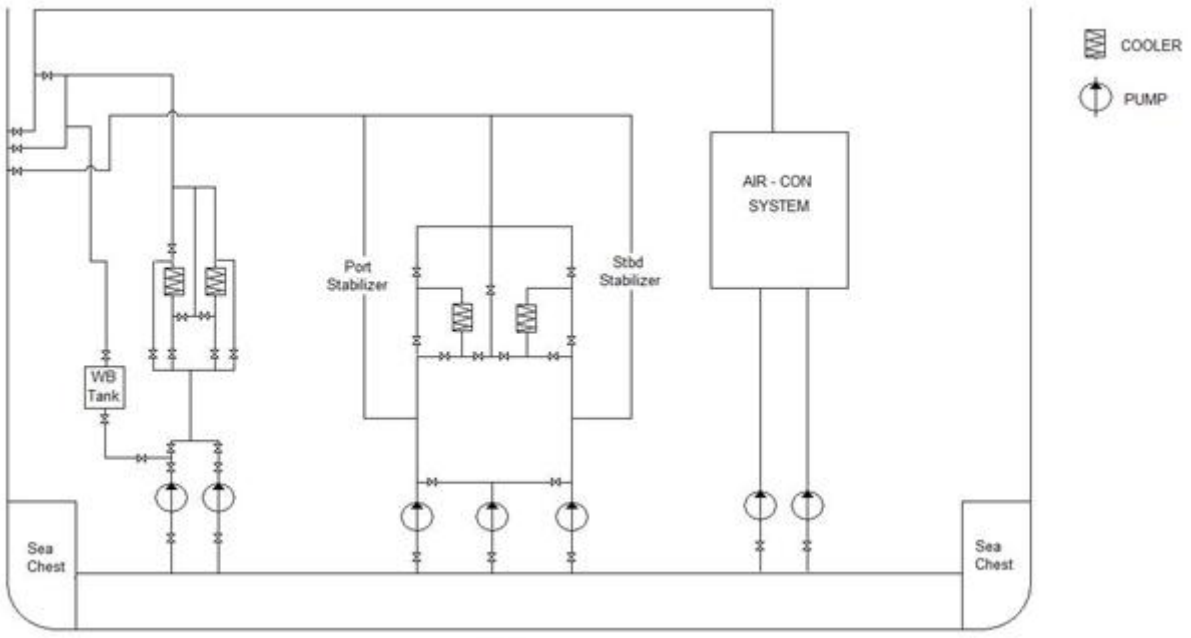

Fig 16 Schematic diagram showing the cooling system

The analysis is performed on one centrifugal pump which services the main cooling system. To carry out the analysis a number of input variables were required. The downtime due to breakdown was taken from OREDA 2002 and set equal to 168 hours or 7 days which allows for any logistical delay in spare part procurement. For the downtime due to inspection the expert opinion of an experienced marine chief engineer was used. A detailed description of the chief engineer's industrial experience and academic qualifications is listed in the appendix. Daily inspection of the centrifugal pump involves visual inspection of suction and discharge pressure, audio inspection for any abnormal noise and electrical inspection of the current being drawn by the electric motor. The chief engineer suggested that this daily inspection on average would take 10-15 minutes. In light of this the downtime due to inspection was taken as 12.5 minutes or 0.2083 hours. When considering the arrival rate of defects it is argued that the failure rate of a system and the arrival rate of defects are intrinsically linked. In order for this to be true the component or system would have to be operated under a breakdown maintenance policy. OREDA data is not presented for systems operating under a breakdown maintenance regime. However for the purpose of the analysis it is assumed that the OREDA failure data for a centrifugal pump and the arrival rate of defects are equivalent. OREDA gives the failure rate per 10^6 hours for a centrifugal pump, in all modes of failure, as 1277.00. This is based on a population of 350 pumps over 59 installations. Table 2 details the input parameters for the analysis.

Table 2 Table showing the input parameters for the analysis

Inspection Downtime	$\mathbf{d_s}$	0.2083 hrs
Breakdown Downtime	$\mathbf{d_b}$	168 hrs
Arrival rate of defects	$\mathbf{k_f}$	0.001277 hrs^{-1}

4.3 Estimation of Delay-time Probability Density Function

In a case study based on a specific system the probability density function of the delay-time would be estimated using historical failure data and operator questionnaires. This process in itself takes a great deal of time and logistical work. The purpose of this work was to demonstrate the simulation method of DTA, therefore the analysis was performed using a number of different Weibull distributions for the delay-time and may not represent accurately the true distributions of the delay-times for the real life systems. Table 3 shows the shape and scale parameters used for the different analyses. A number of shape and scale parameters are used to give an idea of their effect on the analysis.

Table 3 Table showing the shape and scale parameters
of the Weibull distributions used in the analysis

k	**Λ**
10	5
8	6
3	10
2	20

4.4 Initial Modelling Assumptions

When performing the analysis for the case study the following modelling assumptions were made.

- Inspections take place at regular intervals of T hours and each inspection is identical.
- The arrival rate of defects is constant and distributed according to an exponential probability density function.
- Failures are repaired instantaneously and the system is returned to a ‘good as new’ state.
- The mission time is set to 10 years and is sufficiently large that downtime due to breakdown and inspection during the analysis can be considered negligible.
- Inspections are perfect in that any defect present will be identified and the failure arrested within the inspection period.

5. Case study Results

5.1 Fishing Vessel – Perfect Inspections

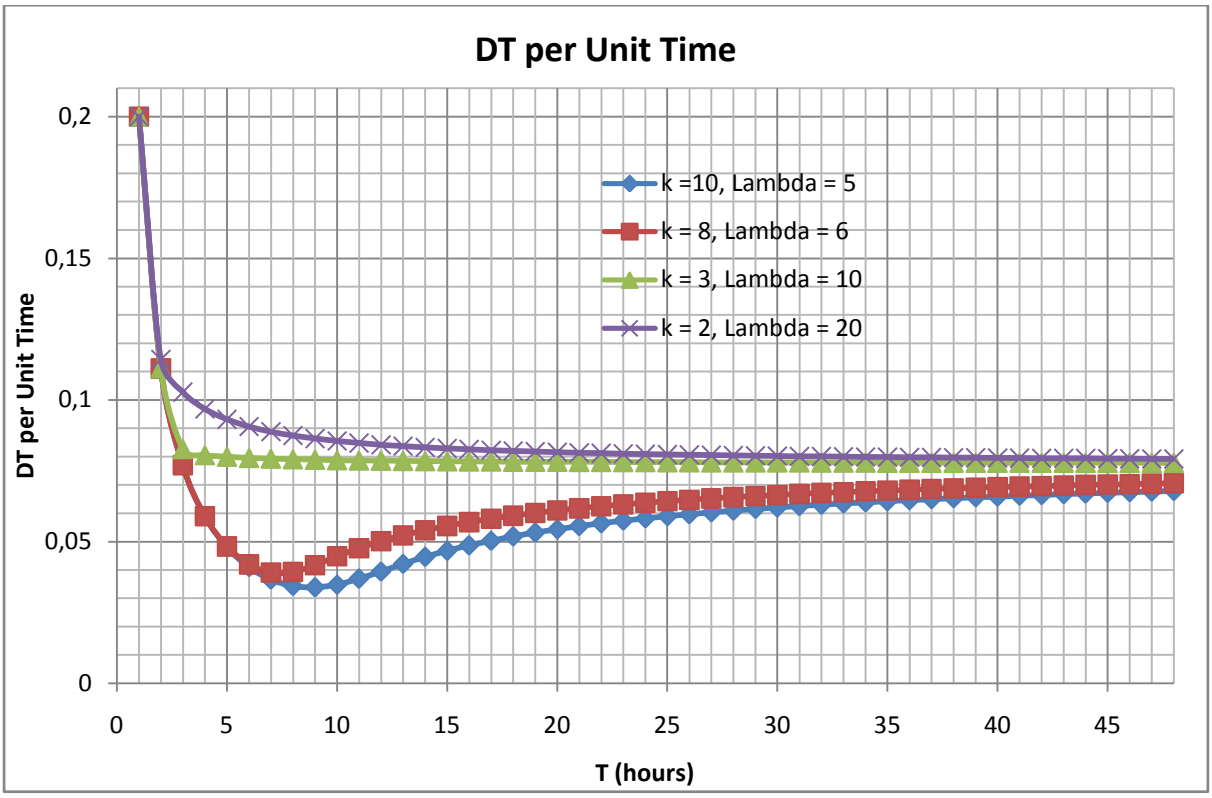

Fig 17 Graph showing DT per unit time against T

The analysis was conducted using a FORTRAN programme in the way outlined in the methodology previously. Fig 17 shows the results of the analysis. The programme was run a number of times using different shape and scale parameters, k and λ. It can be seen from the graph that when the shape parameter, k is high, then the analysis produced the best results. When k=10 and λ =5, DT per unit time was minimised at T=9 hours to give a DT per unit time of 0.034 hours. When k=8 and λ=6, DT per unit time was minimised at T=7 hours to give a DT per unit time of 0.04 hours. When k=3 and λ=10, no definitive minimum point was established. Also when k=2 and λ=20, no definitive minimum point was established. If the results where k=10 and k=8 are considered then an optimum inspection of 9 and 7 hours would be recommended respectively.

5.2 Cooling System - Centrifugal Pump – Perfect Inspections

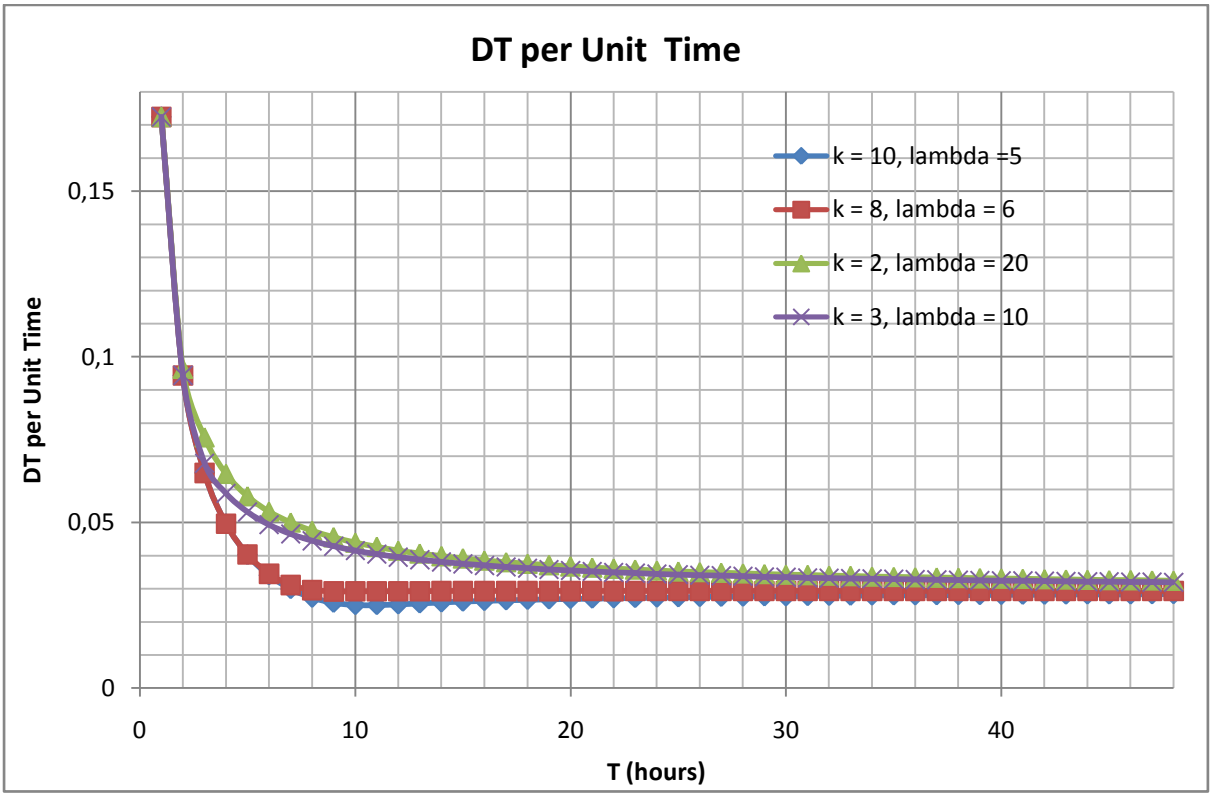

Fig 18 Graph showing DT per unit time against T

The analysis was conducted using a FORTRAN programme in the way outlined in the methodology previously. Fig 18 shows the results of the analysis. The programme was run a number of times using different shape and scale parameters, k and λ. It can be seen from the graph that when the shape parameter, k is high, then the analysis produced the best results. When k=10 and λ =5, DT per unit time was minimised at T=11 hours to give a DT per unit time of 0.025 hours. For all other values of K and λ considered, no definitive minimum point was established. From the results where k=10 and λ=5, an optimum inspection of 11 hours would be recommended.

5.3 Fishing Vessel – Imperfect Inspections

The analysis was conducted using a FORTRAN programme in the way outlined in the methodology previously. Fig 19 shows the results of the analysis. The programme was run using shape and scale parameters, k=10 and λ=5, which produced the most definitive result for perfect inspection. It can be seen from the graph that when imperfect inspections are considered the value of minimum DT per unit time is increased. The recommendation for the optimum inspection interval remains appropriate at T=9 hours giving a downtime per unit time of 0.041 hours.

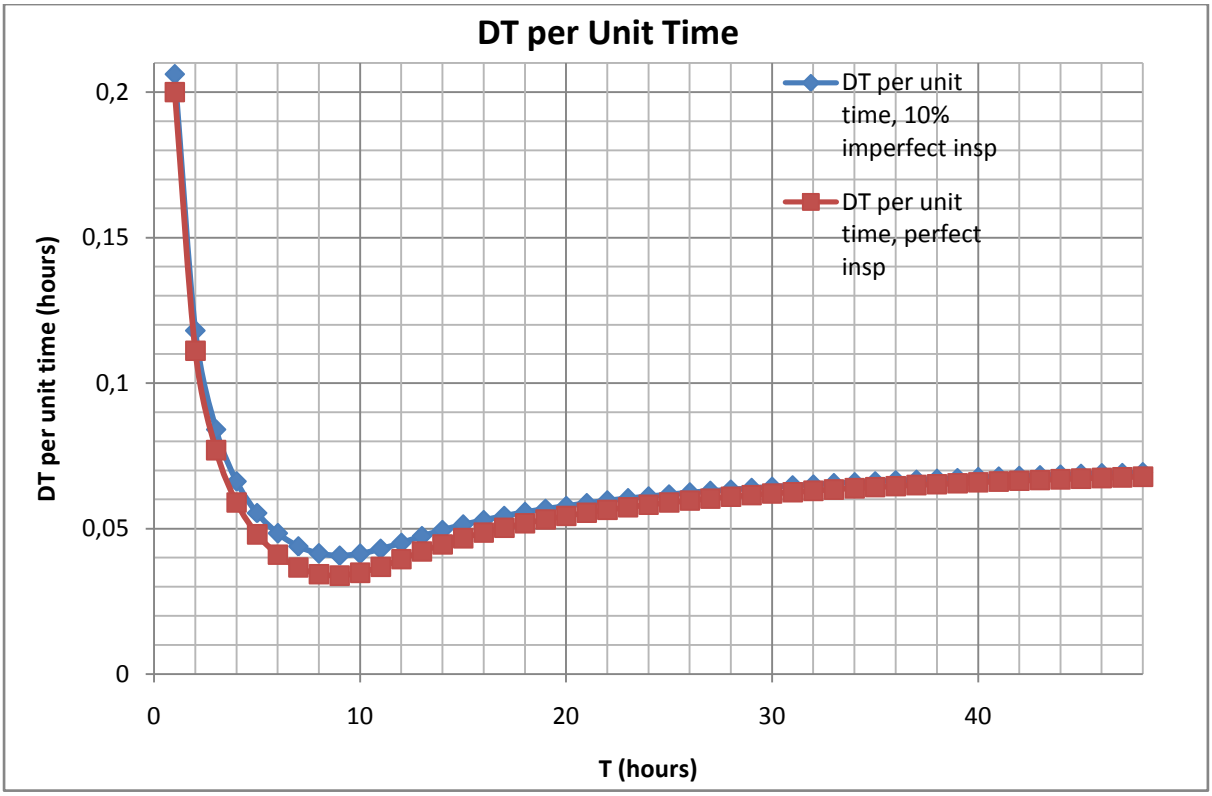

Fig 19 Graph showing DT per unit time against T considering imperfect inspections

5.4 Cooling System – Centrifugal Pump – Imperfect Inspections

The programme was run using shape and scale parameters, k=10 and λ=5, which produced the most definitive result for perfect inspection. Fig 20 shows the results of the analysis. It can be seen from the graph that when imperfect inspections are considered as in the first case study the value of minimum DT per unit time is increased. The recommendation for the optimum inspection interval remains appropriate at T=11 hours giving a downtime per unit time of 0.027 hours.

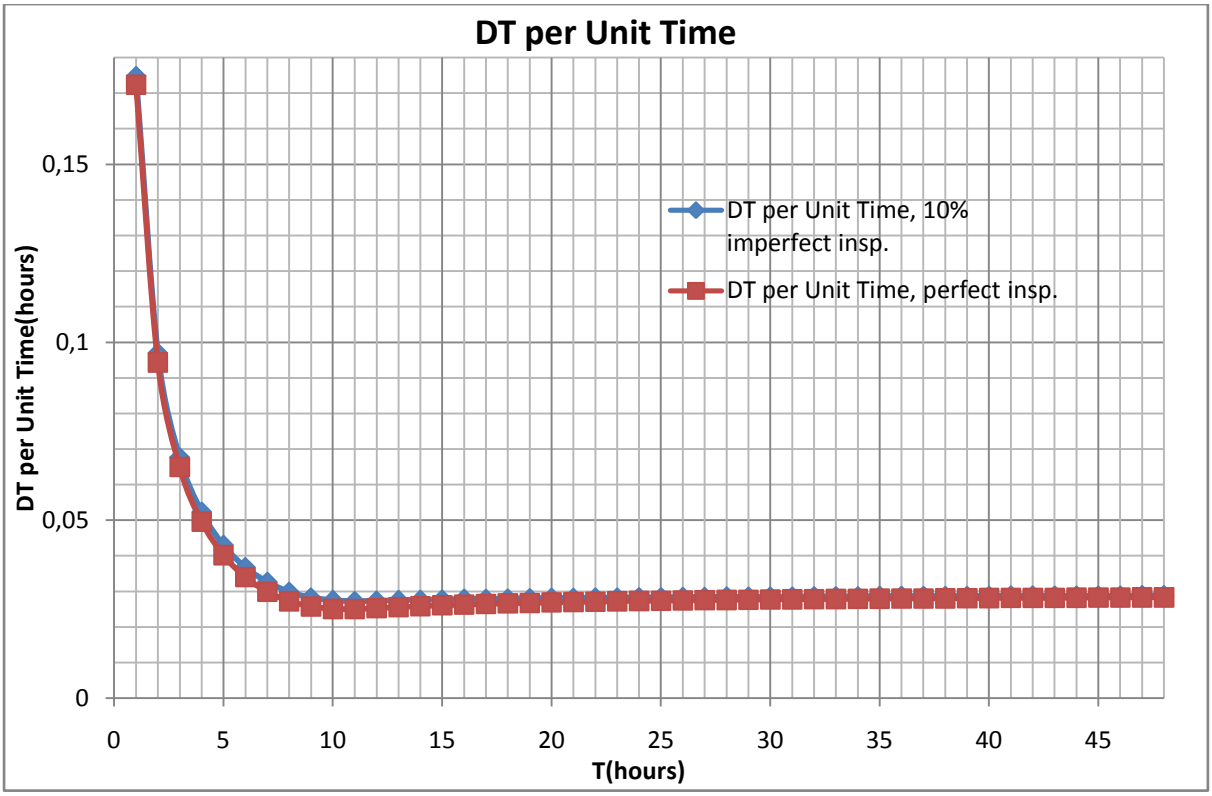

Fig 20 Graph showing DT per unit time against T considering imperfect inspections

5.5 Fishing Vessel – Imperfect Repair

The programme was run using shape and scale parameters, k=10 and λ=5, which produced the most definitive result for perfect inspection. Fig 21 shows the results of the analysis. It can be seen from the graph that the consideration of imperfect repair has a similar effect on the downtime per unit time achieved as imperfect inspection did previously. The recommendation for the optimum inspection interval remains appropriate at T=9 hours giving a downtime per unit time of 0.042 hours.

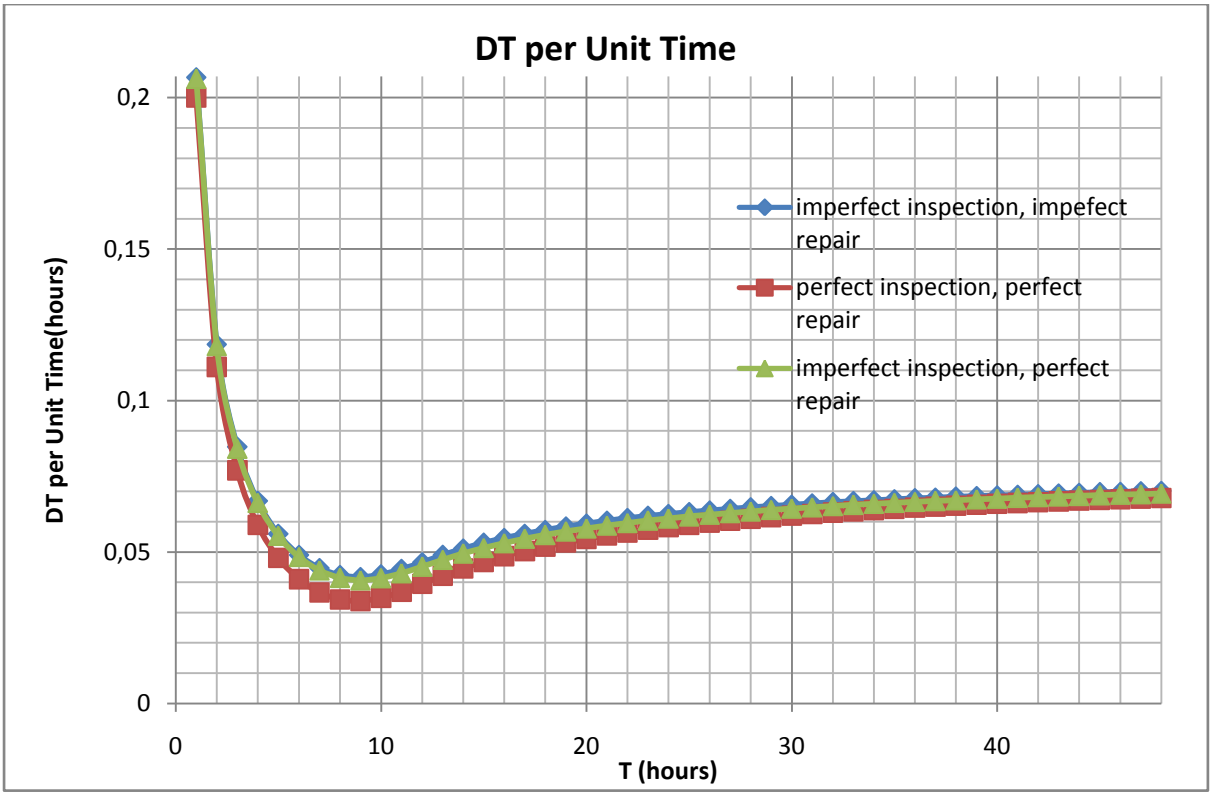

Fig 21 Graph showing DT per unit time against T considering imperfect inspections with perfect repair, imperfect inspections with imperfect repair and perfect inspections with perfect repair

5.6 Cooling System – Centrifugal Pump – Imperfect Repair

The programme was run using shape and scale parameters, k=10 and λ=5, which produced the most definitive result for perfect inspection. Fig 22 shows the results of the analysis. It can be seen from the graph that the consideration of imperfect repair has a similar effect on the downtime per unit time achieved as imperfect inspection did previously. The recommendation for the optimum inspection interval remains appropriate at T=11 hours giving a downtime per unit time of 0.028 hours.

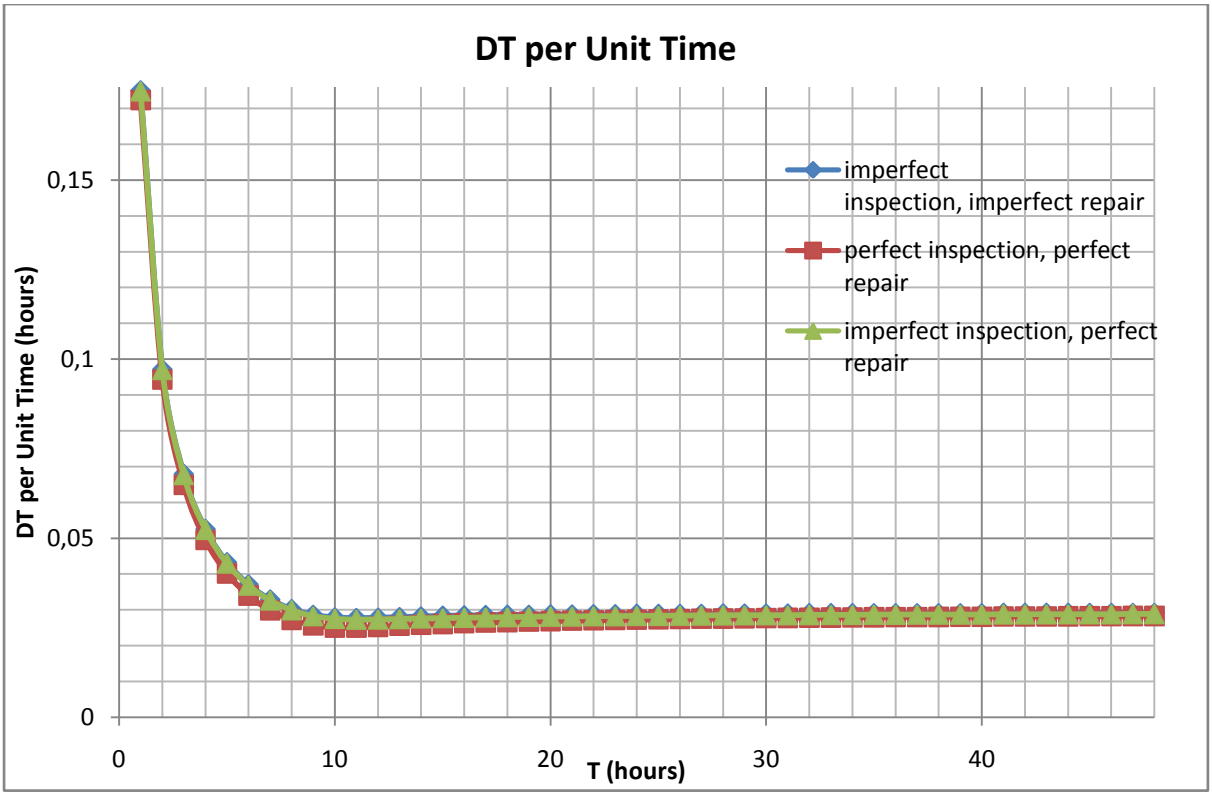

Fig 22 Graph showing DT per unit time against T considering imperfect inspections with perfect repair, imperfect inspections with imperfect repair and perfect inspections with perfect repair

6. Sensitivity Analysis

A sensitivity analysis provides a way of partially validating a model. For this model three axioms are detailed and must be satisfied before the sensitivity analysis can be considered complete.

- An increase in the arrival rate of defects should result in a proportional increase in the DT per unit time.
- Further increase in the arrival rate of defects should reflect a consistent increase in the DT per unit time.
- An increase in more than one input parameter should result in a larger increase in DT per unit time than that caused by an increase in a single input parameter.

The sensitivity analysis was conducted on a single case presented previously, with perfect inspections and perfect repairs. The more complex cases involving imperfect inspection and repair are extensions of this model; therefore, partial validation of this model will also provide partial validation of the more complex cases. The case study involving the input parameters for the cooling system centrifugal pump was used. The models for both the fishing vessel and the centrifugal pump both

follow the same methodology, therefore partial validation of one model is sufficient. The results of the sensitivity analysis can be seen in fig 23.

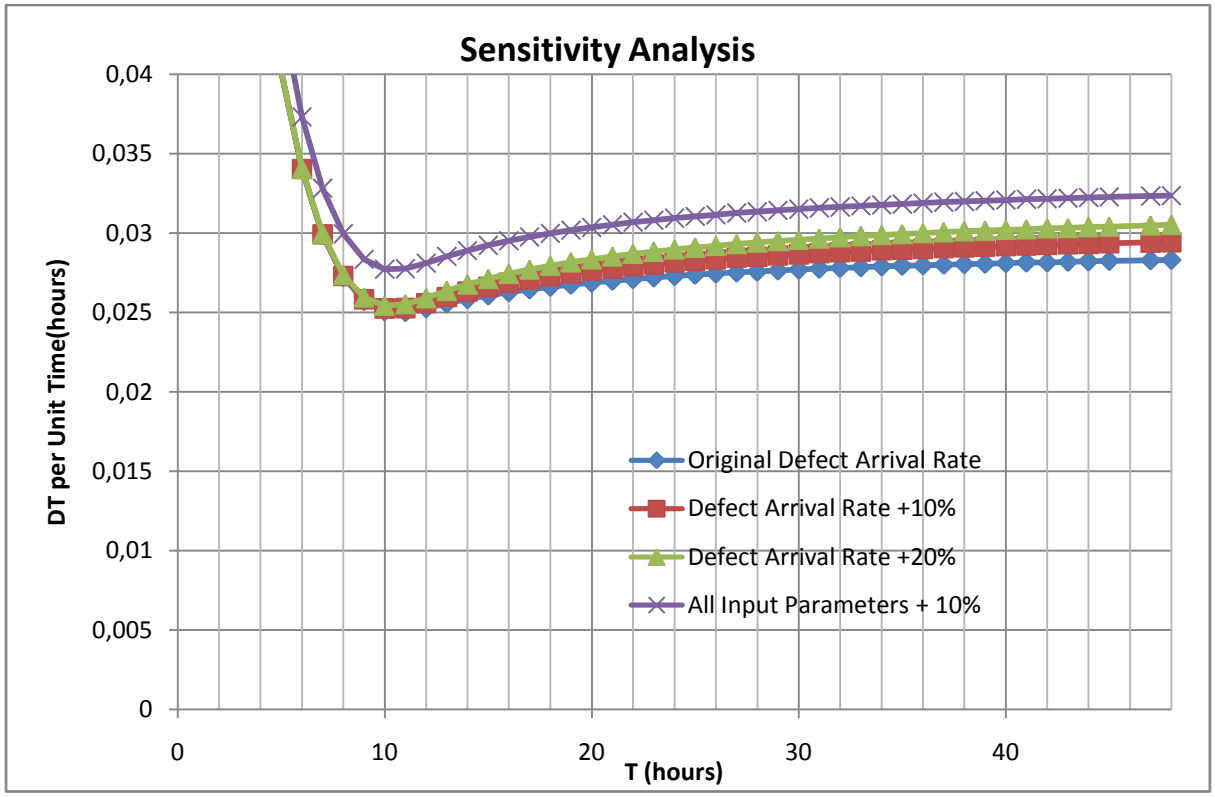

Fig 23 Graph showing the results of the sensitivity analysis

It can be seen from the results shown in fig 23 that when the arrival rate of defects is increased the DT per unit time also increases. Furthermore when the arrival rate of defects is further increased the DT per unit time increases again by a proportional amount. When all of the input parameters are increased the DT per unit time is increased by a greater magnitude, when compared to alteration of a single input parameter i.e. arrival rate of defects. These results satisfy the axioms outlined previously, thus giving validation to the model.

7. Discussion

The analysis programme can be easily altered to consider a different set of equipment, with different input parameters. The only limitation to the simulation method is the ability of the programmer to generate random numbers distributed to different distributions. The method gains accuracy when the mission time is set at larger values. This is often at the expense of time to compute simulation results. As computers increase in both speed and processing power this will become less of a problem, however the analyst should always give careful consideration to the suitability of the mission time. Short mission times will produce more results in a shorter period of time but this may be at the

expense of accuracy. Conversely exceptionally long mission times will produce very accurate results but may prove unrealistic in terms of an average component lifetime and may also prove impractical in terms of processing time.

When considering the results of any analysis reflection on the propriety of the modelling assumptions must be made. The assumption that all inspections that take place are perfect and that all defects are recognised and corrected is improbable. However the simulation programme can easily be amended to take into account the case of imperfect inspection. In order to examine the impact of imperfect inspections the analysis was repeated with the premise that inspections were only perfect 90% of the time. In the remaining 10% the defects went unnoticed at inspection and developed into full breakdown failures. It can be seen from the results shown that imperfect inspection intervals result in an increase of the DT per unit time. The DT per unit time increases as the amount of imperfect inspections increase, reducing the amount of imperfect inspections reduces the DT per unit time. The optimal inspection interval remains unchanged. Further increase or reduction in the amount of imperfect inspections has a similar affect of 'shifting' the curve vertically away from or towards the perfect case.

The assumption that the system is returned to 'good as new' after inspection and repair is also one that seems unrealistic. This may not prove to be the case in real life, systems may be put back into service in a degraded state after inspection or repair. This is ultimately dependant upon the experience and skill of the maintenance personnel and the quality of the replacement parts. To examine the effect of imperfect repair, the analysis was repeated with the assumption that after an inspection and subsequent corrective action the system is put back online with an arrival rate of defects increased by 20%. It can be seen from the results that this increases the level of downtime per unit time achieved. The optimal inspection periods remain unchanged.

All of the simulations implemented in the paper use a random seed function whenever a random number is generated. This provides suibtably random results. Due to the nature of the pseudo-random number generator function used in the simulation, non random seed values would produce repeated results and the generation of the random would become some what deterministic in nature.

The results of both models which concerned imperfect inspection and imperfect repair are logical. If inspections are imperfect then there is an increased chance for system breakdown, this is reflected in the increase of downtime per unit time. In the case of imperfect repair the arrival rate of defects increases, this leads to more defects and results in an increase of the downtime per unit time. The strength of the MCM of DTA is the method's ability to deal with different situations in a logical and straightforward way. The inclusion of imperfect inspection and repair comes at the cost of a few

additional lines of code. To consider the same problems using traditional analytical methods would result in a significant increase in mathematical rigour. Marine engineers, having often achieved their qualifications in a vocational system, often lack the mathematical skills necessary to perform such an analysis via analytical methods. The simulation method presented circumnavigates this knowledge gap and provides a useful tool for marine engineers in an accessible way.
The results were as expected in that a minimum downtime was found. Before running the analysis the analyst had only very general ideas of expected reults. The model is only partially validated by the sensitivity study and further work is needed to produce a theoretical result.

The method could prove to be a very useful tool in defining inspection regimes for particular pieces of equipment. For the method to be fully effective an inspection regime would have to be implemented to provide the simulation program with accurate historical failure data. The more data gathered the more accurate and effective the analysis would become. Any decisions made concerning the maintenance regime onboard will ultimately be decided by the owner/operator of the vessel. It may be the case in certain situations that it is not possible to carry out inspection at the recommended interval. It is not always convenient or even safe to take certain systems offline during passage, this would obviously be system specific and engineering judgement would play a large part in how the inspection regime could be altered or adjusted. The decision to implement DTA will depend upon existing operating and maintenance culture onboard.

8. Conclusion

The purpose of this work was to demonstrate an alternative method for DTA other than traditional analytical methods. Previous research work reported on DTA is often arduous in terms of the mathematical models presented. It has demonstrated the benefit of the method but the esoteric nature of the mathematical models, has often prevented engineers in industry from implementing the method. The intention of the researchers of this work was to present a methodology of achieving the same results in a more accessible way to a wider range of engineers. Based on the evidence of the results presented the methodology outlined for performing the analysis will provide optimal inspection periods for a given set of data. This work also demonstrates the power and flexibility contained within the MCM to consider a number of different models and methods. A need is also identified for ship owners/operators to invest more time into the collation of failure data specific to their vessels. Different vessels operating in different areas and conditions will display different failure characteristics. The collection of failure data and its use in the analysis of systems with respect to reliability and appropriate maintenance scheduling could only prove beneficial to ship operators.

There is certainly huge scope for further work especially when the simplifying assumptions are considered. In the models presented two of these assumptions were relaxed. The more interesting of the two is the assumption that defect arrival rate is constant. In the analysis the arrival rate was changed as a result of different inspection and breakdown actions, however the arrival rate always obeyed the same distribution. Further work could be done to examine the effect of changing the distribution of the arrival rate of defects throughout the analysis. There is also scope for work considering the age of components and the effect of component age on defect arrival rate.

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9. Appendix: Industrial Experience and Academic Qualifications of the Chief Engineer for Expert Judgement.

Occupation	Year	Description
Fourth Engineer Officer	1987-10th October 1989	Ocean going vessels (General cargos and Bulk Carriers).
Third Engineer Officer	30th December 1989-11th October 1991	Ocean going vessels (General cargos and Bulk Carriers).
Second Engineer Officer	1992- 11th June 1995	Ocean going vessels (General cargos and Bulk carriers).
Chief Engineer Officer	15th May 1996 up to	Ocean going vessels

	03. April.2003	(Container carriers 3300 TEU, General cargos and Bulk carriers).
Engineering superintendent at Aker Ostsee Shipyards Wismar& Warnemunde – Germany	June 2003-July 2004	Construction and fabrication of Six Container Carriers. 4X2500TEU and 2X2700TEU
Senior Engineering Superintendent	July 2004 up to July2008	Container Carriers 4X3300TEU 4X2500TEU 2X2700TEU
Research Fellow/Lecturer at LJMU	July 2008-Present	Maritime Security and Risk Assessment