Optimizing maintenance to manage the major accident risk

Peter Okoh, Department of Production and Quality Engineering; Norwegian University of Science and Technology, 7491 Trondheim, Norway

There has been a paradigm shift in the design of unmanned platforms following the Piper Alpha disaster in 1988. Firefighting systems are usually not installed anymore based on the reason that the risk reduction benefit they offer to maintenance personnel for unmanned platforms is not commensurate with their frequency of visits unlike in a manned facility, i.e. a negative risk balance. Maintenance grouping contributes to the reduction of maintenance frequencies which should reduce major accident risk, but on the other hand, as the workload increases the likelihood of making errors increases which increases risk. The use of more manpower also increases exposure to risk. The main objective of this paper is to investigate how maintenance grouping and the workload can be balanced in relation to reducing the major accident risk. The paper builds on a review of literature on maintenance optimization, human reliability and risk.

Keywords: Maintenance, Maintenance Grouping, Optimization, Workload, Major Accident Risk

Introduction

According to Evans & Thakorlal (2004), safety systems such as fire pumps offer negative risk balance with respect to an unmanned platform, i.e. maintenance visits increased the exposure of personnel to risk than the benefit from such systems in a manned facility – a negative risk balance. This implies that the installation of a fire pump, for e.g., will create the need for visits to the platform to maintain it in addition to other visits aimed at maintaining the facility itself. Besides, increased maintenance frequency implies increased likelihood of making errors (Reason, 1997) and this increases risk. This issue of negative risk balance was borne from reviews following the Piper Alpha disaster in 1988 (Evans & Thakorlal, 2004).

Maintenance grouping is a kind of initiative that enhances maintenance optimization by combining maintenance activities based on some policies and criteria leading to savings in set-up cost (Nicolai & Dekker, 2008; Vatn, 2008; Castenier et al, 2005; Wildeman et al, 1997; Dekker et al, 1997). However, this original objective of maintenance grouping can be extended to cover risk reduction benefit in relation to major accident risk installations.

With no grouping of maintenance activities, it can be expected that the major accident risk associated with maintenance will decrease as we increase the degree of grouping, i.e. personnel exposure to high risk installations will decrease with reduced frequencies of maintenance visits. However, beyond an optimal maintenance load, the workload on the personnel becomes unacceptably high which increases the probability of human error or more personnel may be deployed which increases exposure to risk (Nicolai & Dekker, 2008).

Although several studies have been carried out on maintenance grouping over time, an article that sufficiently addresses the possible imbalance between workload and grouping maintenance has yet to be seen. Existing methods of maintenance grouping are divided into two: Static grouping and dynamic grouping. Static grouping is further divided into indirect static grouping and direct static grouping (Wildeman, 1996; Dekker et al., 1997). Dynamic grouping differs from static grouping by being flexible to adjustments based on new information and unexpected interruptive events, whereas static grouping is rigid with the grouping remaining unchanged throughout the lifespan of the system (Wildeman, 1996; Vatn, 2008). Detailed introductory theories of both strategies can be found in some of the referenced literatures.

The main objective of this paper is to investigate how maintenance grouping and the workload can be balanced in relation to reducing the major accident risk.

The rest of the paper will be structured as follows: (2) Negative Economic Dependency: A Challenge for Maintenance Grouping; this will be a further analysis on the subject, (3) How to Balance Maintenance Grouping and the Workload; this section will review workload management and link it to an existing grouping strategy – direct static grouping, (4) Conclusion; this ends the paper with highlights of what has been accomplished in the work.

Negative Economic Dependency: A Challenge for Maintenance Grouping

A challenge for grouping maintenance is the issue of negative economic dependency i.e. a situation whereby it becomes more profitable to maintain components individually than simultaneously; the opposite is positive economic dependency which involves cost saving from joint maintenance (Nicolai & Dekker, 2008; Dekker et al, 1997). According to Nicolai & Dekker (2008), the concerns raised over negative economic dependency encompass a tendency to human resources violations (via unsafe increase in an individual's workload) and the need for extra human resources. This contributes to periodic maintenance problem (PMP). A human-risk-related PMP has been studied earlier by van Zante-de Fokkert et al. (2007) in which the focus was on preventing fatalities associated with a previous unmanageable track maintenance workload per night.

In grouping, it is usual to aim to complete the maintenance of items that have been grouped together within a fixed time interval at a given opportunity, which leads to maintenance being carried out simultaneously to take advantage of a shared maintenance set-up cost. There exists a decision-making situation of choosing between increasing the number of employees and increasing the workload of existing personnel. Increasing number of personnel will increase cost of maintenance and exposure of more personnel. Hence, there is the attraction to increase the workload of the existing workers. However, increase in worker's workload beyond a critical point will increase the probability of accident in high-risk installations.

Finding the balance between changes in workload and grouping maintenance is a challenge that can be solved by finding a way to address the cost of overload (i.e. cost of excessive workload) which includes cost of introducing new failures and cost of accident due to human factors.

How to Balance Maintenance Grouping and the Workload

Increasing workload of workers, most especially during simultaneous operations, increases the probability of introducing failures during operations and the probability of triggering events, and these will have great economic and safety implications for high-risk operations (Le May et al., 1982). This is consistent with the position of Moray (1988) which supports the view that personnel error will decrease by virtue of optimized apportionment of workload which will in turn promote safety and production values.

Concurrent and complex tasks can be very demanding on workers information processing capacity (Pretorius & Cilliers, 2007) and this can be seen in grouping maintenance which involves a multi-task environment. A review and reappraisal on workload has been done by Xie & Salvendy (2000) both for single task and multiple task situations; the latter is more of interest to grouping maintenance in which we have to deal with more than one activity. Consideration for workload is important for maintenance grouping to be able to set limits for addition of more activities to a given group.

According to Le May et al. (1982), the primary measure of workload will be analogous to standard system reliability workload measure, consisting of the ratio of time required to time available such that:

$$W = \frac{T_r}{T_a} \qquad (1)$$

Where,

W = workload

T_r = time required by the operator to perform a specific subtask

T_a = time required on the Operations Sequence Diagrams (OSDs) for that particular subtask

However, Xie & Salvendy (2000) consider the ratio of Le May et al. (1982) which is being supported by Hendy et al. (1997) as insufficient to describe workload comprehensively. According to Xie & Salvendy (2000), the magnitude of mental workload can be sufficiently described by two attributes of workload, accumulated and average workload (i.e. T_r/T_a as defined earlier by Le May et al. (1982)), accumulated workload being a measure of the total amount of workload an operator experiences during the task, and average workload being a measure of the workload intensity (i.e. average value of instantaneous workloads which is of same measure as accumulated workload per unit time). Xie & Salvendy (2000) further established mathematical relationships between average and accumulated workload for a single-task situation as follows:

$$W_{ac}(t) = \int_0^t W_{in}\,(u)du \qquad (2)$$

$$W_{av}(t) = \frac{W_{ac}(t)}{t} \qquad (3)$$

$$W_{av} = \frac{K.(W_{eff} + W_{ine})}{t_a} \qquad (4)$$

Where,

W_{ac} = accumulated workload, i.e. the total quantity of workload experienced during the task.

W_{in} = instantaneous workload, i.e. a measure of the dynamics of workload.

W_{av} = average workload = intensity of workload, i.e. the average of instantaneous workloads.

W_{eff} = effective workload = taskload, i.e. related to the task characteristics, for e.g. duration.

W_{ine} = ineffective workload, i.e. related to individual factors, for e.g. knowledge, stress.

t = time

t_a = time available to perform the work

K = degrading factor i.e. a factor that affects overall workload, influenced by attitude

The values of K range between 0 and 1, where 0 is allocated for a situation where operators show absolute indifference and perform no action on the given tasks, 1 is allocated where operators are diligent and fully focused on tasks, and between 0 and 1 is allocated where operators are partly committed to the tasks and perform actions only on part of the tasks (Xie & Salvendy, 2000).

According to Parasuraman & Rovira (2005), “there is a large body of empirical evidence and supporting theory showing that operator performance shows significant costs in speed or responding and accuracy when operators shift between two or more tasks.”

Hence, for a multi-task situation which is synonymous with maintenance grouping, the expressions above can be extended as follows (Xie & Salvendy, 2000):

$$W_{av} = \frac{(\sum_i W_i) + K.M_l}{t_a} \qquad (5)$$

Where,

W_i = workload for task i

M_l = management load, which is the additional mental effort applied to control simultaneous tasks, switching from task to task.

According to Xie & Salvendy (2000), Equation 4 implies that when performing tasks concurrently, mental workload always create higher workload than the simple sum of all the workload when performing tasks one after the other, if same sub-tasks do not exist. They (Xie & Salvendy, 2000) reiterated that the presence of some similar sub-tasks may reduce accumulated multi-task workload, implying that a set of common sub-tasks could be handled simultaneously by a worker without leading to increase in the overall mental workload.

Equations 1 and 5 could be adopted for industrial maintenance such that maintenance workload in a multi-task environment is defined as follows:

$$W_m = \frac{(\sum_{i=1} d_i) + K.M_l}{t_m} \qquad (6)$$

Where,

W_m = average maintenance workload

d_i = duration of maintenance for task i

t_m = total time available for maintenance

K, and M_l are as defined before

Xie & Salvendy (2000) did not specify how to calculate the management load. Hence, an initiative is taken to express the management load for maintenance grouping as:

$$M_l = K \cdot t_s \qquad (7)$$

Where,

t_s = expected total switching time between tasks

Hence, Equation 5 can be rewritten as:

$$W_m = \frac{(\sum_{i=1} d_i) + K.t_s}{t_m} \qquad (8)$$

To minimize the manpower violation aspect of negative economic dependency in grouping maintenance, it is suggested to ensure that addition of tasks to a given group satisfies Equation 9 which is given by:

$$K.t_s + \sum_{i=1} d_i \leq t_m \qquad (9)$$

A demonstration of how the workload factor can be applied on a given maintenance grouping strategy will be done in the following with static grouping as an example.

According to Wildeman (1996), direct static grouping may be organized as follows:

Maintainable items are combined into m groups such that each group, say G_j (for j = 1,2,..,n), is a subset of $m = \{G_1, G_2, .., G_n\}$, for $G_j \cap G_k = \{\}$, and $\cup_j G_j = \{ G_1, G_2, .., G_n\}$. Maintenance activities in each group are executed at the same interval, say T_j. The cost per time unit for a group can be defined as (Wildeman, 1996; Vatn, 2012):

$$C(\mathbf{T}) = \Sigma_{j=1:m} \{S/T_j + \Sigma_{i \in Gj} [c^P{}_i/T_j + c^U{}_i \lambda_{E,i}(T_j)]\} \qquad (10)$$

Where,

C(T) = cost per time unit for a group.

$c^P{}_i$ = individual preventive maintenance (PM) cost, excluding setup cost.

$c^U{}_i$ = individual cost upon failure, including costs of corrective maintenance (CM), safety, downtime and other losses.

S = set-up cost i.e. costs of preparing for PM of a group of items maintained simultaneously. Set-up costs are assumed to be the same for all activities.

$\lambda_{E,i}(T_j)$ = effective failure rate for item i when maintained at interval of span T_j

Hence, follows optimization to find the optimal value of T that minimizes the cost per time unit for a group $G_{j,}$ (for j = 1,..,n).

Unfortunately, Equation 10 does not account for the management of a group's maintenance workload after the group has been established and the joint maintenance interval determined. If we fail to match the demands of a resulting group with reasonable human resources, we increase the likelihood of accidents as maintenance personnel cave in to excessive workload. We can address this challenge by adapting Equation 11 from Equation 10 as follows:

$$C(\mathbf{T}) = \Sigma_{j=1:m}\{(S+ c^O{}_j\,)/T_j + \Sigma_{i\in Gj}\,[c^P{}_i/T_j + c^U{}_i\,\lambda_{E,i}(T_j\,)]\,\} \qquad (11)$$

Where,

$c^O{}_j$ = cost of overload on personnel in group $G_{j,}$ (for j=1,..,n), including cost of introducing new failures and cost of accident due to human factors – a penalty for violation.

Considering the need to address this challenge (i.e. this aspect of negative economic dependence) of grouping, the heuristics proposed for direct static grouping by Vatn (2012) based on the work of Wildeman (1996) may be adapted as follows:

1. Find individual maintenance interval τ_i, i.e., minimizing $C(\tau_i) = (S + c^P{}_i\,)/\tau_i + c^U{}_i\,\lambda_{E,i}(\tau_i)$
2. Sort the intervals in increasing order, i.e., $\tau_{(1)} < \tau_{(2)} < \ldots$
3. Look for clusters in the intervals, and let these forms groups G_1, G_2,…
4. If $K.t_s + \sum_{i=1} d_i \leq t_m$ for a given group, $G_{j,}$ (for j=1,..,n), Let $c^O{}_j = 0$
5. ELSE, Let $c^O{}_j$ = \$, where \$ is a specified monetary value (a penalty).
6. Given this group, $G_{j,}$ for j=1,..,n, minimize equation(10) with respect to **T**, i.e. $C(\mathbf{T}) = \Sigma_{j=1:m}\{(S+ c^O{}_j\,)/T_j + \Sigma_{i\in Gj}\,[c^P{}_i/T_j + c^U{}_i\,\lambda_{E,i}(T_j\,)]\,\}$
7. Go To 3 and vary the groups slightly to check if a better solution may be obtained.

Example

Consider an offshore riser system which consists of the following three components, emergency shutdown valve (ESDV), the pipe itself and a subsea isolation valve (SSIV). Let the data to use for the maintenance optimization be given as shown in Table 1.

Table 1: 1st stage of input for optimization

Component name	Component number, i	□	□₀	□₀	*S*	c^P	c^U
ESDV	1	3	0.001	14	2	8	60
Pipe	2	3	0.0016	20	2	9	60
SSIV	3	4	0.001	26	2	9	50

In Table 1, λ0 represents the effective failure rate (historical rate) with the current maintenance interval τ0, whereas □□is the ageing parameter (considering that failure is weibull distributed) and the other terms in this example are as defined earlier.

Given that, $\lambda_E(\tau)\approx [\Gamma(1+1/\alpha)/\mathrm{MTTF}]^{\alpha}\ \tau^{\alpha-1} \approx \lambda_0\ (\tau\,/\tau_0)^{\alpha-1}$, where MTTF represents the Mean Time To Failure, and substituting this into Equation 10 yields,

$$C(\tau) = \frac{S + c^P}{\tau} + \lambda_E(\tau)c^U = \frac{S + c^P}{\tau} + \lambda_0(\tau/\tau_0)^{\alpha-1}c^U$$

Hence, the derivative $\frac{\mathrm{dC}(\tau)}{\mathrm{d}\tau} = 0$ is such that:

$$\tau = \tau_0 \cdot \left(\frac{S + c^P}{(\alpha-1)c^U\lambda_0\tau_0}\right)^{\frac{1}{\alpha}}$$

This gives part of the results shown in Table 2.

Table 2: 2nd stage of input for optimization

Component name	**Component number, i**	□	□$_0$	□$_0$	***S***	c^P	c^U	τ
ESDV	1	3	0.001	14	2	8	60	25.4
Pipe	2	3	0.0016	20	2	9	60	28.4
SSIV	3	4	0.001	26	2	9	50	33.7

Let us assume that two components are to be maintained simultaneously. Possible groups out of these include G_1 = Components 1 and 2, G_2 = Components 2 and 3, and G_3 = Components 1 and 3. This is further analyzed in Table 3.

Table 3: 3rd stage of input for optimization

Components combination	**T *(Selected τ)***	**K**	t_s	$\sum d_i$	t_m	$K.t_s + \sum_{i=1} d_i \le t_m$ **?**	c^O
1 and 2	25.4	1	1	7	8	Yes	0
2 and 3	28.4	1	2	9	8	No	60
1 and 3	25.4	1	2	10	8	No	60

As shown in Table 3, T (the minimum τ), is selected for each group of components, the combined workload is analyzed and the cost of overload (c^o) is specified.

Hence, recalling Equation 11 for components combination 1 and 2,

$$C(T) = \sum \left\{ \frac{S + c^O}{T} + \sum \frac{c^P}{T} + c^U \lambda_E(T) \right\} = \sum \left\{ \frac{S + c^O}{T} + \sum \frac{c^P}{T} + c^U \lambda_0 (\tau/\tau_0)^{\alpha - 1} \right\}$$

$$C_{1\&2} = \left\{ \frac{2+0}{25.4} + \frac{8}{25.4} + 60 * 0.001 \left(\frac{25.4}{14} \right)^{3-1} + \frac{9}{25.4} + 60 * 0.0016 \left(\frac{28.4}{20} \right)^{3-1} \right\}$$

$$= 0.0787 + 0.3150 + 0.1975 + 0.3543 + 0.1936 = \mathbf{1.1391}$$

The implication of this result is that with regards to the case example, any option other than combination 1 and 2 will result to more cost and risk. Besides, two items, components 1 and 2 which otherwise would have been maintained in two separate maintenance visits have been justifiably combined to be maintained in just one visit, i.e. the maintenance time for component 2 is brought forward to coincide with that of component 1. Hence, the frequency of maintenance visits is reduced (i.e. maintenance set-up cost is shared and workers exposure to risk is reduced).

Note:

1. The figures used in the example are arbitrary values for demonstration purpose only.
2. The maintenance grouping concept can also be applied on systems with a large number of components over a given maintenance planning horizon, say N years.

Conclusion

The maintenance grouping strategy is practicable. It has been applied on the Norwegian railway system by Vatn (2008) and on offshore wind systems by Hameed & Vatn (2012). In the hydrocarbon industry, the strategy will reduce frequency of maintenance visits and avoid the exposure of the personnel to unnecessary risk.

This paper has shown that in addition to the originally intended benefits of economic savings through set-up costs sharing, grouping maintenance can reduce the frequencies of maintenance and hence reduce the exposure of personnel and the probability of inducing new failures, thus reducing risk. The condition for realizing the objective of maintenance grouping strategy, i.e. savings in set-up costs which also promotes safety rather than compromise it, has been analysed and incorporated into an existing grouping strategy - direct static grouping.

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