AIRCRAFT SYSTEMS WITH LIMITED RESOURCES AND POWER MANAGEMENT

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Abstract

Increasing airplane efficiency is an aircraft manufacture's major task. The electrical system might contribute to this by a weight optimization of its part supplying non-flight relevant loads. Network capacities are adapted to the typical power demand of those systems. But how far to go down? A method to answer this question is explained in this paper. As architecture with limited resources is accompanied by a power management function, this paper closes with an introduction to power management concepts and technical limits.

1. ABBREVIATIONS

AC Alternating Current
A/C Aircraft
ATA Air Transport Association
DC Direct Current
FH Flight hour
IFE In-Flight Entertainment System
PDF Probability Distribution Function
PM Power Management
RCCB Remote Controller Circuit Breaker
SPDB Secondary Power Distribution Box
SSPC Solid State Power Controller
SYS System

2. INTRODUCTION

For many years, efforts to optimize eco-efficiency and environmental protection have become ever more important to the aviation industry. The reduction of aircraft weight is one major task to support these efforts. One system whose optimization might contribute to aircraft weight reduction is the electrical generation and distribution system [1]. Load measurements have shown potential to lower its system weight by a concept founded on both limited resources and power management. This concept must comply with both safety and reliability requirements as well as airline and passenger demands.

For standard system safety and reliability assessments with "unlimited" resources a broad set of approved analysis methods is provided, see e.g. [2-9]. The major approaches are fault trees and dependency charts. For decades, they have successfully been used to show aircraft compliance with safety, reliability and certification requirements. Showing requirement-compliance of a system with limited resources should start off with these approaches in order to foster their acceptance in aviation industry. In former work, such approach was illustrated, see [10], but ceased at one point, which proved the method, but required extension to customizable systems[1].

Thus, after an introduction to the electrical aircraft supply and distribution system, this paper shall pick up this point and break down the method to allow full application. Since a system with limited resources will come in association with an effective power management function, the paper eventually elaborates on concepts for power management and their limitations on an aircraft in brief. The summary highlights the main findings.

3. THE ELECTRICAL SYSTEM

The electrical system consists of four stages. These stages are the electrical power generation, the electrical power distribution, the electrical loads as well as monitoring and protective functions.

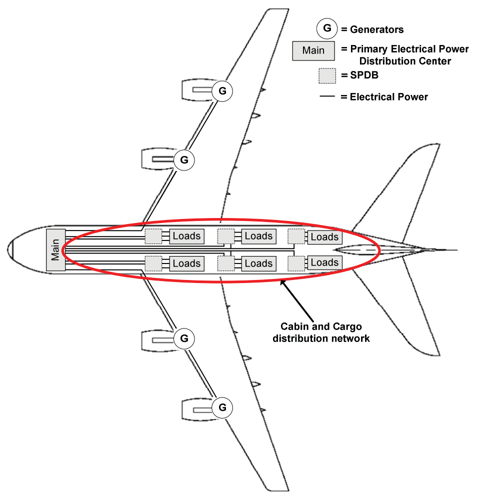

Figure 1: Simplified electrical aircraft system

[1] This paper focuses on reliability-compliance. Effects of intrinsic failures are part of other investigations.

Figure 1 illustrates the electrical system. The four main generators, placed inside the engines, supply the electrical network, whereas every generator forms its own electrical grid. If one generator fails, another will take the unsupplied grid over. Large power feeders connect the generators to the primary electrical power distribution center (Main). From there, heavy loads (I>15 A) are supplied by the Main directly. Many heavy loads are relevant to a save flight and landing, but high power loads, such as the galleys, connect to there, too. An option to supply light loads (I≤15 A) is the secondary power distribution center which sustains technical loads. Depending on the technical load's function, it is more or less important to a safe flight and landing. Light commercial loads[2] are connected to the electrical system via secondary power distribution boxes (SPDBs). Commercial loads are not required for a safe flight or landing[3]. Even though not demanded for a safe flight or landing, the loss or the erratic function of commercial loads can compromise aircraft fleet reliability if these contingencies lead to one out of the following four events [11]:

1) Flight delay of more than 15 minutes,
2) Flight cancellation,
3) Flight diversion
4) In-flight turn backs

Power transmission capacities have been sized on maximum power demand of all supplied loads expected to be active in a flight phase. Hence, system or equipment failure can cause these events only.

In a system with limited resources, this will change. No fault is required to run into the loss or partial loss of a commercial system. Scenarios with irregularly high power demands of several systems at the same time will suffice and lead to under-capacities. In analogy with the failure rate for system failures, a so-called under-capacity-rate was derived in previous work [10]. By using an under-capacity-rate very similarly to the failure rate application in fault tree analyses, limited resources can be sized in compliance with aircraft reliability demands. As initially mentioned, previous work ceased at a point which proved the method to be valid, but left space to extensions. The following sections will describe this extension. It shall not remain unmentioned that the limitation of resources is analyzed for the non-flight/landing relevant part only. That is, the studies are limited to the supply lines between the - Main - and the SPDBs.

4. DESIGNING REALIABILITY INTO SYSTEMS WITH LIMITED RESOURCES

In general, the distribution network is sized based on the sum of the connected load's power consumption. Flight phase dependent operations are taken into account. In this case, network capacities will suffice at any time as long as no fault occurs, see Figure 2. A fault might be a short or open circuit.

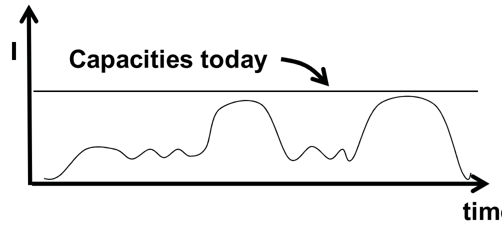

Figure 2: Network capacities under maximum power demand approach

In networks with limited resources, this will change. Depending on the degree of network reduction, under-capacity scenarios will repeat more or less often even without faults, see Figure 3.

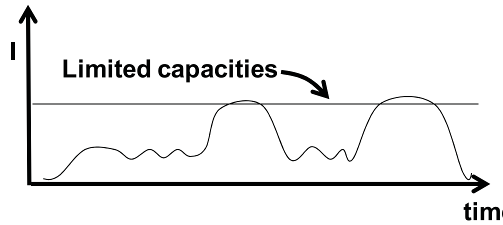

Figure 3: Network capacities in systems with limited resources

Technical faults or unusually high power demands of many electrical loads at the time would either lead to the full loss of the supply line, as the protective device would trip off if no power management was implemented, or partial loss of commercial systems with power management realization. A full loss would very much likely cause one out of the four events responsible for reliability drop and so compromise aircraft fleet reliability. Along with PM functions loads can be paused or chocked in operation whose loss will not lead to one out of the four contingencies. Fleet reliability is upheld. In the latter case, respective choice of an under-capacity rate will determine the amount of PM activities and most likely influence complexity of both hardware and software and eventually development and ship-set costs. In both cases, with or without PM, proper determination of the under-capacity rate is a trade-off between weight savings and reliability objectives, both, in their ways, effecting operational costs.

As introductorily described, an approach to determine this repetition has been introduced in previous work. It is based on an extension of the common fault tree approach to standard safety and reliability assessment. At a high level, this extension is shown in Figure 4.

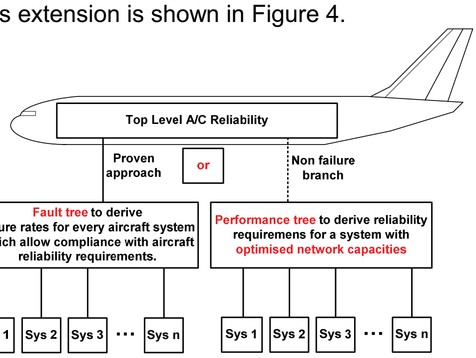

Figure 4: High level approach to design reliability into systems with limited resources.

[2] Galleys belong to the category - commercial loads -, either.
[3] Exceptions apply in minor aspects.

Applied to cabin and cargo feeders whose reliability are better than required, this performance tree branch is given in Figure 5.

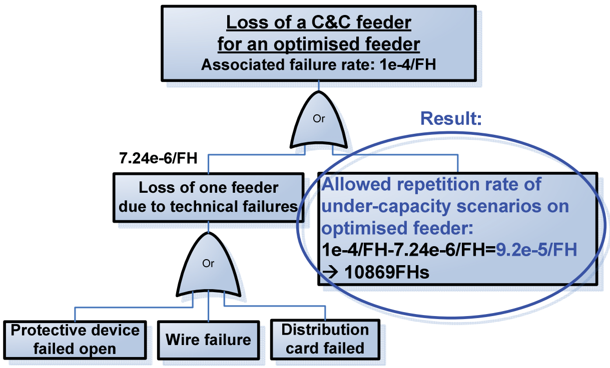

Figure 5: Example Application of extended fault tree approach to design reliability into feeders with limited resources.

For instance, if the required average fleet reliability of a cabin and cargo feeder was λ=1e-4/FH and the actual reliability was at λ=7.24e-6/FH the reliability buffer could be given to the limited resources and would result in λ_R ≈9.2e-5/FH. This means that about an average repetition under-capacity rate of $T = 1/\lambda_R = 10869$ FH ≈ 11000 FH could be realized. As the actual reliability is better than required this buffer can be used. If it was not, this approach could be used by taking this into account during the design phase. For the following explanations an example average fleet under-capacity rate of $T = 1/\lambda_R = 10869$FH ≈ 11000FH per feeder between the PEPDC and the SPDBs will be used.

4.1. Designing reliability into systems with flexible configurations

The above explanations allow determining the limited feeder capacities for a given configuration (system set-up) only. For a new configuration it is necessary to compile another one. Another combination will produce continuous load levels other than before which all occur with probabilities other than the analyzed configuration. Still a basic performance tree exists to all possible configurations. It is pictured in Figure 7 for the general system set-up in Figure 6 for loads L1 ... Ln.

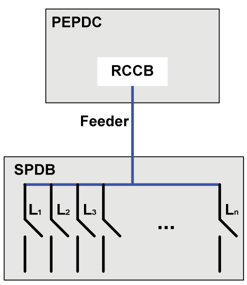

Figure 6: Arbitrary load combination to a feeder

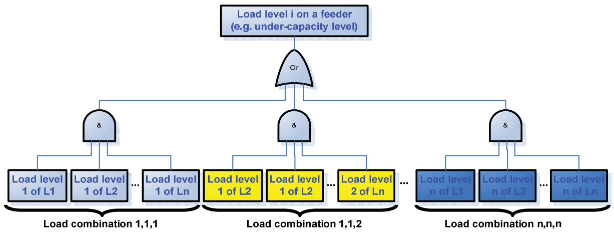

Figure 7: Basic performance tree to all possible feeder states

Every AND-gate (&-gate) represents a possible combination of loads and thus a power value the feeder can take. As the load combinations can cause different power values i on the feeder and as they cannot occur at the same time, they are linked by OR-gates. More than just one load combination can lead to the same level on the feeder. For instance, there can be more than just one combination leading to let's say a current of 23.4 A. The probability for every load combination can be calculated if the probability to every load's single state is known. The latter has been extracted by measurements. The upper performance tree is valid only when the systems are statistically independent. Otherwise, loads have to be clustered and represented as one load within the performance tree.
The probability to every load's power level is given as probability density function (PDF) $f_{Ln,}(i)$. The PDF $f_{feed}(i)$ of the resulting feeder load can then be described by the convolution [12]:

$$(1)\quad f_Z(i) = \sum_{j=0}^{i} f_X(j) \cdot f_Y(i-j) =: f_X(i) * f_Y(i)$$

Mathematically, this is nothing else but the above performance tree when AND-gates are replaced by multiplications and OR-gates by additions.

For the application computer programs the current over time plots of the loads are transformed into histograms. They approximate the PDF. In doing so, for the loads the information a) possible load level $I_{m,n}$ and b) respective probability $f_{m,n}$ are gained. This is formed into a matrix according to Equation (2) and (3). This allows the application of the convolution according to (1) by convoluting first row one and two of matrix (3), the result of the first convolution with row 3 and so on. The final output is the feeder's PDF.

$$(2)\quad I_{SSPCs} = \begin{pmatrix} I_{1,1} & I_{1,2} & I_{1,3} & \cdots & I_{1,n} \\ I_{2,1} & \cdots & & & \\ I_{3,1} & & \cdots & & \\ \cdots & & & \cdots & \\ I_{m,1} & & & & I_{m,n} \end{pmatrix}$$

$$f_{SSPCs} = \begin{pmatrix} f_{1,1} & f_{1,2} & f_{1,3} & \cdots & f_{1,n} \\ f_{2,1} & \cdots & & & \\ f_{3,1} & & \cdots & & \\ \cdots & & & \cdots & \\ f_{m,1} & & & & f_{m,n} \end{pmatrix} \quad (3)$$

Depending on the approach to approximate the PDF of every single load on the feeder, the feeder PDF will be of a certain kind. There are two options. All values can be taken to approximate the PDFs or the extreme values per flight hour. In [10] an approach by extreme value theory (peak per flight hour) has been chosen, based on a method applied in hydrology, see also [13], as it is the appropriate. For comparison reasons, both options are presented in section 4.4. Once the feeder distribution function has been established, the respective feeder limit based on all data, can be found by $1\text{-}P_{Ü} = 1\text{-}\lambda_R$, see also Figure 8.

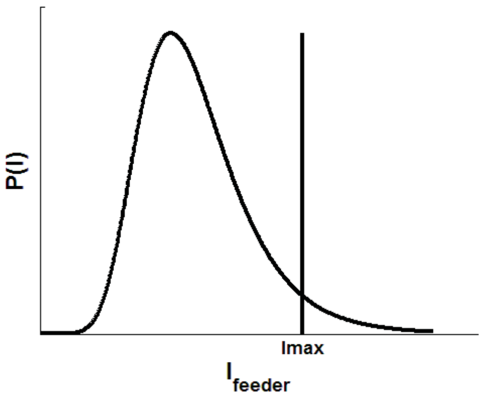

Figure 8: Example of resulting feeder PDF after convolution.

Important item to consider for proper application of the convolution is that the load-states, into which the systems are staged, have the same step size. That is, if load L1 is staged into 0.5 A, 1 A, 1.5 A plateaus with respective frequency of occurrence ("probability"), then all other loads Ln must follow the same step size. If not, the results of the convolution will be incorrect. For the below validation, the step size 0.015 was chosen which is 0.5 % of the lowest protective device rating used.

$$I_{rel} = \begin{pmatrix} I_{rel,1,1} & I_{rel,1,2} & I_{rel,1,3} & \cdots & I_{rel,1,n} \\ I_{rel,2,1} & \cdots & & & \\ I_{rel,3,1} & & \cdots & & \\ \cdots & & & \cdots & \\ I_{rel,m,1} & & & & I_{rel,m,n} \end{pmatrix} \quad (4)$$

Enabling the application of this approach to all cases and new configurations demands knowledge of the relative system consumption $I_{rel,}$ and probabilities f_{rel}, see equation (4). Once the relative information is available, this method is fully applicable. This data is being collected in side studies.

Prior to the application of the method, the major prerequisite, independence, is to be secured. Subdivision is made into two steps, check of inter-system dependencies as well as intra-system dependencies.

4.2. Inter-system dependency

Figure 9 and Figure 10 itemize major AC and DC cabin and cargo loads supplied by the Secondary power distribution boxes and sorted by installed power.

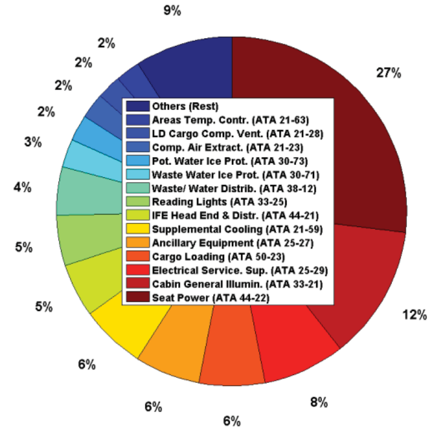

Figure 9: Overview of major AC loads in the cabin and cargo distribution system

For all systems which are explicitly mentioned as separate load in the pie charts, the dependency check has been carried out. Systems ATA 30-71 and ATA 30-73 state an exception as no recordings are available.

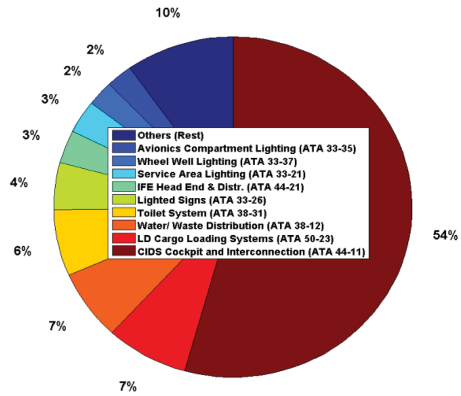

Figure 10: Overview of major DC loads in the cabin and cargo distribution system

In the tables below which hold the study results, numbers according to TAB 1 have been used to refer to the AC systems.

44-22	1	21-59	6	21-28	11
33-21	2	44-21	7	21-63	12
25-29	3	33-25	8	44-11	13
50-23	4	38-12	9	38-31	14
25-27	5	21-23	10	33-26	15

TAB 1. ATA-number assignment

Dependency can be shown by different methods whose application as cluster should be preferred due to the uncertainties in every single step. The used methods are:

1) Expert knowledge on implemented systematic dependencies
2) Constancy of power demand over whole flight
3) Correlation coefficients see [14],[15],
4) Visual check.

Initially, expert knowledge has been applied. TAB 2 and TAB 3 give the results of systematic dependencies. Most systems are independent. However, cabin lighting and reading lights are coupled. Reading lights are altered when cabin lighting is dimmed under a threshold.

Sys	1	2	3	4	5	6	7	8	9	10	11	12
1	-	I	I	I	I	I	I	I	I	I	I	I
2		-	I	I	I	I	I	D	I	I	I[4]	I
3			-	I	I	I	I	I	I	I	I	I
4				-	I	I	I	I	I	I	I	I
5					-	I	I	I	I	I	I	I
6						-	I[4]	I	I	I	I	I
7							-	I	I	I	I	I
8								-	I	I	I	I
9									-	I	I	I
10										-	I	I
11											-	I
12												-

TAB 2. AC systems - systematic dependencies[5]

Sys	13	4	9	14	15
13	-	I	I	I	I
4		-	I	I	I
9			-	I	I
14				-	I
15					-

TAB 3. DC systems – systematic dependencies[5]

Other dependencies could come in with cabin (area) temperatures as well as passenger behavior depending on the system function. A correlation test has been applied to detect these links. Prior to the correlation test, a system check on constancy has been performed. Systems that are constant[6] in power consumption all flight were excluded from the correlation test. Reading lights (ATA 33-25) and Compartment air extraction (ATA 21-23) can be declared constant (C).

Three correlation coefficients exist. Among them it is recommended to choose the Spearman rank correlation coefficient which discovers non-linearity and is robust against outliers. A second coefficient, the Pearson correlation coefficient discovers linear dependencies only and is not robust against outliers, see [14]. A coefficient by Kendall which also discovers non-linearity has a lower so-called test-strength than Spearman 0. Spearman is described to over-estimate the correlation coefficient if not all prerequisites are given. Monotony is one and is not always given. This will not lead to reliability issues as it rather detects positive dependencies where there is none. So the mistake made is acceptable. Some potential might get lost with this coefficient as it might not detect mutually exclusive behavior and makes it independent. After all studies in association with expert knowledge and visual check, it can be concluded that mutually exclusive load curves do not exist. Not even the cabin lighting system and reading lights show this kind of dependency, even though it could be expected. Thus, applying Spearman's rank correlation coefficient is valid. Its equation is given in (5).

$$(5)\quad r_s = \frac{\sum_{v=1}^{n}\left(R(x_v)-\overline{R(x)}\right)\left(R(y_v)-\overline{R(y)}\right)}{\sqrt{\sqrt{\sum_{v=1}^{n}\left(R(x_v)-\overline{R(x)}\right)^2}\sqrt{\sum_{v=1}^{n}\left(R(y_v)-\overline{R(y)}\right)^2}}}$$

with $R(x_v)$, $R(y_v)$ as the rank values of every value of x (system 1) and y (system 2) [15]. Equation (5) is the general form and does not require certain prerequisites for it to be validly applied.

Correlation coefficient $\lvert r_S \rvert$	Interpretation
0	No correlation
0-0.5	Weak correlation
0.5-0.8	Mid correlation
0.8-1	Strong correlation
1	Perfect correlation

TAB 4. Interpretation of correlation coefficients [15]

Strictly lived, any correlation coefficients unequal zero are to be interpreted for the systems to be dependent[7]. However, a weaker, more realistic, interpretation has been applied. Relevant literature categorizes the coefficients according to TAB 4. Thus, the following has been applied as dependency check:

1) $r_s \in (-0.5, 0.5) \rightarrow$ independent
2) $r_s \in [-0.5, -0.8) \rightarrow$ independent
3) $r_s \in [-0.8, -1] \rightarrow$ mutually exclusive
4) $r_s \in [0.5, 1] \rightarrow$ dependent

[4] Specific exceptions apply.
[5] (I=independent, D=dependent same direction, E=mutually exclusive).

[6] For the definition of constancy see appendix I.
[7] Provided, an accompanying test confirms significant deviation from zero.

Furthermore, the correlation coefficient has been applied to all flight phases. For every combination it has been derived over several lengths from 10 s, 30 s, 60 s, 300 s, 600 s, 1200 s, 1800 s, 2400 s, and 3600 s. This wide-spread assessment helped to get a handle on how correlation changes with correlation period. In particular, 10 s has been picked to see whether significant short-term dependencies exist, which should be taken into account for feeder sizing as the protective devices trip in an area of ms up to seconds. The period 30 s was chosen as DC currents with continuous operation from 30 s and higher are declared permanent loads. The same applies to 300 s for AC loads. 60 s state a proper size for some operations in systems like seat power where seat actuation use may last this long. Longer times might give clues if systems are equally driven by any cabin operations such as catering as well as dusk and dawn operations. It turned out that the short-term coefficients (10 s, 30 s, 60 s) extend over the whole coefficient area from approximately -0.9 to 0.9 for a great deal of investigated combinations and do not bring clear results for dependency categorization. Figure 11 and Figure 12 illustrate this by means of the correlation study between the seat power supply system (ATA 44-22) and the cabin lighting system as well as with the IFE head end distribution system.

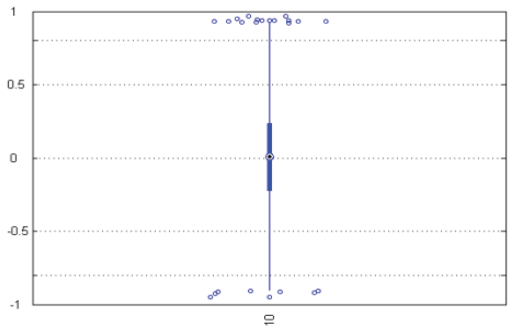

Figure 11: Correlation coefficients for ATA 44-22 with cabin lighting (10 s)

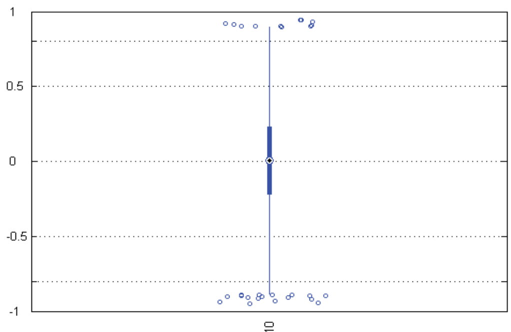

Figure 12: Correlation coefficients for ATA 44-22 with IFE Head-end distribution (10 s)

This unclear wide spread chances with coefficients from 300s and longer periods, see Figure 13 and Figure 14. By these values better differentiations are visible. For the final decision to declare two systems (in-)dependent an objective measure has been applied. If more than 5 % of all correlation coefficients per correlation length were ≥+0.5 the systems compared where declared dependent. This can be considered a conservative approach in favor of reliability.

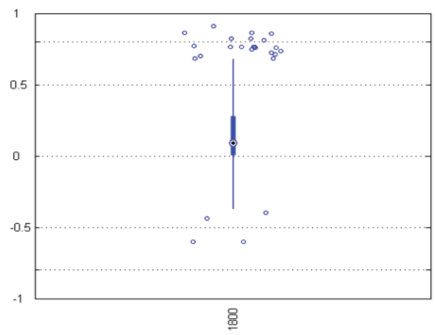

Figure 13: Correlation coefficients for ATA 44-22 cabin lighting (1800 s)

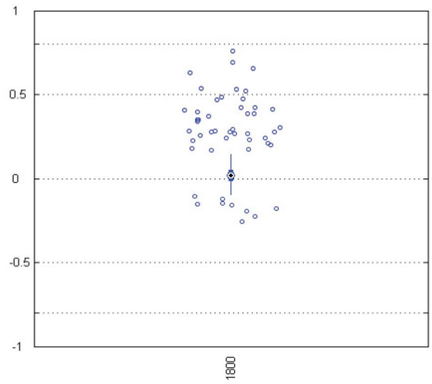

Figure 14: Correlation coefficients for ATA 44-22 with IFE Head-end distribution (1800 s)

Another major aspect to adapt the correlation periods is given by the fact that a flight is divided into 12 flight phases. These can be as short as some seconds (e.g. take off) and as long as some hours (cruise). Therefore, varying dependencies would be possible over the flight phases. Since in nearly all checks from 300 s and longer over all reasonable combinations hardly values above 0.5 occur, it can be concluded that there is no particular dependency between two systems in a specific flight phase. As this clear independence is not given for the seat power supply system and cabin lighting as well as the lighting system and a ventilation system, a closer look has been carried out. No center of gravity for a particular flight phase became visible.

Sys	1	2	5	7	8	9	10	11
1	-	D	I	I	C	I	C	I
2		-	I	I	C	I	C	D
5			-	I	C	I	C	I
7				-	C	I	C	I
8					-	C	C	C
9						-	C	I
10							-	I
11								-

TAB 5. Results of dependency study with Spearman's correlation coefficient - AC systems.

System	13	9	14	15
13	-	I	I	I
9		-	I	I
14			-	I
15				-

TAB 6. Results of dependency study with Spearman's correlation coefficient - DC systems.

The supplemental cooling system as well as the cargo loading system and the electrical service supply system should remain excluded from the correlation study up to now. The amount of data is by far less than the quantity of data for all the other systems as they are off during any other flight phase than ground and parking. Due to this reduced amount data, a valid comparison with other results is not expected.

However, expert knowledge definitely is sufficient for at least both the cargo loading system and the servicing. Cargo loading is not connected to e.g. passenger behavior in the cabin and the cabin's temperature as other systems (ventilation systems) in the cabin should be. Servicing (cabin vacuuming) is not carried out with passengers aboard and cleaning stuff will not be impacted by outside cabin temperature as it is regulated. A dependency of supplemental cooling on floor panel heaters may be possible as the heaters warm up the floor around the galleys. So, heating up the floor in the galleys might lead to more cooling of the trolleys. However, the measurements to floor panel heaters show a clear increase in heating power to the end of the flight in most cases, when supplemental cooling is reduced due to less food stored in the galleys. In association with expert knowledge they shall be considered independent of other systems. Also, ATA 21-63 was excluded from the correlation analysis as its function to cool is not steered by a current amplitude only but rather a quite constant absolute amplitude and a cyclic on/off rhythm. This is not comparable with the other load shapes.

Although both systems depend on different parameters, the cabin lighting system (ATA 33-21) on flight operations and night/day time and the ventilation system on temperature in the cargo compartment (ATA 21-28), a visual check confirms similarities between the cabin lighting system and the lower deck cargo compartment ventilation. Over a long period during flight, both systems show flat curves. Once temperature and pressure have settled in cruise, ventilation is constant. As soon as it is bright by day or dark on a night flight, the cabin lighting seems to be kept quite constant according to the measurements. Worse to feeder loading is, however, particularly after a night flight, when the aircraft descends cooling power must be increased and cabin lighting is regulated up for landing. Here the dependency is to be taken seriously.

The combined assessment of expert knowledge, Spearman's rank correlation and visual check are summarized in TAB 7 and TAB 8. If possible, a separation of the dependent systems by connecting them onto different feeders is recommended under limited resources.

Sys	1	2	3	4	5	6	7	8	9	10	11	12
1	-	D	I	I	I	I	I	I	I	I	I	I
2		-	I	I	I	I	I	I	I	I	D	I
3			-	I	I	I	I	I	I	I	I	I
4				-	I	I	I	I	I	I	I	I
5					-	I	I	I	I	I	I	I
6						-	I	I	I	I	I	I
7							-	I	I	I	I	I
8								-	I	I	I	I
9									-	I	I	I
10										-	I	I
11											-	I
12												-

TAB 7. AC combined dependency assessment

System	13	4	9	14	15
13	-	I	I	I	I
4		-	I	I	I
9			-	I	I
14				-	I
15					-

TAB 8. DC combined dependency assessment

4.3. Intra-system dependency

Besides an inter-system dependency check the connection of loads of the same kind has been looked at. This will be referred to as intra-system dependency assessment. For all systems, strong dependencies could be shown to other loads of the same function. It is, thus, recommended not to connect all loads of one system onto the same feeder under limited resources. The likelihood for an under-capacity to occur to that system rises with the amount of same loads on it. Also, the convolution is not applicable, addition is to be used.

4.4. Validation

In Section 4.1 two options to gain the supply line size were introduced. One option is to take all values to approximate the probability distribution functions, the second demands to take the peak values per flight hour, whereas the second one is to be preferred and the only appropriate according to relevant literature. For study purposes both options have been elaborated. TAB 9 and TAB 10 show the results.

Feeder	a	b	c	d	e	f
Reference	35	50	35	35	25	50
SSPCs	35	50	35	35	25	50
Feeder-All	35	50	25	35	25	50
SSPC-All	35	50	25	35	25	50
Optimum	35	50	35	35	25	50

TAB 9. Part 1 - Results feeder sizing (all currents are in A)

Feeder	g	h	i	j	k	L
Reference	50	35	50	50	50	35
SSPCs	50	50	50	35	50	50
Feeder-All	50	35	50	50	50	35
SSPC-All	50	35	50	50	50	50
Optimum	50	50	50	35	50	50

TAB 10. Part 2 - Results feeder sizing (all current are in A)

Line "Ref." (Reference) was gained by taking the actual feeder load, and then collect the peak values of every flight hour followed by shaping the PDF. The threshold at 11000 FH under-capacity rate defined the feeder size. This threshold has also been taken for the lines below. Line "SSPCs" were derived by applying the above method taking extreme values per flight hour and every single SSPC (cluster). Line "F-All" shows the results when all values at feeder level were taken to get a feeder sizing. Line "S-All" states all values of every single SSPC were taken.

Although not very clear in the table as the feeder can be selected in steps only, it became visible during the analysis that the current gained by taking all values were often much lower by some amps than the extreme value results. These results would have led to a high risk for power management activities if these deltas would have led to pick lower rating. Hence, it is not recommended to use those values for network sizing in actual application.
The sizing by extreme values on SSPC level remains. Due to the fact that the described approach cannot cope with effects that current might, by chance, cancel each other out at a certain point in time or add up, the results in line "SSPCs" deviate from those in line "Ref.". In the case of feeder h (I_Δ=7.4 A/I_{nr}=1.9 A)[8] and L (I_Δ=4.2 A/I_{nr}=2.9 A), the convolution approach would have demanded 50 A feeders, although 35 A would have sufficed. For feeder j (I_Δ=1.95 A/I_{nr}=0.9 A), a lower size than actually required would have been chosen. In case j, the risk for power management activities would have been slightly raised, see section 4.5. For feeder h and L the risk to go to a smaller feeder size could have been estimated and a decision made to go to 35 A.

Basically, the feeder size could be lowered to 25 A[9] on all feeder if one is willing to increase the risk for PM activities. For the assessment the empirical PDFs were chosen. Previous work showed that the fitting of extreme value distribution does not allow a general approach. Taking the empirical PDF has the disadvantage that, depending on the under-capacity rate, at least the number of flight hours is required which equals the under-capacity rate. If the fitting of deterministic PDFs was possible, an extrapolation could be considered, see [13]. Since mostly the correct or even higher feeder sizes were calculated, applying the method shall be considered valid. Line "Opt." (optimization) shows the possible new feeder sizes. Note, any decision to reduce the sizes requires more data.

[8] I_Δ=Delta between results /I_{nr}=Delta to next rating
[9] Lower limit due to protective devices in a row.

4.5. Risk of under-capacities in systems with limited resources

How much is the risk of an overload to happen at an under-capacity rate T = 1/λ_R = 10869FH ≈ 11000FH during a 5-hour flight, 15-hour-flight or any other realistic duration?

Answering this question is possible with the binomial distribution, see also [13]:

$$(6) \quad f(k \mid n, p) = \binom{n}{k} p^k (1-p)^{n-k}$$

with k as the number of under-capacity rates in n flight hours with an average under-capacity rate of p = 9.2e-5/FH.

So, the risk for the under-capacity event to occur at 11000 FHs at least once in an n-hour-flight is to be calculated, one must reckon 1-f(0|n,1/11000 FHs). If the probability 1-F(8|n,1/11000 FHs) for the under-capacity to occur e.g. 8 times during a flight with duration of n flight hours, the cumulative distribution function is required.

$$(7) \quad F(k \mid n, p) = \sum_{i=0}^{k} \left(\binom{n}{i} p^i q^{n-i} I_{(0,1,\ldots,n)}(i) \right).$$

The indicator function $I_{(0,1,\ldots,n)}(i)$ ensures that k only adopts values of 0,1,...,n [16]. Figure 15 shows for the under-capacity rate 1/11000 FHs the probability/risk for the event to occur in one flight on this one feeder.

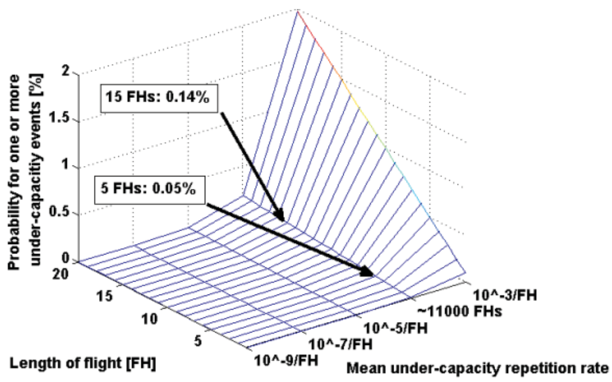

Figure 15: Probability for at least one under-capacity event over different mean under-capacity rates and durations of flight

The risk for a 5-hour-flight to run into at least one overload on a feeder is 0.05 % and for a 15-hour-flight is 0.14 % which is acceptably low. Was the average under-capacity rate lower or higher, the respective risk for an event to occur at least one time would change accordingly.
At an average repetition rate of 1000 FHs the risk for an event to occur on the feeder goes up to 0.5 % for a 5-hour flight. Figure 16 details the risk variation for a 5-hour-flight over the repetition rates.

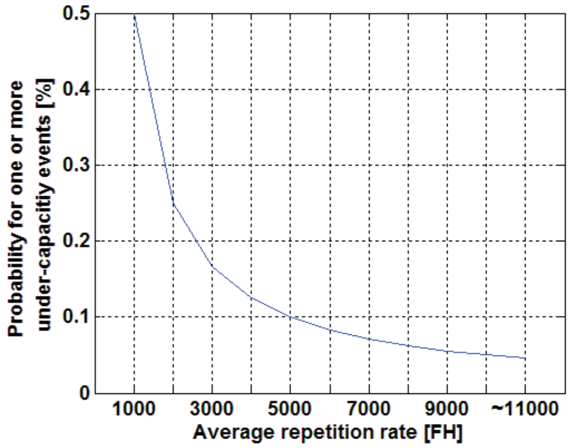

Figure 16: Varying repetition rate vs. risk of occurrence of 5-hour-flight

Depending on an acceptable risk the repetition rate can be increased. The increase is easier acceptable with the implementation of a smart power management. This would make sure that an under-capacity is neither detected by crew nor passengers. This compensates for the rest risk.

5. SUPPLY LINE POWER MANAGEMENT

A system with limited resources, the way it has been described above, requires a power management (PM) function. It will help to keep the protective device from tripping in under-capacity scenarios and thus keep actual reliability constant. Besides many others, the definitions according to Figure 17 shall be introduced and elaborated on below.

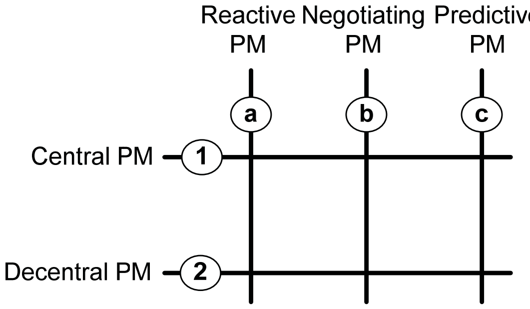

Figure 17: Power management definitions

On the one hand, power management controlled by a central unit/entity is imaginable. This unit receives the electrical current data of the level it is supposed to power-manage. When an under-capacity occurs it commences appropriate PM action. In order to handle appropriately, it collects all data of lower load levels and takes suitable action to clear it. After having made a decision, this central unit issues signals to lower the load. On the other hand, there are power management concepts with distributed computation power. There will be no central unit executing the full PM algorithm but many local units sharing the computation task.

"Reactive PM" describes a PM which only acts when the under-capacity scenario has happened while a proactive PM knows what is going to happen on the feeder e.g. by loads asking/signing up for power. If not enough power is available, loads will be set into waiting position. PMs exhibiting knowledge of what is going to happen on the feeder by having learnt shall be referred to as predictive PMs. A PM function allowing the change-over of loads to another phase of the feeder or even another feeder is a promising extension of any PM as it lowers the probability for visible under-capacities.

All PM options seem to have their own advantages and disadvantages. Some determining factors for which PM is best are given by limits of the electrical system to be managed.

5.1. System limits in brief

A major driver for response times of PM during under-capacities is the protective device on which the PM works. Response time demands anti-proportional reduction to over-installation. Previous results permit to take a 4-time over-installation as absolute upper limit with tendency to less. Lower factors appear to offer a reasonable trade-off result between weight savings, reliability, power management complexity as well as configurations efforts.

The respective response time drives the requirements of the communication path or, if it has been implemented by other decisions, it might be vice versa. Bandwidth restrictions would limit over-installation. Typical technologies on modern aircraft for mass data communication are the standard ARINC 664 (100 Mbits/sec), based on fast switched Ethernet or CAN [9]. Other, fuzzier restrictions are power management complexity (configuration efforts) as well as any action noticeable by the passenger.

6. SUMMARY AND CONCLUSION

For many years, efforts to optimize eco-efficiency and environmental protection have become ever more important to the aviation industry. The reduction of aircraft weight is one major task to support these efforts. One system whose optimization might contribute to aircraft weight reduction is the electrical system. Load measurements have shown potential to lower its system weight by a concept founded on both limited resources and power management.
This paper introduces a method to determine the reliability of such reduced network resources. It uses the fault trees for standard safety and reliability analysis. The fault tree is extended by a performance tree whose components can be calculated by convolution. It could be shown that very good and save results in terms of reliability can be gained. This method will allow to size feeder not on maximum power consumption anymore but optimized power values for non-flight relevant system and configurable systems. This will save weight. Mathematics is introduced which allows determining the risk for under-capacities during a flight for a given average fleet under-capacity rate.

As a power management is required, the paper closes with a section on PM. It looks at technical limits to be considered and described different PM concepts. There advantages and disadvantages depend on the limits the environment offers.

I. APPENDIX

A system shall be declared constant if delta power during operation divided by the maximum power under analysis is less than 5 %, results see TAB 11.

System [ATA]	AC/DC	Rated	Variation [%]
21-23	**AC**	constant	~0.45%
21-28	**AC**	not constant	~50%
21-29	**AC**	not constant	~50%
21-59	**AC**	not constant	~50%
21-63	**AC**	not constant	~70%
25-27	**AC**	not constant	~40%
25-29	**AC**	not constant	~35%
33-21	**AC**	not constant	~36%
33-24	**AC**	not constant	~25%
33-25	**AC**	constant	~3%
33-34	**AC**	not constant	~82%
38-12	**AC**	not constant	~50%
44-21	**AC**	not constant	~14%
44-22	**AC**	not constant	~9%
50-23	**AC**	not constant	~80%
33-24	**DC**	not constant	~11%
33-26	**DC**	constant	~0.016%
38-12	**DC**	not constant	~14%
38-31	**DC**	not constant	~38%
44-11	**DC**	not constant	~30%
50-23	**DC**	not constant	~55%

TAB 11. Constant and non-constant systems

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