

Practical Prognostics for Helicopter CBM

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Abstract

This paper describes the results of humaware's research into the architecture of the infrastructure required to implement prognostics in a CBM environment for the UK MoD and others. Prognostics technology is being developed for a wide range of platforms to provide the maintenance support logistics network a forecast of maintenance demand. The impact of prognostics technology in the management of CBM, or Directed Logistics/Performance Based Logistics is discussed. There are two conflicting requirements for prognostics in CBM. The first is in strategic forecasting to provide a better scaling of the network to assist in the leaning of the processes. Lean networks are necessarily less agile. It is in improving agility that prognostics provide the largest opportunity to improve MRO network performance. Being able to improve both the leanness whilst simultaneously improving its agility of the network prognostics sets a new paradigm in logistics management. In particular the impact of prognostics on the Lean-Agile dilemma is described with a practical example.

The differing components of a platforms prognostic capability are analyzed. These include reliability data, usage/abuse data and health data. These three types of data need to be integrated to provide a uniform prediction of the platforms future airworthiness. Similarly the technology for integration of prognostics with logistics agents is necessary to forecast the impact of changes identified by the platforms prognostics on the MRO logistics network. The paper describes a unified method of achieving this integration based on Discrete Event Simulation techniques.

Finally the constraints on the architecture for any resulting prognostics based Maintenance Management ERP system are discussed. Near and Far horizon forecasts place differing demands and constraints on the ERP systems design and the data acquisition systems that serve the system.

A New Paradigm for MRO Management

A&D sector Primes are expanding their MRO businesses by bidding for Contracting For Availability programmes to meet the new demands of Performance Based Logistics and similar initiatives by both civil and military operators. In this paper the author uses the term CFA to encompass a range of new contract models that essentially transfer the risk of maintaining fleet availability from the operator to the MRO supplier. These contracting models are otherwise known as: Vendor Logistics Support; Integrated Operational Support; Service By the Hour or Power By The Hour contracts. So popular are these contracting models that it is now difficult to obtain MRO contracts for new platforms on any other basis. With a CFA contract the operator now expects the MRO supplier to provide all of the resources necessary to sustain a platform's availability at a guaranteed level over its operational life. The MRO supplier is faced with making a significant investment to re-engineer their processes to meet the higher standard of performance that compliance with the operator's contractually mandated availability expectations demand. The supplier also needs to be able to realize an adequate financial return from a new CFA contract in order to justify this investment.

Implicate with both a CFA contracting model and the consequential process re-engineering is the need to understand and quantify the challenges of managing the transfer of risk from the operator to supplier for sustaining platform availability. A key feature in this transfer of risk is that the MRO supplier now has the end-to-end responsibility for the logistics supply chain: improving the performance of the supply chain is the key to improving both its performance and profitability.

In business terms the operator makes significant gains from a CFA contract:

1. No flying means no cost and indeed there is compensation if the MRO supplier does not meet its obligations,
2. Simplifying and streamlining their engineering support organization, thus reducing fixed costs and the ability crystallize these now redundant assets
3. Removing the long term liabilities of maintaining the aircraft from the balance sheet and converting them to a direct cost on the profit and loss account.

These factors taken together represent a significant reduction in business risk for the operator, which has now been transferred to the supplier.

The MRO supplier also gains:

1. From improved cash flow,
2. Guaranteed long term business,
3. Improved utilization of assets,
4. Increased market share.

Whilst there is a significant increase in business risk, the supplier does gain more business with a significantly improved cash flow and a more secure profit stream. Most importantly the supplier has the opportunity to extract further efficiencies from the business to justify the process re-engineering investment costs.

The Lean – Agile Dilemma

Agility is the principle requirement of the MRO network in order that it can be described as executing Performance Based Logistics. The agile network will provide the right part in the right place at the right time, with the necessary resources to perform the maintenance. In order to be agile the supplier needs to be able to forecast on an individual LRU basis the demand for parts and resources. A lean network provides these resources with the most efficient use of assets and material. Increasing a network's leanness or agility requires investment.

As shown in Figure 1 investing to lean the processes, such as reducing stock levels and improving asset utilization, to extract the efficiencies necessarily reduces network agility; as the network will have less free resource.

However, investing to increase the agility of the network to meet the operator's performance expectations requires increasing stock and reducing asset utilization; thus reducing the leanness of the network. These conflicting investment choices are the source of the "lean - agile dilemma". The challenge for MRO management is to resolve this dilemma.

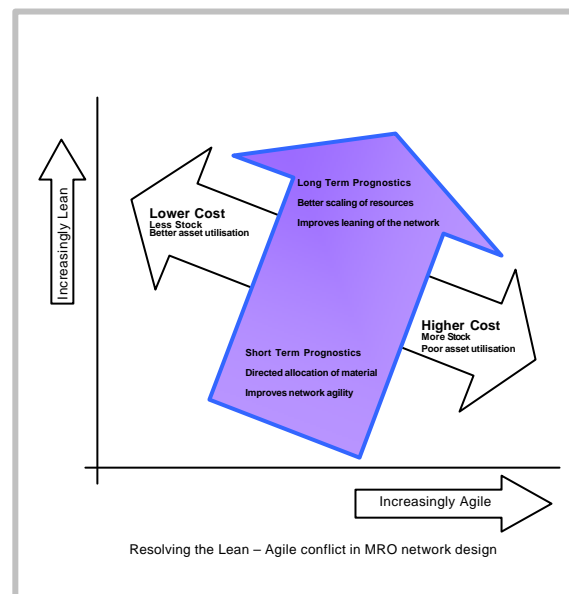


Fig 1

Using prognostics to predict maintenance demand has two separate impacts on the dilemma. Long horizon prognostics can improve the scaling of resources utilized in the network in line with the aging of the fleet as well as any changes in the fleet's operational profile, environment and reliability. Short horizon prognostics can be used to direct resources in line with a forecast of demand, rather than carrying stock or under-utilizing assets as a reserve to maintain platform availability. Directing material base on forecasted demand at an individual LRU level can therefore increase the agility of the network. This is represented in Fig 1, where the investment in prognostics can simultaneously improves both the leanness and agility of the network, without the inherent conflicts of the classical investment options. This is provided that the prognostics technology can support a forecast horizon that can be varied from days to years.

Role of Prognostics in Resolving the Dilemma

Reliability data may be sufficient to provide the information required to correctly scale the network resources globally for all the platforms in the fleet, but it not provide the necessary network agility as shown in Fig 2. The reliability forecast is represented by the probability of failure over an interval, with no indication of when in that interval the failure will occur. The number of failures in the interval can be correctly assessed, but with no indication of which LRU's will fail or when.

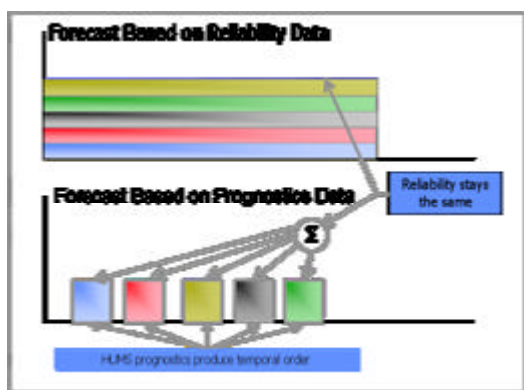


Fig 2

On the other hand, prognostics technology is designed to provide, by the use of a proportional hazard model, the probability of failure of an individual LRU and the prognostics interval to the point of failure. It is the prognostics interval for each LRU that is the element of the prognostics processing which provides the temporal separation in the forecasted LRU failures. Given that this temporal separation exists then it is possible to provide the logistics management with a forecast of where and when the maintenance effort will be required. The reliability over the forecast interval produced by the prognostics should be reconcilable with the reliability data produced by RCM technology, providing the ability to utilize a prognostics model over the whole range of forecast horizons.

There are three components to a prognostic model:

- 1 Maintenance handbook compliance
- 2 Usage/Abusage proportional hazard model

- 3 Health data directly indicating an incipient defect.

These components need to be integrated to provide the prognostics model. The handbook compliance represents a hard limit of a Time Between Overhaul mandating when the LRU has to be removed. The usage/abusage with the health data derived from a Health & Usage Monitoring system can be used to evaluate the proportional hazard contribution to the model.

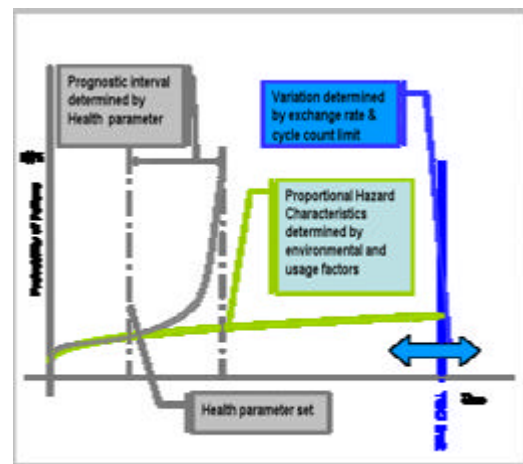


Fig 3

The Health monitoring function is the one that primarily provides the differentiation in the time to failure that is required for agility, as shown in Fig 3. This is providing that the prognostics process is integrated with the health monitoring in near real time. Detecting of the onset of an insipient defect for an LRU and projecting the corresponding prognostic interval on its probability of failure profile derived from the LRU's reliability data, as shown in Fig 3, provides the temporal separation of events. The proportional hazard model can also do this if there are sufficient parameters to determine failure with 100% probability of detection; this is rarely the case.

A third variable needs to be monitored in order to provide a maintenance forecast; the flying rate. Proportional hazard, prognostics interval and the requirement to remove components for overhaul are all expressed and monitored in flight hours: maintenance occurs in calendar time. This requires that an exchange rate between flying rates and calendar time needs to be monitored. Changes in exchange rate can

have as large an impact on the maintenance forecast as changes in the parameters of the proportional hazard model.

An analytic approach to reconciling all of these three components of the prognostics model is difficult to realize. The approach taken by Humaware is to use a tool for reliability modeling developed for Material Resource Planning; Discrete Event Simulation. Using a simulation approach to modeling the process permits the proportional hazards model to be constructed from all three components of the model and tailored to the prognostics technologies that are available for the LRU, however limited. The model is built by running the simulation many times to exercise the different random variable in the data to produce a forecast of the underlying characteristics over time of the LRU's failures. The sufficiency of the HUMS data to determine the parts' failure modes in the LRU will determine the accuracy of the forecaster in predicting the individual LRU's failures. In the common case where there is an insufficiency of data then the prognostics model is an enhanced proportional hazard model forecasting the likely hood of failure as a probability which is significantly less than 1, but does vary over time giving a degree of temporal separation.

Structure of a Prognostics Based Maintenance Demand Forecaster

The DES simulation approach to forecasting uses the Monte Carlo method to predict the average maintenance demand based the TBO limits, proportional hazard and reliability data with the exchange rate for the platform. If a HUMS reports any changes to the proportional hazard data, or an health alert is set, then the probability of failure profile over time for that LRU is modified to reflect the prognostic interval associated with the HUM alert. The reliability data for the remaining platforms is reduced to ensure that the overall reliability characteristics for the fleet are maintained by the simulation.

The forecast period is a key factor that determines the characteristics of the forecaster. For a forecast period of less than the HUMS prognostics interval then the forecaster will be able to determine which platforms will fail in the period and when; to provide the network agility

feature as described above. For this capability near real time HUMS data is required to update the prognostics model in a timely manner. For longer forecast periods the initial status of the HUM parameters will have little effect on the forecast and it is the assumptions made about the proportional hazard and exchange data that will dominate the maintenance demand forecast. Essential to a long term forecast is the ability to predict the performance of the MRO loop so that LRU's can be returned into service, and then fail again, thus forecasting performance over the entire life cycle of the LRU.

The elements of a maintenance demand forecaster that incorporates all these factors is summarized in Figure 4.

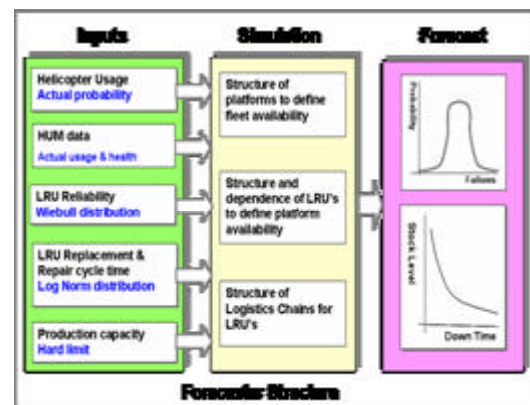


Fig 4

The forecaster has three main components; the inputs derived from differing data sources, the simulation engine and the forecaster outputs.

The inputs consist of:

- Helicopter Usage. This is the actual distribution of flying rates expressed as an exchange rate. The exchange rate is the fundamental variate in the simulation and is essential.
- HUM data. This consists of both the proportional hazard data and the health event with the associated prognostic interval. This is the most complex element of the inputs and is the element that determines the accuracy of the forecast.

- c. LRU reliability. The forecast needs to reflect the overall reliability characteristics of the LRU's.
- d. LRU replacement & repair cycle times. These characteristics of the logistics system are needed to provide replacement LRU's for long term simulations
- e. Production capacity. These are limits such as the number of spare LRU's and the capacities of the maintenance centers. These are not statistical numbers, but they are hard limits which give the forecast its structure.

All of these data except the capacities are statistical in nature and the DES approach needs to be able to handle a large number of stochastic processes. The same Monte Carlo approach integrated into the DES technology used to generate the prognostics model is utilized to integrate the large number of stochastic processes that drive the forecaster.

The simulation needs the structural elements of network:

- A The structure of the LRU's in the platform
- B The distribution of platforms in the fleet
- C The geographical distribution of the fleet

All of these are known, but for the short horizon forecast the near real time distribution of these structural elements will be required.

The results of the simulation are statistical estimates of maintenance events and their impact on the MRO loop. Key Performance Indicators can be incorporated to enable the fleet's and MRO loop's performance can be measured; such as the number of additional LRU's held in stock and the consequent platform downtime.

Prognostics Gateway Architecture

The Maintenance Demand Forecaster requires that prognostics can be derived from HUMS data. An interface between the HUM systems fitted to the fleet and the MDF has to be implemented, this is termed the Prognostics Gateway. The architecture of the Humaware Prognostics Gateway is shown in Figure 5.

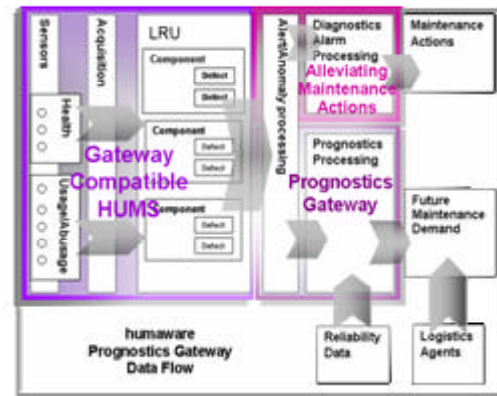


Fig 5

There are two principal ambitions for what can be achieved from using HUMS data by the utilizing of prognostics technology.

1. With the additional visibility of failure modes both parametric, from the health data, and non parametric, from the Usage/Abuse data, are used to alleviate maintenance actions with the concomitant cost savings; maintenance credits. This is capability is outside the scope of this paper.
2. Use the HUMS and reliability data to provide a forecast of LRU failures to improve maintenance planning. As described above, prognostics data has to be integrated with logistics agents to generate the Maintenance Demand Forecast. It is this purpose of the Prognostics Gateway to extract and process the information from the HUMS data to build the prognostics model for the forecaster.

The data flow for the Gateway commences by the HUM systems acquiring data from both the Health and Usage Sensors. For each of the LRU's installed on the platform the sensor data is processed to provide the diagnostics indicators that relate to the specific defects that drive the maintenance interventions. It is the ability to produce defect specific diagnostics indicators that determines whether the HUM system is Prognostics Gateway compatible; this is not a feature of every HUM system currently fitted to

helicopters. The features of such a HUM system are described in Reference 1. The primary function of the HUM system is to acquire and process sensor data to produce the diagnostic indicators that relate to the range of defects to be detected. This range is usually determined by flight safety considerations rather than the demands of prognostics. The diagnostic indicators need to be sufficient to determine with a high probability of detection and low false alarm rate that an LRU defect is extant. For prognostics a higher performance is required of these indicators in that the incipient causes of the defects need to be identified with the same robustness as for the HUMS defect diagnosis, so that the future occurrence of the defect can be predicted.

The first stage of the Prognostics Gateway is therefore to use a toolkit of data mining and anomaly detectors technology to identify that for either; a) the maintenance intervention mitigation functions there is an absence of the incipient defects and b) for the maintenance demand forecasting function their existence. The approach taken to anomaly detection taken by Humaware to develop the Prognostics Gateway functions is to integrate a novel CFAR threshold setting and Box-Car automatic trending technology, described in Reference 2, with a knowledge engineering technology. This work is sponsored by the UK MoD. The reason for this hybrid approach is that the very large number of HUM indicators, particularly those derived from vibration data, that are non-ergodic and non-stationary in nature. This reduces the effectiveness of classical Bayesian cluster analysis and anomaly detection techniques. The CFAR and Auto-trend alert generating techniques are effective on non-ergodic and non-stationary data and are autonomic in nature. The techniques are both sensitive and robust enough to reliably detect incipient defects. The knowledge base is required as the impact of each of the indicators is not the same and not all information relating to defect detection is not usually contained in the HUMS indicator set. This provides a robust method of extracting the HUMS alert status for incipient faults for the prognostics modeling.

Both the range of defects and the number indicators make the Prognostics Gateway a complex and idiosyncratic functional element in

the Maintenance Demand Forecaster. Once the effective indicators have been isolated the prognostics model can be built, as described above. These models are highly dependent of the LRU type and the depth of the HUM technology available and will not be of a standard construction. If the HUM technology is insufficient then the Maintenance Demand Forecaster will provide poor discrimination of individual LRU failures. The approach will allow the forecaster to be implemented with the quality of improving forecaster accuracy as the HUMS competency improves.

Implementation of a Maintenance Demand Forecaster

Humaware has built a MDF for the European 6th Framework Aerospace Technology programme – SMMART, reference 3. The objective of SMMART – System for Mobile Maintenance Accessible in Real Time – is to provide the new infrastructure necessary to realize a Performance Based Logistics Maintenance support network that can utilize CBM technology. The Maintenance Demand Forecaster is one of the key components. The Architecture of the Maintenance Demand Forecaster is shown in Figure 6.

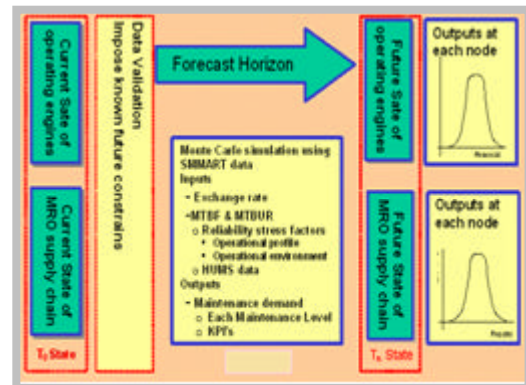


Fig 6

The structure of the DES Maintenance Demand Forecaster is one where the current state of both of the fleet and the MRO network are derived from the supporting data management systems to derive the initial or T_0 State. There are functions to validate the data and impose the known constraints that are known to apply over the forecast horizon. These constraints would include known changes of fleet disposition,

operational profiles, proposed changes in MRO network structure, improvements in Turn Around Times and improvements in reliability.

Each LRU, platform, operational base and maintenance centre is represented as a node in a network. These state variables and the parameters that control the simulation are used to construct the network in the simulation. In the Humaware MDF this is a data driven process so that any changes in the network structure that occur over time automatically update the simulation's node structure.

The forecast horizon has major impact on the accuracy of the forecast. The T_0 State contains state data such as the disposition of the LRU's in the MRO chain and the disposition of the platforms in the fleet. A large number of parameters from the Prognostics Gateway such as the exchange rate and usage parameters need to be aggregated over a period to provide a reasonable estimate of their current value. It is important that the period for the aggregation reflects the forecast horizon. For a short horizon forecast it is the short term local conditions in parameters, such as exchange rate, that are important: for a long horizon forecast these short term variations in the parameters will produce a biased result. Similarly using long term aggregation of data for a short horizon forecast will also produce a biased and inaccurate result. Consequently in the MDF the aggregation of data to generate these parameters is a function of the forecast horizon.

The forecast horizon also impacts the state data contained in the T_0 State. The shorter the horizon the more accurate the T_0 State has to be, as the Output State will be more dependent on the Input State than the changes imposed on the network that result from the helicopter flying. For a long horizon forecast it is the flying rates and the performance of the MRO loop that dominate the Output State, rather than the Input state. There are clearly system design issues here, but these are outside the scope of this paper.

The DES Simulation uses the Monte Carlo method to produce the output; the T_n State. The simulation then computes of the output state variables for each node in the network and the associated KPI's. The T_n State consists of statistical estimates of variates such as the

number of LRU removals and number of repairs. The statistics can be used to provide an unbiased estimate of the future state, or an optimistic or pessimistic estimate thus enabling the output state to be tested for robustness.

Humaware MDF implementation

The Humaware implementation of the MDF reflects the architecture shown in Fig 7.



Fig 7

This architecture follows that described in Figure 3. The input T_0 State is contained and managed in an Access data base. It has connectors to the Prognostics Gateway and the RCM and ERP data bases to extract the state variable data and aggregated parameters. The DES Simulation Engine is a COTS package developed by the Lanner Group PLC, Reference 4. The Simulation is controlled and the results reported in Excel.

The simulation is constructed with standard nodes which are automatically configured from the T_0 database as shown in Figure 8.

For each LRU, in Figure 8 the LRU is the engine, there is a standard representation of a maintenance centre, from organizational level to depot level, as nodes in the network. Each type of node in the network reflects the depth of maintenance than can be undertaken at the node i.e. level 1 is on platform; level 2 is off platform; level 3 is LRU split for module replacement and level 4 module overhaul and repair. Each of these nodes has a TAT and a capacity. Other nodes include pools of spare LRU's and new parts, modules and LRU's. These can also be produced as new replacements that are provided against forecast production schedules

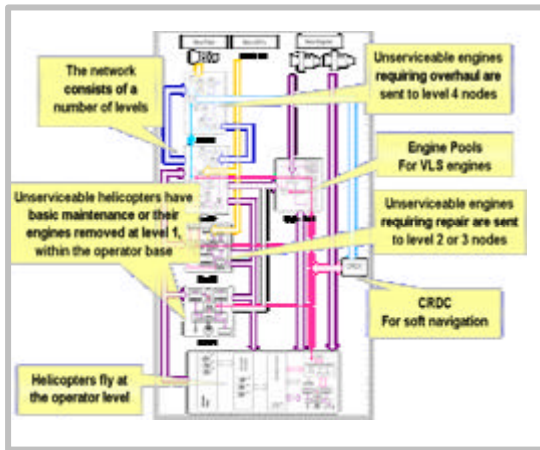


Fig 8

.There is in the simulation network a phantom node; the CRDC (Central Resource & Dispatch Control). The CRDC is used to implement what is termed as “soft navigation” rules. LRU’s and modules do not navigate through an MRO loop according to a rigid network definition. When there are shortages and other constraints, MRO management intervenes to minimize TAT by redirecting material to nodes that have available resource to mitigate disruption to supply. It is the role of the CRDC in the simulation to emulate the actions of management in directing material through the network. It is not an optimizer, but the CRDC contains a set of rules that typify management actions. This is a necessary feature of the simulation to ensure that it is a reasonable representation of the behavior of the network and therefore provides an accurate forecast based on real world network behavior rather than an idealized representation of the network.

Whilst the CRDC and the supporting commercial layer of the network is an invention of the simulation, it is necessary to represent the directing of material on the basis of forecasted demand rather than actual demand and hence simulate the primary benefit of investing in a prognostics capability; that is of managing an agile network base on forecasted demand with the concomitant benefits discussed above.

Finally there is the operational level node as shown in Fig 9

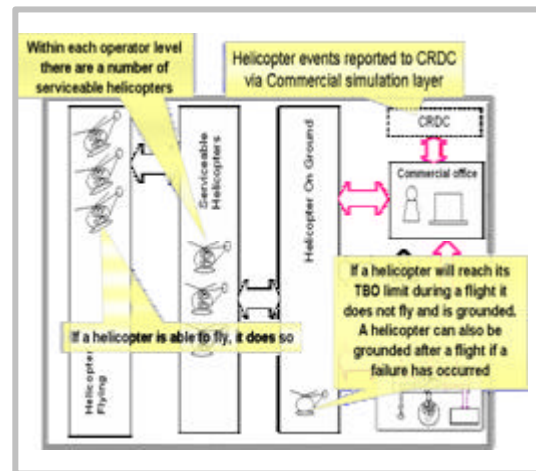


Fig 9

In a DES the process of deriving the failure profile is by simulating the process of helicopter flying. The helicopters are flown for periods that conform to the mean and standard deviation of the exchange rate parameter. The reliability criteria are applied and the proportional hazard parameters evaluated. For every flight the occurrence of a failure is evaluated by applying the probability defined by the reliability and proportional hazard statistics derived from the Prognostics Gateway. If the statistical evaluation is that an LRU has failed then the helicopter is grounded for the next flight for maintenance. This event is reported to the CRDC via the commercial layer in the simulation and the appropriate maintenance centre is identified for the LRU maintenance and it is then dispatched. Over very many runs of the simulation the statistics for the prognostics model for the removal rate and maintenance demand can be generated.

The health monitoring side of HUM is simulated in two ways. If the first is if an indicator is set in the T_0 state then the prognostics interval, another statistical value, is applied before the helicopter is grounded by the simulation. The HUMS indicator is reported to the CRDC. The helicopter is then permitted to fly until the prognostics interval is exhausted and then it is grounded. This simulates the operation HUMS in the field and allows for the management of material based on HUMS forecasts of failure.

For long horizon forecasts the probability of detection for key HUM indicators is used in

conjunction with the reliability data to generate the HUM reports to the CRDC to enable the operation of an agile network to be forecast over the whole forecast interval.

Currently, proportional hazard criteria are dominated by the operational profile and the environment of the helicopter. An example of the control of proportional hazard in the DES is shown in Fig 10.

Proportional Hazard Reliability Stress Factors					
	Coastal Off Shore	Desert	Hot and High	High FOD Risk	Normal
Corporate-VIP	1	1	1	2	0.25
Emergency Medical Services	1	1	1	2	0.5
Military	1.5	1.3	1.3	2	0.5
Oil & Gas	1.5	1	1	2	0.5
Police	1	1	1	2	0.5
Aerial Work	1	1.5	1.5	2	1

Fig 10

The basic reliability data is stressed by a combination of environmental and operational profile factors. These stress factors are applied such that the overall reliability remains unchanged so that the simulation will retain the regression to mean characteristics of the real world. The Prognostics Gateway aggregates the stress factor data.

The control of the DES utilizes the Monte Carlo method; consequentially a control dashboard is incorporated into the MDF to manage the process. Each output variable and KPI will take different number of simulations runs over the forecast horizon to produce a statistically valid output. .



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Fig 11

In the control dashboard the user can select 16 variables that typify the performance of the network, which are then used to manage the Monte Carlo processing, as shown in Fig 11. The control dashboard displays the convergence of the simulation to a stable output state. When the confidence interval has closed to within a factor of the mean set by the user it turns green on the screen. When all indicators are green the simulation is complete.

On completion the outputs can be interrogated as shown in Fig 12.



Fig 12

Files of the output T_n state variables and the KPI's can be produced and exported to optimizer routines and ERP systems. A wide range of graphics are available to review the data.

The forecasted T_n state has to be verifiable. There is embedded in the humware MDF an auto-verification feature which utilizes the Monte Carlo method that controls the simulation. The forecasted T_n state for a standard forecast interval is compared with the actual T_0 state when that interval has expired for a set of selected variables and KPI's that are deemed to characterize the network.. This process runs in the background and once sufficient forecast intervals have expired the statistics for the deference in the states are review for any significance. The simulation network structure and parameters can then be tuned to remove any systematic error. This process provides the

necessary confidence in the simulation and the consequently the forecasts.

Impact study for an MRO supplier

An MRO supplier for the civil helicopter industry found that it was able to meet their CFA contractual requirements as long as the proportion of the operator's fleet on CFA contracts was less than 10%. However, as the CFA contracts grew, the MRO supplier started to experience problems with the supply chain. The MRO supplier was keen to put the whole fleet on a CFA basis and although the supplier could see the opportunity for increased revenue, they were concerned about guaranteeing aircraft availability and the subsequent financial penalties that would be enforced by the operators should they not be able to meet the contracted availability requirements. What should be a cash positive and profitable business opportunity for the MRO supplier might become a cash drain and a balance sheet liability.

In summary the issues for MRO supplier were;

1. Would prognostics provide a sufficiently improved forecast of demand to enable the MRO supplier to achieve sufficient financial benefit from managing 100% of the fleet to justify the additional commercial risk?
2. What would be the technical requirements, cost and benefit for implementing prognostics across the MRO suppliers supported fleet?

The MRO supplier's logistics chain consisted of:

1. The parts manufacturer who undertook repairs and overhauls for the fleet,
2. The Original Equipment Manufacturer who managed the MRO network,
3. Two service centers reporting to the aircraft manufacturer that undertook Line Replaceable Unit replacement and servicing,
4. Seven operators that were a mix of large and small fleet sizes of the similar helicopter types operating in

offshore support, tourism, HEMS and aerial work.

A significant proportion of the fleet was fitted with Health & Usage Monitoring Systems or HUMS. The value of HUMS was already well understood by both the operator and the MRO supplier in terms of safety, but HUMS data was not being effectively used within its enterprise ERP to assist with forecasting demand for maintenance.

The total fleet size was over 100 helicopters flying a total of 150,000 missions per year. As indicated above, CFA contracts currently made up 10% of the fleet and the operator wanted to raise this to 100% of the fleet. To service the 100 helicopters, there were 40 engines held in stock, mostly at the operator's facility. This stocking level was estimated by the MRO supplier to result in an loss of operational availability of 4,000 flight hours per year. In a CFA contract the MRO supplier has the responsibility for all the stock and the management of the complete logistics chain and recognized that there are opportunities to extract more value from the CFA contract by reducing these stocking levels and re-organizing the logistics chain.

The LRU that caused the majority of the helicopter down time was the engine and it was decided to make the engine the subject of the study. Any thing above the negotiated helicopter availability now incurs a financial penalty to the MRO supplier. This then becomes the basic measure of agility. To lean the supply chain the MRO supplier needed to understand what impact the number of spare engines in repair loop had on the AOG. The objective was to determine the optimum number of spare engines needed. The reduction of spare engines from the current level of 40 was taken as a key measure of efficiency gain. The cost of achieving this efficiency gain could be measured in terms of the loss of availability of the helicopter.

The MDF was used to study to understand the impact on helicopter availability by reducing the number of engines circulating within the logistics chain. The MDF was run for different stock levels and the results are shown in Figure 13, which quantify's the effect of reducing the stock levels in terms of missed flight hours – as

expected the lower the stock to higher the loss of operational helicopter availability.

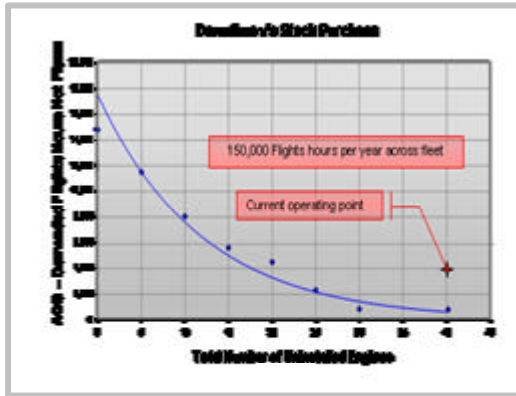


Fig 13

The MRO supplier now had the information required to make a judgment of the number of engines to be held in stock based on the re-organized logistics chain and when costs are introduced to the Figure 14 it transpires that 25 was the optimum number of spare engines. However, this still left the MRO supplier paying an AOG penalty of 2,000 hours per year. The MRO supplier could see that simply increasing the number of engines in stock from 40 would have a rapidly diminishing rate of return. In fact, no matter how many engines were held in stock, the MRO supplier was always going to be faced with some operational availability penalties. As can be seen from Figure 14 the MRO supplier has the opportunity in a CFA environment to reduce both Stock levels and increase availability from the current operating point, but how?

The use of prognostics to increase agility is proposed and using the Commercial Layer of the MDF and emulation the proposed prognostics models the MDF simulation was run to evaluate the agile management of the network.

The optimum set point for the leanness of the network is based on a stocking level of 25 engines. The impact of the prognostics was assessed by varying the proposed prognostics interval and plotting this against the loss of availability as shown in Fig 14. In general, the greater the prognostics interval the better the opportunity the MRO supplier had to direct an engine to the helicopter that needs it. Having this warning period also gave the MRO supplier an additional opportunity to improve the agility

of the network and forecast the manpower resources required to perform the maintenance.

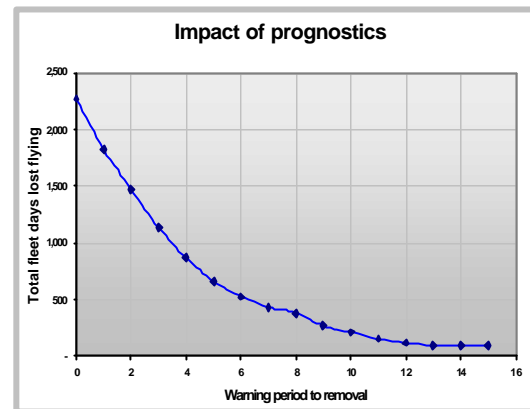


Fig 14

The results showed that based on the current MRO suppliers logistics organization and for a prognostics interval of 14 days the loss of availability could be reduced to as little as 70 flying hours. This was an acceptable loss of availability for contractual purposes for the MRO supplier and a prognostics interval of 14 days was well within the capabilities of the data supplied by the HUMS currently fitted. It can be demonstrated that the current HUMS technology a prognostics model could easily be developed to deliver a prognostics interval well in excess of 14 days; however any increase in prognostics interval would have no further impact on availability.

Other KPI's relating the investment criteria were evaluated utilizing the MDF with similar results.

Clearly then a CBM management approach in a CFA environment for this MRO supplier could be quantified and the benefits demonstrated.

Conclusions

It has been shown from the reported impact study that to re-engineering MRO businesses to implement Performance Based Logistics it is necessary to become lean before you can become agile. If material is in the wrong place or is not available then no amount of forecasting can improve performance. The impact study also demonstrates that if all the material in the network is sufficient to support the loop times in the chain and the prognostics are timely, then to manage to repair and replacement of the

unserviceable LRU's based on a demand forecast can produce a dramatic improvement in helicopter availability. In this paradigm the prognostics capability required is not particularly demanding for the technology.

The impact study demonstrates that to solve the Lean – Agile dilemma then there is a requirement to be able to produce a long horizon strategic maintenance demand forecast to ensure that the material supply in the network is scaled correctly. To implement a management of material to achieve the agility demanded for CFA contracts then an accurate short horizon maintenance demand forecast is also required. The DES approach developed by Humaware can be used for the evaluation of either the leaning or agility issues by simply varying the forecast horizon appropriately.

It has also been shown that build an effective Maintenance Demand Forecaster for use with the management's ERP then a competent Prognostics Gateway has to be developed to provide the source data in near real time and aggregate the data for the parameters used by the simulation..

This paper demonstrates that the key features of the architecture of both the MDF and the Prognostics Gateway. Both elements use Discrete Event Simulation technology and the Monte Carlo method to integrate all of the non-linear stochastic processes necessary to provide a meaningful forecast. The same architecture and data is used for both the strategic long horizon and tactical short horizon forecasts, this results in a high degree of coherency between the forecasts what ever the horizon. The architecture of the MDF includes the novel feature of soft navigation of the MRO network and features that permit navigation based on forecasted demand and emulate the performance of management to provide accurate forecasts.

The whole simulation is data driven and can be embedded into MRO industry's ERP systems. The same technology can be used to implement and manage the CBM strategy as was used to evaluate it. For the demonstration of the forecaster technology in the SMMART system the MDF is integrated into a SAP ERP using SAP Netweaver™. Integrating all of data management systems required to support the

Maintenance Demand Forecaster is a non trivial activity.

It is also necessary to develop the Prognostics Gateway technology to a level where both the probability of failure and the time to failure can be robustly estimated. Without this the temporal separation in LRU failures, it will not be possible for the forecaster to improve significantly network agility, thus limiting the technology to be a tool for strategic problem solving only.

The installed HUM systems need to be specified such that they can provide the type of data that relates directly to defect detection and also sufficient data for the prognostics task. This requires that the technology can provide indicators for each of defect types that is required to provide prognostics for the LRU.

The technology discussed in this paper has been used effectively to support impact studies to determine the degree of network performance improvement can be achieved, a necessary activity to substantiate the return on what is necessarily a significant investment. It has also demonstrated how to manage an agile network based on forecasted demand – a true CBM capability.

Significant development activity is now been undertaken to develop these tool sets with demonstrators available in 2008. The Humaware Maintenance Demand Forecaster with the associated Prognostics Gateway represents a practical approach to the development of a CBM capability for any platform and can accommodate any level of HUMS technology. The adequacy of the HUMS technology can be assessed with the MDF and the performance of the Prognostics Gateway technology can be improved as the HUM systems capability is developed.

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MRP	Materials Resource Planning
OEM	Original Equipment Manufacturer
RCM	Reliability Centred Maintenance
TAT	Turn Around Time
TBO	Time Between Overhaul

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List of Acronyms

A&D	Aerospace and Defence
AOG	Aircraft On Ground
CFA	Contracting For Availability
COTS	Commercial Off The Shelf
CRDC	Central Resource & Dispatch Control
DES	Discrete Event Simulation
ERP	Enterprise & Resource Planning
HUM	Health & Usage Monitoring
LRU	Line Replaceable Unit
MDF	Maintenance Demand Forecaster
MRO	Maintenance Repair & Overhaul