Reducing turn-round variability through the application of Six Sigma in aerospace MRO facilities

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Abstract

Purpose – The purpose of this paper is to outline the application of a Six Sigma (SS) methodology as a means of reducing supply chain risk in aerospace maintenance repair and overhaul (MRO) functions. In this contribution the LSS method is used to estimate the economic impact on the selection of the most appropriate maintenance strategy pertaining to aircraft display units (DUs) as well as providing a reduction in turn round time (TRT) variation of the DUs.

Design/methodology/approach – The paper develops a SS approach which includes the development of the Monte Carlo technique as a mechanism to identify the most cost effective MRO strategy whilst simultaneously reducing variability in TRT servicing of the DUs. This application enabled the authors to obtain further proof of concept and also to apply a number of focused quality improvement techniques to systematically reduce TRT variation.

Findings – An effective development of the SS approach is proposed and the effectiveness of the method is subsequently evaluated highlighting the benefits to the host organisation. The SS methodology demonstrates that it is possible to identify the most cost effective MRO strategy and thus suggests a suitable DU replacement policy which in turn allows engineers to develop the appropriate maintenance schedules for the company.

Practical implications – The design, development and implementation of this SS methodology offers an approach to achieving a more cost effective MRO strategy whilst reducing TRT variability which can lead to greater predictability of operations which in turn enables the company to effectively synchronise supply with demand. The paper offers practicing maintenance managers and engineers a practical example for increasing productive efficiency and output.

Originality/value – This SS strategy contributes to the existing knowledge base on maintenance systems and subsequently disseminates this information in order to provide impetus, guidance and support towards increasing the development companies in an attempt to move the UK manufacturing sector towards world class manufacturing performance.

Keywords Six Sigma, Reliability, Matching supply and demand, Repair strategy

Paper type Case study

1. Introduction

Effective asset maintenance and repair is a critical function in the aerospace industry. Aside from the safety implications, the cost of repair and overhaul (especially when an asset has to be replaced before the recommended number of flying hours) is huge and could, if left unattended, place the company under serious financial strain.

Through a case study approach, this paper applies the Six Sigma (SS) methodology to the application of asset management practice and develops an effective approach to creating a robust asset management strategy for the subject company. Through the application of the Monte Carlo Simulation (MCS) method which is integral within this SS methodology, it is possible to logically assess how its application can systematically reduce turn-round time (TRT) variability as well as being able to assess the most economical aerospace maintenance, repair or overhaul (AMRO) strategy of specific components.

2. Literature review

Both SS and the MCS method have developed over the years to become standard and highly effective business process methodologies/techniques used by both academics and practitioners to systematically identify and resolve specific operational and business problems.

The theoretical development of the MCS method is shown by Metropolis and Ulam (1949) and was used by the physicists at the Los Alamos nuclear research centre in the USA during the Manhattan Project (Metropolis, 1987). The method has since been used in many different applications including banking and finance, as well as in engineering and medical sectors. The work of Thomas *et al.* (2011) describe the use of MCS method in a reliability context through developing a bearing replacement strategy for the steel industry. At the heart of the method is the use of pseudo random numbers to predict future failures in various systems. Using random numbers as indicators of systems failure, it is ideally suited for predicting machine failures, especially when the machine being monitored is operating in the "random" or "constant failure rate" section of its life cycle (bath tub) curve.

SS is a relatively new concept in relation to MCS. Developed at Motorola in the 1980s and popularised by General Electric and others in the 1990s, SS's data-driven approach to improving virtually any type of process has been applied successfully in a broad range of industries. Because of this versatility and the fact that all companies rely on processes, SS continues to grow in popularity. SS has its roots firmly embedded in the more established philosophies of TQM, Lean and tools such as SPC. The work of Dahlgaard and Dahlgaard-Park (2006) shows that the lean production philosophy and the SS steps are essentially the same and both have developed from the same root – the Japanese TQM practices and go on to highlight that the improvement process from SS – the DMAIC process, can be regarded as a short version of the Quality Story, which was developed in Japan in the 1960s as a standard for QC-circle presentations.

Holtz and Campbell (2003) state that the SS methodology has both tactical and strategic applications. Tactically, SS is a powerful tool for improving virtually any process not performing to the desired level. Using highly trained individuals in the tools and principles of SS, organisations can focus resources on underperforming processes to achieve high-leverage results. It is an "end to end" process improvement methodology, which uses objective data to identify sources of excess process-variation, which can then be eliminated. Reducing variation leads directly to improving the consistency of process performance and therefore its output, the principles and tools can be applied to virtually any problem or strategic decision faced by an organisation.

Antony *et al.* (2007) provide key findings on the application of SS in service environments. Since the MRO function is essentially a service operation, the work by these authors is of importance to this paper. The authors identify that that the majority of service organisations in the UK have been engaged in a SS initiative for just over three years at the time of publication and found that management commitment and involvement, customer focus, linking SS to business strategy, organisational infrastructure, project management skills, and understanding of the SS methodology are the most critical factors for the successful introduction, development and deployment of SS in the service sector. They go on to further identify that the typical SS tools employed include process mapping, benchmarking, change management tools, etc., with less typical tools employed include; Kano model, SPC and Quality Function Deployment. Process capability analysis, etc. This paper includes the development of a number of these strategic issues (understanding the DMAIC process, management commitment, etc.) and the application of a number of SS tools identified in this work. However, this paper extends the range of tools by including the development of the Monte Carlo method as a means of achieving variability reduction in a service oriented environment.

A more focused study relating to the application of SS in MRO environments was developed by Ho *et al.* (2008). In their work, the authors identify the critical factors for aircraft maintenance, repair, and overhaul companies during the initial incorporation stage of SS programmes. Through secondary data analysis, the authors identify 14 key success factors. From here the authors survey employees of an Asian maintenance, repair, and overhaul company and via Factor analysis, five key factors that are pertinent to successful completion of Green Belt improvement projects are identified. Two of the five key factors are "defining business strategies based on customer demand" and, "the use of data analysis with data that is easily obtainable". This paper provides a development of these two key factors in that through a combined MCS/SS approach, a step change in business strategy is achieved that is based on specific customer demand through the effective and novel use of easily obtainable statistical data from the failure profiles of aircraft cockpit DUs.

Although there is a huge body of academic and industrial experience relating to the development and application of both MCS and SS, work relating to the effective integration of the MCS in to an SS framework is only now starting to be realised. However, the use of the MCS directly in the implementation of SS projects is still not fully exploited. For instance, the work of Sarkar *et al.* (2011) uses MCS as a method for developing a criterion for selection of critical sub-processes for SS project selection and uses MCS alongside other statistical tools to assist practitioners in the selection of the critical sub-processes to be studied. Additionally, in a paper published in 2011, Zhan outlines the application of MCS in work aimed at using the Design of Experiments technique to reduce MCS simulation time.

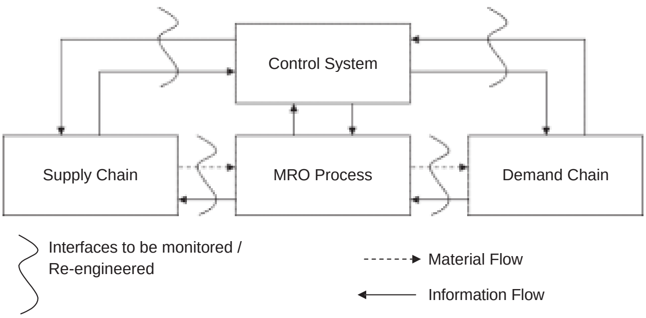
Extending the search towards the application of SS and MCS in AMRO work shows equally scant results. Most MCS applications are based around the design and test of aircraft components and systems as outlined by Dogan (2007) on Direct Simulation MC methods, whilst Mathaisel (2005), proposes the development of a Lean architecture for transforming AMRO facilities without applying any statistical-based analysis techniques.

When considering the application of SS on "systems" based issues like the one detailed in the case study, it is important to consider the wider issues concerning the supply chain and demand profiles which will ultimately influence the impact that SS will have on the outcome of the project. Sawhney *et al.* (2010) outline the need to consider a systems-based approach when implementing Lean and SS approaches in order to improve the reliability, performance and sustainability of lean systems. Clearly in AMRO facilities, a number of supply chain systems issues also arise and these need to be considered carefully at all stages of the SS DMAIC process.

Taking a "systems" perspective, the uncertainty circle (Mason-Jones and Towill, 1998) is a convenient way to describe the performance of a business system which can go on to form the basis of assessing the performance of a company. If uncertainties are considered in a business system, as anything which can reduce the efficiency and effectiveness of an organisation to produce products and/or provide services, then it is possible to identify that any uncertainty within a production system can potentially lead to a reduction in company performance leading to mismatched supply and demand which results in waste and inefficiencies. Through the systematic reduction of uncertainty it is possible to improve operational and supply chain performance and move towards a more resilient operation through achieving a more seamless supply chain system (Christopher and Towill, 2000). The uncertainty circle identifies four areas of uncertainty that can affect the performance of a company. These are; demand, supply, process and controls the relative effectiveness and ability of the control systems used to monitor and control the value adding process, supply and demand chains so that early failure is identified and resolved quickly to ensure the company remains on target by taking appropriate action.

As an example of each issue identified in the uncertainty circle, an AMRO facility may find uncertainties associated with; erratic, frequent and problematic downtime of its test equipment, changing customer schedules and erratic demand profiling which leads to increased demand disturbance, poor supplier delivery performance which affects adversely supplier performance and inaccurate and distorted production plans, wrong and inaccurate process control features which inhibits the company's ability to control its repair and maintenance operations in the way it ideally should. Also the issue of the time taken for the faulty part to arrive and the problem to be assessed by the engineering team is key to operational effectiveness. The four areas of uncertainty are shown in Figure 1 in the form of an "uncertainty circle". The elements of the circle are directly taken from the concept of a traditional business system. The uncertainty circle is based on the control of a company's internal processes in responding to the effects of customer demand and the ability of the system to match supply and demand as closely as possible thereby maximise the potential efficiency (McCarthy, 2004).

Therefore, the aim of developing more a productive and higher performing AMRO supply chain system has two perspectives, namely; one that is internal to the AMRO company and concentrates upon improving internal efficiency and effectiveness of the facility through reducing systems uncertainty and stabilising its performance and, the second perspective concentrates upon the external customer interface through the creation of greater operating capacity which in turn, enables the AMRO and airline companies to increase productivity and protect and build their respective revenue streams. A similar



Source: Adapted from Mason-Jones and Towill (1998)

Figure 1.
Uncertainty circle

approach towards identifying and then integrating maintenance and operational losses is analysed by Tsutsui and Takata (2012). Their work results in a proposed lifecycle maintenance planning system capable of dealing with the complexities of uncertainty and risk associate with AMRO systems . Work conducted by Duffuaa and Andijani (1999) also identified an integrated planning system that undertakes stochastic modeling of various MRO functions and linking them with airline operations in an attempt to improve airline functions and efficiency. Therefore, the need to manage the randomness and uncertainty within AMRO operations is well-established.

The implication of both these perspectives on a company's uncertainty circle is important and requires the company to ensure that the associated demand and supply chain system are adequately synchronised to meet demand requirements. Likewise, the value adding processes must be arranged and managed correctly and efficiently in order to ensure sufficient capability, capacity and flexibility to respond to the demand profile placed upon it. This in turn requires the control systems which monitor, regulate the synchronise the complex inter-relationships between supply side delivery with demand side requirements and AMRO process performance have the required level of robustness without over-dampening the system with excessive control of the AMRO process where flexibility and responsiveness are key drivers to meeting TRT times.

This paper is therefore is aimed at applying an integrated SS/MCS methodology in an AMRO facility in an attempt to define a suitable asset management strategy for the company as well as simultaneously reducing TRT variation which will lead to greater operational performance. The use of the MCS method as part of the SS strategic implementation is seen to provide an effective and unique approach to estimating future costs and hence replacement strategies for a company. The reader is guided to the work of Marquez *et al.* (2003) in which they develop the MCS method for assessing asset availability in generic production systems.

The described case study outlines the approach adopted by the SS team and identifies the DMAIC stages of the SS methodology showing where the MCS method is used to assist in defining the most cost effective AMRO method as well as reducing TRT variability through its application.

3. The case study

Defining the problem

The company is an AMRO facility which undertakes a range of MRO functions for a wide range of airline companies. As a result of the diversity of its operations, the company requires high inventory levels and, due to the uncertainty of failure, part stock-outs and resulting delays in repairing major components are frequent and costly. Therefore, the expected trade-off between high inventory retention and a corresponding lower occurrence of stock-outs is not seen.

The company largely functions as a repair facility for avionic work but it also undertakes significant levels of planned maintenance work on mechanical systems. Due to the increased pressure being placed on the company to reduce component TRT and reduce the cost of its MRO functions, the company needed to first establish the issues surrounding the need for high inventory levels and second, to determine the appropriate and most cost effective service strategy for their components. The company employed the SS approach paying particular attention to avionic repair facility given that the nature of component failure was much more unpredictable and inventory costs were higher than other facilities within the factory.

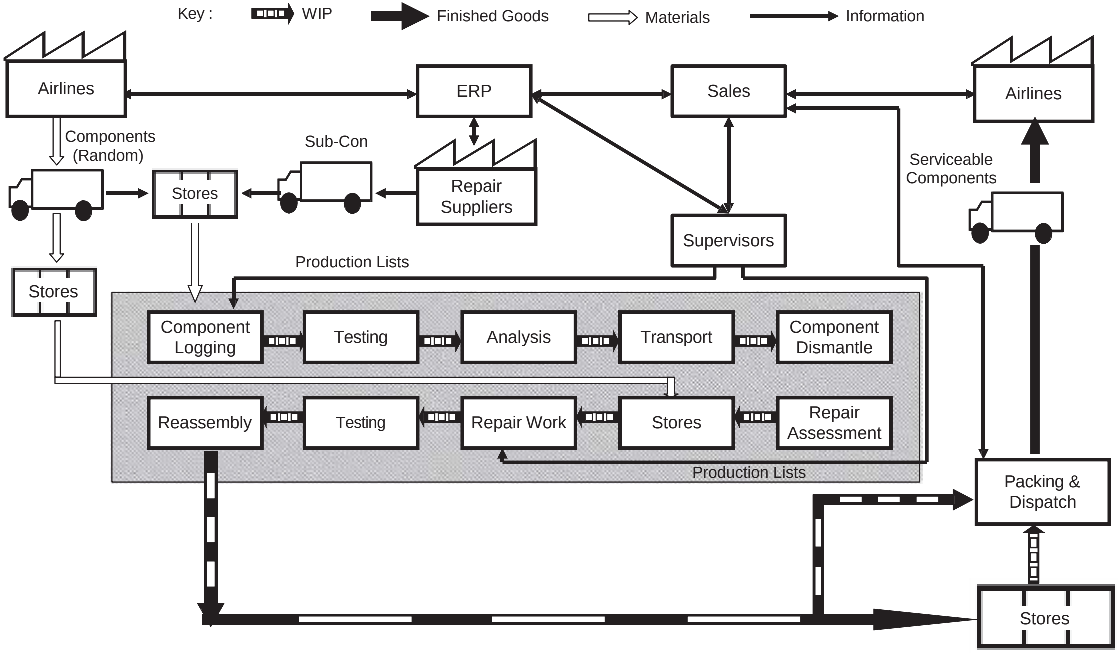
A SS implementation team was created which consisted of a number of managers, engineers and technicians from the company. The authors acted as SS project managers guiding the team through the stages of the SS process, namely the define, measure, analyse, improve and control (DMAIC) stages. A number of meetings held by the SS team identifies the component(s) causing the most serious problems in the company. As part of the SS define stage, a comprehensive value stream mapping (VSM) exercise was undertaken (Figure 2 shows a simplified version) to assist in the identification of common system bottlenecks and areas of poor systems performance. By analysing the routes and flow of a number of components (including; flight recorders, display units (DU), radar systems, etc.) it was possible to develop a picture of how the AMRO facility, as a whole, coped with product mix and differing repair requirements.

The fundamental issue that emerged was that the company operated a “repair only – breakdown maintenance” approach to product maintenance and as such suffered from the inability to plan work effectively and synchronise its inventory correctly to match the failure patterns of each product arriving at the facility. The company had not considered a move towards a planned maintenance approach since traditional beliefs dictated that a repair strategy was more suitable. As a result, the monitoring and measuring of failure profiles of each component in an attempt to plan future maintenance functions had not been undertaken. After further analysis, it was agreed that the item causing the greatest impact on operational efficiency was the cockpit DUs. As with any electronic system, its reliability is subject to correct operation but in some cases, inherent system failures can be considered as naturally occurring and independent of the method of use. Analysis of the failure profiles of the 178 DUs serviced by the company up to 70,000 hours showed that all DUs operated within the random failure area for each unit and that no burn-in or burn-out stages were seen. This provided the team with the opportunity to work off a stable data set. Apart from being a highly safety critical item, the DUs impact on the AMRO systems performance was significant since the cost of repair and replacement of the parts is high and the response of the extended supply chain to supply products on time and in full is relatively slow. The company in turn responds to this issue by holding high inventory levels in order to reduce systems uncertainty. Some of the issues which emerged from the VSM exercise are highlighted below.

Issue no. 1. The customer TRT expectation for the DUs was 14 days. In the main, the company adhered to this target on average. However, in order to meet this demand, the company had to work a two shift system and often had to salvage parts off other DUs in order to ensure compliance with customer expectations. The reason for this problem was that engineers were largely unaware of the condition of the component upon arrival at the plant. If the component required minimal repair then the DUs could be dispatched some considerable time before the 14 day deadline whereas if the component arrived with a major failure, it could take up to 30 days to repair the DU because of the unavailability of parts which needed to be ordered from sub-contractors or suppliers.

Clearly, the lack of understanding of the serviceability levels surrounding the incoming DUs from the airline companies was generating demand end uncertainty which later manifested itself in creating supply end disruptions as the associated supply chain companies responded to meet the fluctuating demands. Overall systems uncertainty especially in AMRO facilities is highly problematic and leads to such facilities needing to hold higher inventory levels in order to cope with the demand fluctuations brought on not only by the various states of disrepair of the product but

Figure 2.
Simplified VSM of MRO process



Source: Authors

also uncertainty generated though "lumpy" demand from the airline companies. The company attempts to reduce demand end uncertainty through parts commonality and inventory planning (Bartezzaghi and Verganti, 1995) but this has a limited effect on total inventory levels and associated costs due to the sheer diversity of the repair programmes undertaken by the company.

Issue no. 2. Analysis of spares inventory within the AMRO facility highlighted that the company held over £2 million of spare parts in stock at any one time. However, by calculating the stock TRTs, only 14 per cent of the stock was rotated on a monthly basis and 64 per cent of stock was rotated on a yearly basis. In one case, over £0.5 million of assets has not been used in the last ten years thus indicating a lack of an effective asset management strategy being employed (Tam and Price, 2008). To further complicate issues, relatively high volume repair items such as DUs suffered long periods of stock-outs which resulted in customer penalties and retrofitting at the airline premises once the parts came in to stock thus incurring significant additional cost.

What was clear from the analysis was that the inventory was not synchronised with the demand profile being seen at the airline side operations. The spikey incoming demand profiles accompanied by varying levels of product serviceability also exacerbated the situation. Further study into the AMRO process also revealed that if inventory levels were reliable and were available to the maintenance teams at all times then there was excess capacity in the company to cope with an additional 30 per cent or so increase in product volume. This indicated therefore that the constraint in the system lay within the supply chain rather than within the AMRO facility itself. Therefore, if all parts were made available to their teams, the DUs could potentially be turned around within the 14 day deadline thus enabling time and cost to be removed from the system. Therefore, the problem statement that the SS team had identified was "to systematically reduce the servicing turn-round-time of aircraft display units (DUs) and to identify the most cost effective AMRO strategy for dealing with the components".

4. Measuring and analysing the issues

An extensive analysis of all DU data based on the number of flying hours that each DU had completed since new was undertaken. The Time Since New (TSN) data were collected for 178 DUs that the company had repaired since new (see Table I). All the DUs in this range had clocked up more than 70,000 flying hours (but W 80,000 hours). Over 36 per cent of the DUs had clocked up more than 76,000 hours but in order to ensure correct data analysis, only the failure data from 0 to 70,000 hours for each DU was used. The number of repairs that each DU had undertaken during the 70,000 hours

Table I.
DU failure profiles (including failure by type)

DU failure profile × 1,000 hrs	Failures by type Mode 1 fail	Mode 2 fail	Mode 3 fail	Total number of fails	Cum. number of fails	Cum. % of fails
0-10	0	0	0	0	0	0
11-20	144	351	136	631	631	18
21-30	177	486	177	840	1,471	43
31-40	129	342	120	591	2,062	60
41-50	114	348	110	572	2,634	77
51-60	90	270	100	460	3,094	91
61-70	66	180	72	318	3,412	100

was also collected and categorised in 10,000 flying hour periods. The accumulated failure profile for each DU in relation to it TSN was calculated. For instance, there were no failures seen in any of the 178 DUs between 0 and 10,000 hours whereas 631 failures were logged between 10,001 and 20,000 hours (indicating that DUs were experiencing more than a single failure in one time period). A peak of 840 failures was seen between the range of 20,001 and 30,000 hours. Further analysis of the 840 failure peak highlighted that 16 failures were due to "double failures" occurring where units were repaired but failed again in the same way within a 100-hour operating timescale thus necessitating the DU to be returned to the company for additional repair. This issue was seen at other time periods but contributed to <2 per cent of the failure profile.

Further and more detailed sensitivity analysis of the DU failure data obtained through a Pareto analysis (Figure 3) identified that the DUs operating within the 0-70,000 flying hour operational window failed due to one of three major reasons. These were:

(1) replacement/repair of the LCD screen due to a malfunction, cracking of the screen or bleeding of the LCD;

(2) circuit board burn outs caused by fuse, or electrical system overload; and

(3) ancillary breaks such as the breaking of switches, dials, etc., which render the DU unserviceable.

When analysing the frequency of failure by type, circuit board burn outs (1,977 occurrences in 178 units giving an average of 11.11 (rounded to 12) failures per part over 70,000 hours) occurred more than twice as frequently as screen failures (729 occurrences in 178 units giving an average of 4.1 (rounded to five) failures per part over 70,000 hours) whereas ancillary breakages occurred very infrequently at approximately half that of screen failures (715 occurrences in 178 units giving an average of 4.01 (rounded to five) failures per part over 70,000 hours). Analysis of this data indicated that DU failure tends to be random in nature and no burn-in or burn-out phases were seen. Therefore, any future asset management strategy would ideally need to cater for random failures.

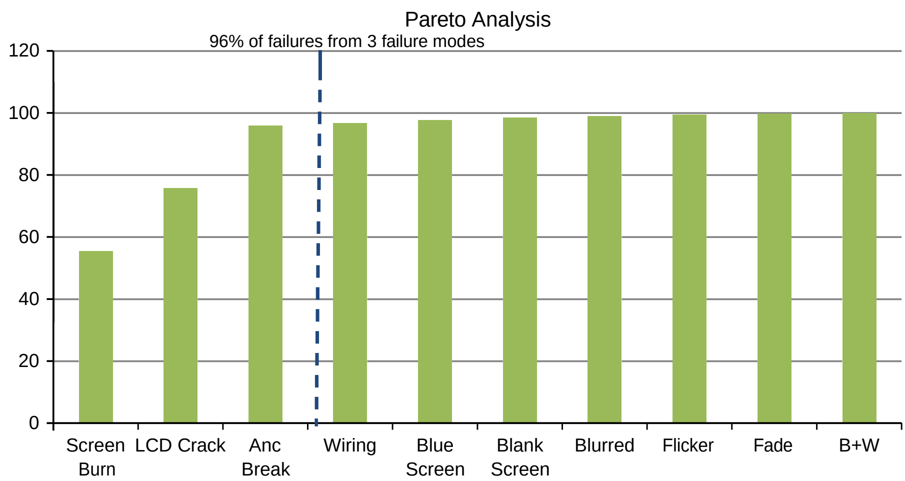


Figure 3.
Sensitivity analysis of failure modes

Analysis of the TRTs for each DU entering the AMRO facility is shown in Table II and in Figure 4. The table identifies a steady shift away from the TRT target of 14 days as the DUs accumulate more operational flying hours. Figure 4 further shows the variability in hitting TRT target time of 14 days. Whilst the average TRT seems acceptable it is the increase in variation in meeting TRT that increases considerably as the DU remains in service longer. Further analysis of the reasons behind the increase in TRT variability can be attributed in the main to the increase in the time the DUs are placed in "holding repair" awaiting parts from the sub-contractor and/or supplier. Variability in TRT therefore is directly attributed to parts stock-outs and the subsequent time that the component spends in "holding repair" due to a supply chain in need of optimisation and greater synchronisation with its demand signal. This in turn impacts heavily on the maintenance schedule and incurs considerable additional cost in rescheduling maintenance activities as a result of an uncertain supply chain (Tantardini *et al.*, 2012). Therefore, earlier fault diagnosis achieved through undertaking testing and pre-screening of the parts further up the supply chain would help to reduce uncertainty of the components entering the AMRO facility which will provide more time to mobilise the supply chain to respond.

From the analysis undertaken, the key issue emerging is that of the supply end of the system is unable to respond efficiently to the fluctuations generated at the demand end of the supply chain. The authors found that the company failed to adopt

DU failure profile × 1,000 hrs	Number of fails	Average target TRT (days)	Average actual TRT (days)
0-10	0	14	0
11-20	631	14	12
21-30	840	14	14
31-40	591	14	14
41-50	572	14	18
51-60	460	14	19
61-70	318	14	13

Table II. TRT analysis of DUs per 10,000 operational hours

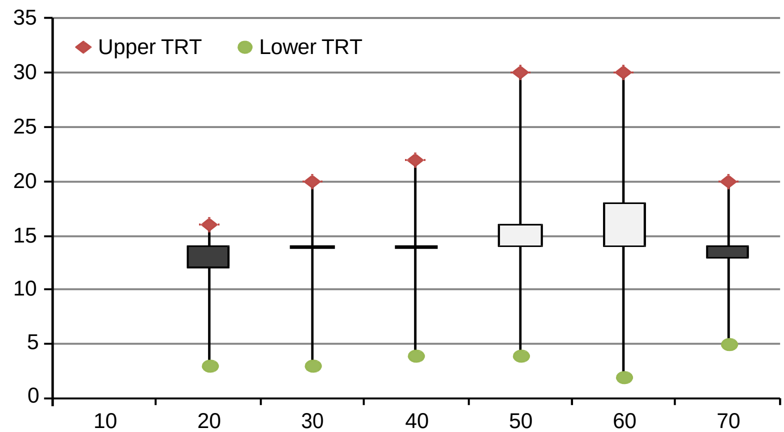


Figure 4. Variability of TRT per 10,000 operational hours

a suitable strategic supply chain approach to cope with the uncertainty at the demand end (Yi *et al.*, 2011). It was observed that there was sufficient capacity available within the AMRO process to cope with the increased volume but TRT times were being compromised because the DUs spent excessive time in holding repair awaiting parts.

Obviously, the need to apply more effective supply chain management practices will inevitably lead to improvements in response times from the supply chain as a whole. However, due to the randomness of the failures experienced, ensuring complete synchronisation between demand and supply to achieve a truly seamless supply chain cannot be entirely achieved (Towill and Childerhouse, 2006).

5. Integrating the Monte Carlo approach (analyse/improve phases)

The MCS method uses pseudo random numbers to generate the potential failure of a component in service and hence can identify a replacement/repair point in the life of a component. However, randomised events need to be confirmed in reality and so there must be a small, but sufficient, quantity of failure data available relating to Asset performance before the simulation can begin.

The initial stage of applying the MC method was to identify the most appropriate asset for analysis. The data, in this contribution, were collected from 178 DU taken off operational flight lines. Due to the nature of aircraft design, each DU would have been installed in the conventional manner and each DU would have experienced the same operating characteristics, flight loadings and operating cycles, therefore it can be argued that any additional other factors can be eliminated, since all DUs are deemed to operate under the same conditions.

The next stage is to obtain full lifecycle data from as many DUs as feasibly possible. In this case, 178 DUs were analysed and their failure profiles logged. The life of each DU was logged and categorised as shown in Table I. From this data the cumulative frequency of the DU failures (by type of failure and total) was calculated and cumulative frequency curves created (shown in Figure 5). Interestingly, the data in Figure 5 showed that the cumulative frequency of failure by type curve matched very closely the overall cumulative frequency of failure curve. Also, all three modes of failure

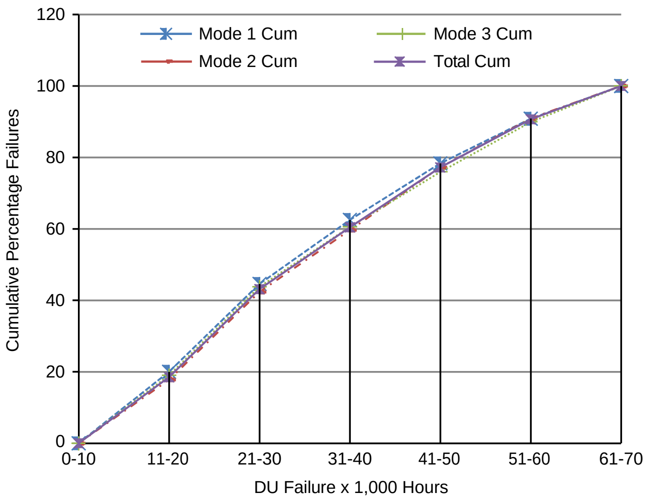


Figure 5. Cumulative distribution function – DU failure profiles by type and total

were seen across the range of flying hours (from 11,000 to 70,000). Since very little variation existed between the "failure by type curves" and the "total cumulative failure curve", the total cumulative distribution function (CDF) was deployed and was used to predict the simulated failures during the MC analysis (Marquez and Iung, 2007).

Once the CDF for the DUs was created, the next stage of the analysis requires the generation of random numbers for each DU. Random numbers were generated for three possible failure modes, namely screen failure and replacement; circuit board failure and replacement; and ancillary component failure and replacement. Since the frequency of failure (shorter corresponding MTBF) differed between the types of failure, the number of random numbers selected for each failure mode were created that best reflected the failure frequency. When assessing the failure modes further it was seen that the frequency of failure by type of failure (see Table I) differ significantly. On average 58 per cent of failures were observed as mode 2 failures whereas approximately 21 per cent of failures were mode 1 and a further 21 per cent were mode 3 failures.

The selection of the number of random numbers to undertake the simulation is primarily based upon the accuracy required and the amount of computation needed to provide a suitable data set for subsequent analysis. Creating too many data points results in significant additional computational resource without necessarily increasing data accuracy. In this instance, the authors used the data obtained from the frequency of failure by type in order to specify the number of simulation points to be used. Therefore, 12 random numbers were selected to represent circuit board burn out (failure mode 2) whereas five random numbers were selected for LCD replacement (failure mode 1 and for failure mode 3. Note that since no failures occurred between 0 and 10,000 flying hours, the generation of the random numbers occurs between the limits of 10,000 and 70,000 flying hours.

Table III shows the list of random numbers generated for the DUs for the three failure modes. These random numbers will be used to represent simulated failure points for the purpose of this exercise.

Using the cumulative frequency curve and the random numbers generated for each DU, it is then possible to simulate the DU life of each failure For instance, using Figure 5 and the first random number for the DU in mode 1 as being "24" thus asking the question "what would the flying hours be if a DU failed with a screen breakage at 24% of its cumulative life?". To find the flying hours, construct a line across from 24 on the vertical scale and project this down from its intersection with the cumulative failure

Mode 2 failure	Mode 1 failure	Mode 3 failure
24	46	1
30	1	99
71	99	10
64	45	85
20	90	27
6		
85		
19		
41		
32		
67		
74		

Table III. String of random numbers between 20,000 and 70,000 hours curve, onto the horizontal "hours" axis. In this case, this gives an operational life of 17,000 hours before the DU will require repair. However, as previously stated, since no failures of any sort were seen before 10,000 hours, any failure point with W 10,000 hours was removed and a new random number generated. Repeating this exercise, for the other random numbers, creates the completed grid of random failure points and their expected time to failure. Table IV shows the full table of DU life against the random failure point for the DUs.

Following the simulation, a decision was required as to what the replacement/repair strategy should be. As mentioned previously, the current strategy was to repair each DU when they failed. Whilst this approach seemed to work effectively due primarily to the random nature of failure, it may not be the most cost effective or efficient method when it comes to ensuring delivery to target since the risk and occurrence of parts stock-outs is high especially when there is an "aircraft on ground" situation. The simulation data yielded the following failure profiles as shown in Table V.

Given the expected failure pattern (based on the random failure events) shown in Table III, it is now possible to test different replacement strategies. In this contribution, three strategies were considered:

(1) repair each DU when it fails;

(2) undertake full maintenance of DU including replacement of all circuit boards and LCD screen every 20,000 operating hours and replacement of ancillary equipment; and

(3) replace all DU parts every 40,000 hours and repair DU if it failure occurs before 40,000 hours.

Table IV.
Simulated failure profile

Mode 2 failure	SHTF[a]	Mode 1 failure	SHTF	Mode 3 failure	SHTF
24	17,000	46	28,100	52	31,300
30	21,000	32	21,300	99	69,400
71	39,000	99	69,400	10	11,300
64	36,500	45	27,200	85	51,000
20	18,500	90	59,700	27	19,300
46	28,100				
85	51,000				
19	17,050				
41	26,800				
32	21,900				
67	37,700				
74	44,000				

Note: [a]SHTF, simulated hours to failure

Table V.
Grouped failure calculations of simulated data

Operating hours	Failure mode 1	Failure mode 2	Failure mode 3
10,001-20,000		3	2
20,001-30,000	3	4	
30,001-40,000		3	1
40,001-50,000		1	
50,001-60,000	1	1	1
60,001-70,000	1		1

To evaluate the comparative strategies, cost data was collected for inclusion in the analysis. In this paper the following values were used:

(1) Autotest cycle ¼ 12 hours @ £50.00 per hour.

(2) Repair circuit board cost ¼ £3,520 per part.

(3) Repair LCD cost ¼ £6,300 per part.

(4) Ave ancillary replacement ¼ £200.00 per part with average labour repair cost for parts ¼ £100.00.

Strategy 1. Repair each DU when failure occurs

Calculating the average cost of repair for a DU operating between 0 and 70,000 hours is:

12 circuit board failures.

Five LCD failures.

Five ancillary failures.

Total failures ¼ 22.

Auto test cycle (mandatory) ¼ 22 × 12 × £50 ¼ £13,200.

Repairing circuit board ¼ £3,520 × 12 ¼ £42,252.

Repairing LCD ¼ £6,300 × 5 ¼ £31,755.

Replacing ancillary ¼ (£200 + £100) × 5 ¼ £1,500.

70,000 hour cycle cost per DU ¼ £88,707.

Strategy 2. Replacement and maintenance strategy

By aiming to undertake a maintenance and replacement strategy it is expected within reasonable limits that the DU will be brought back to its initial level of serviceability. It is therefore expected that the DU will operate for 10,000 flying hours without experiencing further failure. Based on a strategy of replacing the circuit boards at 10,000 flying hour intervals and LCD screens every 10,000 flying hours and replacing ancillaries on condition, the following expected failure profile is calculated from Table IV:

Replace all three circuit boards every 10,000 hours.

Replace LCD screen after 10,000 hours.

Replace ancillary parts every 10,000 hours:

(1) Autotest cycle ¼ 12 hours @ £50.00 per hour.

(2) Replacement circuit board cost ¼ £600 with average labour repair cost for all three circuit boards ¼ £620.

(3) Replacement LCD cost ¼ £5,000 with average labour repair cost for LCD ¼ £900.

(4) Ave ancillary replacement ¼ £200.00 per part with average labour repair cost for parts ¼ £100 (five parts replaced).

Based on replacement of all parts every 10,000 hours, the number of times a DU will enter the service area will be seven times in 70,000 operating hours:

Auto test cycle (mandatory) ¼ 7 × 12 × £50 ¼ £4,200.
Replacing circuit boards ¼ (£600 × 3 + £1,860) × 7 ¼ £25,620.
Replacing LCD ¼ (£5,000 + £900) × 7 ¼ £41,300.

Replacing ancillary ¼ (£200 + £100) × 5 ¼ £1,500.

Replacement of all parts every 20,000 hours ¼ £72,620.

Strategy 3.
Replacement of DU parts every 40,000 hours and repair DU if it fails before 40,000 hours:

From Table III, number of failures up to 40,000 hours is:

0 × mode 2 failures.

3 × mode 1 failures.

3 × mode 3 failures.

When considering full replacement of parts every 40,000 hours then the total number of replacement points is 17 up to an including 40,000 hours (16 points by repair and 1 due to 40,000 service).
After 40,000 hours, it is assumed that the DU will operate without need for additional repair or replacement up to 50,000 hours. Therefore, the number of failures between 50,000 and 70,000 hours is one failure for mode 2, two failures modes 1 and 3 (taken from Table IV). The expected 80,000 full replacement is not simulated since the DUs had not reached this limit yet:

Auto test cycle (mandatory) ¼ 17 × 12 × £50 ¼ £10,200.

Repairing circuit board ¼ (£3,520) × 10 ¼ £35,210.

Replacing circuit board ¼ (£600 + £620) × 3 ¼ £3,660.

Repairing LCD ¼ (£6,300) × 4 ¼ £19,593.
Replacing LCD ¼ (£5,900 + 900) × 1 ¼ £5,900.
Replacing ancillary ¼ (£200 + £100) × 5 ¼ £1,500.
40,000 hour cycle cost per DU ¼ £76,063.

Additional cost of individual repair after 40,000 hours (additional five points of failure):

Auto test cycle (mandatory) ¼ 5 × 12 × £50 ¼ £3,000.

Repairing circuit board ¼ (£3,520) × 1 ¼ £3,520.
Repairing LCD ¼ (£6,300) × 2 ¼ £13,062.
Replacing ancillary ¼ (£200 + £100) × 2 ¼ £600.
Additional repair costs ¼ £20,180.

70,000 hour cycle cost per DU ¼ £96,243.

6. Towards a SS/AMRO strategy (improve and control)

The MCS approach adopted within the SS framework shown in this contribution, allowed engineers to evaluate three DU AMRO strategies. Given cost accuracy, it is evident the MCS method has identified the optimal AMRO strategy is to move towards changing all parts at regular 10,000 hours operating cycles (i.e. strategy 2). This is made easier in this exercise due to the nature of the DU failure profile in that the DU is reliable up to 10,000 hours with no reported failures. Exploiting this level of reliability allows the engineers to consider a strategy that on the face of it seems to be the most costly approach. The identification of the most appropriate AMRO strategy in this exercise relies heavily upon the labour costs (with repair taking considerably longer than replacement in this instance). If the cost profiles were to change then this could have a significant effect on which strategy becomes more cost effective (Sun *et al.*, 2007).

Through identifying the most cost effective AMRO strategy, the company has now taken a strategic move towards developing a maintenance and replacement strategy rather than a repair-based approach. Work has included a full reassessment of the component parts that require replacement within the DU as well as the development of standard maintenance tasks that are carried out depending upon the TSN values for each DU. Through developing standardised maintenance and replacement practices, TRTs were stabilised since it was possible to more accurately predict throughput times which in turn stabilised the supply chain delivery. Supply chain stabilisation was achieved by engineers reassessing component stock levels and working with the supply chain companies on increase reliability of supply to meet demand.

This improvement work resulted in TRT reduction and the associated variability in TRT. Figure 6 shows the effect on TRT and TRT variability on early stage DUs as a result of the adoption of a new AMRO strategy. This is early stage information and only applies to a sample of 50 DUs which have gone on to operate above 90,000 hours. The results show a distinct trend towards attaining the target TRT and more importantly, variability in TRT is converging through seeing a drop in upper TRT thus indicating lower stock outs and less components in "holding repair".

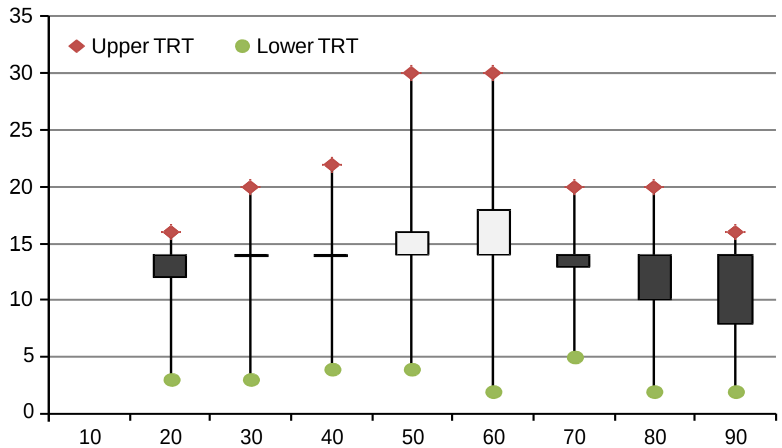


Figure 6.
TRT reduction through changing AMRO strategy

7. Evaluation and conclusions

This paper has reported on the application of the SS method to the study of DU failure in an application within the aerospace industry. Although the MCS technique which sat within the SS framework has been widely employed in many different application areas over many years, its usefulness and validity in this study, has proven that, simulation tools and techniques still have their place in management science (Thomas *et al.*, 2011; Marquez and Iung, 2007; Dogan, 2007, etc.). In this study the MCS was instrumental in highlighting potentially significant maintenance cost savings whilst the SS DMAIC approach was able to take action for improving the systems by enabling the company to redesign its maintenance system and its stock levels to ensure greater stock turn rounds and better synchronisation of the stock levels with the parts usage. This allowed the company to redesign the sub-contracting system which enabled the supply chain to stabilise and level schedule rather than reacting to spiky demand cycles.

As a direct consequence of the SS driven re-design study, equipment modification was undertaken and a substantive portion of the overall maintenance cost burden of over £1,000,000, over a 70,000 hour operational period, was eliminated. Thus the MC approach can therefore prove to be of benefit to a cost reduction exercise. The true cost of the effect of stock-outs has not been calculated in this paper, but the very fact that stock-outs have been eliminated due to the improved inventory synchronisation ensures that costs savings in this area have been achieved. Further analysis and monitoring of DU life is scheduled to continue, in the expectation of identifying the onset of DU failure where, if appropriate, further life analysis and costing will be undertaken.

It is still too early to fully understand whether the change in AMRO strategy has been effective in improving the serviceability of all DUs. It is anticipated that through the regular maintenance and replacement of parts that the general serviceability of the product will increase thus leading to lower overall repair burden on the assets involved.

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