A comparison of modelling approaches for the time-limited dispatch (TLD) of aircraft

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Abstract

The time-limited dispatch (TLD) of aircraft allows operators to efficiently meet certification requirements. In order to display that these requirements are met it is necessary to model the aircraft systems to which TLD is being applied. Currently variations of fault tree analysis and Markov analysis are commonly used. However, in order to apply either of these methods a number of assumptions are made in order to assist in the analysis. Monte Carlo simulation (MCS) is presented here as an alternative method of demonstrating the required level of system reliability. A simple system is analysed using a time-weighted average approach, a reduced fault state Markov approach and a MCS approach. MCS is seen to offer benefits when modelling the application of TLD to a simple system that could also be seen in the modelling of the application of TLD to real aircraft systems.

Introduction

Time-limited dispatch (TLD) was first utilised after the introduction of Full Authority Digital Electronic Control (FADEC) systems to commercial aircraft about 20 years ago. These electronic engine control systems regulate engine thrust from the beginning of fuel metering up to the time of fuel shutoff. When FADEC systems were introduced it was to be the first time that a hydromechanical control (HMC) system would be unavailable to pilots in the event of an electronic system failure [1].

FADEC systems are designed around a dual channel control system, and as such incorporate a degree of redundancy. Each engine has a FADEC system in which all critical loops and functions have either dual systems or redundant elements. Although it was expected that this would lead to greater control system integrity, the dispatch criteria imposed when FADECs were introduced actually led to an increase in delays and cancellations of flights [2], [3]. This was due to the fact that, in the absence of any dispatch guidelines for FADEC systems, a conservative approach was taken in which dispatch was forbidden with faults in more than one channel of an engine. However, because of the high reliability of the FADEC systems in comparison to the HMC systems, an opportunity arose to utilise the redundancy present to allow dispatch with faults present in the FADECs. Required airworthiness standards would still be met and aircraft operators would benefit from the reduction in delays and cancellations of flights. The new approach, which allowed dispatch with reduced levels of redundancy, was called time-limited dispatch (TLD).

TLD allows the dispatch of aircraft with faults present whilst assuring a level of system reliability. This level was set according to the levels that were required of the HMC systems that were used prior to the introduction of FADECs. A maximum limit of 10 events per 10^6 flight hours (flt. hrs.) is set for the *average* loss of thrust control (LOTC) rate of the system [2]. In achieving this average a further restriction of an upper limit of 100 events per 10^6 flt. hrs. is applied for the *instantaneous* LOTC rate of dispatchable system configurations.

When implementing TLD an aircraft may be dispatched over differing periods of time according to the significance of the faults present in the system [2]. These dispatch intervals, which give the maximum time allowed for dispatch before the faults must be addressed, fall into four categories, these being:

- Do Not Dispatch (DND),
- Short Time Dispatch (STD),
- Long Time Dispatch (LTD),
- Manufacturer/Operator Defined Dispatch (MDD).

The DND category, when applied, means the faults present in the system prohibit dispatch of the aircraft and the faults must be addressed immediately. The STD category allows operation of the aircraft in the short term before corrective maintenance must be undertaken and the LTD category allows dispatch in the longer term. The final category, MDD, is reserved for faults that do not affect the LOTC rate of the system [2]. The LOTC rate for faults in the LTD category must not exceed 75 events per 10^6 flt. hrs. STD category faults have a LOTC rate that lies between 75 and 100 events per 10^6 flt. hrs. and for DND category faults the instantaneous LOTC rate exceeds 100 events per 10^6 flt. hrs.

Maintenance Strategies

Two maintenance strategies exist that may be used to maintain a system on which TLD is being implemented. There is no restriction to which strategy must be used when maintaining a system. In fact, if desired, one of the strategies may be used to maintain STD category faults while the other is used to maintain LTD category faults. The two maintenance approaches are described below.

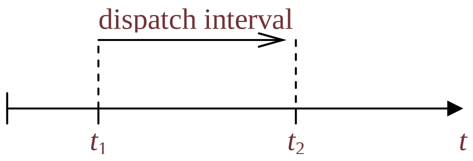

Figure 1. MEL Maintenance.

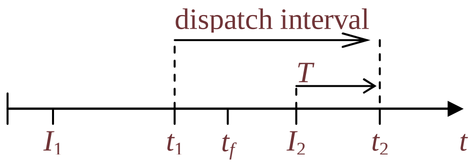

Figure 2. PIR Maintenance.

MEL Maintenance: Minimum equipment list (MEL) maintenance [2] is generally applied to STD faults. When MEL maintenance is used the exact time of occurrence of the fault must be known, at which time a ‘countdown’ is started of the appropriate dispatch interval. When the countdown ends the fault must be repaired in order to allow further dispatch of the aircraft. This process is illustrated in Figure 1, where a fault occurring at time t_1 initiates a dispatch interval ending at t_2. If the fault is not repaired at or before t_2 further dispatch of the aircraft is prohibited at that time.

PIR Maintenance: The second method of maintenance is periodic inspection/repair (PIR) maintenance, normally used with LTD category faults. This involves checking the system for faults at regular intervals. In this case the exact time of occurrence of the fault will not be known. If a fault is discovered at an inspection it is assumed to have occurred at the midpoint of consecutive inspections [2]. The dispatch interval is then deemed to have begun at the midpoint of the inspections and the allowed period of dispatch from the inspection where the fault was discovered is calculated. A PIR maintenance scenario is illustrated in Figure 2, in which I_1 and I_2 represent consecutive inspections of the system for faults. A fault, which occurred at time t_f is discovered at I_2 and, because the exact time of the fault is not known, is assumed to occur at t_1, the midpoint of the inspection interval. The countdown of the dispatch interval is then assumed to have begun at this time and it will end at t_2. This allows dispatch of the aircraft for a further time T after I_2. The inspection interval for a fault category must not exceed twice the dispatch interval for faults of that category. In that way the average exposure to faults cannot exceed the appropriate dispatch interval. However, note that the maximum possible exposure of the system to a fault could be twice the dispatch interval. Contrast this with the MEL maintenance approach where the maximum possible exposure of the system to a fault is equal to the dispatch interval.

PIR could be used to address the maintenance requirements of more than one category of faults. In systems where this is the case inspections for faults of a certain category may uncover faults that fall into another dispatch category. If this occurs the fault may be dealt with as if discovered at the next inspection for its own category [2]. For example, the presence of a STD fault at a LTD inspection would be noted but the STD fault would be treated as if found at the next inspection for STD faults.

The Simultaneous Presence of Multiple Faults in the System

Despite the high reliability of FADEC system components there exists the opportunity for more than one fault to be present in the system at any one time. If this happens there are a number of different issues that could arise and impact upon the maintenance of the FADEC system. Examples of such scenarios are outlined below for the MEL maintenance strategy. These examples are by no means exhaustive, but merely hint at the complexities involved in modelling the TLD process. Indeed, when one begins to consider PIR maintenance or a combination of MEL and PIR and, although such situations would be rare, the presence of more than two faults, the maintenance options available become more complex.

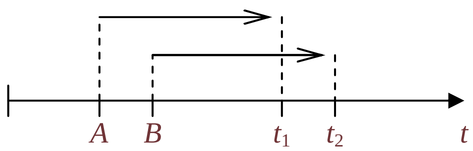

Figure 3. Multiple Faults (MEL Maintenance).

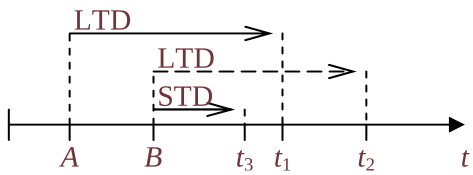

Figure 4. The Combination of Multiple Faults (MEL Maintenance).

Consider Figure 3, which depicts the occurrence of two faults, A and B, repaired using MEL maintenance. The dispatch intervals for these faults will end at t_1 and t_2 respectively. As t_1 is reached a number of options are possible. Clearly, fault A must be cleared from the system at this time in order to allow further dispatch. In addition to this either:

- B may be allowed to remain in the system, allowing dispatch until t_2, or
- B may also be cleared from the system, allowing unlimited dispatch after t_1.

Figure 4 depicts a similar scenario to that shown in Figure 3. Faults *A* and *B*, when occurring in isolation, cause the initiation of LTD intervals, ending at t_1 and t_2 respectively. However, as soon as both *A* and *B* are present within the system, the allowable period of dispatch is reduced to the STD category. This means that, as fault *B* occurs the system may then be dispatched only until time t_3, not t_2 as would be the case if fault *A* had not occurred. Upon reaching t_3 there are three possible maintenance strategies:

- Both faults, *A* and *B*, may be cleared from the system, allowing unlimited dispatch of the system,
- Fault *B* alone may be cleared from the system, allowing dispatch until t_1, at which point fault *A* must be addressed, or
- Fault *A* alone may be cleared from the system, allowing dispatch until t_2, at which point fault *B* must be addressed.

Of course, this scenario assumes that t_3 occurs before t_1. If fault *B* occurred at such a time that t_3 occurred after t_1 then fault *A* would have to be cleared from the system at t_1 before the STD maintenance deadline was reached at t_3.

When faults combine in the way just described to reduce the dispatch interval, the order of occurrence of the faults may have an effect on whether the dispatch interval is reduced or not. For instance, in the example shown in Figure 4, if fault *B* follows fault *A* a STD interval is initiated. If the ordering of these faults was unimportant the same reduction in dispatch interval would be seen if fault *A* followed fault *B*. However, if the ordering of these faults was important it may be that *A* following *B* would not lead to the same reduction in dispatch interval as when *B* followed *A*.

The scenarios described above merely hint at the complexities of TLD and the repair processes involved in the maintenance of a FADEC system. When analysing the use of TLD in the maintenance of a FADEC system the ability of the model used to deal with these complexities may be of importance if accurate results are to be obtained.

Modelling TLD

Before applying TLD to a FADEC system it is important to be sure that the system will still meet the levels of safety required of it. To do this a mathematical model of the system is constructed and an analysis is performed to monitor the effects of TLD on the system and obtain the average LOTC rate of the system. Two methods of analysis that are widely used are described in [1] and [3]. These approaches are based on Fault Tree Analysis (FTA) and Markov Analysis and are briefly described below. Also described is a third technique, Monte Carlo simulation (MCS), proposed by the authors as a suitable alternative method of conducting a TLD analysis.

Time-Weighted Average (TWA) Approach

This TLD modelling approach obtains a value for the LOTC rate of the system by adding the following three quantities:

1. The sum of the failure rates of faults in the mechanical/ hydromechanical portion of the FADEC system.
2. The sum of the failure rates of the system due to unrevealed electrical/ electronic faults.

3. A time-weighted average (TWA) of the failure rates of the system from each of its dispatchable configurations.

This last quantity is obtained by multiplying the fraction of time spent in each dispatchable system configuration by the failure rate to LOTC from that particular configuration. Consider a FADEC system with n dispatchable configurations and let the first of these (configuration 1) represent the full-up system state, the configurations numbered from 2 to m represent the configurations allowing STD and the configurations from $m + 1$ to n represent the configurations allowing LTD. Let λ_i represent the failure rate into the i^{th} dispatchable configuration. Define T_i, the dispatch interval for the i^{th} dispatchable system configuration as follows:

$$T_i = \begin{cases} T_{STD}, & \text{if } i = 2, \ldots, m, \\ T_{LTD}, & \text{if } i = m+1, \ldots, n, \end{cases} \tag{1}$$

where T_{STD} is the short time dispatch interval and T_{LTD} is the long time dispatch interval. Thus an expression for the TWA LOTC rate of the system is:

$$\lambda_{TWA} = \lambda_{HMC} + \lambda_{UR} + \sum_{i=1}^{n} t_i \lambda_{i,L}, \tag{2}$$

where λ_{HMC} represents the sum of failure rates due to mechanical/ hydromechanical faults and λ_{UR} represents the sum of failure rates due to unrevealed electrical/ electronic faults. t_i is the fraction of time spent dispatching from dispatchable configuration i and $\lambda_{i,L}$ represents the system failure rate to LOTC from the i^{th} dispatchable configuration. Equation (2) is a general form of the equations given in [1], [3] and [4]. Because t_i represents the fraction of time dispatching from system state i we require that the total of all n of these fractions is unity. Thus we obtain the following expression for t_1, the fraction of time spent dispatching from the full-up state:

$$t_1 = 1 - \sum_{i=2}^{n} t_i. \tag{3}$$

An approximation for t_i with $i = 2,\ldots,n$, i.e. the fraction of time spent dispatching from the *faulty* dispatchable configurations, is:

$$t_i = \lambda_i T_i. \tag{4}$$

This is equivalent to the approximation given in the original version of SAE ARP5107 [3].

The system failure rate to LOTC from the i^{th} dispatchable system configuration, $\lambda_{i,L}$, is calculated in [1] by dividing the failure probability to LOTC by the average flight time. This "probability per flight hour" is equated to the desired failure rate. Thus

$$\lambda_{i,L} = \frac{Q_{i,L}}{t_{flt}}, \tag{5}$$

where $Q_{i,L}$ is the failure probability of LOTC from the i^{th} dispatchable configuration.

Thus, by substituting (3), (4) and (5) into (2), an expression for the TWA LOTC rate of the system may be obtained.

In a revision to the original SAE ARP5107 document a revised method of calculating the time fractions t_i, $i = 2,\ldots,n$ is given [4]. This method is claimed to better balance the fractions of time spent in each dispatchable system configuration because, rather than assuming the system is in the full-up state for all the time, it is assumed to be in the full-up state for t_1. The new values for t_i are:

$$t_i = t_1(\lambda_i T_i), \tag{6}$$

In this case (3) and (6) give a system of n linear simultaneous equations which can be solved for t_i, $i = 1,\ldots,n$. Then, together with (5) these may be substituted to give an expression for the TWA LOTC rate of the system.

Reduced-State Markov Model Approach

The reduced fault state Markov approach is similar to a conventional Markov modelling approach. However, there are two notable differences, these being:

1. The number of system states is greatly reduced.
2. An artificial simulated repair transition is added to the model.

The reduced-state Markov approaches described in [1], [3] and [4] are similar in that the number of system states is reduced by considering usually only single fault states, i.e. states where only one fault exists in the system in addition to the full-up state and the LOTC state. Dual and higher order fault states may be added to the model if considered of particular importance or if the FADEC system architecture requires it. A reduced-state Markov model for a general system is shown in Figure 5. This particular model is similar to that given in SAE ARP5107 revision 1 [4]. As a single mechanical/ hydromechanical fault could cause LOTC from any fault state a transition is added from the full-up (state 1) and all single fault states (states 2,…,n) to

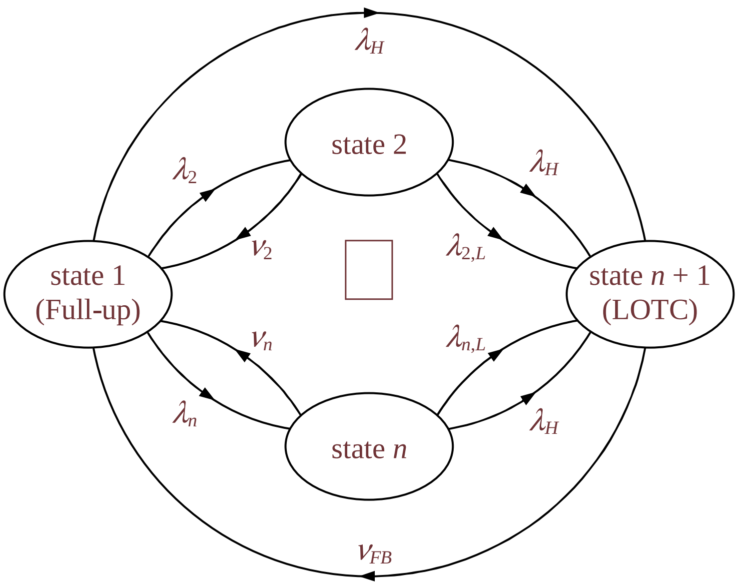

Figure 5. A Single Fault State Markov Model.

the LOTC state. The other addition to the model, over a conventional model, is the feedback loop, a simulated repair from the LOTC state to the full-up state. This is added to the model in order to allow a steady state solution to be calculated. Considering the Markov model shown in Figure 5 the transition rate matrix, **A**, is given by:

$$\mathbf{A} = \begin{bmatrix} -\left(\lambda_H + \sum_{i=2}^{n} \lambda_i\right) & \lambda_2 & \cdots & \lambda_n & \lambda_H \\ \nu_2 & -\left(\nu_2 + \lambda_{2,L} + \lambda_H\right) & 0 & 0 & \lambda_{2,L} + \lambda_H \\ \vdots & 0 & \ddots & 0 & \vdots \\ \nu_n & 0 & 0 & -\left(\nu_n + \lambda_{n,L} + \lambda_H\right) & \lambda_{n,L} + \lambda_H \\ \nu_{FB} & 0 & \cdots & 0 & -\nu_{FB} \end{bmatrix}. \tag{7}$$

All terms that are off-diagonal and are not elements of the first or last columns are zero. The term λ_H represents the sum of λ_{HMC} and λ_{UR}. This leads to a system of n+1 differential equations, given by:

$$\dot{\mathbf{Q}}(t) = \mathbf{Q}(t)\mathbf{A}, \tag{8}$$

where

$$\mathbf{Q}(t) = [Q_1(t), Q_2(t), \ldots, Q_{n+1}(t)], \tag{9}$$

and $Q_i(t)$ is the probability of the system being in state i at time t. At steady state the rate of change of each of these probabilities is zero, therefore equation (8) becomes:

$$\mathbf{QA} = \mathbf{0}, \tag{10}$$

which is a system of n+1 linear simultaneous equations. These equations are dependent and in order to obtain an independent system one of the equations is arbitrarily chosen to be replaced by the constraint equation:

$$\sum_{i=1}^{n+1} Q_i = 1. \tag{11}$$

In order to find the LOTC rate of the system the average failure rate into the LOTC state, n+1, is used. The definition of the reduced-state Markov (RSM) LOTC rate is hence:

$$\lambda_{RSM} = \frac{\text{Probability flow into state } n+1}{1 - \text{Probability of being in state } n+1}, \tag{12}$$

which is:

$$\lambda_{RSM} = \frac{\lambda_H Q_1 + \sum_{i=2}^{n} \left(\lambda_{i,L} + \lambda_H\right) Q_i}{1 - Q_{n+1}}. \tag{13}$$

Equations 2 through to n of the set of simultaneous equations obtained above (from columns 2 to n of matrix **A**) yield the following expressions for Q_i:

$$Q_i = \frac{\lambda_i}{v_i + \lambda_{i,L} + \lambda_H} Q_1, \quad i = 2, \ldots, n, \tag{14}$$

which may be substituted into (13), along with a rearrangement of (11), to give:

$$\lambda_{RSM} = \frac{\lambda_H + \sum_{i=2}^{n} \left(\frac{\lambda_i \lambda_{i,LH}}{v_i + \lambda_{i,LH}} \right)}{1 + \sum_{i=2}^{n} \left(\frac{\lambda_i}{v_i + \lambda_{i,LH}} \right)}, \tag{15}$$

where $\lambda_{i,LH}$ is the sum of $\lambda_{i,L}$ and λ_H. This is the general form of the solution for the reduced-state Markov model as given in [4]. If the repair intervals are as defined in equation (1) then the repair intervals are given as the reciprocals of the dispatch intervals, i.e.

$$v_i = \frac{1}{T_i}. \tag{16}$$

Equations (15) and (16) may now be used to obtain the LOTC rate using different values of STD and LTD intervals.

Monte Carlo Simulation

The first step in performing a Monte Carlo simulation (MCS) is to create a computer code that will model the behaviour of the system over time. The code contains a structured, logical set of rules that will describe how the system reacts to every event that may occur during its use [5]. When modelling TLD such events could be component repairs, failures, sequences of failures or TLD maintenance deadlines and the like. The generation of a uniform set of random numbers is key to the success of any MCS. In a TLD simulation these random numbers are used to generate component failure times using the relevant failure or repair distributions for each component. The simulations are run until such a time that the system fails or the maximum lifetime of the system is reached. After each simulation the relevant parameters are stored and once these parameters lie within the required tolerance the series of simulations is ended.

When TLD is modelled using MCS the scheduling of events that affect the system is of the utmost importance. Component failure times are initially added to the schedule. The simulation time is advanced to the time of the first event chronologically in the schedule. As a component fails the status of the system is checked and if the system fails the simulation ends. If the system doesn’t fail upon the failure of a component then a list of TLD criteria is checked to see if a TLD maintenance deadline or periodic inspection should be added to the schedule because of the component failure. The deadline or inspection could be added because of that failure alone, or because of that failure acting in combination with other component failures. The schedule and the correct ordering of events is perhaps the most important part of the simulation of

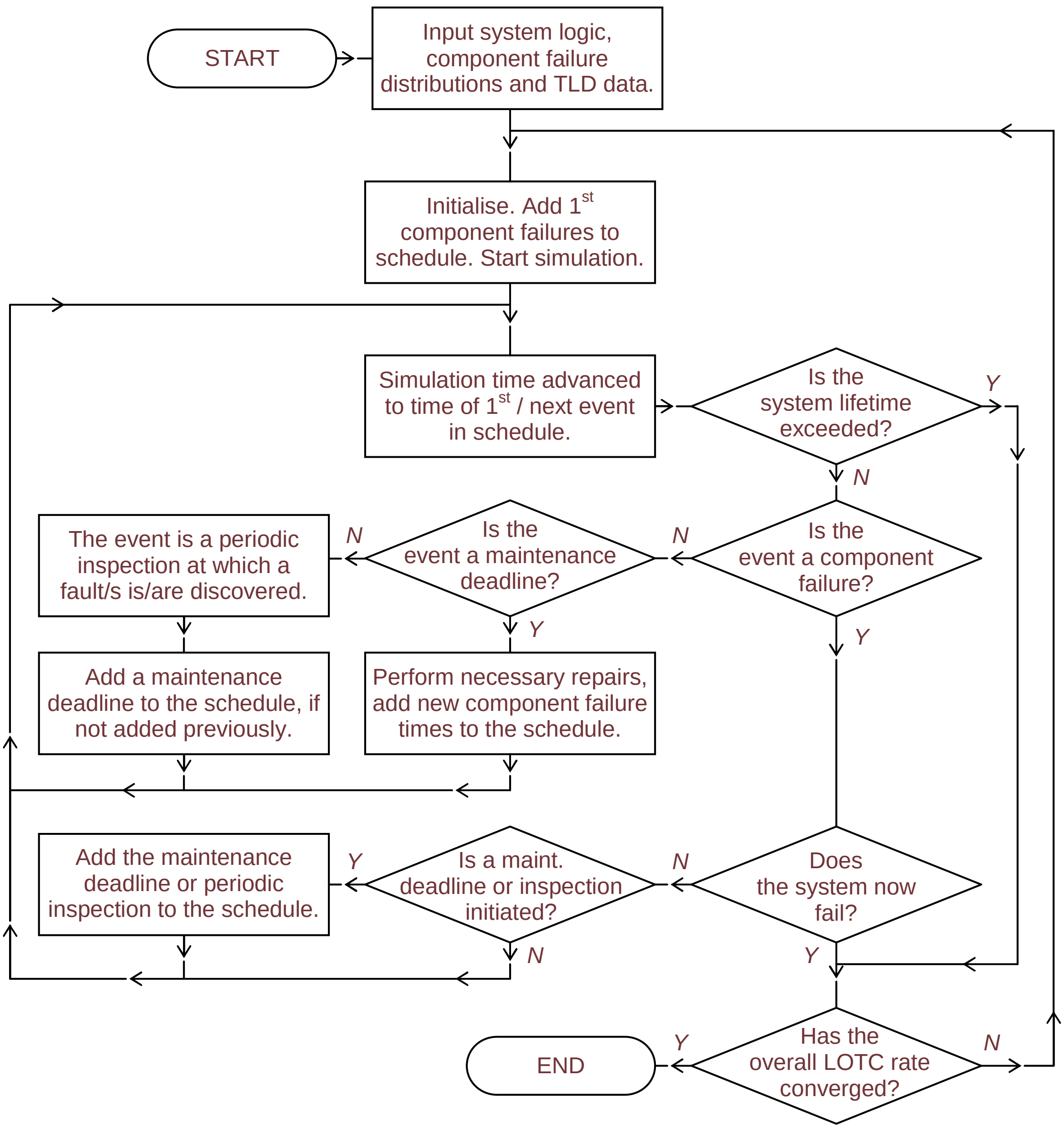

Figure 6. The Algorithm for the Main Module of the MCS Code.

TLD. The structure utilised in the MCS code used here stores the positions of events previous to and after each event and these must be updated as, for example, the first event chronologically is removed from the schedule or deadlines are removed from the schedule after faults are repaired.

One of the major advantages of implementing a MCS is the large degree of flexibility or complexity that may be involved in the code. For instance, when a maintenance deadline is reached, the different repair strategies that are possible may be easily carried out. It would be possible, for example, to clear all faults from the system at each deadline, to clear all faults falling into the same dispatch category or to simply address the fault that caused the deadline. Other strategies are possible and part of the beauty of MCS lies with the fact that different maintenance strategies could be tested before being applied to a real system. MCS is also able to model different strategies better than the usual TWA or Markov-based approaches.

The algorithm for the main module of the MCS code used in this work is shown in Figure 6. Due to the fact that any maintenance operations (TLD deadlines and inspections) cannot occur mid-flight the time of such operations are adjusted to occur between flights. This is done by moving the operation forward to the beginning of the flight in which it would otherwise fall.

The code written and used to model TLD here is flexible in that it can use data from any fault tree of a system failure mode. In addition to the fault tree, the failure distributions of the components and the TLD dispatch criteria to be applied to the system are passed to the code before simulations begin. The failure rate of the system is calculated after every 1000 simulations and the solution is obtained to the required number of significant figures. This is done by checking the value of the failure rate is unchanged for a number of consecutive calculations.

Example System

The system modelled in this work is a simple one, containing only 4 components. The system architecture is shown in Figure 7. As can be seen from the diagram, it essentially consists of two channels, 1 and 2, each of which contains a power supply and a CPU. However, in order to add further redundancy to the system, a link between the two channels is provided that allows, for example, the channel 1 power supply to provide power to the channel 2 CPU if its own power supply fails. The failure rates of

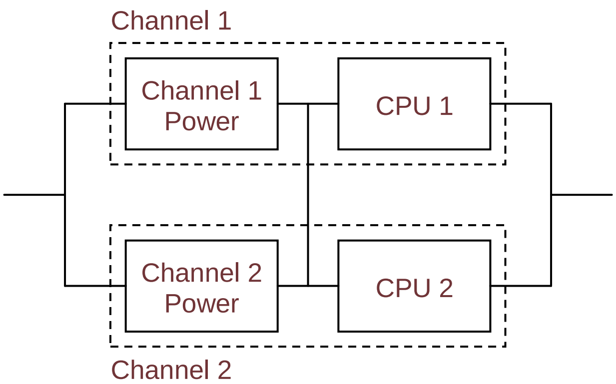

Figure 7. The Simple FADEC System Representation.

the individual components are given in Table 1, along with the dispatch category that will be applied if one of them fails. These dispatch categories were determined for each component by considering the instantaneous failure rate (to LOTC) with that component failed, using the approximation given in equation (5). The same approximation was used to estimate the instantaneous failure rate (to LOTC) of each of the dual fault states, i.e. the system configurations where two faults are present in the system. These failure rates suggested that all dual faults would fall into the DND category and thus need not be included in the SAE TWA and Markov analyses. However, these dual faults are included in the MCS as DND faults. Higher order fault states than this needn’t be considered for this system since once three components are failed the system is definitely failed.

When modelling the system using the TWA and reduced-state Markov approaches the failure rate due to mechanical/hydromechanical faults, λ_{HMC}, and the failure rate due to unrevealed faults, λ_{UR}, were not considered in the SAE analyses.

Component	Failure rate (failures per hour)	Dispatch Category
Power 1	9.0×10^{-5}	STD
CPU 1	5.2×10^{-5}	LTD
Power 2	8.0×10^{-5}	STD
CPU 2	6.5×10^{-5}	LTD

Table 1. Component Failure Rates and Dispatch Categories.

TWA results were obtained for both methods of calculating the time fractions, see equations (4) and (6), given in the original [3] and revised [4] versions of SAE ARP5107. As was mentioned previously, the Markov results were obtained for a single fault state model, since higher order faults would fall into the DND category and needn't be included in the analysis. This is also the case for the TWA model but these DND category faults are included in the MCS model. Results were obtained for the MCS for a number of different maintenance strategies and approaches. STD and LTD faults were addressed using all possible combinations of the MEL and PIR maintenance approaches. Thus both STD and LTD faults were dealt with using MEL maintenance in one set of simulations, one with MEL and the other with PIR in the next set and finally both would be maintained using PIR maintenance. When PIR maintenance was used to maintain faults the inspection interval was varied as a function of the dispatch interval and defined as 1.0, 1.5 and finally 2.0 times the dispatch interval. At the maintenance deadlines the faults could be repaired in a number of different ways in order to allow further dispatch after the deadline. For this system the repairs were carried out in three different ways, each of which represented carrying out a varying amount of work on the system. These were:

1. Repair the last fault of the group of faults that initiated the maintenance deadline.
2. Repair all of the group of faults that initiated the maintenance deadline.
3. Clear all faults present in the system at maintenance deadlines.

The first of these maintenance approaches represents perhaps the minimum amount of work that could be carried out at a maintenance deadline in order to allow further dispatch. An example of applying this approach would be as follows. If CPU1 failed a LTD interval would be initiated. If Power1 was to fail in the subsequent period before the maintenance deadline a DND maintenance deadline would be added to the end of the current flight. In this maintenance approach Power1 would be repaired, leaving the CPU fault present in the system until the LTD maintenance deadline occurs. The second approach would be a slightly more rigorous approach to repairs than the first because, for instance, in the example given above, as the DND maintenance deadline was encountered all faults that caused it, i.e. Power1 and CPU1, would be repaired. The final maintenance approach listed above is most likely to be the one that will produce the lowest LOTC rate, since when any maintenance deadline occurs all faults that are present in the system are repaired and the system is thus returned to a full-up state. For the MCS the maximum lifetime of the system was assumed to be 200000 flt. hrs. This corresponds to a period of use of approximately 37 years for a system used for 15 hours per day. The length of a flight (used in the TWA approach and the MCS)) was set to be 5 hours. This was assumed in a worked example in [1].

Results

Results were obtained for a STD interval length of between 50 and 200 flight hours (flt. hrs.) in 50 flt. hr. steps with the length of the LTD interval varying between 200 and 2000 flt. hrs. in 200 hour increments. Below are some of the results obtained for the 200 flt. hr. STD interval.

Figure 8 shows a comparison of the results from the SAE approaches and MCS with STD faults addressed using the MEL maintenance approach and LTD faults addressed using the PIR maintenance approach, which appears to be the most commonly-used maintenance combination in practice. The PIR inspection intervals are set at 1.5 times the dispatch intervals and at maintenance deadlines all faults are cleared from the system (the third of the approaches listed earlier). We can see from this graph that the TWA method with the original time fraction coefficients produces the highest calculated LOTC rate and that the TWA method with the revised time fraction coefficients produces a calculated LOTC rate that is consistently lower than this over the range of LTD intervals. The single state Markov is again lower but the lowest calculated LOTC rate comes from the MCS. Assuming that the MCS models the system more accurately than the other models, which is a reasonable assumption, this means that the TWA and single fault state Markov methods of analysis are suitable models for this system since the LOTC rate is overestimated.

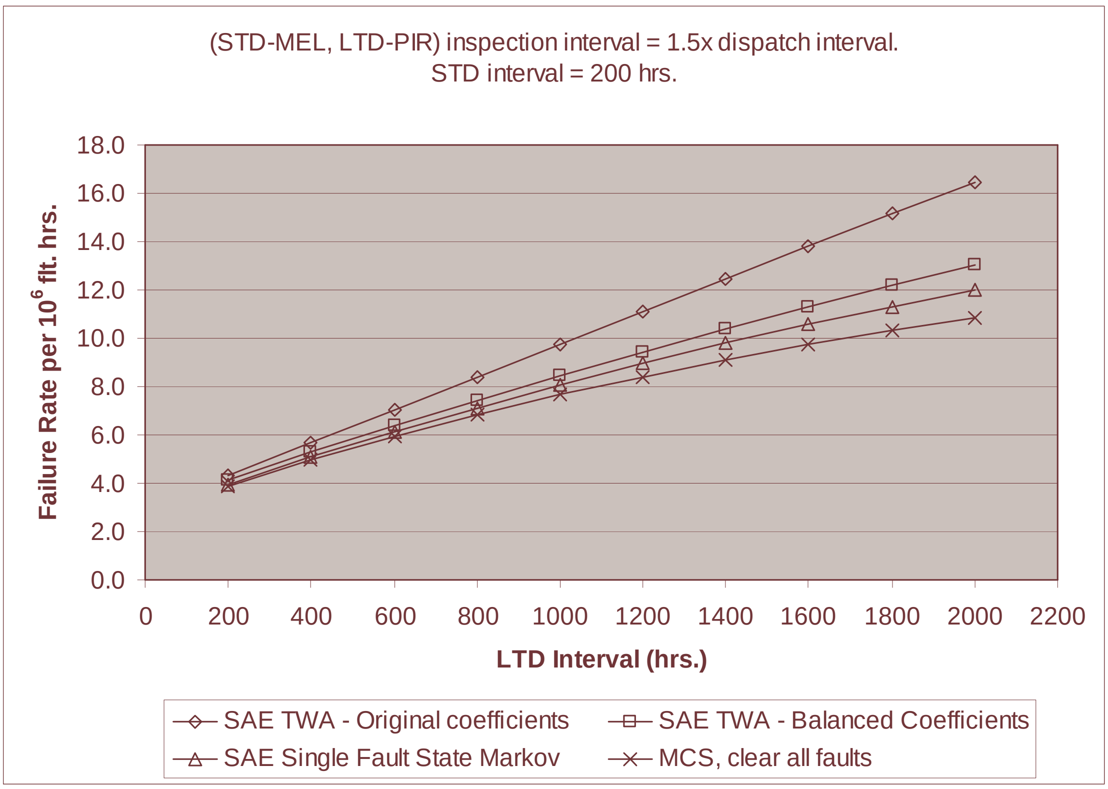

Figure 8. A Comparison of the SAE ARP5107 Approaches With MCS.

Figure 9 shows a comparison of results for the three different maintenance approaches described earlier. Again, STD faults are addressed using MEL maintenance and LTD faults are addressed using PIR maintenance with the inspection interval set at 1.5 times the dispatch interval. This graph shows that there is a significant difference in the predicted LOTC rate for the three maintenance approaches. While repairing the last fault of the group that caused the deadline the predicted LOTC rate is greater than the LOTC rate when repairing all faults that initiated the deadline or clearing all faults present in the system at the maintenance deadlines. The final two maintenance approaches give very similar results, the LOTC rate obtained when all faults are cleared from the system at maintenance deadlines being slightly lower. One would expect that this particular difference could be even more pronounced if a larger system were being modelled. With this in mind consider figure 10, which shows a comparison of the MCS results for the best and worst of the maintenance approaches with the results from the TWA method (with balanced time coefficients) and the single fault state Markov method. We can see here that the single fault state Markov approach actually gives a LOTC rate that is lower than that predicted when the system is repaired by repairing only the last fault of the group causing a maintenance deadline. The TWA method still overestimates the LOTC rate, even for this maintenance approach. As we saw earlier, both SAE methods overestimate the LOTC rate when all faults are cleared from the system at maintenance deadlines. In order to better quantify these differences consider figures 11 and 12, which show the percentage differences of the LOTC rate obtained using the TWA and single fault state Markov methods from the predicted LOTC rate from the MCS. Figure 11 clearly shows that when maintenance involves clearing all faults from the system the TWA method (with the original time coefficients) overestimates the LOTC rate in

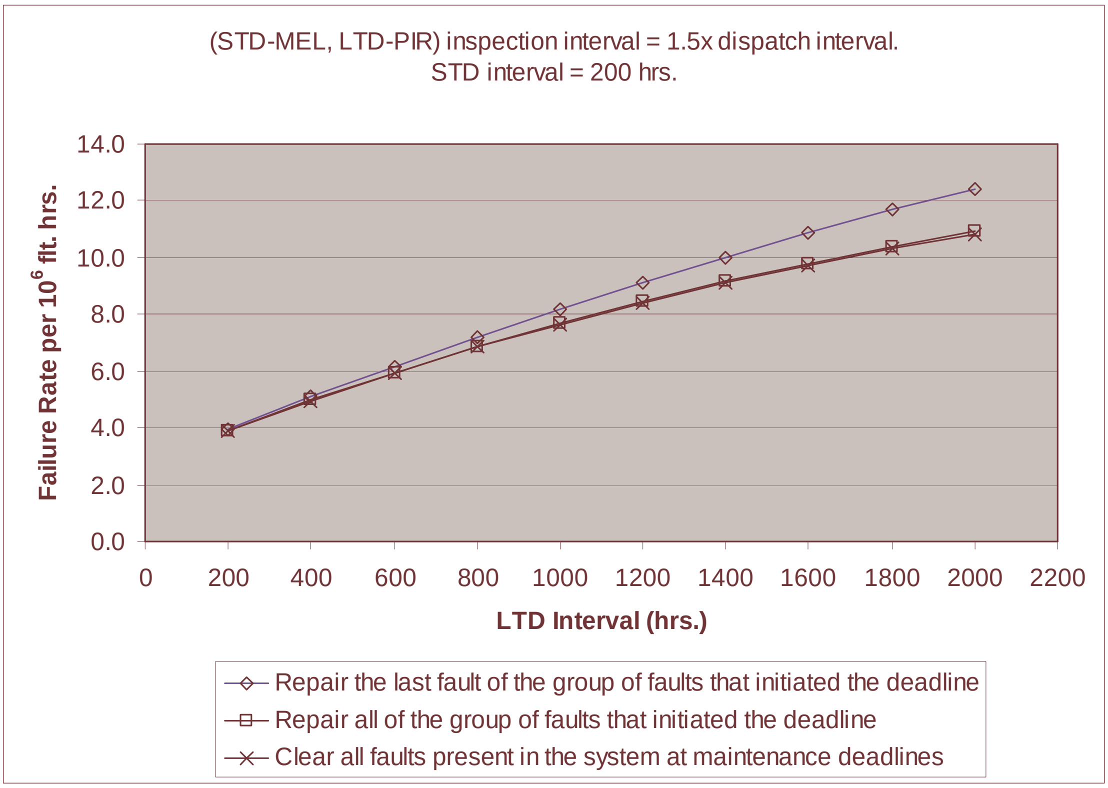

Figure 9. A Comparison of MCS Results for Different Maintenance Approaches.

comparison to the MCS by between 11.7% and 50.4% over the LTD interval range of 200 to 2000 flt. hrs. Over the same range the TWA method with the balanced time coefficients overestimates the LOTC rate by between 5.7% and 18.8% and the single fault state Markov model overestimates the LOTC rate by between 1.75% and 9.68%. Figure 12 shows that the TWA method with original time coefficients overestimates the LOTC rate in comparison to the MCS by between 7.2% and 27.6% over the LTD interval range between 200 and 2000 flt. hrs. The TWA method with balanced time coefficients overestimates very slightly, the percentage overestimate actually falling from 1.5% to 0.8%. However, the single fault state Markov approach underestimates the LOTC rate in relation to the MCS by 2.3% at a value of 200 flt. hrs for the LTD interval. This percentage rises to 6.9% at a value of 2000 flt. hrs. for the LTD interval.

The question now is what effect these differing modelling approaches would have on the dispatch of the system considered as an example here. Considering again figure 8 it can be seen that, given the upper limit for the average LOTC rate of 10 failures per 10^6 flt. hrs. that, given a STD interval of 200 hrs., the LTD interval could be set at about 1050 hrs. if the TWA method (with the original time coefficients) was used to model the system. Using the same method, but with the balanced coefficients, would allow the LTD interval to be set at about 1300 hrs., a vast improvement. However, the single fault state Markov model would allow the LTD interval to be set at about 1450 hrs. and the MCS would allow a dispatch interval for LTD faults of around 1650 hrs if all faults were to be cleared from the system at the same time. However, from figure 9 we can see that, if the maintenance approach involves repairing the last fault of the group that initiated the deadline, the maximum allowed LTD dispatch interval would be around 1400 hrs.

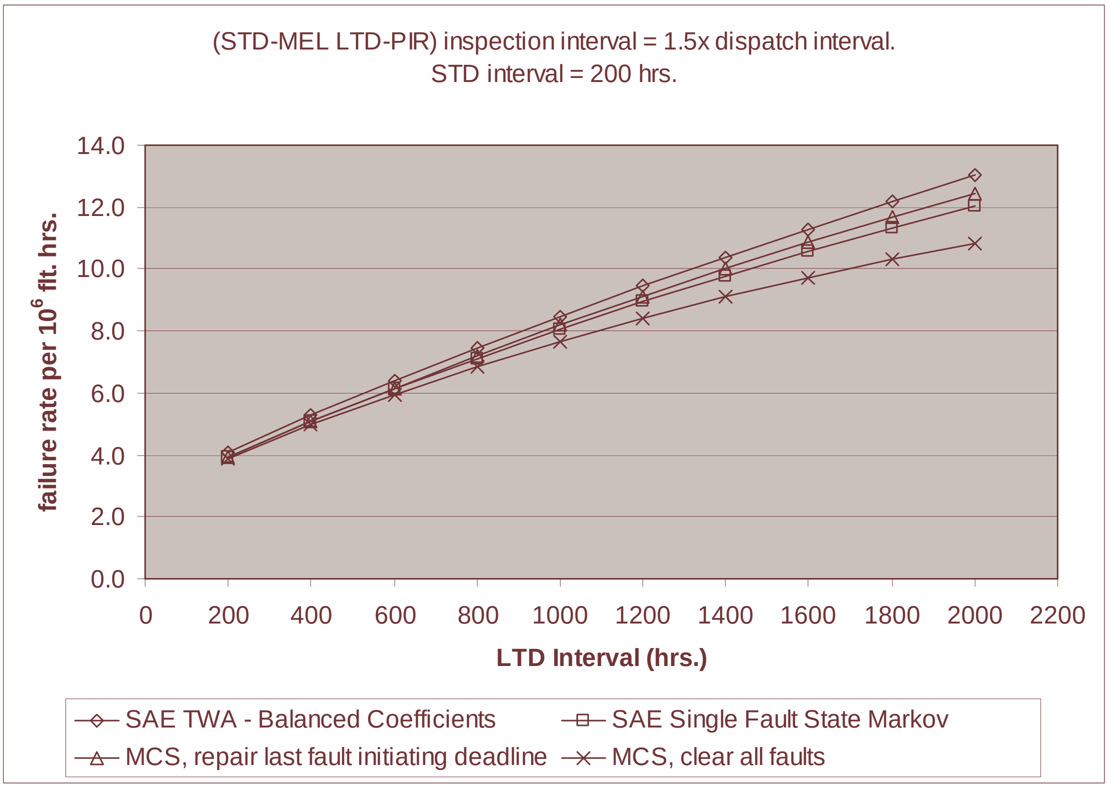

Figure 10. A Comparison of Differing Maintenance in MCS With SAE ARP5107 Approaches.

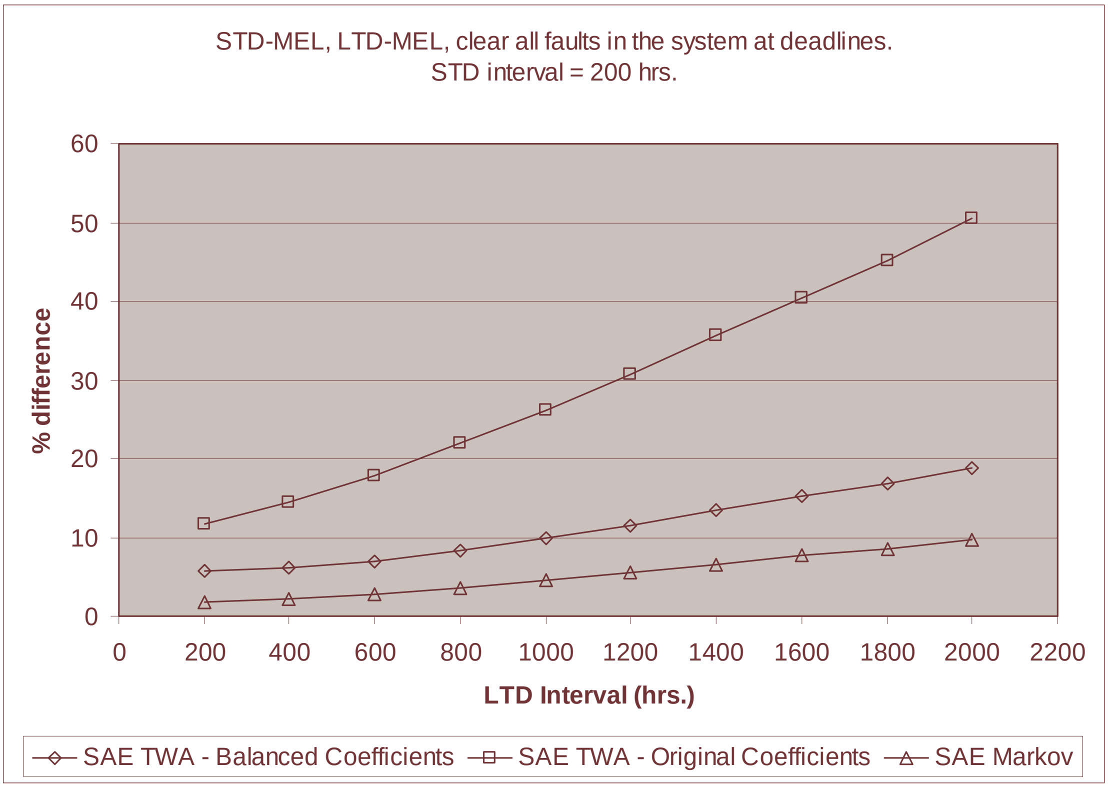

Figure 11. Percentage Difference of SAE Approaches From MCS.

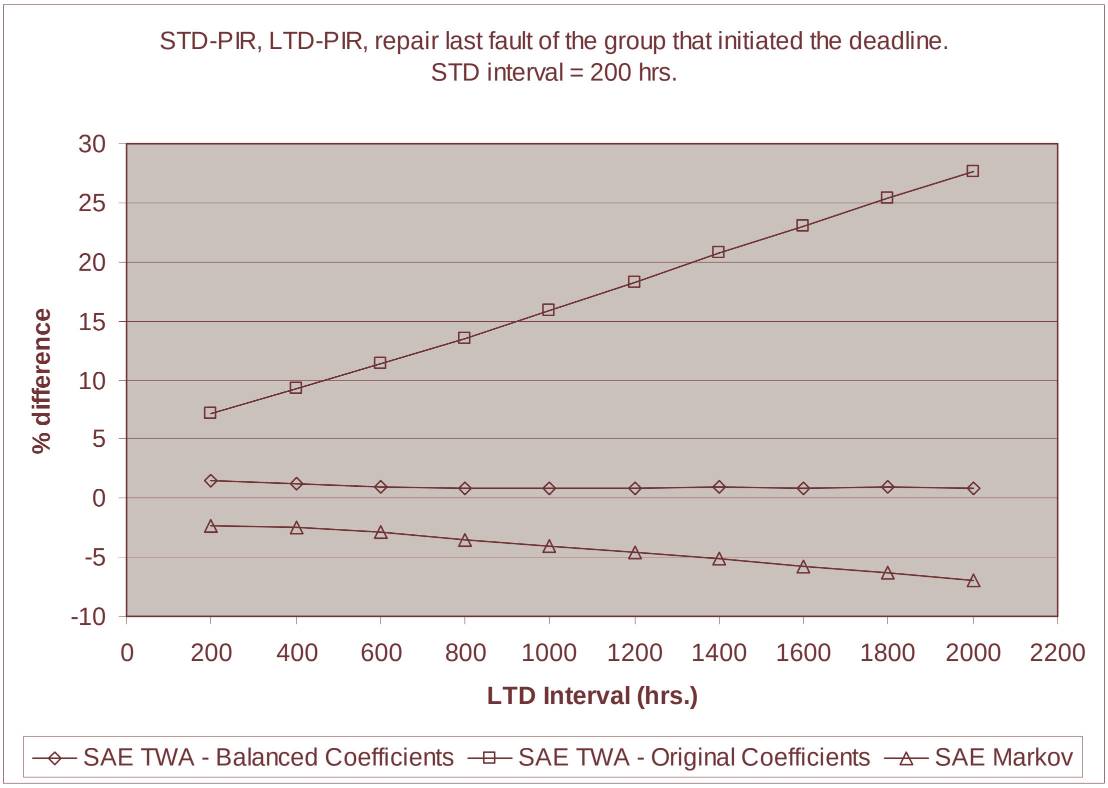

Figure 12. Percentage Difference of SAE Approaches From MCS.

Only a small sample of the MCS results obtained are given because all the results showed similar trends to those presented above and the scenarios involved here were considered to be a good representation of a general approach to TLD. The shorter the STD interval, the smaller was the LOTC rate for particular LTD interval values, as would be expected. As would also be expected, increasing the length of the inspection interval when PIR maintenance was used led to an increase in the LOTC rate of the system. This increase in the LOTC rate was most pronounced when PIR was used to address LTD category faults, regardless of the maintenance approach used for STD faults. This may be due to the difference in length of the dispatch intervals themselves and therefore the relative lengths of the inspection intervals. For instance, for the maximum modelled LTD interval of 2000 hrs. the inspection interval (and hence potential exposure time of this failed system state to further faults) would be 4000 hrs. Contrast this with the situation for the maximum modelled STD interval of 200 hrs. where the inspection interval would only be 400 hrs.

Conclusions

A number of conclusions may be drawn from the modelling of the use of TLD on this simple system. The first, and perhaps most important, is that MCS allows the flexibility to model a large number of potential maintenance scenarios and observe the effect of these on the LOTC rate of the system. In short, a more exact modelling of the system lifetime is obtained. For this system the different maintenance approaches were demonstrated to have such an effect on the LOTC rate that the single fault state Markov approach, for one such maintenance approach was seen to underestimate the LOTC rate of the system in comparison to the MCS. It should be noted that the maintenance approach in question (repairing the last fault of the group of faults that caused the deadline) may not necessarily be a realistic approach and that it may be possible to modify the single fault state Markov approach in order to better model such a repair strategy. However, this may bring an element of doubt as to whether the SAE modelling approaches would always guarantee a LOTC rate of 10 or less failures per 10^6 hrs for any system. Of course, the application of TLD to a more complex, realistic system may result in more accurate results or at least a guaranteed overestimate of the LOTC rate of the system. This requires further investigation.

The use of MCS could clearly prove to be a useful tool in the modelling of TLD. Indeed, if one looks from certification viewpoint, MCS could allow the demonstration of compliance of the LOTC rate, whilst being able to maximise/optimise the dispatch intervals in order to establish the most advantageous maintenance strategy. MCS could also offer most accurate measure for the LOTC rate of the system and be used to obtain other information about the system, such as the instantaneous LOTC rates from various system states.

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