RELIABILITY ANALYSIS OF AIRCRAFT SYSTEM ARCHITECTURES

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Abstract

The paper reports on research that has been executed by LMS internally. The aim was to investigate the use of these multi-physics models for the identification of the overall reliability of a system architecture based on the reliability or mean-time-to-failure (MTTF) of its individual components. Therefore, a methodology was developed that is based on a stochastic approach and was demonstrated and validated with a prototype implementation based on system simulations in LMS Imagine.Lab AMESim. The results indicate with a sufficient number of simulation runs, the results convert to the theoretical results. A case study of a simplified aircraft electrical network demonstrated that also control logic can be taken into account while the simulation time is still acceptable.

1 Introduction

For the safety of aircraft operations, the reliability of its systems is paramount. Therefore the reliability of the systems is one of the main drivers in the design of the aircraft system architecture. These analyses are traditionally done with bespoke simulation tools. However due to the ever-increasing complexity of aircraft systems, the analysis and evaluation of the reliability of aircraft system architectures became more and more cumbersome. At the same time, detailed multi-physics simulations models are created of the same systems to simulate their static and dynamic performance. The aim of the presented work is to investigate the use of these multi-physics models for the identification of the overall reliability of a system architecture based on the reliability or mean-time-to-failure (MTTF) of its individual components. The advantage would be that no complementary models need to be created specifically for the reliability analysis and that a high-level of detail and dynamic effects can be taken into account.

In the next section, the main reliability concepts are discussed. In section 3, the multi-physics system simulation LMS Imagine.Lab AMESim is presented. The proposed methodology is presented in section 4. In the subsequently sections, validation test cases and case study are presented. In the final section, the main conclusions are drawn and possible future work is described.

2 Reliability concepts

2.1 General principle

Reliability is an important concept in the research of failure of -different- components in a system. A definition is: ‘The probability of a component that a certain level of performance is reached in a given period’ [3]. Clearly, reliability is a time-dependent concept. Reliability has a close connection with the concept of probability. The probability of an event (e.g. a flat tire) is defined as:

$$P = \frac{amount of flattires}{total amount of rides} \tag{1}$$

Probability is independent of time. It gives the chance of ’having a flat tire’, in the assumption the circumstances are the same (e.g. the trip of the station to home). Reliability is a much wider concept. It’s time-dependent, and so, a time-input is needed. Once given, reliability simplifies to a chance - of not failing- and the link with probability is clear. If the reliability-function of having a flat tire while riding a bike is known, the only input needed to calculate the probability of having a flat tire - in previous example-is the time needed for the trip from the station to home -again, with the assumption of the same circumstances-.

Reliability and unreliability are 'opposite' concepts, and so, there is a simple relation between them:

$$R(t) + F(t) = 1 \qquad (2)$$

Where R(t) is the reliability-function and F(t) the unreliability-function. Because R(t) stands for the chance of success, unreliability stands for the chance of failure, both are clearly time-dependent.

2.2 Concepts and definitions

3.3.1 Mean Time To Failure (MTTF) and Mean Time Between Failure (MTBF)

'Mean time to failure' is the mean time of component until it fails. It indicates when a replacement will be necessary. MTTF is defined as:

$$MTTF = \frac{1}{N}\sum_{i=1}^{N} T_i \qquad (3)$$

To obtain this expression, N items of a component are taken, and for each item, the time till failure is recorded. This time equals Ti. The next step is take the global sum and to divide this by the amount of items. The result is the MTTF of the component. 'Mean Time Between Failure' is an equivalent expression as MTTF, with the difference that the component will be 'restored' instead of being replaced.

3.3.2 Mean Failure Rate en Failure Rate

'Failure Rate' expresses the amount of failures per second -logically, this can be smaller than one-. The 'Mean Failure Rate' λ is the inverse of the MTTF:

$$\bar{\lambda} = \frac{1}{MTTF} \qquad (4)$$

'Failure Rate' is an instantaneous concept, and so, a similar expression, as previous formula, is not available unless assumptions are made. Like reliability, it's a time-dependant function. However, there is an interesting connection between failure rate λ(t) and reliability R(t). More precisely:

$$R(t) = exp[-\int_0^t \lambda(\xi)d\xi] \qquad (5)$$

It seems, once the failure rate is known, the reliability function can be obtained. Moreover, failure rate will become an important concept in the proposed methodology.

2.3 The Bathtub-Curve

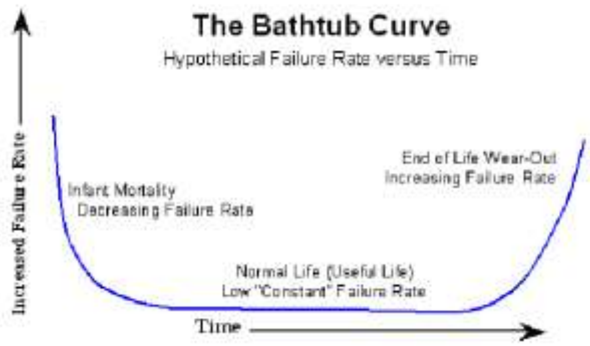

Fig. 1. Example of bathtub-curve

As said before, failure rate is time-dependent, and so, an instantaneous concept. However, there is a function, which approaches the progress in time of the failure rate pretty well. This function is called 'Bathtub Curve', and is shown in figure 1. This function is the typical course of the failure rate. Three parts are present in the curve. The first part is characterized by a high failure rate (in this stage, the weak items of the component are failing). This high failing is also present in the end-stage (where the items will fail due to wear). Most of the time however, failure rate is approximately a constant. During this time, the normal life -useful life- of the component takes place. As a result, it seems a good approximation to work with a constant failure rate. Due to this assumption, the formulas of failure rate and reliability simplifies to:

$$\lambda(t) = \lambda \tag{6}$$

$$R(t) = exp[-\lambda \int_0^t \xi dt] = exp(-\lambda t) \tag{7}$$

3 Multi-physics system simulation

System simulation aims to simulate and analyse the dynamic behaviour of technical systems. Advanced simulation environments can combine multiple domains or physics. A system model is composed of components which represent physical parts of the required system. These components are described by analytical or tabulated models representing the physical behaviour of the system. Based on physics, analytical models use a set of equations, mainly Ordinary Differential Equations (Fig. 2), that are used to qualify the dynamics of the component. Each component exchanges information in both direction using flux and effort variables to satisfy energy conservation. Additionally, a component is parametric and can be defined before a simulation.

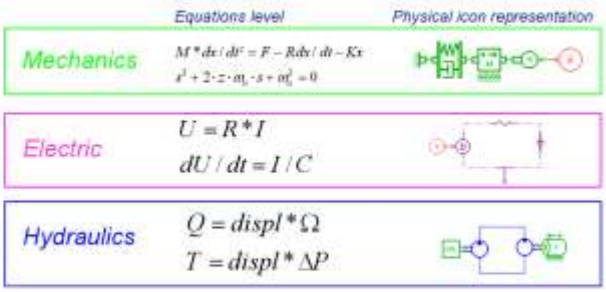

Fig. 2 Alternative representations of different systems

Assembly of the model generates a complete non-linear space state function that can be automatically solved. Advanced solvers can even make their algorithm choices as a function of the numerical stiffness of the system modelled. This approach enables to simulate the behaviour of systems long before detailed CAD geometry is available. Hence, it is also often referred to as 1D simulation as opposed to 3D simulation based on CAD geometry.

LMS Imagine.Lab AMESim (Fig. 3) is a platform for system simulation. A physics-based model of the system is created by assembling pre-defined validated components from libraries using a graphical representation of the components. It enables building multi-physics models using a library of validated components, including Modelica models, from different technical domains, including mechanics, hydraulics, electrics and thermal.

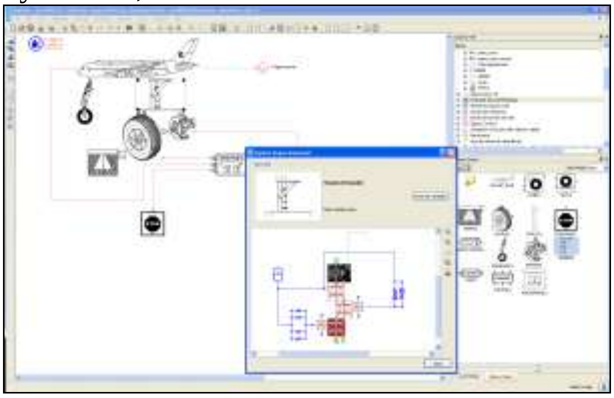

Fig. 3 LMS Imagine.Lab AMESim

4 Proposed Methodology

The methodology that has been developed is based on a stochastic approach. This means that a Monte Carlo simulation with a high number of multi-physics simulations of a system is executed and the average is used to identify the reliability of the system. Therefore, all relevant components in the system need to be assigned their MTTF values. All these components can have two states: working or failed. It is assumed that at the beginning of a simulation, all components are working. Subsequently, the time of failure of each component is probabilistically determined based on its failure rate. Furthermore, the components need to be specified which characterise the overall reliability of the system. These are typically the power consumers. For every simulation, the time of failure of these components is recorded. This can be done by evaluation power consumption of a component over time. The moment the power consumption drops to zero it considered that the moment that it fails. The average failure times of the critical components will indicate their overall MTTF and hence also the MTTF of the system architecture.

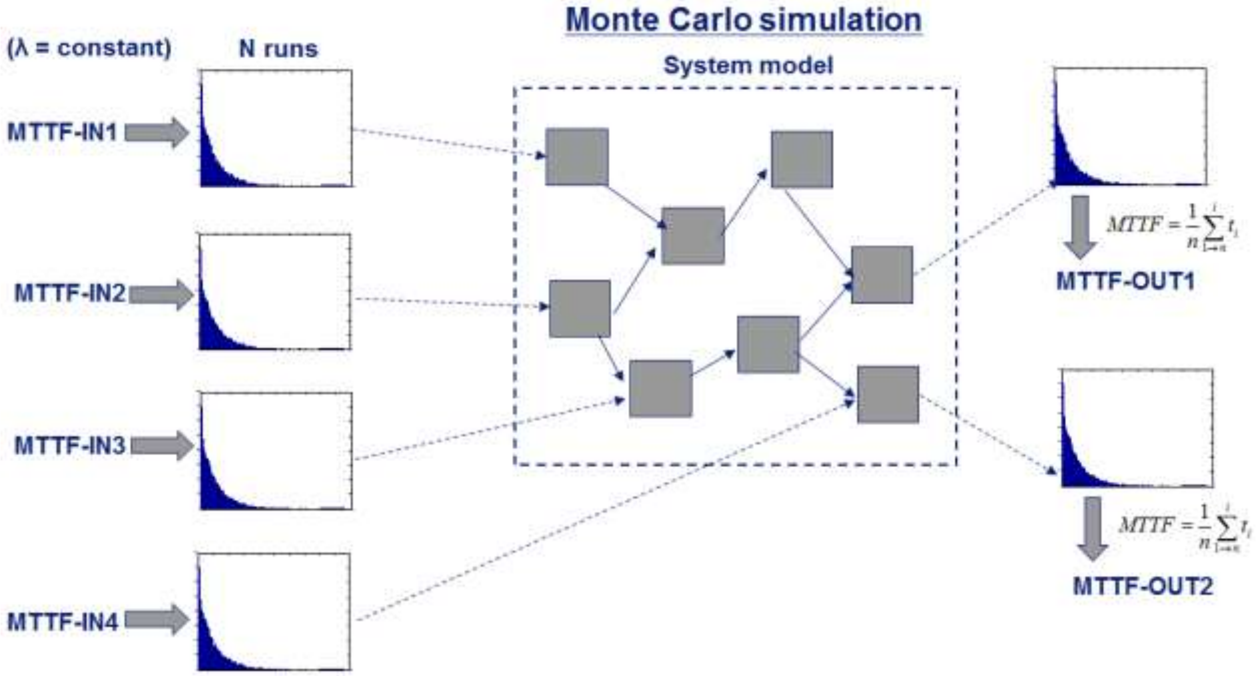

Fig. 4. Proposed methodology

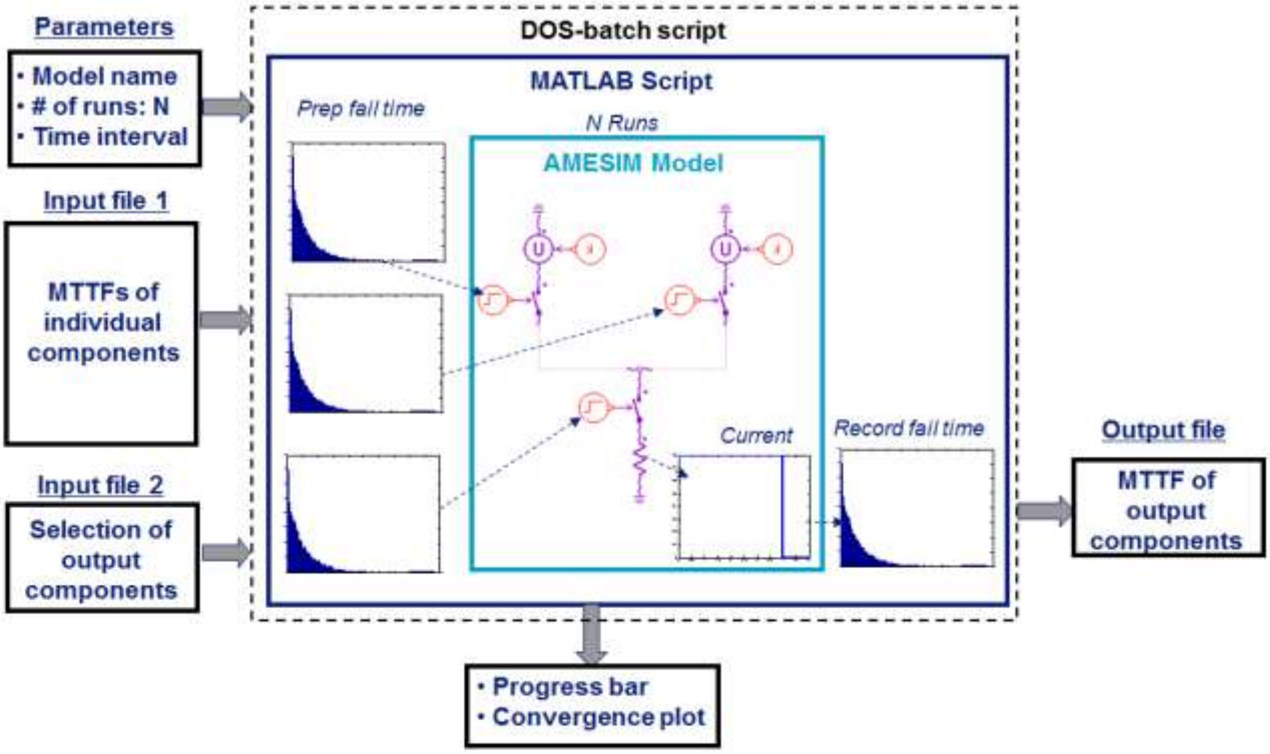

Fig. 5. Implementation concept

This methodology has been evaluated with the implementation of a prototype tool in Matlab in combination with LMS Imagine.Lab AMESim. The overall simulation process was automated with an MS-DOS batch script. The Matlab script determined the failure times of the individual component for every simulation run based on the provided MTTF data of the component and probability distribution as described in equation (7). Subsequently, the Matlab script executes a large number of simulations and for every simulation extracts the results. The results are subsequently combined with the results of all previous simulation. This means that at every simulation, the overall results are available and convergence can be evaluated. For the simulation of the systems itself, parameterised model of LMS Imagine.Lab AMESim where updated and executed by the Matlab script. At every time, all variables for all components are computed, e.g. current, voltage, flow rate, force, etc. The Matlab script extracted the required data at the end of each simulation run.

5 Validation Tests

5.1 Introduction

To validate the methodology, a set of simple system models have been selected wherefore the reliability of the critical component could easily be computed analytically. As the focus was on electrical networks, the validation models are also some basic electric networks. For simplicity of the analytical computations, the MTTF is always equal to 1000hr for all components.

5.2 Serial network

First, a basic electric network was used that is composed of a single power supplier that is connected to a single power consumer. Hence this is a serial network for with the total reliability or MTTF can be easily computed as:

$$MTTF = \int_0^\infty R(t)dt = \left[-\frac{e^{-\lambda_a t - \lambda_b t}}{\lambda_a + \lambda_b} \right]_0^\infty \qquad (8)$$

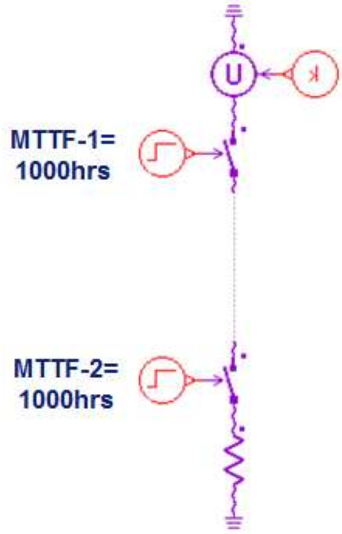

Fig. 6. Electric serial network

Two Monte Carlo simulation were performed, one with 1000 simulation runs and one with 100000 runs. The MTTF from these simulations approached the theoretical MTTF with less than 1% error as shown in the table below.

	MTTF
Analytical	500hrs
10 000 Runs	493.2hrs
100 000 Runs	499.4hrs

Table 1. Results of test case 1

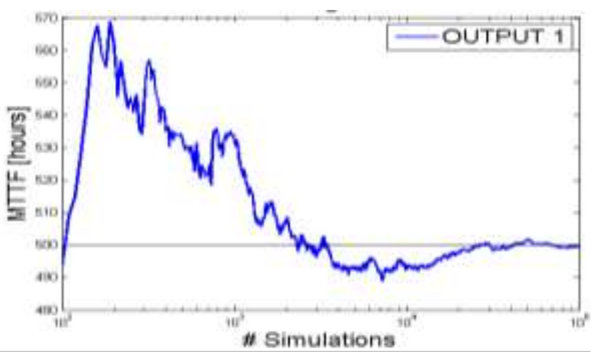

Fig. 7. Convergence plot of test case 1

Furthermore the convergence plot of the latter simulation is shown in Fig. 7. This plot indicates that the simulation had converted to the final result and hence the result is not by coincidence close to the theoretical results. Note that the scale of the X-axis is logarithmic.

5.3 Parallel network

The second network is composed of the power supplies in parallel that are both connected to 1 power consumer. In this case, the power consumer is considered perfect, i.e. it does not have a failure mode. Hence only the power suppliers have an associated MTTF.

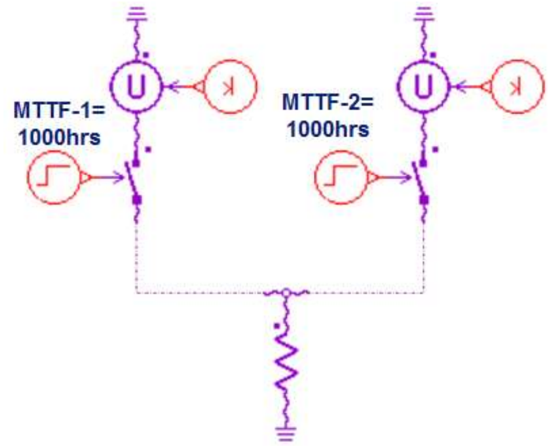

Fig. 8. Electric parallel network

The MTTF of the system can be computed analytically as follows:

$$MTTF = \int_0^\infty R(t)dt = \left[\frac{e^{-\lambda_a t}}{-\lambda_a} + \frac{e^{-\lambda_b t}}{-\lambda_b} - \frac{e^{-\lambda_a t - \lambda_b t}}{-\lambda_a - \lambda_b} \right]_0^\infty \quad (9)$$

The results are shown in Table and indicate again that the results of simulations with 10000 and more runs have less than 1% error compared to the theoretical results.

	MTTF
Analytical	1500hrs
10 000 Runs	1509.6hrs
100 000 Runs	1500.6hrs

Table 2. Results of test case 2

The convergence plot shows again the results van converted.

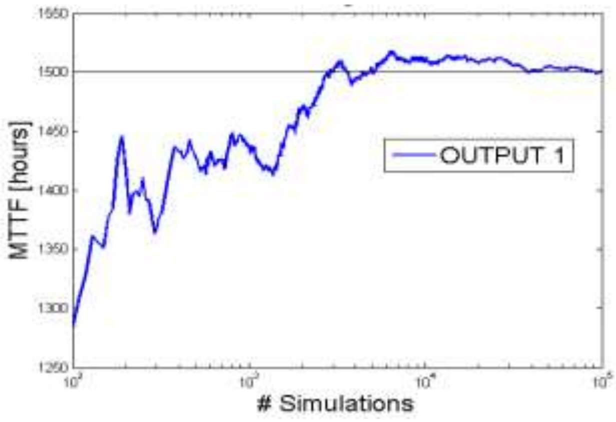

Fig. 9. Convergence plot of test case 2

5.3 Mixed network

In the final validation test, an electrical network with 5 components has been used. This is composed of the 2 parallel power suppliers and 2 parallel power consumers with are interconnected with a bus bar which also has a reliability associated.

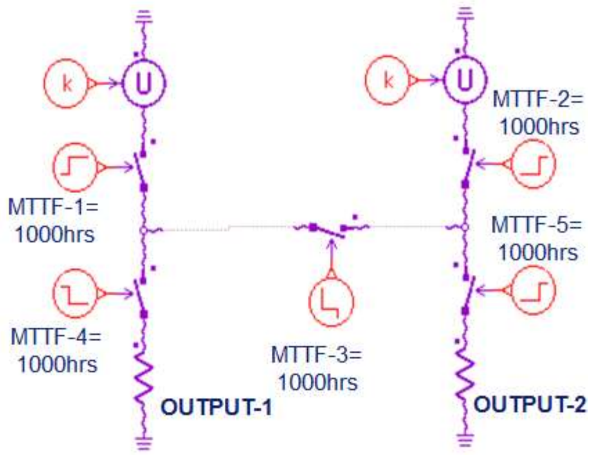

Fig. 10. Electric mixed network

This system has 2 failure modes, one for each power consumer. However since the system is completely symmetric, the MTTF for each consumer will be the same and can be calculated as follows:

$$MTTF = \left[\frac{e^{-\lambda_c t - \lambda_a t}}{-\lambda_a - \lambda_c} + \frac{e^{-\lambda_c t - \lambda_b t - \lambda_e t}}{-\lambda_c - \lambda_b - \lambda_e} - \frac{e^{-\lambda_c t - \lambda_b t - \lambda_e t - \lambda_a t}}{-\lambda_a - \lambda_b - \lambda_e - \lambda_c} \right]_0^\infty \quad (10)$$

The results are shown in Table and indicate again that the results of simulations with 10000 and more runs have less than 1% error compared to the theoretical results.

MTTF	Output 1	Output 2
Analytical	583.3hrs	583.3hrs
10 000 Runs	581.2hrs	581.1hrs
100 000 Runs	584.6hrs	584.0hrs

Table 3. Results of test case 3

The convergence plot shows again the results van converted.

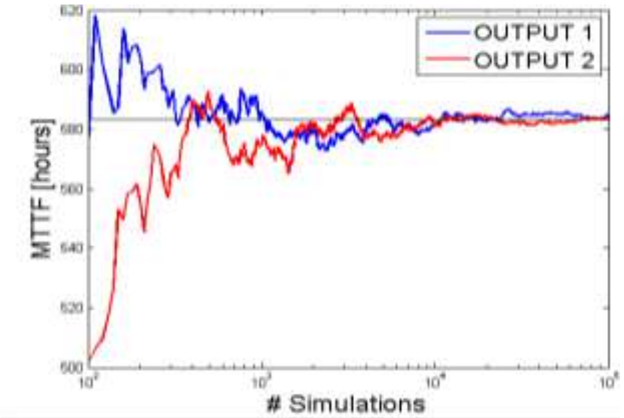

Fig. 11. Convergence plot of test case

6 Case study

Finally, a more advanced case study was analysed. This case study is a simplified electrical architecture of an aircraft that consists of 2 main and 2 back-up power suppliers together with 3 groups of power consumers (Fig. 12). Each group has respectively 3, 2 and 1 power consumers. The groups are considered to be the non-essential, essential and vital power consumers.

Also the control logic was embedded in the system model which detects the main suppliers that are available and can start the back-up power suppliers. This was predefined as shown in table 4.

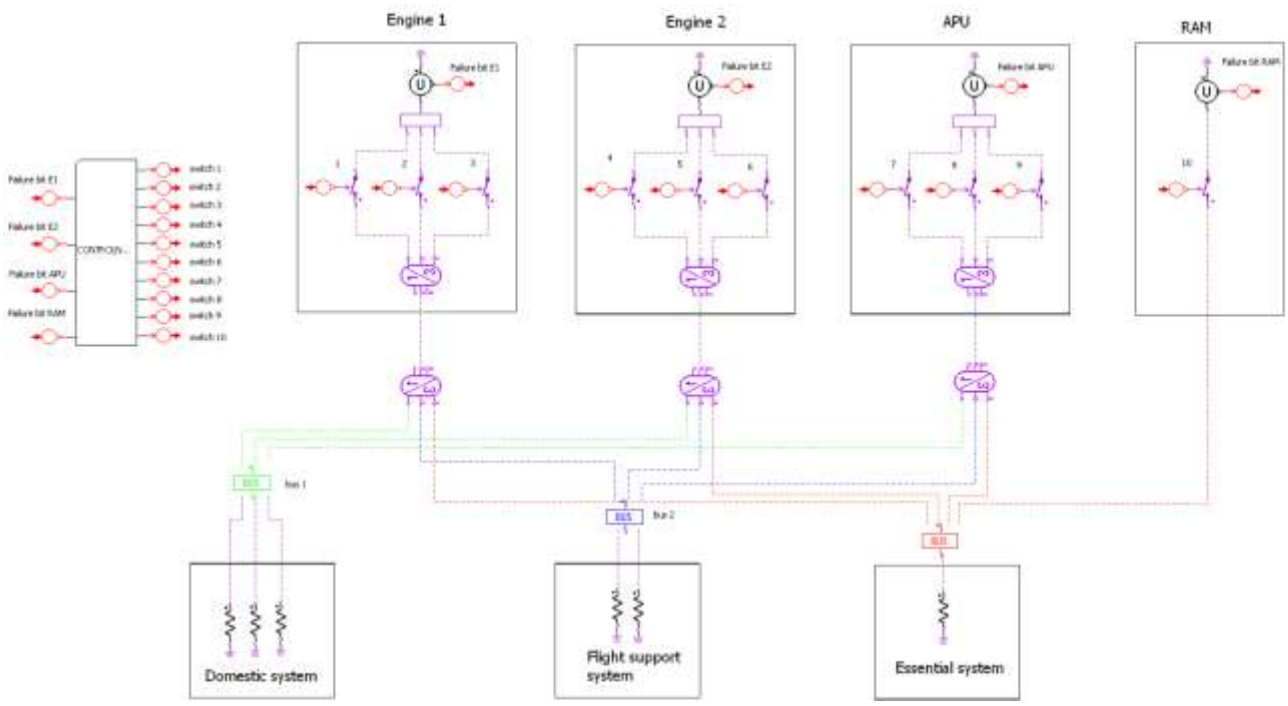

Fig. 12. Case study of simplified aircraft electric network

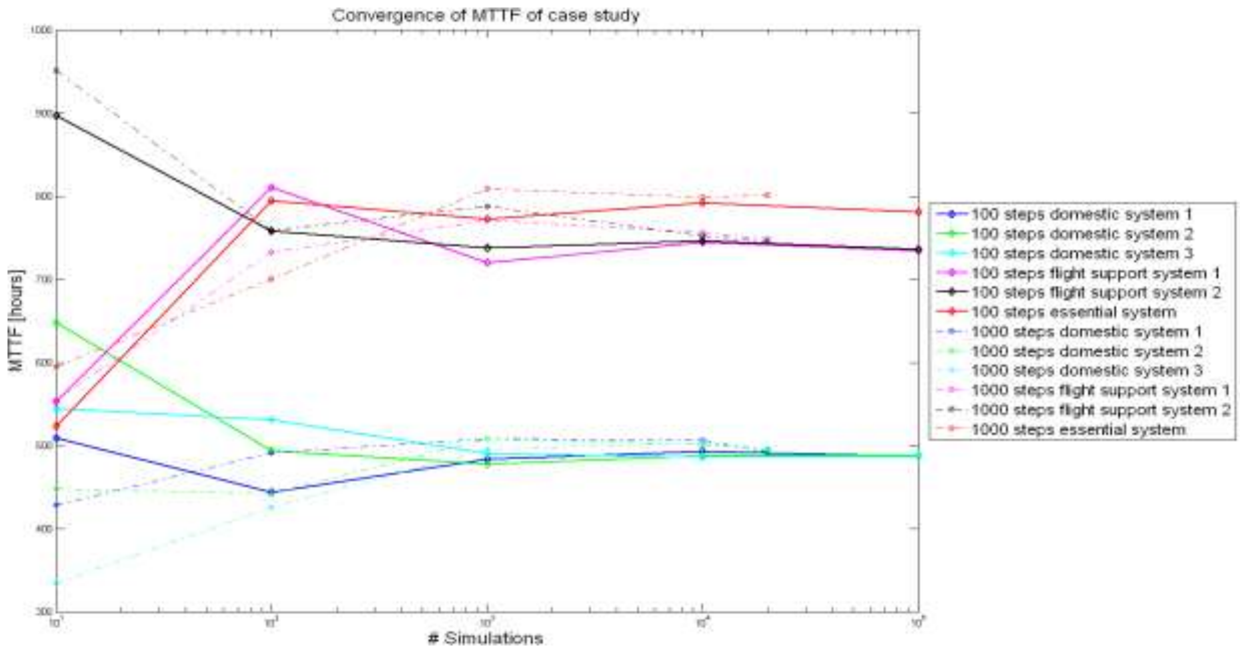

Fig. 13. Convergence plot of case study

No failures: ▪ Engine 1 used for domestic system ▪ Engine 2 used for flight support and essential flight system
Engine 1 failure: ▪ APU used for domestic system ▪ Engine 2 used for flight support and essential flight system
Engine 1 and APU failure: ▪ Domestic system shut down ▪ Engine 2 used for flight support and essential flight system
Engine 2 failure: ▪ Engine 1 used for domestic system ▪ APU used for flight support and essential flight system
Engine 2 and APU failure: ▪ Domestic system shut down ▪ Engine 1 used for flight support and essential flight system
Engine 1 and engine 2 failure: ▪ Domestic system shut down ▪ APU used for flight support and essential flight system
Engine 1 and engine 2 failure and APU failure: ▪ RAM deployed and used only for essential flight system

Table 4. Definition of controller logic

In this case study, the MTTF of all components where set to 1000hrs. This may not be very realistic but it facilitated the interpretation of the results. In particular, any different between the MTTF of the different groups of consumers can only be due to the control logic. In this manner, the results can be evaluated without the possibility to compare the results with analytical results.

Number of simulations: 50 000	**MTTF**
Non-essential system 1	472.4hrs
Non-essential system 2	469.2hrs
Non-essential system 3	472.2hrs
Essential system 1	726.1hrs
Essential system 2	725.8hrs
Vital system	768.3hrs

Table 5. Case study results

The results are summarised in the table above. It can be observed that the group of non-essential have the lowest MTTF which is as expected because the controller logic was set such that this group would be the first to be disconnected in case there is a shortage of power. The group with the vital power consumers has the highest reliability with is also in line with the controller logic. The convergence plot (Fig. 13) indicates that all MTTF values have converted for the considered number of simulation runs. Hence increasing the number of simulations runs will not affect the results much.

Finally, the performance of the simulation was evaluated. The simulation of the case study was executed on a standard work station pc. The total time of simulation was 3.4h for the complete 50 000 runs. This means a simulation time of each runs is on average 0.24s. However, the CPU of single simulation is only 16ms. This means a lot of time is lost due to overhead operations such as read and writing files and license checks. Hence this is still a lot of scope to reduce the total simulation time.

7 Conclusions and future work

It is concluded that with the proposed approach, it is possible to analyse the reliability of complex systems, such electrical networks of aircraft. Because the approach makes use of the same multi-physics simulation models that are used to analysis their performance, the reliability analysis can take into account complex control logic, redundant systems and different operating conditions without need to create separate simulation models. Future work will focus on the evaluation of the methodology with more industrial case studies where also dynamic effects and gradual degradation of component performance need to be considered. Additionally, the minimisation of the computational time will be further investigated.

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