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# Effects of new technologies on the airplane final cost


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# INTRODUCTION

In recent decades, technological and scientific progress applied to the aerospace industry have undoubtedly made giant strides. A clear example of this is the replacement of the turbojet engines in favor of those turbofan, which allowed a significant saving of fuel for each flight carried out. This change has also helped to significantly reduce the atmospheric pollution produced due to the emission of flue gas into the atmosphere. However, any change made to an aircraft leads to a more or less significant change in its final cost. One of the many topics of this thesis is precisely the determination of the change in the final cost of an aircraft as a result of new technologies applied on it. Following this topic, it will be treated the main new technologies that are already applied on modern aircraft and the ones that will be applied on future planes, in terms of operation and use. Finally, an applied example on estimating the final cost following the implementation of a new technology on a regional turboprop will be discussed. The question that arises now is: how can we determine this increase/decrease of cost?
Before trying to calculate it, it is important to determine the final cost of the aircraft itself without considering the application of a new technology on it. As a matter of fact, there are many methods that allow us to calculate it; however they all consider 6 different phases:

- **Phase 1: Planning and conceptual design**
- **Phase 2: Preliminary design and system integration**
- **Phase 3: Detail design and development**
- **Phase 4: Manufacturing and acquisition**
- **Phase 5 Operations and support**
- **Phase 6: Disposal**

Each of these phases is characterized by a cost that depends on many factors (such as: maintenance costs for phase 4, ground tests cost and in flight tests cost for phase 3 and so on…).
The sum of the costs of all these 6 different phases forms the total cost of the aircraft. As we can easily see in Figure 1.1, the conceptual and preliminary design phases are responsible for locking in most of the Life-Cycle -Cost (LCC) of an airplane. By using

the word “life cycle cost”, it is meant the total cost of an airplane program incurred during the airplane life from phase 1 until phase 6.
For a more exhaustive discussion of this topic, see chapter 1.

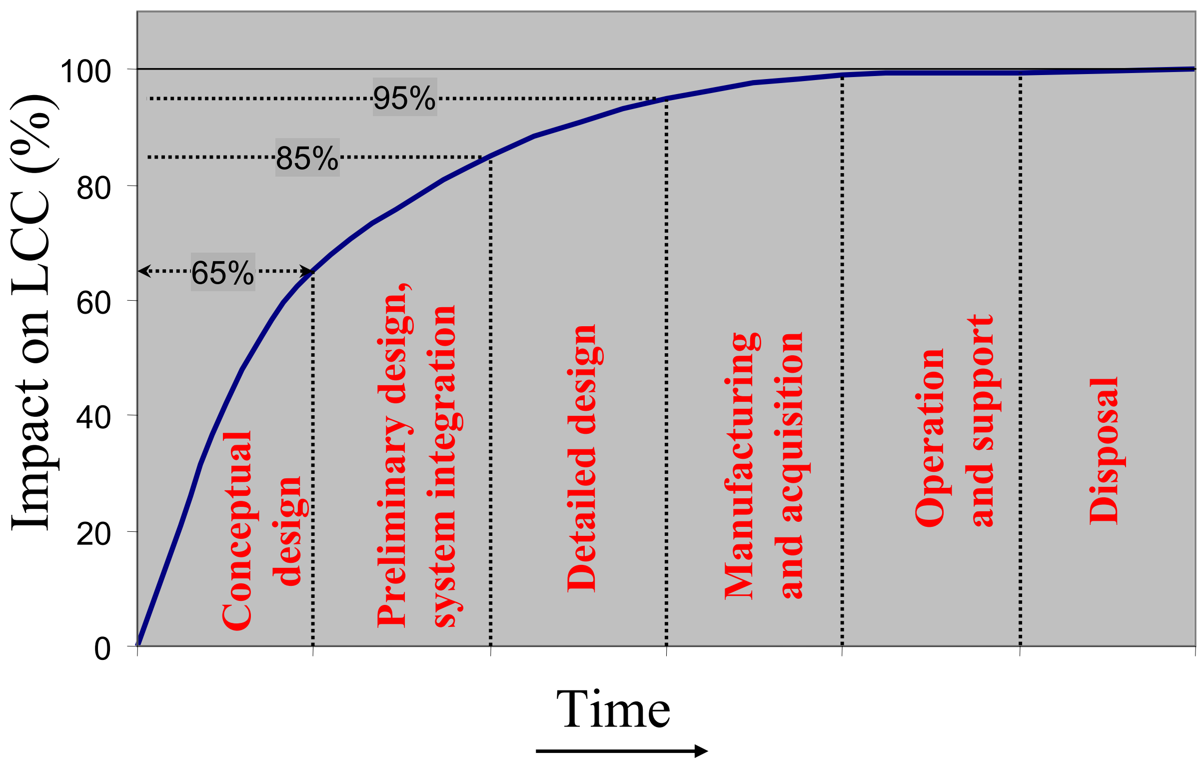


Figure 1.1 Impact of the various phases on the Life-Cycle-Cost of an airplane [1]

Once the most appropriate method to calculate the final cost of the aircraft in question has been chosen, it is time to choose which new technology is best to implement on it. Nowadays there are many of them: from the simple use of new materials (such as composite materials or morphing materials) to the use of solar energy as main propulsion system. First of all, it is useful to classify the new applicable technologies according to their goals. The main improvements that these technologies can bring are classifiable as follows:

- Lighten up the structure of the aircraft (composite materials, hybrid alloys, etc..)
- Reduce drag (transonic shock control, natural laminar flow, etc…)

- Reduce $CO_2$ emissions (different propulsive systems, alternative fuels, etc…)
- Decrease operations costs (improving the on board avionics)
- Decrease noise (acoustically absorbent materials, increasing BPR, etc…)

It is also possible to classify the new technologies basing on their TRL (Technology - Readiness - Level). The technology readiness level is a number between 1 and 9 indicating the level of estimating technology maturity of the new technology during the acquisition process. The TRL is applicable to every technology in every field, not just in the aerospace industry, as shown in Figure 1.2. The higher the number is, the less time is needed to deploy the technology wanted.

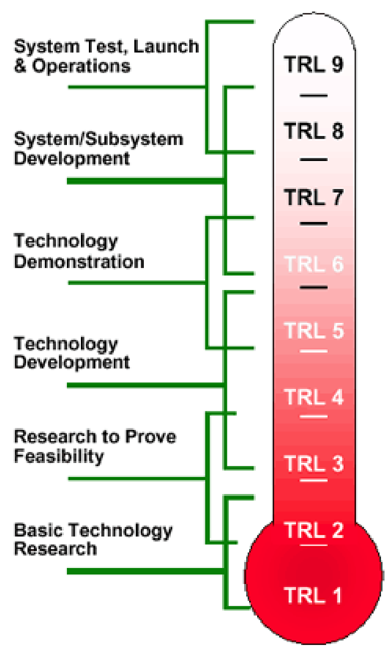


Figure 1.2 The 9 stages of the TRL [2]

One last method to classify new technologies deals with separating them by the money investment needed to develop the technology. A clear example of these two last divisions is shown in table 1.1.

| | Available for existing fleet | TRL | Estimated investment required |
|---|---|---|---|
| Geared turbofan | Already existing | 9 | More than 1billion |
| New engine core concepts | Not before 2020 | 2 | More than 1billion |
| Variable geometry Chevron | Already existing | 5 | 10 million |
| Non-Bryton cycles | Not before 2020 | 2 | 100 million |
| Engine retrofits | Already existing | 8 | 100 million |
| Variable fan noozle | Already existing | 7 | 10 million |

Table 1.1 Classification of some new technologies based on TRL, estimated investment required and availability [3]

In particular, in this thesis, we will divide new technologies by their field of applications. More precisely, these are the ones which will be treated:

- Drag Reduction Coatings (DRC)
- Active load alleviation
- Advanced alloys
- Fuel Cells
- Hybrid wing-body

AIRFRAME

- Variable geometry chevron
- Geared Turbofan
- Adaptive cycles
- Boundary layer ingesting inlet

ENGINE

- Hydro-processed renewable jet (HRJ)
- Liquid hydrogen

ALTERNATIVE FUELS

Once exhaustively described the main new technologies that are able to bring important benefits for the aerospace industry and for the whole world too, we will proceed with implementing a method to calculate the total cost of an aircraft that takes into account the implementation of a possible new technology into his project. This method has been obtained by implementing an algorithm on the Matlab software. It highlights the increases (or decreases) in the final cost of the aircraft following the implementation of new technologies on it. As a matter of fact, the new technology will

replace a component in use and, with this method, we will see if it costs more to produce and implement this technology or the component that has been normally used on it.
As a final argument, this thesis proposes two applicative examples of the method just discussed on small to medium range aircrafts (ATR-72 500 and A-320 200). It will be assumed to implement some new technologies on it and we will see how the final cost of them varies. More precisely, the new technologies that will be treated in this thesis are:

1) The morphing wing
2) Electric actuators
3) SHM system
4) Advanced propellers
5) Advanced EPGDS
6) Laminar aerodynamic
7) Geared turbofan
8) New engine materials
9) Adaptive winglets

For each of them, we will see how the four main cost categories change and, eventually, we will also see how these changes impact on the example application costs by using Matlab. Eventually, a consideration about the extra benefits a combination of 2 new technologies could bring will be done, showing the results in terms of money saved per each combination.

# CHAPTER 1

## 1.1 COST ESTIMATION

The main purpose of this chapter is to present the reader an accurate methodology that allows to calculate the total cost of an aircraft; from the initial idea to the end of its operational life. First of all, it is useful to define some terms that will often be used in this discussion:

- **COST** ⟶ The cost of an airplane is the total amount of expenditure of resources (measured in local currency) needed to manufacture that specific airplane.
- **PRICE** ⟶ The price of an aircraft is the amount of money paid for the aircraft by the customer (the latter may be a company or also a private customer)
- **PROFIT** ⟶ The profit can be easily calculated by doing the difference between cost and price: PROFIT = PRICE - COST. It is the amount of money (in local currency) that the aircraft manufacturer earns as a result of the sale of that specific airplane.

As previously said, the evolution of an airplane; from design to manufacturing, operation and finally disposal, (also known as: the airplane program) can be easily divided in 6 phases. Each of them has its own costs. In this chapter, we will treat each of these phases in detail; highlighting the main cost items of each one and we will also analyze what each specific phase deals with.

- **PHASE 1: Planning and conceptual design** ⟶ This phase consists primarily of mission requirements research. This eventually leads to a mission specification. During this step, the producer of the aircraft, starts to make a preliminary sizing of it: defining an initial layout of wing, fuselage and tail. Some important parameters such as the maximum take-off weight ($W_{TO}$), the maximum takeoff thrust ($T_{TO}$), the maximum lift coefficient ($C_{Lmax}$), the wing surface (S) and the weight per engine ($W_{eng}$) are discussed and analyzed in this phase.

- **PHASE 2**: **Preliminary design and system integration** $\longrightarrow$ In this phase, design trade studies are conducted to find a combination of technology and cost which will result in a viable airplane program. The decision of the layout of the wing, fuselage and empennage is fully completed. Moreover, the flap effects on stability control, the landing gear disposition and the propulsive system integration are studied at this step of the airplane program.
- **PHASE 3: Detail design and development** $\longrightarrow$ At this step of the airplane program, the aircraft and systems integration are finalized for certification flight testing and for production as well.
- **PHASE 4: Manufacturing and acquisition** $\longrightarrow$ During this phase, the airplane is manufactured and delivered to the customer.
- **PHASE 5: Operations and support** $\longrightarrow$ In this phase, the aircraft is being acquired by the user and is being operated with the accompanying support activities (maintenance, refueling, etc…)
- **PHASE 6: Disposal** $\longrightarrow$ This last phase marks the end of the operational life of the aircraft. Disposal activities may include the destruction of the airplane itself and disposal of the remaining materials. This step becomes strictly necessary when the airplane has reached the limit of its technological life.

Just for preliminary cost estimating purposes, the entire life cycle cost of an airplane program is broken down into 4 cost sources:

- **RDTE** (Research-Development-Test and Evaluation) **cost:** $C_{RDTE}$ $\longrightarrow$ This cost source accounts for all costs incurred in phases 1, 2 and 3. A method for estimating this cost is presented in chapter 1.2.
- **Acquisition cost:** $C_{ACQ}$ $\longrightarrow$ This cost source includes the manufacturing cost ($C_{MAN}$) and the manufacturer's profit ($C_{PRO}$). More precisely, this cost is the difference between these latter: $C_{ACQ} = C_{MAN} - C_{PRO}$. These costs are incurred during phase 4. A method for estimating this cost is presented in chapter 1.3.
- **Operating cost:** $C_{OPS}$ $\longrightarrow$ This cost source represents all the possible costs incurred while operating the airplane. The aircraft manufacturer and his suppliers usually incur certain support costs during this phase. These costs are incurred during phase 5. A method for estimating this cost is presented in chapter 1.4.

- **Disposal costs:** $C_{DISP} \longrightarrow$ This is the cost incurred in disposing of the airplane (phase 6). A method for estimating this cost is presented in chapter 1.5.

According to what has been written up to now, it is clear that the entire life cycle cost of an airplane program can be expressed as the sum of all these 4 cost sources:

$$LCC = C_{RDTE} + C_{ACQ} + C_{OPS} + C_{DISP} \tag{1.1}$$

As we can see in Figure 1.3, the operating cost source is much larger than the acquisition one. On the other hand, the latter is much larger than the research, development, test and evaluation cost source: $C_{OPS} >> C_{ACQ} >> C_{RDTE}$.

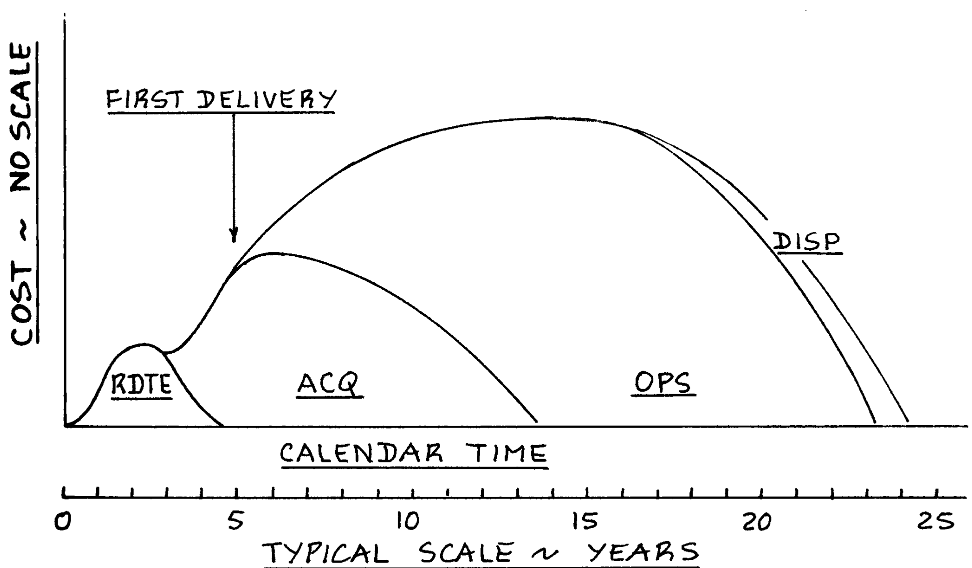


Figure 1.3 Schematic representation of life cycle cost history of typical airplane programs [4]

As previously said in the introduction, the conceptual and preliminary design phases are the ones that are responsible for locking in most of the life cycle cost of an aircraft. That leads to state that significant leverage affecting the life cycle cost exists only in these two phases.

In general, the objective of an aeronautical enterprise (no matter if it's a commercial one or a military one) is to make a profit. The profit made before taxes is referred to as the operating margin. Since the tax situation of a company may vary from year to year and from country to country, the operating margin of an enterprise is not the same as its profit. Anyway, whatever management goals are, the cost of the developing, certifying, producing and operating an aircraft must be known, with some certainty, before the decision to "launch" an airplane program is made. Moreover, because airplane programs take many years to evolve through the 6 phases, the inflation plays an important role in estimating program costs too.
Estimates for cost magnitudes are usually given in "then-year" dollars (or local currency). It is usual to scale cost data from one "then-year" to another with a cost escalation factor: CEF, as shown in figure 1.4.

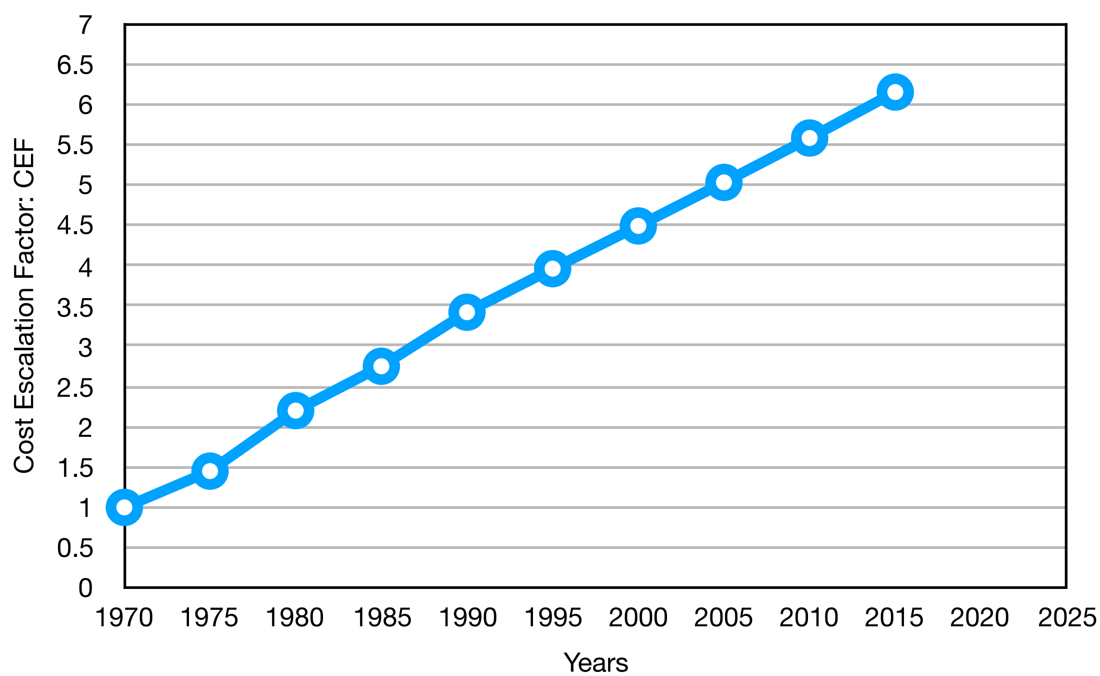


Figure 1.4 Variation of cost escalation factor with time [5]

The CEF has been arbitrarily set to a value of 1.0 for 1970 on the figure above. We can say that cost from one year to another may be scaled as follows:

$$Cost_{19XX} = Cost_{19XX}(\frac{CEF_{19XX}}{CEF_{19YY}}) \tag{1.2}$$

Where: the ratio $\frac{CEF_{19XX}}{CEF_{19YY}}$ is called: CEF ratio and the term $CEF_{19YY}$ must be different from $CEF_{19XX}$.

## 1.2 METHOD FOR ESTIMATING RDTE COST

The purpose of this chapter is to present a method for estimating research-development-test and evaluation cost for airplanes. This kind of cost is accumulated during phases 1,2 and 3. These phases include those activities which take a new aircraft all the way from the planning and conceptual design to its certification. This concept applies not only for commercial airplanes but also for military ones as well. RDTE costs are usually divided into seven cost categories:

- Airframe engineering and design cost: $C_{aedr}$
- Development support and testing cost: $C_{dstr}$
- Flight test airplane cost: $C_{ftar}$
- Flight test operations cost: $C_{ftor}$
- Test and simulation facilities cost: $C_{tsfr}$
- Cost to finance the RDTE phases: $C_{finr}$
- RDTE profit: $C_{pror}$

Very intuitively, it can be said that the total RDTE cost is given by the sum of these 7 categories:

$$C_{RDTE} = C_{aedr} + C_{dstr} + C_{ftar} + C_{ftor} + C_{tsfr} + C_{finr} + C_{pror} \tag{1.3}$$

Once we know what RDTE cost depends on, we can estimate the cost of each of these categories. Please note that in this thesis we only analyze the estimate of costs for commercial aircrafts and NOT for military ones, because parts of the model that will be dealt with soon might be different or there might even are other items that do not concern civil aviation (weapon, armaments, different avionics, etc…).
For what concerns the airframe engineering and design cost, we can say that it depends on many factors, such as:

1) Planning, conceptual design and associated cost studies
2) Preliminary design, system integration cost studies
3) Engineering for wind tunnel models, mock-ups and engine tests
4) Design of wind tunnel, models and mock-ups (Figure 1.5 records the number of wind tunnel tests needed for several airplane programs)
5) Design and construction of dedicated test facilities (if needed)
6) Detail design and development
7) Release and maintenance of drawings and specifications (the drawings can be both “hand-made” and CAD. The latter allows companies to reduce the cost of this phase)
8) Liaison with manufacturing and with vendors
9) Incorporation and analysis of design changes
10) Development of specifications for materials
11) Analysis of reliability, maintainability and accessibility

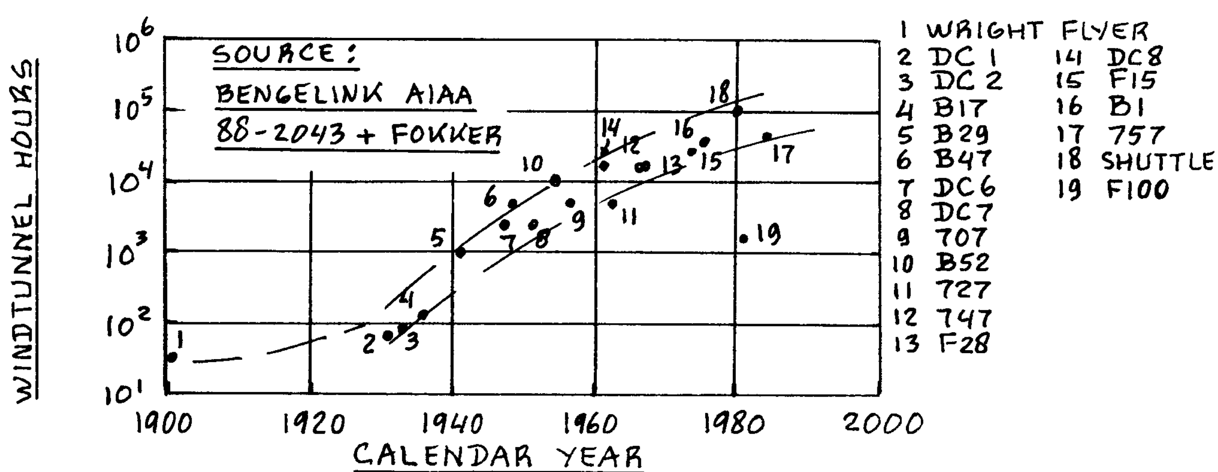


Figure 1.5 Wind tunnel hours required in typical aircraft programs [6]

The total engineering man-hours needed to complete phases 1-3 can be expressed with this following formula:

$$MHR_{aedr} = 0.04(W_{amapr})^{0.79}(V_{max})^{1.52}(N_{rdte})^{0.18}(F_{diff})(F_{cad}) \quad (1.4)$$

While, the airframe engineering and design cost associated with phases 1,2 and 3 can be estimated with:

$$C_{aedr} = MHR_{aedr} R_{er} \quad (1.5)$$

Where:

- $W_{ampr}$ is the so-called: Aeronautical-Manufacturers-Planning-Report. It can be computed using the below formula:

$$W_{ampr} = W_{empty} - (W_1 + W_2 + W_3 + W_4 + W_5 + W_6 + W_7 + W_8) \quad (1.6)$$

where: $W_1$ is the weight of wheels, brakes, tires and tubes (please note that this is NOT the total landing gear weigh). $W_2$ represents the weight of the engines and $W_3$ is the weight of the starter. $W_4$ is the weight of the cooling fluid used to cool down the engines while they work. $W_5$ represents the weight of batteries, electrical power supply, and electrical power conversion equipments. $W_6$ is the weight of all the avionic equipment. Finally, $W_7$ is the weight of air-conditioning units and $W_8$ is the weight of the APU. All of the are expressed in kg.
Note that these 8 items are NOT normally manufactured by the airplane company. They are rather purchased from vendors.

- $V_{max}$ is the maximum design speed of the aircraft (in kts)
- $N_{rdte}$ is the number of airplanes built during RDTE phases
- $F_{diff}$ is a judgment factor which accounts for the difficulty of a new airplane program (1 for conventional airplanes; 1.5 for programs involving a moderately aggressive use of advanced technology and 2 for programs involving a very aggressive use of advanced technology)
- $F_{cad}$ is a judgment factor accounting for the effect of CAD capability on airframe engineering and design cost (1.2 for manufacturers which are in CAD learning mode; 1 for manufacturers which are using manual drifting techniques and 0.8 for manufacturers which are highly experienced in the use of CAD)
- $R_{er}$ is the engineering dollar rate (or local currency used) per hour charged for the airframe engineering activity. However, as this information is usually hard to find out, it is preferred to use currently hourly rates (see Figure 1.6).

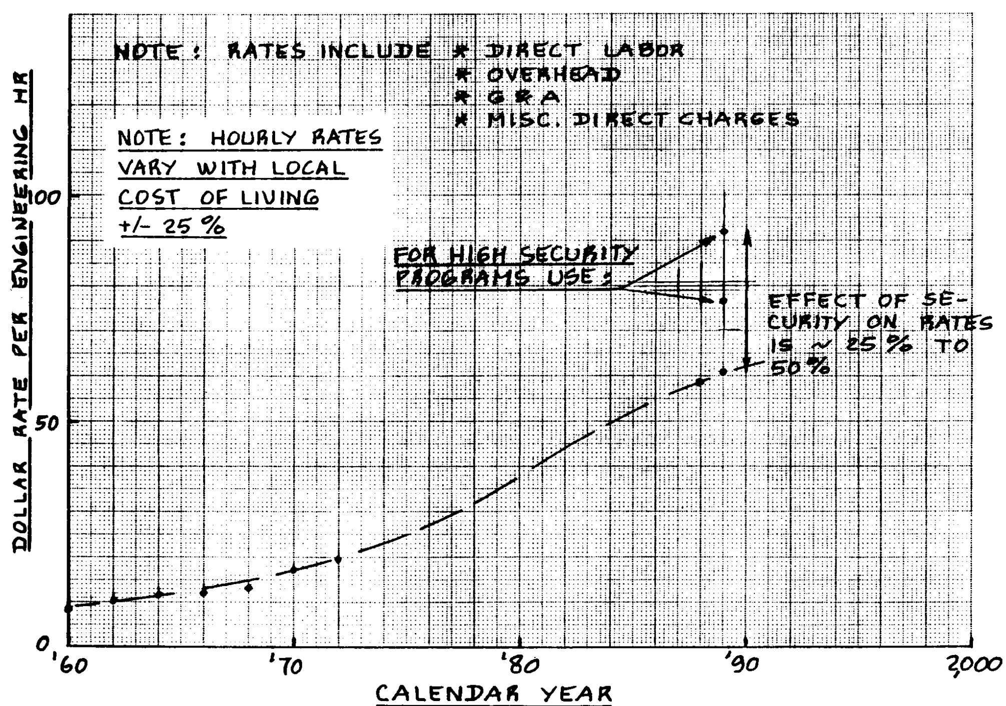


Figure 1.6 Variation of engineering man hour rates during the years [7]

For what concerns the second of the seven categories, we can say that typical activities which are responsible for the development, support and testing costs are:

1) Wind tunnel testing
2) Systems testing
3) Structural testing
4) Propulsion testing

The total cost of the above named activities is called: $C_{dstr}$ and it is estimated by using the following empirical formula:

$$C_{dstr} = 0.008(W_{ampr})^{0.87}(V_{max})^{1.9}(N_{rdte})^{0.34}(CEF)(F_{diff}) \tag{1.7}$$

Now that the first two categories are fully treated, we can discuss about the flight test airplanes cost ($C_{ftar}$). This cost category is normally broken down into the following cost components:

- $C_{(e+a)r}$ → Cost of engines and avionics
- $C_{manr}$ → Manufacturing labor cost
- $C_{matr}$ → Manufacturing material cost
- $C_{tool}$ → Tooling cost
- $C_{qcr}$ → Quality control cost

The total flight test airplanes cost is obtained by summing all these last cost components:

$$C_{ftar} = C_{(e+a)r} + C_{manr} + C_{matr} + C_{tool} + C_{qcr} \tag{1.8}$$

More precisely, the term $C_{(e+a)r}$, can be expressed as:

$$C_{(e+a)r} = (C_{er}N_e + C_{avionics} + C_{pr}N_p)(N_{rdte} - N_{st}) \tag{1.9}$$

Where:

- $C_{er}$ is the cost per engine
- $N_e$ is the number of engines per aircraft
- $C_{pr}$ is the cost per propeller
- $N_p$ is the number of propellers per airplane (please note that $N_p$ is not necessary the same as $N_e$)
- $N_{st}$ is the number of static test airplanes (these latter are NOT normally equipped with engines, propellers and avionic systems)

There is a formula to calculate the manufacturing cost of the flight test aircrafts ($C_{manr}$):

$$C_{manr} = (MHR_{manr})R_{mr} \tag{1.10}$$

Where $MHR_{manr}$ is the number of manufacturing man-hours required from phase 1 to phase 3. This parameter may be calculated as:

$$29(W_{ampr})^{0.74}(V_{max})^{0.54}(N_{rdte})^{0.52}(F_{diff}) \tag{1.11}$$

And $R_{mr}$ is the manufacturing labor rate in dollars (or local currency) per man-hour.
With the parameter $C_{matr}$ we mean the cost of materials to manufacture the flight test airplanes. Again, we can use an empirical formula to determine it:

$$C_{matr} = 37.63(F_{mat})(W_{ampr})^{0.69}(V_{max})^{0.62}(N_{rdte})^{0.79}(CEF) \tag{1.12}$$

Where the parameter $F_{mat}$ is a correction factor which depends on the type of materials used in the construction of the aircraft ($F_{mat}$= 1 for airplanes made primarily of conventional aluminum alloys; $F_{mat}$ = 1.5 for stainless steel airframes; $F_{mat}$ = 2 for aircrafts where the primary structure is made with composite materials; Li-Al alloys and/or ARAL; $F_{mat}$ = 3 for carbon composites airframes).

For what concerns the tooling cost ($C_{tool}$), we can say that this kind of cost is associated with the manufacturing of flight test airplanes. It can be estimated from:

$$C_{tool} = (MHR_{toolr})R_{tr} \tag{1.13}$$

Where $MHR_{toolr}$ represents the tooling men-hours required during phases 1-3 and $R_{tr}$ is the tooling labor rate in dollars (or local currency) per men-hour. This last parameter is easily found by consulting Figure 1.5. Moreover, it is possible to express $MHR_{toolr}$ as follows:

$$MHR_{toolr} = 4.01(W_{ampr})^{0.76}(V_{max})^{0.9}(N_{rdte})^{0.18}(N_{rr})^{0.06}(F_{diff}) \tag{1.14}$$

Where $N_{rr}$ is the RDTE production rate per month (a typical value of it is 0.33 units per month).

Last but not the least, we have to discuss the quality control parameter: $C_{qcr}$. It includes every cost needed during quality checks when manufacturing the flight test airplanes. It can be calculated with the following empirical formula:

$$C_{qcr} = 0.13(C_{manr}) \tag{1.15}$$

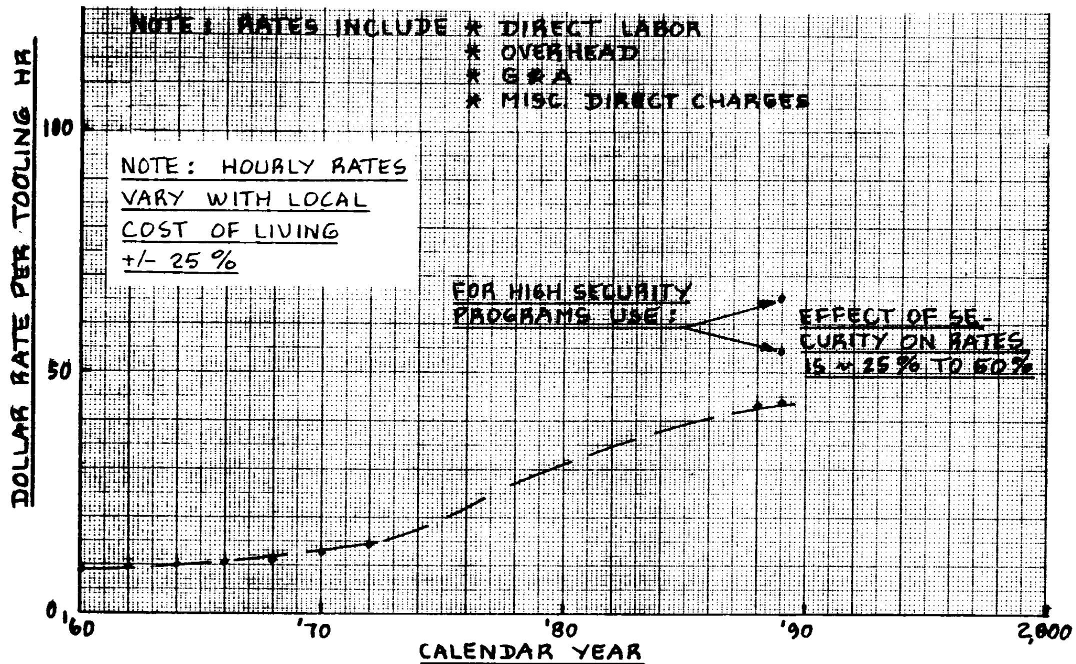


Figure 1.7 Variation of tooling men-hour rates during time [8]

For what concerns the fourth category: the flight test operations cost ($C_{ftor}$), we can say that it is strongly influenced by two different cost categories:

1) Flight testing of flight test airplanes
2) Simulation activities associated with flight testing

The total cost for these activities may be calculated from:

$$C_{ftor} = 0.001(W_{ampr})^{1.16}(V_{max})^{1.37}(N_{rdte} - N_{st})^{1.28}(CEF)(F_{diff})(F_{obs}) \tag{1.16}$$

In many airplane programs, it will be found necessary to build new, dedicated test facilities, especially when testing new technologies. Unfortunately, there are not sufficient data in the literature to predict this type of cost. If, because of the special nature of the aircraft, new facilities must be constructed, then it is suggested to use this following formula to predict the test and simulation facilities cost:

$$C_{tsf} = (F_{tsf})C_{rdte} \tag{1.17}$$

Where $F_{tsf}$ is a cost adjustment factor that can just assume 2 values: $F_{tsf}$ = 0 if no extra facilities are required or $F_{tsf}$ = 0.2 if extra facilities are required.

In many instances, a manufacturer will borrow money to finance the RDTE phases. Borrowing money in turn costs money. Methods for estimating these costs are far beyond the purpose of this thesis. However, it is important to keep in mind this cost because it might result in huge amount of money at the end of the airplane program. Lacking better information, we can estimate this kind of cost from:

$$C_{finr} = (R_{finr})C_{RDTE} \tag{1.18}$$

Where $0.1 < R_{finr} < 0.2$ depending on the interest rates which are available.

In 99.9% of cases, an aircraft enterprise will want to make a profit on RDTE activities. The profit cost category may be estimated from:

$$C_{pror} = (F_{pror})C_{RDTE} \tag{1.19}$$

Where $F_{pror}$ is normally equal to 0.1 for a suggested profit of 10%. Please note that the actual profits are strongly influenced by market conditions and by management strategies.

## 1.3 METHOD FOR ESTIMATING MANUFACTURING AND ACQUISITION COST

The main goal of this chapter is to give the reader a method for estimating manufacturing costs: $C_{MAN}$ and acquisition costs as well: $C_{ACQ}$. These 2 cost categories are incurred during phase 4 of an airplane program. The difference between them gives the profit made by the manufacturer itself:

$$C_{ACQ} = C_{MAN} + C_{PRO} \tag{1.20}$$

If we want to calculate the price paid by the user of an airplane (which is his acquisition cost), we can use this empirical formula:

$$AEP = \frac{C_{MAN} + C_{PRO} + C_{RDTE}}{N_m} \tag{1.21}$$

Where AEP stands for Aircraft-Estimated-Price and $N_m$ represents the number of aircrafts produced to production standard during an airplane program. This last formula is only valid if we make two assumptions. The first one is that no spare parts are bought by the user (in most cases, customers will want to buy a certain number of spare parts) and the second one is that the RDTE airplanes are not sold during the program.

The total airplane program manufacturing cost can be easily found by summing up these following cost categories:

- Airframe engineering and design cost : $C_{aedm}$
- Airplane production cost: $C_{apcm}$
- Production flight test operations cost: $C_{ftom}$
- Cost of financing the manufacturing program: $C_{finm}$

Let's start by analyzing the first one. The airframe engineering and design typically consists of these activities:

1) Engineering design work necessitated by problems uncovered during phases 1,2 and 3.
2) Design studies due to special customers requests
3) Eventual mistakes made during the manufacturing process or changes made while manufacturing of components.
4) Release of drawings (or CADs) and specifications
5) Liaison engineering with manufacturing and with vendors
6) Incorporation and analysis of design changes
7) Development of specifications for materials and processes
8) Analysis of reliability, maintainability and accessibility

The total cost of all the activities listed above can be expressed with the following formula:

$$C_{aedm} = [(MHR_{aedprogram})R_{em}] - C_{aedr} \tag{1.22}$$

Where:

- $(MHR_{aedprogram})$ is the total amount of engineering men-hours needed for the whole airplane program. This term can be estimated from:

$$MHR_{aedprogram} = 0.04(W_{ampr})^{0.8}(V_{max})^{1.52}(N_{program})^{0.18}(F_{diff})(F_{cad}) \tag{1.23}$$

Where $N_{program}$ is the number of aircrafts produced during an airplane program.

- $R_{em}$ represents the engineering men-hour rate in dollars (or local currency) per hour for the entire airplane program. It is assumed equal to $R_{er}$ most of the times

For what concerns the airplane program production cost ($C_{apcm}$), we can say that it normally consists of the following cost components:

1) Cost of engines and avionics (acquired from vendors): $C_{(e+a)_m}$
2) Cost of the interiors: $C_{intm}$
3) Manufacturing labor cost: $C_{manm}$
4) Manufacturing material cost: $C_{matm}$
5) Tooling cost: $C_{toolm}$
6) Quality control cost: $C_{qcm}$

We can easily compute $C_{apcm}$ as the sum of all the above listed terms:

$$C_{apcm} = C_{(e+a)_m} + C_{intm} + C_{manm} + C_{matm} + C_{toolm} + C_{qcm} \tag{1.24}$$

The first cost category is probably the most important one of the whole 6. As a matter of fact, in commercial airplanes the total cost of avionics range from 5% to 15% of the aircraft total cost. It can be estimate using a similar formula to 1.9:

$$C_{(e+a)_m} = (C_{em}N_e + C_{avionics} + C_{pm}N_p)N_m \tag{1.25}$$

The terms $C_{em}$ e $C_{pm}$ are respectively the cost per engine during the manufacturing phase and the cost per propeller during that same phase. Please note that they might be different from the ones used in formula 1.9 ($C_{er}$ and $C_{pr}$).

The interior cost is very difficult to determine and there are no exact formulas to calculate it. This happens because $C_{intm}$ depends on many factors such as: the type of commercial aircraft that is manufactured (cargo or passenger), the number of passengers that it can accommodate and safety constraints (in case of fire, for example, seats must not give off toxic substances). This cost category is generally expressed in “USD per passenger” (or local currency).

Now that we went through the first two categories, we can talk about the manufacturing labor cost. It is defined as the labor cost incurred in manufacturing $N_m$ airplanes to production standards. It can be estimate as follows:

$$C_{manm} = (MHR_{manprogram})R_{mm} - C_{manr} \tag{1.26}$$

Where $R_{mm}$ is the manufacturing labor rate per hour for the entire program (usually assumed equal to $R_{mr}$ and $MHR_{manprogram}$ represents the total men-hour required for the manufacturing of $N_{program}$ aircrafts and it can be calculated with the following formula:

$$MHR_{manprogram} = 29(W_{ampr})^{0.74}(V_{max})^{0.54}(N_{program})^{0.52}(F_{diff}) \tag{1.27}$$

For what concerns the material cost incurred when manufacturing $N_m$ airplanes to production standards, we can say that it may be found from this equation:

$$C_{matm} = C_{matprogram} - C_{matr} \tag{1.28}$$

Where $C_{matprogram}$ is the total materials cost associated with building $N_{program}$ airplanes. It can be estimate this way:

$$C_{matprogram} = 37.6F_{mat}(W_{ampr})^{0.69}(V_{max})^{0.62}(N_{program})^{0.79}(CEF) \tag{1.29}$$

Nevertheless, the tooling cost plays an important role in determining an airplane program production cost. It is defined as the tooling cost needed to produce $N_m$ aircrafts and it can be expressed as:

$$C_{toolm} = (MHR_{toolprogram})R_{tm} - C_{toolr} \tag{1.30}$$

Where $R_{tm}$ is the tooling for rate in local currency per men-hour and it's usually the same as $R_{tr}$ while $MHR_{toolprogram}$ represents the total number of tooling men-hours required to produce $N_{program}$ airplanes. It can be estimate with the following empirical formula:

$$MHR_{toolprogram} = 4(W_{ampr})^{0.76}(V_{max})^{0.9}(N_{program})^{0.18}(N_{rm})^{0.06}(F_{diff}) \tag{1.31}$$

Where $N_{rm}$ is the aircraft manufacturing rate in units per month.
Eventually, the quality control cost associated with building $N_m$ airplanes can be easily calculated with: $C_{qcm} = 0.13(C_{manm})$ which is very similar to (1.15).

For what concerns the third category: the production flight test operations cost ($C_{ftom}$), we can say that it can be easily computed with:

$$C_{ftom} = N_m(C_{ops/hr})(t_{pft})(F_{ftoh}) \tag{1.32}$$

Where:

- $N_m$ is the number of airplanes built to production standards
- $C_{ops/hr}$ represents the airplane operating cost per hour

- $t_{pft}$ represents the number of flight test hours flown by the manufacturer before aircraft delivery to the customer ($t_{pft}$ = 2 hrs for general aviation airplanes and $t_{pft}$ = 10 hrs for jet transports)
- $F_{ftoh}$ is the overhead factor associated with the production flight test activities (it is generally equal to 4)

There is no point in discussing the last cost category (cost of financing the manufacturing program: $C_{finm}$) because it is possible to use the same equations (1.18 and 1.19) to calculate it, provided that $C_{MAN}$ is used instead of $C_{RDTE}$.

## 1.4 METHOD FOR ESTIMATING OPERATING COST

The purpose of this chapter is to give a method for calculating the operating cost of commercial airplanes: $C_{OPS}$. As commercial aircrafts production may vary considerably from year to year, it is important to make this assumption: whatever numbers of airplanes are acquired by different operators, they are acquired in one particular year and at one particular price. The operating cost source is divided into two cost categories:

$$C_{OPS} = \sum_{i=1}^{N} (C_{OPS_d})_i (N_{acq})_i + \sum_{i=1}^{N} (C_{OPS_{in}})_i (N_{acq})_i \qquad (1.33)$$

Where:

- $(C_{OPS_d})_i$ represents the program direct operating cost for the $i^{th}$ airplane customer expressed in USD per aircraft (or local currency). This cost may be expressed with the following formula:

$$(C_{OPS_d})_i = (DOC)_i (R_{bl})_i N_i \tag{1.34}$$

- $DOC_i$ is the direct operating cost per nm (nautical mile) of the airplane as flown by the $i^{th}$ customer (expressed in USD/nm or local currency)
- $(R_{bl})_i$ represents the total annual nautical miles flown by the $i^{th}$ customer
- $N_i$ is the number of years during which the aircraft is operated by the $i^{th}$ customer (normally: $N_i$ = 20 years for commercial aircrafts)

- $(N_{acq})_i$ is the number of airplanes acquired by the $i^{th}$ customer
- $(C_{OPS_{in}})_i$ represents the program direct operating cost for the $i^{th}$ airplane customer expressed in USD per aircraft (or local currency). The following formula is normally used to estimate this kind of cost:

$$(C_{OPS_{in}})_i = (IOC)_i (R_{bl})_i N_i \tag{1.35}$$

- $IOC_i$ is the indirect operating cost per nautical mile the airplane as flown by the $i^{th}$ customer, expressed in USD/nm or local currency

As the reader may have noticed, $C_{OPS}$ has been expressed as a sum over $i$ customers. This happens because direct and indirect costs vary considerably from one customer to another. Another assumption that we do in this chapter is that we consider the operating cost equal for every customer in order to simplify the calculations. Consequentially, for the remainder of this chapter, the subscript $i$ will therefore be omitted without ambiguity.

For what concerns the total annual block miles ($R_{bl}$), we can say that it can be expressed as:

$$R_{bl} = V_{bl}U_{bl} \tag{1.36}$$

Where:

- $V_{bl}$ is the block speed in nautical miles per hour (nm/hr). If we consider no wind affecting the airplane, we can calculate this term by dividing the block distance (in nm) by the the block time (in hours):

$$V_{bl} = \frac{R_{bl}}{t_{bl}} \tag{1.37}$$

- $U_{bl}$ represents the annual utilization of the aircraft, expressed in block hours. It mainly depends on the kind of airplane used and on routes flown by it.

More precisely, the block distance $R_{bl}$ depends on the routes flown by the airplane. The longer the route, the higher $R_{bl}$ will be. Moreover, we can calculate the block time $t_{bl}$ as the sum of various times, as suggested in the following formula:

$$t_{bl} = t_{gm} + t_{cl} + t_{cr} + t_{de} \tag{1.38}$$

An accurate description of it can be found in figure 1.9. In particular, $t_{gm}$ represents the time spent in ground maneuvers in general (pulling away from the gate, taxing to the runway, takeoff run, landing ground run, taxing to the gate). In Figure 1.6, $t_{gm}$ is split in two terms: $t_{gm_1}$ (representing takeoff maneuvers) and $t_{gm_2}$ (representing landing maneuvers). Anyway, the term $t_{gm}$ is expressed in hours and it can be calculated using 1.39.

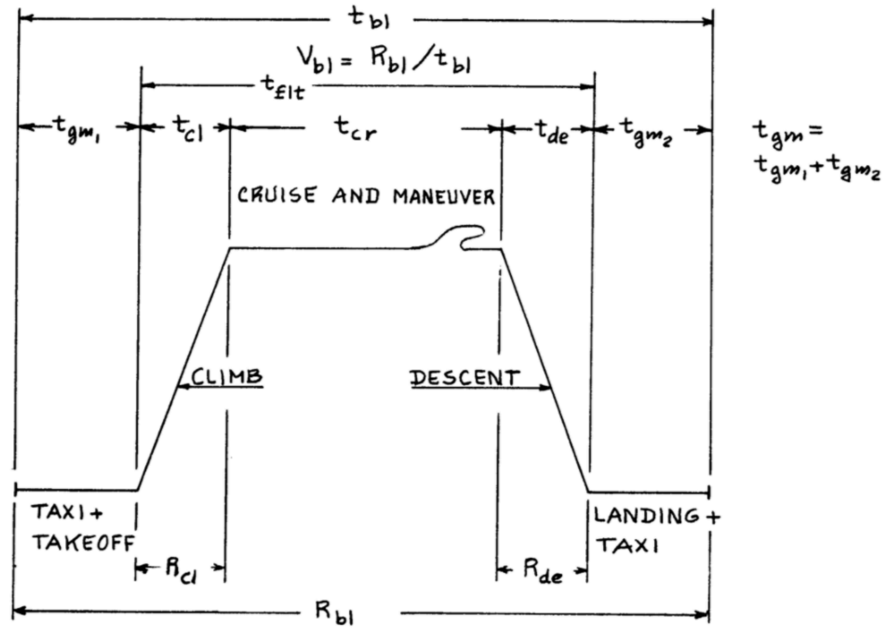


Figure 1.8 Mission profile definition [9]

$$t_{gm} = 0.51 \bullet 10^{-6}(W_{TO}) + 0.125 \tag{1.39}$$

The term $t_{cl}$ is the time needed for the aircraft to climb and to accelerate to cruise speed, expressed in hours. On the other hand, the time spent in cruise (also expressed in hours) is called $t_{cr}$ and it can be obtained by using the formula 1.40.

$$t_{cr} = \frac{(R_{bl} - R_{cl} - R_{de} + R_{man})}{V_{cr}} \tag{1.40}$$

Where:

- $R_{cl}$ is the space an airplane needs to climb and to accelerate to cruise speed, in nm. It can be expressed as:

$$R_{cl} = V_{cl} t_{cl} \tag{1.41}$$

- $V_{cl}$ represents the TAS (True-Air-Speed) of the aircraft during the climb measure in kts

- $R_{de}$ is the distance covered by the airplane during its descent, expressed in nm. The following formula allows us to calculate it:

$$R_{de} = V_{de} t_{de} \tag{1.42}$$

- $V_{de}$ and $t_{de}$ are the TAS of the aircraft during its descent phase and the time it needs to descend also expressed in kts

- $R_{man}$ is the distance covered by the airplane while maneuvering because of Air-Traffic-Control (ATC) constraints. It is always expressed in nautical miles. In particular:

$$R_{man} = V_{man} t_{man} \tag{1.43}$$

- $V_{man}$ represents the speed of the aircraft when maneuvering is required by ATC constraints. It is suggested to use: $V_{man}$ = 250 kts if the airplane is below 10,000 ft and $V_{man} = V_{cr}$ when the airplane is above 10,000 ft.
- $t_{man}$ is the time spent during air traffic control maneuvers, in hrs.

By using the term $V_{cr}$, we refer to the airplane cruise speed. This speed is normally an aircraft mission specification and we don't need to calculate it. Finally, for what concerns the annual utilization of the airplane in block hours ($U_{bl}$), we can say that it is strongly influenced by the type of aircraft and by the routes flown. Unfortunately, there are no exact formulas which allow us to determine it for it depends on too many variables. A representative utilization data for some types of airplanes is found in tables 1.2 and 1.3.

| | **A320** | **B-737** | **B-757** |
|---|---|---|---|
| **American Airlines** | 7.8 | 9.2 | 8.8 |
| **United** | 9.2 | 7.9 | 8.0 |
| **Delta** | 8.9 | 7.9 | 8.4 |

Table 1.2 2017 airplane utilization of narrow-body jets in block hours per day [10]

| | **A-350** | **B-777** | **B-787** |
|---|---|---|---|
| **American Airlines** | 9.0 | 10.2 | 9.7 |
| **United** | 8.4 | 11.2 | 8.0 |
| **Delta** | 7.0 | 10.8 | 8.6 |

Table 1.3 2017 airplane utilization of wide-body jets in block hours per day [11]

## 1.5 DIRECT OPERATING COSTS

As we saw in equation 1.33, the operating cost of an airplane is strongly influenced by its direct operating costs (DOC). The purpose of this section is to present a method for estimating these kind of costs incurred while operating commercial aircrafts. First thing first, what do we mean with “direct operating costs”?. They can be defined as the costs of resources used by an organization just to maintain the existence of its products. The method that will be soon presented is called: the ATA-method and it can be applied only to passenger commercial airplanes. It consists of dividing all the direct operating costs into various categories of cost. As a matter of fact, we can express DOC as a sum of the following terms:

DOC = $DOC_{fl} + DOC_{maint} + DOC_{depr} + DOC_{lnr} + DOC_{fin}$ (1.44)

Where:

1) $DOC_{fl}$ is the direct operating cost of flying
2) $DOC_{maint}$ represents the direct operating cost of maintenance
3) $DOC_{depr}$ is the direct operating cost of depreciation
4) $DOC_{lnr}$ is the direct operating cost of landing fees, navigation fees and registry taxes
5) $DOC_{fin}$ represents the direct operating cost of financing

For what concerns the first of these 5 categories, we can say that it depends on 3 different elements: the crew cost ($C_{crew}$), the fuel and oil cost ($C_{pol}$, where: “pol” stands for: petroleum-oil-lubricants) and the airframe insurance cost ($C_{ins}$). All of them are measured in USD/nm (or local currency). As a matter fact:

$$DOC_{fl} = C_{crew} + C_{pol} + C_{ins} \tag{1.45}$$

The crew cost regroups the salaries of the captain, the copilot and the flight engineer (per nautical mile), that are on board of the aircraft during its operations. There are no precise formulas that predicts the exact cost of this category in literature. This happens because the number of crew members which must be carried depends on government regulations and these regulations are different from country to country. Please note that flight attendants are not considered as “crew” and their cost goes under the indirect operating costs (see section 1.6).
On the other hand, an expression that allows us to determine $C_{pol}$ exists indeed. It it shown in 1.46.

$$C_{pol} = (\frac{W_{F_{bl}}}{R_{bl}} \frac{F_P}{F_D}) \bullet (\frac{W_{OL_{bl}}}{R_{bl}} \frac{O_{LP}}{O_D}) \qquad (1.46)$$

Where:

- $W_{F_{bl}}$ is the block fuel used in kg and it is the same as the mission fuel used

<u>NOTE :</u> The mission fuel consumption (which obviously affects $W_{F_{bl}}$) of an airplane tends to decrease with the passing of time because of the following reasons:

— Engine deterioration
— Airframe surface deterioration (seals, finish, etc…)

In order to consider this factor, it is suggested to use a 0.5% increase in fuel consumption per year of service.

- $R_{bl}$ represents the block distance in nautical miles
- $F_P$ is the fuel price measured in USD/gallon (or local currency). There is no accurate way to predict how fuel prices will vary in the future (for it depends on too many variable); however Figure 1.9 shows how fuel prices have varied from 2010 till 2016
- $F_D$ is the fuel density in kg/gallons. There are many jet fuels available at the moment (Jet A, Jet A-1 and Jet B) but they all have the same density: 3.8 kg/gallon.
- $W_{OL_{bl}}$ represents the total weigh of oil and lubricants used measured in kg. It strongly depends on the powerplants and systems in need of lubricants.

In particular, for turbine engines, $W_{OL_{bl}}$ can be estimated as follows:

$$W_{OL_{bl}} = 0.7 N_e t_{bl} \tag{1.47}$$

Where $N_e$ represents the number of engines the aircraft is equipped with and $t_{bl}$ can be found by reversing formula 1.37.

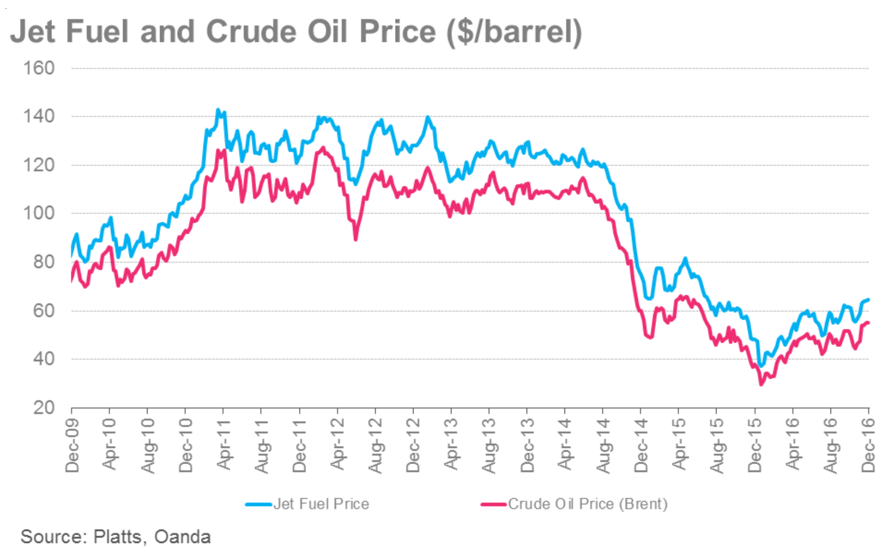


Figure 1.9 Variation of fuel prices from 2009 till 2016 [12]

NOTE: A barrel of oil is defined as 1 barrel = 42 gallons or 1 barrel = 159 liters (as 1 gallon is 3.78 liters)

- $O_D$ is the oil density in kg/gallon (it is normally equal to 3.33 kg/gallon)
- $O_{LP}$ represents the price of oil and lubricants in USD/gallon (or local currency)

Just like in case of fuel prices, there is no accurate way to forecast oil prices in the future. Finally, we can say that there is another method to calculate the direct operating cost of oil and lubricants. It just consists on assuming that cost as the 5% of the direct operating cost of fuel.

For what concerns $C_{ins}$, airplane operators carry airframe insurance for the following reasons:

1. Ground and in flight risk of experiencing airframe damage or total loss
2. Passenger liability in case of injury/death
3. Third party liability in case of injury/death

Insurance rates highly depends on the so-called hull loss rate. The hull loss rate is defined as number of planes crashed over the number of planes flying safely in a certain amount of time. Figure 1.10 gives the reader an idea of the average number of flight accidents in the world and how this trend decreased with the passing of time thanks to the increase of safety measures. Talking about a method to estimate the cost of airframe insurance per nautical mile is far beyond the goal of this thesis but it is normally accepted worldwide to calculate this cost as the 2% of the whole direct operating costs ($C_{ins} = 0.02DOC$).

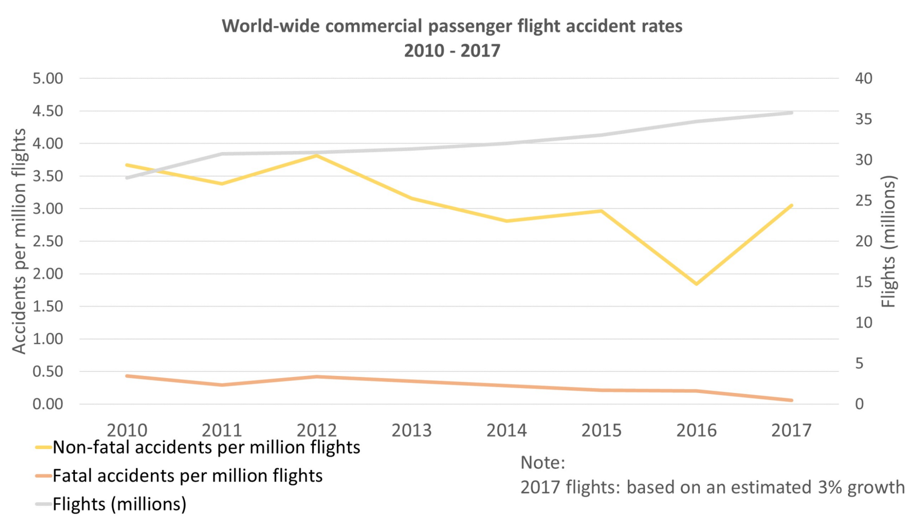


Figure 1.10 Flight accidents per million flights in the world from 2010 until 2017 [13]

Doing maintenance works on the aircraft is a very important as well and it constitutes a big part of all the direct operating costs presented at page 32. As a matter of fact, $DOC_{maint}$ can be expressed as the sum of these following 5 categories:

1) $C_{lab-ap} \longrightarrow$ is the labor cost of airframe and systems maintenance in USD/nm (or local currency). It can be estimate as follows:

$$C_{lab-ap} = 1.03\frac{(MHR_{map-bl})R_{l-ap}}{V_{bl}} \tag{1.48}$$

Where: $MHR_{map-bl}$ represents the number of airframe and systems maintenance men hours needed per block hours; $R_{l-ap}$ is the airplane maintenance labor rate expressed in USD/hr and $V_{bl}$ is the block speed. Table 1.4 shows the maintenance men-hours per flight hour related to the annual utilization of the airplane.

| Airplane type | Annual utilization (in flight hours) | Maintenance men-hours per flight hour |
|---|---|---|
| **B-737-800** | 20,900 | 62,7 |
| **B-747-400** | 33,450 | 135.75 |
| **A-320** | 30,400 | 128.25 |

Table 1.4 Maintenance men-hours data for some commercial airplanes [14]

2) $C_{lab-eng} \longrightarrow$ is the labor cost of engines maintenance in USD/nm (or local currency). The following empirical formula allows us to determine it:

$$C_{lab-eng} = 1.03N_e\frac{(MHR_{meng-bl})R_{l-eng}}{V_{bl}} \tag{1.49}$$

Where: $(MHR_{meng-bl})$ represents the number of engine maintenance hours required per block hour per engine and $R_{l-eng}$ is the engine maintenance labor rate per men-hour in USD/hr (or local currency). For modern commercial aircrafts with highly mature engines, the trend is for the engine maintenance men-hours to constitute about 10% of the total maintenance men-hours per flight hour.

3) $C_{mat-ap} \longrightarrow$ it represents the cost of maintenance materials for the airframe and systems, in USD/nm (or local currency). It can be expressed with the following formula:

$$C_{mat-ap} = 1.03\frac{(C_{mat-apblhr})}{V_{bl}} \tag{1.49}$$

Where: $C_{mat-apblhr}$ is the airframe and systems maintenance cost per airplane block hour, measured in USD/hr (or local currency).

4) $C_{mat-eng} \longrightarrow$ is the cost of maintenance materials for the engines in USD/nm (or local currency). There is a formula to calculate it and that is:

$$C_{mat-eng} = 1.03N_e\frac{(C_{mat-engblhr})}{V_{bl}} \tag{1.50}$$

Where $C_{mat-engblhr}$ represents the engine maintenance materials cost per engine per aircraft block hour, measured in USD/hr (or local currency).

5) $C_{amb} \longrightarrow$ it represents the applied maintenance burden in USD/nm (or local currency). It may be estimated from:

$$C_{amb} = \frac{1.03[(f_{amb-lab}MHR_{map-bl}R_{l-ap}) + (N_eMHR_{eng-bl}R_{l-eng}) + f_{amb-mat}(C_{mat-apblhr} + N_eC_{mat-engblhr})]}{V_{bl}} \tag{1.51}$$

In particular, $f_{amb-lab}$ and $f_{amb-mat}$ are two factors that take into account cost sources such as: building, lighting, heating as well as administrative costs associated with airplane maintenance, where: $1 < f_{amb-lab} < 1.4$ and $0.4 < f_{amb-mat} < 0.7$, depending on the airplane company. Finally, the reader must have noticed that formulas 1.48-1.51 are all multiplied by 1.03. That happens because extra maintenance costs due to flight delays are accounted in every formula related to maintenance costs.

Another important factor that plays an important role in calculating direct operating costs is the depreciation. It can be defined as: a method of reallocating the cost of a tangible asset over its useful life span of it being in motion. It is the diminution in the value of an asset during time. The direct operating cost depreciation can be computed as the sum of the depreciation costs of every single part of the aircraft. As a matter of fact:

$$DOC_{depr} = C_{dap} + C_{deng} + C_{dprp} + C_{dav} + C_{dapsp} + C_{dengsp} \tag{1.52}$$

Where:

- $C_{dap}$ is the cost of airplane depreciation without considering engines, propellers, avionics systems and spare parts
- $C_{deng}$ represents the cost of engine depreciation without propellers mounted on it in $C_{dprp}$ is the cost of depreciation of propellers
- $C_{dav}$ is the cost of depreciation of all avionics systems
- $C_{dapsp}$ represents the cost of depreciation of the airplane spares
- $C_{dengsp}$ is the cost of depreciation of the engine spare parts

All these depreciation costs are expressed in USD/nm (or local currency). For a more precise discussion about the depreciation periods used by many companies and the residual value of the above mentioned aircraft parts, see Figure 1.11.

| Item | Suggested Depreciation Period | | Residual Value in Percent | Depreciation Factor* | |
|---|---|---|---|---|---|
| Airframe | $DP_{ap}$ | = 10 | 15 | $F_{dap}$ | = 0.85 |
| Engines | $DP_{eng}$ | = 7 | 15 | $F_{deng}$ | = 0.85 |
| Propellers | $DP_{prp}$ | = 7 | 15 | $F_{dprp}$ | = 0.85 |
| Avionics | $DP_{av}$ | = 5 | 0 | $F_{dav}$ | = 1.00 |
| Airplane Spares | $DP_{apsp}$ | = 10 | 15 | $F_{dapsp}$ | = 0.85 |
| Engine Spares | $DP_{engsp}$ | = 7 | 15 | $F_{dengsp}$ | = 0.85 |

* Depreciation factor =

= {1 - (Residual Value)/(Original Price)}

Figure 1.11 Most commonly used depreciation periods and depreciation factors for aircraft parts [15]

For what concerns the direct operating cost of landing fees and registry taxes, we can say that they both depend on the airplane size (the bigger the airplane, the more expensive these two are), local airport authorities decisions and on the government decisions. On the other hand, the direct operating cost of navigation fees is highly influenced by the type of rout the aircraft is doing (the longer the route, the more expensive the fee will be). All the three of them are measured in USD/nm (or local currency).

Finally, the direct operating cost of financing the airplane depends on the way an operator is financing his fleet of aircrafts. Methods and formulas used to estimate this cost category are far beyond the scope of this thesis, but we can say that financing costs normally run to 7% of the whole DOC as found from equation 1.44.

## 1.6 INDIRECT OPERATING COSTS

The main goal of this section is to give the reader an idea of what indirect operating costs consists of, while operating a commercial airplane. As a matter of fact, the indirect costs associated with aircraft operations vary significantly from one enterprise to another. Also, the airplane designers have very little influence over this cost category. The indirect operating cost per nautical mile can be measured as the sum of these following cost components:

$$IOC = IOC_{pax} + IOC_{asfc} + IOC_{pse} + IOC_{gaa} \tag{1.53}$$

Where:

- $IOC_{pax}$ represents the indirect operating cost for passenger services such as: meals and beverages for passengers; passengers insurance and cabin attendants salaries
- $IOC_{ascf}$ is the indirect operating cost for airplane and traffic servicing, and controls. It includes all the costs related to gate servicing and to the number of people/ equipment required to move out or approach the aircraft to the gate
- $IOC_{pse}$ is the indirect operating cost for promotion, sales and entertainment in general. Every commissions to travel agencies, publicity, advertising campaigns and entertainment systems go under this cost category
- $IOC_{gaa}$ represents the indirect operating cost for general administrative expenses. More precisely, this indirect cost regroups the expenses for requirements concerning administrative and accounting personnel as well as their facilities and requirements for corporate staffers and their facilities too.

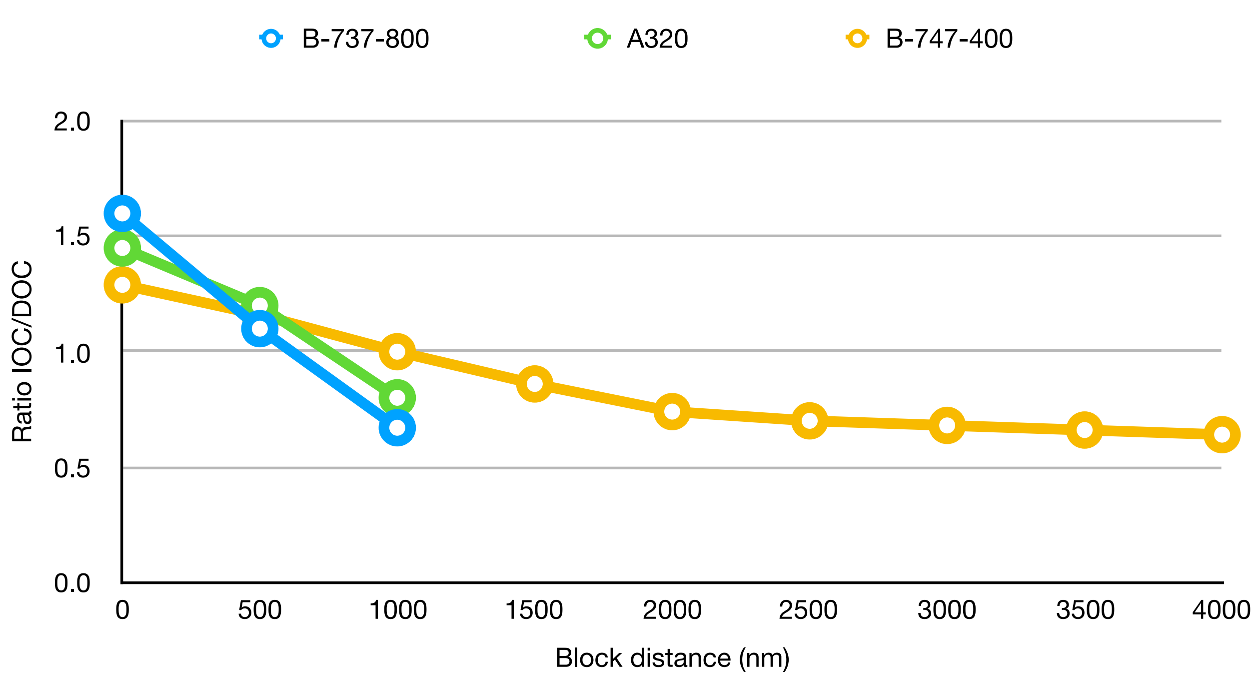


Figure 1.12 Effect of block distance on the ratio of IOC to DOC [16]

All these four cost components are expressed in USD/nm (or local currency). Eventually, there is also an empirical method that allows us to determine the total IOC.
It says that the whole indirect operating costs can be expressed as a simple fraction of DOC: $IOC = f_{ioc}(DOC)$. As we can see from Figure 1.12, the term $f_{ioc}$ is strongly influenced by the block distance.

# CHAPTER 2

## 2.1 NEW TECHNOLOGIES

Nowadays, there are many reasons why there is a continuous search for new technologies such as: lighten up the structure of the aircraft, reduce drag, reduce $CO_2$ emissions, decrease operations costs, decrease noise; that can be applied on commercial aircraft. The most important of all, however, is the reduction of $CO_2$ emissions into the atmosphere. As a matter of fact, the mitigation of man-made climate change is a major challenge to most industries and it is an important issue of international policy too. Aviation contributes approximately 2% of carbon dioxide emissions and an estimated 3% of all greenhouse gases. However, because of the continuous increase of air traffic volume, this contribution is expected to grow, which is not acceptable for any industry in the longer term. Anyway, each type of new technology brings a different benefit. The main ones are:

1) Decreasing $W_{TO}$
2) Decreasing the fuel needed for every flight
3) Increasing the efficiency of the combustion cycle

As we saw in the introduction, there are many ways to classify new technologies (both available and future ones). However, in this chapter we will be classifying them by their functionality and their place of application on the aircraft. As a matter of fact, they can deal with:

- Airframe
- Engine
- Alternative fuels

As it can be easily understood, the complete treatment of all the future technologies that are currently being studied or which are already operating on aircrafts, would go beyond the goal of this thesis. In fact, in this chapter, we will limit ourselves in describing the main new technologies applicable in the above mentioned categories.

## 2.2 AIRFRAME

The survey of airframe technologies focuses on the following five different areas: aerodynamics, structural concepts, materials, on-board systems (which are not part of the propulsive system itself) and innovative design concepts for wing-body structures. The amount of $CO_2$ emitted because of kerosene-burning chemical reaction only depends on the amount of fuel consumed. If alternative fuels are used, the emission of $CO_2$ in the atmosphere decreases but fundamental rules of aircraft fuel consumption still apply. The variables influencing fuel consumption can be easily examined using formula 2.1 (also know as the Brèguet equation):

$$W_F = W_{TO}(1 - e^{\frac{R_{bl}}{X}}) \tag{2.1}$$

Where the term $X$ can be obtained as follows:

$$X = \frac{L}{D}\eta\frac{H}{g} \tag{2.2}$$

Where:

- $\eta \longrightarrow$ Is the overall engine efficiency
- $\frac{L}{D} \longrightarrow$ Represents the lift-to-drag ratio
- $H \longrightarrow$ Is the calorific value of the fuel used (in $\frac{MJ}{kg}$)

Equation 2.1 can be also written as:

$$\frac{W_F}{W_P} = (1 + \frac{W_E}{W_P})[e^{\frac{R_{bl}g(C_{D0} + \frac{S}{\pi e b^2}C_L^2)}{C_L \eta_{th} \eta_{prop} H}} - 1] \tag{2.3}$$

This way, we can obtain the fuel consumption in kg per kg payload. In particular:

- $W_P$ is the weight of the whole aircraft payload in kg
- $C_{D_0}$ is the zero-lift drag coefficient
- $S$ represents the wing area measured in $m^2$
- $b$ is the wing span (in $m$)
- $e$ is the Oswald factor
- $C_L$ represents the aircraft lift coefficient
- $\eta_{prop}$ is the propulsive efficiency coefficient
- $\eta_{th}$ represents the engine thermal efficiency coefficient

So, in order to minimize the fuel weigh $W_F$ (thus minimizing $CO_2$ emissions), these following options are available:

1) Maximize $C_L$, $e$ and $b$
2) Minimize $C_{D_0}$ and $S$
3) Minimize the ratio $\frac{W_E}{W_P}$
4) Maximize $\eta_{prop}$ and $\eta_{th}$
5) Maximize $H$

The new technologies that we will be dealing with in this chapter, have the purpose of fulfilling one (or more) of the points mentioned above.

### 2.2.1 DRAG REDUCION COATINGS

Manufacturers continually look for new surface finishing techniques and coatings in the quest to reduce skin friction drag. The main thrust of these investigations is the retrofittable and easily maintainable coatings that could farther decrease aircraft skin friction drag. These coatings fall into two different categories: those that maintain laminar flow and delay the transition to a turbulent boundary layer and those that work with already existing boundary layers to minimize thickness and avoid flow separation. These two techniques can be used in different areas of the same airplane in order to reduce drag. More precisely:

**Laminar Flow Drag Coatings:** The transition from laminar to turbulent boundary layer occurs due to the build up of small flow disturbances that create adverse pressure gradients in the boundary layer itself. The rate at which this occurs is a function of the overall pressure gradient and properties of the actual surface. Significant work has been undertaken to develop appropriate shapes of the leading edge of the aircraft wing, nacelle, fuselage, and empennage with the goal of delaying the onset of turbulence. However, this shaping is neither applicable to existing aircraft as retrofit, nor it is always strong to resist operational degradation. As consequence, there is a search for coatings that reduce the creation of the small flow disturbances at the origin of turbulence. This reduction can be achieved through the use of films that smooth out the skin of the airplane. Additionally, these coatings have the potential to make the build up of occlusions less likely that lead to degradation to laminar flow (e.g. dead insects on the aircraft skin). This technology would approximately result in a 5% total drag reduction.

**Turbulent Flow Drag Coatings:** The best-known coatings used to reduce turbulent flow drag are aerodynamic riblets. These are normally small grooves (or protrusions) aligned with the local air flow (see Figure 2.1). Many studies indicated that the effects of this technology on a turbulent boundary layer decreases the local skin fraction in the order of 10%. These devices could be used in conjunction with surfaces which are too large to keep a laminar boundary layer along their entire length. NASA estimates that natural laminar flow regions  would occupy approximately 20% of wing and tail surface areas of a commercial aircraft by 2020. This could be especially useful for fuselages and inboard sections of the airplane wing. Moreover, some test on a A-320 model with riblets flying at Mach 0.7, indicated a viscous drag saving of 8%. Unfortunately, these test highlighted that these devices were vulnerable at surface contaminations and also, they showed a small resistance to ultraviolet radiation. Because of these reasons, an increased airframe maintenance would be necessary.

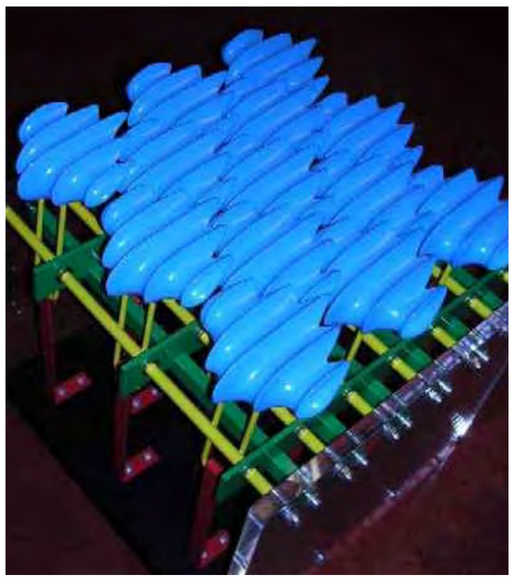

Figure 2.1 Surface riblet example [17]

### 2.2.2 ACTIVE LOAD ALLEVIATION SYSTEMS

An active load alleviation system is defined as any device which is able to reduce or distribute the aerodynamic loads on the aircraft wing by an active reaction of its control surfaces to these loads. These devices allow the wing structure to be lighter and the aerodynamics of the wing to be tailored to each specific flight condition. The most used load alleviation system worldwide deals with locating accelerometers on the wingtips, combined with outboard ailerons, to decrease the gust loads on the outboard section of the wing. This system allows to increase the wing span ($b$) and the aspect ratio without increasing the structural weight of the airplane. This system can be already found on many modern airplanes such as: A-350, B-787 and B-777F. This device is responsible for a 7% reduction of induced drag as well. Moreover, this load alleviation system does not only decrease the loads affecting the wing and the stabilizers but also on the fuselage; for it reduces the movements of the aircraft center of gravity. A even more modern version of the same concept is the active aeroelastic wing. It combines active load alleviation with a significant reduced stiffness to bend itself into the most appropriate shape for a given flight condition. By actively controlling wing twist and shape it is possible to decrease the need for large control surfaces, thus reducing the structural weight of the airplane. As a matter of fact, this technology has been only demonstrated on a military jet (the F/A-18) and it still has to be tested on commercial aircrafts (see Figure 2.2).

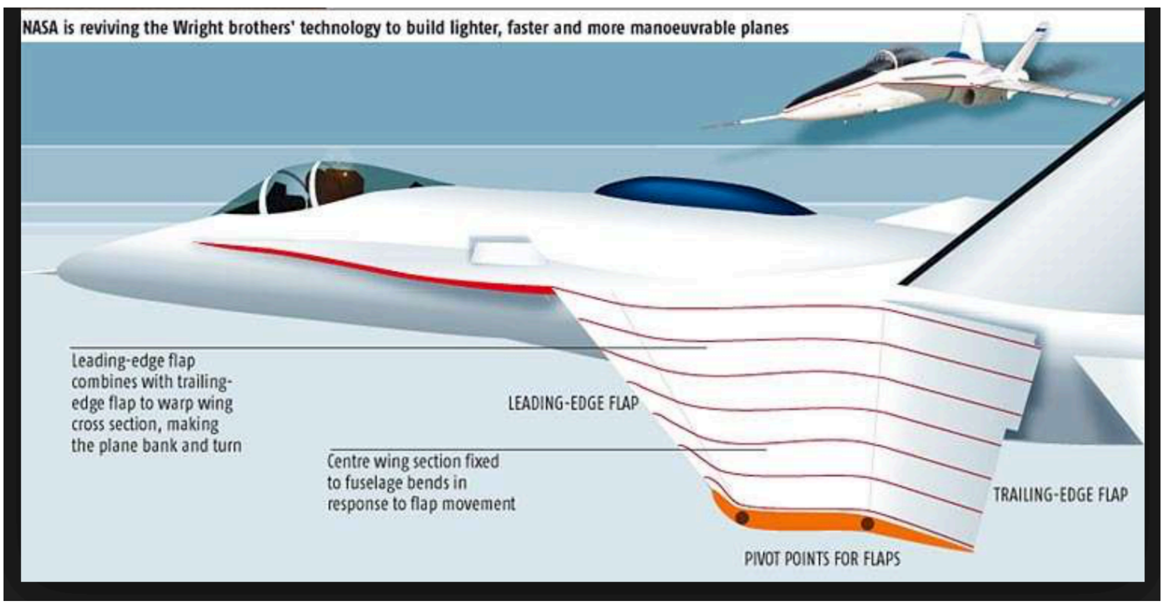


Figure 2.2 Active aeroelastic wing tested on the F/A-18 [18]

### 2.2.3 ADVANCED ALLOYS

Most damage and strength-critical structural components of current aircrafts are made of Aluminium. For decades, aluminium alloys have shown a great rate of improvement in strength, corrosion resistance, durability and damage tolerance. However, nowadays new types of alloys are being studied and tested which, on the whole, seem to have better performances than the ones used so far. There are mainly three advanced alloys which are being studied at the moment:

1) **Aluminium-Lithium alloys** ⟶ Compared to conventional aluminium alloys, these ones have lower density and higher modulus (higher bending strength). This is made possible thanks to the presence of lithium. Each weight percentage of lithium decreases the alloy density by 3% and increases its modulus by 6%. Anyhow, the main problem concerning these kind of alloys is that they have a lower fracture toughness than the conventional aluminium alloys. That is why these advanced alloys are still under studying.
2) **Advanced Titanium alloys** ⟶ Titanium alloys are expanding their market share in the aviation sector mainly thanks to their high strength-to-weight ratio, good damage tolerance and great corrosion resistance. The only big issue concerning these alloys is their price. In fact, they are very expensive compared to the currently used aluminium alloys. Ti-alloys could be a good alternative to high strength steel for this latter contains hydrogen while the Ti-alloys ones does not. Moreover, the superior corrosion resistance traits of Ti-alloys make them competitive for embedded components which cannot be inspected frequently (resulting in decreasing maintenance costs). Space limitation is another motivation behind the preference of these alloys rather than the current aluminium ones. As a matter of fact, the higher strength of Ti-alloys allows the same load to be carried out by a physically smaller structural member. Nowadays, These kind of alloys are used on many commercial airplanes, such as: A-350, B-747 and B-777 especially on their landing gears.
3) **Aluminium-Magnesium-Scandium alloys** ⟶ We still do not know much about these type of alloys for they are still under studying. However, Al-Mg-Sc alloys are the newest type of aluminium-based alloys under development. They have excellent corrosion resistance without being clad or painted. These new alloys are in the near commercial development phase for welding and low cost creep forming materials, despite the high cost of Scandium.

## 2.2.4 FUEL CELLS

A fuel cell is a device that directly converts chemical energy into electricity via an electrochemical reaction. The typical base reactants are: hydrogen ($H_2$) as the fuel, which is normally taken from hydrogen containing fuels such as: methanol and hydrocarbons and oxygen ($O_2$) from the air and the only redox product of this reaction is water. Fuel cells are classified according to they electrolyte types. As we can see from Figure 2.3, these devices had and will have a remarkable growth in years thanks to their cleanness and high conversion efficiency.

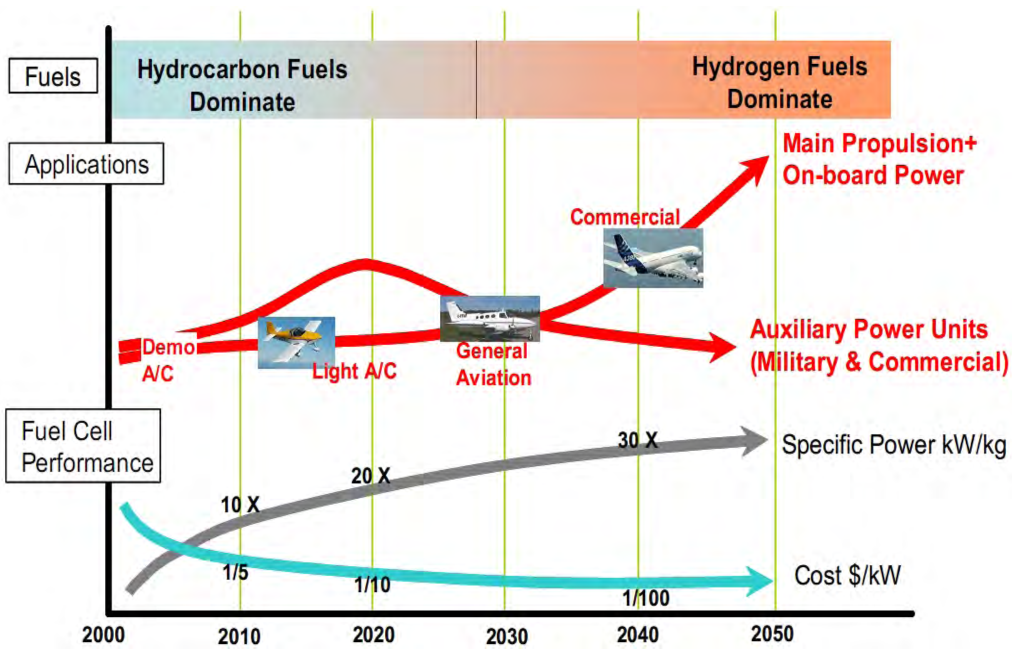


Figure 2.3 Envisioned aviation applications of fuel cell technology [19]

There are mainly three different fuel cells technologies used on current commercial aircrafts and they are:

- **Proton exchange membrane fuel cells** ⟶ These fuel cells are considered to be the leading technology for future airplanes. As a matter of fact, the name derives from the fact that its polymer electrolyte conducts hydrogen cations (or protons) from the cathode to the anode. Their positive qualities are: high specific power, compactness, fast start up time, low temperature operation and high durability. On the other hand, the water management (as product of the redox reaction) is still a problem and furthermore, the need for platinum as a catalyst is still a cost driver. Moreover, having hydrogen of very high purity is needed to prevent poisoning of $CO$ of the membrane and this factor impacts on the cost of the fuel cell itself. These last factors are the reasons why these type of fuel cells are still under studying.

- **Solid oxide fuel cells** ⟶ A solid oxide fuel cell (SOFC) is a high temperature, anionic fuel cell whose electrolyte conducts anions (oxygen ions) from the cathode to the anode. Even if they operate in temperature regions that approach roughly 1100 °C, the electrolyte made of oxide ion-conducting ceramic materials remains in solid state. This results in allowing the shaping of SOFCs into different geometric configurations (tubes, planes, etc…). These fuel cells have a much higher electrochemical efficiency than the proton exchange membrane ones, thanks to their high operative temperatures. Furthermore, working at high temperatures allows a meaningful synergy with bottoming cycles (such as those of gas turbine engines). Therefore, an aeronautical SOFC system could use ordinary hydrocarbon fuels that are normally used on commercial aircrafts (like Jet-A) without the logistical and storage concerns that are associated with using $H_2$ as a fuel. However, many technical issues remain before this technology can become feasible for transport applications. In fact, these fuel cells have low specific power and, even more important than the latter, there would be a strong need to protect the surrounding space from the very high operative temperatures.
- **Solid acid fuel cells** ⟶ As the name implies, these fuel cells use solid acid-based materials as their electrolyte. This technology exploits the reorienting properties of cesium hydrogen sulphate at high temperatures to conduct protons. Compared to the previous two fuel cells, these ones offer several advantages for the commercial aviation market. In fact, they normally operate at the nominal pressure of 1 atm (which is ambient pressure at ground level) and they do not need coatings to protect the surrounding spaces from hot temperature for their normal operating temperature range from 100 °C to 300°C. These above mentioned factors are claimed to results in savings in weight and volume, as well as enhancing the economical advantages of a solid acid fuel cells based system to the point of being competitive with internal combustion engines. Unfortunately, this technology is stuck at TRL 7 at the moment and predictions say it will not be operative on commercial planes before 2025.

## 2.2.5 INNOVATIVE AIRCRAFT CONFIGURATIONS

Since the end of World War 2, there has been a single design concept for commercial transport aircrafts: a cylindrical fuselage with swept wings and podded engine nacelles. Since then, the only possible design modifications regarded the locations of the engines. In fact, some companies prefer to mount engines under the airplane wing while others rather use the aft-fuselage mounted engines. These configurations have served the aviation industry well, achieving important results in terms of fuel efficiency and operating costs. However, there are several new potential concepts under studying that may offer even higher performances. The one we are going to analyze in this chapter is the **Hybrid-Wing-Body** concept. The hybrid (or blended) wing body concept originated at McDonnel Douglas in the late 1990s. Initial studies indicated that, for the design shown in Figure 2.4, that type of design concept could bring up to a 25% reduction in fuel burnt per-seat over an 800 passengers conventional tube and wing configuration. However, this 800 seats concept still has many issues to be solved such as dealing with the fact that an airplane like that would have a wingspan of 90-100 meters and today's airport rules limit aircrafts size to no more than 80 meters length by 80 meters span. At this moment, this technology is only moving its first steps and is has not even being tested yet. Due to many design, maintenance and airport compatibility problems that still have to be solved, the commercialization of a hybrid-wing-body airplane is likely not to come before 2030 timeframe.

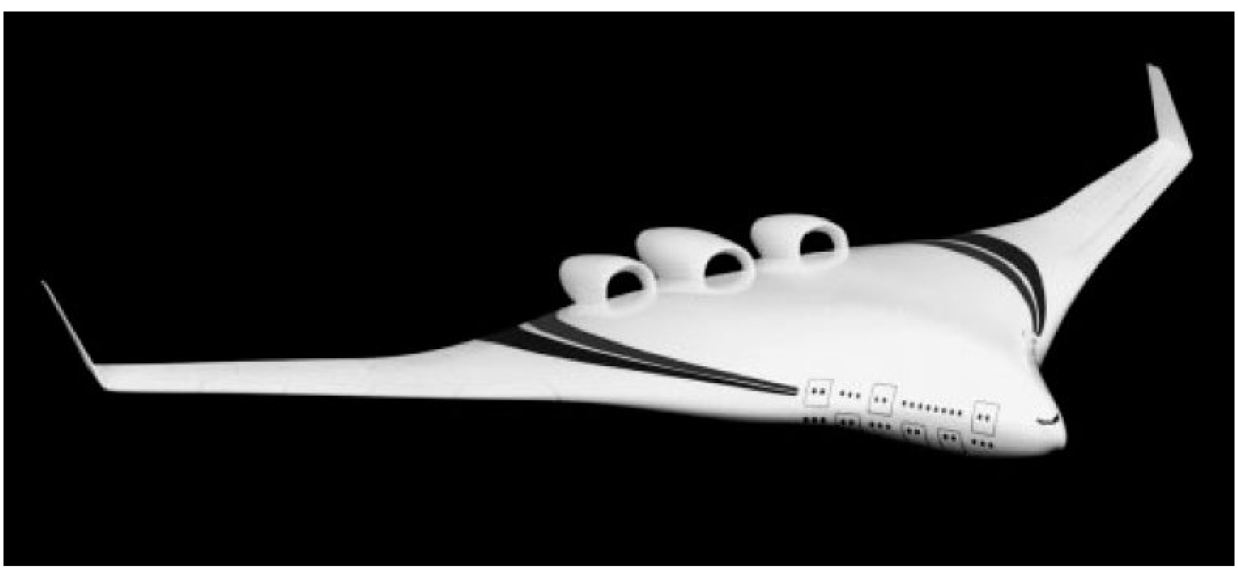

Figure 2.4 Hybrid-wing-body concept according to McDonnel Douglas [20]

## 2.3 ENGINE

Since the late 1950s, commercial airplanes have been mainly propelled by gas turbine engines, which take the form of turbojets, turbofans and turboprops. These configurations have served aviation well by achieving significant increases in efficiency and capability in the ensuing decades. Anyway, while the performance of current high bypass turbofan engines can still be improved at component level, a big step forward in fuel efficiency is expected from new engine architectures, such as the geared turbofan, new engine core concepts, variable geometry chevrons, new adaptive cycles and variable fan nozzles. The expected improvements in fuel burnt, $CO_2$ emissions reductions as well as noise reductions, largely rely on these new concepts.

### 2.3.1 VARIABLE GEOMETRY CHEVRON

In 2016, Boeing successfully flight-tested a variable geometry chevron on a B-777-300ER, equipped with 4 GE-115B engines. This technology consisted of a chevron made of a Ni-Ti-Nol shape memory alloy that changed its geometry according to different flight conditions. As a matter of fact, the main source of engine noise is the turbulent mixing of the hot jet exhaust, fan stream and ambient air. Variable geometry chevrons immersed into the flow, at the nacelle trailing edge have shown to reduce jet


Figure 2.5 Applicative example of a variable geometry chevron [21]

noise appreciably (up to 2dB) during the take off phase and decrease shock cell noise as well (3-5 dB approximately) during cruise. Unfortunately, the practical use of these devices dictates a compromise between noise reduction and engine performance. That happens because this technology has proved to increase aerodynamic drag too. As we can easily see in Figure 2.5, the chevron shapes can vary from a configuration optimized for the take off phase to another one optimized for cruise.

### 2.3.2 ADVANCED ENGINE MATERIALS

For commercial aircraft propulsion systems, the research for advanced materials has two main purposes:

**1)** Provide higher combustion temperature for a more efficient combustion (thus resulting in an unwanted increase of $NO_x$ formation)
**2)** Improve components specific strength, in order to decrease operating costs that derives from maintainability and operating life

Nowadays, in order to achieve these goals, we have four different technologies:

- **Thermal barrier coatings** ⟶ These devices are used to increase the operating temperature of engine components; specifically the gas inlet temperature. As previously said, by increasing the operating temperature, this technology is responsible for an increase in $NO_x$ emissions in the atmosphere. The application of TBC (Thermal-Barrier-Coatings), in conjunction with an active cooling system, has enabled operations at combustion gas temperatures in excess of 250 °C above the melting point of super alloys (especially in the early stage turbine blades and vanes). However, before this technology can be demonstrated to be successfully reliable, some issues must be overcome:

- They do not provide self-renewing protection
- Extension of service life thanks to TBC is subject to scatter
- Effective means of monitoring TBC life has been elusive

- Operating life prediction methods are not yet accurate

- **New Ti-alloys for engine components** ⟶ Ti alloys and Ni-based superalloys constitute the larger weight fraction of modern gas turbine engines. Recently, a new alloy is being studied: IMI-834. It is an α+β Ti-alloy, made of 85% of Ti and Al and Sn as others main components (see Figure 2.6). It has the potential of replacing Ni-based superalloys thanks to its capability to withstand higher temperatures (70 °C more than conventional Ni-based super alloys). Intuitively, should this advanced replace current Ni-based superalloys, then that alone would lead to consistent savings in system weight. In addition to that, many efforts have been made to develop Ti-based intermetallic compounds for high temperature applications. On the other hand, these compounds ($Ti_3Al$, $TiAl$ and $Ti_2AlNb$) still have some problems associated with low ductility, environmental sensitivity and high costs. In case of replacing current Ni-based super alloys with TiAl, an estimated 40% reduction in compressor and turbine blades weight is expected.

| Elements | wt.% |
|---|---|
| Al | 5.75 |
| Sn | 4.02 |
| Zr | 3.54 |
| Nb | 0.71 |
| Mo | 0.505 |
| Si | 0.305 |
| C | 0.065 |
| O | 0.09 |
| N | <0.002 |

Figure 2.6 Chemical composition of IMI-834 Ti alloy [22]

- **Advanced Ni-based super alloys** ⟶ These super alloys are mainly used for engine components for which strength in high temperature environments, toughness, resistance to degradation in corrosive environments are needed. In general, these materials constitute 40-50 % of an aircraft engine total weight. More precisely, they are extensively used where elevated temperatures are kept during operations like in the combustor and turbine. Ni-based super alloys can withstand up to 1100 °C and nowadays, a single crystal Ni-based super alloy is being studied.

This particular alloy would allow an increase of operating temperature of 50 °C. That means that the cooling flow inside the turbine blades can be reduced to have an impact of fuel burnt by decreasing the energy needed for the cooling system. Furthermore, a 50 °C improvement is equivalent to prolonging the creep rupture life by 600%. For a complete description of the current materials used inside a gas turbine engine and their performance, see Figure 2.7.

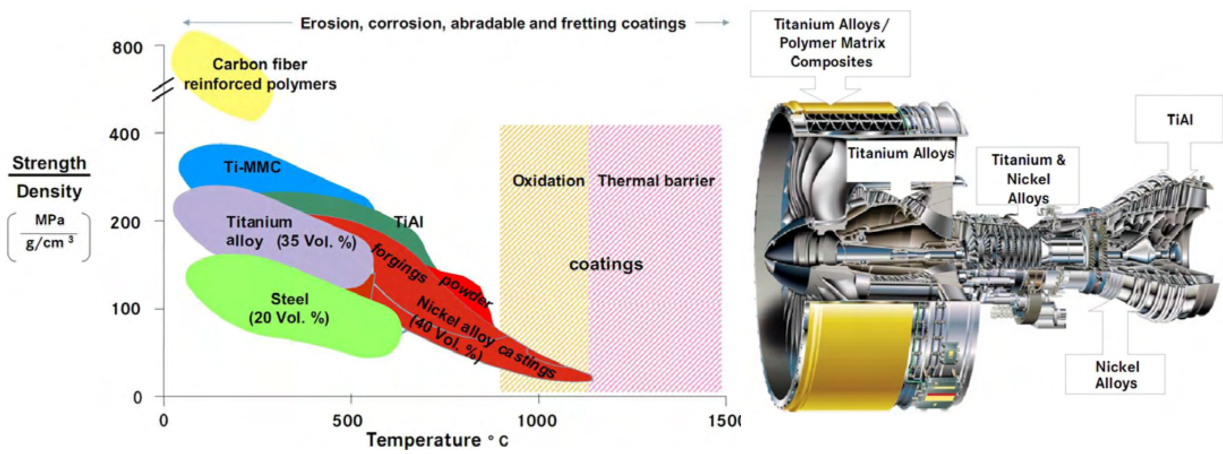


Figure 2.7 Material strength and temperature capability (left) and candidate for engine components (right) [23]

- **Powder metallurgy** ⟶ Compared to ingot metallurgy processes (which are the current ones used to produce engine components), this productive process promise alloys of improved strength, toughness and corrosion resistance. Powder metallurgy also has the potential to produce Al-based alloys capable of withstanding up to 480 °C (while we all know that Al-based alloys produced out of a ingot metallurgy process cannot work beyond 200-250 °C). This last advantage will definitely make them more competitive over the more high-end materials in both airframe and engine applications.

## 2.3.3 GEARED TURBOFAN

The geared turbofan is a next-generation, high bypass-ratio turbofan engine, currently under development by many aircraft enterprises. The new feature of this concept is the integration of an epicyclical gearing system into the shaft connecting the fan and the low-pressure compressor and turbine stages, as shown in Figure 2.8. The main achievement of this technology is that enables the fan and the LPC to share a common shaft and yet, rotate at their own optimal speeds. Decoupling the fan from the LP stages brings many benefits such as: weight and operative costs reductions. The most important one, however, is the reduction in fuel burnt, as both the fan and the LP stages can operate at their maximum efficiencies. Moreover, the planetary gearbox installed behind the fan contains reduction gears too. That means that the fan rotates at lower speeds than the LP stages. Lower rotational speeds can lead not only to a quieter engine without reducing the dimension of the fan, but also a fan with a larger diameter for the same blade tip speed. The primary benefit deriving from being able to increase fan diameter is the reduction in fuel burnt due to a higher bypass-ratio. Furthermore, each single blade can be made lighter thanks to the slow rotational speed of the fan. All these factors combined lead to say that a geared turbofan will definitely reduce the engine total weight, the total fuel burnt and operating costs.

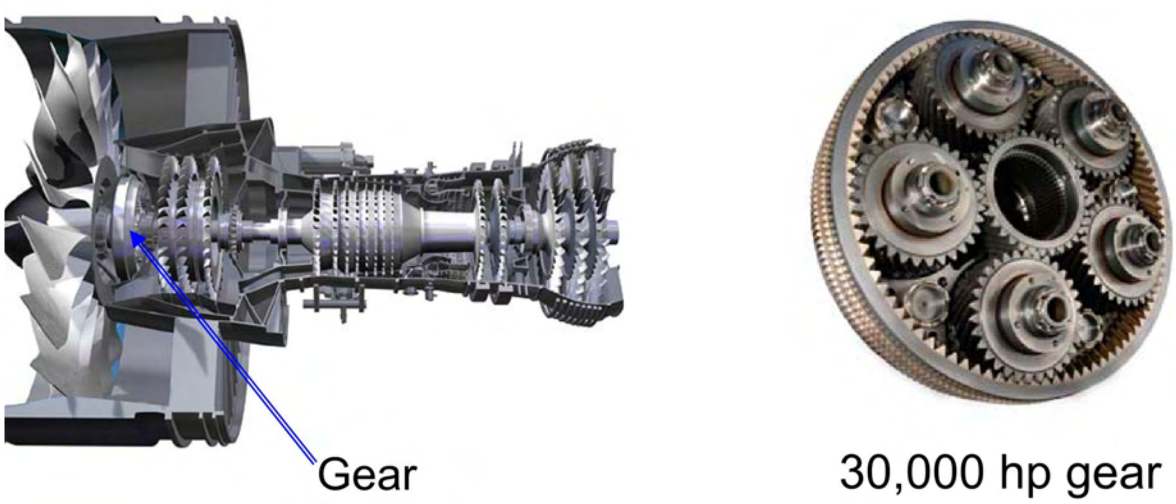


Figure 2.8 Geared turbofan mechanism [24]

This technology is also beneficial for the LP compressor and turbine for the same reasons. In fact, a low pressure turbine rotating at higher speeds is able to drive the compressor and fan with fewer stages. Also, a faster rotating compressor can be produced with less stages for the same mass flow rating. Both of these factors can bring to an overall reduction in the number and weight of LP-stage components. Eventually, nowadays studies have shown that installing a geared turbofan on a single aisle commercial airplane will reduce the fuel burnt by 12% per flight, will save approximately 1.5 US million dollars per year and allowing a 10 dB reduction in noise emission which will indirectly help in saving fuel and reduce flight times. For example, an eastbound aircraft taking off from Los Angeles at night could take off due east, rather than climbing due west to achieve a reduced noise signature over the city. As a matter of fact, optimizing flight paths is estimated to save, on average, 10-12 minutes of the total flight time (thus, saving fuel as well). Table 2.1 shows a summary of the performances of a geared turbofan and its specifications known to date.

| | |
|---|---|
| Status | Two exclusive agreements |
| | Ground trials on a 30,000 lbf-thrust-class version is ongoing |
| Key Performance Targets | |
| Fuel burn | 12% reduction vs. state-of-the-art turbofans |
| Noise | 15dB below Stage IV |
| Emissions | 70% below CAEP/2 limit |
| Costs | 40% reduction in maintenance |
| Published Technical Data | |
| Thrust range per engine | ▪ 15,000 lbf (MRJ – 70 PAX)<br>▪ 17,000 lbf (MRJ – 90 PAX)<br>▪ 23,000 lbf (CSeries – 110 & 130 PAX)<br>▪ 40,000 lbf (Maximum) |
| Bypass ratio | 11:1 (for CSeries) |
| Fan diameter | ▪ 56 inches for MRJ<br>▪ 70 inches for CSeries<br>▪ 77 inches for 30,000 lbf-class |
| Fan RPM | One third of LP stages |
| HP architecture | Eight-stage compressor |
| | Two-stage turbine |
| LP architecture | ▪ Three-stage compressor<br>▪ Two- or three-stage turbine |
| Rotational speed of LP stages | 9,000 RPM |

Table 2.1 Summary of published geared turbofan data so far [25]

### 2.3.4 ADAPTIVE CYCLES

Lately, many aircraft companies started to think about changing the whole engine architecture rather than just optimizing it in order to achieve an even higher decrease of fuel burnt and $NO_x$ emissions. The “FREENOX” jet engine, for example, is a new engine architecture which is under studying at the moment and it uses two new technologies to achieve a very high thrust-to-weight ratio. As a matter of fact, an endothermic reaction system (see Figure 2.9) produces activated oxygen. This way, the fuel combustion phase is improved during the different flight stages. This system carries out optimizes mixtures (activated oxygen, compressed air and fuel) depending on the current flight stage, taking into account factors such as: outside air temperature, pressure and altitude. The design of the combustion chambers, the fuel injection system and the cooling system is intended to reduce $NO_x$ emissions. The compressed air required to operate the endothermic reaction system is generated in a central compressor unit in the fuselage, before being distributed to each engine. Additionally, it is expected to add propulsion to the aircraft during the cruise phase, when the system decreases power to the engines. This way, fuel consumption and $CO_2$ emissions decrease as well. The developers forecast a total mission fuel burnt reduction of 30% compared to current available engines and a considerable noise reduction too.

Figure 2.9 The FREENOX concept (left: engine, right: endothermic reaction system) [26]

## 2.3.5 BOUNDARY LAYER INGESTING INLET

Recent trends in the manufacturing of engine nacelles and their integration with the engine itself have focused on minimizing noise (thus, decreasing fuel burnt and flight times). However, there are many potential developments in nacelle design that promise not only to reduce noice but also mitigate engine installation losses. The main technology that would allow these achievements is the boundary layer ingesting inlet. Motivated by the drive to develop a silent airplane, designers have been investigating burying and/or shielding the whole propulsion system from external flows. This typically involves placing the engine inside the fuselage or the wing. Anyhow, the issue is that the aircraft body disrupts the flow. In nowadays aircrafts, either an engine inlet is located outside of the boundary layer or the disturbed air is diverted, as it contributes to efficiency losses. The boundary layer ingesting inlet, however, re-energizes the wake of the aircraft by ingesting the incoming boundary layer. The bad side of this technology is that the distortion of the air flow occurs at the engine fan face. Unfortunately, this has the potential to decrease fan efficiency and increase the structural stress on the fan blades. Because of this reason, this technology still has a low TRL and many studies on how to solve this problem must be still carried on.

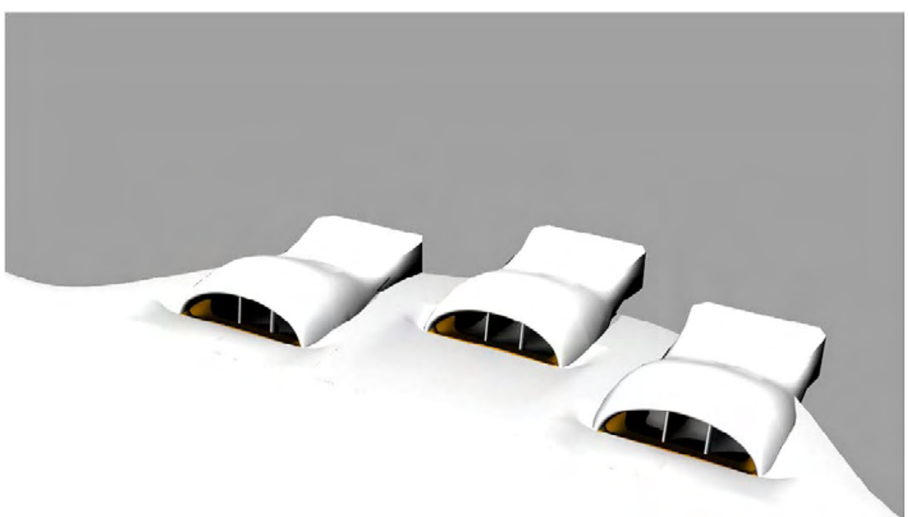

Figure 2.10 Boundary layer ingesting inlet [27]

## 2.4 ALTERNATIVE FUELS

This section looks at potential fuels that could one day be used in gas turbine aircrafts engine. In a short term period, only drop-in fuels are acceptable for commercial airline operations. With the word “drop-in fuels” we mean fuels which do not require changes in aircraft/engine architectures and can be mixed with current kerosene (Jet-A or Jet-A1). Obviously, these fuels must meet some requirements. The main properties a a drop-in fuel must have are: the freezing point, energy content and specific density. There is not a worldwide regulation for which every aircraft must respect, however, the main certification standards are ASTM International (American-Standards for Testing and Materials) and the United Kingdom Ministry of Defense Standard. Potential drop-in fuels include both fuels with a comparable chemical structure to conventional jet fuels types as well as different kinds of chemical structures. The key advantage of these fuels is that they induce minimal changes to existing aircraft designs and fuel handling procedures. Up to now, many demonstrative flights using alternative fuels have been successfully tested, proving that we are not that far away from implementing them on every commercial flight. Fuels can be produced using many different production paths: thermochemical, biochemical and hybrid. Anyway, only two processes are capable of producing alternative fuels that are drop-in: Biomass gasification followed by Fisher-Tropsch synthesis and Hydro-processed renewable jet process. We are going to analyze the second one.

### 2.4.1 HYDRO-PROCESSED RENEWABLE JET

Drop-in liquid fuels produced with this technology are produced from plants or animal lipids via hydro chemical deoxygenation and selective cracking/isomerisation. The process uses a metal catalysis to make the fatty acid reacts with hydrogen so saturated molecules can be formed. Moreover, hydrogenating oils and fats result in clean paraffins that have a similar molecular structure to F-T derived fuels. For this reason, this type of fuel is expected to be the easiest alternative fuel to be certified for commercial aviation in the next decade. Boeing and partners have already produced a significant quantity of HRJ fuel which was used for three different flight demonstration (Air New Zealand in 2008, Continental Airlines in 2009 and Japan Airlines in 2009). This fuel is produced from a variety of non edible vegetable oils such as: camelina, jatropha and algal oils. This alternative liquid fuel would allow a significant decrease of $CO_2$

emissions in the atmosphere thanks to its green production process. For a more precise description of how this process works, see Figure 2.11.

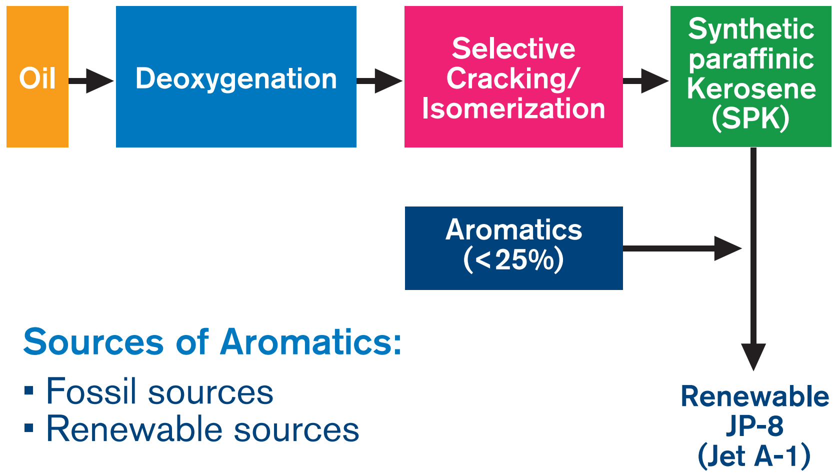


Figure 2.11 Hydro-processed renewable jet fuel process [28]

## 2.4.2 LIQUID HYDROGEN

In recent decades, many studies focused on implementing hydrogen as the main commercial aviation fuel. In fact, this type of fuel will definitely reduce the overall fuel load per flight, let alone the fact that it would completely erase the problem of $NO_x$ emissions. However, if liquid hydrogen were to be used as a combustible fuel, several challenges related to storage, combustor design, generation and handling would have to be overcome. Nevertheless, there are precedents in which a liquid hydrogen powered airplanes have been successfully flown. For example, the first one was a TU-155 with a re-designed and hydrogen fueled NK-86 engine completed a demonstration flight back in 1988. In that case, all hydrogen related components were stored inside a pressurized container for safety reasons. Although the low volume density of liquid hydrogen forced the airframe to grow larger and by so, decreasing its aerodynamic properties, gains were quantified in: saving fuel load (66% to 75%), reduction in $W_{TO}$ (25% to 50%), increase in specific thrust (10% to 13%) and reduction in engine dimensions (5%). Unfortunately, the use of liquid hydrogen as an aviation fuel is not applicable in the foreseeable future (not before 2030 at least), as it would require extensive changes to the fuel infrastructure and aircraft equipment. Last but not the least, commercial planes that are able to fly on hydrogen would need to be equipped with appropriate systems to guarantee safety.

# CHAPTER 3

## 3.1 NEW TECHNOLOGIES COSTS

In this chapter we are going to focus on the main new technologies that are currently used on some aircrafts or are soon going to be used on them. More easily, the technologies which will be dealt with in this chapter are the ones that have a high TRL at the moment. For each of them, there will be an introduction, describing how they work on the aircraft, a list of the benefits they bring in terms of: weight, saved fuel, $CO_2$ emissions, etc…

These first two partes will not be treated in detail for they are not the goal of this thesis. The aim of these two is to give the reader an idea of what these new technologies are but the main goal of this chapter is still describing in detail the costs of these ones. In particular, the new technologies that will be treated in this chapter are the following ones:

1) The morphing wing
2) Electric actuators
3) SHM system
4) Advanced propellers
5) Advanced EPGDS
6) Laminar aerodynamic
7) Geared turbofan
8) New engine materials
9) Adaptive winglets

All these previously listed new technologies have many things common. For example, they all reduce the fuel needed to complete a mission or they are all also responsible for saving money in the overall cost of an airplane in a long term program. Let’s analyze them one by one.

## 3.2 THE MORPHING WING

The first technology is probably the most important of all the eight previously listed as it can guarantee a huge save of fuel per mission and weight as well. As a matter of fact, a morphing wing is a particular kind of wing that is able to change its form depending on external conditions. The production process required to produce a morphing wing is the same one required to produce a wing used on nowadays aircrafts. However, the big difference between these latter is the presence of morphing materials in the first one. In fact, these ones are responsible for the change in shape of the wing itself when the flying conditions change. As a matter of fact, materials that change shape and return to their initial form are known as: morphing materials. They can be metals or polymers that have a 'memory' or are covered with a 'skin' that will induce a shape change when triggered. According to a morphing project group supported by the NASA Institute for Advanced Concepts in Atlanta, the aircraft body and wings would consist of a material made of ionic polymer-metal composite. This material is able to deform when exposed to an electric field. If the voltages were applied correctly, the material would be able change its form. The main obstacle to morphing aircraft technology is that the morphing design is very multi-disciplinary and that all of these disciplines require additional research before the technology can be brought together to build a prototype. Anyway, this technology has already been tested on military aircrafts and it has been forecast that it will be available on commercial airplanes before 2025. There are many **advantages** related to equip an aircraft with a morphing wing:

- **Fuel saving** ⟶ Having the ability to adapt to different external conditions means being able to reduce drag and increase speed. These two, consequently, allow the airplane to save fuel during its mission.
- **Reducing Weight** ⟶ As a matter of fact, a morphing wing doesn't need control surfaces on it like ailerons and flaps. This means having less structural weight on the wings, making the entire airplane lighter than it would be with a classical wing configuration.
- **Reducing airframe noise** ⟶ With no flaps or ailerons on the wing, there will be no noise when there will be the need to change the configuration of the wing during different flight phases.

However, mounting and using a morphing wing on an aircraft brings some **disadvantages** too, such as:

- **High number of components** ⟶ A morphing wing needs a high number of actuators inside it in order to work. This means increasing the complexity of the wing design
- **Reduced space** ⟶ As a matter of fact, the high number of actuators required to keep the morphing wing fully functional, means that the void space inside the wing is reduced a lot
- **Cost** ⟶ This technology is very expensive under every cost category (production, investment required, operating costs, etc…) and won't be fully available on commercial aircrafts before 2025 as it only has a TRL of 3.

During the structural aircraft design conference in Belfast in 2014, it has been presented how much fuel would it be saved during a 1200 km range mission for a regional aircraft. The calculations assumed the aircraft to be fully loaded with passengers (around 100 passengers), no bulk load and an average day with moderate wind (less than 2 kts). The results of these calculations are shown in table 3.2. On the other hand, table 3.1 shows the total fuel burnt using the same regional aircraft with a classical wing configuration.

| Segment | Fuel[kg] | Fuel[%] |
|---|---|---|
| Climb | 618 | 24.7 |
| Cruise | 1,078 | 43.0 |
| Descent | 480 | 19.2 |
| Take-off | 45 | 1.8 |
| Taxi-out | 74 | 3.0 |
| APU | 150 | 6.0 |
| Taxi-in | 50 | 2.0 |
| Total Fuel Burn | 2,504 | |

Table 3.1 Fuel use report, classical wing configuration [29]

| Segment | Fuel[kg] | Fuel[%] |
| --- | --- | --- |
| Climb | 615 | 24.7 |
| Cruise | 1,070 | 43.0 |
| Descent | 479 | 19.2 |
| Take-off | 45 | 1.8 |
| Taxi-out | 74 | 3.0 |
| APU | 150 | 6.0 |
| Taxi-in | 50 | 2.0 |
| Total Fuel lurn | 2,492 | |

Table 3.2 Fuel use report, morphing wing configuration [30]

As we can see from the tables above, there is a 0.32% saving in fuel burn for this short-range mission. Intuitively, the saving percentage in fuel burnt will be even higher for long-range mission. However, the most important impact a morphing wing has on the benefits is the weight reduction one. In fact, it has been estimated that, depending on the wig size (the bigger the aircraft, the bigger the wing of course) a morphing wing could reduce the total weight by 3% - 5% of an aircraft. For every new technology that we consider, we must take into account if the entire cost of it is worth the development of the technology. As a matter of fact, we need to consider many cost categories. The total cost of the morphing wing, for example, doesn't only consists of the cost needed to develop it but we need to consider the operating cost of it, the maintenance cost of it, etc…

Moreover, airline companies must also consider if the new technology will bring business benefits to them in a long-term period, beside reducing environmental factors such as the noise, $CO_2$ emissions and $NO_x$ emissions. More precisely, we can split the cost categories as follows:

- Estimated investment required to develop the technology (EIR)
- Annual operating costs per airline
- On-aircraft investment costs
- Retrofits cost per aircraft
- Maintenance costs
- Production costs

The first category includes all the costs required to study and research the new technology (intuitively, the higher the TRL the cheaper this cost will be). The second one represents all the possible costs incurred while operating the fleet of airplanes a company has. The on-aircraft investment costs are the ones related to change the design of some parts of the airplane, when it needs to be done, in order to mount the new technology on it. Retrofits costs represent the costs incurred while trying to fit the technology on the aircraft itself (some technologies, for example, require to change the installation method on the airplane). The maintenance costs are parts of the operating costs of the airplane but, in this case, they are set aside of it because they represent a very important cost to be highlighted. Eventually, the production costs are the costs incurred during the production of the new technology, after it has been deeply studied and researched. Before giving numbers and percentages to these cost categories, it is important to state that these ones are average numbers/percentages because they strongly vary from airplane to airplane (they depend on many factors like the size of the aircraft, its design, etc…). All these costs concerning the morphing wing are grouped in table 3.3. All the costs have been expressed in US $. Finally, all the percentages and costs are related to the entire aircraft and not only to its parts.

| | EIR | Annual operating costs | On-aircraft investment costs | Retrofits costs | Maintenance costs | Production costs |
|---|---|---|---|---|---|---|
| **MORPHING WING** | 550 M | $-0.4\ \%$ | 1 M | $N/A*$ | $-0.9\%$ | $+1.3\ \%$ |
| | * The retrofits costs are the same as the ones needed for a classic wing configuration | | | | | |

Table 3.3 Cost categories for the morphing wing [31]

As we can easily see from the table above, this technology needs a huge investment cost in order to be fully developed. As a matter fact, morphing materials are still far away from being fully understood. On the other hand, the on-aircraft operating costs are roughly the same ones as a classical wing configuration. The annual operating costs (especially the ones related to the maintenance phase) are less than a normal wing wing ones. This mainly happens because this particular wing configuration allows the aircraft to reduce the overall weight and the fuel burnt per mission and, as previously said, it will not be necessary to do maintenance inspections on the control surfaces (ailerons, flaps, etc…) for they will not be on the wing. Eventually, the production costs of it will definitely be higher due to the presence of morphing materials. As we know from chapter one, there is not a single total cost for an aircraft or for one of its parts. In fact, it is better split the overall cost into different categories. The list below shows the percentages of cost per each category, compared to the ones for a classical wing configuration.

- ***RDTE costs*** $\longrightarrow$ 550 million US $ circa. More than 500 % the RDTE cost required to develop a nowadays wing
- ***Acquisition costs*** $\longrightarrow +1.3$ % assuming the same percentage of profit as the one used for a classical wing configuration. Note that $C_{ACQ} = C_{MAN} - C_{PRO}$ as seen in chapter one
- ***Operating costs*** $\longrightarrow -0.4$ %, as seen in table 3.3.
- ***Disposal costs*** $\longrightarrow$ A $-0.2$ % in saving has been estimated during this phase. This is due to the fact that a morphing wing doesn't need control surfaces; meaning less material to get rid of

All these percentages are estimated values because these numbers have been found after calculations based on data we are still not 100% sure about (this technology is not yet ready to be used on modern aircrafts).

## 3.2 ELECTRIC ACTUATORS

Traditionally, the aerospace industry used hydraulic and pneumatic actuation systems, owing to low cost and high-power densities. Nevertheless, in recent times, due to limitations like weight, performance, and maintenance requirements, hydraulic actuators have been replaced by electric ones. According to the US Naval Research, the use of integrated electric designs can enhance efficiency, effectiveness, and survivability, with simultaneous increase in design flexibility. As a matter of fact, an electric actuator is an electromechanical device that converts the rotary motion of a direct current motor into a linear motion allowing to lift, adjust, tilt, push or pull high loads just by pressing a button. For what concerns the production process we can say that there is not a single process available because there are many direct current motors that can be linked to actuators such as the single-phase one, the triple-phase one, etc…

Each of them has a specific goal and that depends on the aim of the actuator. Moreover, actuators that will be set on a commercial airplane have different shapes and functionalities. That means having a huge variety of different industrial processes depending on the future form of the actuator itself. All these factors are responsible for making swing the production costs of this technology. Electric actuators have already been developed and tested onto commercial aircrafts. Nowadays, this technology is fully applied onto some airplanes such as the Boeing 787. In particular, the B-787 was the first more-electric aircraft, in terms of actuation and control systems, in the commercial aviation industry. As previously hinted, the use of these kind of actuators bring many **advantages**; in particular:

- **Reduced weight** ⟶ According to many analyses performed by Boeing, electrically powered technology can reduce the weight of the system equipment, ranging from few hundred to several thousand pounds, which directly correlates to reduction in fuel consumed, and hence, saving several million dollars in operation and acquisition costs. By changing hydraulic and pneumatic actuators to electric ones, several components, like fluids, external pumps, DCVs, piston-cylinder arrangement, etc., can be removed, thereby eliminating their weight.
- **Increased efficiency and reliability of system performance** ⟶ Simply put, systems efficiency is improved by eliminating the need to convert the engine shaft power to hydraulic power. As a matter of fact, the extraction of electric power from the engine provides an efficient way to operate the braking, cabin pressurization, and engine starting systems. The electric driver system provides real-time feedback through motor controllers, which can be linked to diagnostic systems, thereby simplifying diagnostic error finding.
- **Less complex design** ⟶ Electric actuators provide more accurate control and faster reaction times, which increases system reliability. As the number of parts are less, the design is much simpler, and the system experiences less downtimes caused by the failure of complex mechanical components. Since only the installation of the actuator, electric power, and feedback cables are involved, the installation time is less. Furthermore, these systems are not affected by pressure drops, unlike hydraulic pumping systems.
- **Improved safety and reduced risks** ⟶ The key benefit of electric actuators over hydraulic actuators is that there is no leakage of hydraulic fluids, like flammable oil, which has been the cause of many aircraft accidents in the past.

However, as every engineering product, electric actuators presents some **disadvantages** as well. The main ones are:

- **Reduced power output** ⟶ Compared to hydraulic actuators, electric ones produce less power with the same amount of weight. In fact, the heavier the electric motor is, the more power it will produce. In order to have the same power output, electric actuators would have to be heavier than hydraulic ones.
- **Dissipated power** ⟶ Unlike hydraulic actuators, electric actuators need separate devices to store the dissipated power. This means having more components per actuator, hence more weight and complexity.
- **Idle operations leaks** ⟶ Electric actuators are unfortunately known for having leaks of dissipated power even during idle operations. This could result in not having enough power required and thus having the need to increase the weight of the electric motor.

This technology does not only allow a good saving of weight and fuel burnt per mission, but it is also present a huge money saving for commercial airline companies as shown in table 3.4.

| | EIR | Annual operating costs | On-aircraft investment costs | Retrofits costs | Maintenance costs | Production costs |
|---|---|---|---|---|---|---|
| **ELECTRIC ACTUATORS** | 100 M | $-0.1$ % | 10 K | $N/A*$ | $-0.4$ % | $-0.2$ % |
| | * The retrofits costs are the same as the ones required for hydraulic systems | | | | | |

Table 3.4 Cost categories for electric actuators [32]

Unlike other new technologies that will be treated in this chapter, electric actuators do not need a huge development cost (EIR). In fact, as previously said, this technology has already been studied and tested and many airline companies already uses it on many of their aircrafts. Still, 100 millions will be needed to develop this technology for short-range airplanes where the use of hydraulic actuators is still largely accepted. Furthermore, as this technology allows to reduce both the weight of the aircraft and the fuel needed per mission, the operating costs per year will be less than the ones required for using hydraulic or pneumatic actuators. The on-aircraft investment costs are “only” 10 thousands dollars because there is no need to drastically change the design of some parts of the aircraft, there only must be found the space required to store the electric motor. For what concerns the retrofit costs, there is no saving nor losing of money for mounting this technology onto an airplane. This happens because the cost needed to install hydraulic actuators onto an aircraft is the same as the one required to install electric actuators (for example, the disposal of all the cables and wires needed for an hydraulic actuators system is roughly the same one required for installing electric motors linked to their actuators). As previously quoted, this technology does not need cables or wires to work and its design is much simpler than the hydraulic actuator one; these two thing combined make maintenance works easier and less expensive to perform. Finally, there is a small saving in the production costs as well because manufacturing the electric motor and link it to the actuator costs less than manufacturing all the wires required for a hydraulic actuator. Splitting the overall costs into the four different cost categories we have seen in chapter one, we can say that:

1) ***RDTE costs*** $\longrightarrow$ 100 million dollars required to develop and test the technology onto regional, short-range aircrafts. This cost category would not count if the airplane we consider is one where this technology has already been tested and successfully mounted on
2) ***Acquisition costs*** $\longrightarrow -0.2$ % for manufacturing electric actuators has roughly the same cost of manufacturing hydraulic ones. If we consider the same amount of profit for both of them, then assuming a $0$ % increase of the acquisition costs for this technology is fine
3) ***Operating costs*** $\longrightarrow -0.1$ % as seen in table 3.4
4) ***Disposal costs*** $\longrightarrow +0.2$ % than hydraulic actuators. This happens because it is harder to get rid of electric motors rather than electric wires, due to recycling issues and internal components that might need storage facilities when their operative life end

All these costs and percentages have been made considering the comparison between electric actuators and hydraulic actuators on a Boeing 787 (which was the first commercial aircraft flying with this technology).

## 3.3 SHM SYSTEMS

Structural-Health-Monitoring systems have the goal to give, at every moment during the life of a structure, a diagnosis of the “state” of the constituent materials and of the full assembly of these parts forming the entire structure. We can easily say that this technology is a new and improved way to make a Non-Destructive-Evaluation (NDE) of the structure. As a matter of fact, a SHM system involves the integration of: sensors, data transmission systems, computational power and processing abilities inside the structures. That makes it possibly to reconsider the design of the structure itself sometimes, if required. Aircraft maintainers and operators who use SHM systems are able to determine if structural damage has occurred, when it has occurred and precisely where the damage is located. Rather than just reporting loading cycles on a structural component, a SHM system will report actual changes in structural components. There is a good awareness of the benefits of SHM systems within the aerospace community for many years, however these systems are now becoming important now with the uprising presence of composite airframes where traditional metal fatigue models are not useful and where damage is often not apparent at the surface. Structural health monitoring systems, like the NDE ones, can be passive or active. Figure 3.1 represents the two possible situations. In both cases, the structure is equipped with sensors and interacts with the surrounding environment, in such a way that its state and its physical parameters are evolving.

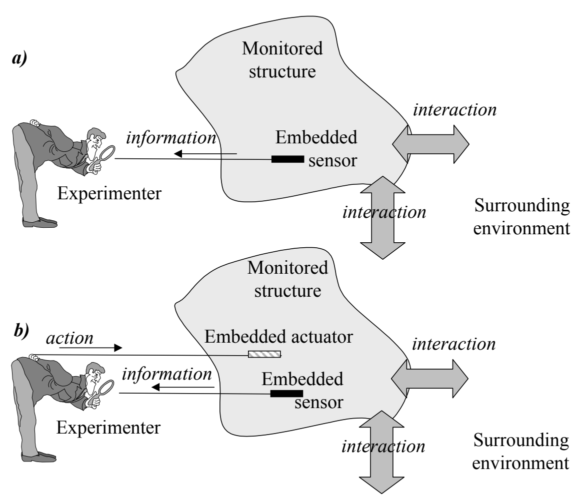


Figure 3.1 Passive SHM system (a) and active SHM system (b) [33]

In particular, if the experimenter is just monitoring this evolution thanks to the embedded sensors, we can call his action “***passive monitoring***”. On the other hand, if the experimenter has equipped the structure with both sensors and actuators, he or she can generate perturbations in the structure, thanks to actuators, and then, use sensors to monitor the response of the structure. In such a case, the action of the experimenter is “***active monitoring***”. The passive one is obviously cheaper than the active one but it is less accurate. Anyway, this last has more components and that increases the complexity of the design and of the maintenance of its components. However, the active monitoring option is still at a low TRL, while the passive one is already at the testing phase onto some aircrafts. So, from this moment onwards, we will refer everything (cost categories, advantages and disadvantages) to a passive SHM system. This technology has, of course, its advantages and disadvantages. For what concerns the first ones, we can say that:

- ***Maintenance*** ⟶ SHM systems slightly change the work organization of maintenance services by aiming to replace scheduled and periodic maintenance inspection with performance-based maintenance. In fact, avoiding dismounting parts where there is no hidden defect drastically minimizes the human involvement, and consequently reducing labor, downtime, human errors and, most important, maintenance costs.
- ***Operating life*** ⟶ Monitoring the health of a component in real time means knowing exactly when it becomes necessary to replace it. This prevents from changing the component before it is strictly necessary to do so, thus increasing its operating life.

On the other hand, however, structural health monitoring systems bring some disadvantages with them too. The main ones are listed below:

- ***Complex design*** ⟶ This technology requires a huge amount of sensors, detecting devices, hardware and wires as well. The more components a technology has, the more complex its design is. In fact, if SHM systems allow to save money during maintenance works, some extra maintenance is needed to check the components this technology is equipped with. Moreover, as previously said, SHM systems could be so complex that it is sometimes possible to reconsider the design of the aircraft structure itself.

- ***Algorithms and processing data*** ⟶ In order to have a precise evaluation of the structure health, complex algorithms and devices that allow a fast processing data are required. This means that this technology needs a huge amount of power to work, thus increasing the electrical energy on board and the weight of the structure.

The figure below shows how maintenance costs and the reliability of an aircraft would change if a SHM system would be mounted on it.

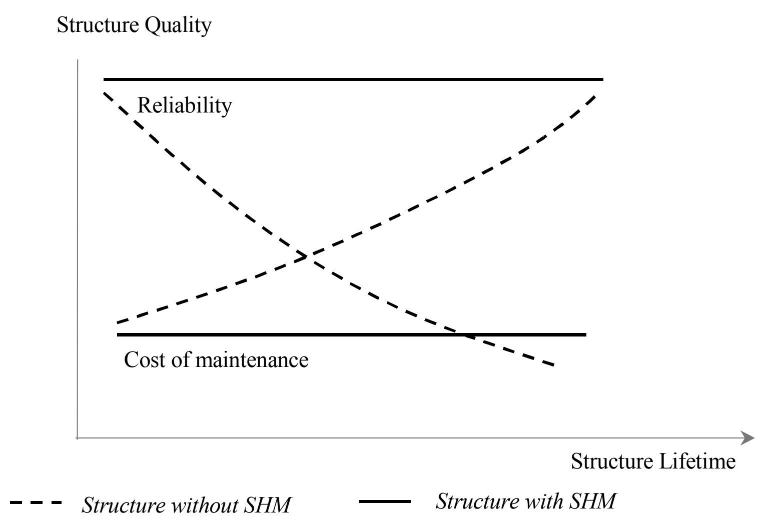


Figure 3.2 Benefits of SHM systems on commercial aircrafts [34]

The economic impact of the introduction of SHM systems on aircrafts is not easy to evaluate. It strongly depends on the usage conditions and, furthermore, it is difficult to appreciate the impact on the fabrication cost of the structure. Intuitively, the cost of this technology must not be so high as to cancel out the expected maintenance cost savings. It is easier to evaluate the time saved by the new type of maintenance based on the introduction of SHM. As a matter of fact, for a modern commercial airplane featuring both metal and composite structure, an estimated 40% can be saved on inspection time through the use of smart monitoring systems. Table 3.5 presents the figures resulting from this evaluation.

| Inspection type | Current inspection time (% of total) | Estimated potential for smart systems | Time saved (% of total) |
|---|---|---|---|
| Flight line | 16 | 0.40 | 6.5 |
| Scheduled | 31 | 0.45 | 14.0 |
| Unscheduled | 16 | 0.10 | 1.5 |
| Service instructions | 37 | 0.60 | 22.0 |
| | 100 | | 44.0 |

Table 3.5 Estimated time saved on maintenance operations by the use of SHM systems [35]

Saving time during maintenance operations means saving money. Still, in the aeronautic domain, there is also a benefit for constructors. Taking into account the permanent presence of sensors at the design stage will permit a reduction in the safety margins in some critical areas. Weight reduction will be then possible, giving higher aircraft performance, lower fuel consumption and greater maximum range. More precisely, the table below gives an estimated range of cost savings this technology would be able to give.

| | EIR | Annual operating costs | On-aircraft investment costs | Retrofits costs | Maintenance costs | Production costs |
|---|---|---|---|---|---|---|
| **SHM system** | 100 M | $-0.7$ % | 1 M | 100 K | $\sim -5.5$ % | $+0.2$ % |

Table 3.6 Cost categories for a SHM system [36]

The EIR costs for this technology are not as high as for other ones like the morphing wing because even if SHM systems are not yet ready to be mounted on modern aircrafts, they still have a high TRL. In fact, their installation onto commercial planes should be set no later than 2025. There is a good cost saving in the operating costs ($-0.7$% per year) due to the good amount of money saved during maintenance operations this technology allows. The production costs are, however, higher than manufacturing a classical structure because of the presence of sensors, processing units and wires. The on-aircraft investment costs are much higher than considering an aircraft without SHM systems because mounting this technology on a commercial plane means modifying its main structure sometimes and that requires a huge investment of money. On the other hand, the retrofits costs are 100 K per year as there is not much work required to install this technology onto an aircraft once the layout of the mainframe has been manufactured. If we have to split all these costs into the four cost categories we have seen in chapter one, then:

- ***RDTE costs*** $\longrightarrow$ Approximately 100 million US dollars needed to fully develop this technology as it is still under testing phases (TRL = 7)
- ***Acquisition costs*** $\longrightarrow +0.2$ % of the cost needed to manufacture and produce an airframe structure without structural health monitoring systems mounted inside it (assuming the same profit percentage used for a classical airframe configuration)
- ***Operating costs*** $\longrightarrow -0.7$ % as shown in table 3.6
- ***Disposal costs*** $\longrightarrow +0.1$ % than the airframe structure itself for there will be more material to get rid of. In fact, when a SHM system reaches the end of its operative life; all the wires, sensors and processing units composing it must be dispose and it is far more difficult disposing electrical components than metallic ones

## 3.4 GEARED TURBOFAN

This technology is probably the most important one between the ones that are treated in this thesis. As a matter of fact, it has been estimated that a geared turbofan would be able to obtain the greatest saving of fuel burnt and thus operative costs. As previously said in chapter 3, the main new feature of this concept is the integration of an epicyclical gearing system into the shaft connecting the fan and the low-pressure compressor and turbine stages. It is not the aim of this paragraph to repeat the same things said in chapter two, so I will limit to list the benefits and the disadvantages this new technology offers and focus on its cost categories. For what concerns the first ones, we can say that:

1) ***Weight reduction*** $\longrightarrow$ Decoupling the fan from the Low-Pressure-Compressor (LPC) and having thinner blades allow a significant engine weight reduction.
2) ***Less fuel burnt per mission*** $\longrightarrow$ As the fan and the LPC are no more connected to each other, they can both work at their maximum efficiency and that means needing less fuel for each mission. Furthermore, this technology allows to have a bigger fan (more precisely, a fan with a bigger diameter) and that allows to higher up the bypass-ratio (BPR) thus reducing the fuel burnt per mission.

3) ***Noise reduction*** ⟶ Thanks to the fact that the fan will be bigger than classic ones, it can revolve at lower speed thus reducing the sound it makes. That can reduce the length of the missions as well as previously explained in chapter two.

However, even if this technology brings more advantages than disadvantages, there are some of them which need to be taken into account:

1) ***Design complexity*** ⟶ Adding a planetary gearbox behind the fan means changing the design of the first parts of the aircraft engine. That means having an adding expense in the production cost phase and an ulterior component in the engine.
2) ***Increased downtime periods*** ⟶ Having one more component in the engine frame means that that item must be checked and controlled every time a maintenance work is required. That translates into increased downtime periods and, consequentially, a lost of money.

As a matter of fact, this new technology does not only allow a huge saving of cost in different categories but it also has a high TRL. In fact, it is estimated that modern commercial aircrafts should be able to fly with a geared turbofan within 2020. More precisely, the impact this technology has onto the various cost categories is clearly shown in the table below:

| | EIR | Annual operating costs | On-aircraft investment costs | Retrofits costs | Maintenance costs | Production costs |
|---|---|---|---|---|---|---|
| **GEARED TURBOFAN** | 250 M | $-3.2\ \%$ | 1 M | $N/A*$ | $-2.8\ \%$ | $+2.1\ \%$ |
| | *The retrofits costs are the same as the ones needed for current turbofan engines | | | | | |

Table 3.7 Cost categories for a geared turbofan [37]

The money invested to develop and test this technology onto commercial jets has been estimated to go around 250 million US dollars even if we are now at the final stages of developing geared turbofans (that means only a very small part of still needs to be spent). It is easy to understand why the EIR cost is very high; for this is a technology that will fully change the layout of the turbofan engine. As previously said, a geared turbofan allows to save fuel, weight and flight times. All of these mean a great saving in the operating costs; which are influenced by the maintenance costs (maintenance costs are a part of the whole operating costs). On the other hand, as it will be necessary to add a component in the engine, the production cost of it will increase by 2.1% of the total production cost of the engine. The on-aircraft investment costs are a little bit higher than the ones needed to manufacture a modern turbofan engine as installing a planetary gearbox behind the fan means changing the layout and the design of the engine itself even if it is a slight modification. Eventually, for what concerns the retrofits costs, we can say that there is not a significant variation of costs for the installation method of the engine as a whole (including the planetary gearbox in it) because the way the engine is mounted on the aircraft is the same one with or without the new component in the engine. If we want to divide the increases and decreases of costs by using the four categories we dealt with in the first chapter, then the list below shows how they change:

- ***RDTE costs*** $\longrightarrow$ Around 250 million US dollars. This is the cost that has been required to research, develop and test this technology. As previously said, the geared turbofan is almost ready to be used on commercial planes and only a small part of those money is still needed
- ***Acquisition costs*** $\longrightarrow$ Assuming the same profit percentage for manufacturing a turbofan and a geared turbofan engine, we can say that there is a $2.1$ % of increase of costs than for a modern turbofan engine
- ***Operating costs*** $\longrightarrow$ $-3.2$ % as shown in table 3.7
- ***Disposal costs*** $\longrightarrow$ $+0.05$ % than the ones required to get rid of a classic turbofan engine. As a matter of fact, the slight difference is due to the presence of an additional component in the engine that needs to be disposed as well

## 3.5 LAMINAR AERODYNAMIC

With the word “laminar aerodynamic” we wean every possible technology that could defer the transition between a laminar flow to a turbulent one in the boundary layer on the upper surface of the wing. As a matter of fact, when the airflow interacts with the upper side of the wing, it generates a boundary layer which is, at the beginning, a laminar flow. This latter is a laminar regime when the airflow occurs with the sliding of infinitesimal layers on each other without any type of fluid mixing, even on a microscopic scale, the flow is governed by viscous forces and is constant over time. On the other hand, a turbulent regime is a motion of a fluid (the airflow, in our case) in which the viscous forces are not sufficient to counteract the forces of inertia. As a consequence, the motion of the resulting fluid particles occurs chaotically, without following ordered trajectories as in the case of regime laminar. At some point, on the upper wing surface, the airflow passes from laminar to turbulent and that causes performance decreases in term of generated lift. For this reason, the later this transition occurs, the better. The laminar–turbulent transition is an extraordinarily complicated process, which at present is not fully understood and it is not the goal of this thesis to fully describe it. However, we do know which factors influence this transition. The main ones are: the viscosity of the flow, its speed, the shape of the wing, the roughness of the wing surface and the skin fraction between the boundary layer and the wing itself. As we cannot do anything about the first two of them, it is possible to work on the last three. We will not deal with changing the shape of the wing in order to get an optimal laminar-turbulent transition for it would require a detailed description and it goes beyond the purposes of this document. What we are going to deal with are riblets and machining that allow to reduce the wing surface roughness. For what concerns the first ones, we can say that they are normally small grooves (or protrusions) aligned with the local air flow. Many studies indicated that the effects of this technology on a turbulent boundary layer decreases the local skin fraction in the order of 10%. By decreasing it, the passage from laminar to turbulent happens closer to the tail edge, thus increasing the generated lift. Another effect this technology brings is reducing the drag that would be generated by the turbulent laminar flow. In fact, the closer to the tail edge the transition happens, the less drag will be generated. If the overall drag is reduced, the aircraft would need less fuel to accomplish its mission as it will be less difficult for it to fly through the airflow. On the other hand, surfaces of real objects are usually affected by micro-geometric irregularities, these ones cause the object (the wing in our case) to have roughness on it. The rougher the wing is, the more drag it will produce and, more important, the closer to the wing tip the laminar-turbulent separation will happen.

These last two factors drastically increase the fuel required per mission. Nowadays there are many surface finishing treatments allowing to reduce the roughness of a wing surface. The two technologies have in common that they both decrease drag and move the laminar-turbulent transition point closer to the wing tip. Unfortunately, if surface finishing machining are available today, we cannot say the same for riblets. In fact, these latter will only be available on commercial aircrafts around 2020 (they have a TRL of 7). If we combine these two technologies together, we will obtain some ***advantages***:

- ***Fuel saving*** ⟶ As previously said, decreasing drag means decreasing the fuel needed every mission as an airplane equipped with both of them would face less air resistance during its flights
- ***Easy design*** ⟶ As shown in Figure 2.1, riblets are not complicated to manufacture and for this reason they are quite cheap and easy to produce comparing to other new technologies

However, riblets and surface finishing treatments have their ***disadvantages*** too. The main ones are:

- ***Expensive machining*** ⟶ Unfortunately, the operations needed to decrease the roughness of the wing surface are expensive and sometimes it is not worth to spend a huge amount of money for a slight decrease of roughness
- ***Ultraviolet damage*** ⟶ Some tests that have been conducted on riblets showed that they have a small resistance to ultraviolet radiation. Because of these reason, an increased airframe maintenance would be necessary

If we combine these two technologies together and we imagine mounting them on a commercial aircraft; the way they change the cost categories is clearly shown in table 3.8.

| | EIR | Annual operating costs | On-aircraft investment costs | Retrofits costs | Maintenance costs | Production costs |
|---|---|---|---|---|---|---|
| **RIBLETS + SURFACE FINISHING MACHININ G** | 1 M | $-0.7$ % | 1 M | 1 M | $+0.4$ % | $+1.3$ % |

Table 3.8 Cost categories for riblets and surface finishing machining [38]

As it can be easily understood, riblets are not too difficult to research, develop and test as they are basically small grooves (or protrusions) aligned with the local air flow (see Figure 2.1). For this reason, "only" 1 million US dollars are enough for this cost category. The annual operating costs are slightly improved due to the fuel saved thanks to the drag reduction and the increase of lift these two technologies can obtain. On the other hand, maintenance costs increase only because of the presence of riblets (there is no need for extra maintenance on finished surfaces as they are treated like normal surfaces) which are additional elements to take care of. For what concerns the production costs we can say that they are slightly increased mainly due to the need to do surface finishing treatments in order to decrease the roughness of the wing surface. As a matter of fact, these operations are quite expensive nowadays and, on the other hand, this cost category is not much afflicted by rubles for it is very easy to manufacture and produce them. The on-aircraft investment costs are around 1 million dollars as the presence of riblets on the wing itself do change the design of the wing, even if with a little change. Eventually, around the same amount of money is required for the retrofits costs because the installation method of the wing on the aircraft change if riblets are on it. Surface finishing treatments do not affect these last two cost categories at all. Last but not the least, the four cost categories of chapter one applied to to these two technologies can be expressed as follows:

1) ***RDTE costs*** ⟶ Around 1 million dollars. As previously said, riblets are not complicated items to research and test. Of all the other technologies we will deal with in this chapter, they are the cheapest one regarding the RDTE costs. This cost category does not apply to surface finishing machining, as it is possible to apply it on current airplanes
2) ***Acquisition costs*** ⟶ Assuming zero profit on these two technologies (which is not that far from the truth for profits are normally set for massive new technologies

such as the morphing wing, the geared turbofan, etc…) we can assume a $+1.3\%$, due to the expensive processes needed for decreasing the wing surface roughness

3) ***Operating costs*** $\longrightarrow -0.7\%$ as shown in table 3.8
4) ***Disposal costs*** $\longrightarrow \sim 0\%$ as a surface finished wing will be disposed the same as a classic wing and because riblets can be disposed without too many efforts for they are small and they are not made of toxic materials.

## 3.6 ADVANCED EPGDS

The term EPGDS stands for Electric Power Generation and Distribution System and as the name may suggest, it is a technology that deals with improving the electric system of the aircraft itself. More precisely, the EPGDS system is used to supply the electrical energy for all onboard electrical equipment. The EPGDS has DC and AC generating systems. The DC generation system includes a battery system while the AC one does not. The EPGDS provides for energy conversion, distribution, storage, control, protection, monitoring, and indication to the flight crew. Provision is made for external connection of DC or AC external power while on the ground too. The Electrical Power Generation and Distribution System has an Electrical Power Control Unit (EPCU) to control, monitor and distribute DC and AC power to the airplane electrical buses. The EPCU automatically re configures the EPGDS for power source and bus failures, by the closing and opening of bus ties contacts. Contacts control is determined by automatic functions during the operation of the aircraft. Manual inputs are achieved through the selection of switches in the flight deck that may be vetoed by the EPCU. The direct current system generally operates at 270 volts while the alternative current one operates at 230 volts. The EPGDS generates electrical power via two variable frequency generators and provides necessary interfaces with avionics and member systems to convey data and serve embedded utility loads throughout the aircraft. Moreover, the EPGDS provides secondary load management through its five secondary power distribution assemblies, which receive alternating or direct current (AC/DC) power inputs from power centers, then manage and distribute the power to load equipment. The main new feature of this new technology is that it provides electrical power using a higher amount of voltage instead of amperage, thus increasing the safety and the reliability of the whole system. The first airplane company that began to develop and test this system onto its commercial aircrafts was Bombardier Aerospace. Nowadays, this technology has a TRL of 6 for regional aircrafts. As a matter of fact, in many cases, the TRL is different from liners and regional airplanes as there might be

different problems regarding the implementation of the technology on it due to their different size and shape. Moreover, sometimes a new technology brings far more economical benefits if installed onto a liner than onto a regional jets and viceversa. This is one more reason why sometimes the TRL is different from the two of them. Anyhow, every specified TRL in this thesis is referred to liners.
As all the other new technologies we treated in this chapter so far, this one has its own ***advantages***; the main ones are listed below:

- ***Weight and volume saving*** ⟶ The installation of the new technology on current aircrafts can save up to 10% of the weigh and the volume of current electrical systems. This mainly happens thanks to the presence of lighter generators and batteries.
- ***Reliability*** ⟶ Changing from using higher amperage and smaller voltage to the contrary turns into an upgrading in reliability of the whole system due to the less chances to have short circuits.

Unfortunately, the electric power generator and distributing system has its own ***disadvantages*** as well. As a matter of fact, this technology has:

- ***Equipment availability*** ⟶ Unfortunately, there are only few suppliers of high voltage EPGDS. While it is easy to find suppliers selling high amperage electrical generation and distributing systems, the same cannot be said for high voltage ones. This would inevitably increase the acquisition/production cost of it.
- ***Cost*** ⟶ This technology does not allow a good saving of production costs compared to the ones required to manufacture current electrical systems. As a matter of fact, the main advantage of this technology is the weight saving and the reliability improvement.

This new technology is basically the advanced, more reliable, version of the aircraft electrical power system. By increasing the voltage and decreasing the amperage the whole system becomes more efficient and better than the current one. For what concerns the cost categories of the advanced EPGDS, we can say that:

| | EIR | Annual operating costs | On-aircraft investment costs | Retrofits costs | Maintenance costs | Production costs |
|---|---|---|---|---|---|---|
| **A-EPGDS** | 100 M | $-0.4$ % | 1 M | $\sim 0^{*}$ % | $\sim 0^{**}$ % | $\sim 0^{***}$ % |
| | * The retrofits costs are the same as the ones needed for current electrical systems | | | | | |
| | ** The maintenance costs are the same as the ones needed for current electrical systems | | | | | |
| | *** The production costs are the same as the ones needed for current electrical systems | | | | | |

Table 3.9 Cost categories for A-EPGDS [39]

As we can easily see from table 3.9, this technology does not need a huge investment cost in order to be developed because it is already flying on some regional aircrafts. The annual operating costs are slightly better than a modern electrical power system for there is a small saving of weight (with the same redundancy level) if we consider the whole system. This turns into a fuel saving per each mission (the less an aircraft weights, the less fuel it will burn with the same speed) and thus, decreasing the operating costs. The last three cost categories do not change at all for the upgrade this technology offers is only related to the change of distributing method. In fact, instead of distributing and generate electrical power with high amperage and low voltage, like it is done on current commercial aircrafts, and advanced EPGDS generates and distributes it using high voltage and low amperage. This allows an improvement in reliability and a slight weight saving, but the retrofits costs and the maintenance costs, as well as the production costs remain unaffected. For what concerns the on-aircraft investment costs, we can say that the 1 million US dollars cost is explained due to the need to change some parts of the aircraft in order to fit the system (in particular, some space must be created to place the generators and the cables that will reach every part of the airplane).
Eventually, the cost categories can be additionally split into the four different categories we have seen in chapter one.

1) ***RDTE cost*** $\longrightarrow$ Around 100 million dollars. This category is the same as the EIR costs and, as previously said, there is not need to invest a huge amount of money on this cost category as the A-EPGDS is already at TRL 6.

2) ***Acquisition costs*** $\longrightarrow$ Assuming the same amount of profit kept for current electric power systems, we can state that there is no big difference between the acquisition costs of advanced electric power generator and distribution systems and the current ones
3) ***Operating costs*** $\longrightarrow -0.4$ %, as written in table 3.9
4) ***Disposal costs*** $\longrightarrow \sim 0$ % as there is no difference between high voltage-low amperage equipment and the high amperage-low voltage one in terms of disposing.

## 3.7 ADVANCED PROPELLERS

Nowadays, short range and regional aircrafts are becoming more and more used due to the increase of air traffic. Many of them mount propellers (some of them use just one propeller mounted on the nose of the aircraft and others use two of them; one per each wing). Many upgrades can be made onto these devices such as increasing their efficiencies, their rotational speed and, most important, reducing the chances of ice formation on the blade tips. Today, many commercial airplane companies are studying and testing new innovative designs for propellers. First thing first, a propeller is a device made of a certain number of blades that is essentially a rotating wing. It transfers the power produced by an engine to force air to move through the diameter of the propeller. This way, the accelerating the airflow passes under the wing and it generates lift, thus allowing the airplane to fly safely. An aircraft can have from one up to four blades in its propellers, depending on the power needed to fly that aircraft (the more blades a propeller has, the faster the airflow). As a matter of fact there have been discovered many techniques to increase the overall propellers efficiency so far, such as: increasing the number of blades till six of them, use composite materials for propellers and developing constant speed propellers. However, a new technology that is currently under studies and it will bring many benefits to today's propellers are the ***proplets***. First of all, what is a proplet? As it can be seen from picture 3.3, this technology consists of a curved edge propeller (normally in aluminium or composite material) and it basically works the same way as a winglet on a wing. In fact, proplets change lift distribution near blade tip to reduce induced drag, thus allowing to save fuel. Moreover, just as with a winglet, a proplet must be properly loaded to achieve a performance benefit otherwise it would behave like a current propeller. Another achievement this technology brings is related to noise reduction. Proplets, can indeed decrease propellers noise, especially during take off and landing, thus reducing airport taxes and flight times (there would be no need to follow ascending/descending flight paths that avoid urban areas as the noise emissions would be acceptable).

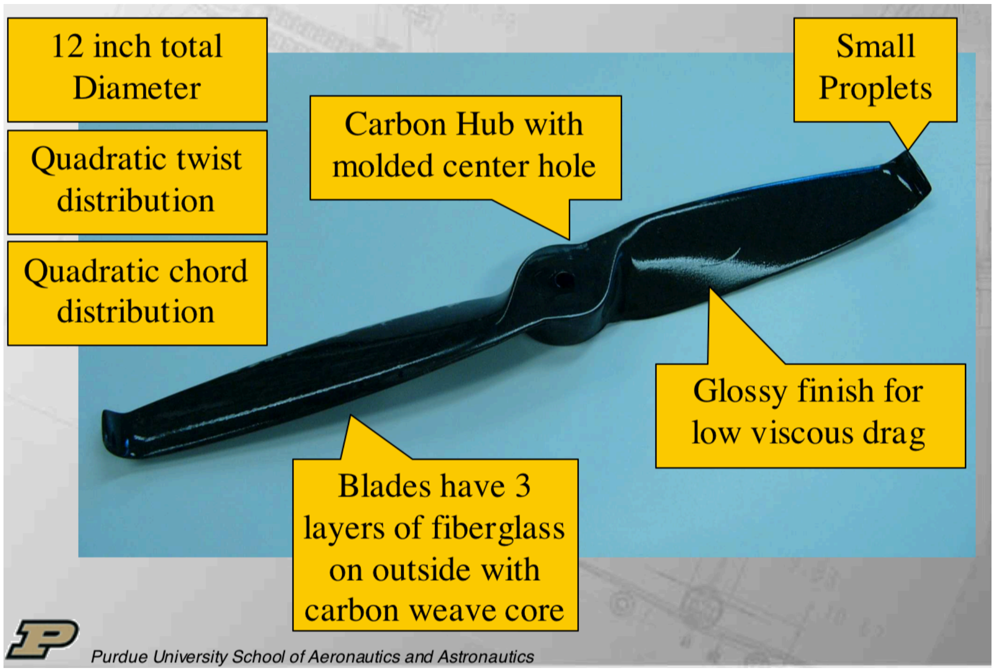


Figure 3.3 Single blade propeller with proplets [40]

As previously hinted, this technology offers many ***advantages*** and the most important ones are:

- ***Less fuel burnt*** $\longrightarrow$ Thanks to the efficiency increase and the induced drag reduction, propellers with proplets can save up to 5% of fuel per each mission. This saving will obviously lead to an operating cost saving as well.
- ***Noise reduction*** $\longrightarrow$ This technology allows a $-6$ dB noise reduction during take off and landing. This achievement is realized thanks to the shape of the proplets on the edges of the propeller. Basically, they reduce the air vibration on the propeller itself, thus reducing the noise emitted.

Unfortunately, producing and implementing this new technology onto new regional/short-range aircrafts has its own ***disadvantages***. The main ones are:

- ***Structural constraints*** ⟶ Propellers with edge proplets maintain a performance benefit when the proplets are very thin. As a matter of fact, this leads to keep lower rotational speeds in order not to damage the propeller. In general, this technology needs to be taken seriously under control in terms of structural health as the thinner a blade is, the more frequently it may damage.
- ***Expensive and long-term tests*** ⟶ In order to design and test this technology, many tests and calculations must be done. These ones normally requires days (if not weeks) to be completed and thus, incrementing costs and time required to produce them.

Studying, developing and testing new propeller designs, in order to improve its performances, is something that has been done for decades. In particular, the idea of applying the winglets technology onto propellers was first developed in 2013 and now it has a TRL of 6. Estimates say that proplets will be fully available on commercial regional airplanes by 2022 and they are only available now for some military aircrafts. For what concerns the cost categories of this new technology, we can say that:

| | EIR | Annual operating costs | On-aircraft investment costs | Retrofits costs | Maintenance costs | Production costs |
|---|---|---|---|---|---|---|
| **Advanced propellers** | 100 M | $-3$ % | $\sim 0^*$ % | $\sim 0^{**}$ % | $+1.8$ % | $+1.1$ % |
| | * The on-aircraft investment costs are the same as the ones needed for current propellers | | | | | |
| | ** The retrofits costs are the same as the ones needed for current propellers | | | | | |

Table 3.10 Cost categories for advanced propellers [41]

The estimated investment and research cost is around 100 million dollars due to the medium-high TRL this technology has at the moment. In fact, in the aerospace field, this amount of money is not too big and that is thanks to the research and test that have been made so far. The annual operating costs slightly decrease due to a good saving of fuel burnt per mission and to the noise reduction during take off and landing (which translates into a fuel saving too) even if the maintenance costs increase. This latter happens because of the reduced blades thickness. In fact, the less thick they are, the more pronte to crack propagation they will be and thus, it will be necessary to

increase maintenance controls. It is also possible to increase the resistance of the balde with using modern materials like composite and/or new aluminum alloys. This way maintenance checks would be the same as for current materials used for aircraft propellers but, on the other hand, the blades manufacturing cost will definitely increase. For this reason, in one way or another, we have to accept the increase of maintenance cost for this new technology. The production costs increase as well for more accurate machining operations will be necessary in order to shape the correct proplets on the edges of the blades and to make the blades thinner. The retrofits costs are the same as the ones required for mounting propellers without proplets because the installation method does not change at all. The same goes for the on-aircraft investment costs as there is no need to change any part of the aircraft to fit this technology on it. In fact, proplets main innovation is located on the edged of the blades and it has nothing to do with the rest of the airplane.
Moreover, splitting these cost categories into the original four ones we have seen in the first chapter:

1) ***RDTE costs*** $\longrightarrow$ Around 100 million US dollars. Proplets does not need an intense and complicated research and testing program compared to other new technologies and this cost is also quite “low” due to the previous research, development and testing program that has been made so far
2) ***Acquisition costs*** $\longrightarrow$ Assuming the same amount of profit for propellers with proplets and current ones, we can say that there is a $+1.1$% of cost because of some extra work needed to produce these new kind of blades
3) ***Operating costs*** $\longrightarrow$ $-3$% per year, as shown in table 3.10
4) ***Disposal costs*** $\longrightarrow$ $-0.6$ % due to less material to get rid off. As a matter of fact, this technology brings many benefits only if the blades are thinner than current ones and that means having less material to be disposed

## 3.8 ADAPTIVE WINGLETS

In today's aviation, winglets are well-known devices. They were first introduced in the 1980s and since then, they are still used nowadays due to the benefits they bring. As a matter of fact, winglets devices increase the lift generated at the wingtip, by smoothing the airflow across the upper wing near the tip, and reduce the lift-induced drag caused by wingtip vortices, improving lift to drag ratio. They can have different shapes, depending on layout choices and on which benefit the company wants to favor. However, once their shape has been chosen, it remains fixed and that is a proper disadvantage in terms of performances. In fact, if a winglet design had been studied for maximizing the performances during the cruise phase, it might not do the same during the take off and landing phases or viceversa. In order to go over this problem, many commercial aircraft companies are now studying adaptive winglets devices. The idea of an adaptive winglet has been successfully investigated in the recent past through theoretical studies and small scale experiments as well. More precisely, adaptive winglets are winglets where the geometry can be adjusted to the changing flow conditions. This technology has the potential to improve the aerodynamic performance during climb and high-speed off-design conditions by providing adapted wing lift distribution throughout the surface. Additionally, they can significantly reduce aerodynamic loads at critical flight points, having a variable trailing edge control. Several patents have been produced by the major aircraft manufacturers as Airbus, Boeing and McDonnell Douglas. The adaptive winglet is expected to operate during long (cruise) and short (climb and descent) mission phases to reduce aircraft drag and optimize lift distribution providing, at the same time, a better roll and yaw control capability. Figure 3.4 gives us an example of how this technology would work during the different phases of the mission. Technically, the mechanical system is designed to face different flight situations by a proper action on the movable parts represented by two independent and asynchronous control surfaces with variable camber and differential settings.

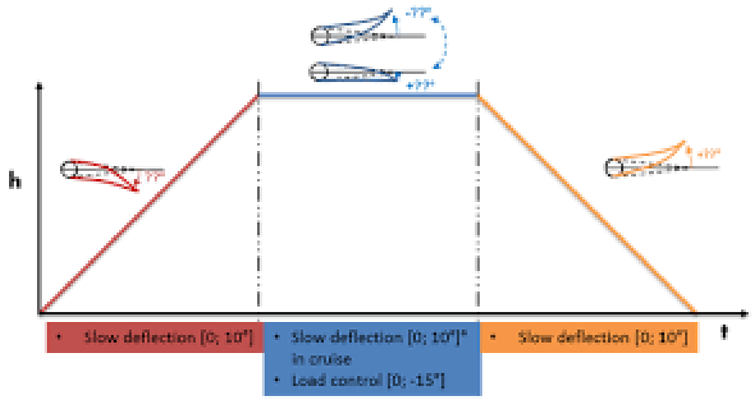


Figure 3.4 Possible deflections of the wingtip during take off, cruise and landing [42]

A set of suitable electromechanical actuators are integrated within the limited space inside the winglet loft-line, capable of holding prescribed deflections for long time operations. Such a solution would mitigate the risks associated with critical failure cases with beneficial impacts on the overall airplane safety. Unfortunately, although the growing interest shown from aviation industry, there is still a big step towards bringing the adaptive winglet concept to a real flight application. Adaptive winglets have now a TRL of 7 and they can bring many ***advantages*** to current aircrafts in terms of performances. In particular:

1) ***Drag reduction*** ⟶ Adaptive winglets, if applied and mounted correctly on the wing, can save up to 20% of the overall drag that otherwise would affect the aircraft during the cruise phase; thus reducing the fuel burnt.
2) ***Increased lift*** ⟶ Recent studies shown that this technology would bring a +2% of generated lift during the take off phase (the moment when generating lift is the most important thing at all) and a +4% of generated lift during the overall mission, thus reducing the fuel needed and increasing the stability of the aircraft itself.

Unfortunately, the installation of adaptive winglets on current commercial aircrafts would bring ***disadvantages*** as well. The main ones are listed below:

1) ***Increased weight*** ⟶ Adding moving parts and actuators into the wing would necessary lead to increase its weight and, consequentially, the aircraft total weight as well. Studies have shown that this technology would increase the overall airplane weight of 2.1%; thus increasing the fuel required per mission and increasing the operating costs too.
2) ***Increased maintenance cost/time*** ⟶ Another bad effect of increasing the number of parts inside the wing is that the maintenance downtime is increased (as well as its cost) for there would be more parts to be checked. This will obviously affect the annual operating costs by increasing them.

Decreasing the overall drag and increasing the generated lift on one side and increasing weight and maintenance downtime on the other affect the cost categories as shown in table 3.11.

| | EIR | Annual operating costs | On-aircraft investment costs | Retrofits costs | Maintenance costs | Production costs |
|---|---|---|---|---|---|---|
| **Adaptive winglets** | 300 M | $-1.2$ % | 75 M | $\sim 0^{*}$ % | $+2$ % | $+1$ % |
| | * The retrofits costs are the same as the ones needed for current winglets | | | | | |

Table 3.11 Cost categories for adaptive winglets [43]

As a matter of fact the EIR cost are explained due to the fact that this technology is quite expensive to develop as we need to take into account that even if all the components forming it have been developed, they still need to be tested onto current commercial aircrafts and their synergy still has to be proven as well. For what concerns the annual operating costs, we can say that they only slightly decrease for the fuel saving incurred thanks to drag reduction and generated lift increase is deeply influenced by the maintenance costs increase. This latter happens due to the increasing number of components adaptive winglets require in order to properly work and so, more components means more maintenance downtime and thus, more money needed for this phase. There are no retrofits costs as once adaptive winglets are installed on the wing, the installation method of this latter onto the aircraft itself does not change at all. On the other hand, 10 million US dollars would be necessary for on-aircraft investments as some wing inner parts have to be changed in order to fit all the

components (actuators, movable parts, control surfaces, etc…) allowing winglets to move. Eventually, as it could have been easily imaginable, there is a remarkable increase of production costs. This happens because there are a lot of small new components that need to be produced in order to assemble this new technology: actuators, control surfaces, movable parts, etc… and, of course, they would not be required on current, non-movable, winglets.
Furthermore, if we have to split all these costs into the four original categories we have described in the firs chapter, we would say:

- ***RDTE costs*** $\longrightarrow$ Around 300 million US dollars. As previously said, adaptive winglets still have to be tested onto commercial aircraft before making them available to the aviation industry. It is a long and difficult process, full of regulations to respect and this justifies this big amount of money needed for this category
- ***Acquisition costs*** $\longrightarrow$ As this category is described by the difference between the production costs and the profit gained, we can say that there is a $+1\%$ of money required for this category, assuming the same amount of profit as for current winglets.
- ***Operating costs*** $\longrightarrow$ As shown in table 3.11, there is a $-1.2\%$ of cost saving per year
- ***Disposal costs*** $\longrightarrow$ $+1.5\%$ as it would be necessary to get rid of many more components that it would be with a current, non-movable, winglet. Moreover, all the components required to make adaptive winglets work are made of metallic or composite materials, which make them even more difficult to dispose.

## 3.9 NEW ENGINE MATERIALS

First of all, with the word "new engine materials", a vast field of technologies is meant. For instance, there could be many new and advanced materials under development nowadays that could be applied onto next generation aircraft engines with the aim to increase one (or some) of its performances. In this chapter we will mainly deal with materials that would allow to increase the temperature inside the combustion chamber and materials allowing a good increase of structural performances such as: creep resistance, endurance, fatigue, corrosion resistance, and so on. One one hand, increasing the combustion temperature will allow the aircraft to fly faster and on the other hand, installing light, resistant materials on the engine will decrease the airplane weight and extend its operational life by decrease its number of maintenance checks. Intuitively, the materials that will used on an aeronautical engine are to be chosen according to the kind of stresses they will have to sustain. For example, the materials used for the combustion chamber will not be the same as those used for the high pressure compressor since the first will have to sustain high thermal loads and low mechanical loads while the contrary will happen on the last ones. As it can be easily understood, new engine materials that would be highly resistant to temperature will be placed where the combustion takes place while the ones that can resist to higher mechanical stresses would be placed all over the engine except than in the combustion chamber. The main aim of these new materials is to increase the engine overall performances, thus reducing the operating costs of the airplane itself. Nowadays there are many advanced engine materials under development; however, in order not to list all of them for it is not the goal of this thesis, only the most important three of them will be treated. The fist one is the ***Ti-Al (titanium aluminide)*** it is thought to be used on both low-pressure turbine blades and high-pressure compressor blades because it has the potential to improve the thrust-to-weight ratio in aircraft engines because it's only half the weight of nickel alloys which are the most common used material in these blades so far. Furthermore, this material is more easily machined than Ni alloys and yet, it guarantees better mechanical performances. General Electric was a pioneer in this development and uses TiAl low-pressure turbine blades on its GEnx engine, the first large-scale use of this material on a commercial jet engine; in this case, in the Boeing 787 Dreamliner. Another new material which is under development that could replace the one used to produce the engine case is the ***Al-Li alloy.*** The addition of lithium strengthens aluminum at a lower density and weight, two catalysts of the aerospace material evolution. Moreover, its high strength, low density, high stiffness, damage tolerance, corrosion resistance, and weld-friendly nature make it a better choice than traditional aluminums in commercial engine frames. Finally, the ***ceramic-matrix composites*** are reasonably new to aerospace industry and, thanks to their low density/weight, high hardness, and most importantly, superior thermal and chemical resistance, would be keen to be used in the combustion chamber. They are basically made of a ceramic matrix reinforced by a refractory fiber, such as silicon carbide (SiC) fiber. There is no doubt that if there three new materials would be synergistically used in the engine, they would all bring many improvements. As a matter of fact, the main ***advantages*** they offer are:

1) ***Reduced weight*** ⟶ As previously hinted, these materials can save up to 30% - 35% of the total engine weight without compromising its resistance characteristics at all. This means reducing the aircraft total weight as well, thus saving fuel too.
2) ***Improved performances*** ⟶ Both mechanical and thermal performances would be considerably increased if these materials were to be used in the engine. As consequence, improving the mechanics performances will lead to extending the aircraft operating life and decreasing its maintenance checks, thus having more time to make profit over the aircraft and reducing the maintenance costs.

As every other new technology we examined in this chapter, this one here has its own ***disadvantages*** as well. The most important ones are:

1) ***Cost*** ⟶ As these materials are quite new in the aviation industry, the whole production process needed could be very expensive (especially for the ceramic-matrix composites). Even if the technology to produce these materials exists, a lot of time is still needed for them to be fully operational on every flight because of their costs.
2) ***Different problem reactions*** ⟶ Using different materials in the engine may turn into a differentiation of arising problems. For example, since composites are often constructed of different ply layers into a laminate structure, they can "delaminate" between layers where they are weaker. On the other hand, metallic materials cracks in a different way and that may lead to different, more frequent and longer maintenance checks. Also, metal alloys expand and contract more on variations in temperature as compared to composites. This may cause an imbalance at joinery and may lead to failure.

For what concerns the costs categories of this new materials, we can say that it is quite difficult to  classify each of them for all the wide range of new engine materials available or currently under development. In this chapter, we consider the three materials we have previously treated and imagine they were all installed on a modern commercial aircraft. In this case, the cost categories would be defined by the table below:

| | EIR | Annual operating costs | On-aircraft investment costs | Retrofits costs | Maintenance costs | Production costs |
|---|---|---|---|---|---|---|
| **New engine materials** | 300 M | $-3.4$ % | $\sim 0$* | $\sim 0$**% | $-1.8$ % | $+2.6$ % |
| | * The on-aircraft investment costs are the same as the ones needed for current engine materials | | | | | |
| | * * The retrofits costs are the same as the ones needed for current engine materials | | | | | |

Table 3.12 Cost categories for new engine materials [44]

The Estimated-Investment-Required to research, develop and test these new materials are not zero as, even if they already exists on the market and many commercial planes fly with one or more of these new engine materials, there is still need to test and do some research onto aircrafts where they are still not mounted on. There is no saving, nor loss of money in the on-aircraft investment costs and in the retrofits costs as there is no need at all to change the configuration of the engine to mount them on (these materials would simply replace the current ones in their exact positions) nor to change the installation method on the engine, for they would be mounted on the engine right in the same way as other materials would. The annual operating cost remarkably decrease instead as these three materials will allow a good fuel saving thanks to the engine weight reduction they bring. Furthermore, they will also allow a good cost decrease in terms of maintenance, for these materials have much better mechanical performances than the current ones and that means less maintenance checks due to a higher fatigue resistance, and a longer operational life thanks to their higher stiffness. Unfortunately, the production costs can do nothing but increase, as it takes a longer and more expensive production process to manufacture an Al-Li engine frame rather than a classical aluminium one, let alone manufacturing a ceramic-matrix composite combustion chamber.
Finally, dividing these cost categories of this last new technology into the original four cost categories we have seen in chapter one, the result would be:

- ***RDTE costs*** ⟶ Approximately 300 million US dollars needed as the materials still need to be tested on aircrafts where they are not yet applied on.
- ***Acquisition costs*** ⟶ Assuming the same percentage of profit for these materials and the current ones used nowadays on aircraft engine, there would be an increase of $+2.6\%$ because of the expensive production process of some of these materials

- ***Operating costs*** $\longrightarrow -3.4\%$ as shown in table 3.12
- ***Disposal costs*** $\longrightarrow +2.1\%$ for these materials as it is harder to get rid of a an Al-Li alloy rather than just aluminium due to the presence of Lithium in the first one. Moreover, a ceramic-matrix composite is much more difficult to dispose than a Titanium alloy (a very common material in current combustion chambers) for the presence of the refractory fiber, which is really hard to destroy or dispose. For what concerns the Ti-Al, we can say that it has basically the same disposal expenditure of the current materials used in both low-pressure turbine blades and high-pressure compressor blades (Nickel-based superalloys).

Now that every new technology has been deeply analyzed, a specification needs to be done. Previously in this thesis we stated that the TRL levels of every single technology has been referred to the ones of jet liners. In order to scale them to regional turboprops aircrafts, an adjustment coefficient must be taken into account. Intuitively, the RDTE cost always be less for turboprops rather than for jet liners (we will see this different in chapter 4) as they have a simpler, easier design and thus, that decreases the overall RDTE cost. There are many ways to formulate and empirical coefficient allowing us to scale that cost phase for the two different kind of airplanes. It has been decided to consider two variables: the cruise speed and the maximum take off weight of the aircraft. In particular, it has been decided to multiply the liner MTOW by 2/3 as this parameter does not influence the RDTE phase as mush as $V_c$ does. For obvious reasons, this coefficient must be set to one for jet liners while it must be between 0 and 1 for turboprops. Once computed, that coefficient will be multiplied by each RDTE cost we previously found in this chapter, showing the RDTE cost of every new technologies considered for turboprop aircrafts. Using a formula, the adjustment coefficient can be found with:

$$K_{lin} = \frac{(V_c \bullet MTOW)_{lin}}{(V_c \bullet \frac{2}{3} MTOW)_{lin}} = 1 \tag{3.1}$$

$$K_{trp} = \frac{(V_c \bullet MTOW)_{trp}}{(V_c \bullet \frac{2}{3} MTOW)_{lin}} \neq 1 \tag{3.2}$$

# CHAPTER 4

## 4.1 REGIONAL AIRCRAFTS: ATR-72 & A-320

The world “regional” describes a kind of short to medium range turbofan or turboprop-powered aircrafts, whose use all over the world started to grow just after the advent of airline deregulation in the United States in 1978. The all have in common the feature of being small airplanes designed to fly up to 100 passengers on short-haul flights. This class of aircrafts is normally flown by regional airlines that are either contracted by or subsidiaries of larger airlines. The beginning of the production of first regional aircrafts began in the mid-1950s, due to the increasing demand of even more economical designs. The first regional aircrafts were almost always turboprops for they have a far lower maintenance costs than turbofans. One reason for the downturn of the turboprop market was the introduction of first regional jets. However, even if a small number of jets entered service during those years, they could not stand against in terms of cost-operation with the turboprops design. As a matter of fact, they were suitable for routes with small number of passengers, in contrast to short routes where fuel economy was the aim to reach. Anyway, as time went on, the engine technology improved and this difference narrowed. This process went on until the higher utilization factors due to higher cruising speeds, cancelled any remaining advantage deriving from having lower operating costs. The first commercial aircraft to achieve it was the Bombardier’s twin-engine Canadair Regional Jet (CRJ), which became a best-seller in its times. The CRJ’s range was enough to allow him to fill mid-mid-range routes too, routes that were previously served by much larger and bigger airplanes, such as the Boeing 737 and DC-9. Although not as economical as the turboprops, flying directly to and from small airports (bypassing big hubs), they managed to reduce the need for low-cost regional airliners. Moreover, turboprops are quite to outside observers but they are very noise inside; something that does not happen in turbofan-powered aircrafts. Nowadays, the trend is to keep studying larger aircrafts with improved economics. The clearest example of these kind of airplanes is the 70-110 seat E-Jet series of the CS-series that, in particular, borders the line between “mainline” and “regional” aircraft, for their passengers’ cabin comfort is far better than the one of traditional narrow-body jets like the Boeing 737 or the Airbus A-320.

First of all, the ATR-72 is a twin engine turboprop produced and manufactured by the Italian-French company ATR. It first flew in 1989 as a longer and bigger variant of the small ATR-42 with the goal of increasing the seating capacity (from 42 to 72). Two Pratt & Whitney Canada PW124B-series turboprop engines powers it with four or six-bladed (depending on the performances required)propellers provided by the famous propellers company: Hamilton Standards. With a maximum of 2750 shp, its take-off performances are very competitive. There are four different variants of modern ATR-72 aircrafts; as a matter of fact they are:

- ATR-72 100: the first series
- ATR-72 200: the second series
- ATR-72 500: the reference for this study
- ATR-72 600: with avionic and power improvements

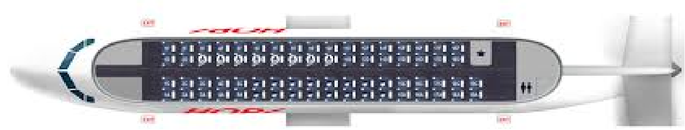

Figure 4.1 The ATR-72 500 while flying (on the left) and its capacity (on the right) [45]

On the other hand, the Airbus A-320 consists of short to medium range, narrow-body, commercial passenger twin-engine jet airliner, manufactured by Airbus. The assembly of this aircraft takes place in Toulouse (France) and Hamburg (Germany). A plant in Tianjin, China, has also been producing A-320 for Chinese airlines since 2009 while a final assembly facility in Mobile, Alabama, United States, delivered its first A-320 in April 2016. This airplane can accommodate up to 150 passengers and has a range of 3300 nautical miles. The first A-320 flew on 22 February 1987, and was first delivered in March 1988 to Air France. The Airbus A-320 pioneered the use of digital fly-by-wire flight control systems, as well as side-stick controls, in commercial aircraft. There has been a continuous improvement process since their introduction. The A-320 series has two variants:

- Airbus A-320 100 ⟶ The first series
- Airbus A-320 200 ⟶ The reference for this study

We are going to analyze the second one as it is more modern and still used nowadays. The primary changes of the A-320 200 over the A-320 100 are the wingtip fences and the increased fuel capacity, allowing an increased range. Powered by two CFM56-5 engines, supplying 25000 Lbf of thrust, its flight performances are far better than the ATR-72 500. Figure 4.2 shows an external view of the Airbus A-320 200 and its seats capacity.


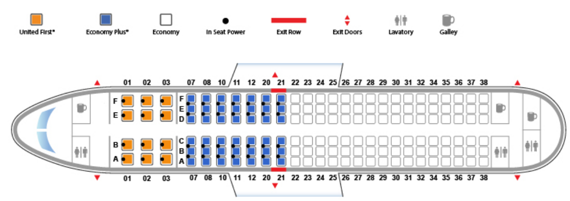

Figure 4.2 External view of an A-320 200 along with its internal capacity [46]

## 4.2 ATR-72 500 & A-320 200 RDTE COSTS

Once having described the regional aircrafts group, the ATR-72 500 and the Airbus A-320 200, an input’s overview will be presented in this section for every single Life-Cycle-Cost category. The method we will be using is the ROSKAM one, which has been deeply presented and analyzed in chapter one. The formulas used in order to get the results shown in the next tables are the ones from 1.1 to 1.52 and the software Matlab has been used to this purpose. As can be easily seen from table 4.1, two CEFs were used because some of them were older than others. The inputs for the calculation of the RDTE cost are shown in the table below:

| RDTE-INPUT | | ATR-72 500 | A-320 200 |
|---|---|---|---|
| | | | |
| $CEF$ | From 1990 to 2017 | 1.95 | 1.95 |
| $CEF_2$ | From 1971 to 2017 | 6.14 | 6.14 |
| $MTOW$ | Max take-off weigh [Lb] | 50265 | 169756 |
| $V_c$ | Cruise speed [Kts] | 275 | 488 |
| Thrust | Engine cruise trust [Lbf] | 7150 | 25000 |
| $SHP_{TO}$ | Propeller take-off power [shp] | 2160 | — |
| $N_e$ | Number of engines | 2 | 2 |
| $N_p$ | Number of propellers | 2 | — |
| $N_m$ | N. of manufactured aircrafts | 875 | 875 |
| $W_{avio}$ | Avionic sys weight [Lb] | 670 | 1172.5 |
| $R_e$ | Engineering rate [USD/h] | 178.42 | 178.42 |
| $R_m$ | Manufacturing rate [USD/h] | 92.82 | 92.82 |
| $R_t$ | Tooling rate [USD/h] | 120.1 | 120.1 |
| $N_{RDTE}$ | Number of RDTE aircrafts built | 3 | 5 |
| $N_{st}$ | N. of airframes built | 1 | 2 |
| $N_r$ | N. of aircrafts built per month | 0.33 | 0.33 |
| $F_{mat}$ | Material factor | 1.5 | 1.5 |
| $F_{obs}$ | Low-observable factor | 1 | 1 |
| $F_{diff}$ | Program complexity factor | 1.33 | 1.7 |
| $F_{CAD}$ | CAD factor | 0.8 | 0.8 |
| $F_{tsf}$ | Cost-adjustment factor | 0 | 0.1 |

| RDTE-INPUT | | ATR-72 500 | A-320 200 |
|---|---|---|---|
| $N_{prot}$ | N. of prototypes built | 2 | 3 |
| $Finance$ | [%] | 20 | 20 |
| $Profit$ | [%] | 20 | 20 |

Table 4.1 ROSKAM RTDE cost program inputs

These data are essential in order to obtain results from the Roskam model. After having put these terms into the chapter one formulas, we can see, from Table 4.2, that the most expensive RDTE cost item is the one related to the FTA manufacturing. This happens because a new aircraft has to be built, along with all its systems and airframe, with the goal of being tested for the first time. Furthermore, this model is the only one this cost category; no other cost model take it into account. This is one of the reasons why the Roskam model has been preferred to others in this thesis, along with its accuracy and reliability.

| RDTE-OUTPUT | | ATR-72 500 | A-320 200 |
|---|---|---|---|
| | | | |
| Airframe engineering & Design Cost | M-USD | 113.18 | 876 |
| Development Support & Testing Cost | M-USD | 21.13 | 238.7 |
| | | | |
| FTA Cost | M-USD | 445.55 | 2251 |
| | | | |
| Cost of engines and avionics | M-USD | 4.8 | 19.5 |
| Manufacturing cost | M-USD | 190.12 | 944.6 |
| Material cost | M-USD | 23.63 | 104.5 |
| Tooling cost | M-USD | 202.27 | 1059.4 |
| Quality control cost | M-USD | 24.71 | 122.8 |
| Flight-test operational cost | M-USD | 4.74 | 75.78 |
| Test & simulation facilities cost | M-USD | 0 | 688.31 |

| RDTE-OUTPUT | | ATR-72 500 | A-320 200 |
|---|---|---|---|
| | | | |
| **TOTAL RDTE COST** | M-USD | **974.33** | **6883.1** |

Table 4.2 ROSKAM RDTE cost program outputs

For what concerns the A-320 RDTE cost, we can say that this particular cost is referred to the A320 family (which includes: A318, A319, A320 and A321) for the researches, tests and studies for the four of them are made all together as there are few differences between them, thus meaning a much higher RDTE cost required if there would one RDTE phase per each model singularly.Looking at the results of the above table, we can say that the total RDTE cost is around 1 billion dollar. This amount of money is in line with data concerning this cost category applied to this particular aircraft. Furthermore, it is important to note that the material coefficient (see table 4.1) had been set to 1.5 instead of 1. This choice had been made as the ATR-72 500 has got some structural parts made of composite material. In particular, this aircraft has its tail and secondary flight control structure made by composite, as well as its wing-body interaction. Eventually, the list below shows why some other coefficients were chosen:

- The formula: $W_{ampr} = 10^{[0.1936+0.8645(logW_{TO})}$ was used instead of 1.6 in order to simplify the calculations and because of lack of precise data
- $V_{max} = V_c$ for both the ATR-72 500 and the A-320 200 are civil aircrafts
- $F_{diff}$ = 1.33 for the ATR-72 500 because the use of advanced technology on these airplanes is not that aggressive ($F_{diff}$ is a number between 1, which means the aircraft has no new, advanced technology on it, and 2 which, on the contrary, means that it has a lot of it) and $F_{diff}$ = 1.5 for the A-320 200 as its development involves a moderately aggressive use of advanced technology
- $F_{CAD} = 0.8$ which means that the manufacturers of the ATR-72 500 and A-320 200 are very well experienced in the use of CAD programs ($F_{CAD} = 0.8$ for well experienced manufacturers; $F_{CAD} = 1$ for manufacturers using manual drifting techniques and $F_{CAD} = 1.2$ for manufacturers who are still in CAD learning mode)
- $F_{obs} = 1$ as this airplane does not need to be invisible to radars ($F_{obs}$ = 1 for civil aircrafts and $F_{obs}$ = 3 for stealth aircrafts)

- $F_{tsf} = 0$ for there is no need to have extra test and simulation facilities ($F_{tsf} = 0.2$ if the would be required)

## 4.3 ATR-72 500 & A-320 200: MANUFACTURING AND ACQUISITION COSTS

Once again, the Roskam cost model is still the best one for calculating this cost category too, as it is very precise in dividing this cost category into its every single phase, considering all of them. As can be easily seen from table 4.3, the fact that there are far less inputs than in the RDTE phase is related to the fact that most of them have already been set during the previous cost category and, for this reason, there is no need to repeat them in this cost category. As a matter of fact, the table below shows all the extra inputs needed to calculate these two costs, that were not present in table 4.1:

| **MAN & ACQ INPUT** | | **ATR-72 500** | **A-320 200** |
|---|---|---|---|
| | | | |
| $Pax$ | N. of passengers | 72 | 164 |
| $R_{e1}$ | Engineering rate [USD/h] | 160.6 | 240.9 |
| $R_{m1}$ | Manufacturing rate [USD/h] | 89.5 | 134.25 |
| $R_{t1}$ | Tooling rate [USD/h] | 115.83 | 173.74 |
| $N_r$ | N. of aircrafts built per month | 7 | 50 |
| $F_{over}$ | Overhead factor | 4 | 4 |
| $F_{int}$ | Interior factor [USD/pax] | 1000 | 2000 |
| $F_{Th}$ | Flight test hours [h] | 10 | 10 |
| $f_{ACQ}$ | Acquisition factor | 1.15 | 1.15 |

Table 4.3 ROSKAM manufacturing & acquisition cost program inputs

The cost-rates (engineering, manufacturing and tooling) have changed because they are normally slightly lower during this phase than during the RDTE one. On the other hand, the number of aircrafts built per month is higher during this phase than in the previous one, for it is easier and faster to go through this phase rather than the RDTE one. The interior factor $F_{int}$ (expressed in USD/pax) takes into account the price spent by the company per each passenger on the plane ($F_{int} =$ 0 for military aircrafts, $F_{int} = 500$ for light general aviation airplanes, $F_{int} = 1000$ for regional transport airplanes, $F_{int} = 2000$ for jet transports and $F_{int} = 3000$ for business jets). The flight test hours represent the hours spent to certificate every single ATR-72 500 and A-320 200 before their sale. Finally, the overhead factor $F_{over}$ is accorciate with the production flight test activities and, for regional transport aircrafts, this factor is equal to 4.

The manufacturing and acquisition outputs are very important as they can be combined with the RDTE cost, to get the AEP (Airplane-Estimated-Price): probably the most relevant price of the whole production. Using the Matlab software, the ATR-72 500 AEP is 15.93 million US dollars, which is pretty close to its market value, while the Airbus A-320 200 is . The results of the Matlab software are shown in the table below:

| **MAN & ACQ OUTPUT** | | **ATR-72 500** | **A-320 200** |
|---|---|---|---|
| | | | |
| Airframe engineering & Design cost | M-USD | 174.84 | 2170.7 |
| Aircraft production cost | M-USD | 8701.1 | 39206 |
| Cost of engines and avionics | M-USD | 2103.8 | 5708.1 |
| Interior production cost | M-USD | 198.37 | 903.68 |
| Manufacturing cost | M-USD | 3404 | 19576 |
| Material cost | M-USD | 2098.9 | 6174.7 |
| Tooling cost | M-USD | 453.54 | 4298.8 |
| Quality control cost | M-USD | 442.51 | 2544.8 |
| Flight test operations cost | M-USD | 112 | 112 |
| Manufacturing cost | M-USD | 14980 | 69147 |
| Acquisition cost | M-USD | 17976 | 82977 |
| | | | |

| MAN & ACQ OUTPUT | | ATR-72 500 | A-320 200 |
|---|---|---|---|
| **TOTAL AEP** | M-USD | **21.65** | **102.7** |

Table 4.4 ROSKAM manufacturing and acquisition cost program outputs

However, at this point an explanation has to be done. We have set $N_m$ as 875 for both the ATR-72 and the A-320: if this value could have been truth for the ATR, we cannot say the same for what concerns the A-320. In fact, the A-320 200 produced all over these years are around 4200. It has been decided to maintain $N_m = 875$ for both of them as otherwise the A-320 AEP would have been too low and hence, not realistic. This had happened because of the the aggressive learning curve (fall in the cost of production per unit due to the increased involvement in the production process) the ROSKAM method uses. As a matter of fact, this model perfectly works for military aircrafts and medium to short range airplanes which are not produced in huge quantity.

## 4.4 ATR-72 500 & A-320 200 OPERATING & DISPOSAL COSTS

For what concerns the operating cost, the Roskam model is still the best one for calculating it because it is the only one that takes into account the importance of the depreciation periods and depreciation coefficients. Once again, in order to calculate $C_{OPS}$, the software Matlab was used. As it has been made for the manufacturing and acquisition costs, the parameters that had already been set in the RDTE cost inputs are not reported one more time. The inputs are shown in table 4.5:

| OPERATING INPUT | | ATR-72 500 | A-320 200 |
|---|---|---|---|
| | | | |
| $B_d$ | Range [nm] | 230 | 874.43 |
| $BFW$ | Burned fuel weight [Lbs] | 1220 | 4636 |
| $MMH_{eng}$ | Engine MMH/FH | 0.8 | 1 |
| $MMH_{air}$ | Airframe MMH/FH | 0.8 | 1 |

| OPERATING INPUT | | ATR-72 500 | A-320 200 |
|---|---|---|---|
| $F_c$ | Fuel cost [USD/GALLON] | 2 | 2 |
| $F_{density}$ | Fuel density [lb/gallon] | 6.4 | 6.4 |
| $N_{officer}$ | N. of first officers | 1 | 1 |
| $N_{captain}$ | N. of captains | 1 | 1 |
| $N_{fass}$ | N. of flight assistants | 2 | 4 |
| $ENG_d$ | Engine depreciation [Y] | 15 | 20 |
| $AIRF_d$ | Airframe depreciation [Y] | 15 | 20 |
| $AVION_d$ | Avionic depreciation [Y] | 10 | 10 |
| $AIRFs_d$ | Airframe spare parts depreciation [Y] | 15 | 20 |
| $ENGs_d$ | Engine spare parts depreciation [Y] | 15 | 20 |
| $AIRFs_f$ | Airframe spare parts factor | 0.4 | 0.4 |
| $ENGs_f$ | Engine spare parts factor | 0.5 | 0.5 |
| $AIRFd_f$ | Airframe depreciation factor | 0.9 | 0.9 |
| $ENGd_f$ | Engine depreciation factor | 0.9 | 0.9 |
| $AVIONICd_f$ | Avionic depreciation factor | 0.95 | 0.95 |
| $AIRFs_{df}$ | Airframe spare parts depreciation factor | 0.9 | 0.9 |
| $ENGs_{df}$ | Engine spare parts depreciation factor | 0.9 | 0.9 |
| $K_j$ | Crew factor | 0.26 | 0.26 |
| $SAL_{captain}$ | Captain annual salary [USD] | 80000 | 80000 |
| $SAL_{officer}$ | First officer annual salary [USD] | 70000 | 70000 |
| $SAL_{fass}$ | Flight assistant annual salary [USD] | 28000 | 28000 |
| $AH$ | Annual crew flight hours [h] | 900 | 900 |
| $TEF$ | Travel expense factor [USD/blhr] | 7 | 7 |
| $R_{lap}$ | Airplane maintenance labor rate [USD/h] | 16 | 16 |
| $R_{leng}$ | Engine maintenance labor rate [USD/h] | 16 | 16 |

| OPERATING INPUT | | ATR-72 500 | A-320 200 |
|---|---|---|---|
| $H_{em}$ | Attained period between engine overhaul [h] | 3000 | 3000 |
| $K_{hem}$ | Attained period between engine overhaul factor | 1.4 | 1.4 |
| $f_{amblab}$ | Overhead distribution factor for labor cost | 1.3 | 1.3 |
| $f_{ambmat}$ | Overhead distribution factor for material cost | 0.6 | 0.6 |
| $C_{apnf}$ | Navigation fee per flight [USD/flight] | 10 | 10 |
| $f_{change}$ | Crew interchange factor | 2.8 | 2.8 |
| $f_{tax}$ | Taxes coefficient | 5 | 5 |
| $f_{disp}$ | Disposal factor | 0.012 | 0.012 |

Table 4.5 ROSKAM operating cost program inputs

As we can easily see from table 4.5, there are far more input data required to compute the operating cost. This happens because both the direct operating costs and the indirect ones take into account many factors, from crew members salaries to the depreciation of every single aircraft system. For instance:

- $K_j$, the crew factor, accounts for such items as: vacation pay, cost of training, crew premium, crew insurance and payroll tax. It strongly varies from operator to operator and it is often suggested to use 0.26 as a value of reference
- $TEF$ is associated with each tipe of crew member. It deals with costs related to hotel stay and travel expenses in general. Since flight crews normally stay in the same hotel, it is not necessary to vary this coefficient from one member to another
- $K_{Hem}$ is an empirical coefficient which has been derived from figure 4.3
- $f_{amblab}$ and $f_{ambmat}$ are factors intended to cover expenses such as: building, lighting, heating, as well as administrative costs related to the airplane maintenance. They were derived from figure 4.4
- $f_{change}$ represents the crew interchange factor ($1.5 < f_{change} < 3.5$). More precisely, it takes into account that every aircraft does not have a single crew operating all year long but they interchange

- $f_{tax}$ is a coefficient that takes into account the increase of taxes (landing fees, registry taxes and navigation fees) occurred between 1971 and 2017

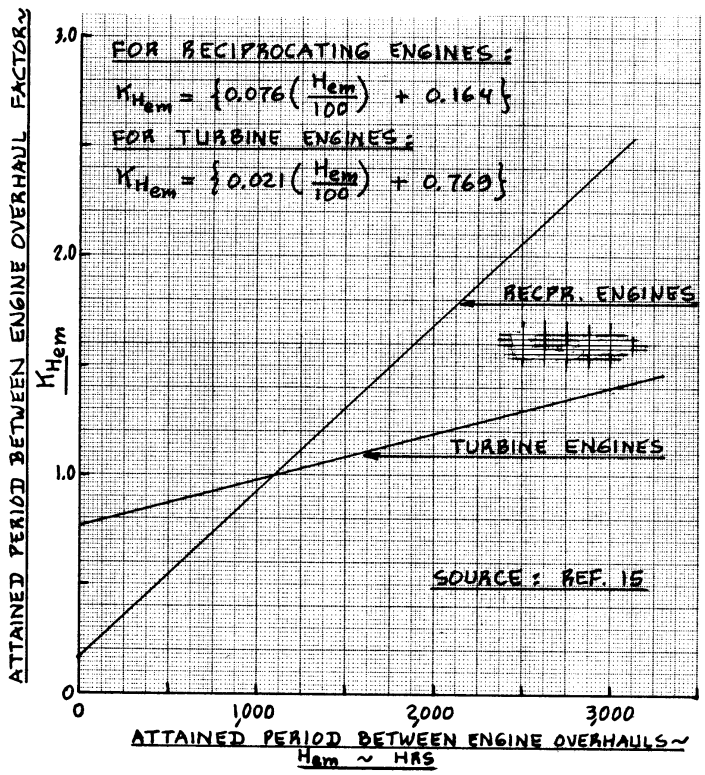


Figure 4.3 $H_{em} - K_{Hem}$ graphic for turbine and reciprocating engines [47]

different kind of airplane management

| | Personal | Corporate | Airlines |
|---|---|---|---|
| $f_{amb/lab}$ = | 0.80-0.90 | 0.90-1.00 | 1.00-1.40 |
| $f_{amb/mat}$ = | 0.20-0.30 | 0.30-0.40 | 0.40-0.70 |

Figure 4.4 $f_{amblab}$ and $f_{ambmat}$ for different kind of airplane management [48]

A precise and detailed estimation on the block hour value has been made as well. The world "block-hour" represents the average journey made by the aircraft itself. Once the block hour gross amount is known, the sub-items were calculated and put in the Matlab software. After having estimated them, the aircraft block speed $V_{bs}$ was computed assuming the aircraft speed per flight phase. The results are shown in the following table:

| OPERATING INPUT | | ATR-72 500 | A-320 200 |
|---|---|---|---|
| | | | |
| $t_{man}$ | Ground maneuver [h] | 0.15 | 0.15 |
| $t_{cl}$ | Climb [h] | 0.25 | 0.2 |
| $t_{de}$ | Descent [h] | 0.2 | 0.15 |
| $t_{atc}$ | Maneuver ATC [h] | 0.08 | 0.08 |
| $t_{cr}$ | Cruise | 0.54 | 1.5 |
| $t_{bl}$ | Block-time [h] | 1.14 | 2 |
| $V_{bs}$ | Block speed [Kts] | 201.75 | 437.21 |

Table 4.6 ROSKAM block hours division

As said before, the Roskam model is the best cost model for the operating cos phase as well for it takes into account the depreciation. The cost estimation relationships (CERs) are given in US dollars per nautical mile, as we have considered the aircraft block hours; derived in table 4.6. The results are summarized in the following table:

| OPERATING OUTPUT | | ATR-72 500 | A-320 200 |
|---|---|---|---|
| | | | |
| Crew cost | USD/nm | 4.29 | 2.48 |
| Fuel & Oil cost | USD/nm | 1.74 | 1.74 |
| Insurance cost | USD/nm | 1.36 | 1.69 |
| **DOC of flying** | USD/nm | 7.39 | 5.91 |
| Airframe/Sys (labor) | USD/nm | 0.065 | 0.037 |
| Airframe/Sys (material) | USD/nm | 2.76 | 5.9 |
| Engines (labor) | USD/nm | 0.17 | 0.098 |
| Engines (material) | USD/nm | 0.41 | 0.56 |
| Applied maintenance burden | USD/nm | 2.1 | 3.94 |

| OPERATING OUTPUT | | ATR-72 500 | A-320 200 |
|---|---|---|---|
| **DOC of maintenance** | USD/nm | 5.52 | 10.55 |
| Airframe depreciation | USD/nm | 2.14 | 3.2 |
| Engines depreciation | USD/nm | 0.12 | 0.1066 |
| Avionic depreciation | USD/nm | 0.22 | 0.23 |
| Airframe spare parts depreciation | USD/nm | 0.93 | 1.33 |
| Engine spare parts depreciation | USD/nm | 0.092 | 0.08 |
| **DOC of depreciation** | USD/nm | 3.51 | 4.97 |
| Landing fees | USD/nm | 2.18 | 1.94 |
| Navigation fees | USD/nm | 0.21 | 0.057 |
| Registry taxes | USD/nm | 0.23 | 0.29 |
| **DOC of fees/taxes** | USD/nm | 2.62 | 2.28 |
| | | | |
| **TOTAL DOC** | USD/nm | 19.43 | 24.18 |
| **TOTAL IOC** | USD/nm | 9.72 | 12.09 |
| **Total Operating Cost** | USD/nm | 29.15 | 36.27 |

Table 4.7 ROSKAM operating cost program outputs

In order to compute the operating costs per year, per aircraft fleet, we must use formulas 1.34 and 1.35:

$$C_{OPS} = (DOC)(R_{bl})_i N_i + (IOC)_i (R_{bl})_i N_i = 13.5 \text{ [B-USD]} \quad \text{for ATR-72 500} \qquad (4.1)$$

$$C_{OPS} = (DOC)(R_{bl})_i N_i + (IOC)_i (R_{bl})_i N_i = 42.5 \text{ [B-USD]} \quad \text{for A-320 200} \qquad (4.2)$$

This is the cost an aircraft company has to undergo every year in order to fly its fleet of ATR-72 500 and A-320 200. The term $R_{bl}$ (the block distance) is nothing more than the product between $V_{bs}$ and $t_{bl}$ and it was computed in the Matlab software. The indirect operating costs have been calculated simply as the half of the DOC and it is an estimate which is close to market estimates as well. The result shown in 4.1 and 4.2, are the operating costs of the entire fleet per year; if we want to obtain the operating cost of the single aircraft per year, we only need to divide that result by $N_i$, thus having: $C_{OPS} = 15.49$ million USD for the ATR-72 500 and $C_{OPS} = 48.57$ million USD for the A-320 200. If we want to know the total operating costs (meaning the operating cost incurred during the whole time the aircrafts are flying during their operative lives) we only need to multiply the terms $(DOC)(R_{bl})_i N_i$ and $(IOC)(R_{bl})_i N_i$ by $AIRF_d$, which is normally the operative time taken as reference for these types of airplanes. In formula:

$$Total(C_{OPS}) = (DOC)(R_{bl})_i(N_i)AIRF_d + (IOC)(R_{bl})_i(N_i)(AIRF_d) = 203.3 \text{ [B-USD]} \quad (4.3)$$

$$Total(C_{OPS}) = (DOC)(R_{bl})_i(N_i)AIRF_d + (IOC)(R_{bl})_i(N_i)(AIRF_d) = 850 \text{ [B-US]} \quad (4.4)$$

The 4.3 is related to the ATR-72 500 while the 4.4 is related to the A-320 200. Now we have all the variables that allow us to calculate the life cycle cost (LCC): the total cost required to research, develop, test, produce and fly our ATR-72 500 and A-320 200 fleets. Using formula 1.1.

$$LCC = C_{RDTE} + AEP + Total(C_{OPS}) + C_{disp} = 225.96 \text{ [B-USD] for ATR-72 500} \quad (4.5)$$

$$LCC = C_{RDTE} + AEP + Total(C_{OPS}) + C_{disp} = 958.29 \text{ [B-USD] for A-320 200} \quad (4.6)$$

Where the disposal cost for both aircrafts has been calculated using the following two formulas:

$$C_{disp} = f_{disp}(LCC) = 2.71 \text{ [B-USD]} \quad \text{for the ATR-72 500 fleet} \quad (4.7)$$

$$C_{disp} = f_{disp}(LCC) = 11.5 \text{ [B-USD]} \quad \text{for the A-320 200 fleet} \quad (4.8)$$

Where $f_{disp}$ is a factor associated with all the difficulties encountered in get rid of the materials and components the aircrafts are made of and it takes into account if some parts of the aircraft can be recycled and reused after the end of their operative lives. It strongly depends on many factors such as: the materials used, the form of the airplanes, the size of the aircrafts, etc…
There are precise and complex methods which would allow us to compute this voice cost; however they consider too many factors (such as: the labour cost, the material cost, the energy cost, the facilities cost, the tooling & equipment cost, the eventual residual value of the aircraft, the cost of recycle and re-certifications and various other miscellaneous costs like the overhead cost) for which it is difficult to find data easily, unlike the data found, concerning RDTE, Manufacturing & Acquisition and Operating phases. Furthermore, a deep discussion of such methods would go far beyond the aims of this document. For this reason, we have used a single factor which is often found in literature, that takes into account all the previous variables quoted (normally, the disposal cost is around 1% of the LCC or, all the same, around 10% of the AEP).

## 4.5 ATR-72 & A-320 200 NEW TECHNOLOGIES COST VARIATIONS

Now that we calculated every cost category for our regional aircrafts, it is time to implement the new technologies we dealt with in chapter 3 on them and see how the four cost categories will change. As the reader can easily imagine, the RDTE costs will always increase as researching, developing and testing something completely new, like one of the technologies we treated in this thesis, on one the ATR-72 500 or A-320 200 will require a lot of money that is not expected to be spent on the original airplane project. On the other hand, there is one cost saving during the manufacturing and acquisition phase: the one related to electric actuators. This happens because this new technology is less expensive to be produced than hydraulic actuators as they have roughly the same cost of manufacturing hydraulic ones. As we can see from table 4.10, all the other technologies bring an increase of AEP for their production cost is higher than the previous technology used in their place. For what concerns the operating costs per year, we can say that all the technologies listed in the previous chapter decrease this cost category. As a matter of fact, they all bring benefits in terms of operating costs. A different trend must be taken into account for the disposal costs; in fact the decreasing or the increasing trend of this category strongly depends on the single technology itself. Some of them (such as the electric actuators and the SHM) are more difficult to get rid off when they reach the end of their operative life, thus increasing the disposal cost. On the other hand, some of them (such as the morphing wing and the advanced propellers) are easier to get rid off when they reach the end of their operative life, thus decreasing the disposal costs. Last but not least, it will be shown the effects of the technologies on the Life Cycle Cost of the aircrafts. Depending on the increases and/or decreases per each cost category, the LCC will be less or more than the one computed considering the ATR-72 500 and the A-320 200 without new technologies mounted on them. Nevertheless, we do not forget to multiply each RDTE cost of every new technology for the ATR-72 200, for it is a turboprop aircraft, by the adjustment factor ($K_{trp}$) as seen in formula 3.2 in chapter 3. In particular:

$$K_{trp} = \frac{(V_c \bullet MTOW)_{ATR}}{(V_c \bullet \frac{2}{3}MTOW)_{A320}} = \frac{275 \bullet 50265}{488 \bullet \frac{2}{3}169756} = 0.75 \quad (4.1)$$

The results of this cost categories changes are shown in the following tables, in particular from table 4.8 to table 4.17.

| | Morphing wing | Electric actuators | SHM system | Geared turbofan | Laminar aerodynamics | A-EPGDS | Advanced propellers | Adaptive winglets | New engine materials |
|---|---|---|---|---|---|---|---|---|---|
| **RDTE** | 1.38 B | 1.05 B | 1.05 B | — | 1.011 B | 1.05 B | 1.05 B | 1.2 B | 1.2 B |

Table 4.8 RDTE costs of ATR-72 500 considering new technologies

| | Morphing wing | Electric actuators | SHM system | Geared turbofan | Laminar aerodynamics | A-EPGDS | Advanced propellers | Adaptive winglets | New engine materials |
|---|---|---|---|---|---|---|---|---|---|
| **RDTE** | 7.43 B | 6.98 B | 6.98 B | 7.13 B | 6.93 B | 6.98 B | — | 7.18 B | 7.18 B |

Table 4.9 RDTE costs of A-320 200 considering new technologies

| | Morphing wing | Electric actuators | SHM system | Geared turbofan | Laminar aerodynamics | A-EPGDS | Advanced propellers | Adaptive winglets | New engine materials |
|---|---|---|---|---|---|---|---|---|---|
| **AEP** | 21.93 M | 21.61M | 21.7 M | — | 21.93 M | 21.65 M | 21.89 M | 21.87 | 22.22 M |

Table 4.10 AEP costs of a single ATR-72 500 considering new technologies

| | Morphing wing | Electric actuators | SHM system | Geared turbofan | Laminar aerodynamics | A-EPGDS | Advanced propellers | Adaptive winglets | New engine materials |
|---|---|---|---|---|---|---|---|---|---|
| **AEP** | 104.03 M | 102.49 M | 102.9 M | 104.85 M | 104.03 M | 102.7 M | — | 103.72 M | 105.37 M |

Table 4.11 AEP costs of a single A-320 200 considering new technologies

| | Morphing wing | Electric actuators | SHM system | Geared turbofan | Laminar aerodynamics | A-EPGDS | Advanced propellers | Adaptive winglets | New engine materials |
|---|---|---|---|---|---|---|---|---|---|
| **OP** | 15.42 M | 15.47 M | 15.38 M | — | 15.38 M | 15.42 M | 15.02 M | 15.3 M | 14.96 M |
| | Ma -0.9% Tot -0.4% | Ma -0.4% Tot -0.1% | Ma -5.5% Tot -0.7% | — | Ma +0.4% Tot -0.7% | Ma ~0% Tot -0.4% | Ma +1.8% Tot - 3% | Ma +2% Tot -1.2% | Ma -1.8% Tot -3.4% |

Table 4.12 Operating costs per year of a single ATR-72 500 considering new technologies

| | Morphing wing | Electric actuators | SHM system | Geared turbofan | Laminar aerodynamics | A-EPGDS | Advanced propellers | Adaptive winglets | New engine materials |
|---|---|---|---|---|---|---|---|---|---|
| **OP** | 48.38 M | 48.52 M | 48.23 M | 47.02 M | 48.23 M | 48.38 M | — | 47.99 M | 46.92 M |
| | Ma -0.9% Tot -0.4% | Ma -0.4% Tot -0.1% | Ma -5.5% Tot -0.7% | Ma -2.8% Tot -3.2% | Ma +0.4% Tot -0.7% | Ma ~0% Tot -0.4% | — | Ma +2% Tot -1.2% | Ma -1.8% Tot -3.4% |

Table 4.13 Operating costs per year of a single A-320 200 considering new technologies

| | Morphing wing | Electric actuators | SHM system | Geared turbofan | Laminar aerodynamics | A-EPGDS | Advanced propellers | Adaptive winglets | New engine materials |
|---|---|---|---|---|---|---|---|---|---|
| **LCC** | 225.47 B | 225.74 B | 224.59 B | — | 219.89 B | 224.79 B | 220.07 B | 223.8 B | 219.6 B |

Table 4.14 LCC costs of the whole ATR-72 500 fleet considering new technologies

| | Morphing wing | Electric actuators | SHM system | Geared turbofan | Laminar aerodynamics | A-EPGDS | Advanced propellers | Adaptive winglets | New engine materials |
|---|---|---|---|---|---|---|---|---|---|
| **LCC** | 956.58 B | 957.38 B | 952.63 B | 933.23 B | 953.56 B | 955 B | — | 949.46 B | 932.26 B |

Table 4.15 LCC costs of the whole A-320 200 fleet considering new technologies

| | Morphing wing | Electric actuators | SHM system | Geared turbofan | Laminar aerodynamics | A-EPGDS | Advanced propellers | Adaptive winglets | New engine materials |
|---|---|---|---|---|---|---|---|---|---|
| **DISP** | 2.70 B | 2.717 B | 2.714 B | — | 2.711 B | 2.711 B | 2.69 B | 2.75 B | 2.76 B |

Table 4.16 Disposal costs of the whole fleet of ATR-72 500 considering new technologies

| | Morphing wing | Electric actuators | SHM system | Geared turbofan | Laminar aerodynamics | A-EPGDS | Advanced propellers | Adaptive winglets | New engine materials |
|---|---|---|---|---|---|---|---|---|---|
| **DISP** | 11.47 B | 11.52 B | 11.51 B | 11.5 B | 11.49 B | 11.49 B | — | 11.16 B | 11.17 B |

Table 4.17 Disposal costs of the whole fleet of A-320 200 considering new technologies

Now that we have described and quantified the effects of every single new technology onto every cost category, it is time to analyze the interactions between them. As a matter of fact, some of the technologies we have seen in chapter 3 have consequences if applied with some others. In particular, as shown in the following three tables, there are cost savings for the RDTE phase as well as for the acquisition and the operating one. These savings occur when the combination of the two technologies together happen. However, only some of the new technologies we have described bring some extra cost savings for not all of them operate on the same system or subsystem.

| **RDTE** | Morphing wing | Electric actuators | SHM system | Advanced propellers | Advanced EPGDS | Laminar aerodynamics | Geared turbofan | Adaptive winglets | New engine materials |
|---|---|---|---|---|---|---|---|---|---|
| Morphing wing | — | NO (20%) | YES | YES | YES | NO (20%) | YES | NO (10%) | YES |
| Electric actuators | NO (20%) | — | YES | YES | NO (10%) | YES | YES | NO (5%) | YES |
| SHM system | YES | YES | — | YES | YES | YES | YES | NO (5%) | YES |
| Advanced propellers | YES | YES | YES | — | YES | YES | YES | YES | YES |
| Advanced EPGDS | YES | NO (10%) | YES | YES | — | YES | YES | YES | YES |
| Laminar aerodynamics | NO (20%) | YES | YES | YES | YES | — | YES | YES | YES |
| Geared turbofan | YES | YES | YES | YES | YES | YES | — | YES | YES |
| Adaptive winglets | NO (10%) | NO (5%) | NO (5%) | YES | YES | YES | YES | — | YES |
| New engine materials | YES | YES | YES | YES | YES | YES | YES | YES | — |

Table 4.18 Benefits of new technologies combined during the RDTE phase

| **MAN & ACQ** | Morphing wing | Electric actuators | SHM system | Advanced propellers | Advanced EPGDS | Laminar aerodynamics | Geared turbofan | Adaptive winglets | New engine materials |
|---|---|---|---|---|---|---|---|---|---|
| Morphing wing | — | NO (20%) | NO (10%) | YES | YES | NO (50%) | YES | YES | YES |
| Electric actuators | NO (20%) | — | YES | YES | YES | YES | YES | NO (5%) | YES |

| **MAN & ACQ** | Morphing wing | Electric actuators | SHM system | Advanced propellers | Advanced EPGDS | Laminar aerodynamics | Geared turbofan | Adaptive winglets | New engine materials |
|---|---|---|---|---|---|---|---|---|---|
| SHM system | NO (10%) | YES | — | YES | YES | YES | YES | NO (3%) | YES |
| Advanced propellers | YES | YES | YES | — | YES | YES | YES | YES | YES |
| Advanced EPGDS | YES | YES | YES | YES | — | YES | YES | YES | YES |
| Laminar aerodynamics | NO (50%) | YES | YES | YES | YES | — | YES | YES | YES |
| Geared turbofan | YES | YES | YES | YES | YES | YES | — | YES | YES |
| Adaptive winglets | YES | NO (5%) | NO (3%) | YES | YES | YES | YES | — | YES |
| New engine materials | YES | YES | YES | YES | YES | YES | YES | YES | — |

Table 4.19 Benefits of new technologies combined during the production phase

| **OPERATING** | Morphing wing | Electric actuators | SHM system | Advanced propellers | Advanced EPGDS | Laminar aerodynamics | Geared turbofan | Adaptive winglets | New engine materials |
|---|---|---|---|---|---|---|---|---|---|
| Morphing wing | — | YES | YES | YES | YES | NO (15%) | YES | YES | YES |
| Electric actuators | YES | — | YES | YES | YES | YES | YES | YES | YES |
| SHM system | YES | YES | — | YES | YES | YES | YES | YES | YES |
| Advanced propellers | YES | YES | YES | — | YES | YES | YES | YES | YES |

| **OPERATING** | Morphing wing | Electric actuators | SHM system | Advanced propellers | Advanced EPGDS | Laminar aerodynamics | Geared turbofan | Adaptive winglets | New engine materials |
|---|---|---|---|---|---|---|---|---|---|
| Advanced EPGDS | YES | YES | YES | YES | — | YES | YES | YES | YES |
| Laminar aerodynamics | NO (15%) | YES | YES | YES | YES | — | YES | YES | YES |
| Geared turbofan | YES | YES | YES | YES | YES | YES | — | YES | YES |
| Adaptive winglets | YES | YES | YES | YES | YES | YES | YES | — | YES |
| New engine materials | YES | YES | YES | YES | YES | YES | YES | YES | — |

Table 4.20 Benefits of new technologies combined during the operating phase

In these tables, the cumulated benefits achieved by combining two new technologies is shown with the world "NO". Furthermore, under every "NO" there is a percentage standing for the amount of cost saved per each phase, if the the new technologies are put together in the same aircraft. On the other hand, the world "YES" means there is no extra cost saving if the two technologies would be mounted on the same airplane. In particular, the cost relationships between technologies during the RDTE phase are:

1) Morphing wing ⟶ Electric actuators, adaptive winglets and laminar aerodynamics
2) Electric actuators ⟶ Advanced EPGDS and adaptive winglets
3) SHM system ⟶ Adaptive winglets

For what concerns the manufacturing and acquisition costs, we can say that there are cost savings between:

1) Morphing wing ⟶ Electric actuators, SHM system and laminar aerodynamics

2) Electric actuators ⟶ Adaptive winglets
3) SHM system ⟶ Adaptive winglets

Finally, the operating cost only shows a relationship between the morphing wing and the laminar aerodynamics as these two technologies are the only ones allowing a proper cost saving during the aircraft operating phase for they both reduce the fuel needed (and thus the aircraft overall weight) by increasing the generated lift and by reducing the overall drag.
Again, we computed how much money has been saved per combination of technologies by using the software Matlab. The results are shown in the following tables.

| RDTE | ATR-72 500 | A-320 200 |
|---|---|---|
| | | |
| Morphing wing + electric actuators | 1.36 B (instead of 1.46 B) | 7.4 B (instead of 7.53 B) |
| Morphing wing + laminar aerodynamics | 1.33 B (instead of 1.42 B) | 7.36 B (instead of 7.48 B) |
| Morphing wing + adaptive winglets | 1.54 B (instead of 1.61 B) | 7.64 B (instead of 7.73 B) |
| Electric actuators + advanced EPGDS | 1.1 B (instead of 1.12 B) | 7.06 B (instead of 7.08 B) |
| Electric actuators + adaptive winglets | 1.25 B (instead of 1.27 B) | 7.26 B (instead of 7.28 B) |
| SHM system + adaptive winglets | 1.25 B (instead of 1.27 B) | 7.26 B (instead of 7.28 B) |

Table 4.21 Benefits of new technologies synergies in the RDTE phase

| AEP | ATR-72 500 | A-320 200 |
|---|---|---|
| | | |
| Morphing wing + electric actuators | 21.84 M (instead of 21.88 M) | 103.6 M (instead of 103.82 M) |
| Morphing wing + laminar aerodynamics | 21.94 M (instead of 22.21 M) | 104.03 M (instead of 105.37 M) |
| Morphing wing + SHM system | 21.95 M (instead of 21.97 M) | 104.08 M (instead of 104.24) |
| Electric actuators + adaptive winglets | 21.82 M (instead of 22.91 M) | 103.48 M (instead of 108.65 M) |
| SHM system + adaptive winglets | 21.9 M (instead of 22.56 M) | 103.89 M (instead of 107 M) |

Table 4.22 Benefits of new technologies synergies in the manufacturing & acquisition phase

| OPERATING | ATR-72 500 | A-320 200 |
|---|---|---|
| | | |
| Morphing wing + laminar aerodynamic | 15.34 M (instead of 15.29 M) | 48.12 M (instead of 47.96 M) |

Table 4.23 Benefits of new technologies synergies in the operating phase

Looking at the first two tables (4.21 and 4.22), we can notice that all every mix brings an increase of cost in the RDTE phase and in the AEP respectively. However, that cost increase would have been even higher if the two new technologies would not have a synergetic effect when combined. On the other hand, in the last table (4.23) we can easily see that there is a slight increase of operating cost when the morphing wing and the laminar aerodynamic are combined. This happens because it only requires one of the two new technologies to maximize the laminar flow on the wing; the combination of the two doesn't bring any extra advantage. On the other hand, they would only increase the aircraft operating costs, as shown in the table above.

# CONCLUSIONS

As seen in all the thesis, the first aim of this document was to fully describe the Roskam method in details. As a matter of fact, it is a method still used nowadays, allowing to estimate the whole Life-Cycle-Cost of an aircraft or a fleet of aircrafts. In particular, we have seen how the Roskam method divided each cost phase (RDTE, Manufacturing & Acquisition and Operating) into different sub categories depending on many variables which were related to the aircraft performances (Max-Take-Off-Weight; cruise Thrust, cruise speed, etc…). Then, the following chapter dealt with the possible new technologies that could be developed and used on the next generation of commercial aircrafts. A general view had been given to them, describing the mechanisms they rely on, their technology readiness level and the estimated period when they could be available to be mounted and used on to commercial airplanes. Moving on to this thesis, we focused on new technologies suitable for regional aircrafts. In particular, nine of them have been deeply analyzed:

1) The morphing wing
2) Electric actuators
3) SHM system
4) Advanced propellers
5) Advanced EPGDS
6) Laminar aerodynamic
7) Geared turbofan
8) New engine materials
9) Adaptive winglets

For each of them, a detailed study on the cost decrease (or increase) per each cost phase has been made. From the data acquired, it can be easily seen that they all bring benefits in terms of operating costs (they all decrease the annual operating cost of an airplane) and, on the other hand, they all increase the RDTE costs and the AEP (except for the electric actuators which decrease it). A different argumentation has to be done for the disposal costs for, in this thesis, it has not been considered as part of the LCC itself. In fact, this cost category has been calculated as the money spent this phase are spent after it reaches the end of its operative life. A summary of the amounts and percentages saved or lost per each phase, per each new technology is given in the following table:

| | RDTE | Production cost | Operating cost | Disposal cost |
|---|---|---|---|---|
| | | | | |
| **MORPHING WING** | 550 [M-USD] | $+1.3$ % | $-0.4$ % | $-0.2$ % |
| **ELECTRIC ACTUATORS** | 100 [M-USD] | $-0.2$ % | $-0.1$ % | $+0.2$ % |
| **SHM SYSTEM** | 100 [M-USD] | $+0.2$ % | $-0.7$ % | $+0.1$ % |
| **GEARED TURBOFAN** | 250 [M-USD] | $+2.1$ % | $-3.2$ % | $+0.05$ % |
| **LAMINAR AERODYNAMICS** | 50 [M-USD] | $+1.3$ % | $-0.7$ % | $\sim 0$ % |
| **ADVANCED EPGDS** | 100 [M-USD] | $\sim 0$ % | $-0.4$ % | $\sim 0$ % |
| **ADVANCED PROPELLERS** | 100 [M-USD] | $+1.1$ % | $-3$ % | $-0.6$ % |
| **ADAPTIVE WINGLETS** | 300 [M-USD] | $+1$% | $-1.2$ % | $+1.5$ % |
| **NEW ENGINE MATERIALS** | 300 [M-USD] | $+2.6$ % | $-3.4$ % | $+2.1$ % |

Table 5.1 Summary of new technologies cost benefits

Eventually the main goal of the last chapter of this thesis was to apply the formulas of the first chapter to two regional aircrafts: the ATR-72 500 and the Airbus A-320 200, using the software Matlab. Once their cost categories and LCC have been computed, the impact of the nine new technologies described in the previous chapter had been analyzed on those two airplanes; showing the cost phases decreases and increases per each one. A summary of this is presented in table 5.2:

| | Morphing wing | Electric actuators | SHM system | Geared turbofan | Laminar aerodynamics | A-EPGDS | Advanced propellers | Adaptive winglets | New engine materials |
|---|---|---|---|---|---|---|---|---|---|
| **RDTE ATR** | 1.38 B | 1.05 B | 1.05 B | — | 1.011 B | 1.05 B | 1.05 B | 1.2 B | 1.2 B |
| **RDTE A320** | 7.43 B | 6.98 B | 6.98 B | 7.13 B | 6.8841 B | 6.98 B | — | 7.18 B | 7.18 B |

| | Morphing wing | Electric actuators | SHM system | Geared turbofan | Laminar aerodynamics | A-EPGDS | Advanced propellers | Adaptive winglets | New engine materials |
|---|---|---|---|---|---|---|---|---|---|
| **AEP ATR** | 21.93 M | 21.61M | 21.7 M | — | 21.93 M | 21.65 M | 21.89 M | 21.87 M | 22.22 M |
| **AEP A320** | 104.03 M | 102.49 M | 102.9 M | 104.85 M | 104.03 M | 102.7 M | — | 103.72 M | 105.37 M |
| **OP ATR** | 15.42 M | 15.47 M | 15.38 M | — | 15.38 M | 15.42 M | 15.02 M | 15.3 M | 14.96 M |
| **OP A320** | 48.38 M | 48.52 M | 48.23 M | 47.02 M | 48.23 M | 48.38 M | — | 47.99 M | 46.92 M |
| **LCC ATR** | 225.47 B | 225.74 B | 224.59 B | — | 219.89 B | 224.79 B | 220.07 B | 223.8 B | 219.6 B |
| **LCC A320** | 956.58 B | 957.38 B | 952.63 B | 933.23 B | 953.56 B | 955 B | — | 949.46 B | 932.26 B |
| **DISP ATR** | 2.70 B | 2.717 B | 2.714 B | — | 2.711 B | 2.711 B | 2.69 B | 2.75 B | 2.76 B |
| **DISP A320** | 11.47 B | 11.52 B | 11.51 B | 11.5 B | 11.49 B | 11.49 B | — | 11.16 B | 11.17 B |

Table 5.2 Summary of the effects of new technologies on two regional aircrafts cost phases

Last but not least, it has been taken into account that some of these new technologies could bring some extra benefits in the RDTE, AEP and operating phases, if combined together, as some of them operate on the same aircraft system or subsystem. Again, it is presented a summary of these extra benefits in the following table:

| | **ATR-72 500** | **A-320 200** |
|---|---|---|
| **RDTE** | | |
| Morphing wing + electric actuators | 1.36 B (instead of 1.46 B) | 7.4 B (instead of 7.53 B) |
| Morphing wing + laminar aerodynamics | 1.33 B (instead of 1.42 B) | 7.36 B (instead of 7.48 B) |
| Morphing wing + adaptive winglets | 1.54 B (instead of 1.61 B) | 7.64 B (instead of 7.73 B) |
| Electric actuators + advanced EPGDS | 1.1 B (instead of 1.12 B) | 7.06 B (instead of 7.08 B) |
| Electric actuators + adaptive winglets | 1.25 B (instead of 1.27 B) | 7.26 B (instead of 7.28 B) |
| SHM system + adaptive winglets | 1.25 B (instead of 1.27 B) | 7.26 B (instead of 7.28 B) |

| | ATR-72 500 | A-320 200 |
|---|---|---|
| **AEP** | | |
| Morphing wing + electric actuators | 21.84 M (instead of 21.88 M) | 103.6 M (instead of 103.82 M) |
| Morphing wing + laminar aerodynamics | 21.94 M (instead of 22.21 M) | 104.03 M (instead of 105.37 M) |
| Morphing wing + SHM system | 21.95 M (instead of 21.97 M) | 104.08 M (instead of 104.24) |
| Electric actuators + adaptive winglets | 21.82 M (instead of 22.91 M) | 103.48 M (instead of 108.65 M) |
| SHM system + adaptive winglets | 21.9 M (instead of 22.56 M) | 103.89 M (instead of 107 M) |
| | | |
| **OPERATING** | | |
| Morphing wing + laminar aerodynamic | 15.32 M (instead of 15.29 M) | 48.03 M (instead of 47.96 M) |

Table 5.3 Summary of new technologies extra benefits onto ATR-72 500 and A-320 200

Finally, for what concerns the future trend and future improvements, we can say that this thesis is a good starting point for the development of a new, more precise cost estimation model for long-range, innovative commercial planes. Moreover, as said during chapter four, the Roskam method is not very suitable for aircrafts which have huge production numbers. However, it is a problem that can be easily overcome in future methods by using corrective coefficients and more precise calculations that would take into account several more aircraft variables. As the need of improving aircrafts performances will always increase, a variety of new technologies will constantly be developed and produced. This way, there will always be the need of precise cost estimation methods sensible to the implementation of them on to commercial aircrafts such as the one presented in this thesis.

# APPENDIX A

This appendix shows the Matlab code used to compute the cost categories of the ATR-72 500 with and without new technologies. Moreover, it has also been used in order to calculate the effects of synergies between two new technologies during the RDTE, Acquisition & Manufacturing and operating phase.

```
%Input variables to compute C_RDTE

CEF = 1.95;           %Cost escalation factor from 1989 to 2017
CEF_2 = 6.14;         %Cost escalation factor from 1970 to 2017
MTOW = 50265;         %Maximum-Take-Off-Weight [Lb]
V_c = 275;            %Cruise speed [Kts]
Thrust = 7500;        %Engine Cruise Thrust [Lbf]
SHP_TO = 2160;        %Propellers horsepower at take-off [hp]
N_e = 2;              %N. of engines
N_p = 2;              %N. of propellers
N_m = 875;            %N. of manufactured aircrafts
W_avio = 670;         %Avionic system weight [Lb]
R_e = 178.42;         %Engineering rate [USD/h]
R_m = 92.82;          %Manufacturing rate [USD/h]
R_t = 120.1;          %Tooling rate [USD/h]
N_RDTE = 3;           %N. of RDTE aircraft built
N_ST = 1;             %N. of airframes built
N_r = 0.33;           %N. of aircrafts built per month
F_mat = 1.5;          %Material factor
F_tsf = 0;            %Adjustment factor
F_obs = 1;            %Low-observable factor
F_diff = 1.33;        %Program complexity factor
F_CAD = 0.8;          %CAD factor
N_prot = 2;           %N. of prototypes built
Finance = 0.2;        %Finance [%]
Profit = 0.2;         %Profit [%]
```

```
%Input variables to compute C_MAN and C_ACQ

Pax = 72;          %N. of passengers
R_e1 = 160.6;      %Engineering rate [USD/h]
R_m1 = 89.5;       %Manufacturing rate [USD/h]
R_t1 = 115.83;     %Tooling rate [USD/h]
N_r1 = 7;          %N. of aircrafts built per month
F_over = 4;        %Overhead factor
F_int = 1000;      %Iterior factor [USD/pax]
FTh = 10;          %Fligh-test hours [h]
f_ACQ = 1.2;       %Acquisition coefficient

%Input variables to compute DOC and IOC

B_d = 230;                 %Block distance [nm]
BFW = 1220;                %Burned fuel weight [Lb]
MMH_eng = 0.8;             %Engine maintenance man-hours per flight hour
MMH_air = 0.8;             %Airframe maintenance man-hours per flight hour
F_c = 2;                   %Fuel cost [USD/gallon]
F_density = 6.4;           %Fuel density [Lb/gallon]
N_officer = 1;             %N. of first officers
N_captain = 1;             %N. of captains
N_fass = 2;                %N. of flight assistants
ENG_d = 15;                %Engine depreciation period [years]
AIRF_d = 15;               %Airframe depreciation period [years]
AVIONC_d = 10;             %Avionic depreciation period [years]
AIRFs_d = 15;              %Airframe spare parts depreciation period [years]
ENGs_d = 15;               %Engine spare parts depreciation period [years]
AIRFs_f = 0.4;             %Airframe spare parts factor
ENGs_f = 0.5;              %Engine spare parts factor
AIRF_d_f = 0.9;            %Airframe depreciation factor
ENG_d_f = 0.9;             %Engine depreciation factor
AVIONIC_d_f = 0.95;        %Avionic depreciation factor
AIRFs_d_f = 0.9;           %Airframe spare parts depreciation factor
ENGs_d_f = 0.9;            %Engine spare parts depreciation factor
t_man = 0.15;              %Ground maneuver time [h]
t_cl = 0.25;               %Climb time [h]
t_de = 0.2;                %Descent time [h]
```

```
t_atc = 0.08;              %Maneuver due to ATC time [h]
t_cr = 0.54;               %Cruise time [h]
t_bl = 1.14;               %Total block-time [h]
V_bs = 201.75;             %Block speed [Kts]
K_j = 0.26;                %Vacation pay and training factor
SAL_captain = 80000;       %Captain salary [USD/year]
SAL_officer = 70000;       %First officer salary [USD/year]
SAL_fass = 28000;          %Flight assistant salary [USD/year]
AH = 900;                  %Crew members flight hours per year [h/years]
TEF = 7;                   %Travel expense factor [USD/blh]
R_lap = 16;                %Airplane maintenance labor rate [USD/mh]
R_leng = 16;               %Engine maintenance labor rate [USD/mh]
ESPPF = 1.5;               %Engine spare parts price factor
K_hem = 1.4;               %Attained period between engine overhaul factor
f_amblab = 1.3;            %Labor overhead distribution factor
f_ambmat = 0.6;            %Maintenance overhead distribution factor
C_apnf = 10;               %Navigation fee [USD/flight]
C_ins = 0.02;              %Insurance direct cost [% of DOC]
C_rt = 0.0022;             %Cost of registry taxes [% of DOC]
Fin = 0.07;                %Direct operating cost of financing [% of DOC]
f_change = 2.8;            %Crew interchange factor
f_tax = 5;                 %tax inflation factor
f_disp = 0.012;            %Disposal coefficient

%New technologies cost coefficients

RDTE_mw = 550000000;           %RDTE cost for the morphing wing
RDTE_ea = 100000000;           %RDTE cost for electric actuators
RDTE_SHM = 100000000;          %RDTE cost for the SHM system
RDTE_gt = 250000000;           %RDTE cost for the geared turbofan
RDTE_la = 50000000;            %RDTE cost for laminar aerodynamics
RDTE_aepgds = 100000000;       %RDTE cost for the advanced EPGDS
RDTE_ap = 100000000;           %RDTE cost for advanced propeller
RDTE_aw = 300000000;           %RDTE cost for the adaptive winglets
RDTE_nem = 300000000;          %RDTE cost for new engine materials
ACQ_mw = 0.013;                %Acquisition cost percentage for the morphing wing
ACQ_ea = 0.002;                %Acquisition cost percentage for electric actuators
ACQ_SHM = 0.002;               %Acquisition cost percentage for the SHM system
```

```
ACQ_gt = 0.021;            %Acquisition cost percentage for the geared turbofan
ACQ_la = 0.013;            %Acquisition cost percentage for laminar aerodynamics
ACQ_aepgds = 0;            %Acquisition cost percentage for the advanced EPGDS
ACQ_ap = 0.011;            %Acquisition cost percentage for advanced propellers
ACQ_aw = 0.01;             %Acquisition cost percentage for adaptive winglets
ACQ_nem = 0.026;           %Acquisition cost percentage for new engine materials
OP_mw = 0.004;             %Operating cost percentage for the morphing wing
OP_ea = 0.001;             %Operating cost percentage for electric actuators
OP_SHM = 0.007;            %Operating cost percentage for the SHM system
OP_gt = 0.032;             %Operating cost percentage for the geared turbofan
OP_la = 0.007;             %Operating cost percentage for laminar aerodynamics
OP_aepgds = 0.004;         %Operating cost percentage for the advanced EPGDS
OP_ap = 0.03;              %Operating cost percentage for advanced propellers
OP_aw = 0.012;             %Operating cost percentage for adaptive winglets
OP_nem = 0.034;            %Operating cost percentage for new engine materials
DISP_mw = 0.002;           %Disposal cost percentage for the morphing wing
DISP_ea = 0.002;           %Disposal cost percentage for electric actuators
DISP_SHM = 0.001;          %Disposal cost percentage for the SHM system
DISP_gt = 0.0005;          %Disposal cost percentage for the geared turbofan
DISP_la = 0;               %Disposal cost percentage for laminar aerodynamics
DISP_aepgds = 0;           %Disposal cost percentage for the advanced EPGDS
DISP_ap = 0.006;           %Disposal cost percentage for advanced propellers
DISP_aw = 0.015;           %Disposal cost percentage for adaptive winglets
DISP_nem = 0.021;          %Disposal cost percentage for new engine materials
K_trp = 0.75;              %Adjustment coefficient for ATR-72 500 for RDTE costs

%Synergy coefficients for the RDTE phase

f_mw_ea = 0.8;        %Morphing wing + electric actuators
f_mw_la = 0.8;        %Morphing wing + laminar aerodynamics
f_mw_aw = 0.9;        %Morphing wing + adaptive winglets
f_ea_aepgds = 0.9;    %Electric actuators + advanced EPGDS
f_ea_aw = 0.95;       %Electric actuators + adaptive winglets
f_shm_aw = 0.95;      %SHM system + adaptive winglets

%Synergy coefficients for the AEP and Operating phases

f_mw_ea_1 = 0.8;      %Morphing wing + electric actuators per AEP
```

```
f_mw_shm_1 = 0.9;       %Morphing wing + SHM system per AEP
f_mw_la_1 = 0.5;        %Morphing wing + adaptive winglets per AEP
f_ea_aw_1 = 0.95;       %Electric actuators + adaptive winglets per AEP
f_shm_aw_1 = 0.97;      %SHM system + adaptive winglets per AEP
f_mw_la_2 = 1.15;       %Morphing wing + laminar aerodynamics per OPERATING

%Coefficients indicating whether the new technology is present or not (1 =
%present; 0 = not present)

newtech_1 = 1;          %The morphing wing IS present
newtech_2 = 0;          %The electric actuators ARE NOT present
newtech_3 = 1;          %The SHM system IS present
newtech_4 = 0;          %The geared turbofan IS NOT present
newtech_5 = 0;          %Laminar aerodynamic IS NOT present
newtech_6 = 1;          %The advanced EPGDS system IS present
newtech_7 = 0;          %The advanced propeller IS NOT present
newtech_8 = 0;          %Adaptive winglets ARE NOT present
newtech_9 = 0;          %New engine materials ARE NOT present

%Arrays needed to compute the cost categories per each possible combination

A = [newtech_1, newtech_2, newtech_3, newtech_4, newtech_5, newtech_6,
newtech_7, newtech_8, newtech_9]
%Array indicating if a new technology is present or not

B = [RDTE_mw*K_trp, RDTE_ea*K_trp, RDTE_SHM*K_trp, RDTE_gt*K_trp,
RDTE_la*K_trp, RDTE_aepgds*K_trp, RDTE_ap*K_trp, RDTE_aw*K_trp,
RDTE_nem*K_trp];
%Array indicating the RDTE costs of every new technology

D = [ACQ_mw, -ACQ_ea, ACQ_SHM, ACQ_gt, ACQ_la, ACQ_aepgds, ACQ_ap,
ACQ_aw, ACQ_nem];
%Array indicating the AEP costs of every new technology

E = [-OP_mw, -OP_ea, -OP_SHM, -OP_gt, -OP_la, -OP_aepgds, -OP_ap, -OP_aw, -
OP_nem];
%Array indicating the Operating costs of every new technology
```

```
c = 1;          %Flag for RDTE
d = 1;          %Flag fpr AEP
e = 1;          %Flag for OP
DISP_1 = 0;  %Disposal coefficient for morphing wing
DISP_2 = 0;  %Disposal coefficient for electric actuators
DISP_3 = 0;  %Disposal coefficient for SHM system
DISP_4 = 0;  %Disposal coefficient for geared turbofan
DISP_5 = 0;  %Disposal coefficient for laminar aerodynamics
DISP_6 = 0;  %Disposal coefficient for advanced EPGDS system
DISP_7 = 0;  %Disposal coefficient for advanced propellers
DISP_8 = 0;  %Disposal coefficient for adaptive winglets
DISP_9 = 0;  %Disposal coefficient for new engine materials

%C_RDTE and C_prot calculation

W_ampr = 10^(0.1936 + 0.8645*(log10(MTOW)));
%Aeronautical-Manufacturers-Planning-Report weight [Lb]

C_e = 10^(2.3044 + 0.8858*(log10(Thrust)));                    %Cost of engines [USD]

C_avionics = 0.1*(10^(3.3191 + 0.8043*(log10(MTOW))));        %Cost of avionics [USD]

C_aed = 0.0396*(W_ampr)^0.791*(V_c)^1.526 * (N_RDTE)^0.183 * (F_diff)*(F_CAD)
*(R_e);
%Airframe engineering and design cost [USD]

C_dst = 0.008325*(W_ampr)^0.873 *(V_c)^1.89 *(N_RDTE)^0.346 *(F_diff)*(CEF_2);
%Development, support & testing cost [USD]

PP = 10^(0.6119 + 1.1432*(log10(SHP_TO)));                    %Propeller price [USD]

C_ea = (C_e * N_e + N_p*PP +C_avionics) *(N_RDTE - N_ST);
%Total cost of engines and avionics [USD]

C_man  =  28.984*(W_ampr)^0.74  *  (V_c)^0.543  *(N_RDTE)^0.524  *  (F_diff)  *  (R_m);
%Manufacturing cost of flight-test aircrafts [USD]
```

C_mat = 37.632*(F_mat)*(W_ampr)^0.689 * (V_c)^0.624 *(N_RDTE)^0.792 * (CEF_2);
%Cost of materials to manufacture flight test aircrafts [USD]

C_tool = 4.0127*(W_ampr)^0.764 * (V_c)^0.899 * (N_RDTE)^0.178 * (N_r)^0.066 * (F_diff) * (R_t);
%Tooling cost associated with manufacturing of flight test aircrafts [USD]

C_qc = 0.13*(C_man);
%Quality control cost associated with manufacturing of flight test aircrafts [USD]

C_fta = C_ea + C_man + C_mat + C_tool + C_qc;
%Total flight test aircrafts cost [USD]

C_fto = 0.001244 * (W_ampr)^1.16 * (V_c)^1.371 * (N_RDTE - N_ST)^1.281 * (CEF_2) * (F_diff) * (F_obs);
%Flight test operations cost [USD]

C_prot = (1115.4 * 1000)*(W_ampr)^0.35 * (N_prot)^0.99 * (CEF_2/CEF);
%Cost of prototypes [USD]

C_RDTE = (C_aed + C_dst + C_fta + C_fto) / (1 - Finance - Profit);
%Total cost of the RDTE phase of a single aircraft [USD]

%C_MAN and C_ACQ calculation

N_program = N_m + N_RDTE; %Total number of aircrafts built by the manufacturer

C_aed1 = (0.0396*(W_ampr)^0.791 *(V_c)^1.526 *(N_program)^0.183 *(F_diff)*(F_CAD)*(R_e1)) - C_aed;
%Airframe engineering and design cost [USD]

C_ea1 = ((C_e * N_e) + (N_p*PP) + (C_avionics))*(N_m);
%Total cost of engines and avionics [USD]

C_int = F_int*Pax*N_m*(CEF_2/CEF); %Cost of the airplane interior [USD]

```
C_man1 = (28.984*(W_ampr)^0.74 *(V_c)^0.543 *(N_program)^0.524 * (F_diff) *(R_m1)) - C_man;
%Manufacturing labor cost [USD]

C_mat1 = (37.632 * (F_mat) *(W_ampr)^0.689 *(V_c)^0.624 *(N_program)^0.792 * (CEF_2)) - C_mat;
%Materials cost [USD]

C_tool1 = (4.0127*(W_ampr)^0.764 *(V_c)^0.899 *(N_program)^0.178 *(F_diff) *(N_r1)^0.066*(R_t1)) - C_tool;
%Tooling cost [USD]

C_qc1 = 0.13*(C_man1);                              %Quality control cost [USD]

C_apc = C_ea1 + C_int + C_man1 + C_mat1 + C_tool1 + C_qc1;
%Airplane program production cost [USD]

C_fto1 = N_m*(3200)*(FTh)*(F_over);
%Production flight test operations cost [USD]

C_MAN = (C_aed1 + C_apc + C_fto1)/(1- Profit - Finance);
%Manufacturing cost[USD]

C_ACQ = f_ACQ*C_MAN;                                %Acquisition cost [USD]

AEP = (C_ACQ + C_RDTE)/N_m;                         %Aircraft-Estimated-Price [USD]

%DOC and IOC calculation

U_ann = 1000*(3.4546*(t_bl) + 2.994 - ((12.289*(t_bl)^2 - 5.6626*(t_bl) + 8.964)^0.5));
%Airplane annual utilization [h]

R_bl_ann = U_ann * V_bs;                            %Total annual block miles [nm]
```

```
C_crew = ((N_captain*((1+K_j)/V_bs)) * (SAL_captain/AH) + TEF/V_bs)*(f_change) +
((N_officer*((1+K_j)/V_bs)) * (SAL_officer/AH) + TEF/V_bs) *(f_change)+ ((N_fass*((1+K_j)/
V_bs)) * (SAL_fass/AH) + TEF/V_bs) * (f_change);
%Crew cost [USD/nm]

C_pol = 1.05*(BFW/B_d) * (F_c/F_density);                %Fuel & oil cost [USD/nm]

C_lab_ap = (1.03 * (MMH_air) * (R_lap))/V_bs;
%Maintenance labor cost for airframe and systems [USD/nm]

C_labeng = (1.03*1.3*(N_e)*(MMH_eng)*(R_leng))/V_bs;
%Maintenance labor cost for engines [USD/nm]

AFP = AEP - N_e*(C_e);                                   %Airframe price [USD]

C_mat_apblhr = 30 + 0.79*(CEF_2/CEF)*(10^-5 *AFP);
%Airframe & systems maintenance materials cost per aircraft block hour [USD/h]

C_mat_ap = (1.03*(C_mat_apblhr))/V_bs;
%Cost of maintenance materials for airframe & systems [USD/nm]

C_mat_engblhr = (5.43*10^-5 * (C_e)*(ESPPF) - 0.47)/K_hem;
%Engine maintenance materials cost per aircraft block hour [USD/h]

C_mateng = (1.03*(1.3)*(N_e)*(C_mat_engblhr))/V_bs;
%Cost of maintenance materials for the engines [USD/nm]

C_amb = 1.03*((f_amblab)*((MMH_air)*(R_lap) + N_e*(MMH_eng)*(R_leng)) +
(f_ambmat*((C_mat_apblhr) + N_e*(C_mat_engblhr))))/V_bs;
%Cost of applied maintenance burden [USD/nm]

DOC_maint = C_lab_ap + C_labeng + C_mat_ap + C_mateng + C_amb;
%Total direct maintenance cost [USD/nm]

C_dap = ((AEP * AIRF_d_f) - (N_e * C_e) - (N_p*PP) - C_avionics)/ (AIRF_d * U_ann *
V_bs);
%Airplane depreciation cost [USD/nm]
```

```
C_deng = (ENG_d_f*(N_e)*(C_e))/(ENG_d*V_bs*U_ann);
%Engine depreciation cost [USD/nm]

C_dav = (AVIONIC_d_f* C_avionics)/(AVIONC_d * V_bs * U_ann);
%Avionic systems depreciation cost [USD/nm]

C_dapsp = ((AIRFs_d_f * AIRFs_f) * (AEP - (N_e * C_e)))/(V_bs * U_ann * AIRFs_d);
%Aircraft spare parts depreciation cost [USD/nm]

C_dengsp = (ENGs_d_f * ENGs_f * N_e * C_e * ESPPF)/(U_ann * V_bs * ENGs_d);
%Engine spare parts depreciation cost [USD/nm]

DOC_depr = C_dap + C_deng + C_dav + C_dapsp + C_dengsp;
%Total direct operating cost of depreciation [USD/nm]

C_aplf = 0.002 * MTOW;                      %Airplane landing fee per landing [USD/Lb]

C_lf = (C_aplf/(V_bs * t_bl)) * (f_tax);      %Cost of landing fees [USD/nm]

C_nf = (C_apnf/(V_bs * t_bl)) * (f_tax);      %Cost of navigation fees [USD/nm]

DOC = (C_crew + C_pol + DOC_maint + DOC_depr + C_lf + C_nf)/(1 - C_ins -
C_rt*(f_tax) - Fin);
%Direct-Operating-Cost [USD/nm]

IOC = 0.5 * DOC;                            %Indirect-Operating-Cost [USD/nm]

TOT = DOC + IOC;                            %Total-Operating-Cost [USD/nm]

C_OPS = (DOC*R_bl_ann + IOC*R_bl_ann);
%Operating costs for the whole fleet of aircrafts, considering its whole operative life
[USD]

LCC = (C_OPS + C_RDTE + AEP*N_m)/(1-f_disp);
%Life-Cycle-Cost for the entire fleet and for its whole operative life [USD]

C_disposal=f_disp*LCC;                      %Disposal cost for a single aircraft [USD]
```

```
%Calculation of RDTE for each new technology

RDTE_1 = C_RDTE + (RDTE_mw)*K_trp;        %RDTE with morphing wing [USD]
RDTE_2 = C_RDTE + (RDTE_ea)*K_trp;        %RDTE with electric actuators [USD]
RDTE_3 = C_RDTE + (RDTE_SHM)*K_trp;       %RDTE with SHM system [USD]
RDTE_4 = C_RDTE + (RDTE_gt)*K_trp;        %RDTE with geared turbofan [USD]
RDTE_5 = C_RDTE + (RDTE_la)*K_trp;        %RDTE with laminar aerodynamics [USD]
RDTE_6 = C_RDTE + (RDTE_aepgds)*K_trp;    %RDTE with advanced EPGDS [USD]
RDTE_7 = C_RDTE + (RDTE_ap)*K_trp;        %RDTE with advanced propellers [USD]
RDTE_8 = C_RDTE + (RDTE_aw)*K_trp;        %RDTE with adaptive winglets [USD]
RDTE_9 = C_RDTE + (RDTE_nem)*K_trp;       %RDTE with new engine materials [USD]

%Calculation of AEP for each new technology

AEP_1 = AEP + (AEP*ACQ_mw);          %AEP with morphing wing [USD]
AEP_2 = AEP - (AEP*ACQ_ea);          %AEP with electric actuators [USD]
AEP_3 = AEP + (AEP*ACQ_SHM);         %AEP with SHM system [USD]
AEP_4 = AEP + (AEP*ACQ_gt);          %AEP with geared turbofan [USD]
AEP_5 = AEP + (AEP*ACQ_la);          %AEP with laminar aerodynamics [USD]
AEP_6 = AEP + (AEP*ACQ_aepgds);      %AEP with advanced EPGDS [USD]
AEP_7 = AEP + (AEP*ACQ_ap);          %AEP with advanced propellers [USD]
AEP_8 = AEP + (AEP*ACQ_aw);          %AEP with adaptive winglets [USD]
AEP_9 = AEP + (AEP*ACQ_nem);         %AEP with new engine materials [USD]

%Calculation of C_OPS for each new technology

C_OPS_1 = (C_OPS - (C_OPS * OP_mw));  %Operating cost with morphing wing [USD]

C_OPS_2 = (C_OPS - (C_OPS * OP_ea));
%Operating cost with electric actuators [USD]

C_OPS_3 = (C_OPS - (C_OPS * OP_SHM)); %Operating cost with SHM system [USD]

C_OPS_4 = (C_OPS - (C_OPS * OP_gt));   %Operating cost with geared turbofan [USD]

C_OPS_5 = (C_OPS - (C_OPS * OP_la));
%Operating cost with laminar aerodynamics [USD]
```

```
C_OPS_6 = (C_OPS - (C_OPS * OP_aepgds));
%Operating cost with advanced EPGDS [USD]

C_OPS_7 = (C_OPS - (C_OPS * OP_ap));
%Operating cost with advanced propellers [USD]

C_OPS_8 = (C_OPS - (C_OPS * OP_aw));
%Operating cost with adaptive winglets [USD]

C_OPS_9 = (C_OPS - (C_OPS * OP_nem));
%Operating cost with new engine materials [USD]

%Calculation of C_DISP for each new technology

C_DISP_1 = C_disposal - (C_disposal * DISP_mw);
%Disposal cost with morphing wing [USD]

C_DISP_2 = C_disposal + (C_disposal * DISP_ea);
%Disposal cost with electric actuators [USD]

C_DISP_3 = C_disposal + (C_disposal * DISP_SHM);
%Disposal cost with SHM system [USD]

C_DISP_4 = C_disposal + (C_disposal * DISP_gt);
%Disposal cost with geared turbofan [USD]

C_DISP_5 = C_disposal + (C_disposal * DISP_la);
%Disposal cost with laminar aerodynamics [USD]

C_DISP_6 = C_disposal + (C_disposal * DISP_aepgds);
%Disposal cost with advanced EPGDS [USD]

C_DISP_7 = C_disposal - (C_disposal * DISP_ap);
%Disposal cost with advanced propellers [USD]

C_DISP_8 = C_disposal + (C_disposal * DISP_aw);
%Disposal cost with adaptive winglets [USD]
```

```
C_DISP_9 = C_disposal + (C_disposal * DISP_nem);
%Disposal cost with new engine materials [USD]

%Calculation of LCC for each new technology

LCC_1 = (C_OPS_1  + RDTE_1 + AEP_1*(N_m) + C_DISP_1);
%LCC with morphing wing [USD]

LCC_2 = (C_OPS_2  + RDTE_2 + AEP_2*(N_m) + C_DISP_2);
%LCC with electric actuators [USD]

LCC_3 = (C_OPS_3  + RDTE_3 + AEP_3*(N_m) + C_DISP_3);
%LCC with SHM system [USD]

LCC_4 = (C_OPS_4  + RDTE_4 + AEP_4*(N_m) + C_DISP_4);
%LCC with geared turbofan [USD]

LCC_5 = (C_OPS_5  + RDTE_5 + AEP_5*(N_m) + C_DISP_5);
%LCC with laminar aerodynamics [USD]

LCC_6 = (C_OPS_6  + RDTE_6 + AEP_6*(N_m) + C_DISP_6);
%LCC with advanced EPGDS [USD]

LCC_7 = (C_OPS_7  + RDTE_7 + AEP_7*(N_m) + C_DISP_7);
%LCC with advanced propellers [USD]

LCC_8 = (C_OPS_8  + RDTE_8 + AEP_8*(N_m) + C_DISP_8);
%LCC with adaptive winglets [USD]

LCC_9 = (C_OPS_9  + RDTE_9 + AEP_9*(N_m) + C_DISP_9);
%LCC with new engine materials [USD]

%Calculation of benefits from synergies

RDTE_mw_ea = C_RDTE + ((RDTE_mw + RDTE_ea)*(K_trp)*(f_mw_ea));
%RDTE sinergy between morphing wing and electric actuators
```

```
RDTE_mw_la = C_RDTE + ((RDTE_mw + RDTE_la)*(K_trp)*(f_mw_la));
%RDTE sinergy between morphing wing and laminar aerodynamics

RDTE_mw_aw = C_RDTE + ((RDTE_mw + RDTE_aw)*(K_trp)*(f_mw_aw));
%RDTE sinergy between morphing wing and adaptive winglets

RDTE_ea_aepgds = C_RDTE + ((RDTE_ea + RDTE_aepgds)*(K_trp)*(f_ea_aepgds));
%RDTE sinergy between electric actuators and advanced EPGDS

RDTE_ea_aw = C_RDTE + ((RDTE_ea + RDTE_aw)*(K_trp)*(f_ea_aw));
%RDTE sinergy between electric actuators and adaptive winglets

RDTE_shm_aw = C_RDTE + ((RDTE_SHM + RDTE_aw)*(K_trp)*(f_shm_aw));
%RDTE sinergy between SHM system and adaptive winglets

AEP_mw_ea = AEP + (((ACQ_mw-ACQ_ea)*(AEP))*(f_mw_ea_1));
%AEP sinergy between morphing wing and electric actuators

AEP_mw_la = AEP + (((ACQ_mw+ACQ_la)*(AEP))*(f_mw_la_1));
 %AEP sinergy between morphing wing and laminar aerodynamics

AEP_mw_shm = AEP + (((ACQ_mw+ACQ_SHM)*(AEP))*(f_mw_shm_1));
%AEP sinergy between morphing wing and SHM system

AEP_ea_aw = AEP + (((ACQ_aw-ACQ_ea)*(AEP))*(f_ea_aw_1));
%AEP sinergy between electric actuators and adaptive winglets

AEP_shm_aw = AEP + (((ACQ_SHM+ACQ_aw)*(AEP))*(f_shm_aw_1));
%AEP sinergy between SHM system and adaptive winglets

OP_mw_la = C_OPS + ((OP_mw + OP_la)*(C_OPS)*(f_mw_la_2));
%Operating cost sinergy between morphing wing and laminar aerodynamics

%Calculation of each cost category for each possible combination

if (newtech_1 == 1 && newtech_2 == 1)

c = f_mw_ea;
```

```
end

if (newtech_1 == 1 && newtech_5 == 1)

c = f_mw_la;

end

if (newtech_1 == 1 && newtech_8 == 1)

c = f_mw_aw;

 end

if (newtech_2 == 1 && newtech_6 == 1)

c = f_ea_aepgds;

end

if (newtech_2 == 1 && newtech_8 == 1)

c = f_ea_aw;

end

if (newtech_3 == 1 && newtech_8 == 1)

c = f_shm_aw;

end

if (newtech_1 == 1 && newtech_2 == 1)

d = f_mw_ea_1;

end
```

```
if (newtech_1 == 1 && newtech_3 == 1)

d = f_mw_shm_1;

end

if (newtech_1 == 1 && newtech_6 == 1)

d = f_mw_la_1;

end
if (newtech_2 == 1 && newtech_8 == 1)

d = f_ea_aw_1;

end

if (newtech_3 == 1 && newtech_8 == 1)

d = f_shm_aw_1;

end

if (newtech_1 == 1 && newtech_6 == 1)

e = f_mw_la_2;

else

e = 1;

end

if (newtech_1 == 1)

DISP_1 = (f_disp * LCC_1 * DISP_mw)/100;
```

```
end

if (newtech_2 == 1)

DISP_2 = (f_disp * LCC_2 * DISP_ea)/100;

end

if (newtech_3 == 1)

DISP_3 = (f_disp * LCC_3 * DISP_SHM)/100;

end

if (newtech_4 == 1)

DISP_4 = (f_disp * LCC_4 * DISP_gt)/100;

end

if (newtech_5 == 1)

DISP_5 = (f_disp * LCC_5 * DISP_la)/100;

end

if (newtech_6 == 1)

DISP_6 = (f_disp * LCC_6 * DISP_aepgds)/100;

end

if (newtech_7 == 1)

DISP_7 = (f_disp * LCC_7 * DISP_ap)/100;

end
```

```
if (newtech_8 == 1)

DISP_8 = (f_disp * LCC_8 * DISP_aw)/100;

end

if (newtech_9 == 1)

DISP_9 = (f_disp * LCC_9 * DISP_nem)/100;

end

RDTE_tot = C_RDTE + ([A]*[B]'*c);
%RDTE cost considering every possible combination [USD]

AEP_tot = AEP + (AEP*[A]*[D]'*d);
%AEP cost considering every possible combination [USD]

OP_tot = C_OPS + (C_OPS*[A]*[E]'*e);
%Operating cost considering every possible combination [USD]

LCC_tot = (RDTE_tot + AEP_tot + OP_tot)/ (1 - (DISP_1 + DISP_2 + DISP_3 + DISP_4 +
DISP_5 + DISP_6 + DISP_7 + DISP_8 + DISP_9));
%LCC cost considering every possible combination [USD]

%Impact of every new technology on each cost category of the RDTE phase

part_aed = C_aed/C_RDTE;        %Percentage value of C_aed respect C_RDTE
part_dst = C_dst/C_RDTE;        %Percentage value of C_dst respect C_RDTE
part_ea = C_ea/C_RDTE;          %Percentage value of C_ea respect C_RDTE
part_man = C_man/C_RDTE;        %Percentage value of C_man respect C_RDTE
part_mat = C_mat/C_RDTE;        %Percentage value of C_mat respect C_RDTE
part_tool = C_tool/C_RDTE;      %Percentage value of C_tool respect C_RDTE
part_fto = C_fto/C_RDTE;        %Percentage value of C_fto respect C_RDTE
part_fta = C_fta/C_RDTE;        %Percentage value of C_fta respect C_RDTE
part_qc = C_qc/C_RDTE;          %Percentage value of C_qc respect C_RDTE

C_aed_1 = part_aed * RDTE_1;              %C_aed with morphing wing [USD]
```

```
save_1 = C_aed_1 - C_aed;                %Saving of C_aed with morphing wing [USD]
C_dst_1 = part_dst * RDTE_1;             %C_dst with morphing wing [USD]
save_2 = C_dst_1 - C_dst;                %Saving of C_dst with morphing wing [USD]
C_ea_1 = part_ea * RDTE_1;               %C_ea with morphing wing [USD]
save_3 = C_ea_1 - C_ea;                  %Saving of C_ea with morphing wing [USD]
C_man_1 = part_man * RDTE_1;             %C_man with morphing wing [USD]
save_4 = C_man_1 - C_man;                %Saving of C_man with morphing wing [USD]
C_mat_1 = part_mat * RDTE_1;             %C_mat with morphing wing [USD]
save_5 = C_mat_1 - C_mat;                %Saving of C_mat with morphing wing [USD]
C_tool_1 = part_tool * RDTE_1;           %C_tool with morphing wing [USD]
save_6 = C_tool_1 - C_tool;              %Saving of C_tool with morphing wing [USD]
C_fto_1 = part_fto * RDTE_1;             %C_fto with morphing wing [USD]
save_7 = C_fto_1 - C_fto;                %Saving of C_fto with morphing wing [USD]
C_fta_1 = part_fta * RDTE_1;             %C_fta with morphing wing [USD]
save_8 = C_fta_1 - C_fta;                %Saving of C_fta with morphing wing [USD]
C_qc_1 = part_qc * RDTE_1;               %C_qc with morphing wing [USD]
save_9 = C_qc_1 - C_qc;                  %Saving of C_qc with morphing wing [USD]

C_aed_2 = part_aed * RDTE_2;             %C_aed with electric actuators [USD]
save_10 = C_aed_2 - C_aed;               %Saving of C_aed with electric actuators [USD]
C_dst_2 = part_dst * RDTE_2;             %C_dst with electric actuators [USD]
save_11 = C_dst_2 - C_dst;               %Saving of C_dst with electric actuators [USD]
C_ea_2 = part_ea * RDTE_2;               %C_ea with electric actuators [USD]
save_12 = C_ea_2 - C_ea;                 %Saving of C_ea with electric actuators [USD]
C_man_2 = part_man * RDTE_2;             %C_man with electric actuators [USD]
save_13 = C_man_2 - C_man;               %Saving of C_man with electric actuators [USD]
C_mat_2 = part_mat * RDTE_2;             %C_mat with electric actuators [USD]
save_14 = C_mat_2 - C_mat;               %Saving of C_mat with electric actuators [USD]
C_tool_2 = part_tool * RDTE_2;           %C_tool with electric actuators [USD]
save_15 = C_tool_2 - C_tool;             %Saving of C_tool with electric actuators [USD]
C_fto_2 = part_fto * RDTE_2;             %C_fto with electric actuators [USD]
save_16 = C_fto_2 - C_fto;               %Saving of C_fto with electric actuators [USD]
C_fta_2 = part_fta * RDTE_2;             %C_fta with electric actuators [USD]
save_17 = C_fta_2 - C_fta;               %Saving of C_fta with electric actuators [USD]
C_qc_2 = part_qc * RDTE_2;               %C_qc with electric actuators [USD]
save_18 = C_qc_2 - C_qc;                 %Saving of C_qc with electric actuators [USD]

C_aed_3 = part_aed * RDTE_3;             %C_aed with SHM system [USD]
```

```
save_19 = C_aed_3 - C_aed;              %Saving of C_aed with SHM system [USD]
C_dst_3 = part_dst * RDTE_3;            %C_dst with SHM system [USD]
save_20 = C_dst_3 - C_dst;              %Saving of C_dst with SHM system [USD]
C_ea_3 = part_ea * RDTE_3;              %C_ea with SHM system [USD]
save_21 = C_ea_3 - C_ea;                %Saving of C_ea with SHM system [USD]
C_man_3 = part_man * RDTE_3;            %C_man with SHM system [USD]
save_22 = C_man_3 - C_man;              %Saving of C_man with SHM system [USD]
C_mat_3 = part_mat * RDTE_3;            %C_mat with SHM system [USD]
save_23 = C_mat_3 - C_mat;              %Saving of C_mat with SHM system [USD]
C_tool_3 = part_tool * RDTE_3;          %C_tool with SHM system [USD]
save_24 = C_tool_3 - C_tool;            %Saving of C_tool with SHM system [USD]
C_fto_3 = part_fto * RDTE_3;            %C_fto with SHM system [USD]
save_25 = C_fto_3 - C_fto;              %Saving of C_fto with SHM system [USD]
C_fta_3 = part_fta * RDTE_3;            %C_fta with SHM system [USD]
save_26 = C_fta_3 - C_fta;              %Saving of C_fta with SHM system [USD]
C_qc_3 = part_qc * RDTE_3;              %C_qc with SHM system [USD]
save_27 = C_qc_3 - C_qc;                %Saving of C_qc with SHM system [USD]

C_aed_5 = part_aed * RDTE_5;      %C_aed with laminar aerodynamics [USD]
save_28 = C_aed_5 - C_aed;        %Saving of C_aed with laminar aerodynamics [USD]
C_dst_5 = part_dst * RDTE_5;      %C_dst with laminar aerodynamics [USD]
save_29 = C_dst_5 - C_dst;        %Saving of C_dst with laminar aerodynamics [USD]
C_ea_5 = part_ea * RDTE_5;        %C_ea with laminar aerodynamics [USD]
save_30 = C_ea_5 - C_ea;          %Saving of C_ea with laminar aerodynamics [USD]
C_man_5 = part_man * RDTE_5;      %C_man with laminar aerodynamics [USD]
save_31 = C_man_5 - C_man;        %Saving of C_man with laminar aerodynamics [USD]
C_mat_5 = part_mat * RDTE_5;      %C_mat with laminar aerodynamics [USD]
save_32 = C_mat_5 - C_mat;        %Saving of C_mat with laminar aerodynamics [USD]
C_tool_5 = part_tool * RDTE_5;    %C_tool with laminar aerodynamics [USD]
save_33 = C_tool_5 - C_tool;      %Saving of C_tool with laminar aerodynamics [USD]
C_fto_5 = part_fto * RDTE_5;      %C_fto with laminar aerodynamics [USD]
save_34 = C_fto_5 - C_fto;        %Saving of C_fto with laminar aerodynamics [USD]
C_fta_5 = part_fta * RDTE_5;      %C_fta with laminar aerodynamics [USD]
save_35 = C_fta_5 - C_fta;        %Saving of C_fta with laminar aerodynamics [USD]
C_qc_5 = part_qc * RDTE_5;        %C_qc with laminar aerodynamics [USD]
save_36 = C_qc_5 - C_qc;          %Saving of C_qc with laminar aerodynamics [USD]

C_aed_6 = part_aed * RDTE_6;            %C_aed with Advanced-EPGDS [USD]
```

```
save_37 = C_aed_6 - C_aed;            %Saving of C_aed with Advanced-EPGDS [USD]
C_dst_6 = part_dst * RDTE_6;          %C_dst with Advanced-EPGDS [USD]
save_38 = C_dst_6 - C_dst;            %Saving of C_dst with Advanced-EPGDS [USD]
C_ea_6 = part_ea * RDTE_6;            %C_ea with Advanced-EPGDS [USD]
save_39 = C_ea_6 - C_ea;              %Saving of C_ea with Advanced-EPGDS [USD]
C_man_6 = part_man * RDTE_6;          %C_man with Advanced-EPGDS [USD]
save_40 = C_man_6 - C_man;            %Saving of C_man with Advanced-EPGDS [USD]
C_mat_6 = part_mat * RDTE_6;          %C_mat with Advanced-EPGDS [USD]
save_41 = C_mat_6 - C_mat;            %Saving of C_mat with Advanced-EPGDS [USD]
C_tool_6 = part_tool * RDTE_6;        %C_tool with Advanced-EPGDS [USD]
save_42 = C_tool_6 - C_tool;          %Saving of C_tool with Advanced-EPGDS [USD]
C_fto_6 = part_fto * RDTE_6;          %C_fto with Advanced-EPGDS [USD]
save_43 = C_fto_6 - C_fto;            %Saving of C_fto with Advanced-EPGDS [USD]
C_fta_6 = part_fta * RDTE_6;          %C_fta with Advanced-EPGDS [USD]
save_44 = C_fta_6 - C_fta;            %Saving of C_fta with Advanced-EPGDS [USD]
C_qc_6 = part_qc * RDTE_6;            %C_qc with Advanced-EPGDS [USD]
save_45 = C_qc_6 - C_qc;              %Saving of C_qc with Advanced-EPGD [USD]

C_aed_7 = part_aed * RDTE_7;          %C_aed with advanced propellers [USD]
save_46 = C_aed_7 - C_aed;            %Saving of C_aed with advanced propellers [USD]
C_dst_7 = part_dst * RDTE_7;          %C_dst with advanced propellers [USD]
save_47 = C_dst_7 - C_dst;            %Saving of C_dst with advanced propellers [USD]
C_ea_7 = part_ea * RDTE_7;            %C_ea with advanced propellers [USD]
save_48 = C_ea_7 - C_ea;              %Saving of C_ea with advanced propellers [USD]
C_man_7 = part_man * RDTE_7;          %C_man with advanced propellers [USD]
save_49 = C_man_7 - C_man;            %Saving of C_man with advanced propellers [USD]
C_mat_7 = part_mat * RDTE_7;          %C_mat with advanced propellers [USD]
save_50 = C_mat_7 - C_mat;            %Saving of C_mat with advanced propellers [USD]
C_tool_7 = part_tool * RDTE_7;        %C_tool with advanced propellers [USD]
save_51 = C_tool_7 - C_tool;          %Saving of C_tool with advanced propellers [USD]
C_fto_7 = part_fto * RDTE_7;          %C_fto with advanced propellers [USD]
save_52 = C_fto_7 - C_fto;            %Saving of C_fto with advanced propellers [USD]
C_fta_7 = part_fta * RDTE_7;          %C_fta with advanced propellers [USD]
save_53 = C_fta_7 - C_fta;            %Saving of C_fta with advanced propellers [USD]
C_qc_7 = part_qc * RDTE_7;            %C_qc with advanced propellers [USD]
save_54 = C_qc_7 - C_qc;              %Saving of C_qc with advanced propellers [USD]

C_aed_8 = part_aed * RDTE_8;          %C_aed with adaptive winglets [USD]
```

```
save_55 = C_aed_8 - C_aed;             %Saving of C_aed with adaptive winglets [USD]
C_dst_8 = part_dst * RDTE_8;           %C_dst with adaptive winglets [USD]
save_56 = C_dst_8 - C_dst;             %Saving of C_dst with adaptive winglets [USD]
C_ea_8 = part_ea * RDTE_8;             %C_ea with adaptive winglets [USD]
save_57 = C_ea_8 - C_ea;               %Saving of C_ea with adaptive winglets [USD]
C_man_8 = part_man * RDTE_8;           %C_man with adaptive winglets [USD]
save_58 = C_man_8 - C_man;             %Saving of C_man with adaptive winglets [USD]
C_mat_8 = part_mat * RDTE_8;           %C_mat with adaptive winglets [USD]
save_59 = C_mat_8 - C_mat;             %Saving of C_mat with adaptive winglets [USD]
C_tool_8 = part_tool * RDTE_8;         %C_tool with adaptive winglets [USD]
save_60 = C_tool_8 - C_tool;           %Saving of C_tool with adaptive winglets [USD]
C_fto_8 = part_fto * RDTE_8;           %C_fto with adaptive winglets [USD]
save_61 = C_fto_8 - C_fto;             %Saving of C_fto with adaptive winglets [USD]
C_fta_8 = part_fta * RDTE_8;           %C_fta with adaptive winglets [USD]
save_62 = C_fta_8 - C_fta;             %Saving of C_fta with adaptive winglets [USD]
C_qc_8 = part_qc * RDTE_8;             %C_qc with adaptive winglets [USD]
save_63 = C_qc_8 - C_qc;               %Saving of C_qc with adaptive winglets [USD]

C_aed_9 = part_aed * RDTE_9;       %C_aed with new engine materials [USD]
save_64 = C_aed_9 - C_aed;         %Saving of C_aed with new engine materials [USD]
C_dst_9 = part_dst * RDTE_9;       %C_dst with new engine materials [USD]
save_65 = C_dst_9 - C_dst;         %Saving of C_dst with new engine materials [USD]
C_ea_9 = part_ea * RDTE_9;         %C_ea with new engine materials [USD]
save_66 = C_ea_9 - C_ea;           %Saving of C_ea with new engine materials [USD]
C_man_9 = part_man * RDTE_9;       %C_man with new engine materials [USD]
save_67 = C_man_9 - C_man;         %Saving of C_man with new engine materials [USD]
C_mat_9 = part_mat * RDTE_9;       %C_mat with new engine materials [USD]
save_68 = C_mat_9 - C_mat;         %Saving of C_mat with new engine materials [USD]
C_tool_9 = part_tool * RDTE_9;     %C_tool with new engine materials [USD]
save_69 = C_tool_9 - C_tool;       %Saving of C_tool with new engine materials [USD]
C_fto_9 = part_fto * RDTE_9;       %C_fto with new engine materials [USD]
save_70 = C_fto_9 - C_fto;         %Saving of C_fto with new engine materials [USD]
C_fta_9 = part_fta * RDTE_9;       %C_fta with new engine materials [USD]
save_71 = C_fta_9 - C_fta;         %Saving of C_fta with new engine materials [USD]
C_qc_9 = part_qc * RDTE_9;         %C_qc with new engine materials[USD]
save_72 = C_qc_9 - C_qc;           %Saving of C_qc with new engine materials [USD]
```

```
%Impact of every new technology on each cost category on C_ACQ

part1_aed = 2*(C_aed1/C_ACQ);       %Percentage value of C_aed1 respect C_ACQ
part1_ea = 2*(C_ea1/C_ACQ);         %Percentage value of C_ea1 respect C_ACQ
part1_int = 2*(C_int/C_ACQ);        %Percentage value of C_int respect C_ACQ
part1_man = 2*(C_man1/C_ACQ);       %Percentage value of C_man1 respect C_ACQ
part1_mat = 2*(C_mat1/C_ACQ);       %Percentage value of C_mat1 respect C_ACQ
part1_tool = 2*(C_tool1/C_ACQ);     %Percentage value of C_tool1 respect C_ACQ
part1_qc = 2*(C_qc1/C_ACQ);         %Percentage value of C_qc1 respect C_ACQ
part1_fto = 2*(C_fto1/C_ACQ);       %Percentage value of C_fto1 respect C_ACQ

C_aed_mw = (1 + ACQ_mw)*(C_aed1);   %C_aed1 with morphing wing [USD]
diff1 = C_aed_mw - C_aed1;          %Saving of C_aed1 with morphing wing [USD]
C_ea_mw = (1 + ACQ_mw)*(C_ea1);     %C_ea1 with morphing wing [USD]
diff2 = C_ea_mw - C_ea1;            %Saving of C_ea1 with morphing wing [USD]
C_int_mw = (1 + ACQ_mw)*(C_int);    %C_int with morphing wing [USD]
diff3 = C_int_mw - C_int;           %Saving of C_int with morphing wing [USD]
C_man_mw = (1 + ACQ_mw)*(C_man1);   %C_man1 with morphing wing [USD]
diff4 = C_man_mw - C_man1;          %Saving of C_man1 with morphing wing [USD]
C_mat_mw = (1 + ACQ_mw)*(C_mat1);   %C_mat1 with morphing wing [USD]
diff5 = C_mat_mw - C_mat1;          %Saving of C_mat1 with morphing wing [USD]
C_tool_mw = (1 + ACQ_mw)*(C_tool1); %C_tool1 with morphing wing [USD]
diff6 = C_tool_mw - C_tool1;        %Saving of C_tool1 with morphing wing [USD]
C_qc_mw = (1 + ACQ_mw)*(C_qc1);     %C_qc1 with morphing wing [USD]
diff7 = C_qc_mw - C_qc1;            %Saving of C_qc1 with morphing wing [USD]
C_fto_mw = (1 + ACQ_mw)*(C_fto1);   %C_fto1 with morphing wing [USD]
diff8 = C_fto_mw - C_fto1;          %Saving of C_fto1 with morphing wing [USD]

C_aed_ea = (1 - ACQ_ea)*(C_aed1);   %C_aed1 with electric actuators [USD]
diff9 = C_aed_ea - C_aed1;          %Saving of C_aed1 with electric actuators [USD]
C_ea_ea = (1 - ACQ_ea)*(C_ea1);     %C_ea1 with electric actuators [USD]
diff10 = C_ea_ea - C_ea1;           %Saving of C_ea1 with electric actuators [USD]
C_int_ea = (1 - ACQ_ea)*(C_int);    %C_int with electric actuators [USD]
diff11 = C_int_ea - C_int;          %Saving of C_int with electric actuators [USD]
C_man_ea = (1 - ACQ_ea)*(C_man1);   %C_man1 with electric actuators [USD]
diff12 = C_man_ea - C_man1;         %Saving of C_man1 with electric actuators [USD]
C_mat_ea = (1 - ACQ_ea)*(C_mat1);   %C_mat1 with electric actuators [USD]
diff13 = C_mat_ea - C_mat1;         %Saving of C_mat1 with electric actuators [USD]
```

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C_tool_ea = (1 - ACQ_ea)*(C_tool1);     %C_tool1 with electric actuators [USD]
diff14 = C_tool_ea - C_tool1;            %Saving of C_tool1 with electric actuators [USD]
C_qc_ea = (1 - ACQ_ea)*(C_qc1);          %C_qc1 with electric actuators [USD]
diff15 = C_qc_ea - C_qc1;                %Saving of C_qc1 with electric actuators [USD]
C_fto_ea = (1 - ACQ_ea)*(C_fto1);        %C_fto1 with electric actuators [USD]
diff16 = C_fto_ea - C_fto1;              %Saving of C_fto1 with electric actuators [USD]

C_aed_SHM = (1 + ACQ_SHM)*(C_aed1);   %C_aed1 with SHM system [USD]
diff17 = C_aed_SHM - C_aed1;             %Saving of C_aed1 with SHM system [USD]
C_ea_SHM = (1 + ACQ_SHM)*(C_ea1);        %C_ea1 with SHM system [USD]
diff18 = C_ea_SHM - C_ea1;               %Saving of C_ea1 with SHM system [USD]
C_int_SHM = (1 + ACQ_SHM)*(C_int);       %C_int with SHM system [USD]
diff19 = C_int_SHM - C_int;              %Saving of C_int with SHM system [USD]
C_man_SHM = (1 + ACQ_SHM)*(C_man1);  %C_man1 with SHM system [USD]
diff20 = C_man_SHM - C_man1;             %Saving of C_man1 with SHM system [USD]
C_mat_SHM = (1 + ACQ_SHM)*(C_mat1);   %C_mat1 with SHM system [USD]
diff21 = C_mat_SHM - C_mat1;             %Saving of C_mat1 with SHM system [USD]
C_tool_SHM = (1 + ACQ_SHM)*(C_tool1);  %C_tool1 with SHM system [USD]
diff22 = C_tool_SHM - C_tool1;           %Saving of C_tool1 with SHM system [USD]
C_qc_SHM = (1 + ACQ_SHM)*(C_qc1);        %C_qc1 with SHM system [USD]
diff23 = C_qc_SHM - C_qc1;               %Saving of C_qc1 with SHM system [USD]
C_fto_SHM = (1 + ACQ_SHM)*(C_fto1);      %C_fto1 with SHM system [USD]
diff24 = C_fto_SHM - C_fto1;             %Saving of C_fto1 with SHM system [USD]

C_aed_la = (1 + ACQ_la)*(C_aed1);   %C_aed1 with laminar aerodynamics [USD]
diff25 = C_aed_la - C_aed1;         %Saving of C_aed1 with laminar aerodynamics [USD]
C_ea_la = (1 + ACQ_la)*(C_ea1);        %C_ea1 with laminar aerodynamics [USD]
diff26 = C_ea_la - C_ea1;              %Saving of C_ea1 with laminar aerodynamics [USD]
C_int_la = (1 + ACQ_la)*(C_int);       %C_int with laminar aerodynamics [USD]
diff27 = C_int_la - C_int;             %Saving of C_int with laminar aerodynamics [USD]
C_man_la = (1 + ACQ_la)*(C_man1);   %C_man1 with laminar aerodynamics [USD]
diff28 = C_man_la - C_man1;      %Saving of C_man1 with laminar aerodynamics [USD]
C_mat_la = (1 + ACQ_la)*(C_mat1);     %C_mat1 with laminar aerodynamics [USD]
diff29 = C_mat_la - C_mat1;       %Saving of C_mat1 with laminar aerodynamics [USD]
C_tool_la = (1 + ACQ_la)*(C_tool1);     %C_tool1 with laminar aerodynamics [USD]
diff30 = C_tool_la - C_tool1;       %Saving of C_tool1 with laminar aerodynamics [USD]
C_qc_la = (1 + ACQ_la)*(C_qc1);          %C_qc1 with laminar aerodynamics [USD]
diff31 = C_qc_la - C_qc1;           %Saving of C_qc1 with laminar aerodynamics [USD]
```

```
C_fto_la = (1 + ACQ_la)*(C_fto1);   %C_fto1 with laminar aerodynamics [USD]
diff32 = C_fto_la - C_fto1;            %Saving of C_fto1 with laminar aerodynamics [USD]

C_aed_ap = (1 + ACQ_ap)*(C_aed1);   %C_aed1 with advanced propellers [USD]
diff33 = C_aed_ap - C_aed1;         %Saving of C_aed1 with advanced propellers [USD]
C_ea_ap = (1 + ACQ_ap)*(C_ea1);       %C_ea1 with advanced propellers [USD]
diff34 = C_ea_ap - C_ea1;              %Saving of C_ea1 with advanced propellers [USD]
C_int_ap = (1 + ACQ_ap)*(C_int);         %C_int with advanced propellers [USD]
diff35 = C_int_ap - C_int;                %Saving of C_int with advanced propellers [USD]
C_man_ap = (1 + ACQ_ap)*(C_man1);  %C_man1 with advanced propellers [USD]
diff36 = C_man_ap - C_man1;      %Saving of C_man1 with advanced propellers [USD]
C_mat_ap = (1 + ACQ_ap)*(C_mat1);    %C_mat1 with advanced propellers [USD]
diff37 = C_mat_ap - C_mat1;        %Saving of C_mat1 with advanced propellers [USD]
C_tool_ap = (1 + ACQ_ap)*(C_tool1);    %C_tool1 with advanced propellers [USD]
diff38 = C_tool_ap - C_tool1;         %Saving of C_tool1 with advanced propellers [USD]
C_qc_ap = (1 + ACQ_ap)*(C_qc1);        %C_qc1 with advanced propellers [USD]
diff39 = C_qc_ap - C_qc1;             %Saving of C_qc1 with advanced propellers [USD]
C_fto_ap = (1 + ACQ_ap)*(C_fto1);        %C_fto1 with advanced propellers [USD]
diff40 = C_fto_ap - C_fto1;            %Saving of C_fto1 with advanced propellers [USD]

C_aed_aw = (1 + ACQ_aw)*(C_aed1);     %C_aed1 with adaptive winglets [USD]
diff41 = C_aed_aw - C_aed1;             %Saving of C_aed1 with adaptive winglets [USD]
C_ea_aw = (1 + ACQ_aw)*(C_ea1);         %C_ea1 with adaptive winglets [USD]
diff42 = C_ea_aw - C_ea1;                %Saving of C_ea1 with adaptive winglets [USD]
C_int_aw = (1 + ACQ_aw)*(C_int);           %C_int with adaptive winglets [USD]
diff43 = C_int_aw - C_int;                %Saving of C_int with adaptive winglets [USD]
C_man_aw = (1 + ACQ_aw)*(C_man1);    %C_man1 with adaptive winglets [USD]
diff44 = C_man_aw - C_man1;          %Saving of C_man1 with adaptive winglets [USD]
C_mat_aw = (1 + ACQ_aw)*(C_mat1);      %C_mat1 with adaptive winglets [USD]
diff45 = C_mat_aw - C_mat1;            %Saving of C_mat1 with adaptive winglets [USD]
C_tool_aw = (1 + ACQ_aw)*(C_tool1);      %C_tool1 with adaptive winglets [USD]
diff46 = C_tool_aw - C_tool1;            %Saving of C_tool1 with adaptive winglets [USD]
C_qc_aw = (1 + ACQ_aw)*(C_qc1);          %C_qc1 with adaptive winglets [USD]
diff47 = C_qc_aw - C_qc1;                %Saving of C_qc1 with adaptive winglets [USD]
C_fto_aw = (1 + ACQ_aw)*(C_fto1);          %C_fto1 with adaptive winglets [USD]
diff48 = C_fto_aw - C_fto1;               %Saving of C_fto1 with adaptive winglets [USD]

C_aed_nem = (1 + ACQ_nem)*(C_aed1);      %C_aed1 with new engine materials [USD]
```

```
diff49 = C_aed_nem - C_aed1;      %Saving of C_aed1 with new engine materials [USD]
C_ea_nem = (1 + ACQ_nem)*(C_ea1);          %C_ea1 with new engine materials [USD]
diff50 = C_ea_nem - C_ea1;          %Saving of C_ea1 with new engine materials [USD]
C_int_nem = (1 + ACQ_nem)*(C_int);           %C_int with new engine materials [USD]
diff51 = C_int_nem - C_int;           %Saving of C_int with new engine materials [USD]
C_man_nem = (1 + ACQ_nem)*(C_man1);   %C_man1 with new engine materials [USD]
diff52 = C_man_nem - C_man1;   %Saving of C_man1 with new engine materials [USD]
C_mat_nem = (1 + ACQ_nem)*(C_mat1);      %C_mat1 with new engine materials [USD]
diff53 = C_mat_nem - C_mat1;     %Saving of C_mat1 with new engine materials [USD]
C_tool_nem = (1 + ACQ_nem)*(C_tool1);      %C_tool1 with new engine materials [USD]
diff54 = C_tool_nem - C_tool1;     %Saving of C_tool1 with new engine materials [USD]
C_qc_nem = (1 + ACQ_nem)*(C_qc1);          %C_qc1 with new engine materials [USD]
diff55 = C_qc_nem - C_qc1;         %Saving of C_qc1 with new engine materials [USD]
C_fto_nem = (1 + ACQ_nem)*(C_fto1);          %C_fto1 with new engine materials [USD]
diff56 = C_fto_nem - C_fto1;         %Saving of C_fto1 with new engine materials [USD]

%Impact of every new technology on each cost category on DOC, IOC and TOT

per_flying = (C_crew + C_pol + (C_ins*(DOC)))/TOT;
%percentage value of DOC_flying respect TOT

per_maint = DOC_maint / TOT;
%percentage value of DOC_maint respect TOT

per_depr = DOC_depr / TOT;
%percentage value of DOC_depr respect TOT

per_tax = (C_lf + C_nf + (C_rt*f_tax)) / TOT;
%percentage value of DOC_texes respect TOT

per_DOC = DOC/TOT;
%percentage value of DOC respect TOT

per_IOC = IOC/TOT;
%percentage value of IOC respect TOT

C_flying_mw = (C_OPS_1/(hours_ATR*365*V_bs)) * (per_flying);
%C_flying with morphing wing [USD/nm]
```

```
saving1 = C_flying_mw - (C_crew + C_pol + (C_ins*(DOC)));
%Saving of C_flying with morphing wing [USD/nm]

C_maint_mw = (C_OPS_1/(hours_ATR*365*V_bs)) * (per_maint);
%C_maint with morphing wing [USD/nm]

saving2 = C_maint_mw - DOC_maint;
%Saving of C_maint with morphing wing [USD/nm]

C_depr_mw = (C_OPS_1/(hours_ATR*365*V_bs)) * (per_depr);
%C_depr with morphing wing [USD/nm]

saving3 = C_depr_mw - DOC_depr;
%Saving of C_depr with morphing wing [USD/nm]

C_tax_mw = (C_OPS_1/(hours_ATR*365*V_bs)) * (per_tax);
%C_tax with morphing wing [USD/nm]

saving4 = C_tax_mw - (C_lf + C_nf + (C_rt*f_tax));
%Saving of C_tax with morphing wing [USD/nm]

DOC_mw = (C_OPS_1/(hours_ATR*365*V_bs)) * (per_DOC);
 %DOC with morphing wing [USD/nm]

saving5 = DOC_mw - DOC;
%Saving of DOC with morphing wing [USD/nm]
IOC_mw = (C_OPS_1/(hours_ATR*365*V_bs)) * (per_IOC);
%IOC with morphing wing [USD/nm]

saving6 = IOC_mw - IOC;
%Saving of IOC with morphing wing [USD/nm]

TOT_mw = DOC_mw + IOC_mw;
%TOC with morphing wing [USD/nm]

saving7= TOT_mw - TOT;
%Saving of TOC with morphing wing [USD/nm]
```

```
C_flying_ea = (C_OPS_2/(hours_ATR*365*V_bs)) * (per_flying);
%C_flying with electric actuators [USD/nm]

saving8 = C_flying_ea - (C_crew + C_pol + (C_ins*(DOC)));
%Saving of C_flying with electric actuators [USD/nm]

C_maint_ea = (C_OPS_2/(hours_ATR*365*V_bs)) * (per_maint);
%C_maint with electric actuators [USD/nm]

saving9 = C_maint_ea - DOC_maint;
%Saving of C_maint with electric actuators [USD/nm]

C_depr_ea = (C_OPS_2/(hours_ATR*365*V_bs)) * (per_depr);
%C_depr with electric actuators [USD/nm]

saving10 = C_depr_ea - DOC_depr;
%Saving of C_depr with electric actuators [USD/nm]

C_tax_ea = (C_OPS_2/(hours_ATR*365*V_bs)) * (per_tax);
%C_tax with electric actuators [USD/nm]

saving11 = C_tax_ea - (C_lf + C_nf + (C_rt*f_tax));
%Saving of C_tax with electric actuators [USD/nm]

DOC_ea = (C_OPS_2/(hours_ATR*365*V_bs)) * (per_DOC);
%DOC with electric actuators [USD/nm]

saving12 = DOC_ea - DOC;
%Saving of DOC with electric actuators [USD/nm]

IOC_ea = (C_OPS_2/(hours_ATR*365*V_bs)) * (per_IOC);
%IOC with electric actuators [USD/nm]

saving13 = IOC_ea - IOC;
%Saving of IOC with electric actuators [USD/nm]

TOT_ea = DOC_ea + IOC_ea;
%TOC with electric actuators [USD/nm]
```

```
saving14= TOT_ea - TOT;
%Saving of TOC with electric actuators [USD/nm]

C_flying_SHM = (C_OPS_3/(hours_ATR*365*V_bs)) * (per_flying);
%C_flying with SHM system [USD/nm]

saving15 = C_flying_SHM - (C_crew + C_pol + (C_ins*(DOC)));
 %Saving of C_flying with SHM systems [USD/nm]

C_maint_SHM = (C_OPS_3/(hours_ATR*365*V_bs)) * (per_maint);
%C_maint with SHM system [USD/nm]

saving16 = C_maint_SHM - DOC_maint;
%Saving of C_maint with SHM system [USD/nm]

C_depr_SHM = (C_OPS_3/(hours_ATR*365*V_bs)) * (per_depr);
%C_depr with SHM systems [USD/nm]

saving17 = C_depr_SHM - DOC_depr;
%Saving of C_depr with SHM system [USD/nm]

C_tax_SHM = (C_OPS_3/(hours_ATR*365*V_bs)) * (per_tax);
%C_tax with SHM systems [USD/nm]

saving18 = C_tax_SHM - (C_lf + C_nf + (C_rt*f_tax));
%Saving of C_tax with SHM system [USD/nm]

DOC_SHM = (C_OPS_3/(hours_ATR*365*V_bs)) * (per_DOC);
%DOC with SHM system [USD/nm]

saving19 = DOC_SHM - DOC;
%Saving of DOC with SHM system [USD/nm]

IOC_SHM = (C_OPS_3/(hours_ATR*365*V_bs)) * (per_IOC);
%IOC with SHM system [USD/nm]

saving20 = IOC_SHM - IOC;
%Saving of IOC with SHM system [USD/nm]
```

```
TOT_SHM = DOC_SHM + IOC_SHM;
%TOC with SHM systems [USD/nm]

saving21= TOT_SHM - TOT;
%Saving of TOC with SHM system [USD/nm]

C_flying_la = (C_OPS_5/(hours_ATR*365*V_bs)) * (per_flying);
%C_flying with laminar aerodynamics [USD/nm]

saving22 = C_flying_la - (C_crew + C_pol + (C_ins*(DOC)));
%Saving of C_flying with laminar aerodynamics [USD/nm]

C_maint_la = (C_OPS_5/(hours_ATR*365*V_bs)) * (per_maint);
%C_maint with laminar aerodynamics [USD/nm]

saving23 = C_maint_la - DOC_maint;
%Saving of C_maint with laminar aerodynamics [USD/nm]

C_depr_la = (C_OPS_5/(hours_ATR*365*V_bs)) * (per_depr);
%C_depr with laminar aerodynamics [USD/nm]

saving24 = C_depr_la - DOC_depr;
%Saving of C_depr with laminar aerodynamics [USD/nm]

C_tax_la = (C_OPS_5/(hours_ATR*365*V_bs)) * (per_tax);
%C_tax with laminar aerodynamics [USD/nm]

saving25 = C_tax_la - (C_lf + C_nf + (C_rt*f_tax));
%Saving of C_tax with laminar aerodynamics [USD/nm]

DOC_la = (C_OPS_5/(hours_ATR*365*V_bs)) * (per_DOC);
%DOC with laminar aerodynamics [USD/nm]

saving26 = DOC_la - DOC;
%Saving of DOC with laminar aerodynamics [USD/nm]

IOC_la = (C_OPS_5/(hours_ATR*365*V_bs)) * (per_IOC);
%IOC with laminar aerodynamics [USD/nm]
```

```
saving27 = IOC_la - IOC;
%Saving of IOC with laminar aerodynamics [USD/nm]

TOT_la = DOC_la + IOC_la;
%TOC with laminar aerodynamics [USD/nm]

saving28= TOT_la - TOT;
%Saving of TOC with laminar aerodynamics [USD/nm]

C_flying_aepgds = (C_OPS_6/(hours_ATR*365*V_bs)) * (per_flying);
%C_flying with Advanced-EPGDS [USD/nm]

saving29 = C_flying_aepgds - (C_crew + C_pol + (C_ins*(DOC)));
%Saving of C_flying with Advanced-EPGDS [USD/nm]

C_maint_aepgds = (C_OPS_6/(hours_ATR*365*V_bs)) * (per_maint);
%C_maint with Advanced-EPGDS [USD/nm]

saving30 = C_maint_aepgds - DOC_maint;
%Saving of C_maint with Advanced-EPGDS [USD/nm]

C_depr_aepgds = (C_OPS_6/(hours_ATR*365*V_bs)) * (per_depr);
%C_depr with Advanced-EPGDS [USD/nm]

saving31 = C_depr_aepgds - DOC_depr;
%Saving of C_depr with Advanced-EPGDS [USD/nm]

C_tax_aepgds = (C_OPS_6/(hours_ATR*365*V_bs)) * (per_tax);
%C_tax with Advanced-EPGDS [USD/nm]

saving32 = C_tax_aepgds - (C_lf + C_nf + (C_rt*f_tax));
%Saving of C_tax with Advanced-EPGDS [USD/nm]

DOC_aepgds = (C_OPS_6/(hours_ATR*365*V_bs)) * (per_DOC);
%DOC with Advanced-EPGDS [USD/nm]

saving33 = DOC_aepgds - DOC;
%Saving of DOC with Advanced-EPGDS [USD/nm]
```

```
IOC_aepgds = (C_OPS_6/(hours_ATR*365*V_bs)) * (per_IOC);
%IOC with Advanced-EPGDS [USD/nm]

saving34 = IOC_aepgds - IOC;
%Saving of IOC with Advanced-EPGDS [USD/nm]

TOT_aepgds = DOC_aepgds + IOC_aepgds;
%TOC with Advanced-EPGDS [USD/nm]

saving35= TOT_aepgds - TOT;
%Saving of TOC with Advanced-EPGDS [USD/nm]

C_flying_ap = (C_OPS_7/(hours_ATR*365*V_bs)) * (per_flying);
%C_flying with advanced propellers [USD/nm]

saving36 = C_flying_ap - (C_crew + C_pol + (C_ins*(DOC)));
%Saving of C_flying with advanced propellers [USD/nm]

C_maint_ap = (C_OPS_7/(hours_ATR*365*V_bs)) * (per_maint);
%C_maint with advanced propellers [USD/nm]

saving37 = C_maint_ap - DOC_maint;
%Saving of C_maint with advanced propellers [USD/nm]

C_depr_ap = (C_OPS_7/(hours_ATR*365*V_bs)) * (per_depr);
%C_depr with advanced propellers [USD/nm]

saving38 = C_depr_ap - DOC_depr;
%Saving of C_depr with advanced propellers [USD/nm]

C_tax_ap = (C_OPS_7/(hours_ATR*365*V_bs)) * (per_tax);
%C_tax with advanced propellers [USD/nm]

saving39 = C_tax_ap - (C_lf + C_nf + (C_rt*f_tax));
%Saving of C_tax with advanced propellers [USD/nm]

DOC_ap = (C_OPS_7/(hours_ATR*365*V_bs)) * (per_DOC);
%DOC with advanced propellers [USD/nm]
```

```
saving40 = DOC_ap - DOC;
%Saving of DOC with advanced propellers [USD/nm]

IOC_ap = (C_OPS_7/(hours_ATR*365*V_bs)) * (per_IOC);
%IOC with advanced propellers [USD/nm]

saving41 = IOC_ap - IOC;
%Saving of IOC with advanced propellers [USD/nm]

TOT_ap = DOC_ap + IOC_ap;
%TOC with advanced propellers [USD/nm]

saving42= TOT_ap - TOT;
%Saving of TOC with advanced propellers [USD/nm]

C_flying_aw = (C_OPS_8/(hours_ATR*365*V_bs)) * (per_flying);
%C_flying with adaptive winglets [USD/nm]

saving43 = C_flying_aw - (C_crew + C_pol + (C_ins*(DOC)));
%Saving of C_flying with adaptive winglets [USD/nm]

C_maint_aw = (C_OPS_8/(hours_ATR*365*V_bs)) * (per_maint);
%C_maint with adaptive winglets [USD/nm]

saving44 = C_maint_aw - DOC_maint;
%Saving of C_maint with adaptive winglets [USD/nm]

C_depr_aw = (C_OPS_8/(hours_ATR*365*V_bs)) * (per_depr);
%C_depr with adaptive winglets [USD/nm]

saving45 = C_depr_aw - DOC_depr;
%Saving of C_depr with adaptive winglets [USD/nm]

C_tax_aw = (C_OPS_8/(hours_ATR*365*V_bs)) * (per_tax);
%C_tax with adaptive winglets [USD/nm]

saving46 = C_tax_aw - (C_lf + C_nf + (C_rt*f_tax));
%Saving of C_tax with adaptive winglets [USD/nm]
```

```
DOC_aw = (C_OPS_8/(hours_ATR*365*V_bs)) * (per_DOC);
%DOC with adaptive winglets [USD/nm]

saving47 = DOC_aw - DOC;
%Saving of DOC with adaptive winglets [USD/nm]

IOC_aw = (C_OPS_8/(hours_ATR*365*V_bs)) * (per_IOC);
%IOC with adaptive winglets [USD/nm]

saving48 = IOC_aw - IOC;
%Saving of IOC with adaptive winglets [USD/nm]

TOT_aw = DOC_aw + IOC_aw;
%TOC with adaptive winglets [USD/nm]

saving49= TOT_ap - TOT;
%Saving of TOC with adaptive winglets [USD/nm]

C_flying_nem = (C_OPS_9/(hours_ATR*365*V_bs)) * (per_flying);
%C_flying with new engine materials [USD/nm]

saving50 = C_flying_nem - (C_crew + C_pol + (C_ins*(DOC)));
%Saving of C_flying with new engine materials [USD/nm]

C_maint_nem = (C_OPS_9/(hours_ATR*365*V_bs)) * (per_maint);
%C_maint with new engine materials [USD/nm]

saving51 = C_maint_nem - DOC_maint;
%Saving of C_maint with new engine materials [USD/nm]

C_depr_nem = (C_OPS_9/(hours_ATR*365*V_bs)) * (per_depr);
%C_depr with new engine materials [USD/nm]

saving52 = C_depr_nem - DOC_depr;
%Saving of C_depr with new engine materials [USD/nm]

C_tax_nem = (C_OPS_9/(hours_ATR*365*V_bs)) * (per_tax);
%C_tax with new engine materials [USD/nm]
```

```
saving53 = C_tax_nem - (C_lf + C_nf + (C_rt*f_tax));
%Saving of C_tax with new engine materials [USD/nm]

DOC_nem = (C_OPS_9/(hours_ATR*365*V_bs)) * (per_DOC);
%DOC with new engine materials [USD/nm]

saving54 = DOC_nem - DOC;
%Saving of DOC with new engine materials [USD/nm]

IOC_nem = (C_OPS_9/(hours_ATR*365*V_bs)) * (per_IOC);
%IOC with new engine materials [USD/nm]

saving55 = IOC_nem - IOC;
%Saving of IOC with new engine materials [USD/nm]

TOT_nem = DOC_nem + IOC_nem;
%TOC with new engine materials [USD/nm]

saving56= TOT_nem - TOT;
%Saving of TOC with new engine materials [USD/nm]
```

# APPENDIX B

This appendix shows the Matlab code used to compute the cost categories of the A-320 200 with and without new technologies. Moreover, it has also been used in order to calculate the effects of synergies between two new technologies during the RDTE, Acquisition & Manufacturing and operating phase.

```
%Input variables to compute C_RDTE

CEF = 1.95;              %Cost escalation factor from 1989 to 2017
CEF_2 = 6.14;            %Cost escalation factor from 1970 to 2017
MTOW = 169756;           %Maximum-Take-Off-Weight [Lb]
V_c = 488;               %Cruise speed [Kts]
Thrust = 25000;          %Engine Cruise Thrust [Lbf]
N_e = 2;                 %N. of engines
N_m = 875;               %N. of manufactured aircrafts
W_avio = 1172.5;         % Avionic system weight [Lb]
R_e = 178.42;            %Engineering rate [USD/h]
R_m = 92.82;             %Manufacturing rate [USD/h]
R_t = 120.1;             %Tooling rate [USD/h]
N_RDTE = 5;              %N. of RDTE aircraft built
N_ST = 2;                %N. of airframes built
N_r = 0.33;              %N. of aircrafts built per month
F_mat = 1.5;             %Material factor
F_tsf = 0;               %Adjustment factor
F_obs = 1;               %Low-observable factor
F_diff = 1.7;            %Program complexity factor
F_CAD = 0.8;             %CAD factor
N_prot = 3;              %N. of prototypes built
f_tsf = 0.1;             %Adjustment factor [% of C_RDTE]
Finance = 0.2;           %Finance [%]
Profit = 0.2;            %Profit [%]

%Input variables to compute C_MAN and C_ACQ

Pax = 164;               %N. of passengers
```

```
R_e1 = 240.9;            %Engineering rate [USD/h]
R_m1 = 134.25;           %Manufacturing rate [USD/h]
R_t1 = 173.74;           %Tooling rate [USD/h]
N_r1 = 50;               %N. of aircrafts built per month
F_over = 4;              %Overhead factor
F_int = 2000;            %Interior factor [USD/pax]
FTh = 10;                %Flight-test hours [h]
f_ACQ = 1.2;             %Acquisition coefficient

%Input variables to compute DOC and IOC

B_d = 874.43;            %Block distance [nm]
BFW = 4636;              %Burned fuel weight [Lb]
MMH_eng = 1;             %Engine maintenance man-hours per flight hour
MMH_air = 1;             %Airframe maintenance man-hours per flight hour
F_c = 2;                 %Fuel cost [USD/gallon]
F_density = 6.4;         %Fuel density [Lb/gallon]
N_officer = 1;           %N. of first officers
N_captain = 1;           %N. of captains
N_fass = 4;              %N. of flight assistants
ENG_d = 20;              %Engine depreciation period [years]
AIRF_d = 20;             %Airframe depreciation period [years]
AVIONC_d = 10;           %Avionic depreciation period [years]
AIRFs_d = 20;            %Airframe spare parts depreciation period [years]
ENGs_d = 20;             %Engine spare parts depreciation period [years]
AIRFs_f = 0.4;           %Airframe spare parts factor
ENGs_f = 0.5;            %Engine spare parts factor
AIRF_d_f = 0.9;          %Airframe depreciation factor
ENG_d_f = 0.9;           %Engine depreciation factor
AVIONIC_d_f = 0.95;      %Avionic depreciation factor
AIRFs_d_f = 0.9;         %Airframe spare parts depreciation factor
ENGs_d_f = 0.9;          %Engine spare parts depreciation factor
t_man = 0.15;            %Ground maneuver time [h]
t_cl = 0.2;              %Climb time [h]
t_de = 0.15;             %Descent time [h]
t_atc = 0.08;            %Maneuver due to ATC time [h]
t_cr = 1.5;              %Cruise time [h]
t_bl = 2;                %Total block-time [h]
```

```
V_bs = 437.21;            %Block speed [Kts]
K_j = 0.26;               %Vacation pay and training factor
SAL_captain = 80000;      %Captain salary [USD/year]
SAL_officer = 70000;      %First officer salary [USD/year]
SAL_fass = 28000;         %Flight assistant salary [USD/year]
AH = 900;                 %Crew members flight hours per year [h/years]
TEF = 7;                  %Travel expense factor [USD/blh]
R_lap = 16;               %Airplane maintenance labor rate [USD/mh]
R_leng = 16;              %Engine maintenance labor rate [USD/mh]
ESPPF = 1.5;              %Engine spare parts price factor
K_hem = 1.4;              %Attained period between engine overhaul factor
f_amblab = 1.3;           %Labor overhead distribution factor
f_ambmat = 0.6;           %Maintenance overhead distribution factor
C_apnf = 10;              %Navigation fee [USD/flight]
C_ins = 0.02;             %Insurance direct cost [% of DOC]
C_rt = 0.0022;            %Cost of registry taxes [% of DOC]
Fin = 0.07;               %Direct operating cost of financing [% of DOC]
f_change = 2.8;           %Crew interchange factor
f_tax = 5;                %Tax inflation factor
f_disp = 0.012;           %Disposal coefficient

%New technologies cost coefficients

RDTE_mw = 550000000;          %RDTE cost for the morphing wing
RDTE_ea = 100000000;          %RDTE cost for electric actuators
RDTE_SHM = 100000000;         %RDTE cost for the SHM system
RDTE_gt = 250000000;          %RDTE cost for the geared turbofan
RDTE_la = 50000000;           %RDTE cost for laminar aerodynamics
RDTE_aepgds = 100000000;      %RDTE cost for the advanced EPGDS
RDTE_ap = 100000000;          %RDTE cost for advanced propeller
RDTE_aw = 300000000;          %RDTE cost for the adaptive winglets
RDTE_nem = 300000000;         %RDTE cost for new engine materials
ACQ_mw = 0.013;               %Acquisition cost percentage for the morphing wing
ACQ_ea = 0.002;               %Acquisition cost percentage for electric actuators
ACQ_SHM = 0.002;              %Acquisition cost percentage for the SHM system
ACQ_gt = 0.021;               %Acquisition cost percentage for the geared turbofan
ACQ_la = 0.013;               %Acquisition cost percentage for laminar aerodynamics
ACQ_aepgds = 0;               %Acquisition cost percentage for the advanced EPGDS
```

```
ACQ_ap = 0.011;                  %Acquisition cost percentage for advanced propellers
ACQ_aw = 0.01;                   %Acquisition cost percentage for adaptive winglets
ACQ_nem = 0.026;                 %Acquisition cost percentage for new engine materials
OP_mw = 0.004;                   %Operating cost percentage for the morphing wing
OP_ea = 0.001;                   %Operating cost percentage for electric actuators
OP_SHM = 0.007;                  %Operating cost percentage for the SHM system
OP_gt = 0.032;                   %Operating cost percentage for the geared turbofan
OP_la = 0.007;                   %Operating cost percentage for laminar aerodynamics
OP_aepgds = 0.004;               %Operating cost percentage for the advanced EPGDS
OP_ap = 0.03;                    %Operating cost percentage for advanced propellers
OP_aw = 0.012;                   %Operating cost percentage for adaptive winglets
OP_nem = 0.034;                  %Operating cost percentage for new engine materials
DISP_mw = 0.002;                 %Disposal cost percentage for the morphing wing
DISP_ea = 0.002;                 %Disposal cost percentage for electric actuators
DISP_SHM = 0.001;                %Disposal cost percentage for the SHM system
DISP_gt = 0.0005;                %Disposal cost percentage for the geared turbofan
DISP_la = 0;                     %Disposal cost percentage for laminar aerodynamics
DISP_aepgds = 0;                 %Disposal cost percentage for the advanced EPGDS
DISP_ap = 0.006;                 %Disposal cost percentage for advanced propellers
DISP_aw = 0.015;                 %Disposal cost percentage for adaptive winglets
DISP_nem = 0.021;                %Disposal cost percentage for new engine materials

%Synergy coefficients for the RDTE phase

f_mw_ea = 0.8;           %Morphing wing + electric actuators
f_mw_la = 0.8;           %Morphing wing + laminar aerodynamics
f_mw_aw = 0.9;           %Morphing wing + adaptive winglets
f_ea_aepgds = 0.9;       %Electric actuators + advanced EPGDS
f_ea_aw = 0.95;          %Electric actuators + adaptive winglets
f_shm_aw = 0.95;         %SHM system + adaptive winglets

%Synergy coefficients for the AEP and Operating phases

f_mw_ea_1 = 0.8;          %Morphing wing + electric actuators per AEP
f_mw_shm_1 = 0.9;         %Morphing wing + SHM system per AEP
f_mw_la_1 = 0.5;          %Morphing wing + laminar aerodynamics per AEP
f_ea_aw_1 = 0.95;         %Electric actuators + adaptive winglets per AEP
f_shm_aw_1 = 0.97;        %SHM system + adaptive winglets per AEP
```

```
f_mw_la_2 = 1.15;         %Morphing wing + laminar aerodynamics per OPERATING

%Coefficients indicating whether the new technology is present or not (1 =
%present; 0 = not present)

newtech_1 = 1;          %The morphing wing IS present
newtech_2 = 0;          %The electric actuators ARE NOT present
newtech_3 = 1;          %The SHM system IS present
newtech_4 = 0;          %The geared turbofan IS NOT present
newtech_5 = 0;          %Laminar aerodynamic IS NOT present
newtech_6 = 1;          %The advanced EPGDS system IS present
newtech_7 = 0;          %The advanced propeller IS NOT present
newtech_8 = 0;          %Adaptive winglets ARE NOT present
newtech_9 = 0;          %New engine materials ARE NOT present

%Arrays needed to compute the cost categories per each possible combination

A = [newtech_1, newtech_2, newtech_3, newtech_4, newtech_5, newtech_6,
newtech_7, newtech_8, newtech_9];
%Array indicating if a new technology is present or not

B = [RDTE_mw, RDTE_ea, RDTE_SHM, RDTE_gt, RDTE_la, RDTE_aepgds, RDTE_ap,
RDTE_aw, RDTE_nem];
%Array indicating the RDTE costs of every new technology

D = [ACQ_mw, -ACQ_ea, ACQ_SHM, ACQ_gt, ACQ_la, ACQ_aepgds, ACQ_ap,
ACQ_aw, ACQ_nem];
%Array indicating the AEP costs of every new technology

E = [-OP_mw, -OP_ea, -OP_SHM, -OP_gt, -OP_la, -OP_aepgds, -OP_ap, -OP_aw, -
OP_nem];
%Array indicating the Operating costs of every new technology

c = 1;          %Flag for RDTE
d = 1;          %Flag fpr AEP
e = 1;          %Flag for OP
DISP_1 = 0;  %Disposal coefficient for morphing wing
DISP_2 = 0;  %Disposal coefficient for electric actuators
```

```
DISP_3 = 0;  %Disposal coefficient for SHM system
DISP_4 = 0;  %Disposal coefficient for geared turbofan
DISP_5 = 0;  %Disposal coefficient for laminar aerodynamics
DISP_6 = 0;  %Disposal coefficient for advanced EPGDS system
DISP_7 = 0;  %Disposal coefficient for advanced propellers
DISP_8 = 0;  %Disposal coefficient for adaptive winglets
DISP_9 = 0;  %Disposal coefficient for new engine materials

%C_RDTE and C_prot calculation

W_ampr = 10^(0.1936 + 0.8645*(log10(MTOW)));
%Aeronautical-Manufacturers-Planning-Report weight [Lb]

C_e = 10^(2.3044 + 0.8858*(log10(Thrust)));                    %Cost of engines [USD]

C_avionics = 0.1*(10^(3.3191 + 0.8043*(log10(MTOW))));         %Cost of avionics [USD]

C_aed = 0.0396*(W_ampr)^0.791*(V_c)^1.526 * (N_RDTE)^0.183 * (F_diff)*(F_CAD)
*(R_e);
%Airframe engineering and design cost [USD]

C_dst = 0.008325*(W_ampr)^0.873 *(V_c)^1.89 *(N_RDTE)^0.346 *(F_diff)*(CEF_2);
%Development, support & testing cost [USD]

C_ea = (C_e * N_e +C_avionics) *(N_RDTE - N_ST);
%Total cost of engines and avionics [USD]

C_man = 28.984*(W_ampr)^0.74 * (V_c)^0.543 *(N_RDTE)^0.524 * (F_diff) * (R_m);
%Manufacturing cost of flight-test aircrafts [USD]

C_mat = 37.632*(F_mat)*(W_ampr)^0.689 * (V_c)^0.624 *(N_RDTE)^0.792 * (CEF_2);
%Cost of materials to manufacture flight test aircrafts [USD]

C_tool = 4.0127*(W_ampr)^0.764 * (V_c)^0.899 * (N_RDTE)^0.178 * (N_r)^0.066 *
(F_diff) * (R_t);
%Tooling cost associated with manufacturing of flight test aircrafts [USD]
```

```
C_qc = 0.13*(C_man);
%Quality control cost associated with manufacturing of flight test aircrafts [USD]

C_fta = C_ea + C_man + C_mat + C_tool + C_qc;
%Total flight test aircrafts cost [USD]

C_fto = 0.001244 * (W_ampr)^1.16 * (V_c)^1.371 * (N_RDTE - N_ST)^1.281 * (CEF_2) *
(F_diff) * (F_obs);
%Flight test operations cost [USD]

C_prot = (1115.4 * 1000)*(W_ampr)^0.35 * (N_prot)^0.99 * (CEF_2/CEF);
%Cost of prototypes [USD]

C_RDTE = (C_aed + C_dst + C_fta + C_fto) / (1 - Finance - Profit - f_tsf);
%Total cost of the RDTE phase of a single aircraft [USD]

C_tsf = C_RDTE * f_tsf;                %Cost of test and simulation facilities [USD]

%C_MAN and C_ACQ calculation

N_program = N_m + N_RDTE;        %Total number of aircrafts built by the manufacturer

C_aed1 = (0.0396*(W_ampr)^0.791 *(V_c)^1.526 *(N_program)^0.183
*(F_diff)*(F_CAD)*(R_e1)) - C_aed;
%Airframe engineering and design cost [USD]

C_ea1 = ((C_e * N_e) + (C_avionics))*(N_m);
%Total cost of engines and avionics [USD]

C_int = F_int*Pax*N_m*(CEF_2/CEF);
%Cost of the airplane interior [USD]

C_man1 = (28.984*(W_ampr)^0.74 *(V_c)^0.543 *(N_program)^0.524 * (F_diff) *(R_m1))
- C_man;
%Manufacturing labor cost [USD]
```

```
C_mat1 = (37.632 * (F_mat) *(W_ampr)^0.689 *(V_c)^0.624 *(N_program)^0.792 *
(CEF_2)) - C_mat;
%Materials cost [USD]

C_tool1 = (4.0127*(W_ampr)^0.764 *(V_c)^0.899 *(N_program)^0.178 *(F_diff)
*(N_r1)^0.066*(R_t1)) - C_tool;
%Tooling cost [USD]

C_qc1 = 0.13*(C_man1);                    %Quality control cost [USD]

C_apc = C_ea1 + C_int + C_man1 + C_mat1 + C_tool1 + C_qc1;
%Airplane program production cost [USD]

C_fto1 = N_m*(3200)*(FTh)*(F_over);
%Production flight test operations cost [USD]

C_MAN = (C_aed1 + C_apc + C_fto1)/(1- Profit - Finance);
%Manufacturing cost[USD]

C_ACQ = f_ACQ*C_MAN;                      %Acquisition cost [USD]

AEP = (C_ACQ + C_RDTE)/N_m;               %Aircraft-Estimated-Price [USD]

%DOC and IOC calculation

U_ann = 1000*(3.4546*(t_bl) + 2.994 - ((12.289*(t_bl)^2 - 5.6626*(t_bl) + 8.964)^0.5));
%Airplane annual utilization [h]

R_bl_ann = U_ann * V_bs;                  %Total annual block miles [nm]

C_crew = ((N_captain*((1+K_j)/V_bs)) * (SAL_captain/AH) + TEF/V_bs) * (f_change) +
((N_officer*((1+K_j)/V_bs)) * (SAL_officer/AH) + TEF/V_bs) * (f_change) +
((N_fass*((1+K_j)/V_bs)) * (SAL_fass/AH) + TEF/V_bs) * (f_change);
%Crew cost [USD/nm]

C_pol = 1.05*(BFW/B_d) * (F_c/F_density);     %Fuel & oil cost [USD/nm]
```

```
C_lab_ap = (1.03 * (MMH_air) * (R_lap))/V_bs;
%Maintenance labor cost for airframe and systems [USD/nm]

C_labeng = (1.03*1.3*(N_e)*(MMH_eng)*(R_leng))/V_bs;
%Maintenance labor cost for engines [USD/nm]

AFP = AEP - N_e*(C_e);                              %Airframe price [USD]

C_mat_apblhr = 30 + 0.79*(CEF_2/CEF)*(10^-5 *AFP);
%Airframe & systems maintenance materials cost per aircraft block hour [USD/h]

C_mat_ap = (1.03*(C_mat_apblhr))/V_bs;
%Cost of maintenance materials for airframe & systems [USD/nm]

C_mat_engblhr = (5.43*10^-5 * (C_e)*(ESPPF) - 0.47)/K_hem;
%Engine maintenance materials cost per aircraft block hour [USD/h]

C_mateng = (1.03*(1.3)*(N_e)*(C_mat_engblhr))/V_bs;
%Cost of maintenance materials for the engines [USD/nm]

C_amb = 1.03*((f_amblab)*((MMH_air)*(R_lap) + N_e*(MMH_eng)*(R_leng)) +
(f_ambmat*((C_mat_apblhr) + N_e*(C_mat_engblhr))))/V_bs;
%Cost of applied maintenance burden [USD/nm]

DOC_maint = C_lab_ap + C_labeng + C_mat_ap + C_mateng + C_amb;
%Total direct maintenance cost [USD/nm]

C_dap = ((AEP * AIRF_d_f) - (N_e * C_e) - C_avionics)/ (AIRF_d * U_ann * V_bs);
%Airplane depreciation cost [USD/nm]

C_deng = (ENG_d_f*(N_e)*(C_e))/(ENG_d*V_bs*U_ann);
%Engine depreciation cost [USD/nm]

C_dav = (AVIONIC_d_f* C_avionics)/(AVIONC_d * V_bs * U_ann);
%Avionic systems depreciation cost [USD/nm]

C_dapsp = ((AIRFs_d_f * AIRFs_f) * (AEP - (N_e * C_e)))/(V_bs * U_ann * AIRFs_d);
%Aircraft spare parts depreciation cost [USD/nm]
```

```
C_dengsp = (ENGs_d_f * ENGs_f * N_e * C_e * ESPPF)/(U_ann * V_bs * ENGs_d);
%Engine spare parts depreciation cost [USD/nm]

DOC_depr = C_dap + C_deng + C_dav + C_dapsp + C_dengsp;
%Total direct operating cost of depreciation [USD/nm]

C_aplf = 0.002 * MTOW;                    %Airplane landing fee per landing [USD/Lb]

C_lf = (C_aplf/(V_bs * t_bl)) * (f_tax);          %Cost of landing fees [USD/nm]

C_nf = (C_apnf/(V_bs * t_bl)) * (f_tax);          %Cost of navigation fees [USD/nm]

DOC = (C_crew + C_pol + DOC_maint + DOC_depr + C_lf + C_nf)/(1 - C_ins -
C_rt*(f_tax) - Fin);
%Direct-Operating-Cost [USD/nm]

IOC = 0.5 * DOC;                          %Indirect-Operating-Cost [USD/nm]

TOT = DOC + IOC;                          %Total-Operating-Cost [USD/nm]

C_OPS = (DOC*R_bl_ann) + (IOC*R_bl_ann);
%Operating costs for the whole fleet of aircrafts, considering its whole operative life
[USD]

LCC = (C_OPS + C_RDTE + AEP*N_m)/(1-f_disp);
%Life-Cycle-Cost for the entire fleet and for its whole operative life [USD]

C_disposal = f_disp*LCC;                  %Disposal cost for a single aircraft [USD]

%Calculation of RDTE for each new technology

RDTE_1 = C_RDTE + RDTE_mw;            %RDTE with morphing wing [USD]
RDTE_2 = C_RDTE + RDTE_ea;            %RDTE with electric actuators [USD]
RDTE_3 = C_RDTE + RDTE_SHM;           %RDTE with SHM system [USD]
RDTE_4 = C_RDTE + RDTE_gt;            %RDTE with geared turbofan [USD]
RDTE_5 = C_RDTE + RDTE_la;            %RDTE with laminar aerodynamics [USD]
RDTE_6 = C_RDTE + RDTE_aepgds;        %RDTE with advanced EPGDS [USD]
RDTE_7 = C_RDTE + RDTE_ap;            %RDTE with advanced propellers [USD]
```

```
RDTE_8 = C_RDTE + RDTE_aw;              %RDTE with adaptive winglets [USD]
RDTE_9 = C_RDTE + RDTE_nem;             %RDTE with new engine materials [USD]

%Calculation of AEP for each new technology

AEP_1 = AEP + (AEP*ACQ_mw);             %AEP with morphing wing [USD]
AEP_2 = AEP - (AEP*ACQ_ea);             %AEP with electric actuators [USD]
AEP_3 = AEP + (AEP*ACQ_SHM);            %AEP with SHM system [USD]
AEP_4 = AEP + (AEP*ACQ_gt);             %AEP with geared turbofan [USD]
AEP_5 = AEP + (AEP*ACQ_la);             %AEP with laminar aerodynamics [USD]
AEP_6 = AEP + (AEP*ACQ_aepgds);         %AEP with advanced EPGDS [USD]
AEP_7 = AEP + (AEP*ACQ_ap);             %AEP with advanced propellers [USD]
AEP_8 = AEP + (AEP*ACQ_aw);             %AEP with adaptive winglets [USD]
AEP_9 = AEP + (AEP*ACQ_nem);            %AEP with new engine materials [USD]

%Calculation of C_OPS for each new technology

C_OPS_1 = (C_OPS - (C_OPS * OP_mw));
%Operating cost with morphing wing [USD]

C_OPS_2 = (C_OPS - (C_OPS * OP_ea));
%Operating cost with electric actuators [USD]

C_OPS_3 = (C_OPS - (C_OPS * OP_SHM));
%Operating cost with SHM system [USD]

C_OPS_4 = (C_OPS - (C_OPS * OP_gt));
%Operating cost with geared turbofan [USD]

C_OPS_5 = (C_OPS - (C_OPS * OP_la));
%Operating cost with laminar aerodynamics [USD]

C_OPS_6 = (C_OPS - (C_OPS * OP_aepgds));
%Operating cost with advanced EPGDS [USD]

C_OPS_7 = (C_OPS - (C_OPS * OP_ap));
%Operating cost with advanced propellers [USD]
```

```
C_OPS_8 = (C_OPS - (C_OPS * OP_aw));
%Operating cost with adaptive winglets [USD]

C_OPS_9 = (C_OPS - (C_OPS * OP_nem));
%Operating cost with new engine materials [USD]

%Calculation of C_DISP for each new technology

C_DISP_1 = C_disposal - (C_disposal * DISP_mw);
%Disposal cost with morphing wing [USD]

C_DISP_2 = C_disposal + (C_disposal * DISP_ea);
%Disposal cost with electric actuators [USD]

C_DISP_3 = C_disposal + (C_disposal * DISP_SHM);
%Disposal cost with SHM system [USD]

C_DISP_4 = C_disposal + (C_disposal * DISP_gt);
%Disposal cost with geared turbofan [USD]

C_DISP_5 = C_disposal + (C_disposal * DISP_la);
%Disposal cost with laminar aerodynamics [USD]

C_DISP_6 = C_disposal + (C_disposal * DISP_aepgds);
%Disposal cost with advanced EPGDS [USD]

C_DISP_7 = C_disposal - (C_disposal * DISP_ap);
%Disposal cost with advanced propellers [USD]

C_DISP_8 = C_disposal + (C_disposal * DISP_aw);
%Disposal cost with adaptive winglets [USD]

C_DISP_9 = C_disposal + (C_disposal * DISP_nem);
%Disposal cost with new engine materials [USD]
```

```
%Calculation of LCC for each new technology

LCC_1 = (C_OPS_1  + RDTE_1 + AEP_1*(N_m) + C_DISP_1);
%LCC with morphing wing [USD]

LCC_2 = (C_OPS_2  + RDTE_2 + AEP_2*(N_m) + C_DISP_2);
%LCC with electric actuators [USD]

LCC_3 = (C_OPS_3  + RDTE_3 + AEP_3*(N_m) + C_DISP_3);
%LCC with SHM system [USD]

LCC_4 = (C_OPS_4  + RDTE_4 + AEP_4*(N_m) + C_DISP_4);
%LCC with geared turbofan [USD]

LCC_5 = (C_OPS_5  + RDTE_5 + AEP_5*(N_m) + C_DISP_5);
%LCC with laminar aerodynamics [USD]

LCC_6 = (C_OPS_6  + RDTE_6 + AEP_6*(N_m) + C_DISP_6);
%LCC with advanced EPGDS [USD]

LCC_7 = (C_OPS_7  + RDTE_7 + AEP_7*(N_m) + C_DISP_7);
%LCC with advanced propellers [USD]

LCC_8 = (C_OPS_8  + RDTE_8 + AEP_8*(N_m) + C_DISP_8);
%LCC with adaptive winglets [USD]

LCC_9 = (C_OPS_9  + RDTE_9 + AEP_9*(N_m) + C_DISP_9);
%LCC with new engine materials [USD]

%Calculation of benefits from synergies

RDTE_mw_ea = C_RDTE + ((RDTE_mw + RDTE_ea)*(f_mw_ea));
%RDTE sinergy between morphing wing and electric actuators

RDTE_mw_la = C_RDTE + ((RDTE_mw + RDTE_la)*(f_mw_la));
%RDTE sinergy between morphing wing and laminar aerodynamics
```

```
RDTE_mw_aw = C_RDTE + ((RDTE_mw + RDTE_aw)*(f_mw_aw));
%RDTE sinergy between morphing wing and adaptive winglets

RDTE_ea_aepgds = C_RDTE + ((RDTE_ea + RDTE_aepgds)*(f_ea_aepgds));
%RDTE sinergy between electric actuators and advanced EPGDS

RDTE_ea_aw = C_RDTE + ((RDTE_ea + RDTE_aw)*(f_ea_aw));
%RDTE sinergy between electric actuators and adaptive winglets

RDTE_shm_aw = C_RDTE + ((RDTE_SHM + RDTE_aw)*(f_shm_aw));
%RDTE sinergy between SHM system and adaptive winglets

AEP_mw_ea = AEP + (((ACQ_mw-ACQ_ea)*(AEP))*(f_mw_ea_1));
%AEP sinergy between morphing wing and electric actuators

AEP_mw_la = AEP + (((ACQ_mw+ACQ_la)*(AEP))*(f_mw_la_1));
%AEP sinergy between morphing wing and laminar aerodynamics

AEP_mw_shm = AEP + (((ACQ_mw+ACQ_SHM)*(AEP))*(f_mw_shm_1));
%AEP sinergy between morphing wing and SHM system

AEP_ea_aw = AEP + (((ACQ_aw-ACQ_ea)*(AEP))*(f_ea_aw_1));
%AEP sinergy between electric actuators and adaptive winglets

AEP_shm_aw = AEP + (((ACQ_SHM+ACQ_aw)*(AEP))*(f_shm_aw_1));
%AEP sinergy between SHM system and adaptive winglets

OP_mw_la = C_OPS + ((OP_mw + OP_la)*(C_OPS)*(f_mw_la_2));
%Operating cost sinergy between morphing wing and laminar aerodynamics

%Calculation of each cost category for each possible combination

if (newtech_1 == 1 && newtech_2 == 1)

c = f_mw_ea;

end
```

```
if (newtech_1 == 1 && newtech_5 == 1)

c = f_mw_la;

end

if (newtech_1 == 1 && newtech_8 == 1)

c = f_mw_aw;

end

if (newtech_2 == 1 && newtech_6 == 1)

c = f_ea_aepgds;

end

if (newtech_2 == 1 && newtech_8 == 1)

c = f_ea_aw;

end

if (newtech_3 == 1 && newtech_8 == 1)

c = f_shm_aw;

end

if (newtech_1 == 1 && newtech_2 == 1)

d = f_mw_ea_1;

end

if (newtech_1 == 1 && newtech_3 == 1)
```

```
d = f_mw_shm_1;

end

if (newtech_1 == 1 && newtech_6 == 1)

d = f_mw_la_1;

end

if (newtech_2 == 1 && newtech_8 == 1)

d = f_ea_aw_1;

end

if (newtech_3 == 1 && newtech_8 == 1)

d = f_shm_aw_1;

end

if (newtech_1 == 1 && newtech_6 == 1)

e = f_mw_la_2;

else

e = 1;

end

if (newtech_1 == 1)

DISP_1 = (f_disp * LCC_1 * DISP_mw)/100;

end
```

```
if (newtech_2 == 1)

DISP_2 = (f_disp * LCC_2 * DISP_ea)/100;

end

if (newtech_3 == 1)

DISP_3 = (f_disp * LCC_3 * DISP_SHM)/100;

end

if (newtech_4 == 1)

DISP_4 = (f_disp * LCC_4 * DISP_gt)/100;

end

if (newtech_5 == 1)

DISP_5 = (f_disp * LCC_5 * DISP_la)/100;

end

if (newtech_6 == 1)

DISP_6 = (f_disp * LCC_6 * DISP_aepgds)/100;

end

if (newtech_7 == 1)

DISP_7 = (f_disp * LCC_7 * DISP_ap)/100;

end

if (newtech_8 == 1)
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```
DISP_8 = (f_disp * LCC_8 * DISP_aw)/100;

end

if (newtech_9 == 1)

DISP_9 = (f_disp * LCC_9 * DISP_nem)/100;

end

RDTE_tot = C_RDTE + ([A]*[B]'*c);
%RDTE cost considering every possible combination

AEP_tot = AEP + (AEP*[A]*[D]'*d);
%AEP cost considering every possible combination

OP_tot = C_OPS + (C_OPS*[A]*[E]'*e);
%Operating cost considering every possible combination

LCC_tot = (RDTE_tot + AEP_tot + OP_tot)/ 1 - (DISP_1 + DISP_2 + DISP_3 + DISP_4 +
DISP_5 + DISP_6 + DISP_7 + DISP_8 + DISP_9);
%LCC cost considering every possible combination

%Impact of every new technology on each cost category of the RDTE phase

part_aed = C_aed/C_RDTE;      %Percentage value of C_aed respect C_RDTE
part_dst = C_dst/C_RDTE;      %Percentage value of C_dst respect C_RDTE
part_ea = C_ea/C_RDTE;        %Percentage value of C_ea respect C_RDTE
part_man = C_man/C_RDTE;      %Percentage value of C_man respect C_RDTE
part_mat = C_mat/C_RDTE;      %Percentage value of C_mat respect C_RDTE
part_tool = C_tool/C_RDTE;    %Percentage value of C_tool respect C_RDTE
part_fto = C_fto/C_RDTE;      %Percentage value of C_fto respect C_RDTE
part_fta = C_fta/C_RDTE;      %Percentage value of C_fta respect C_RDTE
part_qc = C_qc/C_RDTE;        %Percentage value of C_qc respect C_RDTE

C_aed_1 = part_aed * RDTE_1;  %C_aed with morphing wing [USD]
save_1 = C_aed_1 - C_aed;     %Saving of C_aed with morphing wing [USD]
C_dst_1 = part_dst * RDTE_1;  %C_dst with morphing wing [USD]
```

```
save_2 = C_dst_1 - C_dst;             %Saving of C_dst with morphing wing [USD]
C_ea_1 = part_ea * RDTE_1;            %C_ea with morphing wing [USD]
save_3 = C_ea_1 - C_ea;               %Saving of C_ea with morphing wing [USD]
C_man_1 = part_man * RDTE_1;          %C_man with morphing wing [USD]
save_4 = C_man_1 - C_man;             %Saving of C_man with morphing wing [USD]
C_mat_1 = part_mat * RDTE_1;          %C_mat with morphing wing [USD]
save_5 = C_mat_1 - C_mat;             %Saving of C_mat with morphing wing [USD]
C_tool_1 = part_tool * RDTE_1;        %C_tool with morphing wing [USD]
save_6 = C_tool_1 - C_tool;           %Saving of C_tool with morphing wing [USD]
C_fto_1 = part_fto * RDTE_1;          %C_fto with morphing wing [USD]
save_7 = C_fto_1 - C_fto;             %Saving of C_fto with morphing wing [USD]
C_fta_1 = part_fta * RDTE_1;          %C_fta with morphing wing [USD]
save_8 = C_fta_1 - C_fta;             %Saving of C_fta with morphing wing [USD]
C_qc_1 = part_qc * RDTE_1;            %C_qc with morphing wing [USD]
save_9 = C_qc_1 - C_qc;               %Saving of C_qc with morphing wing [USD]
C_tsf_1 = f_tsf * RDTE_1;             %C_tsf with morphing wing [USD]
save_73 = C_tsf_1 - C_tsf;            %Saving of C_tsf with morphing wing [USD]

C_aed_2 = part_aed * RDTE_2;          %C_aed with electric actuators [USD]
save_10 = C_aed_2 - C_aed;            %Saving of C_aed with electric actuators [USD]
C_dst_2 = part_dst * RDTE_2;          %C_dst with electric actuators [USD]
save_11 = C_dst_2 - C_dst;            %Saving of C_dst with electric actuators [USD]
C_ea_2 = part_ea * RDTE_2;            %C_ea with electric actuators [USD]
save_12 = C_ea_2 - C_ea;              %Saving of C_ea with electric actuators [USD]
C_man_2 = part_man * RDTE_2;          %C_man with electric actuators [USD]
save_13 = C_man_2 - C_man;            %Saving of C_man with electric actuators [USD]
C_mat_2 = part_mat * RDTE_2;          %C_mat with electric actuators [USD]
save_14 = C_mat_2 - C_mat;            %Saving of C_mat with electric actuators [USD]
C_tool_2 = part_tool * RDTE_2;        %C_tool with electric actuators [USD]
save_15 = C_tool_2 - C_tool;          %Saving of C_tool with electric actuators [USD]
C_fto_2 = part_fto * RDTE_2;          %C_fto with electric actuators [USD]
save_16 = C_fto_2 - C_fto;            %Saving of C_fto with electric actuators [USD]
C_fta_2 = part_fta * RDTE_2;          %C_fta with electric actuators [USD]
save_17 = C_fta_2 - C_fta;            %Saving of C_fta with electric actuators [USD]
C_qc_2 = part_qc * RDTE_2;            %C_qc with electric actuators [USD]
save_18 = C_qc_2 - C_qc;              %Saving of C_qc with electric actuators [USD]
C_tsf_2 = f_tsf * RDTE_2;             %C_tsf with electric actuators [USD]
save_74 = C_tsf_2 - C_tsf;            %Saving of C_tsf with electric actuators [USD]
```

```
C_aed_3 = part_aed * RDTE_3;         %C_aed with SHM system [USD]
save_19 = C_aed_3 - C_aed;           %Saving of C_aed with SHM system [USD]
C_dst_3 = part_dst * RDTE_3;         %C_dst with SHM system [USD]
save_20 = C_dst_3 - C_dst;           %Saving of C_dst with SHM system [USD]
C_ea_3 = part_ea * RDTE_3;           %C_ea with SHM system [USD]
save_21 = C_ea_3 - C_ea;             %Saving of C_ea with SHM system [USD]
C_man_3 = part_man * RDTE_3;         %C_man with SHM system [USD]
save_22 = C_man_3 - C_man;           %Saving of C_man with SHM system [USD]
C_mat_3 = part_mat * RDTE_3;         %C_mat with SHM system [USD]
save_23 = C_mat_3 - C_mat;           %Saving of C_mat with SHM system [USD]
C_tool_3 = part_tool * RDTE_3;       %C_tool with SHM system [USD]
save_24 = C_tool_3 - C_tool;         %Saving of C_tool with SHM system [USD]
C_fto_3 = part_fto * RDTE_3;         %C_fto with SHM system [USD]
save_25 = C_fto_3 - C_fto;           %Saving of C_fto with SHM system [USD]
C_fta_3 = part_fta * RDTE_3;         %C_fta with SHM system [USD]
save_26 = C_fta_3 - C_fta;           %Saving of C_fta with SHM system [USD]
C_qc_3 = part_qc * RDTE_3;           %C_qc with SHM system [USD]
save_27 = C_qc_3 - C_qc;             %Saving of C_qc with SHM system [USD]
C_tsf_3 = f_tsf * RDTE_3;            %C_tsf with SHM system [USD]
save_75 = C_tsf_3 - C_tsf;           %Saving of C_tsf with SHM system [USD]

C_aed_4 = part_aed * RDTE_4;         %C_aed with geared turbofan [USD]
save_28 = C_aed_4 - C_aed;           %Saving of C_aed with geared turbofan [USD]
C_dst_4 = part_dst * RDTE_4;         %C_dst with geared turbofan [USD]
save_29 = C_dst_4 - C_dst;           %Saving of C_dst with geared turbofan [USD]
C_ea_4 = part_ea * RDTE_4;           %C_ea with geared turbofan [USD]
save_30 = C_ea_4 - C_ea;             %Saving of C_ea with geared turbofan [USD]
C_man_4 = part_man * RDTE_4;         %C_man with geared turbofan [USD]
save_31 = C_man_4 - C_man;           %Saving of C_man with geared turbofan [USD]
C_mat_4 = part_mat * RDTE_4;         %C_mat with geared turbofan [USD]
save_32 = C_mat_4 - C_mat;           %Saving of C_mat with geared turbofan [USD]
C_tool_4 = part_tool * RDTE_4;       %C_tool with geared turbofan [USD]
save_33 = C_tool_4 - C_tool;         %Saving of C_tool with geared turbofan [USD]
C_fto_4 = part_fto * RDTE_4;         %C_fto with geared turbofan [USD]
save_34 = C_fto_4 - C_fto;           %Saving of C_fto with geared turbofan [USD]
C_fta_4 = part_fta * RDTE_4;         %C_fta with geared turbofan [USD]
save_35 = C_fta_4 - C_fta;           %Saving of C_fta with geared turbofan [USD]
C_qc_4 = part_qc * RDTE_4;           %C_qc with geared turbofan [USD]
```

```
save_36 = C_qc_4 - C_qc;             %Saving of C_qc with geared turbofan [USD]
C_tsf_4 = f_tsf * RDTE_4;            %C_tsf with geared turbofan [USD]
save_76 = C_tsf_4 - C_tsf;           %Saving of C_tsf with geared turbofan [USD]

C_aed_5 = part_aed * RDTE_5;     %C_aed with laminar aerodynamics [USD]
save_37 = C_aed_5 - C_aed;       %Saving of C_aed with laminar aerodynamics [USD]
C_dst_5 = part_dst * RDTE_5;     %C_dst with laminar aerodynamics [USD]
save_38 = C_dst_5 - C_dst;       %Saving of C_dst with laminar aerodynamics [USD]
C_ea_5 = part_ea * RDTE_5;       %C_ea with laminar aerodynamics [USD]
save_39 = C_ea_5 - C_ea;         %Saving of C_ea with laminar aerodynamics [USD]
C_man_5 = part_man * RDTE_5;     %C_man with laminar aerodynamics [USD]
save_40 = C_man_5 - C_man;       %Saving of C_man with laminar aerodynamics [USD]
C_mat_5 = part_mat * RDTE_5;     %C_mat with laminar aerodynamics [USD]
save_41 = C_mat_5 - C_mat;       %Saving of C_mat with laminar aerodynamics [USD]
C_tool_5 = part_tool * RDTE_5;   %C_tool with laminar aerodynamics [USD]
save_42 = C_tool_5 - C_tool;     %Saving of C_tool with laminar aerodynamics [USD]
C_fto_5 = part_fto * RDTE_5;     %C_fto with laminar aerodynamics [USD]
save_43 = C_fto_5 - C_fto;       %Saving of C_fto with laminar aerodynamics [USD]
C_fta_5 = part_fta * RDTE_5;     %C_fta with laminar aerodynamics [USD]
save_44 = C_fta_5 - C_fta;       %Saving of C_fta with laminar aerodynamics [USD]
C_qc_5 = part_qc * RDTE_5;       %C_qc with laminar aerodynamics [USD]
save_45 = C_qc_5 - C_qc;         %Saving of C_qc with laminar aerodynamics [USD]
C_tsf_5 = f_tsf * RDTE_5;        %C_tsf with laminar aerodynamics [USD]
save_77 = C_tsf_5 - C_tsf;       %Saving of C_tsf with laminar aerodynamics [USD]

C_aed_6 = part_aed * RDTE_6;         %C_aed with Advanced-EPGDS [USD]
save_46 = C_aed_6 - C_aed;           %Saving of C_aed with Advanced-EPGDS [USD]
C_dst_6 = part_dst * RDTE_6;         %C_dst with Advanced-EPGDS [USD]
save_47 = C_dst_6 - C_dst;           %Saving of C_dst with Advanced-EPGDS [USD]
C_ea_6 = part_ea * RDTE_6;           %C_ea with Advanced-EPGDS [USD]
save_48 = C_ea_6 - C_ea;             %Saving of C_ea with Advanced-EPGDS [USD]
C_man_6 = part_man * RDTE_6;         %C_man with Advanced-EPGDS [USD]
save_49 = C_man_6 - C_man;           %Saving of C_man with Advanced-EPGDS [USD]
C_mat_6 = part_mat * RDTE_6;         %C_mat with Advanced-EPGDS [USD]
save_50 = C_mat_6 - C_mat;           %Saving of C_mat with Advanced-EPGDS [USD]
C_tool_6 = part_tool * RDTE_6;       %C_tool with Advanced-EPGDS [USD]
save_51 = C_tool_6 - C_tool;         %Saving of C_tool with Advanced-EPGDS [USD]
C_fto_6 = part_fto * RDTE_6;         %C_fto with Advanced-EPGDS [USD]
```

```
save_52 = C_fto_6 - C_fto;             %Saving of C_fto with Advanced-EPGDS [USD]
C_fta_6 = part_fta * RDTE_6;           %C_fta with Advanced-EPGDS [USD]
save_53 = C_fta_6 - C_fta;             %Saving of C_fta with Advanced-EPGDS [USD]
C_qc_6 = part_qc * RDTE_6;             %C_qc with Advanced-EPGDS [USD]
save_54 = C_qc_6 - C_qc;               %Saving of C_qc with Advanced-EPGD [USD]
C_tsf_6 = f_tsf * RDTE_6;              %C_tsf with Advanced-EPGS [USD]
save_78 = C_tsf_6 - C_tsf;             %Saving of C_tsf with Advanced-EPGD [USD]

C_aed_8 = part_aed * RDTE_8;           %C_aed with adaptive winglets [USD]
save_55 = C_aed_8 - C_aed;             %Saving of C_aed with adaptive winglets [USD]
C_dst_8 = part_dst * RDTE_8;           %C_dst with adaptive winglets [USD]
save_56 = C_dst_8 - C_dst;             %Saving of C_dst with adaptive winglets [USD]
C_ea_8 = part_ea * RDTE_8;             %C_ea with adaptive winglets [USD]
save_57 = C_ea_8 - C_ea;               %Saving of C_ea with adaptive winglets [USD]
C_man_8 = part_man * RDTE_8;           %C_man with adaptive winglets [USD]
save_58 = C_man_8 - C_man;             %Saving of C_man with adaptive winglets [USD]
C_mat_8 = part_mat * RDTE_8;           %C_mat with adaptive winglets [USD]
save_59 = C_mat_8 - C_mat;             %Saving of C_mat with adaptive winglets [USD]
C_tool_8 = part_tool * RDTE_8;         %C_tool with adaptive winglets [USD]
save_60 = C_tool_8 - C_tool;           %Saving of C_tool with adaptive winglets [USD]
C_fto_8 = part_fto * RDTE_8;           %C_fto with adaptive winglets [USD]
save_61 = C_fto_8 - C_fto;             %Saving of C_fto with adaptive winglets [USD]
C_fta_8 = part_fta * RDTE_8;           %C_fta with adaptive winglets [USD]
save_62 = C_fta_8 - C_fta;             %Saving of C_fta with adaptive winglets [USD]
C_qc_8 = part_qc * RDTE_8;             %C_qc with adaptive winglets [USD]
save_63 = C_qc_8 - C_qc;               %Saving of C_qc with adaptive winglets [USD]
C_tsf_8 = f_tsf * RDTE_8;              %C_tsf with adaptive winglets [USD]
save_79 = C_tsf_8 - C_tsf;             %Saving of C_tsf with adaptive winglets [USD]

C_aed_9 = part_aed * RDTE_9;       %C_aed with new engine materials [USD]
save_64 = C_aed_9 - C_aed;         %Saving of C_aed with new engine materials [USD]
C_dst_9 = part_dst * RDTE_9;       %C_dst with new engine materials [USD]
save_65 = C_dst_9 - C_dst;         %Saving of C_dst with new engine materials [USD]
C_ea_9 = part_ea * RDTE_9;         %C_ea with new engine materials [USD]
save_66 = C_ea_9 - C_ea;           %Saving of C_ea with new engine materials [USD]
C_man_9 = part_man * RDTE_9;       %C_man with new engine materials [USD]
save_67 = C_man_9 - C_man;         %Saving of C_man with new engine materials [USD]
C_mat_9 = part_mat * RDTE_9;       %C_mat with new engine materials [USD]
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save_68 = C_mat_9 - C_mat;          %Saving of C_mat with new engine materials [USD]
C_tool_9 = part_tool * RDTE_9;      %C_tool with new engine materials [USD]
save_69 = C_tool_9 - C_tool;        %Saving of C_tool with new engine materials [USD]
C_fto_9 = part_fto * RDTE_9;        %C_fto with new engine materials [USD]
save_70 = C_fto_9 - C_fto;          %Saving of C_fto with new engine materials [USD]
C_fta_9 = part_fta * RDTE_9;        %C_fta with new engine materials [USD]
save_71 = C_fta_9 - C_fta;          %Saving of C_fta with new engine materials [USD]
C_qc_9 = part_qc * RDTE_9;          %C_qc with new engine materials [USD]
save_72 = C_qc_9 - C_qc;            %Saving of C_qc with new engine materials [USD]
C_tsf_9 = f_tsf * RDTE_9;           %C_tsf with new engine materials [USD]
save_80 = C_tsf_9 - C_tsf;          %Saving of C_tsf with new engine materials [USD]

%Impact of every new technology on each cost category on C_ACQ

part1_aed = 2*(C_aed1/C_ACQ);       %Percentage value of C_aed1 respect C_ACQ
part1_ea = 2*(C_ea1/C_ACQ);         %Percentage value of C_ea1 respect C_ACQ
part1_int = 2*(C_int/C_ACQ);        %Percentage value of C_int respect C_ACQ
part1_man = 2*(C_man1/C_ACQ);       %Percentage value of C_man1 respect C_ACQ
part1_mat = 2*(C_mat1/C_ACQ);       %Percentage value of C_mat1 respect C_ACQ
part1_tool = 2*(C_tool1/C_ACQ);     %Percentage value of C_tool1 respect C_ACQ
part1_qc = 2*(C_qc1/C_ACQ);         %Percentage value of C_qc1 respect C_ACQ
part1_fto = 2*(C_fto1/C_ACQ);       %Percentage value of C_fto1 respect C_ACQ

C_aed_mw = (1 + ACQ_mw)*(C_aed1);   %C_aed1 with morphing wing [USD]
diff1 = C_aed_mw - C_aed1;          %Saving of C_aed1 with morphing wing [USD]
C_ea_mw = (1 + ACQ_mw)*(C_ea1);     %C_ea1 with morphing wing [USD]
diff2 = C_ea_mw - C_ea1;            %Saving of C_ea1 with morphing wing [USD]
C_int_mw = (1 + ACQ_mw)*(C_int);    %C_int with morphing wing [USD]
diff3 = C_int_mw - C_int;           %Saving of C_int with morphing wing [USD]
C_man_mw = (1 + ACQ_mw)*(C_man1);   %C_man1 with morphing wing [USD]
diff4 = C_man_mw - C_man1;          %Saving of C_man1 with morphing wing [USD]
C_mat_mw = (1 + ACQ_mw)*(C_mat1);   %C_mat1 with morphing wing [USD]
diff5 = C_mat_mw - C_mat1;          %Saving of C_mat1 with morphing wing [USD]
C_tool_mw = (1 + ACQ_mw)*(C_tool1); %C_tool1 with morphing wing [USD]
diff6 = C_tool_mw - C_tool1;        %Saving of C_tool1 with morphing wing [USD]
C_qc_mw = (1 + ACQ_mw)*(C_qc1);     %C_qc1 with morphing wing [USD]
diff7 = C_qc_mw - C_qc1;            %Saving of C_qc1 with morphing wing [USD]
C_fto_mw = (1 + ACQ_mw)*(C_fto1);   %C_fto1 with morphing wing [USD]
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diff8 = C_fto_mw - C_fto1;                %Saving of C_fto1 with morphing wing [USD]

C_aed_ea = (1 - ACQ_ea)*(C_aed1);     %C_aed1 with electric actuators [USD]
diff9 = C_aed_ea - C_aed1;               %Saving of C_aed1 with electric actuators [USD]
C_ea_ea = (1 - ACQ_ea)*(C_ea1);        %C_ea1 with electric actuators [USD]
diff10 = C_ea_ea - C_ea1;                 %Saving of C_ea1 with electric actuators [USD]
C_int_ea = (1 - ACQ_ea)*(C_int);          %C_int with electric actuators [USD]
diff11 = C_int_ea - C_int;                 %Saving of C_int with electric actuators [USD]
C_man_ea = (1 - ACQ_ea)*(C_man1);   %C_man1 with electric actuators [USD]
diff12 = C_man_ea - C_man1;            %Saving of C_man1 with electric actuators [USD]
C_mat_ea = (1 - ACQ_ea)*(C_mat1);     %C_mat1 with electric actuators [USD]
diff13 = C_mat_ea - C_mat1;              %Saving of C_mat1 with electric actuators [USD]
C_tool_ea = (1 - ACQ_ea)*(C_tool1);      %C_tool1 with electric actuators [USD]
diff14 = C_tool_ea - C_tool1;              %Saving of C_tool1 with electric actuators [USD]
C_qc_ea = (1 - ACQ_ea)*(C_qc1);          %C_qc1 with electric actuators [USD]
diff15 = C_qc_ea - C_qc1;                  %Saving of C_qc1 with electric actuators [USD]
C_fto_ea = (1 - ACQ_ea)*(C_fto1);          %C_fto1 with electric actuators [USD]
diff16 = C_fto_ea - C_fto1;                %Saving of C_fto1 with electric actuators [USD]

C_aed_SHM = (1 + ACQ_SHM)*(C_aed1);   %C_aed1 with SHM system [USD]
diff17 = C_aed_SHM - C_aed1;              %Saving of C_aed1 with SHM system [USD]
C_ea_SHM = (1 + ACQ_SHM)*(C_ea1);       %C_ea1 with SHM system [USD]
diff18 = C_ea_SHM - C_ea1;                   %Saving of C_ea1 with SHM system [USD]
C_int_SHM = (1 + ACQ_SHM)*(C_int);         %C_int with SHM system [USD]
diff19 = C_int_SHM - C_int;                     %Saving of C_int with SHM system [USD]
C_man_SHM = (1 + ACQ_SHM)*(C_man1);  %C_man1 with SHM system [USD]
diff20 = C_man_SHM - C_man1;             %Saving of C_man1 with SHM system [USD]
C_mat_SHM = (1 + ACQ_SHM)*(C_mat1);    %C_mat1 with SHM system [USD]
diff21 = C_mat_SHM - C_mat1;               %Saving of C_mat1 with SHM system [USD]
C_tool_SHM = (1 + ACQ_SHM)*(C_tool1);    %C_tool1 with SHM system [USD]
diff22 = C_tool_SHM - C_tool1;              %Saving of C_tool1 with SHM system [USD]
C_qc_SHM = (1 + ACQ_SHM)*(C_qc1);        %C_qc1 with SHM system [USD]
diff23 = C_qc_SHM - C_qc1;                   %Saving of C_qc1 with SHM system [USD]
C_fto_SHM = (1 + ACQ_SHM)*(C_fto1);        %C_fto1 with SHM system [USD]
diff24 = C_fto_SHM - C_fto1;                 %Saving of C_fto1 with SHM system [USD]

C_aed_gt = (1 + ACQ_gt)*(C_aed1);        %C_aed1 with geared turbofan [USD]
diff25 = C_aed_gt - C_aed1;                %Saving of C_aed1 with geared turbofan [USD]
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```
C_ea_gt = (1 + ACQ_gt)*(C_ea1);          %C_ea1 with geared turbofan [USD]
diff26 = C_ea_gt - C_ea1;                %Saving of C_ea1 with geared turbofan [USD]
C_int_gt = (1 + ACQ_gt)*(C_int);         %C_int with geared turbofan [USD]
diff27 = C_int_gt - C_int;               %Saving of C_int with geared turbofan [USD]
C_man_gt = (1 + ACQ_gt)*(C_man1);        %C_man1 with geared turbofan [USD]
diff28 = C_man_gt - C_man1;              %Saving of C_man1 with geared turbofan [USD]
C_mat_gt = (1 + ACQ_gt)*(C_mat1);        %C_mat1 with geared turbofan [USD]
diff29 = C_mat_gt - C_mat1;              %Saving of C_mat1 with geared turbofan [USD]
C_tool_gt = (1 + ACQ_gt)*(C_tool1);      %C_tool1 with geared turbofan [USD]
diff30 = C_tool_gt - C_tool1;            %Saving of C_tool1 with geared turbofan [USD]
C_qc_gt = (1 + ACQ_gt)*(C_qc1);          %C_qc1 with geared turbofan [USD]
diff31 = C_qc_gt - C_qc1;                %Saving of C_qc1 with geared turbofan [USD]
C_fto_gt = (1 + ACQ_gt)*(C_fto1);        %C_fto1 with geared turbofan [USD]
diff32 = C_fto_gt - C_fto1;              %Saving of C_fto1 with geared turbofan [USD]

C_aed_la = (1 + ACQ_la)*(C_aed1);        %C_aed1 with laminar aerodynamics [USD]
diff33 = C_aed_la - C_aed1;              %Saving of C_aed1 with laminar aerodynamics [USD]
C_ea_la = (1 + ACQ_la)*(C_ea1);          %C_ea1 with laminar aerodynamics [USD]
diff34 = C_ea_la - C_ea1;                %Saving of C_ea1 with laminar aerodynamics [USD]
C_int_la = (1 + ACQ_la)*(C_int);         %C_int with laminar aerodynamics [USD]
diff35 = C_int_la - C_int;               %Saving of C_int with laminar aerodynamics [USD]
C_man_la = (1 + ACQ_la)*(C_man1);        %C_man1 with laminar aerodynamics [USD]
diff36 = C_man_la - C_man1;              %Saving of C_man1 with laminar aerodynamics [USD]
C_mat_la = (1 + ACQ_la)*(C_mat1);        %C_mat1 with laminar aerodynamics [USD]
diff37 = C_mat_la - C_mat1;              %Saving of C_mat1 with laminar aerodynamics [USD]
C_tool_la = (1 + ACQ_la)*(C_tool1);      %C_tool1 with laminar aerodynamics [USD]
diff38 = C_tool_la - C_tool1;            %Saving of C_tool1 with laminar aerodynamics [USD]
C_qc_la = (1 + ACQ_la)*(C_qc1);          %C_qc1 with laminar aerodynamics [USD]
diff39 = C_qc_la - C_qc1;                %Saving of C_qc1 with laminar aerodynamics [USD]
C_fto_la = (1 + ACQ_la)*(C_fto1);        %C_fto1 with laminar aerodynamics [USD]
diff40 = C_fto_la - C_fto1;              %Saving of C_fto1 with laminar aerodynamics [USD]

C_aed_aw = (1 + ACQ_aw)*(C_aed1);        %C_aed1 with adaptive winglets [USD]
diff41 = C_aed_aw - C_aed1;              %Saving of C_aed1 with adaptive winglets [USD]
C_ea_aw = (1 + ACQ_aw)*(C_ea1);          %C_ea1 with adaptive winglets [USD]
diff42 = C_ea_aw - C_ea1;                %Saving of C_ea1 with adaptive winglets [USD]
C_int_aw = (1 + ACQ_aw)*(C_int);         %C_int with adaptive winglets [USD]
diff43 = C_int_aw - C_int;               %Saving of C_int with adaptive winglets [USD]
```

```
C_man_aw = (1 + ACQ_aw)*(C_man1);        %C_man1 with adaptive winglets [USD]
diff44 = C_man_aw - C_man1;          %Saving of C_man1 with adaptive winglets [USD]
C_mat_aw = (1 + ACQ_aw)*(C_mat1);        %C_mat1 with adaptive winglets [USD]
diff45 = C_mat_aw - C_mat1;          %Saving of C_mat1 with adaptive winglets [USD]
C_tool_aw = (1 + ACQ_aw)*(C_tool1);      %C_tool1 with adaptive winglets [USD]
diff46 = C_tool_aw - C_tool1;        %Saving of C_tool1 with adaptive winglets [USD]
C_qc_aw = (1 + ACQ_aw)*(C_qc1);          %C_qc1 with adaptive winglets [USD]
diff47 = C_qc_aw - C_qc1;            %Saving of C_qc1 with adaptive winglets [USD]
C_fto_aw = (1 + ACQ_aw)*(C_fto1);        %C_fto1 with adaptive winglets [USD]
diff48 = C_fto_aw - C_fto1;          %Saving of C_fto1 with adaptive winglets [USD]

C_aed_nem = (1 + ACQ_nem)*(C_aed1);     %C_aed1 with new engine materials [USD]
diff49 = C_aed_nem - C_aed1;     %Saving of C_aed1 with new engine materials [USD]
C_ea_nem = (1 + ACQ_nem)*(C_ea1);       %C_ea1 with new engine materials [USD]
diff50 = C_ea_nem - C_ea1;       %Saving of C_ea1 with new engine materials [USD]
C_int_nem = (1 + ACQ_nem)*(C_int);      %C_int with new engine materials [USD]
diff51 = C_int_nem - C_int;      %Saving of C_int with new engine materials [USD]
C_man_nem = (1 + ACQ_nem)*(C_man1);   %C_man1 with new engine materials [USD]
diff52 = C_man_nem - C_man1;   %Saving of C_man1 with new engine materials [USD]
C_mat_nem = (1 + ACQ_nem)*(C_mat1);     %C_mat1 with new engine materials [USD]
diff53 = C_mat_nem - C_mat1;     %Saving of C_mat1 with new engine materials [USD]
C_tool_nem = (1 + ACQ_nem)*(C_tool1);     %C_tool1 with new engine materials [USD]
diff54 = C_tool_nem - C_tool1;     %Saving of C_tool1 with new engine materials [USD]
C_qc_nem = (1 + ACQ_nem)*(C_qc1);       %C_qc1 with new engine materials [USD]
diff55 = C_qc_nem - C_qc1;       %Saving of C_qc1 with new engine materials [USD]
C_fto_nem = (1 + ACQ_nem)*(C_fto1);     %C_fto1 with new engine materials [USD]
diff56 = C_fto_nem - C_fto1;     %Saving of C_fto1 with new engine materials [USD]

%Impact of every new technology on each cost category on DOC, IOC and TOT

per_flying = (C_crew + C_pol + (C_ins*(DOC)))/TOT;
%percentage value of DOC_flying respect TOT

per_maint = DOC_maint / TOT;
%percentage value of DOC_maint respect TOT

per_depr = DOC_depr / TOT;
%percentage value of DOC_depr respect TOT
```

```
per_tax = (C_lf + C_nf + (C_rt*f_tax)) / TOT;
%percentage value of DOC_texes respect TOT

per_DOC = DOC/TOT;
%percentage value of DOC respect TOT

per_IOC = IOC/TOT;
%percentage value of IOC respect TOT

C_flying_mw = (C_OPS_1/(hours_A320*365*V_bs)) * (per_flying);
%C_flying with morphing wing [USD/nm]

saving1 = C_flying_mw - (C_crew + C_pol + (C_ins*(DOC)));
%Saving of C_flying with morphing wing [USD/nm]

C_maint_mw = (C_OPS_1/(hours_A320*365*V_bs)) * (per_maint);
%C_maint with morphing wing [USD/nm]

saving2 = C_maint_mw - DOC_maint;
%Saving of C_maint with morphing wing [USD/nm]

C_depr_mw = (C_OPS_1/(hours_A320*365*V_bs)) * (per_depr);
%C_depr with morphing wing [USD/nm]

saving3 = C_depr_mw - DOC_depr;
%Saving of C_depr with morphing wing [USD/nm]

C_tax_mw = (C_OPS_1/(hours_A320*365*V_bs)) * (per_tax);
%C_tax with morphing wing [USD/nm]

saving4 = C_tax_mw - (C_lf + C_nf + (C_rt*f_tax));
%Saving of C_tax with morphing wing [USD/nm]

DOC_mw = (C_OPS_1/(hours_A320*365*V_bs)) * (per_DOC);
%DOC with morphing wing [USD/nm]

saving5 = DOC_mw - DOC;
%Saving of DOC with morphing wing [USD/nm]
```

```
IOC_mw = (C_OPS_1/(hours_A320*365*V_bs)) * (per_IOC);
%IOC with morphing wing [USD/nm]

saving6 = IOC_mw - IOC;
%Saving of IOC with morphing wing [USD/nm]

TOT_mw = DOC_mw + IOC_mw;
%TOC with morphing wing [USD/nm]

saving7= TOT_mw - TOT;
%Saving of TOC with morphing wing [USD/nm]

C_flying_ea = (C_OPS_2/(hours_A320*365*V_bs)) * (per_flying);
%C_flying with electric actuators [USD/nm]

saving8 = C_flying_ea - (C_crew + C_pol + (C_ins*(DOC)));
%Saving of C_flying with electric actuators [USD/nm]

C_maint_ea = (C_OPS_2/(hours_A320*365*V_bs)) * (per_maint);
%C_maint with electric actuators [USD/nm]

saving9 = C_maint_ea - DOC_maint;
%Saving of C_maint with electric actuators [USD/nm]

C_depr_ea = (C_OPS_2/(hours_A320*365*V_bs)) * (per_depr);
%C_depr with electric actuators [USD/nm]

saving10 = C_depr_ea - DOC_depr;
%Saving of C_depr with electric actuators [USD/nm]

C_tax_ea = (C_OPS_2/(hours_A320*365*V_bs)) * (per_tax);
%C_tax with electric actuators [USD/nm]

saving11 = C_tax_ea - (C_lf + C_nf + (C_rt*f_tax));
%Saving of C_tax with electric actuators [USD/nm]

DOC_ea = (C_OPS_2/(hours_A320*365*V_bs)) * (per_DOC);
%DOC with electric actuators [USD/nm]
```

```
saving12 = DOC_ea - DOC;
%Saving of DOC with electric actuators [USD/nm]

IOC_ea = (C_OPS_2/(hours_A320*365*V_bs)) * (per_IOC);
%IOC with electric actuators [USD/nm]

saving13 = IOC_ea - IOC;
%Saving of IOC with electric actuators [USD/nm]

TOT_ea = DOC_ea + IOC_ea;
%TOC with electric actuators [USD/nm]

saving14= TOT_ea - TOT;
%Saving of TOC with electric actuators [USD/nm]

C_flying_SHM = (C_OPS_3/(hours_A320*365*V_bs)) * (per_flying);
%C_flying with SHM system [USD/nm]

saving15 = C_flying_SHM - (C_crew + C_pol + (C_ins*(DOC)));
%Saving of C_flying with SHM systems [USD/nm]

C_maint_SHM = (C_OPS_3/(hours_A320*365*V_bs)) * (per_maint);
%C_maint with SHM system [USD/nm]

saving16 = C_maint_SHM - DOC_maint;
%Saving of C_maint with SHM system [USD/nm]

C_depr_SHM = (C_OPS_3/(hours_A320*365*V_bs)) * (per_depr);
%C_depr with SHM systems [USD/nm]

saving17 = C_depr_SHM - DOC_depr;
%Saving of C_depr with SHM system [USD/nm]

C_tax_SHM = (C_OPS_3/(hours_A320*365*V_bs)) * (per_tax);
%C_tax with SHM systems [USD/nm]

saving18 = C_tax_SHM - (C_lf + C_nf + (C_rt*f_tax));
%Saving of C_tax with SHM system [USD/nm]
```

```
DOC_SHM = (C_OPS_3/(hours_A320*365*V_bs)) * (per_DOC);
%DOC with SHM system [USD/nm]

saving19 = DOC_SHM - DOC;
%Saving of DOC with SHM system [USD/nm]

IOC_SHM = (C_OPS_3/(hours_A320*365*V_bs)) * (per_IOC);
%IOC with SHM system [USD/nm]

saving20 = IOC_SHM - IOC;
%Saving of IOC with SHM system [USD/nm]

TOT_SHM = DOC_SHM + IOC_SHM;
%TOC with SHM systems [USD/nm]

saving21= TOT_SHM - TOT;
%Saving of TOC with SHM system [USD/nm]

C_flying_gt = (C_OPS_4/(hours_A320*365*V_bs)) * (per_flying);
%C_flying with geared turbofan [USD/nm]

saving36 = C_flying_gt - (C_crew + C_pol + (C_ins*(DOC)));
%Saving of C_flying with geared turbofan [USD/nm]

C_maint_gt = (C_OPS_4/(hours_A320*365*V_bs)) * (per_maint);
%C_maint with geared turbofan [USD/nm]

saving37 = C_maint_gt - DOC_maint;
%Saving of C_maint with geared turbofan [USD/nm]

C_depr_gt = (C_OPS_4/(hours_A320*365*V_bs)) * (per_depr);
%C_depr with geared turbofan [USD/nm]

saving38 = C_depr_gt - DOC_depr;
%Saving of C_depr with geared turbofan [USD/nm]

C_tax_gt = (C_OPS_4/(hours_A320*365*V_bs)) * (per_tax);
%C_tax with geared turbofan [USD/nm]
```

```
saving39 = C_tax_gt - (C_lf + C_nf + (C_rt*f_tax));
%Saving of C_tax with geared turbofan [USD/nm]

DOC_gt = (C_OPS_4/(hours_A320*365*V_bs)) * (per_DOC);
%DOC with geared turbofan [USD/nm]

saving40 = DOC_gt - DOC;
%Saving of DOC with geared turbofan [USD/nm]

IOC_gt = (C_OPS_4/(hours_A320*365*V_bs)) * (per_IOC);
%IOC with geared turbofan [USD/nm]

saving41 = IOC_gt - IOC;
%Saving of IOC with geared turbofan [USD/nm]

TOT_gt = DOC_gt + IOC_gt;
%TOC with geared turbofan [USD/nm]

saving42= TOT_gt - TOT;
%Saving of TOC with geared turbofan [USD/nm]

C_flying_la = (C_OPS_5/(hours_A320*365*V_bs)) * (per_flying);
%C_flying with laminar aerodynamics [USD/nm]

saving22 = C_flying_la - (C_crew + C_pol + (C_ins*(DOC)));
%Saving of C_flying with laminar aerodynamics [USD/nm]

C_maint_la = (C_OPS_5/(hours_A320*365*V_bs)) * (per_maint);
%C_maint with laminar aerodynamics [USD/nm]

saving23 = C_maint_la - DOC_maint;
%Saving of C_maint with laminar aerodynamics [USD/nm]

C_depr_la = (C_OPS_5/(hours_A320*365*V_bs)) * (per_depr);
%C_depr with laminar aerodynamics [USD/nm]

saving24 = C_depr_la - DOC_depr;
%Saving of C_depr with laminar aerodynamics [USD/nm]
```

```
C_tax_la = (C_OPS_5/(hours_A320*365*V_bs)) * (per_tax);
%C_tax with laminar aerodynamics [USD/nm]

saving25 = C_tax_la - (C_lf + C_nf + (C_rt*f_tax));
%Saving of C_tax with laminar aerodynamics [USD/nm]

DOC_la = (C_OPS_5/(hours_A320*365*V_bs)) * (per_DOC);
%DOC with laminar aerodynamics [USD/nm]

saving26 = DOC_la - DOC;
%Saving of DOC with laminar aerodynamics [USD/nm]

IOC_la = (C_OPS_5/(hours_A320*365*V_bs)) * (per_IOC);
%IOC with laminar aerodynamics [USD/nm]

saving27 = IOC_la - IOC;
%Saving of IOC with laminar aerodynamics [USD/nm]

TOT_la = DOC_la + IOC_la;
%TOC with laminar aerodynamics [USD/nm]

saving28= TOT_la - TOT;
%Saving of TOC with laminar aerodynamics [USD/nm]

C_flying_aepgds = (C_OPS_6/(hours_A320*365*V_bs)) * (per_flying);
%C_flying with Advanced-EPGDS [USD/nm]

saving29 = C_flying_aepgds - (C_crew + C_pol + (C_ins*(DOC)));
%Saving of C_flying with Advanced-EPGDS [USD/nm]

C_maint_aepgds = (C_OPS_6/(hours_A320*365*V_bs)) * (per_maint);
%C_maint with Advanced-EPGDS [USD/nm]

saving30 = C_maint_aepgds - DOC_maint;
%Saving of C_maint with Advanced-EPGDS [USD/nm]

C_depr_aepgds = (C_OPS_6/(hours_A320*365*V_bs)) * (per_depr);
%C_depr with Advanced-EPGDS [USD/nm]
```

```
saving31 = C_depr_aepgds - DOC_depr;
%Saving of C_depr with Advanced-EPGDS [USD/nm]

C_tax_aepgds = (C_OPS_6/(hours_A320*365*V_bs)) * (per_tax);
%C_tax with Advanced-EPGDS [USD/nm]

saving32 = C_tax_aepgds - (C_lf + C_nf + (C_rt*f_tax));
%Saving of C_tax with Advanced-EPGDS [USD/nm]

DOC_aepgds = (C_OPS_6/(hours_A320*365*V_bs)) * (per_DOC);
%DOC with Advanced-EPGDS [USD/nm]

saving33 = DOC_aepgds - DOC;
%Saving of DOC with Advanced-EPGDS [USD/nm]

IOC_aepgds = (C_OPS_6/(hours_A320*365*V_bs)) * (per_IOC);
%IOC with Advanced-EPGDS [USD/nm]

saving34 = IOC_aepgds - IOC;
%Saving of IOC with Advanced-EPGDS [USD/nm]

TOT_aepgds = DOC_aepgds + IOC_aepgds;
%TOC with Advanced-EPGDS [USD/nm]

saving35= TOT_aepgds - TOT;
%Saving of TOC with Advanced-EPGDS [USD/nm]

C_flying_aw = (C_OPS_8/(hours_A320*365*V_bs)) * (per_flying);
%C_flying with adaptive winglets [USD/nm]

saving43 = C_flying_aw - (C_crew + C_pol + (C_ins*(DOC)));
%Saving of C_flying with adaptive winglets [USD/nm]

C_maint_aw = (C_OPS_8/(hours_A320*365*V_bs)) * (per_maint);
%C_maint with adaptive winglets [USD/nm]

saving44 = C_maint_aw - DOC_maint;
%Saving of C_maint with adaptive winglets [USD/nm]
```

```
C_depr_aw = (C_OPS_8/(hours_A320*365*V_bs)) * (per_depr);
%C_depr with adaptive winglets [USD/nm]

saving45 = C_depr_aw - DOC_depr;
%Saving of C_depr with adaptive winglets [USD/nm]

C_tax_aw = (C_OPS_8/(hours_A320*365*V_bs)) * (per_tax);
%C_tax with adaptive winglets [USD/nm]

saving46 = C_tax_aw - (C_lf + C_nf + (C_rt*f_tax));
%Saving of C_tax with adaptive winglets [USD/nm]

DOC_aw = (C_OPS_8/(hours_A320*365*V_bs)) * (per_DOC);
%DOC with adaptive winglets [USD/nm]

saving47 = DOC_aw - DOC;
%Saving of DOC with adaptive winglets [USD/nm]

IOC_aw = (C_OPS_8/(hours_A320*365*V_bs)) * (per_IOC);
%IOC with adaptive winglets [USD/nm]

saving48 = IOC_aw - IOC;
%Saving of IOC with adaptive winglets [USD/nm]

TOT_aw = DOC_aw + IOC_aw;
%TOC with adaptive winglets [USD/nm]

saving49= TOT_aw - TOT;
%Saving of TOC with adaptive winglets [USD/nm]

C_flying_nem = (C_OPS_9/(hours_A320*365*V_bs)) * (per_flying);
%C_flying with new engine materials [USD/nm]

saving50 = C_flying_nem - (C_crew + C_pol + (C_ins*(DOC)));
%Saving of C_flying with new engine materials [USD/nm]

C_maint_nem = (C_OPS_9/(hours_A320*365*V_bs)) * (per_maint);
%C_maint with new engine materials [USD/nm]
```

```
saving51 = C_maint_nem - DOC_maint;
%Saving of C_maint with new engine materials [USD/nm]

C_depr_nem = (C_OPS_9/(hours_A320*365*V_bs)) * (per_depr);
%C_depr with new engine materials [USD/nm]

saving52 = C_depr_nem - DOC_depr;
%Saving of C_depr with new engine materials [USD/nm]

C_tax_nem = (C_OPS_9/(hours_A320*365*V_bs)) * (per_tax);
%C_tax with new engine materials [USD/nm]

saving53 = C_tax_nem - (C_lf + C_nf + (C_rt*f_tax));
%Saving of C_tax with new engine materials [USD/nm]

DOC_nem = (C_OPS_9/(hours_A320*365*V_bs)) * (per_DOC);
%DOC with new engine materials [USD/nm]

saving54 = DOC_nem - DOC;
%Saving of DOC with new engine materials [USD/nm]

IOC_nem = (C_OPS_9/(hours_A320*365*V_bs)) * (per_IOC);
%IOC with new engine materials [USD/nm]

saving55 = IOC_nem - IOC;
%Saving of IOC with new engine materials [USD/nm]

TOT_nem = DOC_nem + IOC_nem;
%TOC with new engine materials [USD/nm]

saving56= TOT_nem - TOT;
%Saving of TOC with new engine materials [USD/nm]
```

# APPENDIX C

The effects of the new technologies on the airplane final costs have been only reported in terms of RDTE, Manufacturing & Acquisition, Operating and Disposal costs. However, this short appendix shows the impacts each new technology has onto every specific sub-cost categories of each cost phase, for both the ATR-72 500 and the A-320 200. In particular, it has been chosen to apply the same percentage each sub-cost category has, compared to the final cost of each phase. Once this percentage had been easily calculated, the difference of cost between sub-categories, when a new technology is applied, was computed by simply multiplying the specific final cost phase, with the new technology, by the previously obtained percentage. Finally, the disposal phase will not be treated in this appendix as it has no sub-cost categories. The results are shown in the following three tables.

| RDTE-phase | New tech | % ATR | % A320 | ATR-72 500 | A-320 200 | Diff ATR | Diff A320 |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| Airframe engineering & Design cost | No new technology | 11.6% | 12.7% | 113.18 [M-USD] | 876 [M-USD] | — | — |
| Development, support & testing cost | | 2.1% | 3.4% | 21.13 [M-USD] | 238.7 [M-USD] | — | — |
| Engines + avionics | | 0.5% | 0.3% | 4.8 [M-USD] | 19.5 [M-USD] | — | — |
| Manufacturing cost | | 19.5% | 13,7% | 190.12 [M-USD] | 944.6 [M-USD] | — | — |
| Material cost | | 2.4% | 1.5% | 23.63 [M-USD] | 104.5 [M-USD] | — | — |
| Tooling cost | | 20.75% | 15.4% | 202.27 [M-USD] | 1059.4 [M-USD] | — | — |
| Quality control cost | | 2.5% | 1.8% | 24.71 [M-USD] | 122.8 [M-USD] | — | — |
| Flight-test operations cost | | 0.48% | 1.1% | 4.74 [M-USD] | 75.78 [M-USD] | — | — |

| RDTE-phase | New tech | % ATR | % A320 | ATR-72 500 | A-320 200 | Diff ATR | Diff A320 |
|---|---|---|---|---|---|---|---|
| Test & simulation facilities cost | | 0% | 10% | 0 [M-USD] | 688.31 [M-USD] | — | — |
| | | | | | | | |
| Airframe engineering & Design cost | Morphing wing | 20.53% | 27.17% | 276.12 [M-USD] | 1772.3 [M-USD] | +162.94 [M-USD] | +896.3 [M-USD] |
| Development, support & testing cost | | 3.71% | 7.27% | 49.9 [M-USD] | 474.22 [M-USD] | +28.76 [M-USD] | +235.52 [M-USD] |
| Engines + avionics | | 0% | 0% | 4.8 [M-USD] | 19.5 [M-USD] | — | — |
| Manufacturing cost | | 34.51% | 29.31% | 464.15 [M-USD] | 1911.89 [M-USD] | +274.04 [M-USD] | +967.29 [M-USD] |
| Material cost | | 4.24% | 3.21% | 57.02 [M-USD] | 209.38 [M-USD] | +33.4 [M-USD] | +104.88 [M-USD] |
| Tooling cost | | 36.72% | 32.95% | 493.88 [M-USD] | 2149.32 [M-USD] | +291.61 [M-USD] | +1090 [M-USD] |
| Quality control cost | | 0% | 0% | 24.71 [M-USD] | 122.8 [M-USD] | — | — |
| Flight-test operations cost | | 0% | 0% | 4.74 [M-USD] | 75.78 [M-USD] | — | — |
| Test & simulation facilities cost | | 0% | 0% | 0 [M-USD] | 688.31 [M-USD] | — | — |
| | | | | | | | |
| Airframe engineering & Design cost | | 20.53% | 27.17% | 208.37 [M-USD] | 1623.6 [M-USD] | +95.2 [M-USD] | +747.67 [M-USD] |
| Development, support & testing cost | | 3.71% | 7.27% | 37.65 [M-USD] | 434.45 [M-USD] | +16.52 [M-USD] | +195.75 [M-USD] |
| Engines + avionics | | 0% | 0% | 4.8 [M-USD] | 19.5 [M-USD] | — | — |
| Manufacturing cost | | 34.51% | 29.31% | 350.27 [M-USD] | 1751.5[M-USD] | +160.15 [M-USD] | +806.96 [M-USD] |

| RDTE-phase | New tech | % ATR | % A320 | ATR-72 500 | A-320 200 | Diff ATR | Diff A320 |
|---|---|---|---|---|---|---|---|
| Material cost | Electric actuators | 4.24% | 3.21% | 43.03 [M-USD] | 191.8 [M-USD] | +19.4 [M-USD] | +87.32 [M-USD] |
| Tooling cost | | 36.72% | 32.95% | 372.7 [M-USD] | 1969.1 [M-USD] | +170.43 [M-USD] | +909.69 [M-USD] |
| Quality control cost | | 0% | 0% | 24.71 [M-USD] | 122.8 [M-USD] | — | — |
| Flight-test operations cost | | 0% | 0% | 4.74 [M-USD] | 75.78 [M-USD] | — | — |
| Test & simulation facilities cost | | 0% | 0% | 0 [M-USD] | 688.31 [M-USD] | — | — |
| | | | | | | | |
| Airframe engineering & Design cost | SHM system | 20.53% | 27.17% | 208.37 [M-USD] | 1623.6 [M-USD] | +95.2 [M-USD] | +747.67 [M-USD] |
| Development, support & testing cost | | 3.71% | 7.27% | 37.65 [M-USD] | 434.45 [M-USD] | +16.52 [M-USD] | +195.75 [M-USD] |
| Engines + avionics | | 0% | 0% | 4.8 [M-USD] | 19.5 [M-USD] | — | — |
| Manufacturing cost | | 34.51% | 29.31% | 350.27 [M-USD] | 1751.5[M-USD] | +160.15 [M-USD] | +806.96 [M-USD] |
| Material cost | | 4.24% | 3.21% | 43.03 [M-USD] | 191.8 [M-USD] | +19.4 [M-USD] | +87.32 [M-USD] |
| Tooling cost | | 36.72% | 32.95% | 372.7 [M-USD] | 1969.1 [M-USD] | +170.43[ M-USD] | +909.69 [M-USD] |
| Quality control cost | | 0% | 0% | 24.71 [M-USD] | 122.8 [M-USD] | — | — |
| Flight-test operations cost | | 0% | 0% | 4.74 [M-USD] | 75.78 [M-USD] | — | — |
| Test & simulation facilities cost | | 0% | 0% | 0 [M-USD] | 688.31 [M-USD] | — | — |
| | | | | | | | |

| RDTE-phase | New tech | % ATR | % A320 | ATR-72 500 | A-320 200 | Diff ATR | Diff A320 |
|---|---|---|---|---|---|---|---|
| Airframe engineering & Design cost | Geared turbofan | — | 0% | — | 876 [M-USD] | — | — |
| Development, support & testing cost | | — | 9.89% | — | 530.8 [M-USD] | — | +292.09 [M-USD] |
| Engines + avionics | | — | 0.87% | — | 46.69 [M-USD] | — | +27.19 [M-USD] |
| Manufacturing cost | | — | 39.86% | — | 2139.3 [M-USD] | — | +1194.7 [M-USD] |
| Material cost | | — | 4.36% | — | 234 [M-USD] | — | +129.5 [M-USD] |
| Tooling cost | | — | 44.81% | — | 2404.9 [M-USD] | — | +1345.5 [M-USD] |
| Quality control cost | | — | 0% | — | 122.8 [M-USD] | — | — |
| Flight-test operations cost | | — | 0% | — | 75.78 [M-USD] | — | — |
| Test & simulation facilities cost | | — | 0% | — | 688.31 [M-USD] | — | — |
| | | | | | | | |
| Airframe engineering & Design cost | Laminar aerodynamics | 20.53% | 27.17% | 200.52 [M-USD] | 1623.9 [M-USD] | +87.34 [M-USD] | +747.95 [M-USD] |
| Development, support & testing cost | | 3.71% | 7.27% | 36.23 [M-USD] | 434.52 [M-USD] | +15.1 [M-USD] | 195.82 [M-USD] |
| Engines + avionics | | 0% | 0% | 4.8 [M-USD] | 19.5 [M-USD] | — | — |
| Manufacturing cost | | 34.51% | 29.31% | 337.07 [M-USD] | 1751.8 [M-USD] | +146.95 [M-USD] | +807.25 [M-USD] |
| Material cost | | 4.24% | 3.21% | 41.41 [M-USD] | 191.86 [M-USD] | +17.78 [M-USD] | +87.36 [M-USD] |
| Tooling cost | | 36.72% | 32.95% | 358.66 [M-USD] | 1969.42 [M-USD] | +156.39 [M-USD] | +910 [M-USD] |

| RDTE-phase | New tech | % ATR | % A320 | ATR-72 500 | A-320 200 | Diff ATR | Diff A320 |
|---|---|---|---|---|---|---|---|
| Quality control cost | | 0% | 0% | 24.71 [M-USD] | 122.8 [M-USD] | — | — |
| Flight-test operations cost | | 0% | 0% | 4.74 [M-USD] | 75.78 [M-USD] | — | — |
| Test & simulation facilities cost | | 0% | 0% | 0 [M-USD] | 688.31 [M-USD] | — | — |
| | | | | | | | |
| Airframe engineering & Design cost | | 20.53% | 27.17% | 208.37 [M-USD] | 1623.6 [M-USD] | +95.2 [M-USD] | +747.67 [M-USD] |
| Development, support & testing cost | | 3.71% | 7.27% | 37.65 [M-USD] | 434.45 [M-USD] | +16.52 [M-USD] | +195.75 [M-USD] |
| Engines + avionics | | 0% | 0% | 4.8 [M-USD] | 19.5 [M-USD] | — | — |
| Manufacturing cost | | 34.51% | 29.31% | 350.27 [M-USD] | 1751.5[M-USD] | +160.15 [M-USD] | +806.96 [M-USD] |
| Material cost | Advanced EPGDS | 4.24% | 3.21% | 43.03 [M-USD] | 191.8 [M-USD] | +19.4 [M-USD] | +87.32 [M-USD] |
| Tooling cost | | 36.72% | 32.95% | 372.7 [M-USD] | 1969.1 [M-USD] | +170.43 [M-USD] | +909.69 [M-USD] |
| Quality control cost | | 0% | 0% | 24.71 [M-USD] | 122.8 [M-USD] | — | — |
| Flight-test operations cost | | 0% | 0% | 4.74 [M-USD] | 75.78 [M-USD] | — | — |
| Test & simulation facilities cost | | 0% | 0% | 0 [M-USD] | 688.31 [M-USD] | — | — |
| | | | | | | | |
| Airframe engineering & Design cost | | 0% | — | 113.18 [M-USD] | — | — | — |
| Development, support & testing cost | | 4.64% | — | 42.1 [M-USD] | — | +20.97 [M-USD] | — |

| RDTE-phase | New tech | % ATR | % A320 | ATR-72 500 | A-320 200 | Diff ATR | Diff A320 |
|---|---|---|---|---|---|---|---|
| Engines + avionics | Advanced propellers | 1.1% | — | 9.98 [M-USD] | — | +5.18 [M-USD] | — |
| Manufacturing cost | | 43.1% | — | 391.07 [M-USD] | — | +200.95 [M-USD] | — |
| Material cost | | 5.3% | — | 48.09 [M-USD] | — | +24.46 [M-USD] | — |
| Tooling cost | | 45.85% | — | 416.03 [M-USD] | — | +213.75 [M-USD] | — |
| Quality control cost | | 0% | — | 24.71 [M-USD] | — | — | — |
| Flight-test operations cost | | 0% | — | 4.74 [M-USD] | — | — | — |
| Test & simulation facilities cost | | 0% | — | 0 [M-USD] | — | — | — |
| | | | | | | | |
| Airframe engineering & Design cost | Adaptive winglets | 20.41% | 26.54% | 252.87 [M-USD] | 1697.5 [M-USD] | +129.7 [M-USD] | +821.5 [M-USD] |
| Development, support & testing cost | | 3.69% | 7.1% | 43.91 [M-USD] | 454.11 [M-USD] | +22.78 [M-USD] | +215.41 [M-USD] |
| Engines + avionics | | 0% | 0% | 4.8 [M-USD] | 19.5 [M-USD] | — | — |
| Manufacturing cost | | 34.32% | 28.63% | 408.4 [M-USD] | 1831.2 [M-USD] | +218.28 [M-USD] | +886.57 [M-USD] |
| Material cost | | 4.22% | 3.13% | 50.21 [M-USD] | 200.2 [M-USD] | +26.58 [M-USD] | +95.69 [M-USD] |
| Tooling cost | | 36.52% | 32.18% | 434.58 [M-USD] | 2058.23 [M-USD] | +232.31 [M-USD] | +998.83 [M-USD] |
| Quality control cost | | 0% | 0% | 24.71 [M-USD] | 122.8 [M-USD] | — | — |
| Flight-test operations cost | | 0.84% | 2.3% | 10 [M-USD] | 147.1 [M-USD] | +5.26 [M-USD] | +71.32 [M-USD] |

| RDTE-phase | New tech | % ATR | % A320 | ATR-72 500 | A-320 200 | Diff ATR | Diff A320 |
|---|---|---|---|---|---|---|---|
| Test & simulation facilities cost | | 0% | 0% | 0 [M-USD] | 688.31 [M-USD] | — | — |
| | | | | | | | |
| Airframe engineering & Design cost | New engine materials | 0% | 0% | 113.18 [M-USD] | 876 [M-USD] | — | — |
| Development, support & testing cost | | 0% | 0% | 21.13 [M-USD] | 238.7 [M-USD] | — | — |
| Engines + avionics | | 1.15% | 0.97% | 11.91 [M-USD] | 50.22 [M-USD] | +7.11 [M-USD] | +30.72 [M-USD] |
| Manufacturing cost | | 45.04% | 44.25% | 466.61 [M-USD] | 2291.2 [M-USD] | +276.49 [M-USD] | +1346.6 [M-USD] |
| Material cost | | 5.54% | 4.84% | 57.39 [M-USD] | 250.6 [M-USD] | +33.76 [M-USD] | +146.11 [M-USD] |
| Tooling cost | | 47.93% | 49.74% | 496.55 [M-USD] | 2575.5 [M-USD] | +202.27 [M-USD] | +1516.1 [M-USD] |
| Quality control cost | | 0% | 0% | 24.71 [M-USD] | 122.8 [M-USD] | — | — |
| Flight-test operations cost | | 0% | 0% | 4.74 [M-USD] | 75.78 [M-USD] | — | — |
| Test & simulation facilities cost | | 0% | 0% | 0 [M-USD] | 688.31 [M-USD] | — | — |

Table 6.1 Impact of every new technology onto each cost category of the RDTE phase

| ACQ | New tech | % ATR | % A320 | ATR-72 500 | A-320 200 | Diff ATR | Diff A320 |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| Airframe engineering & Design cost | | 1.94% | 5.23% | 174.84 [M-USD] | 2170.7 [M-USD] | — | — |
| Cost of engines and avionics | | 23.4% | 13.76% | 2103.8 [M-USD] | 5708.1 [M-USD] | — | — |

| ACQ | New tech | % ATR | % A320 | ATR-72 500 | A-320 200 | Diff ATR | Diff A320 |
|---|---|---|---|---|---|---|---|
| Interior production cost | No new technology | 2.2% | 2.18% | 198.37 [M-USD] | 903.68 [M-USD] | — | — |
| Manufacturing cost | | 38% | 47.18% | 3404 [M-USD] | 19576 [M-USD] | — | — |
| Material cost | | 23.2% | 14.88% | 2098.9 [M-USD] | 6174.7 [M-USD] | — | — |
| Tooling cost | | 5% | 10.36% | 453.54 [M-USD] | 4298.8 [M-USD] | — | — |
| Quality control cost | | 4.8% | 6.13% | 442.51 [M-USD] | 2544.8 [M-USD] | — | — |
| Flight test operations cost | | 1.24% | 0.27% | 112 [M-USD] | 112 [M-USD] | — | — |
| | | | | | | | |
| Airframe engineering & Design cost | Morphing wing | 2.6% | 11.39% | 188.8 [M-USD] | 2310.3 [M-USD] | +13.96 [M-USD] | +139.6 [M-USD] |
| Cost of engines and avionics | | 0% | 0% | 2103.8 [M-USD] | 5708.1 [M-USD] | — | — |
| Interior production cost | | 0% | 0% | 198.37 [M-USD] | 903.68 [M-USD] | — | — |
| Manufacturing cost | | 50.92% | 37.44% | 3894.4 [M-USD] | 23090 [M-USD] | +490.4 [M-USD] | +3514 [M-USD] |
| Material cost | | 31.08% | 17.17% | 2293.9 [M-USD] | 6732.7 [M-USD] | +195 [M-USD] | +558 [M-USD] |
| Tooling cost | | 6.7% | 14.47% | 467.25 [M-USD] | 4635.1 [M-USD] | +13.71 [M-USD] | +336.3 [M-USD] |
| Quality control cost | | 6.43% | 11.88% | 455.57 [M-USD] | 2714 [M-USD] | +13.06 [M-USD] | +169.2 [M-USD] |
| Flight test operations cost | | 1.66% | 8.42% | 113.94 [M-USD] | 117.71 [M-USD] | +1.94 [M-USD] | +5.71 [M-USD] |
| | | | | | | | |
| Airframe engineering & Design cost | | 2.65% | 12.4% | 175.74 [M-USD] | 2298.1 [M-USD] | +0.9 [M-USD] | +127.4 [M-USD] |
| Cost of engines and avionics | | 0% | 0% | 2103.8 [M-USD] | 5708.1 [M-USD] | — | — |
| Interior production cost | | 0% | 0% | 198.37 [M-USD] | 903.68 [M-USD] | — | — |

| ACQ | New tech | % ATR | % A320 | ATR-72 500 | A-320 200 | Diff ATR | Diff A320 |
|---|---|---|---|---|---|---|---|
| Manufacturing cost | Electric actuators | 52.06% | 39.74% | 3875 [M-USD] | 23339 [M-USD] | +471 [M-USD] | +3763 [M-USD] |
| Material cost | | 31.78% | 18.69% | 2274.4 [M-USD] | 6749.5 [M-USD] | +175.5 [M-USD] | +574.8 [M-USD] |
| Tooling cost | | 6.85% | 15.75% | 461 [M-USD] | 4621.4 [M-USD] | +7.46 [M-USD] | +322.6 [M-USD] |
| Quality control cost | | 6.57% | 12.93% | 449.4 [M-USD] | 2699.7[M-USD] | +6.93 [M-USD] | +154.9 [M-USD] |
| Flight test operations cost | | 0% | 0% | 112 [M-USD] | 112 [M-USD] | — | — |
| | | | | | | | |
| Airframe engineering & Design cost | SHM system | 2.6% | 11.39% | 176.34 [M-USD] | 2284.4 [M-USD] | +1.5 [M-USD] | +113.7 [M-USD] |
| Cost of engines and avionics | | 0% | 0% | 2108 [M-USD] | 5719.6 [M-USD] | — | — |
| Interior production cost | | 0% | 0% | 198.77 [M-USD] | 905.5 [M-USD] | — | — |
| Manufacturing cost | | 50.92% | 37.44% | 3851.4 [M-USD] | 22878 [M-USD] | +447.7 [M-USD] | +3302 [M-USD] |
| Material cost | | 31.08% | 17.17% | 2268.8 [M-USD] | 6659 [M-USD] | +169.9 [M-USD] | +485 [M-USD] |
| Tooling cost | | 6.7% | 14.47% | 459.9 [M-USD] | 4584.8 [M-USD] | +6.36 [M-USD] | +286 [M-USD] |
| Quality control cost | | 6.43% | 11.88% | 450.6 [M-USD] | 2674 [M-USD] | +8.11 [M-USD] | +129.3 [M-USD] |
| Flight test operations cost | | 1.66% | 8.42% | 112.7 [M-USD] | 116.42 [M-USD] | +0.7 [M-USD] | +4.42 [M-USD] |
| | | | | | | | |
| Airframe engineering & Design cost | Geared turbofan | 0% | 0% | — | 2170.7 [M-USD] | — | — |
| Cost of engines and avionics | | 100% | 100% | — | 15051 [M-USD] | — | +9342.9 [M-USD] |
| Interior production cost | | 0% | 0% | — | 903.68 [M-USD] | — | — |
| Manufacturing cost | | 0% | 0% | — | 19576 [M-USD] | — | — |

| ACQ | New tech | % ATR | % A320 | ATR-72 500 | A-320 200 | Diff ATR | Diff A320 |
|---|---|---|---|---|---|---|---|
| Material cost | | 0% | 0% | — | 6174.7 [M-USD] | — | — |
| Tooling cost | | 0% | 0% | — | 4298.8 [M-USD] | — | — |
| Quality control cost | | 0% | 0% | — | 2544.8 [M-USD] | — | — |
| Flight test operations cost | | 0% | 0% | — | 112 [M-USD] | — | — |
| | | | | | | | |
| Airframe engineering & Design cost | Laminar aerodynamics | 2.65% | 12.4% | 178.38 [M-USD] | 2332.6 [M-USD] | +3.54 [M-USD] | +161.9 [M-USD] |
| Cost of engines and avionics | | 0% | 0% | 2103.8 [M-USD] | 5708.1 [M-USD] | — | — |
| Interior production cost | | 0% | 0% | 198.37 [M-USD] | 903.68 [M-USD] | — | — |
| Manufacturing cost | | 52.06% | 39.74% | 3933 [M-USD] | 23744 [M-USD] | +529 [M-USD] | +4168.4 [M-USD] |
| Material cost | | 31.78% | 18.69% | 2308.6 [M-USD] | 6827.8 [M-USD] | +209.7 [M-USD] | +653.1 [M-USD] |
| Tooling cost | | 6.85% | 15.75% | 465.6 [M-USD] | 4690.8 [M-USD] | +12 [M-USD] | +329.1 [M-USD] |
| Quality control cost | | 6.57% | 12.93% | 456.2 [M-USD] | 2741.1 [M-USD] | +13.7 [M-USD] | +196.28 [M-USD] |
| Flight test operations cost | | 0% | 0% | 112 [M-USD] | 112 [M-USD] | — | — |
| | | | | | | | |
| Airframe engineering & Design cost | Advanced EPGDS | 2.65% | 12.4% | 176.1 [M-USD] | 2302.6 [M-USD] | +1.25 [M-USD] | +132 [M-USD] |
| Cost of engines and avionics | | 0% | 0% | 2103.8 [M-USD] | 5708.1 [M-USD] | — | — |
| Interior production cost | | 0% | 0% | 198.37 [M-USD] | 903.68 [M-USD] | — | — |
| Manufacturing cost | | 52.06% | 39.74% | 3882.6 [M-USD] | 23387 [M-USD] | +478.6 [M-USD] | +3811.4 [M-USD] |
| Material cost | | 31.78% | 18.69% | 2279 [M-USD] | 6740.3 [M-USD] | +180 [M-USD] | +565.6 [M-USD] |

| ACQ | New tech | % ATR | % A320 | ATR-72 500 | A-320 200 | Diff ATR | Diff A320 |
|---|---|---|---|---|---|---|---|
| Tooling cost | | 6.85% | 15.75% | 459.66 [M-USD] | 4630.6 [M-USD] | +6.12 [M-USD] | +331.8 [M-USD] |
| Quality control cost | | 6.57% | 12.93% | 450.34 [M-USD] | 2705.9 [M-USD] | +7.83 [M-USD] | +161.1 [M-USD] |
| Flight test operations cost | | 0% | 0% | 112 [M-USD] | 2170.7 [M-USD] | — | — |
| | | | | | | | |
| Airframe engineering & Design cost | Advanced propellers | 0% | 0% | 174.84 [M-USD] | — | — | — |
| Cost of engines and avionics | | 100% | 100% | 4020.2 [M-USD] | — | +1916.4 [M-USD] | — |
| Interior production cost | | 0% | 0% | 198.37 [M-USD] | — | — | — |
| Manufacturing cost | | 0% | 0% | 3404 [M-USD] | — | — | — |
| Material cost | | 0% | 0% | 2098.9 [M-USD] | — | — | — |
| Tooling cost | | 0% | 0% | 453.54 [M-USD] | — | — | — |
| Quality control cost | | 0% | 0% | 442.51 [M-USD] | — | — | — |
| Flight test operations cost | | 0% | 0% | 112 [M-USD] | — | — | — |
| | | | | | | | |
| Airframe engineering & Design cost | Adaptive winglets | 2.6% | 11.39% | 177.75 [M-USD] | 2303.5 [M-USD] | +2.91 [M-USD] | +132.85 [M-USD] |
| Cost of engines and avionics | | 0% | 0% | 2124.8 [M-USD] | 5765.2 [M-USD] | — | — |
| Interior production cost | | 0% | 0% | 200.35 [M-USD] | 912.72 [M-USD] | — | — |
| Manufacturing cost | | 50.92% | 37.44% | 3882.2 [M-USD] | 22467 [M-USD] | +478.2 [M-USD] | +2892 [M-USD] |
| Material cost | | 31.08% | 17.17% | 2287 [M-USD] | 6712.8 [M-USD] | +188.15 [M-USD] | +538.16 [M-USD] |
| Tooling cost | | 6.7% | 14.47% | 463.57 [M-USD] | 4621.4 [M-USD] | +10 [M-USD] | +322.6 [M-USD] |

| ACQ | New tech | % ATR | % A320 | ATR-72 500 | A-320 200 | Diff ATR | Diff A320 |
|---|---|---|---|---|---|---|---|
| Quality control cost | | 6.43% | 11.88% | 54.22 [M-USD] | 2706 [M-USD] | +11.71 [M-USD] | +161.2 [M-USD] |
| Flight test operations cost | | 1.66% | 8.42% | 113.6 [M-USD] | 117.36 [M-USD] | +1.6 [M-USD] | +5.36 [M-USD] |
| | | | | | | | |
| Airframe engineering & Design cost | New engine materials | 0% | 0% | 174.84 [M-USD] | 2170.7 [M-USD] | — | — |
| Cost of engines and avionics | | 100% | 100% | 4020.2 [M-USD] | 15051 [M-USD] | +1916.4 [M-USD] | +9342.9 [M-USD] |
| Interior production cost | | 0% | 0% | 198.37 [M-USD] | 903.68 [M-USD] | — | — |
| Manufacturing cost | | 0% | 0% | 3404 [M-USD] | 19576 [M-USD] | — | — |
| Material cost | | 0% | 0% | 2098.9 [M-USD] | 6174.7 [M-USD] | — | — |
| Tooling cost | | 0% | 0% | 453.54 [M-USD] | 4298.8 [M-USD] | — | — |
| Quality control cost | | 0% | 0% | 442.51 [M-USD] | 2544.8 [M-USD] | — | — |
| Flight test operations cost | | 0% | 0% | 112 [M-USD] | 112 [M-USD] | — | — |

Table 6.2 Impact of every new technology onto each cost category of the acquisition costs

| OP | New tech | % ATR | % A320 | ATR-72 500 | A-320 200 | Diff ATR | Diff A320 |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| DOC flying | No new technology | 22.03% | 12.97% | 7.39 [USD/nm] | 5.91 [USD/nm] | — | — |
| DOC maintenance | | 18.94% | 29.08% | 5.52 [USD/nm] | 10.55 [USD/nm] | — | — |
| DOC depreciation | | 12.05% | 13.7% | 3.51 [USD/nm] | 4.97 [USD/nm] | — | — |
| DOC fees/taxes | | 8.28% | 5.54% | 2.62 [USD/nm] | 2.28 [USD/nm] | — | — |
| DOC | | 66.67% | 66.67% | 19.43 [USD/nm] | 24.18 [USD/nm] | | |

| OP | New tech | % ATR | % A320 | ATR-72 500 | A-320 200 | Diff ATR | Diff A320 |
|---|---|---|---|---|---|---|---|
| IOC | | 33.34% | 33.34% | 9.72 [USD/nm] | 12.09 [USD/nm] | — | — |
| TOT | | — | — | 29.15 [USD/nm] | 36.27 [USD/nm] | — | — |
| | | | | | | | |
| DOC flying | Morphing wing | 11.21% | 0.2% | 2.75 [USD/nm] | 0.86 [USD/nm] | -4.64 [USD/nm] | -5.05 [USD/nm] |
| DOC maintenance | | 27.62% | 36.6% | 7.1 [USD/nm] | 11.7 [USD/nm] | +1.58 [USD/nm] | +1.15 [USD/nm] |
| DOC depreciation | | 0% | 0% | 3.51 [USD/nm] | 4.97 [USD/nm] | — | — |
| DOC fees/taxes | | 0% | 0% | 2.62 [USD/nm] | 2.28 [USD/nm] | — | — |
| DOC | | 62.17% | 62.1% | 15.98 [USD/nm] | 19.81 [USD/nm] | -3.06 [USD/nm] | -3.9 [USD/nm] |
| IOC | | 0% | 0% | 9.72 [USD/nm] | 12.09 [USD/nm] | — | — |
| TOT | | — | — | 25.7 [USD/nm] | 31.9 [USD/nm] | -3.06 [USD/nm] | -3.9 [USD/nm] |
| | | | | | | | |
| DOC flying | Electric actuators | 35.32% | 35.57% | 6.15 [USD/nm] | 4.1 [USD/nm] | -1.24 [USD/nm] | -1.81 [USD/nm] |
| DOC maintenance | | 0% | 0% | 5.52 [USD/nm] | 10.55 [USD/nm] | — | — |
| DOC depreciation | | 0% | 0%% | 3.51 [USD/nm] | 4.97 [USD/nm] | — | — |
| DOC fees/taxes | | 0% | 0% | 2.62 [USD/nm] | 2.28 [USD/nm] | — | — |
| DOC | | 64.68% | 64.43% | 17.8 [USD/nm] | 21.9 [USD/nm] | -1.24 [USD/nm] | -1.81 [USD/nm] |
| IOC | | 0% | 0% | 9.72 [USD/nm] | 12.09 [USD/nm] | — | — |
| TOT | | — | — | 27.52 [USD/nm] | 33.99 [USD/nm] | -1.24 [USD/nm] | -1.81 [USD/nm] |
| | | | | | | | |
| DOC flying | | 0% | 0% | 7.39 [USD/nm] | 5.91 [USD/nm] | — | — |

| OP | New tech | % ATR | % A320 | ATR-72 500 | A-320 200 | Diff ATR | Diff A320 |
|---|---|---|---|---|---|---|---|
| DOC maintenance | SHM system | 35.87% | 29.08% | 3.86 [USD/nm] | 7.8 [USD/nm] | -1.66 [USD/nm] | -2.75 [USD/nm] |
| DOC depreciation | | 0% | 0% | 3.51 [USD/nm] | 4.97 [USD/nm] | — | — |
| DOC fees/taxes | | 0% | 0% | 2.62 [USD/nm] | 2.28 [USD/nm] | — | — |
| DOC | | 64.13% | 63.41% | 17.38 [USD/nm] | 20.96 [USD/nm] | -1.66 [USD/nm] | -2.75 [USD/nm] |
| IOC | | 0% | 0% | 9.72 [USD/nm] | 12.09 [USD/nm] | — | — |
| TOT | | — | — | 27.1 [USD/nm] | 33.05 [USD/nm] | -1.66 [USD/nm] | -2.75 [USD/nm] |
| | | | | | | | |
| DOC flying | Geared turbofan | — | 4.26% | — | 1.66 [USD/nm] | — | -4.25 [USD/nm] |
| DOC maintenance | | — | 34.16% | — | 10.9 [USD/nm] | — | +0.35 [USD/nm] |
| DOC depreciation | | — | 0% | — | 4.97 [USD/nm] | — | — |
| DOC fees/taxes | | — | 0% | — | 2.28 [USD/nm] | — | — |
| DOC | | — | 62.1% | — | 19.81 [USD/nm] | — | -3.9 [USD/nm] |
| IOC | | — | 0% | — | 12.09 [USD/nm] | — | — |
| TOT | | — | — | — | 31.9 [USD/nm] | — | -3.9 [USD/nm] |
| | | | | | | | |
| DOC flying | Laminar aerodynamics | 14.09% | 2.3% | 5.59 [USD/nm] | 3.38 [USD/nm] | -1.8 [USD/nm] | -2.53 [USD/nm] |
| DOC maintenance | | 21.75% | 33.89% | 6.07 [USD/nm] | 11.65 [USD/nm] | +0.55 [USD/nm] | +1.1 [USD/nm] |
| DOC depreciation | | 0% | 0% | 3.51 [USD/nm] | 4.97 [USD/nm] | — | — |
| DOC fees/taxes | | 0% | 0% | 2.62 [USD/nm] | 2.28 [USD/nm] | — | — |

| OP | New tech | % ATR | % A320 | ATR-72 500 | A-320 200 | Diff ATR | Diff A320 |
|---|---|---|---|---|---|---|---|
| DOC | | 65.16% | 64.82% | 18.18 [USD/nm] | 22.28 [USD/nm] | -1.25 [USD/nm] | -1.43 [USD/nm] |
| IOC | | 0% | 0% | 9.72 [USD/nm] | 12.09 [USD/nm] | — | — |
| TOT | | — | — | 27.9 [USD/nm] | 34.37 [USD/nm] | -1.25 [USD/nm] | -1.43 [USD/nm] |
| | | | | | | | |
| DOC flying | Advanced EPGDS | 35.58% | 35.83% | 5.95 [USD/nm] | 3.86 [USD/nm] | -1.44 [USD/nm] | -2.05 [USD/nm] |
| DOC maintenance | | 0% | 0% | 5.52 [USD/nm] | 10.55 [USD/nm] | — | — |
| DOC depreciation | | 0% | 0% | 3.51 [USD/nm] | 4.97 [USD/nm] | — | — |
| DOC fees/taxes | | 0% | 0% | 2.62 [USD/nm] | 2.28 [USD/nm] | — | — |
| DOC | | 64.42% | 64.17% | 17.6 [USD/nm] | 21.66 [USD/nm] | -1.44 [USD/nm] | -2.05 [USD/nm] |
| IOC | | 0% | 0% | 9.72 [USD/nm] | 12.09 [USD/nm] | — | — |
| TOT | | — | — | 27.32 [USD/nm] | 33.75 [USD/nm] | -1.44 [USD/nm] | -2.05 [USD/nm] |
| | | | | | | | |
| DOC flying | Advanced propellers | 13.9% | — | 3.2 [USD/nm] | — | -4.19 [USD/nm] | — |
| DOC maintenance | | 24.58% | — | 6.21 [USD/nm] | — | +0.69 [USD/nm] | — |
| DOC depreciation | | 0% | — | 3.51 [USD/nm] | — | — | — |
| DOC fees/taxes | | 0% | — | 2.62 [USD/nm] | — | — | — |
| DOC | | 61.52% | — | 15.54 [USD/nm] | — | -3.5 [USD/nm] | — |
| IOC | | 0% | — | 9.72 [USD/nm] | — | — | — |
| TOT | | — | — | 25.26 [USD/nm] | — | -3.5 [USD/nm] | — |
| | | | | | | | |

| OP | New tech | % ATR | % A320 | ATR-72 500 | A-320 200 | Diff ATR | Diff A320 |
|---|---|---|---|---|---|---|---|
| DOC flying | Adaptive winglets | 11.5% | 0.8% | 3.92 [USD/nm] | 1.71 [USD/nm] | -3.47 [USD/nm] | -4.2 [USD/nm] |
| DOC maintenance | | 25.41% | 35.97% | 6.77 [USD/nm] | 11.83 [USD/nm] | +1.25 [USD/nm] | +1.28 [USD/nm] |
| DOC depreciation | | 0% | 0% | 3.51 [USD/nm] | 4.97 [USD/nm] | — | — |
| DOC fees/taxes | | 0% | 0% | 2.62 [USD/nm] | 2.28 [USD/nm] | — | — |
| DOC | | 63.13% | 63.23% | 16.82 [USD/nm] | 20.79 [USD/nm] | -2.22 [USD/nm] | -2.92 [USD/nm] |
| IOC | | 0% | 0% | 9.72 [USD/nm] | 12.09 [USD/nm] | — | — |
| TOT | | — | — | 26.64 [USD/nm] | 32.88 [USD/nm] | -2.22 [USD/nm] | -2.92 [USD/nm] |
| | | | | | | | |
| DOC flying | New engine materials | 36.11% | 36.48% | 5.55 [USD/nm] | 3.26 [USD/nm] | -1.84 [USD/nm] | -2.65 [USD/nm] |
| DOC maintenance | | 0% | 0% | 5.52 [USD/nm] | 10.55 [USD/nm] | — | — |
| DOC depreciation | | 0% | 0% | 3.51 [USD/nm] | 4.97 [USD/nm] | — | — |
| DOC fees/taxes | | 0% | 0% | 2.62 [USD/nm] | 2.28 [USD/nm] | — | — |
| DOC | | 63.89% | 63.52% | 17.2 [USD/nm] | 21.06 [USD/nm] | -1.84 [USD/nm] | -2.65 [USD/nm] |
| IOC | | 0% | 0% | 9.72 [USD/nm] | 12.09 [USD/nm] | — | — |
| TOT | | — | — | 26.92 [USD/nm] | 33.15 [USD/nm] | -1.84 [USD/nm] | -2.65 [USD/nm] |

Table 6.3 Impact of every new technology onto each cost category of the TOT

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