EFFICIENCY OF THE ELECTRICAL SYSTEM ON LARGE MODERN CIVIL AIRCRAFT – STATUS QUO ANALYSIS

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Abstract

Aircraft development has the objective to achieve ever more efficient aircraft while maintaining safety, performance and functions. One main lever towards more efficient aircraft is weight reduction. First sporadic electrical loads measurements of the aircraft systems have indicated, that the available electrical network capacities aboard modern large civil aircraft are barely used. Follow-up measurements in the scope of commercial route proving and similar flights have reinforced the impression of a regular low network usage. A great deal of electrical system weight could be saved in an optimised electrical cabin and cargo network on large modern civil aircraft.

Based on these hints, this paper deals with three major items. **Firstly**, it shows the status quo of the electrical network usage. Then, it links this to the electrical load analysis as part of the electrical system design process. **Secondly**, the paper considers the prospective power consumption of More Electric and All Electric Aircraft and the impact on future electrical system architectures. **Thirdly**, this paper gives important measures for the decision making process in terms of new best system architectures. This paper does not intend to conclude on final implementations on the aircraft, as the amount of available data has been too limited so far.

1. ABBREVIATIONS

AC Alternating Current
A/C Aircraft
ADCN Avionics Data Communication Network
AEA All electric Aircraft
APU Auxiliary Power Unit
ATA Air Transport Association
C and C Cabin and Cargo
CFRP Carbon Fibre Reinforced Plastic
Comm. Communication
comp. Compartment(s)
Cond. Condition(s)
DC Direct Current
Distr. Distribution
ELA Electrical Load Analysis
Elec. Electric(al)
FH Flight Hour
FHA Functional Hazard Analysis
Flt. Flight(s)
hydr. Hydraulic
IFE In-flight Entertainment
IMA Integrated Modular Avionics
Man. Manoeuvre
MEA More electric Aircraft
Pax. Passenger(s)
PEPDC Primary Electrical Power Distr. Centre
SEPDC Secondary Electrical Power Distr. Centre
SPSS Seat Power Supply System
SSPC Solid State Power Controller
Sys. System(s)
Temp. Temperature(s)
TRU Transformer Rectifier Unit
U_{nom} Nominal Voltage
U_r Rated Voltage, also U_{nom}

2. INTRODUCTION

Aircraft (short A/C) development has the objective to achieve ever more efficient A/C while maintaining safety, performance and functions. One main lever towards more efficient A/C is the reduction of its weight.

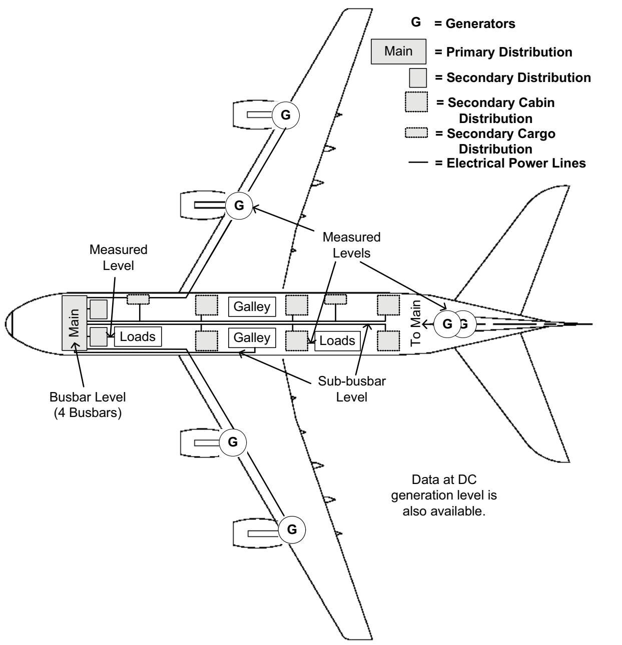

Figure 1: Architecture of the electrical System on large modern civil A/C

Sporadic measurements of the electrical consumers power demand have indicated that the available electrical network capacities are barely used for the A/C under analysis. Measurement campaigns around so-called commercial route proving flights have reinforced the impression of regular low network usage. Commercial route proving flights are part of the type certification process, a civil A/C has to successfully undergo before being certified for in-service operation. Those flights are carried out with realistic A/C configurations together along with realistic quantities of passengers and crews. Realistic routes are flown and airports landed on to prove the availability for use in-service. That is, for many A/C systems data close to reality with regard to system characteristic can be collected. That data will give a good starting point for investigations on system efficiency.

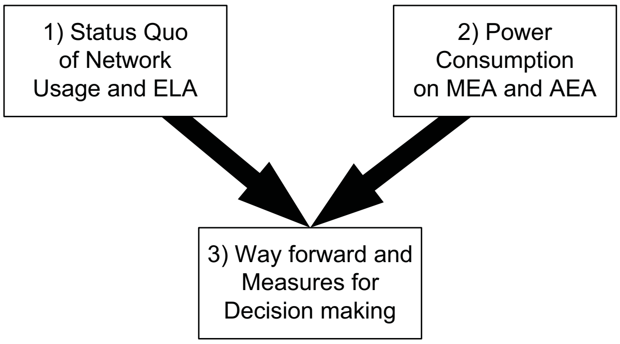

Figure 2: Scope of this Paper

One major intension of this paper is to show the actual situation of network usage. Due to the limited amount of data, it is to be seen as an introduction into further investigations. **Firstly**, it will describe the status quo of the electrical network usage based on the flights introduced above. It will also elaborate on the electrical load analysis as carried out today and has led to the status quo. The paper will hereby focus on the electrical consumers in the secondary cabin and cargo electrical power distribution system. Those are not required for safe A/C operation and landing, while making up a significant amount of the overall electrical power consumed. They would offer a great deal of potential for optimization, if a regular low network usage is confirmed by further studies. **Secondly**, the paper will elaborate on the prospective power consumption on more and all electric A/C , as future electrical network architecture concepts may have to allow for those kinds of A/C. **Thirdly**, this paper intends to give a way forward for the investigations to be done and important measures for the decision making process towards future electrical network architectures. Again, it does not intend to conclude on final implementations on the A/C due to the limited amount of data. Follow-up measurements on in-service A/C are being run increase the number of data.

3. THE ELECTRICAL A/C SYSTEM

Due to safety, reliability and other requirements, a system is not under-dimensioned. Rather they are over-dimensioned. A certain over-dimensioning, a margin, is acceptable as it helps to fulfil the upper requirements and makes the A/C future-proof. However, the degree of over-dimensioning is to be questioned.

3.1. Electrical System Architecture [1] [2]

Figure 1 shows a top view onto the A/C and the basic electrical system architecture. It consists of a normal and an emergency part. The electrical emergency system takes the power supply of safety relevant electrical systems over, in the unlikely event, the normal electrical system fails. It is neither shown in the figure and nor content in the discussions herein. The normal electrical system consists of four levels. Level one is the generation of electrical power. Four main generators in and driven by the main engines, deliver permanent power of up to *150kVA*[1] each at U_r*=115VAC.* Two main generators driven by the auxiliary power unit (APU) have similar power capacities and are mainly employed for ground operations.

The generators are directly connected to four main busbars. Those busbars are physically located in the main or primary power centre in the forward of the A/C. This forms the second level. Every time, a main busbar is connected to one generator only on this A/C. For segregation reasons, normally a busbar is connected to a generator of its own A/C side. In failure scenarios this can change. Transformer rectifier units (TRUs) with $U_{r,out}$=28VDC are also part of the main distribution.

Connected to the main busbars, is the secondary power distribution system, the third level of the electrical system. One distinguishes between the secondary distribution system for technical loads and the cabin and cargo distribution system. The secondary distribution system is typically connected to the primary centre by *15kVA* three-phase *115VAC* feeders and *50A 28VDC* feeders.

The fourth level is formed by the electrical loads. Heavy loads, such as the Galleys, which require currents of $I_r > 15A$ are directly connected to the primary distribution centre. Loads, which locally require currents $I_r \leq 15A$ are connected the secondary distribution system.

3.2. Electrical Load Analysis

Main design rules for the electrical system say that all four main generators must be able to supply the maximum permanent power consumption of all electrical loads at the same time within one flight phase. If one generator fails, the three remaining generators must be able to cover the so-called operational power. Except for some large intermittent loads, the distribution network is also sized against the maximum permanent power consumption. Table 1 gives an arbitrary example of how generation and distribution capacities are sized. **Note: Requirements on maximum voltage drop, mechanical burden of wires and brackets plus thermal heating of wires and bundles are considered for the sizing, too. In particular, voltage drop and thermal requirements significantly increase the network size.** Monitoring, protective and load management functions complete the electrical system.

System	Flight Phase 1	Flight Phase 2	Flight Phase 3
1	10kVA	10kVA	10kVA
2	10kVA	20kVA	15kVA
3	10kVA	20kVA	15kVA
All	30kVA	50kVA	40kVA

Table 1: Example ELA for Generator and Network Sizing

[1] Similar A/C exhibit generators with powers between *100kVA* and *250kVA*. The latter can be found on A/C, which rather use electrical than bleed-air (pneumatic) energy to run systems [2].

based on max. Power. Flight Phase 2 defines the design.

3.3. Status Quo Analysis

Prior to the work load analysis, this part shall introduce the systems, which require electrical power and the theoretical portions of the secondary C and C consumers in the ELA. As an overview at A/C level, Table 6 (appendix) gives all the A/C systems, which require electrical power. Figure 3 and Figure 4 show the portions of the main secondary C and C AC and DC loads. The Seat Power Supply System and the General Illumination System are main AC loads. The Electrical Cargo Loading System is a large intermittent load. Three main DC loads are the Cabin Management System (CIDS), the Water/Waste Distribution and Toilet System. According to the A/C ELA, together they make up about one third of the electrical A/C loads. Along with the Galleys[2], this even exceeds *50%* in some flight phases, which drive the design [3].

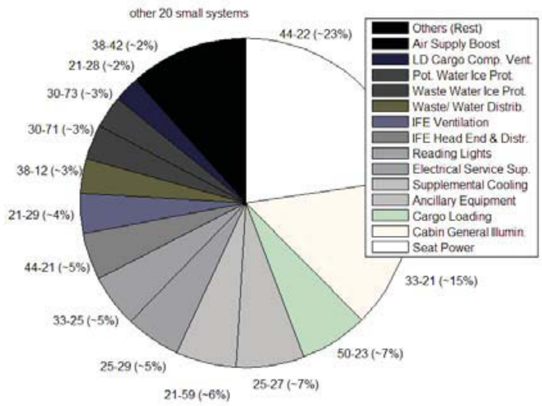

Figure 3: AC C and C Consumers - Theoretical Portions in ELA.

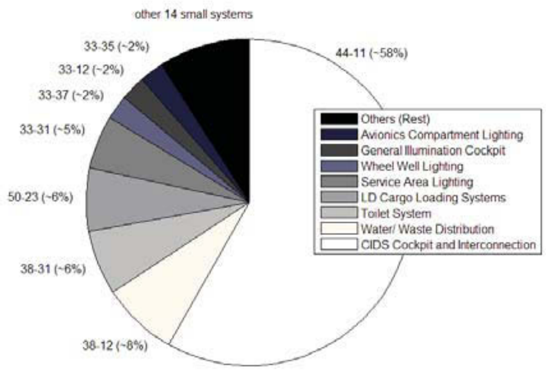

Figure 4: DC C and C Consumers - Theoretical Portions in ELA.

The same A/C and unchanged A/C configuration carried out all the flights used for this analysis. It was a fully equipped A/C with 3-class cabin layout, accommodating up to *519* passengers. Due to installed measurement equipment, approximately *500* passengers could be transported [4]. The quantity of passengers during the flights varied between *23* and *472*, see Table 2. With the flight hours type definition

- NF: Night FHs (0h-06h of origin)
- MF: Morning FHs (06h-12h of origin)
- AF: Afternoon FHs (12h-18h of origin)
- EV: Evening FHs (18h-24h of origin)

one can see, that all types of FHs (day-light, morning, evening and night FHs) are represented in the set of data.

Flt./Pax.	**Date**	**From (Time Origin) – To (Duration)**
23/58	**17.03**	**Toulouse (8:55h) – Frankfurt (3h)**
24/458	**19.03**	**Frankfurt (8:06h) – New York (9:25h)**
25/23	**20.03**	**New York (10:22h) – Chicago (3:38h)**
29/439	**23.03**	**Frankfurt (18:12h) – Hong Kong (11:36h)**
30/111	**24.03**	**Hong Kong (13:22h) – Hong Kong (4:30h)**
31/362	**25.03**	**Hong Kong (8:20h) – Frankfurt (14:24h)**
33/172	**26.03**	**Washington (9:44h) – Washington (4:03h)**
34/472	**27.03**	**Washington (20:57h) – Frankfurt (8:40h)**
35/235	**28.03**	**Frankfurt (9:05h) – Munich (2:42h)**
36/95	**28.03**	**Munich (16:06h) – Toulouse (2:25h)**

Table 2: The ten Flights (of MSN 7) under Analysis

For the following load over time plots, the flight phase definition according to Table 3 is required.

FP 1: Preflight	FP 7: Climb – Step 2
FP 2: Taxi out	FP 8: Cruise
FP 3: Take off – Step 1	FP 9: Approach
FP 4: Take off – Step 2	FP 10: Landing
FP 5: Take off – Step 3	FP 11: Taxi in
FP 6: Climb – Step 1	FP 12: Postflight

Table 3: Flight Phase (FP) Definition

3.3.1. Load Analysis at Generation and Conversion Level

Despite this paper's focus, the first figures will show the loads curves at AC and DC generation level, to understand the overall load behaviour. The figures will be followed by plots, which include the load curves of all flights. The figures will unveil the actual usage of the different capacities and, in particular, an interesting load resemblance (similar characteristics) between the flights. Eventually, plots of the different distribution levels are given.

Figure 5 shows the load at main, APU and external power generation level for a full flight with 439 passengers. Prior to the flight, the APU generators power the A/C. Around the end of flight phase 1, the electrical network was transferred to main generator power. A short period after landing, the APU generators are used again. Then airport ground power is activated. In other flights, this order can change. Although, the quantity of passengers was more than half of this A/C's maximum passenger count[3] and major A/C and cabin and cargo systems were installed, the main generators were constantly loaded between *~10%* and *~25%* only. No clear peaks can be noticed during that phase. If this can be confirmed by a higher quantity and better quality of in-service measurements, the main

[2] Galley measurement data and data of the primary cabin and cargo loads are not available for this status quo analysis.

[3] Maximum possible passenger count 853 [6],

generator load phases might be declarable as very predictable load and “easy” for optimisation. The external power supply load strongly varied between *~30%* and *~100%* of the permanent load limits. It is not as constant as in the main-generator-phases. Explanations for this load characteristic certainly include the operation of the electrical cargo loading system on ground. The APU generator plots show a similar load characteristic as the ground power supply plots, loaded between 40% and 83% of the permanent rating.

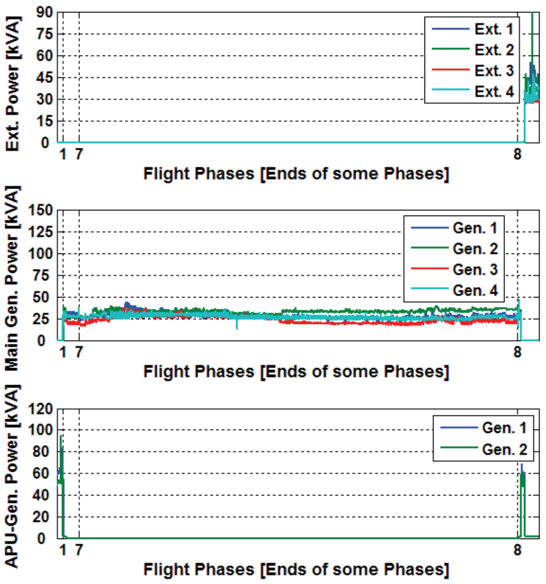

Figure 5: Power at AC Generation Level for Flight "29" with 439 passengers aboard.

The overall power is given in Figure 6 and Table 4. It varies between *~70kVA* and *~200kVA* on ground with average power consumption at *~110kVA*. This is *18%* of the overall maximum permanent power, the main generators can sustain. Considering the configuration and the quantity of passengers flown, the power consumption is lower than expected. The two main observations can be summarised, preliminarily, as a very low absolute load, lower than expected and there are very inconstant loads on ground and some very constant loads once the A/C is ready for flight/moving.

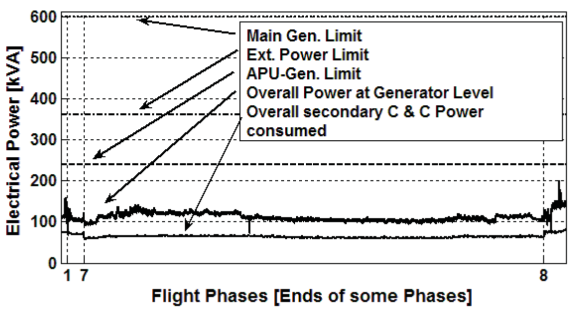

Figure 6: Overall Power Consumption at Generation Level plus Limits and secondary C and C Power Consumption.

Figure 6 also shows the actual overall secondary cabin and cargo power demand over the flight. This curve includes DC power, which has been incorporated by taking the TRU power factor and TRU efficiency into account [5].

FP	Min. [kVA]	Max. [kVA]	Delta [kVA]
1	108	160	52
2	**67**	135	68
3	105	123	18
4	115	119	4
5	114	116	**2**
6	107	116	9
7	97	113	16
8	71	141	70
9	107	114	7
10	106	125	19
11	90	129	39
12	91	132	41
1	77	**201**	**124**
Mean/Std.	111.6/10.1 kVA		

Table 4: Power Consumption in Flight "29"

The average load of the secondary cabin and cargo loads, which is without the Galleys, makes up to *~60%* of the overall power consumption. Due to the fact, that the electrical power consumption is gained by summing up SSPC[4] values, the real power value tends to be lower. A first estimate of the power consumption of all secondary cabin and cargo loads is *50%*, as the mainly resistive or capacitive loads are installed in the C and C perimeter. An analysis is being carried out. Together with the Galleys, when the are on, the power consumption then is higher than *50%*. The commercial consumers dominate the power demand.

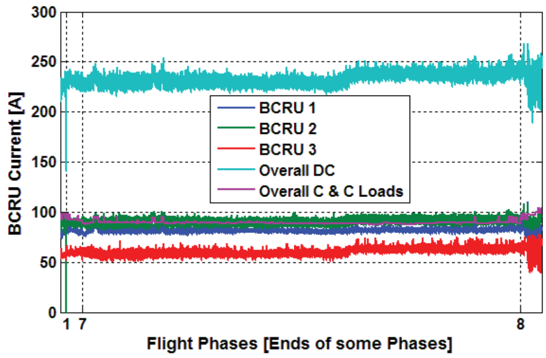

Figure 7: Currents at DC Generation Level (standard deviation = 160W at overall DC Level).

The overall A/C DC and (secondary) Cabin and Cargo DC power demands are given in Figure 7. The curves exhibit very similar and flat characteristics over the entire flight. It is interrupted by a power increase in the middle of the flight during cruise and a wider load band during approach, landing and taxi in and post flight operations. The reason for the two exceptions is to be investigated. The overall DC power varies around a mean value of *6521.2W* and a standard deviation of about *160W=2.5%* of the overall DC power. As the maximum DC power the TRUs (named BCRUs) can deliver is *~25kW*, this configuration requires *25%* of the DC A/C capacities. Converted into AC, the DC power ends up to load the generators by *6521.2W/0.9=7246VA*, which is about *6.5%* in average of the overall power demand. As the DC at DC generation

[4] SSPC = Solid State Power Controller (Switching and protective device sec. C and C output level, see appendix I and Figure 1).

level is a very constant load and is about *6.5%* of the practical and less than *5%* of the ELA overall power consumption, plus, it has a very flat curve, it does not seem to be suitable for an active power management at generation level. However, later at cabin level one will see that the DC power shows large potential for an "off-line power management". It seems, that the network is strongly oversized and a better electrical load analysis is required. At distribution level (wiring) the DC loads are to be kept in mind. The DC feeder state 1/3 of the overall secondary distribution network weight by 5% load share.

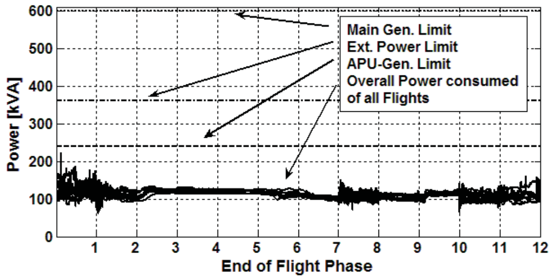

Figure 8: Overall Power at AC Generation Level of all Flight in Table 2.

Figure 8 and 9 show the power demand at AC generation and DC generation level of all flights. The AC loads show a mix of deterministic characteristics, occurring in many airborne FPs and stochastical forms on ground and in cruise. The characterisation of them is one task to be carried out. However, all flights have contents with similar load behaviour. The DC load at generation level again exhibits a flat curve over many flight phases. It shows similar characteristics, such as typical humps, slop drops as well as wider load ranges on ground. These recurring characteristics may make the analysis more secure in terms of network design as the load behaviour may partly become predictable.

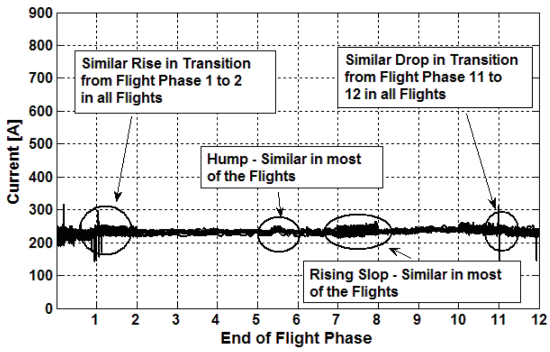

Figure 9: Overall DC Power at DC Generation Level of all Flight in Table 2.

3.3.2. Load Analysis at secondary Cabin and Cargo Level

The Seat Power Supply System, which has its own sub-busbars (feeders) has mainly got the task to bring electrical power to the seats for laptop power supplies and the in-seat IFE equipment, such as screens. In figure Figure 10 one example of their load curves is given. Mainly a basic load drives the characteristic, as the curve is very flat. This is caused by the in-seat IFE equipment as there are data routers and the screens, that need to be kept alive or on "standby". The other SPSS feeders exhibit the same characteristic. On the other AC sub-busbars another two, very different, characteristics show, see also Figure 10. The feeder supplying some parts of the air-conditioning system (supplemental cooling) and reading lights has a high current at the beginning of the measurements on ground and then drops for the flight as the supplemental cooling system is not supplied by the secondary C and C system during cruise. The third sub-busbar characteristic is an oscillating curve lingering around one mean value at *~5.5kVA*. This curve is mainly driven by ventilation and heating systems, which go on and off cyclic-wise. The DC load characteristic is flat during the flight and higher on ground.

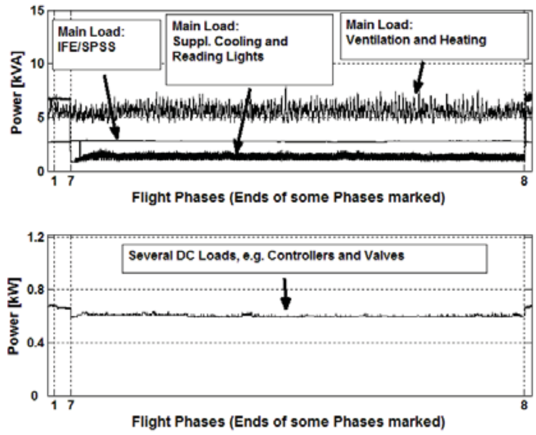

Figure 10: Examples of Sub-Busbar Loads (15kVA/1.1kW) - 4 typical Characteristics show.

The DC power consumption may be higher on ground as the e.g. cargo loading system controls and the wheel well lighting for example are on. The three different AC and the DC characteristic(s) show, that is it not possible to give all-applying statements for network optimisation at that sub-busbar level as the times and amplitudes of the power consumption clearly depend on the kind of loads connected to them. That is, a load analysis has to consider the actual loads, to be valid.

Figure 12 to Figure 15 (all in appendix) give the load curves of all flights for the sub-busbars introduced in Figure 10. One can see the very similar shapes throughout all the flights. Except for some short peaks in cruise the loads on the IFE/SPSS feeders are similarly flat and differ by *200VA* between the flights, although the passenger quantities start from *23* and go up to *472*. Similar can be seen for the other two feeders. That indicates, that if the system behaviour is well described, a clear picture of the load may be gained and the actual currents, that can occur may be well-predictable. The better the load characteristic can be established, the better the network can be optimised at high availability.

3.3.3. Coincidence Factor

The coincidence factor is a common method for the analysis of the electrical load in electrical systems. With P_{max} as the maximum power measured and $P_{max,v}$ as the maximum registered power per system v the coincidence factor is defined according to [7] as:

$$(1) \quad g_f = \frac{P_{max}}{\sum_{v=1}^{n} P_{max,\ v}}$$

To get an impression of how the different electrical system levels are loaded, the coincidence factor has been identified for different secondary cabin and cargo distribution levels. They refer to the A/C configuration under analysis and are given in Figure 11 for the sub-busbar level as box plot. The central mark is the median, the edges of the boxes are the 25th and 75th percentile of the g_f the whiskers extend to the most extreme data points, outliers are plotted individually.

The figures show the coincidence factors on:

1. secondary C_C sub-busbar (feeder) level for the left A/C side (side 1),
2. secondary C_C busbar (portion) level,
3. secondary C_C A/C side level and
4. secondary C_C A/C level.

For the AC feeders/busbars phase A is given only[5]. It has been established flight phase independent. That is, one coincidence factor per flight and the respective distribution level exist. The x-axis in the figures shows the enlisted distribution levels, the y-axis shows the coincidence factor g_f. The vertical spread in the factors is caused by the factors of all ten flights under analysis.

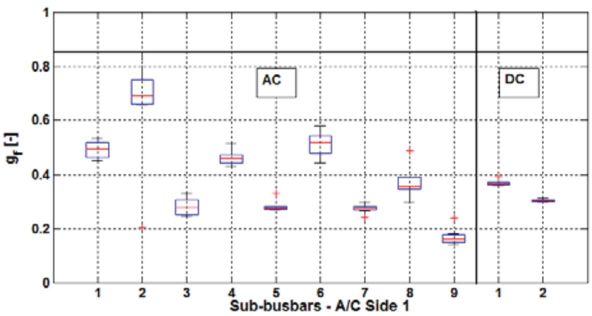

Figure 11: Coincidence Factors on AC and DC Sub-busbars (15kVA/1.2kW) for all Flights.

The coincidence factors at sub-busbar level clearly indicate that no common g_f at that level can be identified for the set of data, as the factors g_f vary between *0.1* and *0.9*. It so seems, depending on the load connected to them, they can take all values between 0 and *1*. However, most of the feeders exhibit $g_f \leq 0.6$. If this was directly translated into smaller feeders, taking all wiring sizing requirements, such as voltage drop and thermal heating, into account, the secondary cabin and cargo distribution network could be reduced by a **minimum** of 50kg [8]. This is a value, which justifies further investigations. If one is inclined to find a common coincidence factor, this may be possible for the DC feeders as they show values ≤ *0.4* on all levels.

At "cabin and cargo busbar" level and higher, the coincidence factor stayed below *0.5*, which is, most likely, caused by the wider mix of different loads, with different characteristics. As those coincidence factors are without the technical loads they cannot be applied to the whole A/C electrical system. However, they show a tendency, the higher the distribution level, the stronger the effect of none-coincidence. At higher levels the potential for weight optimisation is strongly given by the mix of different loads.

[5] Phase B and C show a similar spread of factors.

After the described, two conclusions are possible. There is no common coincidence factor to be applied at AC sub-busbar level other than g_f*=1*, without close consideration of the actual downstream loads. For higher (C and C) AC distribution levels and the DC feeders, there seems to be a maximum coincidence factor around *~0.45* establish-able. **However, as the A/C is a relatively small electrical network** and the respective mix of loads can change very easily in such a small network **it is not recommended to apply the coincidence factors** again without close consideration of the A/C load mix. Nevertheless, there is a clear tendency of falling g_fs with higher distribution levels and indicates, that the usage of larger wires, with higher capacities than *50A* may lead to an over-proportional reduction of A/C weight due to the coincidence effect. This part shows that feeders greater than *15kVA* should be investigated as benefit for future A/C electrical distribution systems. It also shows that a load characteristic investigation on system level is unavoidable. **Follow up activities are to focus in system level and load characteristic studies.**

3.3.4. Availability besides Safety and Reliability

For electrical network optimisation, one will have to look at availability, reliability and safety. During A/C system development, every system on the A/C will undergo a safety assessment. This assessment is to identify system failure conditions and their effects on the A/C safety. Then the system is classified accordingly. If, for instance, the failure conditions lead to the loss of the A/C, it is classified as catastrophic. If it has no safety effect, it is classified accordingly. There are five levels of classification as given in Table 5 along with the development assurance level, which the system development has to follow after classification. Also the different parts of the electrical system are rated according to these levels [2]. Any solution, which aims at optimising the capacities of the electrical system, must not conflict with these safety requirements.

Failure Condition classified	Development Assurance Level	Probability per Flight Hour
Catastrophic	A	$< 1 \times 10^{-9}$
Hazardous/Severe	B	$< 1 \times 10^{-7}$
Major	C	$< 1 \times 10^{-5}$
Minor	D	None
No safety effect	E	None

Table 5: System Safety Classification and Development Assurance Level.

While trying to optimise the electrical system by adapting the capacities to the actually required ones, one encounters the word availability. A reduction of the network capacities theoretically leads to a reduction of the availability of the systems connected to it. The theoretical availability drops below *100%*. One major step prior to the actual optimisation will be to define the availability required for a certain distribution level or system. Broad literature research has always led to the following common definition of availability [9].

(2) $$Availability[\%] = \frac{T_{avail}}{T_{avail} + T_{unavail}} \cdot 100\%$$

Availability is the period of time T_{avail} the system is functioning divided by the period of time the system is functioning plus the period of time $T_{unavail}$ it was out of order. This definition shall be used in all following activities. The availability shall not be confused with the (dispatch) reliability. The (dispatch) reliability is the quantity of flights a flight had to be cancelled, postponed (by *15* minutes) or the quantity of unplanned landings out of *100* flights. In order to determine the system availability after network optimisation one has to consider three kinds of system interdependencies[6] [10].

1) The operation of one system causes a second system to operate, e.g. the activation of a controller (event A) causes the activation of its fan cooling it (event B). This means for the conditional probability to be

(3) $$P(B \mid A) = \frac{P(A \cap B)}{P(B)} = 1$$

with the probability *P(B)=1* for the fan to go on, when event A has occurred.

2) The operation of two systems are mutually exclusive (e.g. heating and cooling on the same environment). Then, this

(4) $$P(B \mid A) = \frac{P(A \cap B)}{P(B)} = 0 = P(A \mid B)$$

applies.

3) Two systems operate independently (e.g. waste water ice protection and IFE usage). Then *P(B|A)=P(B)* and *P(A|B)=P(A)* is valid and

(5) $$P(A \cap B) = P(A) \cdot P(B) \in (0,1)$$

applies, with *P(A)* for the first system to be on and *P(B)* for the second system to be on.

In case 1 the supply capacities for both systems are to be provided. This is covered by today's ELA. In case 2, capacities for the system with the higher power demand would have to be provided only. This case is partly implemented by building the ELA flight phase by flight phase, but not fully considered within one flight phase. In case 3, the capacities according to the required availability would have to be provided. This case has not been considered at all today.

3.4. More and All Electric A/C

The term More Electric A/C (MEA) basically refers to the objective to replace the hydraulic and pneumatic systems by electrical ones. These efforts may end up in an All Electric A/C (AEA)[7]. On the A380 the third hydraulic power circuit has been replaced by back-up actuators powered electrically. It can be considered as a more electric A/C. The modification of A/C systems, whose functions are strongly driven by the use of engine bleed-air, towards an electrical version without bleed air supply, would be a major step towards the AEA. The reason for this approach is the impact on the specific fuel consumption of the engines caused by the pneumatic power off-takes. Mechanical power off-takes, e. g. to run the electrical power sources, only extract the required power, taking into account the efficiency of the conversion from mechanical to electrical power [2], [11], [12], [13], [14], [15].

On MEA and AEA the ECS and the wing-anti ice may more or less be implemented without the usage of bleed-air. One implementation solution of the ECS may be electrically driven compressors, which e.g. pressurize the cabin air. The outside air is conducted into the compressor, which will then provide pressurized air to the respective areas on the A/C. For instance, the cabin altitude/pressure is typically regulated between the pressure on ground and at *~8000ft* during flight, see [2] page 285. When the A/C takes off, a difference between outside air pressure and cabin pressure shows. In cruise the difference will reach its maximum the compressor has to deal will with. This is, when the compressor consumes the maximum electrical power. In descent the cabin altitude is slowly brought back to ground pressure. In all other flight phases the pressure difference will be lower and the compressor will consume less power. Within one flight phase and when the A/C altitude is kept constant, the compressor power will approximately be at a constant level. That is, from the electrical system point of view, the compressor must be considered as permanent load. They can consume a significant amount[8] of electrical power.

The wing anti-ice system, if implemented electrically, may be realised by electrical heating mats integrated in the wing leading edge. Their electrical power demand can be around *100kVA* [2]. As they operate in humid altitudes they can be considered as cyclic intermittent loads, which is by definition a permanent electrical load.

Also, on modern long range A/C hydraulic engine driven pumps can be replaced by electrical ones, which can make up to some *100kVA* intermittent loads. Other loads can be added. This all means, that future electrical system would have to deal with a significantly higher amount of electrical consumers both permanent and intermittent loads.

3.5. Assessment Criteria for new Architectures

Paragraph 3.3 has indicated potential to optimise the electrical system. With or without the confirmation of the

[6] For this first introduction of system interdependencies the systems shall either be on or off. When the system is on, it shall be considered as the event A for system 1 and event B for system 2.

[7] Note: Mature technologies needed to make the AEA an operation success will not be ready before another some years.
[8] Values can go up to *500kVA* at A/C level [1].

status quo by further investigations, if new system architecture is developed it needs to be assessed. For the identification of the best architecture, measureable assessment criteria, as the following list, are required [16]:

1. System Safety and Reliability requirements met?
2. System weight
3. System costs
4. System volume for installation purposes
5. System installation and maintenance efforts
6. System flexibility for customization with minimum efforts
7. System complexity
8. System impact on other A/C systems
9. CFRP suitability
10. MEA and AEA suitability
11. Fuel Cell suitability
12. System certification requirements met?
13. Electrical consumer availability
14. Another commercial criteria

Depending on the weight of every single criterion, another best architecture may turn out.

4. SUMMARY AND CONCLUSION

Aircraft development has the objective to achieve ever more efficient A/C while maintaining safety, performance and functions. One main lever towards more efficient A/C is the reduction of its weight. Load measurements around so-called commercial route proving flights have indicated that the available electrical network capacities aboard modern large civil A/C are barely used. So, this paper has elaborated on three major items:

1. Status quo analysis of network usage and link to today's design rules,

2. prospective power consumption of more/all electric A/C and impact on future electrical network architecture,

3. measures for decision making of future architectures.

Focus of all analyses was the secondary cabin and cargo distribution network. The analysis has enforced previous impressions of low network usage. Especially the derivation of coincidence factors for the secondary cabin and cargo consumers on different distributions levels has shown this. These factors applied to the network-design driving consumer configurations would mean **an estimated weight saving of minimum 50kg in the secondary cabin and cargo distribution network only**. However, prior to any realisation of the weight saving, more studies have to be carried out to confirm these results.

The coincidence factors were analysed for several distribution levels. At 15kVA/1.4kW level (50A sub-busbars) the coincidence factors varied between 0.1 and 0.9, most were below 0.6. At higher distribution levels, they stayed below 0.45. This pointed two things out. The coincidence factor is no reliable size to apply at sub-busbar level for future network design, as it strongly depends on the load connected to the sub-busbar. For higher levels, with a broader mix of loads this seems different. As the A/C is still small in terms of electrical network size, **it is still not recommended to apply the coincidence factor**. Also, the results given above with regard to absolute **values cannot be used for network optimisation** as they refer to a certain configuration only. Again, the studies have to be repeated on a set of different configurations, flight routes, airlines, cultural areas the airplane in employed, etc. **Follow up studies are to focus on the system level and load characteristic.** Does the load act as assumed? E.g. parts of the IFE system, the Laptop supply, are not used as extensively by the passenger as expected.

The analysis showed that the power consumption at AC generation level varied between *10%* and *25%* of the permanent generator capacity in the analysed. Over long periods during the flight, in particular the secondary C and C the loads, remained constant. On ground, when either ground power or APU power are used, the overall power consumption started varying. Loads, such as the electrical cargo loading system, which is operated on ground only, cause this. The DC loads, make up about *6.5%* of the overall measured A/C power consumption and about 5% of the theoretical consumption in the secondary cabin and cargo load sector. They exhibit a very flat power characteristic throughout the whole flight. Except for some peaks, the absolute power consumption is lower than expected for the A/C configuration analysed.

This, among other reasons, is also caused by the certification requirements. A new design based on measurements plus reasonable margin is being investigated. Tendency today is, that this can only come in combination with a power management, which keeps the load under the generation limit in no-failure conditions. Due to their characteristics, **the DC loads can be ruled out for the employment in a Power Management concept at AC generation level.** Including them is not worth the effort. However, their requested power demand is to be provided. A closer look is recommended at distribution level as the DC sub-busbars are heavy. They represent 1/3 of the overall secondary cabin and cargo distribution network on the A/C under analysis by only 5% power share. **That is, at distribution level AC and DC loads are to be included in further analysis.** This is sustained by the low coincidence factors of the DC lines. **Due to their mainly flat characteristics, all secondary cabin and cargo loads show a tendency to a peak load power management concept,** which suppresses unlikely load scenarios.

The overall power consumption of the secondary cabin and cargo loads make up to *50%* of overall power. **Their power consumption across all flight showed a high resemblance.** This statement applies to all distribution levels. This tendency, if confirmed in sufficient studies, can ease the steps towards optimised electrical network architecture. At sub-busbar level four main characteristics could be identified, which indicated that this level is strongly driven by the types of their downstream loads. Again, for a useful analysis, the actual load characteristics must be looked at. Considering higher levels only is not sufficient.

If the network design shall take place by using real measurements plus certain margin, a so-called system availability analysis gains importance, **as the theoretical system availability will drop below *100%*.** The new availability will still have to meet very challenging A/C specifications. For a starting point, this paper proposes a general definition of availability for further investigations and determines the possible system interdependencies. **These are required for an availability analysis based on measurements** and partly stochastical approach. Today's electrical load analysis does not consider all three types of interdependencies and thus offers a potential for network optimisation.

More and All electric A/C tendencies can have a great impact on the power demand, both on intermittent and permanent load side. This may have to be respected in future architectures as well as **other criteria given in this paper.** Depending on the weight for a criterion, different best architectures may turn out.

The **way forward** should encompass three items:

1. Load (dependence) analysis on system level, incl. availability analysis,
2. Architecture analysis,
3. Load management concept analysis (incl. new ELA approach).

I. APPENDIX – DEFINITIONS, FIGURES AND OTHERS

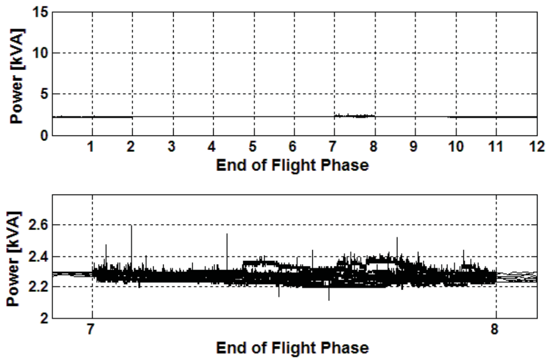

Figure 12: Overall Power in IFE/SPSS Feeders of all Flight under analysis.

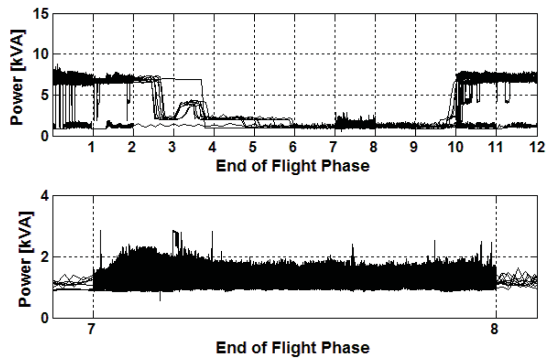

Figure 13: Overall Power on Supplemental Cooling and Reading Lights Feeders of all Flights under analysis.

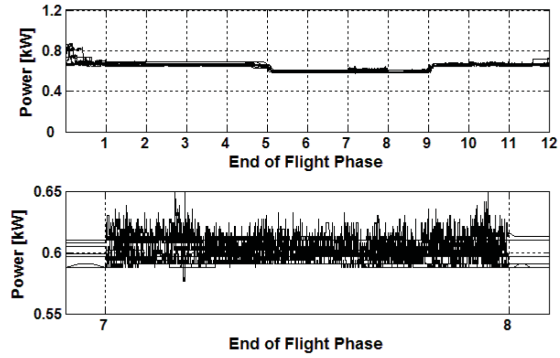

Figure 14: Overall Power on Ventilation and Heating Feeders over all Flights under Analysis.

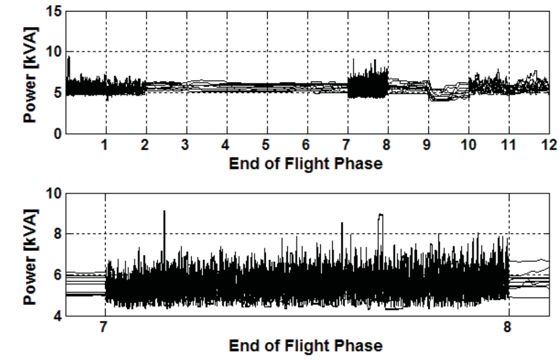

Figure 15: Overall Power on DC Feeders over all Flight under Analysis.

Figure 1 in chapter 3.3 shows the points where currents or power were measured. The data was recorded at generation/conversion and secondary cabin and cargo distribution output level (SSPC level). As the generator-power and TRU-currents were measured directly at that level, the values are correct rms-values for the respective level. The SSPC currents were summed up for higher levels. As the SSPC measures the current amplitude-correct only and following equation applies:

$$(6) \quad |\underline{I}_{act}| \le |\underline{I}_{SSPC,1}| + |\underline{I}_{SSPC,2}| + \ldots + |\underline{I}_{SSPC,n}|$$

the actual currents I_{act} on any higher level is either equal to (for resistive loads) or less (for complex loads) than the calculated ones. This is no safety issue but cuts optimisation-margin down, as the calculated currents may be significantly higher than the true ones. The measurement error of one current sensor device (SSPC) used applied is $\pm 10\% \cdot I_{rated}$.

System (ATA)	Function| Dependencies
Air-Conditioning (21)	Air-conditioning of cabin, cockpit, comp.| temp., pressure, humidity
Communications (23)	Data/Voice and Satellite Comm. Cockpit to Ground| Flight Man.
Electrical System (24)	Monitoring, Network and Power Management| System On/Off
Equipment and Furnishings (25)	Galley and elec. Supply, Cockpit and Cabin Crew Foot Warmers Elec. Stowage comp., Elec. Service Supply, Emergency Sys.| Operations, Outside Temperature Emergency Situations
Fire Protection (26)	Monitoring and Valve Control| A/C Power on/off and fire occurrence
Flight Controls (27)	Movement and Control of Aileron, Rudder, Elevator, Stabilizer, Flaps, Slats, Spoiler| Flight Man., Phase, Weather Cond.
Fuel (28)	Fuel Pumps and Management| Flight time and Man.
Hydraulic Power (29)	Supply of hydr. Power| Usage of hydr. Power, Flight Man.
Ice and Rain Protection (30)	Anti Ice Systems| Air Temp. and Humidity
Landing Gears (32)	Motion/Braking/Steering of A/C on Ground| Flight Man. and Phase
Lights (33)	Cabin/Cockpit/Comp./Exterior Lights| Day Time, Flight Man., Op.
Oxygen System (35)	Supply of microcontrollers and valves| Power on/off and when oxygen is needed in decompression for valves
Water/Waste (38)	Potable Water Heating and Disposal| Air temp. and usage by Pax.
IMA and ADCN (42)	Supply of network switches and I/O modules| Power on/off
Cabin Systems (44)	Cabin Management, IFE, Internet, Telephone for Pax.| Power on/off, Pax. behaviour, cabin crew activities
Information Systems (46)	Air Traffic and Maintenance Information Exchange| Flight Phase and Man.
Cargo and Accessory Compartments (50)	Elec. Cargo Loading, Some Lights for lower deck Comp.| Usage of Cargo Loading Sys.
Others systems with system parts requiring electrical power	Auto Flight (ATA 22), Navigation (34), Indicating and Recording Systems (ATA 31), Pneumatics (ATA 36), Engines General (70),

Table 6: Overview of electrical Consumers at A/C Level.

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