# The Use of Prognostic Systems to Reduce the Duration and Frequency of Helicopter Maintenance

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## *ABSTRACT*

*For aircraft engineers and maintainers, the risk of faults and failures within the mechanical assembly of a helicopter has always been a major concern. It is the nature of a rotary-wing aircraft to have major components such as gearboxes, synchronising shafts and rotors in an unavoidably single load-path configuration. This means that the consequence of mechanical failure is often catastrophic. In recognition of this, the scheduled maintenance practices for helicopters contain large safety margins; minimising the risk of failures at the expense of over-maintenance.*

*Since the late 1990s, the UK MOD has embarked on an ambitious programme to fit HUMS to its helicopters, with the RAF Chinook Mk2 and Mk2a programme being in the vanguard; the only fleets currently fully implemented. These sophisticated monitoring tools provide an accurate measurement of the immediate state of mechanical health for individual helicopters and a real-time measurement of the usage those aircraft experience. From these two sources of information a projection (prognosis) of the trend of mechanical health may be devised and continuously monitored and the need for most forms of mechanical maintenance can be predicted.*

*A reliable estimation of current and future condition should allow operators to address and reduce both of the maintenance cost burdens it bears. It should enable the safety margins set in scheduled maintenance intervals to be reduced and allow maintainers to predict unscheduled spares requirement days or even weeks in advance of the actual maintenance event. Such advance notice of maintenance requirement would allow lean efficiencies in the supply chain to be achieved.*

*A mathematical model presented here predicts ~5% availability improvements for the RAF Chinook fleet through prediction of unscheduled maintenance requirement.*

## 1.0 INTRODUCTION

Since the late 1990s, the UK Ministry of Defence (MOD) has embarked on an ambitious programme to fit Health and Usage Monitoring Systems (HUMS) to its helicopters, with the Chinook Mk2/2a programme being in the vanguard; the only fleets fully implemented. These sophisticated monitoring tools provide an accurate measurement of the immediate state of mechanical health for individual helicopters and a real-time measurement of the usage those aircraft experience. From these two sources of information a projection (prognosis) of the trend of mechanical health may be devised and continuously monitored and the need for most forms of mechanical maintenance can be predicted. This should allow operators to reduce both of the maintenance cost burdens it bears. It should enable the broad safety margins set in scheduled maintenance intervals to be reduced and allow maintainers to predict unscheduled spares requirement in advance of the actual maintenance event. Such advance notice of maintenance requirement would enable lean efficiencies in the supply chain to be achieved.

The MOD has a conflict of interest in maintaining its helicopter fleets such as the Royal Air Force (RAF) Chinook Mk2/2A. These valuable assets are in constant demand for training, military and peace-keeping commitments. This has led many senior officers to conclude that maintaining a high level of aircraft availability is the over-riding priority for the engineering function. In contrast, budget holders wish to reduce the frequency and cost of maintenance and to minimise stock holding. The third dimension in this triangle of competing priorities, illustrated in Figure 1, is airworthiness, or safety. Airworthiness is defined in the MOD (Anon., 1999(1)) as ‘the ability of an aircraft or other airborne equipment to operate without significant hazard’.

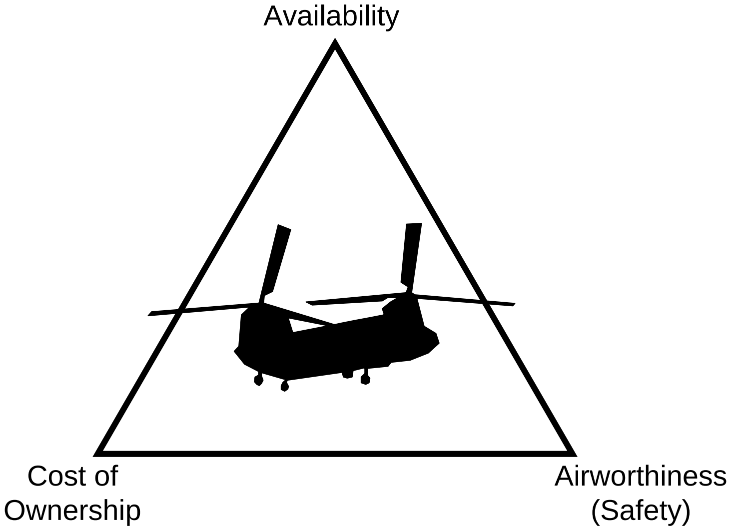

**Figure 1: Safety / cost / availability balance for helicopter ownership.**

The RAF maintenance policy (Anon., 1999(2)) contains the 6 objectives shown below, each of which are identified in parentheses as relating to availability, cost, or safety.

1) To minimise faults that would unacceptably reduce operational capability (availability).
2) To minimise faults that would cause lengthy downtimes (availability).
3) To minimise the resources required for maintenance (cost).
4) To minimise faults that would be expensive to repair (cost).
5) To minimise faults that would be hazardous to aircraft or personnel (safety).
6) To identify means of improving reliability and maintainability (safety).

Health and Usage Monitoring Systems (HUMS) could provide a means of simultaneously increasing safety and availability whilst reducing the cost of aircraft ownership. Larder et al. wrote that ‘there is now another clear driver of HUMS. This is the requirement for an effective tool to streamline maintenance, make this more cost effective, reduce an aircraft’s logistics footprint, and improve aircraft availability’ (Larder et al., 2000). Cook wrote that ‘even a few days of prognostic notice can allow great lean efficiency in a supply chain and reduce aircraft down-time’ (Cook, 2005). Due to the relative immaturity of the currently fielded HUMS, the MOD has not yet exploited this potential contribution to maintenance logistics.

## 2.0 MATHEMATICAL MODELLING

In both military and commercial business management, managers need to understand how fundamental aspects of their operation such as supply, production, distribution and equipment maintenance affect the Key Performance Indicators (KPIs) for the business. Experimenting directly with these business parameters is a risky and time-consuming way of gaining an understanding and is unlikely to discover an optimum solution. As a result, mathematical models of varying complexity and detail are used to statistically represent these operations. In these simulations, managers can quickly explore the effects of various potential business decisions without the delay, cost or risk of altering the business itself. Figure 2 illustrates the role of simulation in MOD decision-making.

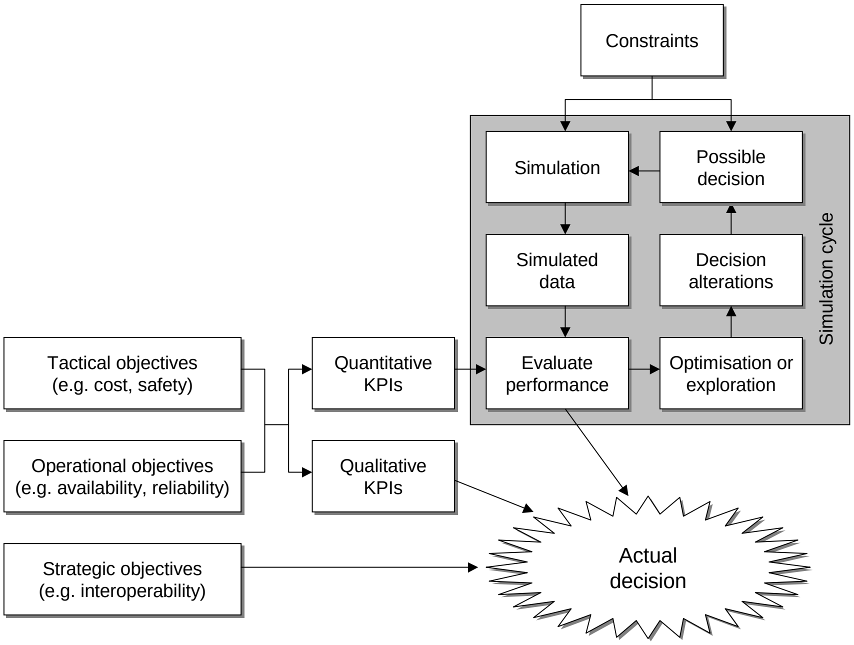

**Figure 2: Role of simulation in MOD decision-making.**

In this project, Discrete Event Simulation (DES) models were developed to estimate the improvements possible through:

1) Providing maintenance time-windows in which Corrective Maintenance (CM) could be safely performed, enabling resource levelling.

2) Predicting CM requirement to allow maintenance stockholding to be minimised.

Current supply chain data is used to define:

- Major components fitted;
- International deployments;
- Stockholding levels;
- Component transport times;
- Component failure rates;
- Component replacement durations;
- Mechanical engineers required for maintenance types; and
- Mechanical engineer availability.

Where possible, the data has been cross-checked against other supply chain information to verify the integrity of the information being used to define the simulation parameters. The outputs from the DES models have also been assessed against expected model results in order to verify the integrity of the simulations. Sensitivity analyses were then conducted against the prognostic interval and the mechanical engineer availability; two essential model parameters for which no definitive value exists. Finally, some degree of model validation was achieved by comparing supply chain parameter predictions from the simulation with independently measured values from the real supply chain.

## 3.0 ACTIVITY CYCLE DIAGRAMS (ACDs)

ACDs are a useful way of defining the structure and elements required for DES modelling. They are constructed from alternating queues and activities and arrows show the flow of entities such as aircraft and stock through the diagram. The ACD in Figure 3 illustrates the activities, queues and entity flows in major-component CM without use of HUMS data for a single Chinook deployment. This diagram shows the system as two cycles – one for aircraft and one for stock – intersecting at the point of CM activity. The diagram highlights important points for the mathematical modelling process, some of which are listed below.

- The limited availability of mechanical engineers due to non-CM tasks.
- The call for stock at component failure, which is defined here as the point at which the aircraft becomes unserviceable due to component damage.
- The division of the queue for CM into aircraft waiting for engineers and D state aircraft (aircraft grounded whilst waiting for spares).
- The simplifications introduced (grey elements in ACD) in not modelling the stock sources other than repair and overhaul through the Defence Aviation Repair Agency (DARA), the full cycle of component rejection and repair and the possibility of urgent 1-day supply of components through dedicated military transport.

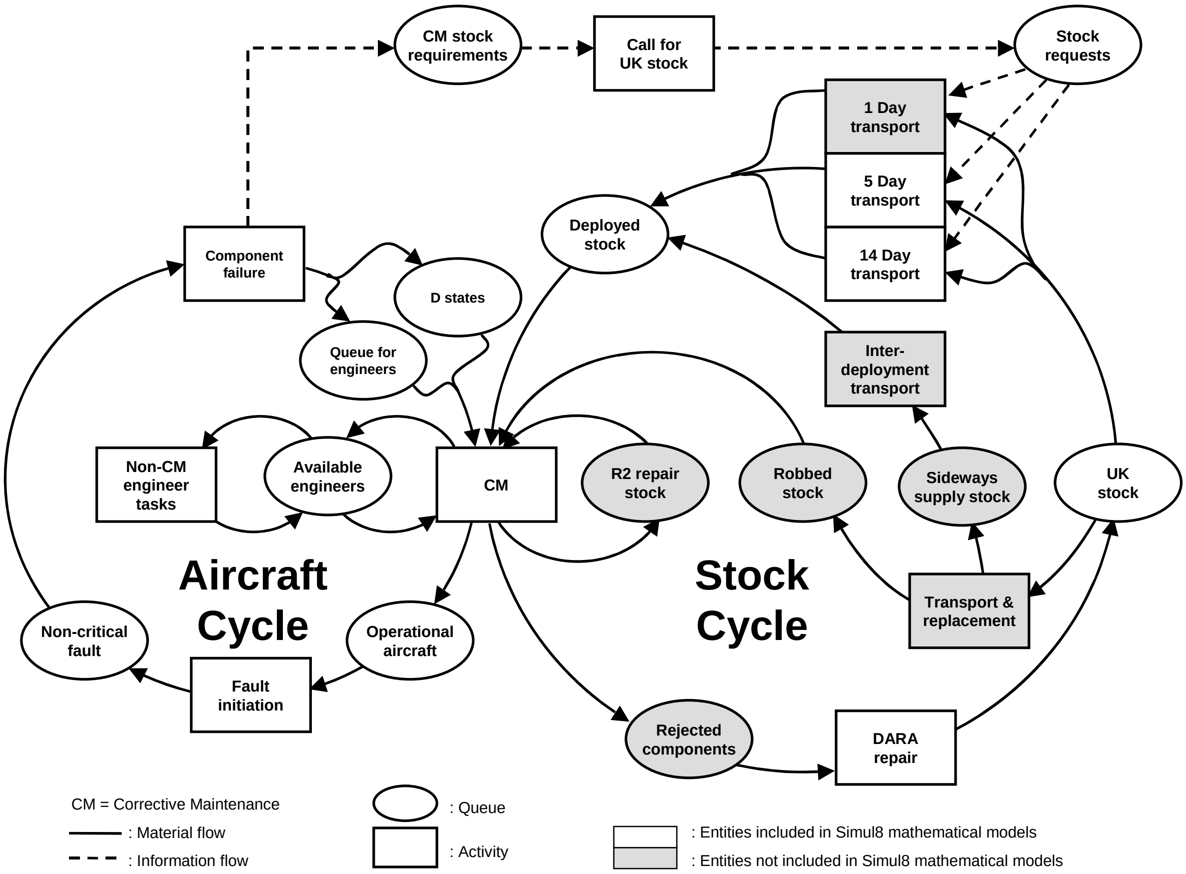

**Figure 3: ACD for single-deployment non-HUMS model.**

The ACD in Figure 4 illustrates the activities, queues and entity flows in major-component CM with the benefit of HUMS data for a single Chinook deployment. There are two improvements in the maintenance and supply processes. Firstly, replacement components (if not in deployed stock) can be called for at the point of fault detection rather than when the aircraft becomes unserviceable. Secondly, a Predictive Maintenance Window (PMW) can be defined from the point of detection to the point of compulsory aircraft grounding. This ‘prognostic interval’ allows required CM to be scheduled around constraints such as engineer availability, stock availability and other maintenance activity.

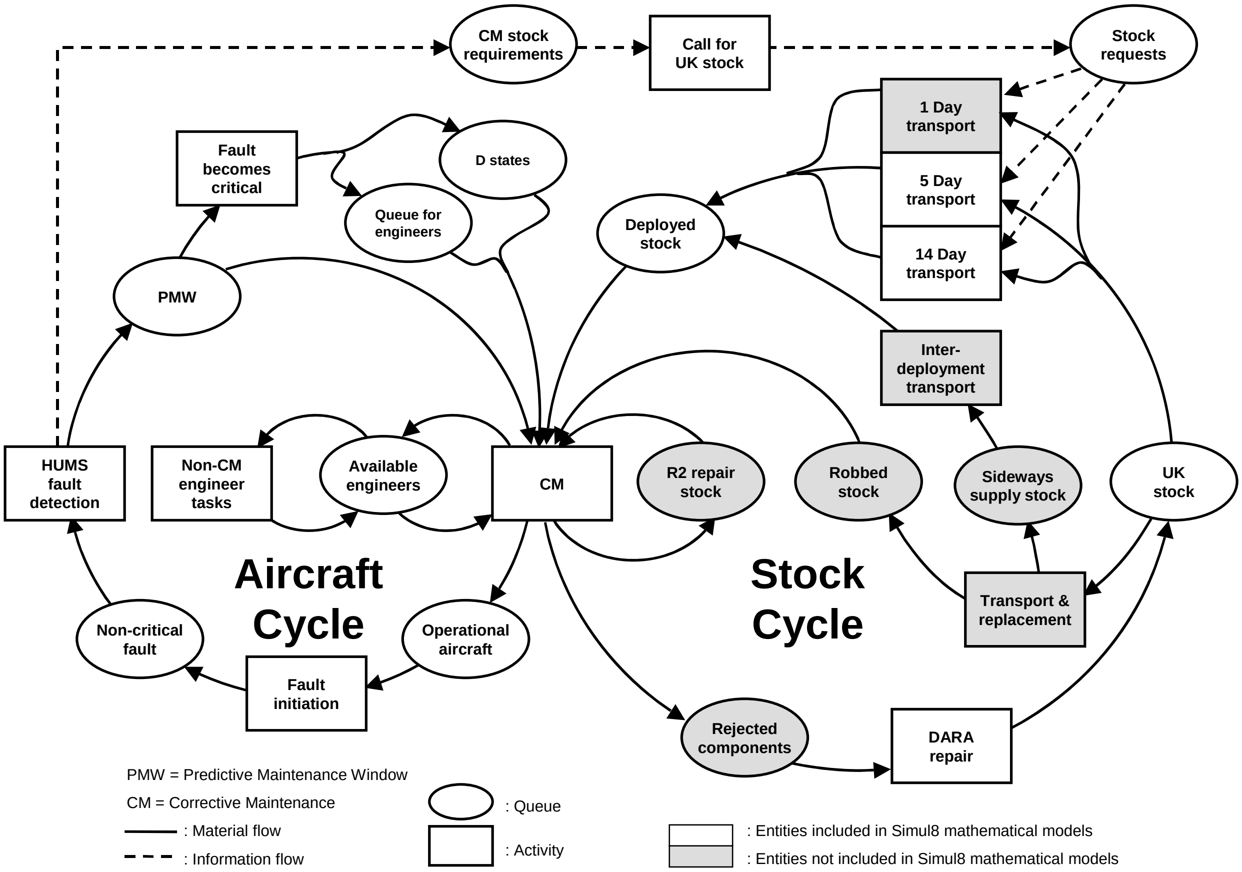

**Figure 4: ACD for single-deployment HUMS model.**

For the full models used in this project, the 11 major component types listed in Table 1 were considered, each with characteristic replacement duration and requirement for mechanical engineers based on operational data. The full models also considered 6 simultaneous deployments as shown in Table 2. These data are based on annual statistics, thus there has been some rounding and interpretation to define an integer number of aircraft at each location in the model.

**Table 1: Major components monitored / tracked on RAF Chinooks.**

| Component | NATO Stock Number |
|---|---|
| 2 x engines (T55-L-712F) | - |
| 2 x engine transmissions | 1615-01-3956839 |
| 2 x cross shafts | 1615-01-3162661 |
| Aft transmission | 1615-01-3154071 |
| Forward transmission | 1615-01-3176446 |
| Combiner transmission | 1615-01-3352689 |
| Synchronising shaft 1 | 1615-01-1130248 |
| 5 x synchronising shafts 2-6 | 1615-01-1125897 |
| Synchronising shaft 7 | 1615-01-1125895 |
| Synchronising shaft 8 | 1615-01-1130292 |
| Synchronising shaft 9 | 1615-01-1193359 |

**Table 2: Deployment of RAF Chinooks.**

| Deployment | Location | Number |
|---|---|---|
| Operation Herrick | Afghanistan | 1 |
| Operation Telic / Crichton | Iraq | 3 |
| Detachments | Various | 4 |
| Falklands | Falklands | 1 |
| UK Base | RAF Odiham | 23 |
| UK Maintenance | DARA Fleetlands | 8 |
| Total | | 40 |

The DES models produced in this work were developed in the Simul8$^{TM}$ modeling package, which was found to be suitable for the requirements of the simulation. Jones reported on a Simul8$^{TM}$ model of airline engine maintenance management and also found that this package is effective for DES modelling of maintenance flow (Jones, 2005). In a Simul8$^{TM}$ model, there are six main elements:

1) Work items. These are the elements that are individually tracked through the model to determine the system behaviour. Work items are defined here for helicopters, stock items and component failure events (virtual work items).

2) Work entry points. These are the elements through which work items arrive in the system with pre-determined stochastic (sampled from a statistical distribution) distributions. Work items are also defined to exist in models prior to start-up, such as the helicopters themselves and the known stock held on deployments.

3) Work centres. These are the elements in which work is performed on individual work items. The duration of the work can be deterministic (zero or fixed duration) or stochastic and the item can be routed out from the centre on paths determined by work item labels or by the ‘visual logic’ programming language within Simul8$^{TM}$. In the models used here there are numerous work centres, including maintenance, HUMS fault detection and transport routing.

4) Queues. These are the elements in which work items are held while waiting to be processed. These can hold any number of work items simultaneously, for a pre-determined duration or until requested. Queues are used here for several purposes including aircraft awaiting maintenance and stock being transported from the UK to deployed operations.

5) Resources. These are mobile elements that are required by work centres in order to complete their tasks. In order to provide some simulation value, resources must be scarce to some extent, which may be due to work centre competition or to the defined availability of the resources. In the models used here, the only resource considered is mechanical engineers; a genuine constraint on maintenance activity.

6) Work Exit Points. These elements are used to allow work items to leave the system.

## 4.0 MATHEMATICAL MODELS

A single-deployment simulation of the Chinook major component maintenance supply chain without HUMS and prognostics is shown in Figure 5. In this figure the cycles of aircraft and stock are illustrated, connected through the CM activity, which has been modelled as 11 separate work centres. The 57 individual elements in this model are described in Table 3.

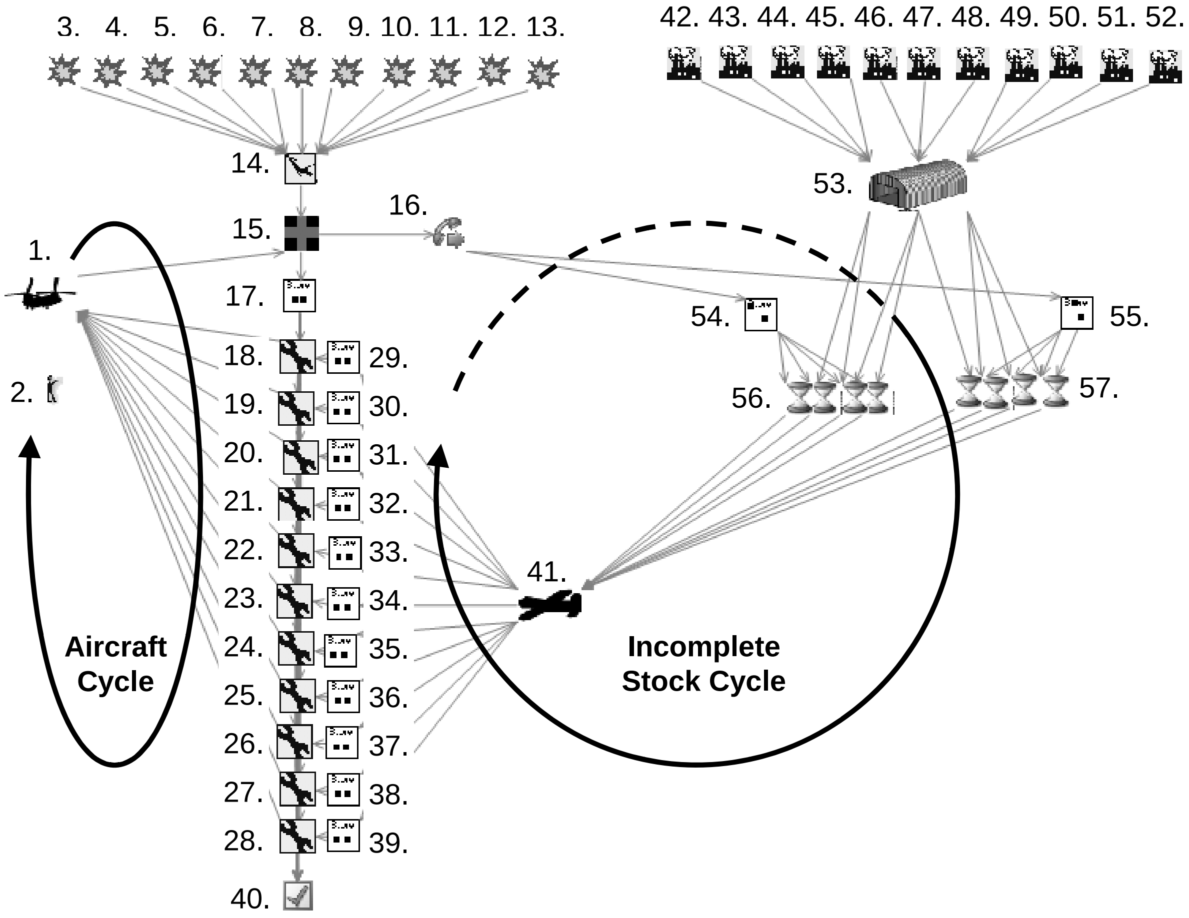

Figure 5: Single deployment mathematical model without prognostics.

Table 3: Single-deployment non-HUMS simulation elements.

| Model Element(s) | Element Type | Description |
|---|---|---|
| 1 | Queue | *Operational aircraft*. Pre-populated with the number of aircraft on this deployment. From current operational data. |
| 2 | Resource | *Engineers*. A required resource and constraint for CM activity, with limited availability due to other commitments such as PM activity, shift patterns and guard duties. Average availability of engineers is 12%. |
| 3-13 | Work entry point | *Failure events*. Deployment-specific inter-arrival times from operational data. Stochastic exponential distribution of arrivals. |
| 14 | Queue | *Damage propagation*. Models the (fixed) time between damage initiation and failure. |
| 15 | Work centre | *Component failure*. Pulls in both an operational aircraft and a failure event. Routes out both a check-stock request and a grounded aircraft requiring maintenance. |
| 16 | Work centre | *Check stock*. Using Simul8™ visual logic, this element checks deployed stockholding for the relevant component. If stock is held, it requests a replenishment (14-day) replacement. If not, it requests a quick (5-day) supply. |
| 17 | Queue | *CM queue*. Grounded aircraft await maintenance here. |
| 18-28 | Work centres | *CM*. In these 11 component-specific deterministic processes, with durations and engineer requirements defined from operational data, aircraft are repaired and returned to operational duty. |
| 29-39 | Queues | *Deployed stockholding*. These 11 queues hold pre-defined levels of deployed stock (based on current data) and collect UK-supplied components. |
| 40 | Work exit point | *CM completed*. Records successfully completed maintenance actions and removes them from the model. |
| 41 | Work centre | *Transport*. Allocates stock to CM queued according to a work item label ‘component’ numbered 1-11. |
| 42-52 | Work entry points | *DARA*. 11 deterministic stock feeds set to ensure that sufficient components are available on demand. The work item label ‘component’ is set to the appropriate number 1-11. |
| 53 | Queue | *UK store*. Collects and stores all UK components for request by deployed maintenance. |
| 54-55 | Queues | *Kanban queues*. Stores stock requests from deployments. |
| 56-57 | Work centres | *Transport delay*. Unites component requests with appropriate components and holds them for 5 or 14 days. |

The single-deployment HUMS model is shown in Figure 6, and the 4 elements that differ from Figure 5 and create the prognostic improvements are highlighted and described in Table 4.

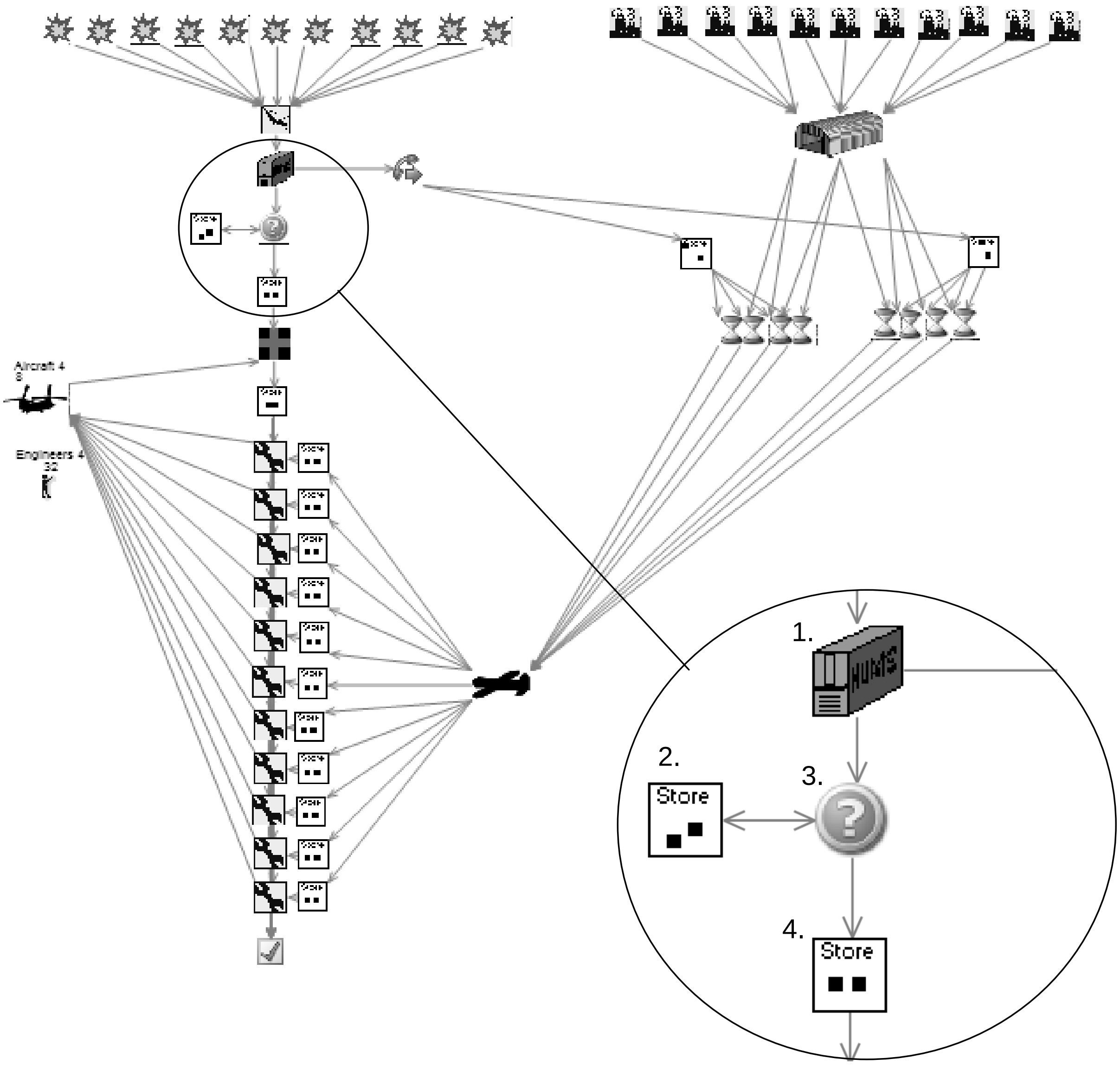

Figure 6: Single deployment HUMS model.

Table 4: HUMS elements in single deployment mathematical model.

| **Model Element(s)** | **Element Type** | **Description** |
|---|---|---|
| 1 | Work centre | *HUMS fault detection*. This element calls for a stock check and component supply if required prior to component failure. |
| 2 | Queue | *Predictive maintenance queue*. In this queue, aircraft with known faults can continue to operate pending maintenance. |
| 3 | Work centre | *Prognostics*. This centre uses Simul8$^{TM}$ visual logic to determine whether there are stock, engineers and work centre available for the relevant CM action. If so, the fault is routed to CM and maintenance is performed. If the fault has become critical (i.e. the prognostic interval has elapsed), the aircraft is grounded. If neither of these are true, the pending fault is routed to the predictive maintenance queue. |
| 4 | Queue | *Aircraft grounding queue*. In this zero-duration queue, faults are held for allocation to operational aircraft. This is necessary to avoid problems associated with direct work-centre to work-centre connections. |

Figure 7 shows the multiple-deployment model without HUMS and Figure 8 shows the multiple-deployment model with HUMS. In these models, an additional label is set for each stock request that ensures that the correct stock replacement route is taken, i.e. that replacement parts required in Iraq don’t accidentally get sent to the Falklands. On each of the 6 deployments the aircraft numbers, major component stockholding, engineer numbers and characteristic failure rates for each of the 11 components are configured from operational data.

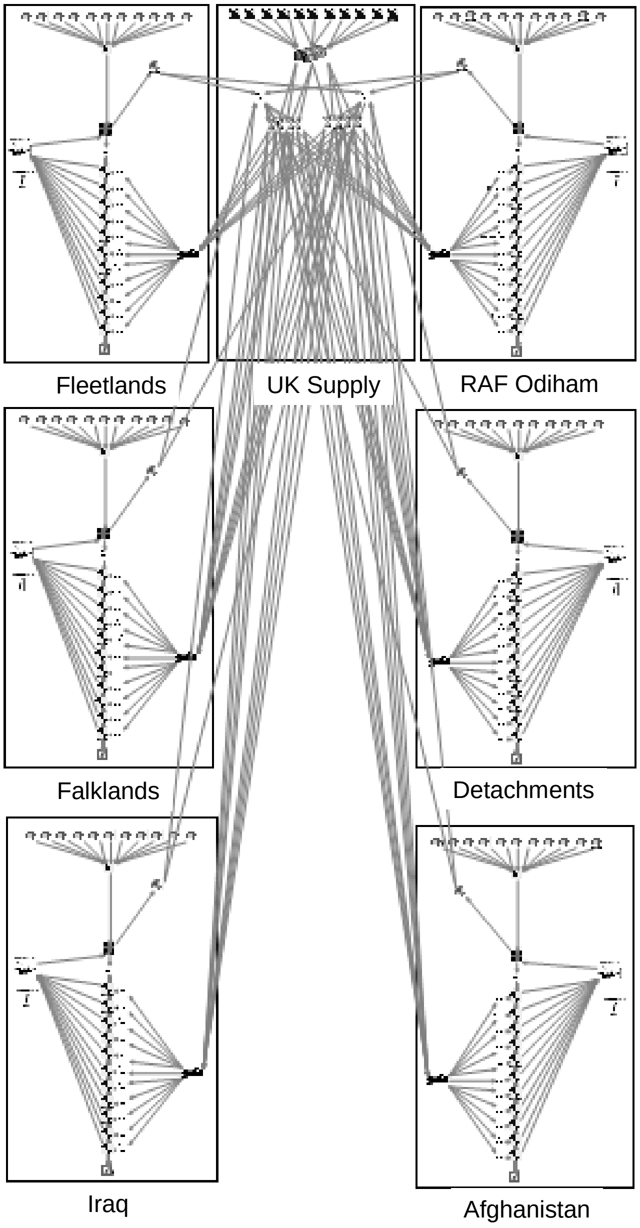

Figure 7: Multiple deployment model without HUMS.

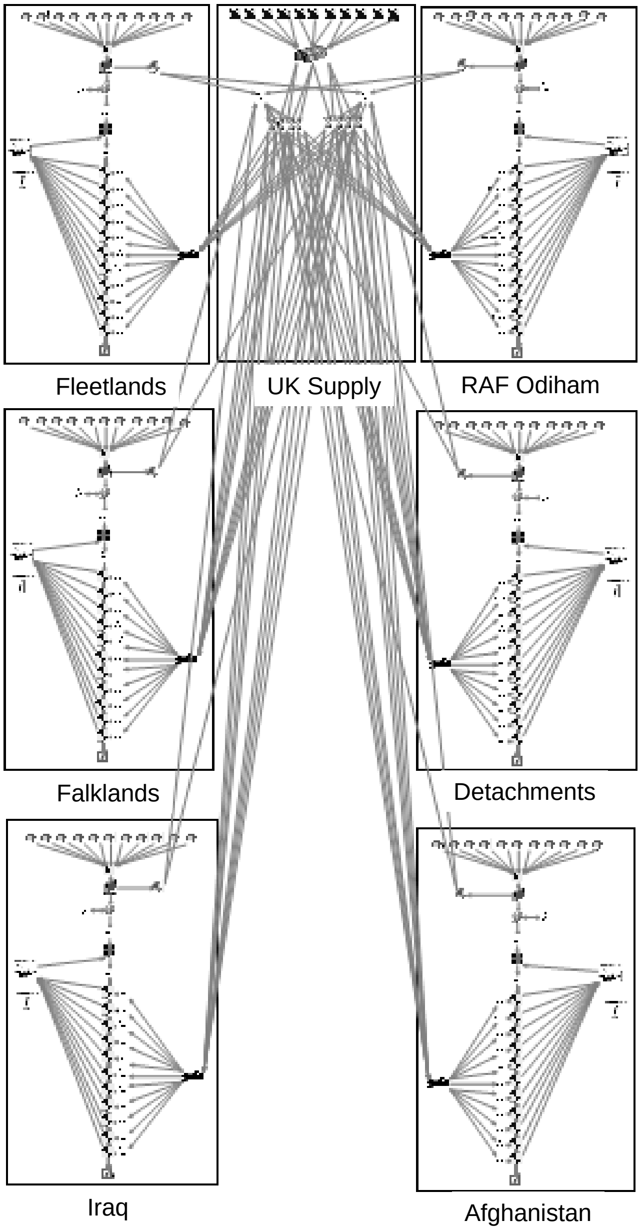

**Figure 8: Multiple deployment HUMS model.**

## 5.0 MATHEMATICAL MODEL RESULTS

In the Simul8$^{TM}$ mathematical models, there is not a separate queue for D state aircraft to distinguish them from other aircraft awaiting CM. Trials conducted with the engineer constraints removed and CM work centre durations set to zero provided simulation results for queues caused by D states alone.

Based on discussion with MOD HUMS engineers, a conservative prognostic interval of 10 days was assumed for the results shown here. Examples were cited in which faults were visible in the HUMS record for 10 to

100 days prior to failure or maintenance, but these were insufficient in number to take a statistical approach so a worst-case assumption was made.

In the results presented here, multiple-run trials have been used in which 100 runs of the simulation are performed to obtain statistical results. Each run within a trial has a warm-up period of 20 days and a data collection period of 1 year. The trial results are then analysed to determine the mean and 95% confidence intervals for key parameters. 95% confidence intervals are shown in the figures as error bars or dashed boundary lines.

The simulations were run to produce a comparison between the normal and prognostic cases and between the zero-stock and current-stock scenarios. Figure 9 shows that the HUMS model predicts zero D state aircraft across all six deployments for major components whether stock is held on deployment or not. This is partly due to the simplifications of the model in which the 10-day fixed prognostic interval is invariably greater than the 5-day fixed transport duration and there is always a sufficient supply of components from the UK store. True D state levels would depend on how well the supply chain can be managed to meet these fixed assumptions, but it is certain that HUMS should have its most pronounced effect in reduction of D states.

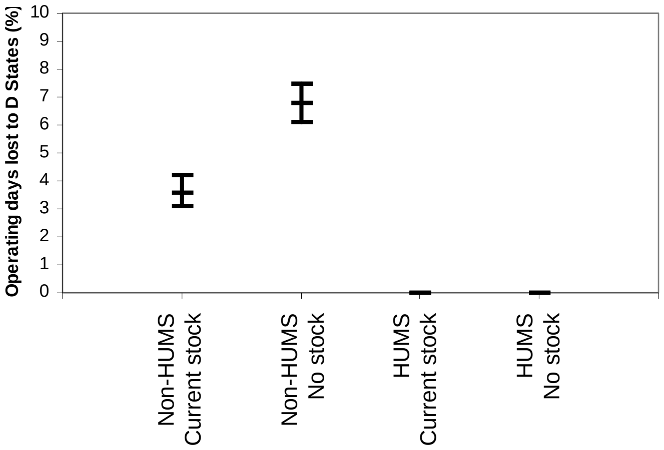

**Figure 9: Prediction of loss to D states – all deployments.**

Figure 10 illustrates the predicted reduction in operating days lost to CM across all six deployments through the use of HUMS and prognostics. This includes the effect of pre-emptive stock requests and the PMW. This figure shows that HUMS could potentially reduce the CM loss from 11.0% to 6.2% under current stockholding levels, or to 7.0% with no deployed stockholding and a completely lean deployed supply process for major components.

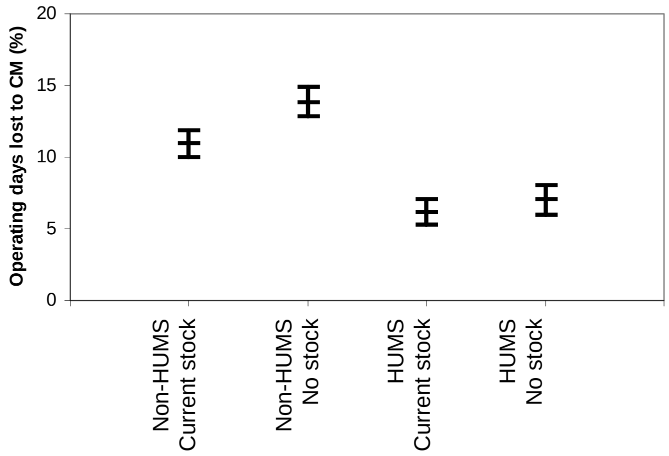

**Figure 10: Prediction of loss to CM – all deployments.**

## 6.0 VERIFICATION OF THE MATHEMATICAL MODEL

To gain confidence in the integrity of the simulation results, tests are performed to verify that the models produce the results that they are designed to produce. This does not prove the validity of the results; it simply indicates whether there are any errors introduced in the modelling process. The simulations in this project were formally verified with two tests:

1) It was shown that the stock transported from UK stores to all deployments in order to meet the stochastic demand of component failures is (within 95% confidence limits) equal to the expected number of replacements in the entire model.
2) The HUMS model with prognostic interval set to zero results in availability and CM queue results equal to the non-HUMS model (within 95% confidence limits).

## 7.0 SENSITIVITY ANALYSIS

Two fixed parameters key to the model output were the prognostic interval and the mechanical engineer availability. These two were subjected to sensitivity analysis, as described below.

The prognostic interval was varied from 0-30 days in 2-day increments and the zero-stock HUMS model trial was replicated for each. The results showed that for larger deployments, 10 days’ prognostic notice is sufficient to gain most of the maintenance planning benefit from HUMS. For smaller deployments such as the Falklands and Afghanistan with limited number of aircraft and mechanical engineers, the benefit of greater notice is significant all the way to the 30-day maximum considered. This is because mechanical engineer availability is a serious limiting constraint for these deployments, thus the flexibility of a broader predictive maintenance window is important. This analysis does demonstrate a clear dependence of the model output on the prognostic interval. Figure 11 shows the effect of prognostic interval on aircraft availability for all 6 deployments.

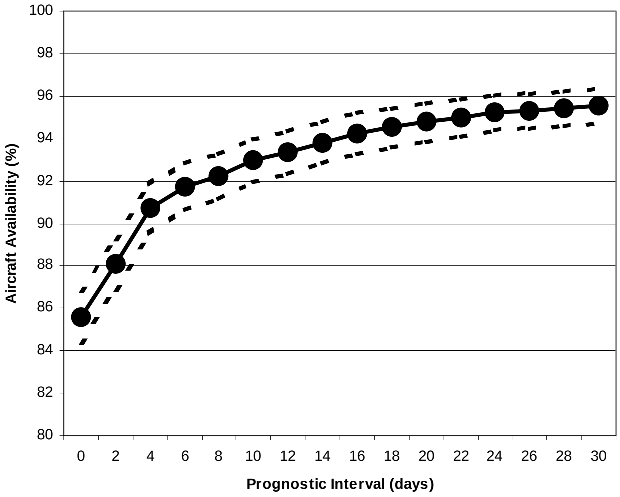

Figure 11: Prognostic interval sensitivity analysis.

The availability of the mechanical engineers was varied from 2%-20% in 2% increments and the zero-stock HUMS model was trialled for each. The results showed that for all deployments other than Afghanistan, the standard of 4 mechanical engineers per aircraft with 12% availability is well-judged and sufficient to minimise the effect of this constraint with minimum waste. Afghanistan, with a high number of engine replacements (8) in the year considered, continues to show significant maintenance improvements with mechanical engineer availability increases all the way up to 20%. Figure 12 shows the engineer availability sensitivity analysis results. In this analysis, the only unavailability considered is that due to unscheduled CM events, hence the apparently high availability levels.

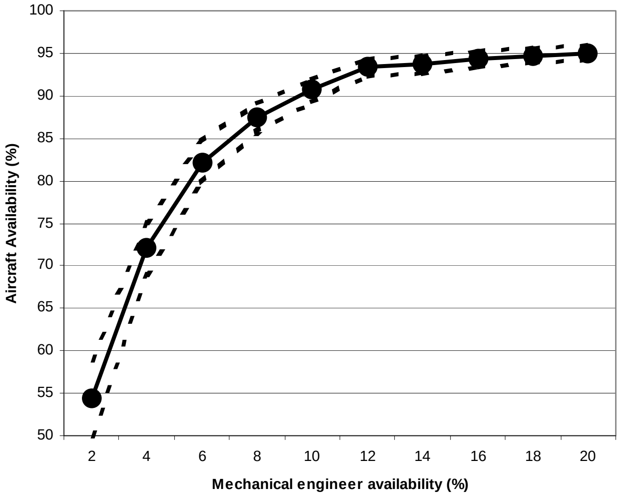

Figure 12: Mechanical engineer availability sensitivity analysis.

## 8.0 VALIDATION OF THE MATHEMATICAL MODEL

To provide confidence in the integrity of a mathematical simulation, we use the model to simulate aspects of the system performance that are actually measurable independently. By examining the correlation between prediction and reality, the validity of the model output can be assessed.

The Chinook Integrated Project Team (IPT) Customer Supplier Agreement (CSA) with Joint Helicopter Commend (JHC) (Anon., 2005) discussed the performance indicators defined for the fleets and the targets set for performance against those targets over the 2005/2006 period. The IPT has confirmed that these targets were achieved, despite the operational tempo during that period. The CSA stated that the proportion of operating time lost to D states for the Mk 2/2a fleet would be 3% and that the proportion of operating time lost to CM would be 14%.

Figure 13 shows that the non-HUMS model has over-estimated the time currently lost to D states by 0.6%. This is an expected result due to the simplifications introduced by disregarding component robbery (components removed from one aircraft to fit to another). This can quickly recover aircraft from D states despite limited or tardy supply, but has not been modelled due to limited data.

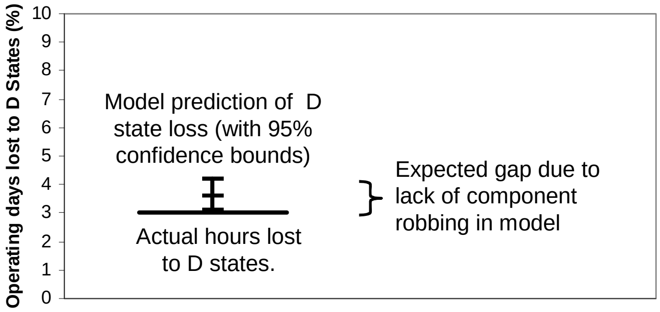

**Figure 13: Model validation – prediction of operating time lost to D states.**

Figure 14 shows that the non-HUMS model has under-estimated the time currently lost to CM activity by 3.0%. This is an expected result due to the simplifications introduced in limiting the simulation scope to 11 major component replacement types. Although these do represent a large proportion of the CM work undertaken, there are also many lesser unscheduled maintenance activities that contribute to the overall parameter measured by the IPT.

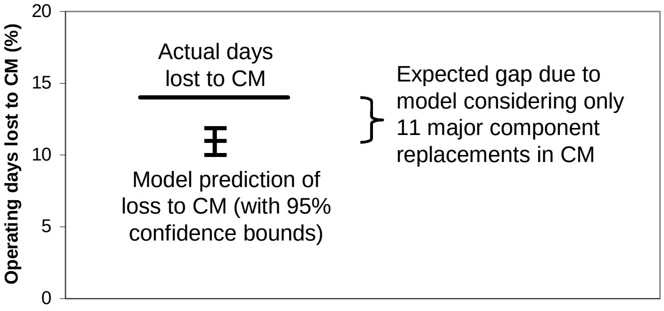

**Figure 14: Model validation - prediction of operating days lost due to CM.**

## 9.0 CONCLUSIONS

In this paper, HUMS and non-HUMS Simul8$^{TM}$ DES multiple-deployment models for the Chinook fleet have been developed and described in detail. These models have been defined as far as possible from genuine operational data, but a number of assumptions and simplifications were introduced during the modelling process; these have also been listed and discussed. Two key parameters for the models were the availability of mechanical engineers and the potential prognostic interval from HUMS. Although expert estimates of these parameters have been obtained and used, sensitivity analyses conducted here show that there is a significant dependence of the model output on these parameters.

Model verification and validation results demonstrate sufficient agreement between simulation and expectation and between simulation and reality to provide confidence in the veracity and validity of the model results.

The simulation results have shown that the D state levels for the RAF Chinook fleet could be greatly reduced through predicting CM and calling for replacements prior to failure. They have also demonstrated that the time lost to CM could be significantly reduced by ensuring that appropriate replacement stock is available and allowing a PMW to schedule CM around maintenance constraints. The results have also shown that a maintenance prediction capability would minimise the effect of reduced or zero deployed stock. This would allow operators to balance the benefits of lean stockless agility for non-war deployments with the increased availability and agility of HUMS and deployed stock combined for war operations.

## 10.0 ACKNOWLEDGEMENTS

This work would not have been possible without the support of the MOD Royal Military College of Science at Shrivenham. Particular acknowledgements are expressed to Wayne Thompson, whose expertise in mathematical modelling was invaluable to this project throughout. Of the numerous people within the MOD that assisted with the data gathering and analysis here, the contribution and patience of Andy Dallman in the MOD Materials Integrity Group was outstanding.

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