Assessment of Electric Taxiing Considering Aircraft Utilization and Maintenance Cost

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ABSTRACT

Electric taxiing is one of the technologies which could help to fulfill the goals of the European Commission's Flightpath 2050. An electric taxiing system propels aircraft on the ground without using its engines and therefore, reduces the emissions on ground. The application of such a system affects the operating cost of an aircraft in several ways, especially fuel consumption but also direct maintenance cost as engine operation time is reduced. Several parameters determine the influence of an electric taxiing system on the operational cost of an aircraft. In this paper the considered parameters are: Aircraft type, aircraft utilization, fuel price, taxiing time, weight and maintenance effort of the electric taxiing system itself. Studies are presented to show the influence of these parameters on the operational cost of a narrow-body and a wide-body aircraft. The results show that especially the type of maintenance schedule of the main engines has a large impact on the operational cost when using an electric taxiing system.

KEYWORDS: *Landing gear, electric taxiing, direct maintenance cost, aircraft utilization*

NOMENCLATURE

Latin
a – Acceleration
AOC – Additional Operating Cost
APD - Aircraft Preliminary Design
APU – Auxiliary Power Unit
ATA – Air Transport Association
c – Cost
COC – Cash Operating Cost
COO – Cost Of Ownership
CU – Calendar Unit
DMC – Direct Maintenance Cost
DOC – Direct Operating Cost
EGTS – Electrical Green Taxiing Systems
ETS – Electric Taxiing System
F – Force
FC – Flight-Cycles
FH – Flight Hour
FOD – Foreign Object Damage
g - Gravity
LLP – Life Limited Parts
MH – Man-Hour
MPD – Maintenance Planning Document
MRW – Maximum Ramp Weight
MTBF – Mean Time Between Failure
MTBR – Mean Time Between Removal
MTOW – Maximum Take-Off Weight
LRU – Line Replaceable Units
OD – Operating Days per year
OWE – Operational Weight Empty
P – Power

t - Time
v - Speed

Greek
η – Efficiency
μ – Friction coefficient

Subscripts
$axle$ – number of drives
$conv$ – conventional
f – Friction
d – dynamic
m – Motor
$Material$ – Material
max – Maximum
mec – Mechanical
NLG – Nose Landing Gear
$Non - routine$ – Non-routine maintenance
ops – Operating

1 INTRODUCTION

Emission free taxiing is one of the goals defined by the European Commission in its Flightpath 2050 [1]. This goal could be reached by equipping the landing gears of an aircraft with electric motors. This would allow to taxi with engines turned off or at least in idle and with running the auxiliary power unit for powering the electric taxiing system. Thus, the fuel consumption and the emissions on ground could be reduced. The feasibility of electric taxiing was already investigated by several institutions and companies, for example Mecham et al. [2] and Schier et al. [3].

Through the additional weight of the electric motor and the required installations, the performance of the aircraft during flight is affected. Fuel burn during flight is increased. Therefore, the utilization of an aircraft equipped with an Electric Taxiing System (ETS) is crucial for the application of an ETS. Range, block hours and taxi time are important parameters for the trade-off between additional weight during flight and reduced fuel consumption on ground. Further aspects impact operational cost, for example by reducing the engine runtime on ground through electric taxiing the maintenance effort for the engines could be reduced depending on the maintenance scheme and aircraft type.

The current typical mode of moving an aircraft on the ground for the departure is a pushback from the gate with a tug, followed by propelling of the aircraft with its own main engines. The alternative to the pushback with the tug would be a powerback, if the aircraft has appropriate reverse thrust capabilities. An application of the required high thrust settings directly at the gate is not favorable. The operation of the aircraft engines on the ground, while providing independent propulsion for the aircraft, has several drawbacks. The engines operate very far from their optimal point of operation and thereby are not very efficient for these conditions. Furthermore, they produce relatively high emissions, which need to be avoided especially on the ramp and in the airport area. Ideally, an aircraft would be efficiently propelled by its own means and independent from separate ground vehicles, while at the same time producing as little emissions as possible. One approach is the application of electrical motors for the pushback and taxiing movements (E-Taxiing).

This paper investigates the influence of an ETS by comparing two conventional reference aircraft with their counterpart having a system for electric taxiing installed. Section 2 gives an overview of the landing gear impact in terms of maintenance cost and system weight. The methodical approach is outlined in section 3 covering the aircraft design impact, maintenance cost estimation and the determination of the power requirements of an electric taxi system. The results of two case studies using a narrow-body aircraft comparable to an Airbus A320-200 NEO and a wide-body aircraft, comparable to an Airbus A330-300, are presented in section 4. The comparison is based on the variation of fuel price, taxiing time, weight and Mean Time Between Failure (MTBF) of the ETS. The paper concludes with a summary and an outlook for future research.

2 LANDING GEAR IMPACT ON AIRCRAFT OPERATIONS

This section provides an overview of aircraft operating cost and the influence of Direct Maintenance Cost (DMC) concerning the landing gear. Furthermore, the impact of the landing gear weight on aircraft level is highlighted.

2.1 Maintenance Procedures and Cost

Aircraft maintenance practice can be split into routine, non-routine and unscheduled tasks. The routine work contains predefined work packages without any on-condition constraints allowing to determine the inspections and maintenance schedules for routine maintenance events throughout its entire operational life. All major aircraft components have a limited life expectancy and a fixed overhaul interval. In aviation maintenance these elements are referred to as Life Limited Parts (LLP). Maintenance tasks are documented in the aircraft's particular Maintenance Planning Document (MPD). The applicable type of threshold limit is defined for each part and is aircraft specific. The limit can either be dependent on Flight-Hour (FH), Flight-Cycle (FC), Calendar Unit (CU) or the number of Operating Days per year (OD). Non-routine tasks are not part of the MPD and in most cases those non-routine findings emerge from scheduled inspections in routine checks and reported peculiarities during daily operation. In fact up to 50% of the total hangar work is non-routine maintenance [4] making it difficult for operators to pre-determine the workload for these tasks. Unscheduled maintenance tasks arise from modified maintenance schedules due to occurred incidents.

Aircraft systems, such as the landing gear, require specific maintenance procedures which expenditures are captured by the Direct Operating Cost (DOC). DOC are defined as expenditures allocated to specific items, and therefore, vary according to the type of aircraft used and the rate of utilization. They can be divided into Cash Operating Cost (COC), Cost Of Ownership (COO) and Additional Operating Cost (AOC). The COO cover depreciation, interest and insurance costs, which are mainly based on the aircraft market value and the annual aircraft utilization. The AOC cover external noise, Nitrogen oxide (NO_x) emission charges and carbon dioxide (CO_2) emission charges according to the European Emission Trading Scheme. The COC sums up expenditures for fuel, crew, maintenance, airport and air service provider charges. The airport charges vary between airports, region and time and typically cover expenditures, such as landing or ground handling fees. The DMC cover labor and material cost associated with airframe and engine maintenance activities. Operational dependencies, such as flight cycle and flight time are considered, as well as, aircraft aging effects and de-rating of the engines [5].

Figure 1 depicts the share of worldwide maintenance, repair and overhaul expenses related to its originated maintenance category. Engine maintenance tasks account for 40% and the remaining share comprise airframe related cost covering heavy components, base and line maintenance. The heavy components maintenance sums up activities such as wheel inspections and tire replacements, brake repairs, landing gear overhaul as well as thrust reverser and Auxiliary Power Unit (APU) overhaul. C-Checks are commonly associated with base maintenance and are summarized under the category of line maintenance, pre-flight transit, daily, weekly and A-Checks. Empirical data state that maintenance cost associated with the landing gear are responsible for 20 % of the total airframe DMC [6].

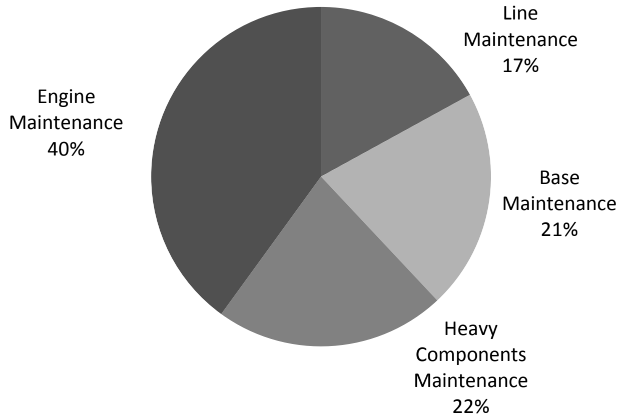

Figure 1: Share of worldwide maintenance, repair and overhaul expenses [7].

2.1 System weight

The landing gear structure makes up a considerable part of the structural weight of a modern civil aircraft. From data presented by Koeppen [8] it can be deducted that for an Airbus A320-200 the mass fraction of the landing gear systems of the Operational Weight Empty (OWE) is in the order of 5 % and 7 % respectively for the Airbus A330-300. The total systems mass accounts to 32 % of the OWE. Figure 2 shows the landing gear mass fraction in relation to the other aircraft systems. The definition of the landing gear system is according the ATA-Chapters (Air Transport Association), in which the landing gear chapter contains all structural components and landing gear specific systems (e.g. hydraulic pipes that exclusively provide pressure to a landing gear component).

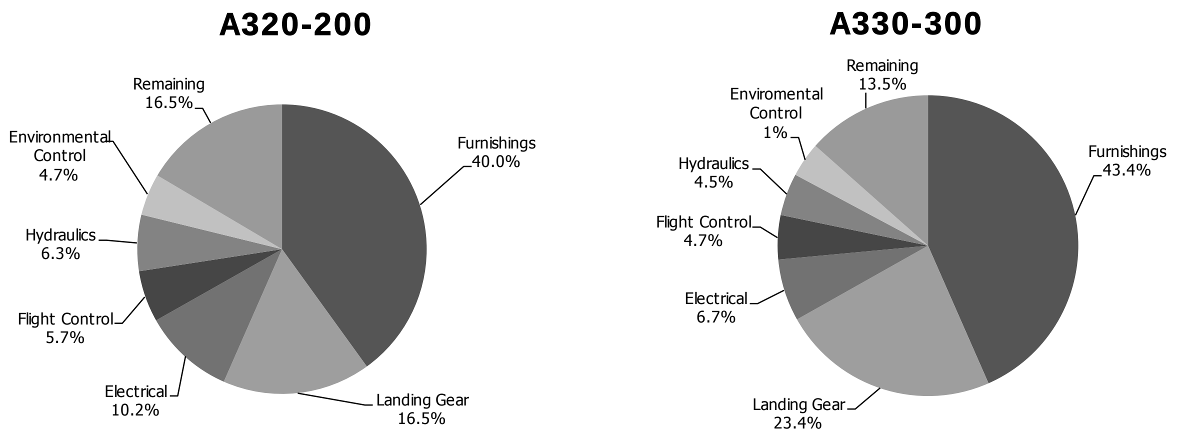

Figure 2: Fractions of system masses of OWE [8]

As Rudolph [9] states, a reduction in structural weight of an aircraft impacts its MTOW with a factor of 1.5 to 2.5, including propagation of the weight changes through the design. Therefore a weight increase in the aircraft MTOW has to be multiplied by this factor in order to assess its impact. As an example, for an A320-200 an increase of 10 % of the landing gear system can lead to an increase of 1.3 % of the MTOW.

3 METHODOLOGY

This section describes the used methodology and the aircraft characteristics of the different aircraft models and the underlying requirements for an ETS.

3.1 Definition of Aircraft and Mission Parameters

Pacelab Aircaft Preliminary Design (APD) [10] was used for the generation of the different aircraft models and for the calculation of the fuel consumption of the different mission ranges. In addition, the flight performance of the aircraft models equipped with an ETS are simulated using APD as well.
The assessment of the ETS on aircraft level is based on two different reference aircraft, as already stated in the introduction section. The key aircraft parameters of the narrow-body reference aircraft, comparable to an Airbus A320-200 NEO, and the wide-body reference aircraft, comparable to an Airbus A330-300, and the key utilization parameters are summarized in Table 1.

Table 1: Key parameters of the considered aircraft.

Parameter	Unit	Narrow-body aircraft	Wide-body aircraft
MTOW	kg	79,000	217,000
Design range	nm	2,800	4,800
Thrust to weight	-	0.31	0.30
Wing loading	kg/m²	645	600
Payload	kg	18,000	28,000
Cruise Mach number	-	0.76	0.80
Years in operation	-	20	
Operational days per year	-	350	

For this study, it is assumed that aircraft models equipped with the ETS are retrofits to the original aircraft. That means that the different MTOWs for the narrow-body and the wide-body are kept constant.
Furthermore, this work assumes that the ETS is powered by the APU during taxiing and that it is installed in the two main landing gears of the aircraft. The use of the APU for powering increases the maintenance effort of the APU itself. This relationship is respected in the performed calculations.

3.2 Calculation of Direct Maintenance Cost

The DMC calculations are based on published maintenance data [11, 12] covering maintenance schedules for diverse aircraft and engine types incorporating flight-time and flight-cycle thresholds.[1] Depending on the operational strategy of an airline, a certain variety in the maintenance planning and the resulting thresholds can be identified. The DMC are split up into different line- and base maintenance categories as well as heavy components and engine maintenance, as illustrated in Figure 3. For each cost item, material and labor cost consisting of man hours and hourly rate are estimated under consideration of operational constraints, such as aircraft utilization. The sum of all cost items describes the total aircraft DMC for airframe and engine related tasks.

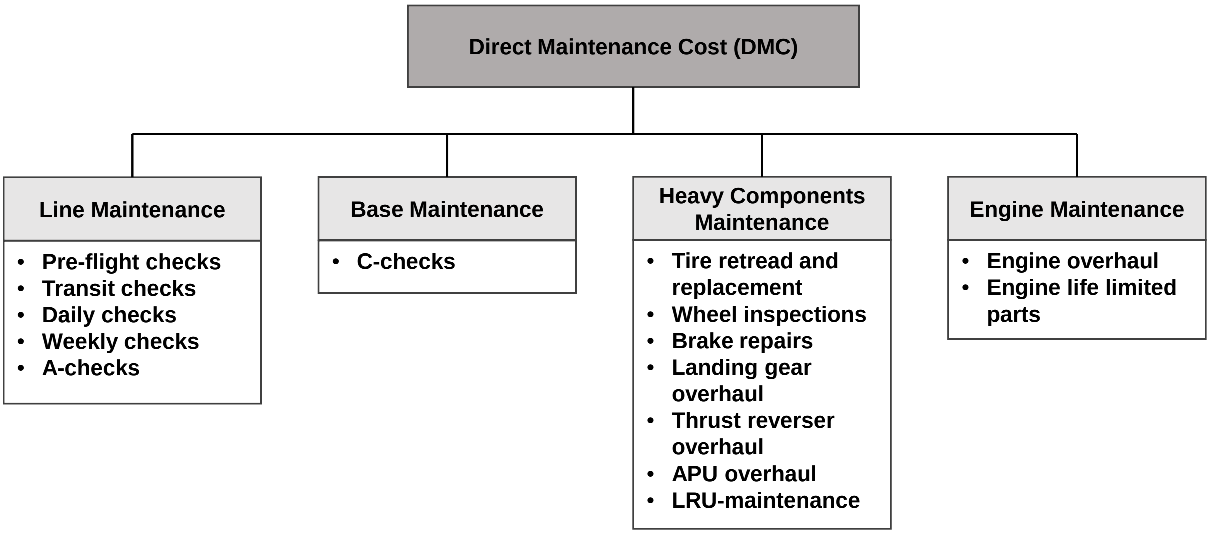

Figure 3: Breakdown of the direct maintenance cost items.

The use of an ETS influences the engine maintenance cost. Due to the use of the ETS, taxiing an aircraft can be performed without using the engines. For the narrow-body aircraft the engine overhaul schedule is determined by the number of flight cycles and for wide-body aircraft by the engine run time. Therefore, for the wide-body aircraft it is possible to delay the engine shop visits as the engine run time can be reduced by the ETS. It is assumed that for run-up of the engines a minmal time of two minutes is required.

3.3 Modelling of the Electric Taxiing Power Requirements

Concepts for E-Taxiing are in development for over a decade. WheelTug is one of the earliest concepts and started its development as early as 2005 with the concept of a propelled nose wheel [13]. Other concepts are the electric wheel hub developed by the German aerospace center [14] and the Electrical Green Taxiing Systems (EGTS) developed by Safran and Honeywell [15]. The latter one does not propel the nose wheel but wheels at the main landing gear.
Relevant performance requirements for taxiing are [15]:

- Acceleration from zero to 10 kts in 20 s for runway crossings,
- Break of torque on a slope with an inclination of 1.5 % with the given Maximum Ramp Weight (MRW)
- Acceleration from zero to final (normal) operation speed of 18 kts within 90 s and
- A sustained maximum speed of 20 kts

[1] The empirical values have been inflationary adjusted to reflect 2016 price levels.

From these requirements, the crossing of a runway is stated to be the one defining the design, due to the highest demanded electrical power. The necessary power can be estimated by basic physical equations and was derived by Chakraborty et al. [16]. The same set of equations for the power requirement was used for this study. The key parameters are introduced below.
Let $P_m(t)$ be the required power of a single electric drive. The shaft power can be determined multiplying the aircraft's current speed v(t) times the tractive propulsion force of each drive $F_d(t)$ divided by the mechanical efficiency of the drive η_{mec}. With this parameters the power for a specific time can be calculated by equation (1).

$$P_m(t) = \frac{F_d(t) \cdot v(t)}{\eta_{mec}}; P_{m,\max} = maxP_m(t), t\epsilon[0, \Delta t] \quad (1)$$

In order to calculate the necessary acceleration for a runway crossing in the required time interval Δt, an acceleration profile has to be assumed. The profile was chosen to decrease linear, starting at its maximum acceleration a_{max} and becoming zero at the end of the acceleration interval. Thereby the acceleration a(t) and hence the speed v(t) can be calculated from equation (2).

$$a_{max} = \frac{2 \cdot \Delta \mathrm{v}}{\Delta t}; \quad a(t) = a_{max}\left(1 - \frac{t}{\Delta \mathrm{t}}\right) \Rightarrow v(t) = v(0) + a_{max}t - \frac{a_{max}}{2\Delta t}t^2 \quad (2)$$

The tractive Force F_d is the force, which has to be generated to overcome the friction force F_f and to accelerate the mass of the aircraft. As Chakraborty et al. [16] describe, a possible value for the shaft power – similar to the actual power of the drives installed on the EGTS – is gained, if the roll friction on the powered wheels (all main landing gear wheels) is considered to be negligible small. Hence, $F_d(t)$ for one main landing gear can be expressed as the force to be required to overcome the friction of the nose gear wheels carrying only the weight share factor f_{NLG} of the MTOW and the required acceleration of the MTOW divided by the number of total drives installed n_{axle} , see equation (3).

$$F_d = \frac{1}{n_{axle}}\left(F_f + m\frac{dV}{dt}\right) \Rightarrow F_d(t) = \frac{1}{n_{axle}}(MTOW \cdot g \cdot f_{NLG} + a(t) \cdot MTOW) \quad (3)$$

In this paper the EGTS approach has been applied on a narrow-body and a wide-body category jet aircraft. The respective value assumptions are listed in Table 2.

Table 2: Parameter value assumptions for the EGTS Power calculation.

Parameter	Unit	Value
η_{mech}	-	0.8
v(Δt)	kts	10
Δt	s	20
μ	-	0.33

The resulting diagram for the acceleration phase, respectively for the two representative aircraft is shown in Figure 4. The simulations state the maximum power shaft output requirements of 58 kW (narrow-body) and 80 kW (wide-body) for an active runway crossing. In comparison, the long acceleration phase of 90 s demands a shaft power of 50 kW (narrow-body) and 69 kW (wide-body), appearing 45 s after releasing the brakes. The values are within the same range as the results of the EGTS program [15]. On a narrow-body aircraft, drives of 50 kW power have been installed. Possible reasons for the deviation are the difference in weight of the test aircraft, that is slightly below the MTOW, and the short period (less than 5 s) where the required power exceeds the rated power (58 kW > 50 kW).

The operational influence on fuel cost is defined by the additional weight of the electrical drive equipment and the reduced fuel consumption during taxiing. The additional weight is furthermore separated into the weight of the drive (assumption by a value in kW/kg) and the weight of the electric wiring supplying the drive unit.

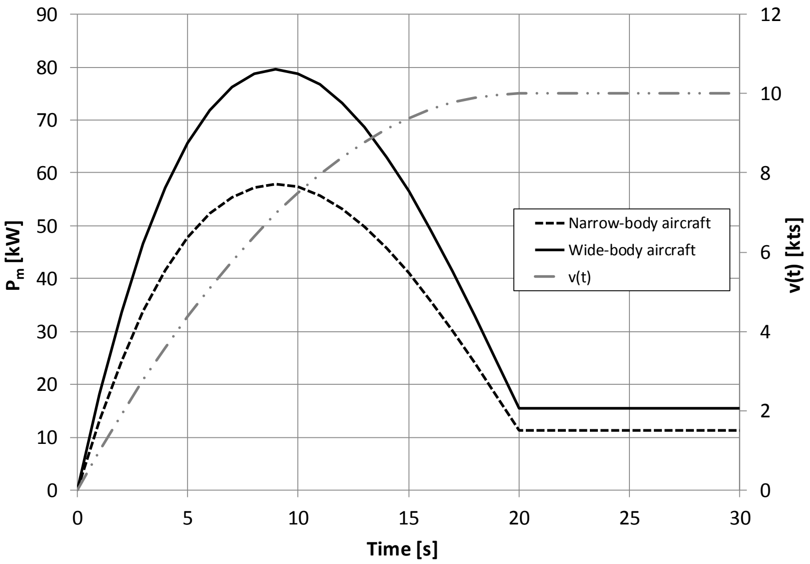

Figure 4: Power requirement and velocity for an acceleration from 0 to 10kts in 20s.

For an estimation of the maintenance effort, it is assumed that the drive has to be exchanged according to the MTBF and Mean Time Between Removal (MTBR). Knowing the failure rate, this value can be applied to the reliability function, according to Penrose et al. [17]. This leads to the relation given by the reliability function depicted in equation (4). It is dependent on the ratio between the actual operating time (t_{ops}) and the MTBF. The personnel expenditure necessary for exchanging the components is not considered in this equation, as its costs are relatively low in comparison to the material cost.

$$DMC_{Non-routine} = \left(1 - e^{\frac{t_{ops}}{MTBF}}\right) \cdot c_{Material} \tag{4}$$

The effort is estimated to be in the same order as a replacement of a set of brakes. As a preventive and failure monitoring maintenance strategy for the electric drives, one-half Man-Hour (MH) is considered for each drive being included in every A-Check. The work performed contains basic cleaning and lubrication of the bearing, together with a detailed visual inspection of the systems.

4 ASSESSMENT

In this section, the results of the simulations are presented. Cost savings for the use of electric taxiing are shown concerning the utilization of the different aircraft types and considering different parameters, which impact the aircraft operation and performance.

4.1 Assessment Process and Scenarios

The impact of the ETS depends on a multitude of different parameters, which are linked to the operational cost of an aircraft. The parameters considered here are the following:

- Fuel price
- Taxiing time
- Weight of the ETS
- MTBF of the ETS

The process of the assessment is displayed in Figure 5. For each aircraft a reference scenario is defined with selected values of the four parameters. For this set of parameters, the delta in cost between conventional aircraft and ETS equipped aircraft is assessed regarding block hours and mission ranges. The values for the parameters for the reference scenarios are displayed in Table 3. For each parameter a high case and a low case scenario is defined, in which the value of the parameter is increased or decreased to see its influence compared to the corresponding reference scenario. The values of the parameters of the high and low case scenarios are displayed in Table 4.

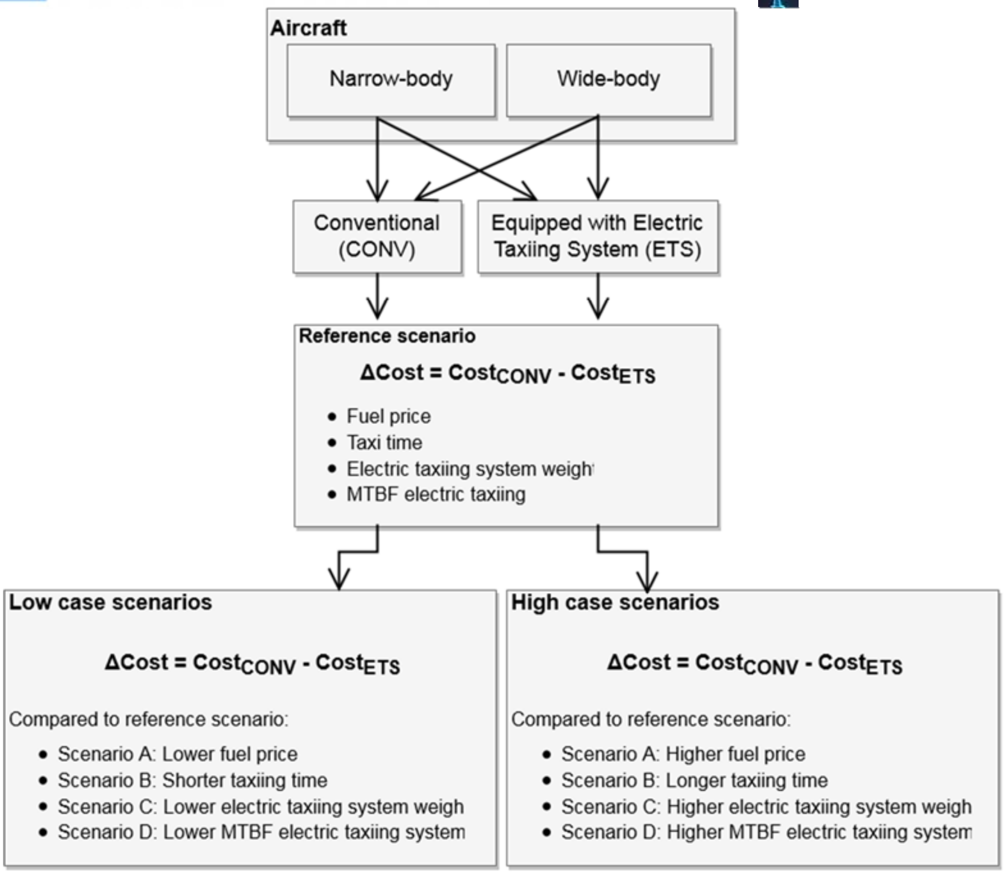

Figure 5: Process of the assessment with low and high case scenarios.

Table 3: Values of the considered parameters for the reference scenarios.

Parameter	Unit	Narrow-body aircraft	Wide-body aircraft
Fuel price	USD/bbl	90	
Taxiing time	min	30	
ETS weight	kg	200	550
Power requirement (see Section 3.3)	kW	58	80
ETS power to weight ratio	kW/kg	0.29	0.15
MTBF	h	10,000	
Material cost	USD	100,000	

Table 4: Change of the considered parameters in the low and high case scenarios compare to the reference scenarios.

Parameter	Unit	Scenario	Low case	High case
Fuel price	USD/bbl	A	-33%	+33%
Taxiing time	min	B	-33%	+33%
ETS weight	kg	C	-100%	+100%
Power requirement (see Section 3.3)	kW	C	±0%	
ETS power to weight ratio	kW/kg	C	-	-50%
MTBF	h	D	-33%	+33%
Material cost	USD	D	±0%	

Figure 6 shows the result of the assessment for the two reference scenarios of the narrow-body and wide-body-aircraft in percent of cost reduction over the entire life time of 20 years. On the x-axes of the two diagrams the mission distance in nautical miles is displayed. The y-axes show the utilization of the aircraft in block hours per day. The black contour lines represent the corresponding number of flight cycles. A higher cost reduction potential is plotted in darker color, as defined in the color bar on the right of the two diagrams.

For example, the black square in the plot for the narrow-body aircraft (Figure 6, plot X) shows that for mission distance of 1500 nm and an utilization of 10 BH/day the cost reduction of using an ETS is calculated to be ~1.5 % compared to the conventional narrow-body without ETS. The example in the reference plot of the wide-body aircraft (Figure 6, plot Y), which is marked with a black circle (Mission distance 3000 nm and 12.5 BH/day), shows that using an ETS would lead to a cost reduction of ~2 % compared to the conventional aircraft without an ETS.

The totally different structure of the plot for the wide-body aircraft compared to the narrow-body aircraft comes from the different applied maintenance schemes of the engines. The required maintenance effort is based on the number of flight cycles for the narrow-body aircraft, where for the wide-body aircraft the shop visits depend on the engine run time. By using electric taxiing, the engine run time can be reduced and engine shop visits can be shifted to a later point in time. Regarding the entire life span of assumed 20 years, for particular block hour utilization (~10 / ~12 / ~13.5 BH/day), the number of shop visits for the engines is reduced, which leads to a considerable cost reduction. Therefore, in plot X areas exist, in which the cost saving is almost independent from the mission range and only depending on the block hours per day.

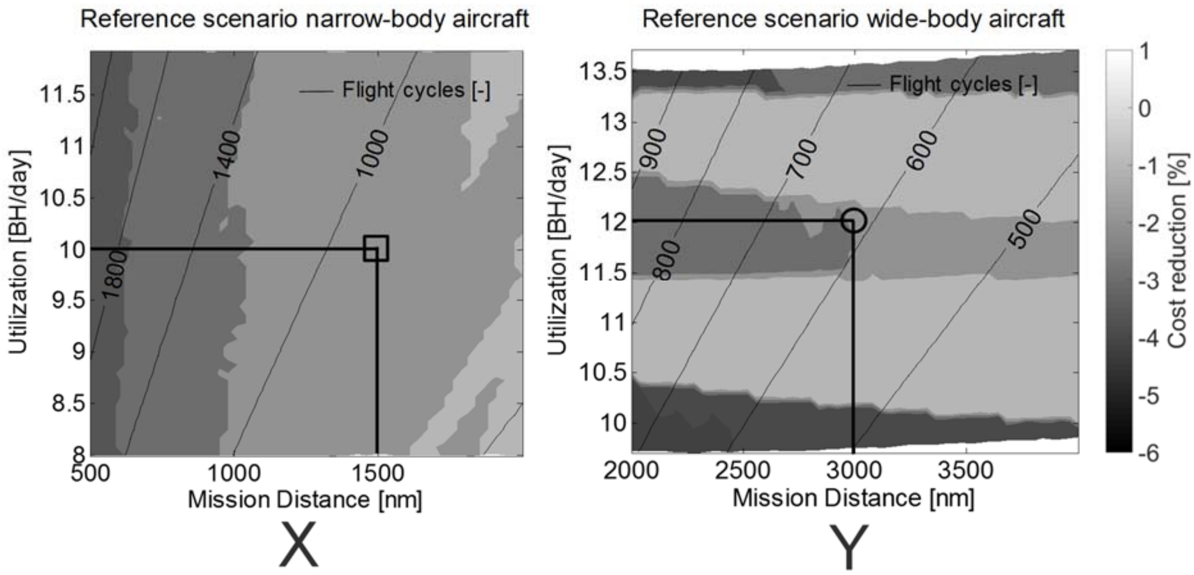

Figure 6: Reference scenarios for the narrow-body (X) and the wide-body aircraft (Y). (The cost reduction scale on the right is valid for both plots)

4.2 Influence of Different Parameters on Direct Operating Cost

To see the influence of the different parameters established in Table 3, the defined scenarios A, B, C and D, see Table 4 and Figure 5 above, are evaluated. In each of these scenarios, the value of one parameters is decreased (low case scenarios) or increased (high case scenarios). The values of the other parameters are kept equal to the reference scenarios..

Figure 7 shows the result of the assessment for the narrow-body aircraft. As expected, the cost reduction is higher for a shorter mission range. The taxiing time and the fuel price have a relatively large impact on the cost reduction, see scenario A and B. For a lower fuel price and a shorter taxiing time as defined in the reference scenario the maximum cost reduction is ~2 % for mission distances of around 500 nm. However, for a higher fuel price the maximum cost saving is ~4.5 % for mission distances of around 500 nm. A longer taxiing time even leads to a maximum cost reduction of ~5.5 % for mission distances of around 500 nm. The weight of the ETS and the MTBF of the ETS have a smaller influence on the cost reduction. The white areas in scenarios B represent the change in the BH due to the shorter or longer taxi time to complete the same mission distance as for the reference scenario.

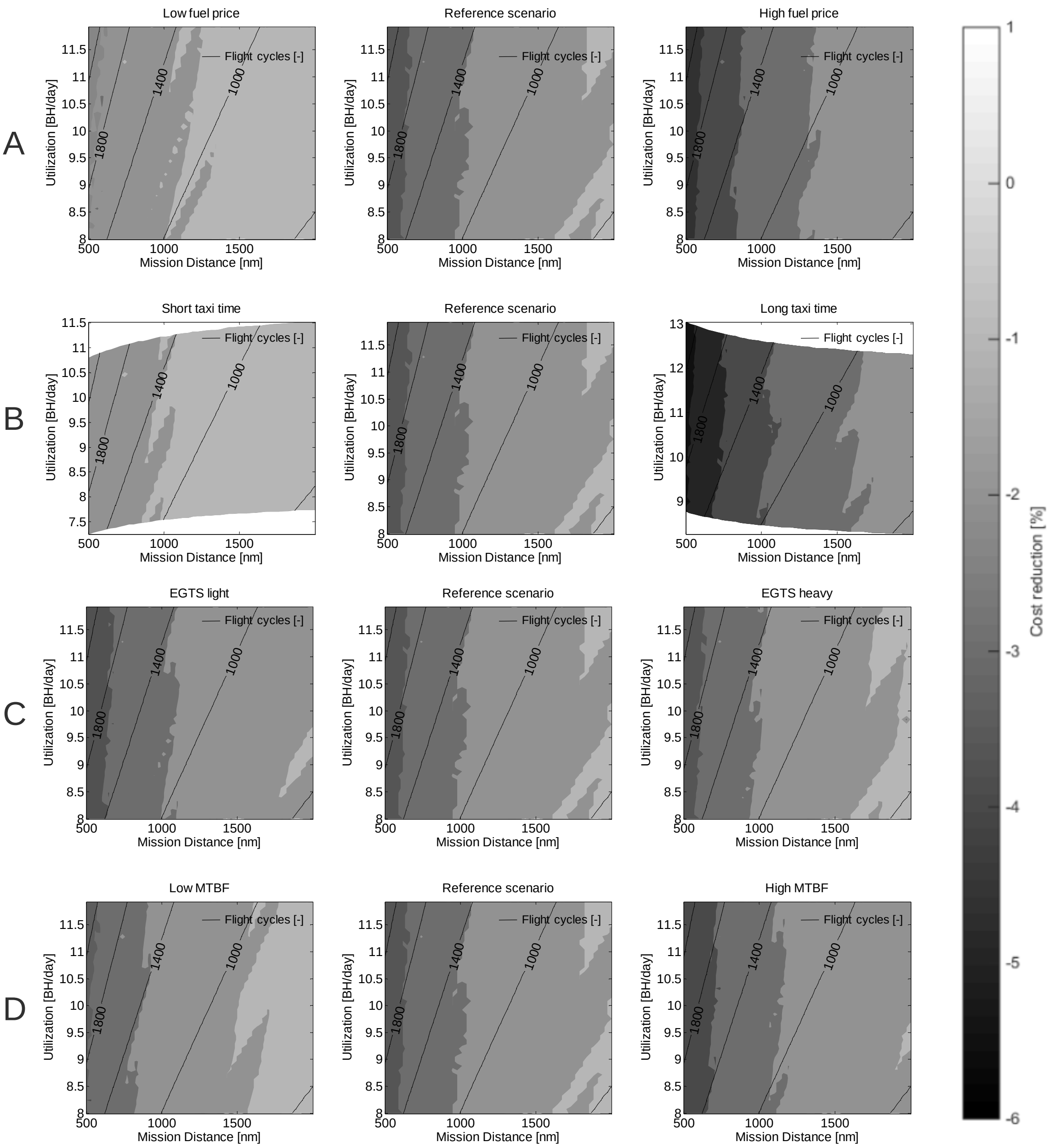

Figure 7: Results of the assessment for the narrow-body aircraft for the different scenarios.(The cost reduction scale on the right is valid for all plots)

The scenarios C and D show that the impact of a heavy ETS is not very high. In scenario D, it is obvious, that a lower effort for the maintenance of the ETS with a higher MTBF leads to an increase in cost savings.

Figure 8 displays the results for the different scenarios for the wide-body aircraft. As for the narrow-body aircraft, the fuel price and the taxiing time have the largest influence on the cost reduction, see scenario A and B. However, in contrast to the results of the narrow-body aircraft, a lower fuel price is more beneficial than a higher fuel price for the cost reduction potential using electric taxiing. This is explained by the additional mass for the ETS and the longer distances, for which a wide-body is used. A low fuel price in combination with the reduced maintenance cost of the engine and relatively low utilization of below 10BH/day results in the highest cost reduction potential of ~5% compared to the reference aircraft without ETS and is independent from the mission range.

The results for the scenarios C and D show a relatively small impact of the weight of the ETS and its reliability.

As already described above, it is possible to identify different areas, in which the cost saving potential is larger than for surrounding zones. This can again be explained by the types of maintenance schemes applied for the engines. In the dark zones with a relatively high cost saving potential of around 4-5 % the total number of engine shop visits can be reduced due to the reduced engine run time in the considered life time (20 years) of the aircraft.

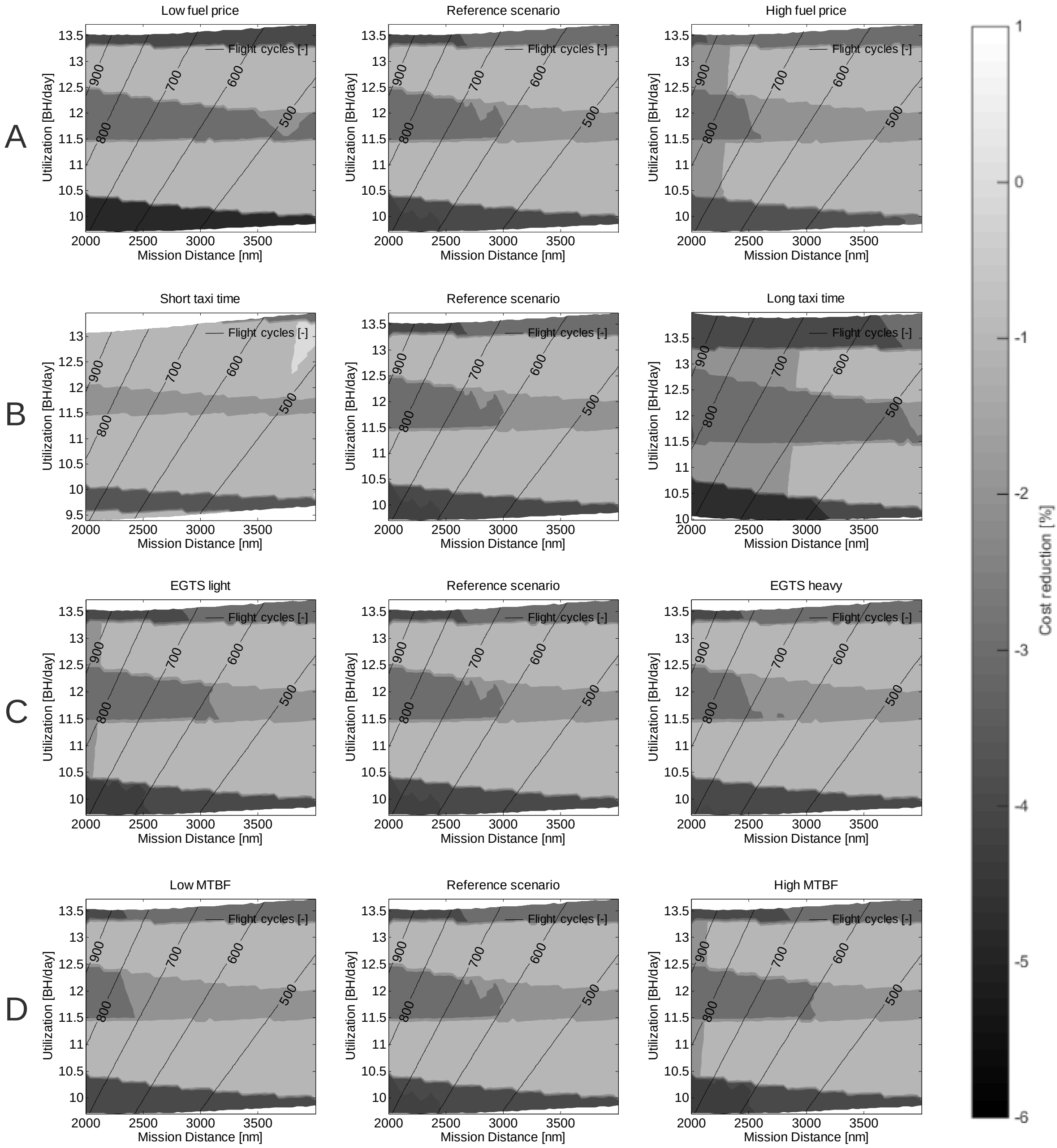

Figure 8: Results of the assessment for the wide-body aircraft for the different scenarios. (The cost reduction scale on the right is valid for all plots)

5 CONCLUSION AND OULOOK

Electric taxiing is investigated as a technology to reduce operational cost of a narrow-body aircraft comparable to an Airbus A320-200 and a wide-body aircraft comparable to an Airbus A330-300. Several parameters are examined regarding their influence on the fuel cost and maintenance cost of the aircraft with focus on the utilization of the two aircraft types considering mission distance and block hours per day. The outcome is that, as expected, the fuel price and the taxiing time have a large influence on the cost reduction potential of electric taxiing. Furthermore, the cost reduction potential is strongly depending on the applied maintenance scheme of the engines. For the narrow-body aircraft the required maintenance effort was calculated based on flight cycles. For the wide-body aircraft the maintenance cost for the engines are calculated depending on the run time of the engines. Therefore, it is possible for a certain utilization of the wide-body aircraft to reduce the operational cost significantly as the number of engine shop visits can be reduced during the life time of the aircraft.

One point for future studies is to investigate what the impact would be to change the engine maintenance schemes of the narrow-body and the wide-body aircraft to see how big the influence is. Future work should also broaden the parameter studies to cover airport charges for ground handling and reduction of Foreign Object Damage (FOD) of the engines when electric taxiing is applied [13]. Additionally, the methodology should be applied on real flight data to have an insight of cost saving potential of electric taxiing.

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