1 Introduction

Demand for air transport services has experienced progressive growth since the 1950s [1]. However, this is not mirrored in a continued growth of airline profits. The so-called operating ratio, the net profit or loss per year, is a value annually calculated by the International Civil Aviation Organization (ICAO) to determine the profitability of its member airlines (for details, see [1] and [2]). This value has been fluctuating between approximately -4.5 % in bad years and 4 % in profitable ones over the past four decades. The average net profit was about 2 % in years, in which positive results were achieved.

In order to move into the profit zone, airlines have to master two types of cost, non-operating costs and operating costs. The term 'non-operating' costs refers to expenses and revenues caused by activities which are not directly involved in an airline's core business, i.e., transport. Among others, those costs can be business results from trading with property, interests to be paid on loans, or gains and losses from currency exchange transactions [1].

Operating costs are to be subdivided into Direct Operating Costs (DOC) and Indirect Operating Costs (IOC). According to [1], a common understanding in the aviation industry of DOC and IOC has led to the following rough categorization. Direct operating costs cover monetary expenditures associated with flight operations, maintenance and overhaul, as well as depreciation and amortization. Indirect operating costs mean cost regarding station and ground expenses, passenger services, ticketing, sales and promotion, as well as other operating costs. In 1994, DOC made up about half of the operating costs for the airlines of ICAO member states, see Table 1.1. This has changed over the years. By 2007, the share of DOC had grown by more than 10 % up to approximately 62 %. One major factor driving that change was the increase in fuel prices. The fuel price made up $\sim$ 40 % of the direct operating costs by then, which is as much as 25 % of all operating costs. Similar percentages were reached in the following years until 2011 [1], [3]. In view of the fact that airline results fluctuate cyclically between low profits in some years and losses in others, reducing fuel costs per passenger kilometer might decide over an airline's survival or bankruptcy or at least help save a significant amount of money.

In 2005, the European Union Emission Trading System (EU ETS) was launched to cut greenhouse gas emissions and thus foster environmental protection. The system grants limits, i.e. yearly allowances, of greenhouse gases to companies. If, at the end of the year, the company's emissions surpassed the allowances granted, they would have to purchase additional volumes from other participants in the trade scheme, or use banked allowances from previous years, if they had them, to

	In 1994	In 2007
Fuel	11 %	25 %
Other DOC	38 %	37 %
IOC	51 %	38 %

Table 1.1: Direct and Indirect Operating Costs (DOC and IOC) with fuel, part of DOC, separated for scheduled airlines of International Civil Aviation Organization (ICAO) member states in 1994 and 2007 according to [1]

avoid being fined. Vice versa, if a company did not exhaust their allowances granted for the emissions, they could sell or bank them. The quantity of allowances granted will be reduced in the coming years in order to further cut emissions. Only at the beginning of 2012, the civil aviation industry joined the EU ETS (for details, see [4] and [5]). Besides the above large percentage in operational costs, airlines now face another major financial aspect for thoroughly monitoring fuel consumption.

Environmental protection through the reduction of fuel consumption can, among other measures, be considered to be a general objective in the European aviation industry. The EU-wide research initiative Clean Sky, launched in 2008 and run by the European Commission and the industry (public private partnership), is just one example of projects in the aviation industry dedicated to environmental protection [6], [7]. With its projects the program will contribute to the objectives set by the Advisory Council for Aeronautics Research in Europe (ACARE) for 2020. These are the reduction of

- CO_2 emissions by 50 % per passenger kilometer,
- NO_X emissions by 80 %,
- noise perception by 50 %

(see [8], [9]). In order to help achieve the goals of ACARE for environmental protection and ease the customers' financial burden, aircraft manufacturers aim at developing ever more efficient aircraft.

1.1 Motivation

Improving the main engines or aircraft aerodynamics are two options for optimizing overall efficiency and performance. The advent of multiple-shaft engines and increased bypass ratios contributed to more efficient and quieter thrust generation [10]. Advanced wing profiles can bring about better aerodynamics, as well [11]. The reductions in airplane and system weight, respectively, is a third option to drive the efficiency of flying.

One system that has shown potential for weight reduction is the electrical system. From the early beginnings of commercial aviation, when the electrical system was a low-power direct current supply, it evolved into a three-phase system with supply voltages at $U_{\mathrm{nom}} = 115/200$ VAC around 1960 and is now changing over to $U_{\mathrm{nom}} = 230/400$ VAC main power supplies. On certain aircraft, even 270 VDC or 540 VDC sustained system branches have been introduced [10]. This development was driven by the steadily rising demand for electrical power, or, in other words, by a steady increase in the quantity of electrical loads on aircraft. Two trends have brought about this rising demand for electrical power.

The first trend is the at least partial replacement of the classic non-electrical hydraulic, pneumatic, or mechanical power distribution systems with their respective electrical version. This development has been referred to as "More-Electric Aircraft" (MEA) and is sometimes only considered to be the gradual movement towards the "All-Electric Aircraft" (AEA), an aircraft without any hydraulic and pneumatic power distribution and/or power offtakes [10], [12] [13], [14], [15]. Benefits of the More-Electric Aircraft approach have been proven and are still seen in overall airplane weight reductions and more efficient engines due to less power taken off for pneumatic and hydraulic systems. Other improvements are described as lower maintenance costs due to less complex fault location and quicker function restoration [10], [12], [13], [16], [17]. The A380 can be considered to be an

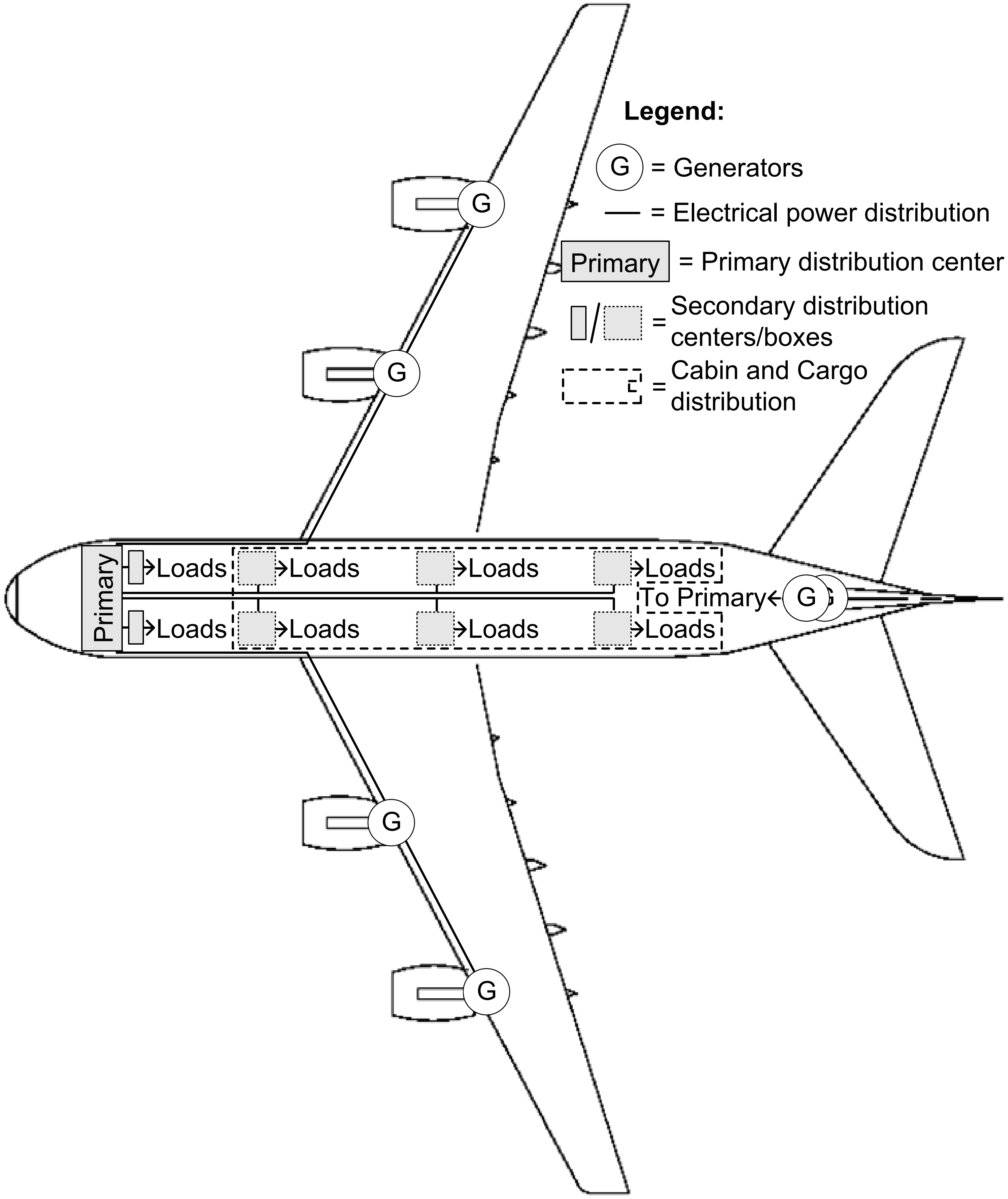

Figure 1.1: Structure of the electrical system on many modern civil aircraft

MEA of the above described type. The typical third hydraulic power circuit has been replaced by electrically powered back-up actuators [10].

The second trend has been the ever-growing use of electrical consumers not relevant for the basic operation of the aircraft that are used to enhance the comfort level and entertainment of passengers and facilitate cabin, maintenance and airport crew operations. Those functions are the modern in-flight entertainment systems along with power supplies to Portable Electronic Devices (PEDs), such as laptops, more sophisticated lighting systems with capabilities to project varying light scenarios into the cabin, or floor panel heaters in front of the aircraft doors to provide adequate warmth to cabin crew feet. The electrical cargo loading system helps achieve healthier working conditions for airport crews. Another major commercial consumer are the galleys (on-board kitchens). All commercial consumers combined can make up more than half of the actual electrical power consumed on large civil aircraft, see [18].

The structure of electrical systems on various modern large civil aircraft is of the following type, see also Figure 1.1. The electrical power is generated by either the generators in the main engines or the generators in the auxiliary power unit in the aft aircraft section. Regardless of the source, it is first transported to the primary power center below the cockpit before being distributed to the electrical loads. Systems with local high power demands are directly connected to the primary distribution center, others are connected to the secondary distribution centers/boxes. Implementations with a split primary distribution center can also be found.

The vast majority of commercial loads is connected to the secondary distribution boxes. These boxes and the power lines upstream and downstream of these boxes will be referred to as Cabin and Cargo distribution. Depending on the approach, the further development of the Cabin and Cargo distribution but also of the remainder of the electrical system can bring about significant weight reductions and hence contribute to increasing aircraft efficiency and performance, which, in turn, will support environmental protection and increase airline profit.

The motivation for this thesis relates to the further development of the electrical system with focusing on a more efficient use and design of the secondary Cabin and Cargo power distribution system based on an effective Power Management (PM) function. In contrast to today's implementation with a system-specific PM for only one system, the approach described in this thesis will encompass a PM for the entire Cabin and Cargo hold, potentially covering all systems that connect to the secondary Cabin and Cargo distribution system. Initial studies based on data of commercial route proving flights, i.e., flights prior to entry into service with cabin crew and passengers aboard, indicated potential for the reduction of the power line capacities between the primary power center and the secondary distribution boxes [18]. A schematic view of the power lines is shown in Figure 1.1. Further considerations of data of in-service flights supported the assumption of this potential, such that weight reductions in a range of about 50 kg to 70 kg can be expected for the secondary Cabin and Cargo distribution [18], [19], [20]. However, savings on upstream levels might afford additional mass reductions [20].

1.2 Objectives and Structure of the Thesis

As introduced above, the objective of this thesis relates to the further development of the electrical system focusing on a more efficient use and design of the secondary Cabin and Cargo power distribution system based on an effective PM function. The difference of the described approach to flying implementations of Power Management is that the existing function is covering one consumer system only. The approach within this thesis aims at extending it to all Cabin and Cargo systems in the secondary Cabin and Cargo electrical distribution system. Studies regarding the use of the capacities of the electrical Cabin and Cargo distribution system have unveiled potential for network reduction which, in turn, stands for weight savings. Nevertheless, to tap into these potential weight savings, detailed studies are required.

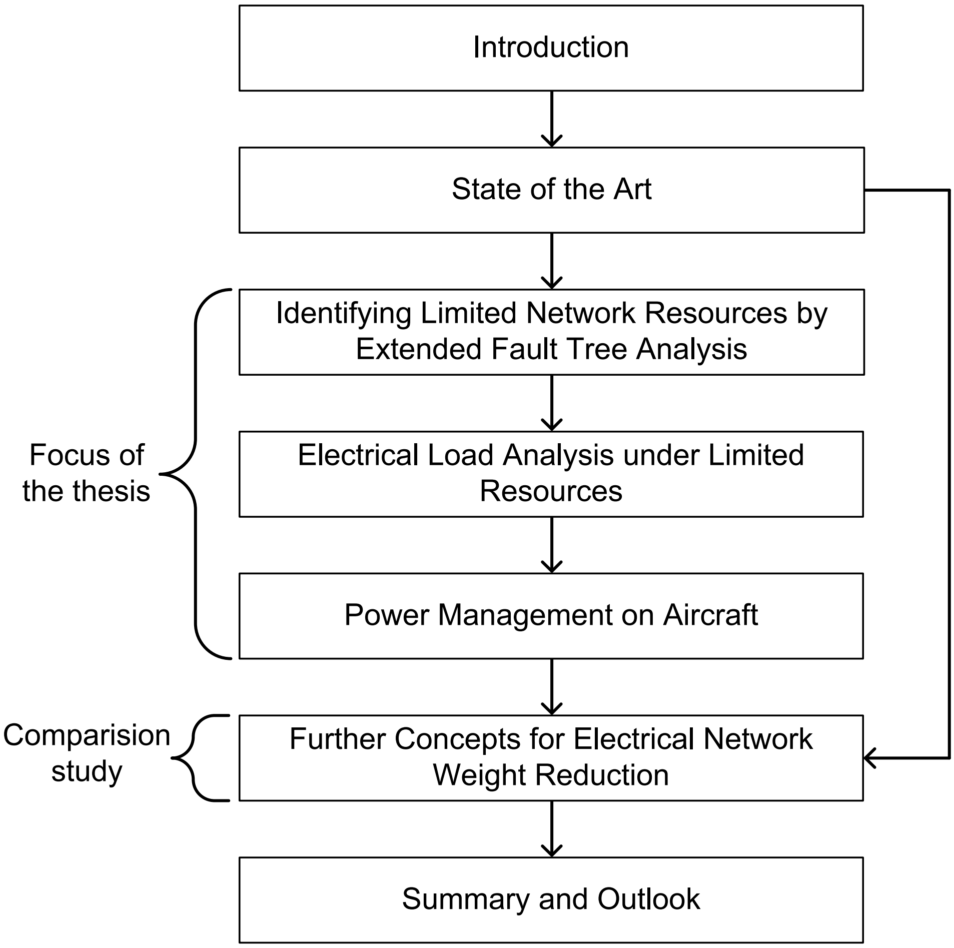

Figure 1.2: Structure of the thesis

Network design by means of e.g. the coincidence factor according to Equation 1.1 as defined in [21],

$$g_\mathrm{f} = \frac{P_\mathrm{max}}{\sum_{v=1}^{n} P_{\mathrm{max},v}} \tag{1.1}$$

with $g_\mathrm{f} \leq 1$, $\sum_{v=1}^{n} P_{\mathrm{max},v}$ as the sum of every single equipment maximum power demand and P_max as the maximum power ever measured, was shown to be highly unsuitable for micro grids like the aircraft electrical system and are not recommended for aircraft application (for details, see [18]). In particular, this finding applies to the secondary distribution level and the system levels. Due to the different types of systems, some being more, others less predictable regarding power consumption, as they are e.g. dependent on passenger behavior, the coincidence factor can vary between nearly one and very low values [18]. It can also vary with different cabin and system configurations, respectively.

The structure of this thesis is set up according to Figure 1.2. After introducing the target platform, other boundary conditions, relevant basics, and results of literature research in Chapter 2, State of the Art, this thesis will first describe how to find the optimum distribution capacities in order to offer a comprehensive tool to develop a secondary Cabin and Cargo distribution system based on an effective PM. Chapter 3 and 4 will phrase an approach for deterministically designing the electrical distribution system with limited resources. The proposed method will provide an answer to the question how far network capacities can be reduced or, in other words, what reductions are acceptable. That approach will use traditional fault tree analysis and extend it to applications under non-failure conditions. Important to note is that the method will be applicable to non-electrical systems with limited resources, too.

Chapter 5 will propose a pertinent PM concept for distribution capacities with limited resources. Focus of the function will be the introduction on the existing platform with minimum hardware impact as well as robustness and easy configuration/customization in series production while fulfilling its task to prevent the secondary distribution system from permanent overload. Different aspects leading to the decision on a final PM concept will be spotlighted, and the conclusive concept for the aircraft will be presented. Using a PM can offer certain weight benefits. Analyses in Chapters 3 to 5 will take measurements of electrical current needs of loads in revenue flights into account.

In order to put this approach into perspective and to create an understanding of the benefits vs. drawbacks and efforts of the PM option, Chapter 6 will describe results of a potential/benefit study for other ways to optimize the electrical distribution system. Advantages and disadvantages will be compared with the results of a benefit study on network optimization with PM. Lastly, this thesis will conclude with a summary and outlook on future work in Chapter 7.