Thesis for the Degree of Bachelor of Science in Engineering -
Aeronautical Engineering 15.0 credits

DESIGN AND IMPLEMENTATION OF
ELECTRICAL LOAD ANALYSIS FOR
CROSS FLEET CONFIGURATION

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Abstract

When aircraft are subject to modifications, the Electrical Load Analysis (ELA) must be updated. Having a well functioning system for documenting modifications is of great importance. Today's lack of a simple, intuitive system for ELA updates makes it a time consuming and complicated task to perform. The SAS fleet also consists of multiple aircraft manufacturers, and this makes the updating even more complicated.

This study has two main purposes: (1) To see if the ELA can be updated the same way for Airbus and Boeing, and to find a solution for a semi-automated cross fleet ELA system. (2) If (1) is possible, to document this solution in SAS' CAME-P (Continuing Airworthiness Maintenance Exposition - Procedures).

Data for this study was obtained from research documents concerning ELA, and documents from the aircraft manufacturers were provided from the supervisor, Celeste Lai in SAS. The conclusion was that there were multiple systems on the market for ELA calculations, but most of them were aimed at the design and construction phase of an aircraft, and also too complicated for ELA updates. Airbus had guidelines on how to update ELA, and were also in the process of developing an ELA system that was not launched yet. Analyzing Service Bulletins (SB), Supplemental Type Certificates (STC), documentation from the type certificate holders, and the system SAS was currently using led to the development of a custom-made Electrical Load Update Spreadsheet, ELUS.

It was concluded that ELUS had to be divided into four sections because of the variety of information provided from the SB's and STC’s. ELUS was tested on SB's and STC’s, and the conclusion was that it would satisfy SAS' need for updating ELA. Several cascading functions in the forms were programmed to ensure improved reliability. The forms were also protected by a password, to reduce the risk of someone deleting functions or formulas by mistake. Only the admin with the password could edit the sheet and its functions. The filter function in Excel could easily be used in the logs to instantly obtain historical information based on several parameters, such as tail-number, busbar, reference etc.

ELUS was a, by the authors, custom-made spreadsheet solution for ELA updates for airlines with a cross fleet configuration. This meant that ELA updates could be performed in a common document for a fleet consisting of multiple aircraft models and manufacturers. The spreadsheet was designed to be as intuitive and self-explaining as possible, with the aim that all departments in SAS would use it. The avionics department was able to have easy access to modification history on specific aircraft, and the registering tasks could be allocated to the entire group of engineers working on modifications. This way a significant workload was removed from the avionics department, with increased time to perform other important tasks as a result. Electrical overloads can occur as a result of missing documentation on previous modifications, and aircraft on ground due to such incidents are a huge cost. Electrical overloads are also a major safety hazard for the airline. ELUS was a tool that could help SAS to avoid such situations in the future.

In addition to ELUS, a chapter in SAS' CAME-P concerning electrical load management was written to provide guidelines on how to use ELUS.

Future work could be to upgrade the semi-automation of the spreadsheet to a Visual Basic (VB) programmed spreadsheet with warning functions concerning overloads. VB could also make the procedure of updating multiple aircraft significantly faster. With VB functions implemented, the risk of error would decrease.
Acknowledgements

This study has been carried out with help from supervisors Dr. Håkan Forsberg at MDH and Celeste Lai at SAS. The authors of this thesis would like to thank the supervisors for the guidance during this process.
## Nomenclature

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>AC</td>
<td>Alternating Current</td>
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<tr>
<td>AD</td>
<td>Airworthiness Directive</td>
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<tr>
<td>Ah</td>
<td>Ampere hours</td>
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<tr>
<td>APU</td>
<td>Auxiliary Power Unit</td>
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<tr>
<td>BAT</td>
<td>Battery</td>
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<tr>
<td>BCL</td>
<td>Battery Charge Limiter</td>
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<tr>
<td>BTC</td>
<td>Bus Tie Contactor</td>
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<tr>
<td>C/B</td>
<td>Circuit Breaker</td>
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<tr>
<td>CAME</td>
<td>Continuing Airworthiness Management Exposition</td>
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<tr>
<td>CAMO</td>
<td>Continuing Airworthiness Maintenance Organisation</td>
</tr>
<tr>
<td>CLIMB</td>
<td>C/B List Interactive Monitoring Boards</td>
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<tr>
<td>CNTOR</td>
<td>Contactor</td>
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<tr>
<td>CPU</td>
<td>Central Processing Unit</td>
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<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DDL</td>
<td>Det Danske Luftfartselskab A/S</td>
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<tr>
<td>DNL</td>
<td>Det Norske Luftfartselskap A/S</td>
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<tr>
<td>DOA</td>
<td>Design Organisation Approval</td>
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<tr>
<td>EASA</td>
<td>European Aviation Safety Agency</td>
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<tr>
<td>ELA</td>
<td>Electrical Load Analysis</td>
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<td>ELUS</td>
<td>Electrical Load Update Spreadsheet</td>
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<tr>
<td>ESS</td>
<td>Essential</td>
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<tr>
<td>EXT</td>
<td>External</td>
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<tr>
<td>FAA</td>
<td>Federal Aviation Administration</td>
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<td>FMEA</td>
<td>Failure Mode Effects Analysis</td>
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<tr>
<td>GEN</td>
<td>Generator</td>
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<td>GLC</td>
<td>Generator Line Contactor</td>
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<td>GND</td>
<td>Ground</td>
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<tr>
<td>GPU</td>
<td>Ground Power Unit</td>
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<tr>
<td>GRND</td>
<td>Ground</td>
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<tr>
<td>HUD</td>
<td>Heads-Up Display</td>
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<td>Hz</td>
<td>Hertz</td>
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<tr>
<td>INV</td>
<td>Inverter</td>
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kVA  kilo Volt-Ampere
LRM  Line Replaceable Module
LRU  Line-Replaceable Unit
LTC  Load Tap Changer
MEA  More Electric Aircraft
POA  Production Organization Approval
RAAF Royal Australian Air Force
RAT  Ram Air Turbine
RCCB  Remote Control Circuit Breaker
RCVRY Recovery
RPDU  Remote Power Distribution Unit
SAS  Scandinavian Airlines
SB  Service Bulletin
SERIES System Electrical Rating Integration Evaluation Software
SHED Sheddable
SILA  Svensk Interkontinenta Lufttrafik AB
SOTA  State Of The Art
SPTI Siemens Power Technologies International
STC  Supplemental Type Certificate
SVC  Service
TR  Transformer Unit
TRU  Transformer Rectifier Unit
VAC  Volts Alternating Current
VB  Visual Basic
VDC  Volts Direct Current
List of definitions

**Normal Operation** "Most probable power consumption in normal operating conditions (flight in normal weather conditions)." [1]

**Maximum Operation** “Most probable power consumption in the most unfavourable conditions (flight in bad weather conditions with all circuits in operation).” [1]

**Busbar load** The arithmetical sum of the related circuit breaker loads.

**Power Factor** The ratio between the real power (W) to the apparent power (Volt-Amperes). Equipment running in steady state condition has a power factor close to one. PF measures circuit efficiency.

**Flight Envelope** The flight envelope describes the potential of the aircraft, such as altitude, airspeed or load factor. [2]

**Flight phase definition Boeing:**

**Ground Operation and Loading** When the aircraft is parked at the tarmac prior to engine start and departure. The aircraft is provided with power from Auxiliary Power Unit (APU), Ground Power Unit (GPU) (external power source) or batteries.

**Taxi** Taxi is defined from when the aircraft is first moving with power from own engines to the point where take-off starts on the runway, or after landing and transporting to gate and engine shut-off.

**Take-Off and Climb** Take-off and climb starts when the aircraft is at the end of the runway. The aircraft starts the take-off run and leaves the runway. The climb starts when the aircraft has left the runway and ends when the aircraft has reached cruise level.

**Cruise** The aircraft is in the cruise phase when it is in level flight.

**Landing** The landing phase starts when the aircraft is using the navigation and indication aids to prepare the landing sequence, to the finishing of the roll-out on ground.

**Flight phase definition Airbus:**

**Nominal Power** The nominal power is the maximum electrical load on the system connected to the circuit breaker.

**Ground** Engines stopped. Aircraft is connected to GPU or powered by APU.

**Start** Engines start.

**Roll** From the part when the aircraft is leaving the gate to leaving the runway. The roll sequence lasts until the landing gear is not compressed any more.

**Take-off** The period between when the aircraft has left the runway to 1500 ft.

**Climb** From 1500 ft to a stabilized level.

**Cruise** The main part of the flight at stabilized level.

**Descent** From cruise level to 800 ft.

**Landing** From the time the landing is prepared in cockpit to touchdown.

**Taxiing** From touchdown to the moment when the engines are shut down.
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1 Introduction

The introduction describes SAS, the problem formulation, the hypothesis, the research questions and the delimitations. This will provide a brief overview of the thesis.

1.1 SAS

Scandinavian Airlines was established in 1946 after a merger between Det Danske Luftfartselskab A/S (DDL), Det Norsk Luftfartselskap A/S (DNL) and Svensk Interkontinentalt Luftrafik AB (SILA) \[^3\]. Today SAS is also a part of Star Alliance. The SAS fleet consist of 138 aircraft (Oct. 2014). The fleet is divided between 12 long-haul aircraft, 114 short-haul aircraft and 12 regional jets \[^4\]. SAS have ordered 60\[^5\] new aircraft to renew and expand the fleet and to provide good service for the passengers. In 2013/2014 28,4 million people travelled with Scandinavian Airlines together with production companies Blue1 and Cimber. The Passengers can choose between 125 destinations and 807 flights each day \[^4\]. SAS is the largest airline in number of destinations, passengers and flights in the Nordic Region \[^4\].

SAS holds these approvals\[^6\]:

- EASA Part M, Subpart G: Continuing Airworthiness Maintenance Organisation (CAMO)
- EASA Part 145: Maintenance Organisation approval
- EASA Part 147: Maintenance Training Organisation Approval
- EASA Part 21/G Production Organization Approval (POA)
- EASA Part 21/J Design Organisation Approval (DOA)

1.2 Problem Formulation

SAS’s fleet represent the following aircraft: Airbus A319, A320, A321, A330 and A340, Boeing 737-600/700/800 and CRJ900 \[^7\]. With this number of different models to pay attention to, the workload of ELA is extensive. Today’s systems are very complicated and complex, and also having both Airbus and Boeing as providers of different electrical load analysis systems makes it challenging to handle, and also a quite time consuming task.

The ELA provided from Airbus and Boeing is only valid on the original configuration at the time of delivery of the aircraft, but once modifications are done, the ELA needs to be updated.

A uniform system for ELA updates is to be developed for the airline. This system should be a cross fleet configuration, and also be easy to use for all employees involved in the process of updating the ELA.

1.3 Hypothesis

The hypothesis in this thesis is: A common method for Electrical Load Analysis (ELA) for airlines with a cross fleet configuration makes the handling of ELA less complicated and more effective.

1.4 Research Questions

A: Is it possible to follow-up ELA the same way for both Boeing and Airbus fleet?
B: Is it possible to develop a method to perform ELA/follow-ups on SAS fleet?
C: Is it possible to integrate semi-automated functions?
D: Is it possible to prove method by testing on real cases?
E: Is it possible to create a CAME-P document for ELA management instructions for SAS based on the new simplified system?
1.5 Delimitations

- Bombardier aircraft will not be included in the ELA update sheet. This is decided by SAS.
- The ELA updates will only be conducted on busbar level, ripple effect on source level is not included.
- The ELA update will only include SB's and STC's.
2 Background

The background section is discussing electrical power in general, and also ELA and what kind of issues the airlines are facing concerning ELA and ELA updates. The different types of documentation concerning modifications on aircraft will be described, and also why the ELA is going to be more important in the future and the objects of this thesis.

2.1 General

Electrical power has become an essential part of our lives and way of living today. From electrical power plants, through electrical grids and power distributing networks, to buildings, factories, homes and transportation systems, electrical power is flowing to provide the functions and lifestyle we solely depend on today. Our society is funded on electrical driven components and circuits and most vital systems of cities are electronically controlled. To calculate and dimension these connecting units, special designed software are very important to get a functional and practical overview. There are several developers of software that provide advanced calculations of power, distribution and loads throughout defined grids by the user. Some systems are very sophisticated and opens up for very advanced calculations, something the pricing of the service reflects. Others are free, but they lack a lot of the essential possibilities in circuiting and bus connections that an aircraft represents.

2.2 Electrical Load Analysis

The electrical load is important to monitor on an aircraft especially because replacing or modifying parts may change the total electrical load in the different phases of flight. By performing an ELA, it is possible to estimate the average and maximum demands the new load put on electrically powered equipment in the different phases of the flight such as ground operation, loading, taxi, take-off, cruise and landing. By using these data it is also possible to calculate the maximum power needed for emergency situations. An electrical load analysis is produced for each different aircraft type, and it is used as a baseline document for every change made to the aircraft different parts.

An ELA must be carried out whenever a modification is to be applied on an aircraft. For SAS for instance, the type certificate holder will provide an ELA in paper form or as an excel file on delivery date.

When an aircraft is obtained from other companies or leasing agents, it is important to get an overview on modifications on busbar loads done prior to delivery. This to prevent busbar overloads in future modifications.

After a modification on the electrical system, the electrical load will be changed, and the original ELA will not be valid anymore. Therefore it is of major importance to keep track of how the electrical load has been changed, in case of future changes and the importance of not getting into an overload situation.

2.3 Issues

Today quite a few airlines lack an effective system for ELA calculations, updates and reporting because their fleet consists of aircraft of different configurations and manufacturers. There are also not many laws and regulations concerning updates of ELA. It is the operators responsibility to document and make sure that the modifications are within the limits of the different components.

The ELA is a complicated and complex operation, and also tedious and time consuming. Because of this, the risk of misinterpretations and mistakes is significant. This leads to a larger workload on the avionics department whenever a design modification is to be implemented, or when an aircraft is to be delivered to another company. The operator taking over the aircraft often want the full history of modifications and load changes. A system that easily can provide an individual log on each aircraft is desirable. SAS want all engineers to be able to update the ELA
even if they are not electrical/avionics engineers. A new, simplified method of updating the ELA would be very helpful.

2.4 Modifications

Modifications on an aircraft can be based on different documents from either the authorities (AD’s), manufacturer of the aircraft (SB’s) or supplemental type certificate holders (STC’s) that are providing modifications for the airline. SAS is a design organisation and holds a DOA (Design Organisation Approval). Today SAS’s modifications are distributed approximately about 60% SB’s and 40% STC’s.

2.4.1 Service Bulletin

A service bulletin is issued by the airframe manufacturer/engine manufacturer. The purpose of the SB is to enhance the safety or reliability of an aircraft. The SB is not mandatory, and will be analyzed by the airline to see if it is necessary to implement it. An SB can be mandatory if it is required by an AD.

2.4.2 Airworthiness Directive (AD)

As mentioned above, the SB can be made mandatory by an AD issued by the authorities. The AD is announced to correct an unsafe condition. This condition is most likely found in comparable products.

2.4.3 Supplemental Type Certificate

If a company want to develop and produce a product and implement changes to an aircraft it needs to be approved by the authorities. If approved, the company will become a supplemental type certificate holder. When the STC holder issues an STC, the modification has to be approved by FAA/EASA and other relevant authorities.

In the SB and STC the operator will find information concerning the modification such as: Planning information, material information and accomplishment instructions. The SB and STC will also describe which airplanes that are subject to the modification(s), which components that are going to be removed and replaced, how the components are affecting the load, which busbars are involved and the net change in battery amps.

Airbus and Boeing have no control over STC’s issued from supplemental type certificate holders. Because of this, the STC designers avoid installing new loads to the essential buses to prevent interference with the operative required and safety related systems.

2.5 More Electrical Aircraft (MEA)

The next generation of aircraft will consist of much more electrically powered solutions and sensors, which in turn will lead to the need of total control of electric power distribution, loads and calculations on a different level than today. By the introduction of the Boeing 787 Dreamliner, a new pace is set in the industry to implement new electronically controlled systems that will replace older, more traditional solutions such as cabin pressurization with bleed air and heating of wing sections with bleed air for ice protection. The implementation of new electrical driven compressors for cabin pressure and electro-thermal ice protection on wing surfaces has led to the demand of more generators and batteries for standby power when the technology of morphing wing structures is ready to be implemented in the production line of aircraft, there will be an additional need for electrical power sources to deliver power for the new technology. Electrical actuators and motors will replace mechanical and hydraulic driven actuators, and this leads to an extended demand of managing the electrical calculations both in the production line of aircraft, but also in the maintenance field. This will be a focus area for airlines in the future when redundancy and sensors leads to less physical maintenance since the system monitors itself, but theoretical
overview and control on loads, busbar limits and electrical distribution within the system will be more important than ever to manage.

2.6 Future Challenges

As the development of aircraft goes in the direction of MEA, the managing software and solutions for both ELA calculations and monitoring will be more central in the maintenance routines of aircraft. Since the development of hardware and Central Processing Units (CPU) goes in a tremendous speed, it will be only a few years before a finished development of an aircraft is outdated and replacement of CPU and hardware components will be required. Compatibility issues, power distribution changes and load change will be very crucial objectives to monitor. With the amount of CPU's installed in today's aircraft and next generation aircraft's ascending use of computer powered functions, the load performances will change over time.

2.7 Objectives

The first objective is to investigate if it is possible to follow-up ELA the same way for Boeing and Airbus fleet. If so, the next goal is to design one (preferably semi-automated) cross-fleet document for ELA updates that would be easy to use. A common document for both aircraft providers would be a great incentive to allocate the workload across the departments within SAS, and make a complex task easier to handle for all employees working on modifications or replacements on existing aircraft. Therefore it is important to keep the level of simplicity at a level so that it would attract all departments involved to take it into use. In a human factors perspective it is important to customize the sheet to make it as easy to use and logical as possible. By creating a spreadsheet that is adjusted to the information provided from the SB’s and STC’s it will make the process of updating the ELA less complicated.

The object is to present a simplified semi-automated ELA update method that could be used on all aircraft by all engineers in SAS. This is going to be presented as a spreadsheet. A spreadsheet has proven to be a sufficient method of updating ELA, and SAS is currently using a spreadsheet today for the same purpose. The system is going to be tested on real cases to prove the functionality, and to be documented in SAS CAME-P as an individual chapter in ELA management.

2.8 CS-25 Regulations

CS-25 regulations are defining standards for airworthiness of aircraft. There are subsections defining the electrical system of large aircraft and the standards these should fulfill.

2.8.1 CS 25.1165 Engine Ignition Systems

For electrical power distribution to an engine ignition system, redundancy is mandatory. For batteries supplying power to the engine's ignition, it is mandatory to have a backup system of generators to provide backup power if the battery is discharged. Battery and generator are paired units. The power demand the aircraft represent must overcome the paired units and this at the maximum demand of all electronic functions and ignition of engines at the same time. Failure on generators, depletion on batteries and low rpm on generators are conditions the ignition system must overcome and be operative under. Redundancy and a warning system under certain discharging conditions are mandatory. Even the engine's ignition cycle represents an electrical load on the system and must be calculated and made sure are operational under any circumstances. [11, p. 1-E-17]

2.8.2 CS 25.1301 Function and Installation

The modifications or units implemented into an aircraft must be designed for the purpose and perform adequately to the functions intended. If there is a performance envelope this must be tagged, addressed and identified. The implementation to the aircraft must be done correspondingly
to the performance envelope. The cabling must also be of such kind that the regulations and limitations are approved.[11, p. 1-F-1]

2.8.3 CS 25.1310 Power Source Capacity and Distribution

If an installation is electrically driven and important for the aircraft’s airworthiness by regulations or functionality, it is also required to be redundantly supplied with power. A system must be able to provide power for these essential functions in a diversity of conditions where loss of engine power, failure and engine shut downs on multi-engine aircraft are a possibility. The system must be designed in a way that even in worst-case scenarios there is enough power delivered to the most crucial systems to keep the aircraft in the air and in a satisfactory manoeuvrable way. The number of engines dictates the available capacity, the larger aircraft with 3-4 engines have more generators and batteries available to handle malfunctions.[11, p. 1-F-3]

2.8.4 CS 25.1351 Electrical Systems and Equipment in General

ELA is fundamental for calculating the need of power demanded by the aircraft design and functions. The capacity of the aircraft electrical power generators must be large enough to power all functions and is calculated by the loads of all the functions and their power demand. The system consisting of batteries, generators, wiring, busbars, actuators and other electrical components must be constructed for redundancy to be guaranteed. Cross connections and single functionality must be implemented accordingly, so in the case of failure, the functionality of the electronic components can be served by alternative sources or keep their functions operative even though other parts of the grid fail. In a situation where failure is a reality, the system must be able to handle this without changing the functionality of the main components that keep the aircraft in the air. All these different scenarios of malfunctions must be fundamental for the power supply calculations, so in such a scenario the power supplied for the mandatory functions are within limits of the operational area of the item. Changing of power source in such situation must be without disturbance to the system. The crew on the aircraft must be able to disconnect different sources and monitor electric power distribution within the grid.

The aircraft must be designed consequently so that it has power available in backup in case of fire or failure in such a level that the operational grade of the aircraft is threatening the ability to land or control the aircraft. A backup system in form of batteries, RAT or APU can deliver power parallel to the main electrical system in an emergency situation making it possible for the crew to make a controlled landing. In case of total electrical system failure the crew must have this alternate source available without any specific actions. The functionality of a back up system must cover control of the aircraft, to ensure a controlled landing, and that navigation- and descent/ascent functions are available for finalizing the flight. The system must be designed with redundancy in such a way that loss of the main system and backup system at the same time is extremely unlikely.[11, p. 1-F-9]

2.8.5 CS 25.1355 Distribution System

The distribution system must be designed to secure redundancy. It must be possible to switch sources, locations and wiring cables in case of generator or engine failure. The electrical power from one generator to a physical installation must be cross fed in order to avoid a generator failure leaving the system powerless, the source can be switched and normal functionality of the item can be withheld without disturbance on the performance or system. By cross feeding and cross cabling, redundancy will make sure that installations demanding electrical power can be fed from multiple sources through multiple channels. The source switching must be fully automated without disturbance to the functionality.[11, p. 1-F-10]
3 Method

The method chapter describes how information and knowledge about ELA, aircraft electrical systems, possible solutions and current practice in the airline were gained.

3.1 Literature Study

A literature study has been carried out to get an overview and a deeper insight of how ELA calculations are being conducted in different industries. To find developers of software that would be possible to implement in the airline industry, a great number of companies had to be examined. Literature study as a method for gathering data and gain information concerning different solutions has given a thorough understanding of how great challenges there are in electrical power calculations. Literature on aircraft electrical and electronic systems has also been helpful to get an understanding of the theory. To get sufficient knowledge in Excel and to understand the possibilities that can be used to get the desired result, Internet has been a very helpful resource.

By performing literature studies and discussing ELA update management with the supervisor in SAS, it was clear that there were no good alternatives available for SAS on the market at the moment. Either the systems were very complicated, mainly for design and construction, or not compatible with having a fleet of aircraft consisting of both Airbus and Boeing.

Celeste Lai who was the supervisor in SAS also provided literature from Airbus, Boeing and SAS. SB's and STC's were of great importance for getting an understanding of what kind of information that was provided to the operator when a modification was to be implemented. Also original ELA’s from Airbus and Boeing were interesting to look at, to understand the great scope of the electrical system in an aircraft.

Other airlines have probably developed their own solutions, but the airline industry is not sharing their company secrets with their competitors.

3.2 Experience

Celeste Lai’s knowledge and experience has been helpful in the process of designing an excel solution that was useful for the purpose. Suggestions and prototypes were analyzed together with her, and based on this adjustments were made.

3.3 Analysis of Current Solution in SAS

The current solution used in SAS has been a guideline in the process of the development of the new ELA update tool.

3.4 Analysis of Available Software on the Market

The research that has been going on in the past by scientists and programmers has led to the software solutions of today. It was therefore important to review these solutions to find strengths and weaknesses. Based on this experience a solution that was custom made for the SAS fleet could be designed.

For the airline industry there are fewer options of suitable software compared to the electrical industry in general, and less tools to solve obstacles that must be overcome to successfully execute the ELA work.

Different software and corresponding literature available on the market was investigated, the system provided from Airbus and the current practice in the airline. Several providers of ELA systems were also contacted by e-mail to get more information on the different systems. Based on these methods and systems a simplified way of updating the ELA was going to be presented. One
of the biggest challenges was to find a way that could suit all aircraft in the airline and that was easy enough to use.

### 3.5 Prototypes

To develop a tool that was suitable for updating the ELA, prototypes were constructed. The prototypes were tested on SB’s and STC’s, and the need for improvements were identified. This procedure was repeated several times until a fully functioning sheet was developed. This tool was called ELUS (Electrical Load Update Spreadsheet)
4 State Of The Art - SOTA

When an aircraft has reached a certain age, modifications have to be done to maintain the desired level of usage, or components have to be replaced with new ones. When introducing new or more electronic components/parts the electrical load on busbars, circuit breakers, inverters (INV), Transformer Rectifier Units (TRU) and generators will change.

The demand for software or programs for keeping track of these modifications is significant, and there are several providers on the market. These systems might be either programs or spreadsheets. What has been discovered is that these solutions are either extremely expensive, too complex to use, mainly for design or construction purposes - not for updates on the electrical load on older aircraft, not compatible with having a fleet of aircraft consisting of both Airbus and Boeing, or the information put into the software is not kept confidential.

Several of these programs/software have been studied, and useful information has been gained on present methods and software available on the market.

4.1 Airbus

In previous years Airbus have delivered their aircraft with a paper version of ELA at the time of delivery. Aircraft delivered from 1st October 2002 come with an excel file containing ELA data that can be updated due to modifications. The airline is responsible for updating the ELA documents throughout the lifetime of the aircraft. Airbus have no responsibility for providing such services.

Customers have asked Airbus to develop a tool to help keeping track of ELA updates after implementing modifications on aircraft post delivery. Airbus offer no current tools available for this purpose. In July 2014 Airbus introduced a tool prototype called CLIMB (C/B List Interactive Monitoring Boards)\[12\] based on feedback from customers. This tool is supposed to make the process of the ELA and validating a modified load easier and less time consuming. This tool is not launched yet.

Airbus have also developed a software called Electrical Load Analyzer (ELAN)\[12\] that is used within the organization. This program is directed to ELA specialists, and is not suitable for untrained staff.

4.2 Boeing

At the moment Boeing does not provide any system or method for updates on the ELA. The manufacturer is not obliged to offer such services, and the airlines have to find solutions that work well for themselves. SAS have a spreadsheet solution for their Boeing aircraft.

4.3 Codarra Advanced Systems

Codarra Advanced Systems is an Australian company that delivers ELA software for industry applications. The software was released in 2004 after close collaboration with the Australian Air Force.

The ELA software from Codarra is not spreadsheet based, but is programmed and designed to as Codarra describes it: “model electrical loads of complex systems” \[13, p.1 ELA flyer\]. The software is depending on heavy computer resources since the calculations are demanding and need great CPU power. Thousands of calculations must be processed to determine performance over numerous concatenated scenarios, and therefore the price of developing this software reflects the cost of buying a license. One user agreement for the Codarra software is 30 384 USD and a server maintenance fee of 4 861 USD a year \[13\].
Codarra Advanced Systems offer tools for calculations on a broad spectrum of platforms. Green and eco friendly houses, cars, military transport vehicles and aircraft are integrated in this software [13, p. 2 ELA flyer]. For advanced load calculations the software from Codarra has been chosen to calculate the loads on Australia’s fleet of Black Hawk helicopters. Lockheed Martin implemented the tool and incorporated it in the ELA work of their production line of Hercules C130’s [14].

The ELA Software from Codarra Advanced Systems satisfies the MIL-E-7016F standard and is therefore ready to be implemented in aerial systems. The software can be applied on both civilian projects and defence systems in air, ground and at sea. The US Navy has also decided to use this software in their ELA calculations and bought a license.

As stated from Codarra Advanced Systems “the ELA software can analyze how much electricity you can use on your vehicles against the generating capacity of the system” [13, p.1 ELA flyer]. Codarra enables analyses covering the different conditions in flight, from take-off to landing, which is very important for ELA in airlines. The program lets the engineers draw the electrical circuits and visualize the network for accurate load and performance calculations. Identified overloads are warned so the engineers can find alternative busbars to connect the new load.

### 4.4 Power System Simulator for Engineering

Power System Simulator for Engineering is software provided by Siemens Power Technologies International (SPTI). Python scripting enables automated functions and programming for power flow analysis. The software enables graphical visualization and customization of the calculations. The system opens up for electrical circuits consisting of up to 150 000 buses. Siemens states that the software opens for “cascading failure vulnerability analysis” [15].

### 4.5 PowerWorld

PowerWorld offers simulator and software for advanced and complex systems consisting of high numbers of buses. The possibility of visual design as basis for calculations are also implemented here, and systems of up to 60 000 buses can be designed and calculated. PowerWorld states that “PWS supports detailed modelling of Load Tap Changer (LTC) and phase-shifting transformers, switched shunts, generator reactive capability curves, generator cost curves, load schedules, transaction schedules, dc lines, multi-section lines, and remote bus voltage control” [16]. The software enables for analysis and calculations of changes that are made to the system, and for verification that these are made correct. The simulator uses one-line diagrams very much like Multisim, and the software lets engineers draw circuits and full diagrams of busbars and generators.

License is stated to be 10 000 USD for the first seat, and the next 2-5 seats are 5000 USD each and these costs are for the basic simulator without add-ons. There are yearly maintenance fees and only one-year free upgrades and support. Site license is set to be 30 000 USD and a full Site License of Simulator with all add-ons is priced to 279.000 USD [17].

### 4.6 Saber Aerospace

Saber is a Microsoft based platform used by aircraft design teams world wide for calculations, simulations, modelling, analysis, visualization, wire harness design and Failure Mode Effects Analysis (FMEA) [18, p. 3]. Saber is used in various industries such as the automotive, aerospace, energy systems and power distribution industry. The idea behind Saber is that by using such software, one can test and verify configurations and systems at the design stage before the actual configuration/system is built, and thereby verify that the desired level of reliability and safety is reached. This saves a great amount of time and money in the design process. Saber RD is easy to use, but should also have extended functions for users with higher demands and it is based on a Windows platform. It is possible to connect Saber to 3-D tools such as Catia V5, Siemens (UGS) and Pro/E. It is also possible to integrate with: MATLAB/Simulink, Zuken, Mentor Graphics, Cadence, Synopsys VCS [19]. The future in aviation is leading towards MEA, and the aircraft systems need
to be robust. Analysis done by Saber can tell how the loads are affecting the performance of the aircraft, and if it is necessary to find alternative solutions.

4.7 SERIES By Marshall

Marshall Aerospace and Defence Group with their main office in Cambridge UK have specialized in “Conversion, modification, maintenance and support of civil and military aircraft, defence vehicle engineering, shelter manufacture, composite solutions and the provision of personnel, training and advice” [20].

Marshall got the chance to together with the Royal Australian Air Force (RAAF) develop a software based tool to calculate electrical loads or to simulate loads when new configurations on the original power system architecture was introduced. Marshall had seen the demand for such tool over a long period of time, but couldn’t develop it because of the cost. Earlier they had used a spreadsheet solution. When the RAAF were interested in such tool for its C-130 series aircraft, Marshall Aerospace and Defence Group finally got the opportunity.

The spreadsheet has been the preferred method because of the possibilities of calculating the electrical loads, but it also has its downsides. Marshall have experienced that the extent and complexity of the spreadsheets were significant, which in turn lead to a higher probability of risk being done in the process. Too much time was used to make sure that the result was real. It was not possible to show spare capacity of the different components. This was not necessary, but a very helpful tool that was possible to implement in a different type of software. Marshall wanted to develop software that was easier and more visual. They developed a software called SERIES (System Electrical Rating Integration Evaluation Software) based on RAAF’s fleet of C-130. A “skeleton” with all components and how they were connected to each other was created. Generators, INV’s, TRU’s and batteries were added and coded with colors depending on if it was AC or DC power. Arrows explained the direction of the connectivity logic. If a component was exchanged or modified, it was possible to load/unload the desired power bus on the skeleton. “Intelligence” was added to the software, so if a load was placed on a bus with insufficient power available, the system could not validate the new load. This function had seemed to be hard to implement in a spreadsheet. Also, if one tried to place a load on a bus that could not deliver the right kind of power type, it was impossible to accomplish the placement. Some components even need different power supplies; the software would detect this and would warn the user if the power supplies were insufficient. No validation would be possible until sufficient power supplies were connected.

The most critical situation in an electrical system is if one or more power sources fail to generate power. The ELA visualizes different phases of flight and even critical situations such as loss of generator power. SERIES even shows how the alternative sources take over the power distribution if a main power source fails. With the possibility of showing the different loads in different phases of flight and even emergency, it was easy to document that a certain modification could handle the loads and be possible to carry out.

SERIES was designed to support three levels of users: Normal user, super user and administrator. Normal Users could simulate modifications on a temporary basis, the Super Users could do permanent changes to the loads. This reflects the system with “checked by” and “sign off” procedures in real life. The Administrator had full access to the functions and data in the software, and could also edit and add new configurations. The Administrator could also extract information to tables, charts and reports. When a change of design is approved, the ELA can be updated by the Super User and stored in the archives.

The information about SERIES is gathered from [21].
4.8 Summary
Airbus’ tool is still not released, so it is hard to say of this solution could fit SAS’s needs. Since it is a tool customized for Airbus it would probably be a challenge to perform ELA updates on Boeing the same way.

Codarra is a software for advanced load calculations and also a quite expensive tool. SAS do not need such a complicated tool at the moment, and it is not necessary to spend this amount of money on software that will not be used to its full extent.

One problem with commercial products like PowerWorld and Power System Simulator for Engineering, is that these products do not support intermediate calculations. These softwares support basic systems and show only final results. The operators are dependent on calculations on intermediate loads.

The airline will have to compute sensitive data, which they don’t want public. The developers only offer licencing agreements which means that the airline doesn’t own the product/software they are using.

There is also a question about support of software; if routines within an organisation are implemented and the software used for solving the problems suddenly are replaced with never editions, compatibility issues may occur. Both when it comes to software as well as hardware. For the organisation to be fully reliable on the software producer, problems may raise if the producer find the older versions not being economically sustainable for upgrades to newer hardware. The cost of adjusting the system to the desired line of business is also high.

Saber is too complex and meant as a tool for design teams in the aircraft manufacturing industry, and is not usable just for updating ELA on an existing fleet of aircraft.

SERIES looks like an interesting software with a good user interface. On the other hand it seems to be too advanced to use for ELA updates and documentation. The price of a user licence is unknown.

Since SAS don’t need advanced and expensive solutions such as Codarra, PowerWorld and Power System Simulator because they at present time don’t perform advanced design changes or construct aircraft electrical systems. A well designed excel sheet with all necessary functions would be a good and less expensive solution that could suit SAS’ needs.

Musti and Ramkhelawan [22] also concluded that solutions based on Excel/Spreadsheet was easier to update, was more economical and had a longer lifetime. Exporting information for use in reports was also easier.
5 Technical Description & Theory

To develop a tool that could solve the challenges concerning electrical load management, it was important to gain knowledge about aircraft electricity. It was also important to find a suitable platform. The technical description explains why Excel was chosen and describes the aircraft electricity in general.

5.1 Excel

Excel was chosen as the preferred software because it has several advantages:

- Programming with macros is possible. This can be used to get semi-automated functions in the spreadsheet.
- It can handle large amounts of data.
- It can be customized to a desired layout.
- It is easy to export data between sheets.
- The sheets can be protected with passwords to ensure that no functions are edited by mistake.
- It is easy to handle and edit.
- Formulas can be implemented.
- Excel is well known to the target group.
- SAS is currently using Excel for their ELA updates today.
- It was available for us.

By creating an excel-sheet with all necessary functions, it was possible to fulfill the requirements that are needed to update and manage electrical load changes.

5.2 Visual Basic

Initially Visual Basic (VB) for Excel was the software used for getting the desired layout, but it turned out to demand quite a lot of knowledge of programming the codes that was necessary for getting the functions needed for the different ELA updates. Because of this, the decision of using regular Excel was taken, otherwise a lot of time would have been spent on learning programming in Visual Basic. This was not the purpose of this thesis, and it was possible to get a result that was almost equally good in Excel. People both in Sweden, India and USA was contacted to get support with programming in VB, but no one had the opportunity to help us.

Also programming buttons and lists with cascading functions would involve a lot of coding, which in the end would end up as a quite complicated code. Regular Excel macros were chosen despite the fact that programming in VB would make the result look better, the functionality would be almost the same.
5.3 Aircraft Electricity in General

Aircraft electricity is mainly created by generators in the aircraft. There are several configurations on how these are placed within the aircraft, and they are all individually adapted to the aircraft design. In an aircraft the number of electronically controlled functions will declare how many generators that must be installed. The generators must be able to deliver enough power for all the functions to operate in worst-case scenarios with redundancy for eventual failure situations. [23, p. 80]. For example, the new Boeing 787 Dreamliner uses electricity to pressurize cabin air and also electricity for anti icing the aircraft’s wing leading edges. This requires an extensive use of generators compared to the traditional way in the industry, which is solving this with the use of bleed air from the engines. Batteries together with generators supply the aircraft’s need of power, and batteries provide standby power in the case of generator failure only. The TRU converts AC generated electricity from the generators to DC for charging of the batteries. Inverters do the opposite by inverting DC electricity to AC electricity and this way an aircraft can have both DC and AC generators combined with batteries and TRU/INV to provide all the required electricity for different applications [23, p. 104-105].

For supplying different voltage and amps through the aircraft, busbars and connectors distribute the power generated in the generators. Busbars enhance the possibility to distribute correct power to the requirements of the application. The galley is one of the most power demanding installations [23, p. 162] in an aircraft, and this system requires 115V/400HZ AC electricity. Smaller loads are served 28V DC like the cockpit instruments. The heating pads on the aircraft’s wings require a higher voltage and amps than the Heads-Up Display (HUD) in cockpit displaying data. Therefore the required power to the wing section is distributed from one Remote Power Distribution Unit (RPDU), and another distributes the lower amp and voltage needed by the HUD in the cockpit section. Aircraft have Auxiliary Power Unit (APU) installed for starting the engines on ground [24, p. 415]. The APU can provide pneumatic pressure, electric power or hydraulic power for the purpose to start the main engines of the aircraft [23, p. xi]. For a turbine engine to start, it needs a certain amount of momentum for being self-sustained with air compression. To achieve the turning of the engines the APU [25, p. 76] is started and provides the energy needed to get the turbine rotating.

MEA use more generators and needs larger battery capacity for emergency situations, but the winnings are less fuel consumption and lighter aircraft, which leads to longer range. The use of more electricity changes the layout of the aircraft design, and removes ducts and heavy titanium tubing from the bleed air system on the engines [8], and the Ram Air Turbine (RAT) is removed.

Aircraft goes through extensive certification and testing phases to ensure everything holds the standards set by the authorities. In the production phase this means that electrical wiring and electrical components will be installed and tested over and over again in both laboratories and during extensive test flights. Since the wiring and installed components ages with the aircraft itself, the chance of error increases with every year [26, p.12.D.3-2]. The components can be exchanged, but the wiring is seldom replaced. It is important that the focus on electrical wiring is raised, since it is such a crucial system of an aircraft and even more central in the next generation aircraft. To avoid future catastrophes, the awareness must be raised and wire health management must be implemented as one of the key elements in aircraft maintenance.

The electric power in an aircraft is driving a high number of functions, and the next generation aircraft are even more electrical driven. Generators, batteries and wiring are only three of the substances in the electrical system. But antennas, sensors, actuators, transformers, Line-Replaceable Units (LRU’s) and Line Replaceable Modules (LRM’s), relays and power distribution panels are also part of electrical systems in aircraft. Direct Current (DC) motors and actuators will be heavily present in next generation aircraft as well. All these components are connected with wiring and in the Airbus A380 it is about 500 km of wiring [27]. With the length of cable present in aircraft today the risk of error also dramatically increases.
5.4 Busbars

As mentioned earlier, the busbars are a part of the electrical distribution system. One side of the busbar is for connecting to protection devices such as fuses or circuit breakers (C/B), and the other side is connected to a power source such as a generator, INV, TRU or battery. The function of a fuse or C/B is to protect the busbar in case of an overload situation occurs.

The buses have different tasks in the system:

- The main bus: This bus consists of loads that are non-essential in the aircraft. If an emergency occurs, such loads can be removed without affecting the safe handling of the aircraft. Examples of such loads are: In-flight entertainment, galley and main cabin lights.

- Essential bus: The safety bus in the aircraft. This bus is connected to equipment and instruments needed for operating the aircraft safely.

- Battery bus: The battery bus ensures that equipment needed for operating and landing the aircraft in an emergency situation is provided with sufficient power.

5.5 Aircraft Electrical System

The aircraft wiring diagrams that displayed the general systems were studied during the literature study. As an objective stated from SAS, understanding the electrical system in an aircraft was important before the design of an ELA update spreadsheet. The aircraft had some individual differences; The Airbus A340 had 4 engines and therefore more generators, and as a consequence more AC busbars than other aircraft models. Since the definitions of these were different, it was important to implement a system that separated the different types of busbars from the different aircraft models. This resulted in the development of cascading drop down lists that were dependent on each other for registering aircraft model, tail number and busbar name. This way the different aircraft models and corresponding busbars would only be available in drop down lists. This solution was derived to make sure that the filtering function would work properly. The chapters 5.5.1 - 5.5.4 show the different aircraft electrical systems in general and how they differ from each other.
5.5.1 Airbus 320

Main units, see figure 1: Auxiliary Power Unit (APU), Battery Charge Limiter (BCL) shown as BAT CONT, Alternating Current (AC) BUS 1 and 2, AC Essential (ESS) BUS and Shedable (SHED) BUS , DC BUS 1 and 2, DC Battery (BAT) BUS , ESS TR, HOT BUS 1 and 2, DC ESS BUS and SHED BUS, RAT shown as EMER GEN, Generator Line Contactor (GLC) , Bus Tie Contactor (BTC) , TRU and Inverter (INV).[28, p. 260-261]

Electrical power system: 115 Volts Alternating Current (VAC) , 400 Hertz (Hz) provided by generators from both engines. Electrical power sent to AC BUS 1 and AC BUS 2. AC BUS 1 distributes power to AC ESS BUS and to the AC ESS SHED BUS via via AC ESS FEED. AC BUS 2 distributes power to AC ESS BUS and to the AC ESS SHED BUS via via AC ESS FEED redundantly. Cross feeding functions for AC BUS 1 AND AC BUS 2. The TR1 rectifies AC to DC from AC BUS 1 to 28 Volts Direct Current(VDC) DC BUS 1. It also distributes DC to the DC BATTERY BUS. DC ESS BUSES are also provided DC from TR1. The TR2 rectifies AC from AC BUS 2 to the DC BUS 2. DC TIE CONTACTOR connects DC BUS 2 to DC BAT BUS which supplies HOT BUS 1 and two through the BCL(shown as BAT CONT). AC ESS BUS also provides power to the DC ESS BUS through ESS TR which rectifies AC to DC power. The RAT or EMER GEN provides redundant power to ESS TR [29, p. 3.4].
5.5.2 Airbus 330

Main units, see figure 2: DC BAT BUS, HOT BUS 1 and 2, DC ESS BUS, DC BUS 1 and 2, DC ESS SHED, AC LAND Recovery(RCVRY), APU Transformer Rectifier (TR), TR 1 and 2, SHED LAND RCVRY, DC LAND RCVRY, STAT INV, AC ESS Ground(GRND), AC ESS BUS, AC ESS SHED, AC BUS 1 and 2(Cross feed implemented), Generator(GEN) 1 and 2 and APU GEN \[30, p. 3.2\].

![Diagram of Airbus A330 electrical system](image)

**Figure 2:** General electrical wiring diagram Airbus A330

Electrical power system: 115 VAC and 200 VAC 400 Hz, 28 V DC. GEN 1 provides power for AC BUS 1, GEN 2 supplies AC BUS 2, where both External (EXT) B, EXT A and APU GEN powers both AC BUS 1 and 2. TR1(TR) rectifies AC from BUS 1 to DC BUS 1, TR2 rectifies AC from BUS 2 to DC BUS 2. Both DC BUS 1 and 2 powers DC BAT BUS. AC BUS 1 and 2 also supplies AC ESS FEED and ESS TR rectifies AC to DC power to DC ESS BUS. APU TR rectifies AC power from AC BUS 2 to DC power for the APU START \[31, p. 2\].
5.5.3 Airbus 340

Main units, see figure 3: 4 AC generators, APU, EMERGENCY GEN, INV, 2 BATTERIES, GROUND CONNECTOR, DC BUS 1 and 2, DC ESS BUS, DC ESS SHED, AC BUS 1, 2, 3 and 4, AC ESS GROUND, HOT BUS 1, 2, DC LAND RCVRY, SHED LAND RCVRY and LAND RCVRY [32, p. 3.2].

![Figure 3: General electrical wiring diagram Airbus A340](image)

Electrical power system: The system delivers 115/200 VAC, 400 Hz, 28 VDC. 4 generators, one on each engine supplies the AC BUSES 1, 2, 3 and 4 with total of 300 kilo Volt-Amperes(kVA). AC BUS 1-2 to TR1, which rectifies AC power to DC power sending it further to DC BUS 1. AC BUS 2-3 sends power to DC BUS 2 through TR2, which rectifies AC to DC power. AC BUS 1-1 and AC BUS 2-4 connects to AC ESS FEED. AC ESS FEED connects to AC ESS SHED BUS but also the ESS TR, which rectifies AC to DC to the DC ESS BUS. AC BUS 2-4 also provides APU TR CNTOR(Contactor) through APU TR for APU START. HOT BUS 1 and 2 provided by DC ESS BUS to DC BAT BUS, together with both DC BUS 1 and DC BUS 2. 2 Batteries charged and provided power by HOT BUS 1 and 2, 2 x 75 Ah(Ampere hours) [33, p. 2].
5.5.4 Boeing 737

Main units, see figure 4: APU GEN, IDG 1 and 2, AC XFR BUS 1 and 2, MAIN BUS 1 and MAIN BUS 2, GND(Ground) SVC(Service) BUS 1 and 2, TRU 1, 2 and 3, MAIN BAT BUS, GND SVC BUS 1 and 2, DC BUS and DC STBY BUS, AC STBY BUS, BAT BUS, HOT BAT BUS, GND SVC DC BUS 1 and 2, SW HOT BAT BUS, STATIC INVERTER, Remote Control Circuit Breaker (RCCB) and EXTERNAL POWER[34, p. 11].

![Figure 4: General electrical wiring diagram Boeing 737-600/700/800](image)

Electrical power system: 115 VAC, 400 Hz provided by generators from both engines, total of two. APU GEN, IDG (GEN) 1 or 2 or AC BUS (external power) sends AC power to AC XFR BUS 1 or 2 (GEN 1 to AC XFR BUS 1, GEN 2 to AC XFR BUS 2), cross feed implemented. AC is rectified from TRANSFER BUS 1 and 2 through TR1 or TR2. Power then goes to DC BUS 1 or 2. Also from 115V AC MAIN BUS 2 (source is GEN BUS 2) is power sent through TR 3 to the BATTERY BUS. BATTERY BUS powers DC STANDBY BUS and INV sends power from BATTERY BUS to AC STANDBY BUS. 115 VAC GND SERVICE BUS powers BATTERY CHARGER and this charger sends power to APU START, HOT BATTERY BUS, SWITCHED HOT BAT BUS, EXTERNAL DC RECEPTACLE and BATTERY. 115V AC MAIN BUS also powers the BATTERY CHARGER during flight [34, p. 11].
6 ELA Guidelines From the Manufacturer to the Airline

When a modification is to be implemented on an aircraft, the manufacturers provide different guidelines on how to update the ELA.

6.1 Airbus

Airbus provide a set of guidelines when it comes to implementing modifications due to SB or STC [35]. These guidelines are supposed to make the handling of STC and SB easier. This document gives the engineer an overview of what kind of ELA formats there are. It also contains the calculation methodology on different levels, such as busbar, converter and generator. The guidelines also describe different rules for validation and installation of SB and STC.

6.2 Boeing

There are no guidelines from Boeing concerning ELA updates. The operator has to follow the paragraph that is concerning “Electrical Load Data” in the SB. This paragraph describes how the new electrical loads are changed.
7 Results

In this chapter ELUS and its functions are described.

The first thing that has to be done when using ELUS is to enable macros by clicking on “Enable Content” when opening Excel, see figure 5. If macros are disabled, the tool, which is based on macros, will not function correctly.

Because there was a need for dividing ELUS into four sections, an entry page was designed, see figure 6:

By choosing the desired task, the user will be redirected to the correct page.
By using the buttons in ELUS it is possible to navigate between the spreadsheets as shown in figure 7.

Figure 7: The figure shows how buttons are used to navigate in ELUS
7.1 Functions

7.1.1 Error Messages

ELUS is based on information that is provided in the SB’s/STC’s. To make the risk of entering incorrect information as limited as possible, several warning functions have been added to the sheet.

Keeping the same format is also important based on the fact that the log is going to be used as an archive. In order to use the filtering functions the best way possible, all parameters should be formatted the same way to get the best results when filtering. By introducing warnings to the cells to keep formats the same, the output will be optimised. The warnings will appear if incorrect values are entered into the cells. The most common error messages are shown in figures 8-13.

![Figure 8: Error message when incorrect format of value is entered](image1)

![Figure 9: Error message when letters are entered instead of chosen from drop-down list](image2)

![Figure 10: Error message when value is entered instead of chosen from drop-down list](image3)
It is possible to enter both positive and negative numbers in the operational/maximum load cells. Some modifications involve removing loads, which means that negative numbers has to be allowed.

It is not possible to enter letters into the cells where values are to be entered. This is because it must be possible to calculate the sum of loads in the log function, and if there are letters together with the numbers, this will not be possible.
7.1.2 Cascading Drop-Down Lists

To make ELUS semi-automated, cascading drop-down lists were programmed. This means that when an aircraft model is chosen, see figure 14. The corresponding tail numbers will be available in the drop-down list in the cell below, see figure 15 (only on Airbus aircraft). The corresponding busbars will also be available further down in the form, see figure 16. This is programmed for all aircraft models. Because of this semi-automatising the risk of making mistakes and the time consumption is reduced.

Figure 14: Drop-down list with available aircraft models

When the correct model is chosen, the correct tail number shall be selected:

Figure 15: Drop-down list with available tail numbers on A330

The busbars will be adjusted to the aircraft model:

Figure 16: Drop-down list with available busbars on the chosen tail number
7.1.3 Buttons

Another function that contributes to making ELUS semi-automated is buttons. By recording macros it was possible to insert buttons that had useful functions in the form. The “Transfer To Log Button”, see figure 17, will copy all information entered in the form to the log below, see figure 18. The information will also be sent to a separate log sorted on the specific aircraft manufacturer as shown in figure 27.

![Transfer to log button](image)

Figure 17: Transfer to log button

All entered information in the sheet will be relocated to the log section:

(a) Log in Airbus form

(b) Log in Airbus form continued

(c) Log in Airbus form continued 2

Figure 18: Example on Airbus Log

In figure 19 is the Airbus AC form displayed with all its functions and accompanying log:

![Airbus AC form](image)

Figure 19: Airbus AC Form

In some cases will all phases of flight have the same value. By pushing the “All”-button, the value in Ground phase will be copied to all phases below.
7.2 Airbus AC and DC

The Airbus AC/DC forms are based on information provided in the SB's/STC's. The forms are shown in figure 20 and 21.

Figure 20: Airbus AC

Figure 21: Airbus DC
7.3 Boeing AC and DC

The Boeing AC/DC forms are based on information provided in the SB's/STC's. The forms are shown in figure 22 and 23.

Figure 22: Boeing AC
7.4 Admin Access

ELUS is designed to be easy to manage and update. All necessary information about aircraft models with corresponding tail numbers, busbars etc. are gathered in the Admin sheet as lists. For safety reasons is the Admin list protected by a password to make sure that no editing is done by mistake. By entering the correct password it is easy to add/remove items on the lists. These lists are used to get the cascading list functions on each SB/STC.

7.4.1 How to update lists

By entering the new aircraft tail number in the space in the red circles in figure 24, the cascading drop-down lists in the corresponding sheets will be automatically updated. For the busbars to connect to the tail number another action has to be done:

On the right hand side of the admin sheet all aircraft are present with busbars. Insert a new column in the area with correct Aircraft Model shown in figure 25. First a new column has to be inserted, then the new tail number has to be entered in BN1 and BN15. Then enter =P3 in BN2 to connect to the correct list of AC busbars, see figure 26. Enter =Q3 in BN16 to connect to the correct list of DC busbars, see figure 26. All busbars will then automatically appear in the column.
Figure 25: Aircraft with busbars

Figure 26: These busbars will be copied to the new tail number in fig 25.
7.4.2 The Log

When all information in the SB or STC is entered in the correct form, it will be moved to the log below the form, but also to a historical log sorted on Airbus or Boeing aircraft, see figure 27.

The log below the form is only for the user to have a visual reference to see what has been entered and transferred to the log earlier, the main log is a powerful tool for the engineers. The main log is based on copies of the logs found in the forms, but it will gather all modifications on all aircraft in the fleet. By using the filter function it is possible to get information on what has been done to a specific aircraft, how much the load has changed on a busbar, it can be sorted by SB/STC numbers. The user can also sort the log by defining multiple parameters. It was not possible to have a common log on Airbus/Boeing because of different input in the forms. ELUS contains two main logs, one for Airbus and one for Boeing aircraft.

By sorting the log on tail number and busbar, and calculating how much the specific busbar has been modified, it is possible to calculate how much spare capacity that is available.

![Figure 27: The filter function](image)

7.5 CAME-P

After ELUS was designed, a chapter on Electrical Load Management in SAS' CAME-P was written. This chapter is illustrated in Appendix A.
8 Discussion

The discussion chapter will include what we have discovered in the process of developing a tool for SAS. The tool will be explained and related research discussed.

8.1 Common Solution?

Early in the project we realised that designing a common sheet for ELA updates could involve certain challenges. Based on the literature studies, we discovered that Airbus and Boeing operate with different terms concerning phases of flight. We could probably define common phases and input cells, but it could then again lead to confusion when the information was to be registered in the sheet based on information from the SB or STC. Today the operator get documentation from several providers such as Airbus and Boeing, but also Delta Engineering, SR Technics and SELL issue STC on aircraft that SAS have in their fleet. These are just a few of numerous supplemental type certificate holders, and the documentation varies from company to company. Based on this documentation the goal was to derive an ELA update sheet that could be used by SAS. One of the main challenges with ELA updates was that the process was already too complex and unclear. By introducing terms in ELUS that was differing from the information provided in the SB/STC, the process would probably be even more unclear. Also if the aircraft is to be delivered to another operator, having documentation that is corresponding with the SB's/STC's is favourable.

8.2 The Process of Designing a New Solution

One of the aims for the thesis was to see if it was possible to follow up ELA updates the same way for Boeing and Airbus aircraft. As mentioned earlier, the current ELA update process has been too complex and has not been defined in SAS CAME-P. This has led to a significant workload on the avionics department. As the project progressed and information was gathered and processed, an understanding for how the spreadsheet should look like evolved. Providers of ELA systems and software were studied, and the conclusion was that none of them had exactly what SAS wanted. Airbus had quite a lot of literature on ELA management, and this literature referred to the requirements on a new ELA updating tool. Boeing on the other hand did not have any preferred method on ELA management and therefore not any available literature on the topic. Based on the information concerning modifications from SB's from Airbus and Boeing, and STC's from various supplemental type certificate holders, the conclusion was that different input to the various sheets was necessary, but it was possible to gather everything in one system with some individual differences. Some brainstorming to get ideas was helpful, followed by multiple prototypes that were made and discarded. The best prototype was shown to the lead avionics engineer in SAS who was also our supervisor, Celeste Lai, and this lead to the final sheet.

The main goal with the excel sheet was to make it easy to handle, easy to update for the administrator, self-explaining and effective to get logs on previous modifications. It was important to keep the users in mind, but also on the other hand make sure that all essential information was entered and all log and admin functions were functioning satisfactorily. Literature on human-computer interaction [36] was read to gain knowledge concerning what to consider when developing software.

Some key elements to keep in mind were: [36, p. 14]

- Effectiveness: How was the software fulfilling the tasks it was designed to do?
- Efficiency: Was the software an aid for the users in the desired way?
- Safety: Was the software and its design helping the users to avoid mistakes and errors being made?
- Utility: Was the software really solving the tasks and functioning the way it was supposed to?
• Learnability: How easy was it to learn how to use the software?

• Memorability: How easy it was to remember how to use the system.

These points were checkpoints when the design of the layout was created.

By analysing these points subsequently, the conclusion was that the new system was an improvement, and also hopefully a tool that SAS could use or develop by implementing VB programming.

• Effectiveness: ELUS handled ELA updates the way SAS wanted by the requirements firstly mentioned in the thesis proposal. It had to be sectioned into Airbus/Boeing and AC/DC, but in the end this made the sheet easier to handle. If all these parameters should be gathered in one sheet, the risk of making mistakes would be increased.

• Efficiency: ELUS was customized to suit SAS’ needs for ELA updates. It also provided several filter functions in the log, which again could help the engineers to calculate how much capacity that was left on busbars on the aircraft or to provide documentation on modification done on specific aircraft. It was also possible to sort the log by SB or STC references to see which aircraft that have been subject to specific modifications.

• Safety: To improve the safety and reduce the risk of making mistakes, the sheets were protected by locking all other cells than the cells that the user was supposed to fill in information. Some of the cells also had warning functions if information was put in incorrectly. Cells where only numbers were to be filled in was programmed with a warning function that would appear when letters were entered. Where it was possible, cells were programmed with drop-down lists to ensure that information that was put in the cell was with identical format for all SB's and STC's. This because of the filter function in the log. The information that could be analyzed in the log had to have the same information to be gathered. The cells where power factor was to be entered were formatted so that it was only possible to enter numbers from 0 to 1. Duty cycle had a similar function where the range was from 0% to 100%. Only the Admin user have access to change data in the log-function and thereby also admin is the one who has to be contacted if incorrect information is entered. The “copy information to multiple aircraft” section also reduced the risk of entering incorrect information since only the correct tail number had to be entered. All other information was copied from the previous aircraft.

• Utility: ELUS solved the tasks and functions the way it was supposed to.

• Learnability: Due to of lack of time at SAS, it was not possible to show the tool to other SAS employees than our supervisor, so it was hard to say how other employees would experience the tool. A chapter for the CAME-P was written with instructions on how to use ELUS. These instructions come with print screens of ELUS together with information and comments on how to use it, so it would be quite easy to understand.

• Memorability: By using a similar layout on the different sheets, the intention was to design a system that was recognisable. To recognise the sheets would make it easier to remember the next time the tool was used.

Keeping ELUS clean from unnecessary functions was important, and multiple revisions were done to improve the user friendliness. By keeping the same information in the sheet that was provided from the source as the fill-in space in the sheet, entering the information should not involve any confusion.
8.3 Log Function

At first an individual log on each aircraft seemed helpful. But after discovering the filter function in Excel, the conclusion was that it was much better to use the filter function to gather the information instead of having approximately 140 different sheets to navigate through. The filter function made it possible to get an overview on what modifications that have been performed on an aircraft during it’s history in the airline. To have control over the individual aircraft has a significant functionality in different occasions. In a case where the operator performs a Part-21 design modification on the aircraft, it is important to keep track of the electrical load changes. To avoid overloads, the total load on the certain component and the associated C/B, TRU’s, generators etc has to be calculated. Airbus and Boeing only provide ELA’s based on the original configurations. Also when the airline decides to sell the aircraft, the airline that has bought the aircraft often want the full history on modifications done on the aircraft. If this information isn’t gathered in the archives, it will be a demanding and time consuming job to provide all the necessary documentation. By using the filter function on the specific tail number, the full overview over previous modifications is provided instantly just by filtering the log on the certain Tail Number.

For the airline such log function will be a valuable and an easy way to see how previous changes have affected the total load on the busbar.

8.4 Programming

At first an attempt to program the sheet in VB was made. VB for Excel is a powerful tool that makes the system layout design look good. But as mentioned in chapter 5.2, VB turned out to demand quite a lot on the coding part. Programming in Excel could lead to a result looking very similar, and the decision of using regular Excel was made.

Programming different macros in Excel was easier to learn fast, but some of the macros took some time to record and as soon as a little mistake were made, the whole process had to be started over. A small change of the cells in the tool also meant that the macro for the specific function had to be updated as well. It was not a difficult task, but certain knowledge of recording macros in excel was necessary. By using macros, the operations that are done on the screen is recorded, saved and assigned to a button.

8.5 How ELUS Works

When the airline recieves a SB or STC it is assumed that the new electrical load is within the limits on the components it is affecting.

Airbus and Boeing have no control over STC modifications done on operator’s initiative, and to avoid situations where busbars are overloaded, the STC designer/part 21 designer avoid installing new loads on essential buses so it will not interfere with major systems in terms of future AD by Boeing/Airbus SB.

The only occasion where the engineer need to check if the implementation is within the aircraft maximum limits is if it is a Part 21 design change done in house. If such design change had been done, the new load has to be added to the current total, both on minimal and maximal operation mode. If the new total load is not exceeding the maximum range of the busbar (found in the paper version of the ELA or the excel file that was delivered with the aircraft), the new load can be added. If the busbar is overloaded in either of the modes, the new load needs to be connected to another busbar.
8.6 CAME-P

CAME describes the operators organization and what kind of routines/procedures the operator have for the technical operation.[37]

The CAME consists of 6 parts:

- Part O: General Organisation
- Part 1: Continuing Airworthiness Management Procedures
- Part 2: Quality System
- Part 3: Contracted Maintenance
- Part 4: Airworthiness Review Procedures
- Part 5: Appendices

The chapter in CAME-P will be placed under Part 1 Continuing Airworthiness Management Procedures. This chapter describes procedures such as[37]:

- The technical log system
- Maintenance and reliability program
- Accomplishment and control of Airworthiness Directives
- Modifications
- Defect reporting
- Engineering activity
- etc

One of the objects of the thesis was to write a chapter regarding ELA management in SAS' CAME-P if it was possible to follow up ELA the same way. Since the conclusion was that it was possible to develop a common system with some certain adjustments, this chapter was written in order to provide guidelines on how to use ELUS.

A template from SAS was used to get the desired layout of the CAME-P. At first an all text document with a complete description of the ELA update procedure was written. After a review we decided to change this and use print screens with accompanying text to describe the procedures. For someone new to the procedure it is easier to relate to pictures with comments on instead of plain text.

The CAME-P document is placed in Appendix A.

8.7 Related Research

ELA data updates are mainly delivered from the aircraft manufacturer or supplemental type certificate holders. The software complexity and diversity is therefore not necessary in maintenance purposes for SAS as in design and construction departments in other aircraft manufacturer companies. Codarra[13] and Marshall[20] provide advanced software with large databases and calculations with many different parameters. These software's require training and have expensive licenses. ELUS is based on SB's and STC's and therefore historic data on each individual tail number is enough to have complete overview of busbar capacity. The spreadsheet solution is easier to update, adapt and provides a solution that easily can be distributed over the three countries connected to the airline. For larger software solutions such as Codarra and Marshall, with design and construction as main focus, a great benefit is raising for the company inventing it when selling it to other companies. The research that is going on on this field is not very focused on ELA updates on a current fleet of different aircraft types, it is focused on ELA on the design and development stage.
9 Conclusions

The tests on SB's and STC's have proven that ELUS is an effective and less time consuming way to handle the ELA updates.

We can draw the following conclusions:

- It is not possible to follow up Airbus and Boeing the same way based on the documentation provided.
- It is possible to follow up SB's and STC's the same way for each aircraft type in the SAS fleet.
- By using macros in Excel programming, it was possible to develop a tool that was semi-automated.
- ELUS was tested on SB's and STC's, and proved to be a tool that was satisfying SAS' needs.
- Programming ELUS in Visual Basic would simplify the input process, make the interface look better and decrease the risk of error.
- Research on several providers of ELA software on the market has been done, but most of them are aiming at the construction part of the aircraft industry instead of providing solutions for an existing fleet of different aircraft.
- Excel is a sufficient platform to use for ELA updates. It is not necessary for SAS to invest in expensive software for ELA that is not made for ELA updates.
- Real cases have proven that an effective log system on tail numbers history is a very effective tool concerning issues on busbar overloads. Being able to effectively gather historic data is important concerning avoiding busbars overload situations.
- By using Excel, which is a familiar interface would probably lower the threshold for taking the tool into use.
- ELUS has been prepared for additional information, so it is easy for the Admin to add tail numbers, busbars etc. that will be automatically added to the drop-down lists.
- Instead of having a individual log on each aircraft the filter function in the log is very helpful. By using the filter function it is easy to get an overview over what has been done to busbars, specific aircraft or a group of aircraft.
- The CAME-P chapter provides guidelines to ensure that the information is added correctly.
- ELUS is a BETA version, which means that it has to be subject to further tests and quality revisions by SAS' engineers before it is implemented in SAS' ELA update procedures. The students cannot guarantee for the functionality of this product.
- By customising ELUS to the SB's and STC's, and also by designing a semi-automated tool, ELUS would make the process of updating ELA less complicated, more effective and more reliable.

9.1 Recommendations for Future Work

ELUS has a great potential of being an ELA update tool for SAS, but future work can improve the interface and functionality.

9.1.1 Interface

Programming the ELA update tool in VB or a similar program instead of a regular excel sheet would improve the visual impression. To ensure safety in the sheet VB would be a better solution instead of using macros, on the other hand updating the tool will probably demand knowledge in VB programming.
9.1.2 Historical Data

To get a complete overview over each aircraft the full history of modifications should be entered into ELUS.

9.1.3 Star Alliance

Star Alliance that consists of different airlines that are operating with a cross-fleet configuration would absolutely benefit from cooperating on developing a system for ELA updates. Based on the material delivered from the aircraft manufacturer it is clear that some upgrades on the reporting system could easily be done by the computer departments of the airlines. Based on the Excel spreadsheet, updating of the busbar loads and modifications could be much safer and minimise the risk of error if done in VB coding. Using this spreadsheet model and programming it in VB should be quite easy for VB experts, so it could even be a service that was provided by the airline for its departments.

9.1.4 Capacity Calculation - Warning Function

In ELUS the tail number log is a very useful function. In the tail number section history of modifications to the aircraft are listed by date, but can be sorted by busbar since it is a spreadsheet. If this was programmed in VB, a confirmation function could be programmed from the load on the busbar calculation, already calculated into the input area of the spreadsheet. The key is to make sure busbar resources are calculated and validated in a historical perspective on respective tail numbers in the input process. By connecting busbars and tail number with SB and STC history, Vlookup, Index and Sort functionality in Excel combined with formulas calculating for example 80 percent usage of the total capacity of the respective busbar, the design engineer would get an input error message in the start of the registration form, forcing the engineer to find an alternative busbar to connect the load to. This would be a very practical function to implement to a spreadsheet meant for a large business organisation spread to different countries. Experts on the field were contacted, but for such functionality to be implemented into such a complex and large spreadsheet the whole system would have been required to be programmed in VB code. Such corresponding functionality requires more programming than the use of macro coding and semi-automated functionality, it would require more time and expertise to implement into a spreadsheet than a bachelor thesis period provides. With the spreadsheet created, this functionality is semi-automated because the values appear in the tailnumber log, but to validate the modification these values need to be manually compared to the original ELA for the aircraft to see if the busbar is overloaded or not. A future improvement would be to make this function automatic.
References


A First Appendix

**ELECTRICAL LOAD MANAGEMENT:**

**Purpose:** The purpose of this procedure is to ensure that the electrical load analysis in conjunction with mandatory and non-mandatory changes on the aircraft is updated and archived correctly in the Electrical Load Update Spreadsheet (ELUS). The responsible engineer fills in correct data in ELUS based on data provided in SB, STC and AD.

**Applicability:** When SB, STC & AD are received, the new data must be logged on the current aircraft. In ELUS, the data provided from Type Certificate Holder and Supplemental Type Certificate Holder must be registered. Part 21 modifications may also be registered in ELUS.

**Responsibility:** The Responsible Engineer fills in data from SB, STC & AD. If incorrect information is entered and transferred to the log, the Admin/lead engineer with permit to edit ELUS has to be contacted to remove the information.

**Applications:** ELUS is a tool with a variety of functions:

- Functions as an archive for electrical load changes modified post-delivery.
- It can display changes done to the individual aircraft.
- It can display changes done to multiple aircraft.
- It can be used as a reference tool to calculate if there is power headroom for future changes on busbars.
- It can be used for documentation of electrical load modifications for future owners.
**Reporting routines:** Whenever ELA data indicates an overload – the appropriate actions must be taken. Either find another suitable busbar or notify authorized personnel for an assessment of the situation.
GUIDELINES FOR ELUS

ELUS is semi-automated and requires that macros are enabled on the file.

Activate functions in the spreadsheet by pushing the button “Enable Content”.
Push the button that describes the task you want to perform. The buttons on the right side will redirect you to the correct page for the registration of data.

The buttons will redirect you to the desired input sheet and should therefore be used to navigate through ELUS.

ELUS contains these different sheets. Admin Lists and the two Logs are password protected and for the Admin user only to edit. The Logs contain all modifications done to all aircraft. Each tail number can be sorted to display full history of individual modifications. The busbars modified on the specific aircraft can also be listed to calculate remaining capacity.
HOW TO NAVIGATE IN ELUS

ELECTRICAL LOAD MANAGEMENT

Airbus AC
Airbus DC
Boeing AC
Boeing DC
DESCRIPTI ONS OF SEMI-AUTOMATED FUNCTIONS:

The date must be typed according to the format YY/MM/DD. Using dots between the numbers will make an error message appear.

Tail numbers are drop down list enabled. Select tail number from the drop down list.

Typing inside the “Tail Nr” cell will make an error message appear.

For AIRBUS, “Aircraft Model” must be chosen first due to different configurations of busbars on Airbus aircraft.

Typing inside the “Aircraft Model” cell will make an error message appear. The aircraft models available in the drop down list will be administrated by a lead engineer or admin user.

For Airbus Aircraft ONLY permanent or intermittent loads are available. Choose P or I from drop down list if information from SB, STC or AD is stated. Typing inside this cell will generate an error message.
Busbar is drop down list enabled. Select busbar from drop down list. Typing inside this cell will generate an error message. If the desired Busbar is not available in the drop down list, select “Other” and type the busbar name in the cell beside.

This is important to do correctly, because busbar history is available in a historical log that can be filtered on tail number and busbar.

The busbar drop down list is dependent on the already selected tail number. DC or AC will automatically be sorted in the ELUS input form. Boeing and Airbus busbars are dependent on the previously selected tail number.

Phase must be selected in the drop down list. Typing inside this cell will generate an error message. Phases are only available choices in AC input forms. Choose between phase A, B and C.

Electrical Identity and Panel are options only in Airbus aircraft. These are found in the original ELA document from Type Certificate Holder.

Duty Cycle is only available in Boeing ELA. Enter only numbers inside the cell. The percentage symbol is outside the cell, so it is NOT to be typed inside the cell. If so an error message will appear. Numbers between 0 – 100 ONLY.
The “ALL” buttons are programmed to send the information typed in the first cell into all the other phases. Phase definitions depend on Airbus and Boing as they define phases differently. This is a shortcut button for typing the numbers into all the cells in the cases where the values are the same. These buttons are found only on AC forms for Boeing and Airbus. The information must be typed with numbers only. Typing letters/symbols in this cell will generate an error message.

The comment field is open for large lines of information if necessary. If there is additional important information regarding the modification, type it here.

The “Transfer To Log” button should be pressed when all data has been correctly entered into the form. It will send the data to the log and clear the form.

If the SB/STC applies for more than one tail number, the “Multiple Aircraft” function can be used. It is dependent on the previous registration. Carefully choose the right Tail Number that shall be logged with
the same data and press the “OK” button. The new tail number will then be logged with the same data as the previous aircraft. The tail number must be chosen from the drop down list. Typing inside this cell will generate an error message.

This button clears the form if necessary. This way the registration process can be started over without manually clearing the form.

This “go-back” navigation button will take you to the front page; ENTRY. Navigate through the ELUS file with these buttons.